Sound Radiation of Singing Voices

Dissertation zur Erlangung der Würde
des Doktors der Philosophie
der Fakultät Geisteswissenschaften
Fachbereich Systematische Musikwissenschaft
der Universität Hamburg

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Hamburg 2019

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Vorsitzender der Prüfungskommission:
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Tag der Disputation:
4. Juni. 2018

Acknowledgment

I would like to address a few words of thanks: Foremost, I would like to thank my supervisor Prof. Dr. Rolf Bader for his steady support and advice. Without that, I would not have had the courage to be involved with the field of acoustics. Warm thanks also to Prof. Dr. Malte Kob, Prof. Dr. Albrecht Schneider and all my wonderful colleagues for their constant helpfulness. In addition, I would like to say many thanks to Claudia Stirnat, Dr. Tim Ziemer and Anne & Dr. Jost Hübner, who supported me in terms of the proofreading of this work. And also many thanks to all the participants involved in the experiments.

Finally, I would like to express my gratitude to my family, especially to my mother Terumi Takada, who had constantly accompanied me at any time since my birth. I want to thank her for her patience, her understanding and her trust in me. In appreciation of that, this doctoral thesis is dedicated to her 70th birthday and my late father Yasunobu Takada.

The phase where I had busied myself with this topic was sure the most challenging period but at the same time one of the most wonderful times in my life.

Thank you again to all!

Hamburg, September 7, 2019

Orie Abe (geb. Takada)

Contents

1 Introduction

The generation of sound in the human voice is a fascinating phenomenon. It is produced by a structured mechanism of the body: The voice originates from air pressure produced by the thorax and the lung, then its stream passes through the vocal cords to produce the original sound of the voice. After that, the raw voice will be modified in the vocal tract and finally transmitted as a result of the aforementioned process. Thanks to this mechanism, the most often-used method of communication among humans is enabled. However, this kind of communication using vocal sounds is not only common amongst human beings but also among certain animals. This applies coequally for singing. Australian physicist Neville H. Fletcher mentioned the following:

"An active animal can typically produce a sustained mechanical power output of up to 10 watt per kilogram of body weight, or 10mW/g, though humans can work at only about one tenth of this rate. Humans and other vertebrates can typically employ only a small fraction, 1 to 10%, of this power for sound production, but insects may be able to use as much as 50%. These figures serve as a guide to the available power input to the acoustic system but, (...), the efficiency with which it is converted to radiated sound is very small." [33].

According to Fletcher, humans usually use only 1% of their total power, when producing their voice with the use of the respiratory system. In extreme cases, the voice can use up to 10% of their available power output [33]. Unquestionably, singing demands more mechanical power than speaking, thus a larger amount of this maximal power might be needed in some fields of singing, such as dramatic opera singing.

Each resonating structure can produce sound when an excitation occurs. In the production of sound with a musical instrument, its radiating structure is the instrument itself and the sound is generated by the player and finally radiated into the air. But when the human voice is employed as an "musical instrument," like the singing voice, the instrument which produces the sound is not outside of the body, as with other musical instruments, but it is the singers body itself: In the body all three the components — the power source (lungs), the sound generator (larynx) and the resonator (vocal tract) — already exist, and no excitation by a player from the outside is used.

But what is "voice sound" generally? Swedish voice researcher Johan Sundberg defines it as follows:

"All sounds can be considered voice sounds if they originate from an airstream from the lungs that is processed by the vocal cords and then modified by the pharynx, the mouth, and perhaps also the nose cavities."[1] [65].

The whole vocal organ of a singer is working as a musical instrument, where in the end, the sound is radiated from the body into the air. Therefore a cognitive control of the bodily functions is necessary. Singers learn in the process of their training to control the relevant parts of the body by exercising. This implies that the singer knows which anatomical structures need to be activated and adjusted, and in which degree these adjustments have to be made, to gain certain effects in regard to sound and certain styles of music or certain expressive features. A classical singer needs to pay special attention to their body to use it like a musical instrument. This is because classical singers rarely use electric amplification, even with large audiences. Furthermore classical singers, specially opera singers, often have to compete against a loud orchestral accompaniment. Therefore a great physical effort is needed.
In contrast, nonclassical singers usually use microphones, so that less physical force is necessary. Here the vocal instrument is used for communicative purpose, just like in spoken communication, but by means of music.

But in any case, this does not change the fact that each singer's voice comes from the body while singing and a maximum of energy is radiated from the mouth. It is easy to presume that the mouth is working as a mouth piece, comparable to the mouth piece of a trumpet, and it can surely do so, when the mouth is open. But the sound can still be audible, even though it is hummed with closed lips. Where does the energy go then? The energy has to be radiated somehow, otherwise the sound would not be

[1] Although the indication of this definition shown above, Sundberg suggests that not all speech sounds are voice sounds. A whisper for example is unvoiced [65]. This means that voice sound may be an unvoiced sound that is not affected by the process of vocal cords. For this reason, he confesses that a correct grasp of the definition of the term "voice sound" is difficult.

hearable. Another interesting fact is that singers sometimes remark that certain parts of their body tend to vibrate while singing. What about such vibrations? Do these have greater or less influence on the total energy of the singing voice? Or is sound radiation from singers restricted to the mouth?

Furthermore, singers also remark that the degree of such vibrations vary in correlation with the vocal technique, the pitch, and the vowel used. Hence it can be expected that the pattern of sound radiation changes if a singer adopts a different vocal technique or sings a different vowel or tone at a different pitch. But, is that actually so, as most musical instruments have complex patterns of sound radiation, which change with direction, pitches played and other factors?

For these reasons, the topic addressed in this study is mainly how strong the radiation energy of the singing voice from the upper body is, in comparison to the mouth radiation, and whether the radiation pattern of a singer's voice can be varied according to vocal technique, pitch, and vowel.

To round up the introduction, I would briefly like to sketch the content of this work: The first chapter, "Voice Production of Singing Voice," takes a quick glance at how the singing voice sound is produced physiologically. In addition, it is explained what we generally mean by using the terms "register" and "singer's formant" when talking about singing voice.

The second chapter, "Singing of Classical and Nonclassical Vocal Styles – Pop and Musical Theater Singing," demonstrates how the characteristics of singing techniques used in the three musical genres are chosen, seen from physiological and acoustical point of views. The differences among classical and nonclassical vocal styles are substantial due to the aesthetic of their music and the physical aspects for that purpose alone.

The third chapter, "Vibration and Radiation of Singing Voice: Previous Researches," introduces the methods and results from already existing research on bodily vibration and sound radiation of singing voice, which relate to my study. Regarding vibrational and radiating energy of singing voice, many researchers have already undertaken investigations on these topics. Vibrational energy seems to have been of interest to voice researchers for a long time. This might be due to the fact that singers often talk about the vibrations perceived at certain parts of their body. Therefore, the third chapter will take a deeper look into this topic that is often considered to be an important factor in classical singing.

The fourth chapter, “Research on Sound Radiation of Singing Voice: Methods and Materials,” is a central chapter in this work and the main subject of my work. The chapter demonstrates research and analytical methods, as well as the materials used in this study. For this study, the sound energy of seven trained singers from four musical genres (classical, musical theater, popular and Soul singers) was measured at fifteen parts of the body while the participants sang five vowels (a – e – i – o – u) at different pitches (90, 120, 180, 250, 380 and 500 Hz) in accordance with their voice classification. With regard to the research method, the previous studies on this topic have mostly been executed using an accelerometer, with which the energy of each desired part of the body has been measured. However, here in my investigation a microphone array of 121 microphones was in use. This made it possible to pick up and analyze the information from different angles, as will be shown in this chapter.

In the fifth and sixth chapter, the results gained and analyzed will be presented from different aspects. The fifth chapter mainly shows radiation patterns of the all singing voices measured at different parts of the body at various pitches. These results will be displayed as visually projected on an image of the upper part of the human body, so that we can follow how the sound radiation changes in the course of the frequencies. In the sixth chapter, the results presented in the fifth chapter will be analyzed statistically and in more detail. Here we can see the motion of radiated energy and the location of the minimum and maximum energy in the frequency range analyzed at a glance.

The seventh chapter is about the total amount of energy collected from all the measured parts of the body in comparison to the mouth radiation. The total energy will be analyzed in two ways – including and excluding the energy from the corners of the mouth, because the energy from these parts would have a large influence on the total energy due to their location close to the mouth, which is usually the strongest source of energy.

Furthermore I would like point out that in the end of the second, the third, the fifth, the sixth and the seventh chapter a brief overview of discussed and introduced aspects are added. The ultimate goal of this research project is to increase our understanding of the actual sound, as it is produced by a singer’s body as he or she sings, and as it is perceived by the listener.

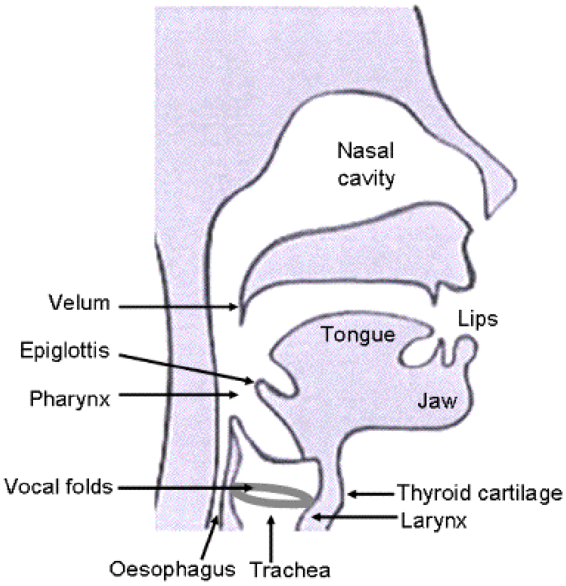
2 Voice Production of Singing Voice

In our daily life, we receive various acoustical signals through the air, including the sound of the human voice. The human voice is one of the most important communication mediums to convey feelings or impressions of the speaker or singer. Each voice art, such as “speaking voice” or “singing voice,” and each voice quality, like pressed or husky, occurs from the body, i.e., the same organs (e.g. vocal cords, vocal tract etc.) are used. However, there are some differences not only between speaking voice and singing voice, but also among voice qualities which arise due to their desired purpose. For example, singers must produce a specific volume, therefore they use their body as an “instrument,” adjusting body parts in a desired way. This may include a larger lung volume and an optimally formed vocal tract. Because of this and for a better understanding of my work “Sound Radiation of Singing Voices,” I will explain some basic facts before introducing my experiment. This chapter deals with the general voice production and a few important features regarding the singing voice.

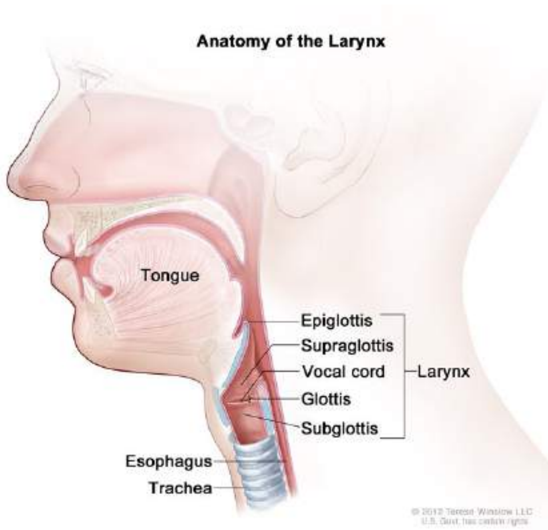
2.1 Anatomy of the Articulatory System

The articulatory system consists of the respiratory organ, the vocal folds / vocal cords and the vocal tract. The lungs are the starting point for a vocal sound production. The air which is produced by the lungs goes through the main bronchi and the trachea. The vocal folds are located at the end of the trachea. The length of the vocal folds is 9 – 13 mm for adult females and 15 – 20 mm for adult males. By a twist of the arytenoid cartilages, more precisely by an adduction and abduction of the vocal folds caused by a control of the arytenoid cartilages, the glottis is opened and closed at the larynx. The

[1]The images are downloaded from the following websites: the image (a) from http://www.phys.unsw.edu.au/jw/voice.html (last visited: 15/10/2018) and the image (b) from https://visualsonline.cancer.gov/details.cfm?imageid=9257 (For the National Cancer Institute © (2012) Terese Winslow LLC, U.S. Govt. has certain rights) (last visited: 19/11/2018).



(a) Anatomy of the human vocal apparatus [87].



(b) Anatomy of the larynx [40].

Figure 2.1: Anatomical illustrations of the human vocal apparatus (a) and of the the larynx (b).[1]

adduction is necessary for producing a voiced sound and the abduction is required to pronounce an unvoiced sound and to take breath. The region from the pharynx to the lips is called the “vocal tract”. The use of many muscles is necessary for a variability of the vocal folds and the vocal tract that contributes to produce different vocal sounds [65].

2.2 The Production Process of Voice

When vocal sound needs to be described in summary, it can be explained with the three steps of the origin of the voice:

1. Air pressure from the lung,
2. collision (vibration) of the vocal cords caused by the air stream in the trachea which passes through the glottis, and thereby generating a pulsating transglottal flow and

3. modulation of this glottally modified airflow in the vocal tract. Finally, the sound generated in the vocal tract is radiated as the final product from the body (see Figure 2.2).

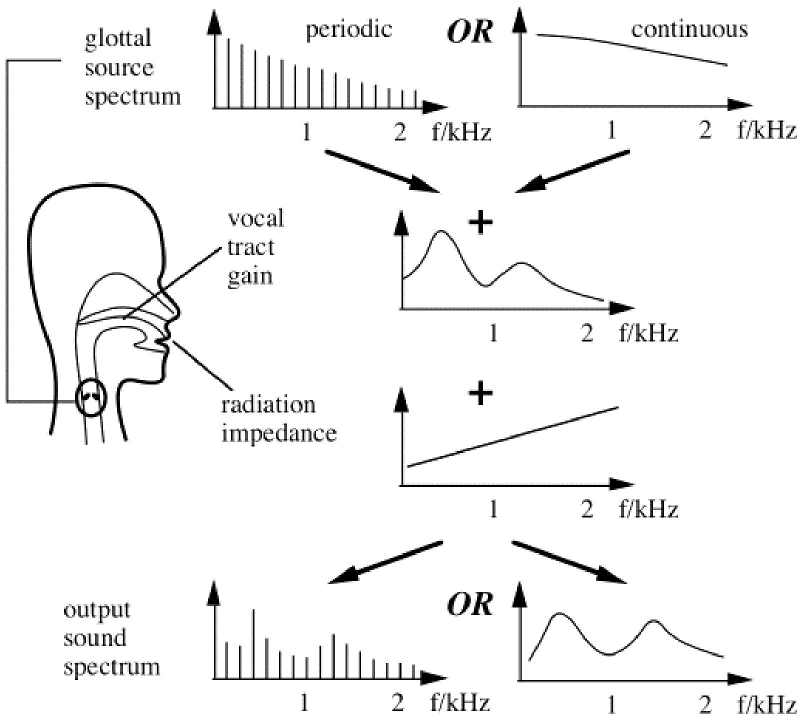


Figure 2.2: Illustration of the source-filter model (from Epps [26]).

The Swedish voice researcher Johan Sundberg calls the generated air flow from the lungs "Direct Current Component (DC component)" and the next two steps "DC-to-AC (alternating current) conversion" and "Modulation of AC signal," respectively [48]. He indicates that the first two steps of this process determine three acoustically essential points: fundamental frequency, amplitude and spectrum [48]. The "fundamental frequency" is produced in each glottal circle by repeated opening and closing of the vocal cords. Further harmonics are generated here as well, which appear as whole number of multiples of the fundamental or the first harmonic [61]. As a result, the three basic musical parameters — pitch, loudness and duration [47] — are also influenced each by the repetition rate of the vocal-fold collision, the level of air pressure, and the lung volume (amount of inhalation). When it comes to loudness, for example, the subglottal pressure, which derives from below the glottis by breath stream, affects the loudness of the singing voice [65]. The breath stream is controlled by respiratory muscles and when a singer wants to produce a soft (pianissimo) tone after inhalation, a careful activation of the inspiratory muscles is needed to generate a low subglottal pressure. And vice versa, when singer wants to produce a loud (fortissimo) tone, in spite of lacking lung volume, a forceful activation of expiratory muscle is needed to generate high subglottal pressure [48] [65]. The correlation of vocal loudness and subglottal pressure can generate an increase in loudness close to +9 dB, if the subglottal pressure is doubled [19]. Furthermore, a few studies reveal a relation between the loudness and the sound level of the voice source spectrum: When vocal loudness is increased, partials at high frequencies show a higher spectrum level than partials at lower frequencies [29] [19]. In addition, the process of the second step, i.e., the glottal flow, also influences timbre, projection and text intelligibility [47]. This means that the characteristic of the singing voice, such as pressed or breathy voice, is determined by laryngeal adduction. For example, if the laryngeal adduction decreases, i.e., closing of both vocal cords is slightly loose, a breathy voice will be produced. Generally, in such very soft phonation, the strongest partial is the fundamental, while in neutral and louder phonation that is not the case and its strongest partial is located nearest to the first formant [48] (What "formant" means will be explained in next sentence).

As already mentioned, the characteristics of vocal sound is dependent on vocal fold oscillation. But for the acoustic and phonatory characteristics of the singing style the configuration of vocal tract is also one of the most important factors: after the second process, the unmodulated, but already generated voice, the so-called "voice source" [65], will be processed further in the vocal tract. Here the voice will be changed by the upper parts of the vocal apparatus, more precisely, by the resonant characteristics of the oral, the pharyngeal and the nasal cavities. The voice source is not a pure tone, it is rather a complex tone which is filtered in vocal tract resonator [48]. However, the parts of the vocal tract that are used depends strongly on factors such as the vocal technique that is employed. But in fact, not only the voice sound quality is changed there, but also the production of vowels and consonants. This is achieved by widening or tightening (configuration change) of the appropriate areas. Especially in the production of the vowels, the factors tongue position, jaw and lip opening, and position change of velum and of larynx in the oral cavity play major roles, as shown in Figure 2.3 (left) [61].

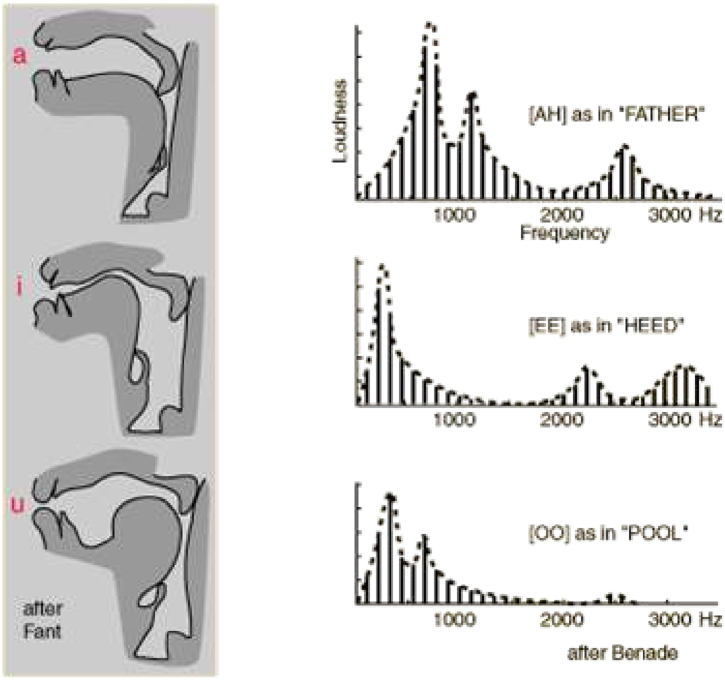


Figure 2.3: Configuration of the vocal tract and produced vowel formants of the vowels /a/, /i/ and /u/ in a male voice (from Fant [29] & Benade [6]).[2]

The right area of Figure 2.3 demonstrate the vowel formant of three spoken vowels /a/, /i/ and /u/ in a male voice. The term "formant" is used for vocal-tract resonances and is manifested as a broad "peak area" in the spectral envelope of the sound [47]. The formants are determined by the configuration of the vocal tract and they are "physically quite distinct phenomena" [43].
Thus, the total of Figure 2.3 shows a distinct interdependency of all three: the production, the configuration of the vocal tract and the vowel formants, as just mentioned. For the vowel /a/ the jaw is, compared to the other vowels, widened the most. This causes the increase of the first formant (F1). But the reduction of the tongue constriction in this vowel leads to the result that the frequency of F1 will decrease, even though the opening of the jaw will be wider [65] [73]. That is why soprano singers open their jaw wider in high frequency range, causing otherwise fundamental frequency (F0) to surpass the first formant [48]. Due to this inevitable jaw widening, for a good voice sound production in high frequency range, which will automatically occur independent of vowel

[2]The figure comes from
http://hydrogen.physik.uni-wuppertal.de/hyperphysics/hyperphysics/hbase/music/vowel.html (last visited: 1/11/2016), however originally from Fant and Benade.

from a certain height of frequency range, pronunciation of vowels or recognition of distinction between sung vowels will be more difficult, and thus song text is often not very comprehensible. However, there are some more methods to solve the problem of singing at high pitches. For example, retracting the mouth corners can shorten the vocal tract, so that the frequencies of the formants will increase. A shortening of the vocal tract by raising the larynx can also contribute to a lowering of F1 [48].

Concerning the second formant (F2), the configuration for the vowels /i/ and /u/ show almost a contrary configuration change in the vocal tract, with regard to tongue position and size of space of the velum that occurs automatically according to changed tongue position: in the case of the vowel /i/, the tongue is elevated to the hard palate in the middle area of the oral cavity, hence the vocal tract will be enlarged near the velum, whereas it is narrowed for the vowel /u/ due to an elevation of the tongue in the rear area of the oral cavity. As a matter of course, this configuration change is accordingly reflected in its formant. As already briefly mentioned, the tongue position determines the movement of F2 (increasing or decreasing), however in fact, the configuration change of the velum that arises due to tongue position shifts F2 (see Figure 2.3): Because of the widening of the vocal tract near the velum, F2 of the vowel /i/ appears around 2 kHz (increased frequency), whereas that for the vowel /u/ and the vowel /a/ occurs around 1 kHz (decreased frequency) with the narrowing of the laryngopharynx. The second formant will be mostly increased, when tongue configuration narrows the vocal tract nearby area of the velum and the lips thrust to the front, as in the pronunciation /u/ of German word "Buch" [65].

Third formant (F3) is influenced by the position of the tongue tip and blade, more precisely, by the size of the space directly behind the front teeth. When this space is wide, F3 will be decreased [65]. Therefore, F3 for the vowels /a/ and /u/ is higher than that of the vowel /i/, as shows in Figure 2.3. The fourth and fifth formant hardly move and their formants depend on the length of the vocal tract, rather than on tuning locations or configuration change in the vocal tract, which are of major influence in the other formants. For example, F4 relates strongly to the form of the larygopharynx [65]. Western vowels are generally identified by the frequencies of the first two formants (F1 and F2) [43]. Other higher frequencies determine voice timbre [69], but such formant frequencies depends on individual vocal-tract morphology and personal habit of pronunciation [65] and vary between voice types [20] and also between speaking and singing in classically trained singers [66].

2.3 Register

In the previous chapter it was described in general how the human voice generates what we finally perceive in our ears, but some important characteristics of singing voices must also be pointed out here to provide an understanding of the mechanism of the singing voice. One of them is the vocal register. A detailed description about the term "register" is controversial, however, American vocologist Ingo Titze mentions that the registers have been used to describe perceptually distinct regions of vocal quality that can be maintained over some ranges of pitch and loudness [78]. There are different designations for the registers, but in the majority of cases, the frequency range where it is sung by chest voice, is named "chest register"[3] and where head voice is used it is called "head register." For male singing voices, the term "falsetto register" is employed instead of the term "head register." For the female singing voice, there is a further term, the so-called "middle register" (or "mixed voice") and the voice from this register is, according to Titze, nothing else than the "head voice," but its amplitude of the vocal-fold vibration is the same as in the chest voice [78][4]. Additionally, the register sung by lowest male voice and highest female voice is sometimes called the "vocal fry register" and "whistle register," respectively.

Each register is generally related to the vibrational characteristics of the vocal folds [38]. According to an experiment with female singers, the characteristics of the chest register belongs to a longer closed phase by means of more adducted phonation and a stronger fundamental frequency and strong higher spectrum overtones than head register [9]. Related to the difference of vocal-fold vibration, in the case of male voices, van den Berg described that the characteristic of the chest register is determined by a strong longitudinal tension in the vocal muscles, as the falsetto register is characterized by a strong longitudinal tension in the vocal ligament. In the chest register, the vocal cords are thicker and vibrate with a larger mass, so that stronger high spectrum overtones are produced compared to the falsetto register [83]. As a result, a louder voice is generated by higher subglottal pressure based on these thicker vocal cords than in the falsetto register [38] [63]. But usually for female voice, the sound intensity is stronger in chest

[3]In some cases, the chest register is also called "modal register" (e.g. in Södersten et al. [63]).

[4]Some voice researchers classify these perceptually different voice qualities in two laryngeal mechanisms: chest, modal and male head voice are categorized as products of the first mechanism (M1) and falsetto, female head voice as products of the second mechanism (M2). Vocal fry and whistle resister are also called M0 and M3, respectively (e.g. in Castellengo et al. [17], Roubeau et al. [58] and Bourne et al. [15]).

and middle register than in head register [43][5].

A register change typically occurs somewhere in the pitch range between D4 (294 Hz) and C5 (523 Hz) [78], however, humans can produce same tone in different registers [9]. For example, according to an experiment with 42 subjects by Roubeau et al., male subjects are singing in the chest register from about D sharp 2 (78 Hz) to F sharp 4 (370 Hz) and female subjects are singing in the same register from about D3 (147 Hz) to G4 (392 Hz). But male singers can produce falsetto voice in the pitch range between about E3 (165 Hz) and E5 (660 Hz) and female singers can also create their head voice in the pitch range between about G3 (196 Hz) and C6 (1046 Hz) [58][6]. This finding clearly shows the overlap of the register ranges and the possibility of register choice for various purposes. The transition to another register can be influenced by vocal-tract modifications, such as lip and jaw opening, jaw retraction, tongue shape, and uvula position [25]: The transition from chest (modal) to falsetto register in male singers is made by minor modifications of the vocal-tract shape, deriving from an elevation of the larynx, for example, and a raised tongue dorsum. By contrast, the transition from chest (modal) to *voix-mixte* register relates with strong vocal-tract modifications, deriving from a pharynx widening, lip and jaw openings, and increased jaw protrusion [23] [25]. For soprano singers, vocal-tract modifications similar to the case of male singers are reported by Echternach et al. [24].

The famous Italian vocal teachers Pier Francesco Tosi and Giovanni Battista Mancini required in 18th century [49], that a mastery of such register changes, i.e., smooth and inaudible transition of register changes is one of the most important factor for classical vocal study. Whereas a voice that is perceived as uneven due to register changes is often used as a sound effect for some kind of emotional expression in popular music genres. The technique of yodel singing consists of permanently, intentionally produced register changes from chest to head or *falsetto* register, and vice versa. Therefore, depending on musical genres, register changes can be useful or annoying.

[5] The terms of laryngeal mechanism M1 and M2 are used by the authors in their paper.

[6] Analyzed by the author based on the findings of Roubeau ed al.. They apply the terms M1 and M2 according to happened laryngeal mechanisms instead of the terms of respective register that I use.

2.4 Vocal Reinforcement by Nonlinear Phenomenon and Inertive Reactance

"For more than half a century, scientists explained the voice's ability to create song by invoking a so-called linear theory of speech acoustics, whereby the source of sound and the resonator of sound (or amplifier) work independently. Researchers have now learned, however, that nonlinear interactions — those in which source and resonator feed off each other — play an unexpectedly crucial role in generating human sound. Such insights now make it possible to describe how great singers produce those amazing sounds." [80].

As Titze argues, the human voice is amplified by a nonlinear phenomenon occurred in the laryngeal vestibule (epilarynx tube), in other words, by a subglottal and supraglottal reactances which contributes to an increase of the energy level at the source [81]. Hence this process, called "inertive reactance", plays a crucial roll for a singer and it occurs *"when singers create special conditions in the vestibule to provide an extra, precisely timed "kick" to each cyclic opening and closing of the folds that reinforces their vibration to create stronger sound waves."* [80]. As shown in Figure 2.4, through glottis opening and closing, the energy (air column) of the airflow from the lungs will be stored above or below the vocal cords:

Glottis opening: When the vocal cords open, air flows between the vocal cords, so that the airflow presses against the motionless air column in the laryngeal vestibule. Rising pressure in the glottis, caused by the inertia of the stationary air column, keeps the vocal cords further apart through its compression force [80].

Glottis closing: The arrow of the picture (B) shows the advancing upward movement of the air mass in the laryngeal vestibule, promoted by the airflow from the lungs. As soon as this movement begins, the elastic recoil[8] of the vocal cords also begins, so that the glottis will be closed. Therefore, the airflow from the lungs will be broken. Those reactions induce a partial vacuum in the glottis that compresses the vocal cords together [80].

Due to this glorious nonlinear interactions singers can use their body as a musical

[7]The image was edited by the author; originally by Adam Questell.

[8]Elastic recoil is understood in the medical field as *"the ability of a stretched elastic object or organ, such as the lung or bladder, to return to its resting position"* [52].

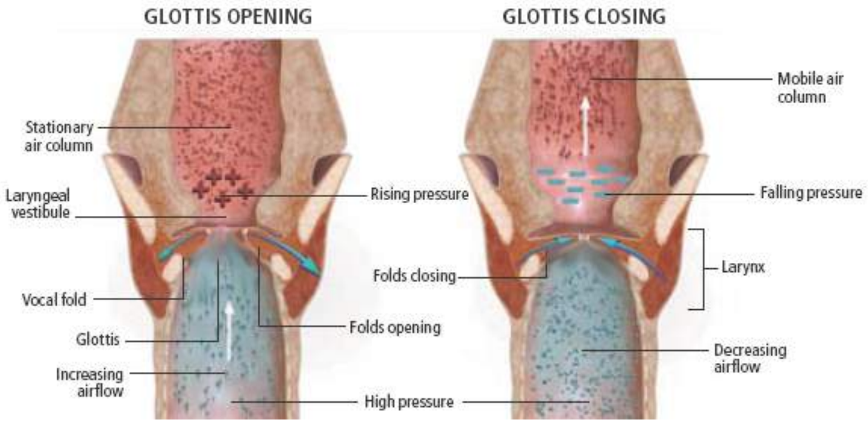


Figure 2.4: Acoustic reactance of the air column in the glottis: A) glottis opening B) glottis closing (from Titze [80]).[7]

instrument to produce sufficiently loud perceived tones. Especially for classical singers who have to able to produce a certain loudness without any acoustical tools, this vocal reinforcement is a very important factor.

2.5 Direction of Air Columns in Vocal Tract

In addition to the motion of air columns in the glottis, Titze also mentions motion of air columns in the vocal tract that change depending on mouth opening, in other words, due to relation between the fundamental frequency and the first formant [79]. As shown in Section 2.4, the motion of air columns above the glottis in the laryngeal vestibule, which constitutes a sound wave in the vocal tract, is not uniform from its velocity because of

1) the existence of air compression and rarefaction of the air in the tube, and 2) standing waves that created by multiple reflections that occur in alternately high and low regions of particle velocity and pressure [79]. This condition of the nonuniform motion of the air columns is independent on how the relation between the fundamental frequency and the first formant stay together. However, as already mentioned, the direction of the air columns depends strongly on this relation.

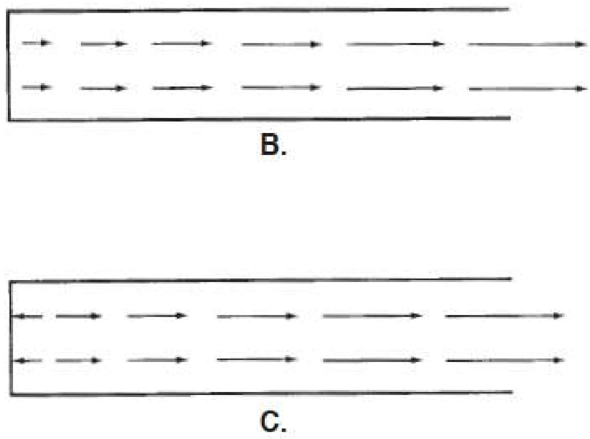


Figure 2.5: Two cases of motion of the air columns in a closed-open tube: the case of F0 <F1 (B) and the case of F0 >F1 (C) (from Titze [79]).

As shown in Figure 2.5, if the fundamental frequency (F0) is below the first formant (F1), the air moves unidirectionally (B). Conversely, if the first formant is below the fundamental frequency, the air particles move in the opposite direction (bidirectional), so that a dynamic volume change of the air columns occurs near the glottis (C). These phenomenons indicate that the inverting motion of air columns will be driven, such as the case C, if fundamentals are located in a higher frequency range and hence above the first formant; for example, the first formant of the vowels /i/ and /u/ appears in the frequency range of about 300 – 400 Hz, whereas that of other vowels, for example the vowel /a/, is located in higher frequency range (see Figure 2.3). This means that it is very likely that the invert motion of air columns arises for some vowels like /i/ and /u/, when the vowels are sung higher than in the frequency range of their first formant, e.g. in tone A4 (440Hz).

2.6 Singer's Formant

Before finishing with the chapter about voice production, I would like to sketch out briefly another important characteristic of the singing voice which concerns classically trained singers.

As mentioned in Section 2.2, classical vocal students have to learn the mastery of the transition of register changes. In addition, students who want to sing accompanied by an orchestra, such as opera students, must also acquire the ability to surpass the volume level of the orchestral accompaniment, for their singing voice to reach the audience. In comparison to popular singers, classical singers do not usually use a microphone while singing, thus it is essential to acquire an expertise for the development of their vocal ability. For singing with a loud orchestra, it is effective to sing using a resonance phenomenon that appears near 3 kHz, the so-called "singer's formant." The singer's formant is a remarkable spectrum envelope peak in voiced sounds which occurs near 3 kHz, and that mostly appears only in classically trained male singing voices, i.e., in bass, baritone, and tenor singers' voices [48] [65][9]. For example, a singer's formant occurs for bass singers at about 2.4 kHz, for baritone singers at about 2.6 kHz and tenor singers at about 2.8 kHz, and these small differences between such voice classifications are consistent with the typical voice timbres of each voice classification [48].

But how can the singer's formant arise? This typical resonance phenomenon of classically trained singers is produced by a clustering of F3, F4, and F5. The convergence of the dispersed frequencies results in an increase of their individual levels, so that a high spectral peak is reached in the frequency range between about 2.5 kHz and 3 kHz [48]. Sundberg mentions that a voice can be said to possess a singer's formant, if the level of the third formant is at least 6 dB higher than what could be expected from the values of F1 and F2 [70]. But from what are the clustering of those frequencies influenced? He wrote;

"The acoustical situation producing the clustering of F3, F4 and F5 is obtained by acoustically mismatching the aperture of the larynx tube, also referred to as the epilaryngeal tube, with the pharynx. This can be achieved by narrowing this aperture. Then, the larynx tube acts as a resonator with a resonance that is not much affected by the rest of the vocal tract but rather by the shape of the larynx tube. Apart from the size of the

[9] Except male choir singers. No singer's formant is found in their singing voice [48].

aperture, the size of the laryngeal ventricle would be influential: the larger the ventricle, the lower the larynx tube resonance." [48].

He suspects that singers lower the larynx to widen the pharynx and laryngeal ventricle, so that the larynx tube resonance is tuned to a frequency close to F3 [48]. Because of this wonderful manner and because of the human biological characteristic of audiology that the frequency range 1 – 3 kHz is the most sensitive range for human hearing [33], the voice of classically trained singers (except sopranos) can be heard in the decaying orchestra sound range of 2 to 4 kHz [65].

However, the occurrence (or level) of the singer's formant depends on many factors, such as the vowel, vocal loudness, fundamental frequency, phonation mode and the singer's competency [71]. The singer's formant appears especially in the back vowels, such as for the vowels /a/, /o/ and /u/, and produces typical timbre brilliance of classically trained singers [66] [70]. As already mentioned, only classically trained male singers possess the singer's formant, but according to studies by Barnes et al. and also by Sundberg, some operatic and international soprano singers could also possess the singer's formant or similar level equivalent to that for these back vowels [5] [70]. However, Sundberg maintains an absence of the singer's formant in the soprano voice in general (e.g. in [48] [70]) [10]. He mentioned that the reason for that is a high fundamental frequency (F0) in the sung frequency range of a soprano: In comparison to other voice types that sing at lower fundamental frequencies, the soprano's phonation frequency is often above 500 Hz, so that this is located in the higher frequency range than in the frequency range where the loudest partials of an orchestra often appear while playing [65] [11]. Furthermore sopranos have more energy near 3 kHz due to singing at a high fundamental frequency, near the range where classically trained male singers possess their singer's formant. And because of the high fundamental frequency of a soprano singer, the clustering of F3, F4 and F5 for producing the singer's formant is rather narrow in the frequency [5] [48]. On the basis of these specific characteristics, sopranos can produce a sufficient loudness without singer's formant. However, there is a difference between professional and nonprofessional soprano singers [65].

These wonderful mechanisms of the vocal tract enable the classical singing voice type

[10] As mentioned, the lack of the singer's formant in the soprano voice is often reported. When it comes to being the singer's formant in the alto voice, it seems that there are several opinions among vocal researchers (e.g. see Sundberg [65]).

[11] The loudest partials of an orchestra's sound tend to appear around 450 Hz [65].

to produce a sufficient loudness, without a microphone as it is used for nonclassical singing, such as popular or musical theater singing.

3 Singing of Classical and Nonclassical Vocal Styles “Pop” and “Musical Theater Singing”

The voice has always been used as the most important communication method by humans, and singing has also been evident in everyday life throughout history. In ancient times, humans listened to the singing of well-trained singers, so that vocal training played a large part of music education. At the time, the singing voice was supposed to be ”bright, powerful and melodious, smooth and gentle, broad fluent, variable enough in pitch and strength” and - finally - loud and clearly audible as well [10]. In the 18th century, the ideal of a classical singing voice changed to another ideal: the ”bright, pure, powerful, flexible, firm, light, even” voice and the vocal range was expected to be broad [37], so the vocal technique, still well known and which adjusted to this new ideal, the ”*Bel Canto*,” was born[1]. But in the 19th century, in association with the origination of new voice subclassifications such ”lyric” and ”dramatic,” that arose from more dramatical opera styles and due to the ever increasing sizes of opera houses, a new requirements with regard to vocal quality arose. The singing voice had to become more powerful, with greater loudness and a darkening of timbre. This tendency became even more prominent after the Second World War and continues to greatly influence vocal aesthetics until the present day. [10].

Besides the developments in the classical vocal tradition, early forms of the vocal technique of today’s popular music, i.e. natural and speech-like singing, began to be practiced intuitively by vocally untrained people as early as the 17th century as well [59].

But the most thriving period of the popular music and popular singing was definitively the 20th century. Since the early 20th century, technologies began to be developed that allowed performers to sing through a microphone and have their voice electrically

[1]Some historical researchers view that the *Bel-Canto* era had already begun in the 17th century. However, the author refers here to an approach of the German musical encyclopedia *Die Musik in Geschichte und Gegenwart* [10].

amplified as well as recorded. These technologies enabled singers not only to sing more naturally and speech-like, so that they could share their very own, personal feelings with their audience. This development also started the commercialization of music, as millions of peoples could listen to the same piece on a recording or on the radio.

For popular singing, various vocal techniques are used to adjust to singer's emotional expressions while singing. "Belting," for example, is one of the most popular singing techniques in commercial popular music styles, such as Pop, Rock, R&B, Jazz, Country, and World music [74]. Belting is a vocal style with a particular tone color, which is often applied in musical theater singing. Its vocal aesthetic is often characterized as being "loud, shouting, vibrant, gusting or nasal" [11] [51]. Although in the early years of the history of musical theater, singers still sang by means of the *Bel-Canto* technique, they had to convert their *Bel-Canto* voice into the belting style from the 1940s onwards, because the repertoire of musical theater became increasingly influenced by Jazz music. So singers had to sing without microphones against the sound of a full brass orchestra. With an operetta-like, light voice it proved impossible to stand up to the loudness of instrumental accompaniment [36].

Another vocal style commonly used in musical theater, that is, however, limited to female singers, is what is called "legit" voice. Legit is based on the classical singing technique such as singing with back vowels and mostly in the head register, so that singers can sing in a wider pitch range incorporating register change, such as female classical singers do [14].

As mentioned above, each vocal technique developed over time in its particular way, in order to fulfill its intended requirement and associated aesthetics. For example, the instrumental quality of the voice is still most important for classical singing, while nonclassical singing attaches importance to "naturalness" of the voice. Individuality and special character in vocal tone is esteemed, and even unevenness of the voice are tolerated in nonclassical vocal music [61]. Without electroacoustic amplification, however, it would be difficult to enable singing with these desired characteristics of nonclassical singing styles.

But how can such diverse qualities of the singing voice be produced? As shown in the previous chapter, differences in voice quality are produced by different conditions in the larynx and in the vocal tract. In this chapter, I will describe various aspects of how the voice quality of the singing techniques investigated in this study – classical, popular and music theater singing – is characterized, and it is shown how these voice qualities differ from each other.

3.1 Differences in Lung Volume and Larynx

Some researchers have determined that differences between classical and nonclassical singing styles relate to the glottal adduction (e.g. [65] [27] [61] [8] [72] [21]): In the classical style, the glottal adduction should be similar to the flow phonation, the Broadway (music theater) style similar to a speech-like phonation, the Pop and Jazz style to a neutral and flow phonation, and the Blues style to a pressed phonation [75] [21]. When it comes to breathing in singing, according to studies of Hein and Thomasson et al., at least in belting and classical (opera) singing, vocal quality is not influenced much by determined breathing patterns [36] [77]. No typical breathing pattern was found for both singing styles in their studies. But the voice source of singing is affected by

1. the lung volume that determines the larynx position,
2. the closed phase and the degree of the glottal adduction, and
3. by the subglottal pressure that changes depending on the lung volume, where the larynx is located in lower position at the high volume then it is with lower lung volume.

This position change of the larynx influences the vocal cords and the high lung volume leads the vocal cords into an abductive position [41]. Such slight or moderate adductive position of the vocal cords with a low larynx position at high lung volume is observed as a typical characteristic of classical singing [72]. Vice versa, belting is characterized by a stronger adduction generated by a high larynx position with a low lung volume [36], and the characteristics of Pop singing using the voice from the classical middle register source, researched by Schutte and Miller, was shown between classical singing in middle register and belting – high larynx position of speech by low lung volume. This is very much like belting, although this singing voice is not produced by the chest register [61].

When it comes to the closed phase of vocal cords, which determines voice sound via produced partials by length of the glottal closed phase, classical singing style in falsetto/middle register showed a short closed phase (<40 %) and nonclassical singing style (belt and Pop) in chest register showed a long closed phase (>50 %) in some studies (e.g. [36] [61] [7] [28]). The voice that is defined by Schutte and Miller as "Pop," produced in classical middle register[2] possesses the short closed phase (<40 %) as in classical singing style [61]. Furthermore, the glottal contact speed quotient demonstrated greater value for belting than for legit-singing because of a variation in singing in chest/modal and head/*falsetto* register. Also the measurement of the glottal open quotient in belt-singing showed a lower value than in legit-singing [14]. This implies, in summary from the research findings mentioned above, that both vocal styles, classical and belt, seem to stand almost in opposite characteristics in terms of analysis from all the mentioned measurements – a low larynx position at high lung volume, a short closed phase, a small value in the glottal contact speed quotient[3] for classical singers and a high larynx position at a low lung volume, a long closed phase and a greater value in glottal contact speed quotient for belters. Furthermore, Stone et al found that the vocal cords are thinner in classical (operatic) than in Broadway singing style [21].
In comparison with belt and legit singing, it seems that they are also almost in opposition to each other in regard to the glottal contact speed quotient and the glottal open quotient. This is not really surprising because of the use of the classical singing technique in legit singing style, as already mentioned above.

The summary of the findings by Schutte & Miller (in Table 3.1) shows a clear difference in the larynx position among the four singing styles: legit (in falsetto) as well as classical chest singing is related to low larynx position, and Pop (in *falsetto*) is related to a comparatively lower larynx position than belting, which is characterized by the chest voice[4]. Some voice researchers revealed that belters sing without a change in the overlapped range of "chest register" and "head register," whereas classical singers choose to change register in the range (e.g. [61] [7]). The popular singing style using classical middle voice source demonstrates intermediate value – high larynx position by low lung

[2]There is little information about Pop singing compared to belt and classical singing style. But, according to Sundberg et al., belting technique is also used in popular music, as already mentioned in the beginning of this chapter.
[3]That is based on the mentioned research finding by Schutte that the varying register change leads to reduce the glottal contact speed quotient of legit singing style. I expect that this occurrence of legit would hold true also for classical singing due to the alternate register change.
[4]For female voice, Schutte and Miller used the term *falsetto* instead of "head register" in their paper.

volume, just like belt, and short closed phase, such as classical singing style [61].

However, as shown in Table 3.1, the comparison of measurement on subglottal pressure shows a different result as previously demonstrated in this section: Only belt indicates high subglottal pressure, whereas the other singing styles suggest moderate subglottal pressure. However, Hein reveals the tendency of belting that the higher the sung tone, the more obvious the increased subglottal pressure becomes [36]. Finally, one more reason why the "belt" voice, which is characterized by chest voice, is perceived differently from classical chest voice: belt is sometimes sung at much higher pitches than classical chest singing and due to the high to very high larynx position, the sound of belt voice differs from that of classical chest voice (see Table 3.1.) [61].

	Vocal-fold adjustment	**Larynx position**	**Subglottal pressure**	**Frequency range**
Classical chest	Chest	Low to intermediate	Moderate	Low[5]
Belt	Chest	High to very high	High	Middle[6]
Legit	Falsetto	Low to intermediate	Moderate	Middle to high[7]
Pop	Falsetto	Intermediate to high	Moderate	Low to middle[8]

Table 3.1: Characteristics of the female voice production in four singing styles (from Schutte & Miller [61]).

3.2 Differences in Vocal Tract Configuration and Resonance

As shown in the previous Section 3.1, various studies clarify how the characteristics of each singing voice quality is determined in the larynx alone. The classical singing style

[5]Generally, the frequency range of a female chest voice goes from D3 (about 147 Hz) to G4 (about 392 Hz) and head voice from G3 (about 196 Hz) to C6 (about 1046 Hz) (see Section 2.3).

[6]According to Schutte & Miller, the frequency range of the belting voice goes from G4 (about 330 Hz) to D5 (about 540 Hz) [61].

[7]No information about the frequency range of legit singing style was found. However due to the fact, that legit based on classical singing technique, it could be assumed that the frequency range of legit singing voice is similar to that of classical singing voice, although classical trained singers may have wider frequency range than legit singers.

[8]AATS (American Academy of Teachers of Singing) describes "separate, rather than unity vocal registers" as a typical stylistic requirement of the singing in Contemporary Commercial Music [55]. This implies that the use of vocal register in popular music is unique to individual, and their own singing style.

revealed a short glottal closed quotient and a moderate subglottal pressure as its typical characteristics, whereas belt showed an almost opposite standing. In the research on operatic and musical theater singing by Björker and also by Stone et al.[9], such moderate subglottal pressure was shown for operatic singing style as well, where the voice must compete with the loud orchestral accompaniment, and they described that this means to possess a stronger fundamental frequency in classical singing than in musical theater or belt singing style [8] [21] [74].
However, it is shown in research on vowels /i/ and /a/ that belt singing produces stronger overtone than operatic singing [72] [28] [88], and Titze and Worley also determined strong second harmonic partials (2f0) for vowel /a/ in belt from their findings from analyzed data on recorded voices of two opera star tenors (Luciano Pavarotti and Roberto Alagna) and two famous belt singers (Jazz singer Cab Calloway and musical theatre singer Tony Vincent)[10][82]. When it comes to operatic singing, Titze and Worley note that these singers have a better balanced energy in the lower harmonic partials and a strong singer's formant cluster, whereas the belters showed only a moderate level of energy. This is because of the simple reason that singer's formant occurs only in classical trained voice, as mentioned in Section 2.6. When it comes to legit, in comparison to belt, studied on the vowel /ε/ and /o/, legit was significantly weaker in sound pressure level and also in spectral energy above 1 kHz than belt at every measured pitch [15] [14].

However, such differences between classical and musical theater singing were clarified not only by the measurements on the vowels, but also in combination with syllables: Stone et al. found in their research on the repeated syllable /pæ/ by operatic and Broadway singers, that for the Broadway style, such a strong level of partials exists in only a limited frequency range of between 0.8 and 1.6 kHz [21]. They explain that such strong level of the partials in the musical theater style could be achieved partly by a greater adduction and by the higher F1 and F2 than in operatic style. In fact, Sundberg et al., found low F1 for all investigated vowels, so that this would be a typical characteristic of classical singing [74], whereas high F1 and F2 seem to be a typical characteristic of musical theater singing, especially of the belt: Based on the finding from their experiment with a female singer who sang using classical and nonclassical singing techniques, Schutte and Miller defined the term "belting" as follow;

[9] More precisely, they researched on operatic and Broadway singing styles. They used hence the label "Broadway," not "belt," because typical characteristics of "belt" were not noted in the subject's singing voice.
[10] Singing at the pitch A4 (A-flat4 by Tony Vincent) from a video recording of respective singers.

"Belting is a manner of loud singing that is characterized by consistent use of "chest" register (>50% closed phase of glottis) in a range in which larynx elevation is necessary to match the first formant with the second harmonic on open (high F1) vowels, that is, ∼G4 – D5 in female voices." [61].

As the study with a female singer conducted by Stone et al., and the measurement on the /ɔ/ (pronounced like "boat") by Schutte and Miller also revealed high F1 and F2, but they determined that the second harmonic partial (2f0) is located near F1 and the third harmonic partials (3f0) appears between F1 and F2. In comparison to belting, classical singing showed lower F1 and F2. Furthermore, the first harmonic partial (f0) is remarkably located below F1, and also the second harmonic partial lay below F2 [61]. A study on legit (sung by female singers), another singing style for musical theatre which is based on classical singing, showed not only no turning adjustments of F1 and F2 to the harmonic partials, which were shown in belt, but also no turning adjustment in the higher frequency range [14], where classical sopranos usually have turning F1 to f0 [43][11]. In the case of Pop, the turning adjustment of both formants (F1 and F2) and two first harmonic partials (f0 and 2f0) was similar to that of classical singing, but its first harmonic partial was much weaker than for classical singing. Schutte and Miller claim this is the reason why each singing style is perceived differently, just like "rounder" and "darker" sound of classical style, and "loud," "bright," and "edgy" sound of belt [61]. Furthermore, Bourne and Garnier assume in terms of their findings that the turning of F1 to 2f0 in belt could produce a high sound pressure level for its characteristic [14].

Also a measurements on belting at the pitches G4 and B4-flat, experimented by Bestebreurtje and Schutte, showed that for the vowel /i/ F1 is located between f0 and 2f0 and for the vowel /ε/, F2 appeared near the fifth harmonic partial (5f0), whereas F1 modified only slightly [7]. But in another study on repeated syllable /pæ/ by Björker, in all formant frequencies, such higher turning of formant frequencies was found rather in belt than in classical singing style[12][8].

[11]In reality, Bourne [14] and Joliveau et al. [43] used the term "vocal tract resonance (R)" instead of using the word "formant." Joliveau et al. describe the following as the reason: *"Historically, the word "formant" has been used to describe both a resonance of the tract and a consequent peak in the spectrum of the output sound. However, these are physically quite distinct phenomena. (...) The term resonance will be used to denote an acoustic resonance of the vocal tract with resonance frequency Ri. Western vowels are generally identified by the frequencies of the first two formants (F1,F2) or those of their associated resonances (R1,R2)."* [43]. In order to avoid confusion caused by using various words/terms and by reference of the last clause by the authors, I decided here to apply the word "formant."

[12]Particularly F2, F4 and F5 were higher for musical theater singing than for opera singing. Her

However, in fact, high F1 exists not only in belt or in belting substyles[13], but also generally in "nonclassical" style because of the reduction of the back cavity to minimal size. In other words, due to higher larynx position, the vocal tract is narrowed by a wider jaw opening and/or spread lips than in classical singing style [61] [72]. Titze and Worley compare the vocal tract of belt to a megaphone (trumpet-like), whereas that of classical singing is described as a similar construction of an inverted megaphone [82]. As shown in Figure 3.1, they found in the already mentioned investigation on singing voice of four well-known male singers, including the opera singer Luciano Pavarotti and belt (Jazz) singer Cab Calloway, that the typical characteristic of operatic voice is produced by larynx lowering and shortening the trachea which arises from the inverted megaphone-like form of the vocal tract, and vice versa, the typical characteristic of belt is produced by larynx raising and lengthening the trachea which is caused by the megaphone-like form of the vocal tract.
This different vocal tract configuration, especially the relation of the vocal tract shape and narrowness of the epilaryngeal (supraglottal) tube, which is located at the entrance from the trachea to the vocal tract tube, are reflected in the strength of the formants.

As the Sundberg's utterance showed in Section 2.6, the roll of the epilaryngeal tube is very important for producing an operatic voice quality, and narrowed epilaryngeal tube causes increasing acoustic length and strengthened harmonics in 2 – 3 kHz range, in particular singer's formant [82]. As shown left in Figure 3.1, Pavarotti's singing voice presents strong vocal tract inertances due to narrowed epilaryngeal tube. Inertance is a term for *a column of air in a tube* [79]. Possessing strong vocal tract inertances mean, in other words, that Pavarotti's singing voice produces a stronger F2 than Calloway's belt voice. But usually, belter shows a stronger F2 than for operatic (classical) singers, as already mentioned. However, Pavarotti's vocal tract configuration – narrow formed epilaryngeal tube and wide entrance to vocal tract tube – changes the inertance very abruptly, so that the inertance bars will have a collapse to the baseline [82]. Such vocal tract configuration produces strong supraglottal formants (F1, F2....etc.), including the singer's formant cluster (shown on F3), and this is why Pavarotti's singing voice

subjects are all males who sang repeated the syllable /pae/ at the pitches C#3 and C#4.

[13]Sundberg et al. investigated five substyles of belt, "heavy," "brassy," "ringy," "nasal," and "speech-like," which are often used also in commercial vocal music, such as Pop, Rock, R&B, Jazz, Country and World music [74].

[14]First two vocal tract configurations are derived from MRI data of a lyric baritone who is specialized in lieder singing style, early music and chanting. The vocal tract configurations of Pavarotti (third row) and Calloway (below) were made by several video recordings of both singers (see Titze & Worley [82]).

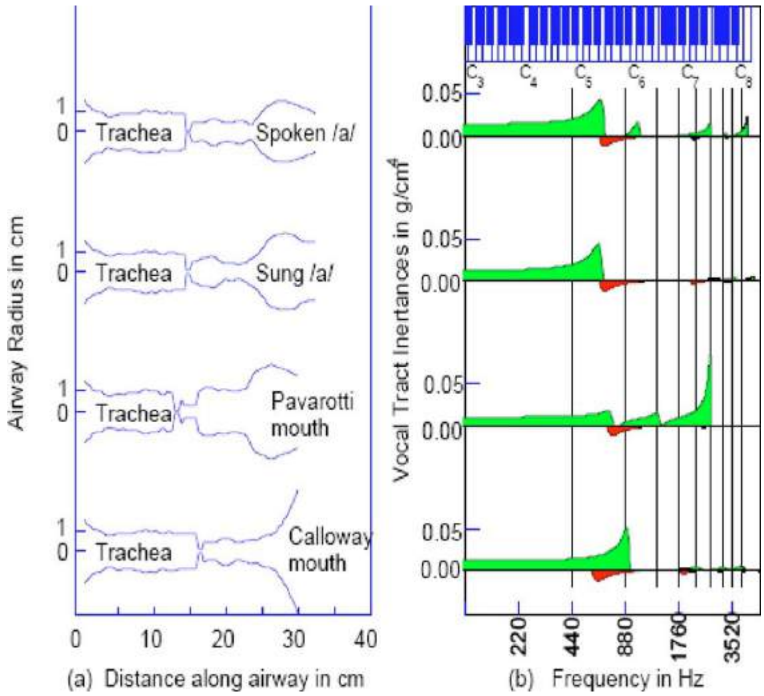


Figure 3.1: a) Vocal tract configurations of the spoke and sung vowel /a/ by a lyric baritone and of the sung vowel /a/ on A4 (around 440 Hz) by Pavarotti and Calloway. b) Resulting inertograms including their supraglottal formants (F1, F2, F3...., green-marked) and subglottal formants (red-coded) (from Titze & Worley [82]).[14]

demonstrated stronger F2 than Calloway's belt voice.

3.3 Characteristics of the Singing Styles (Executive Summary)

By comparing the above-mentioned four singing styles – classical, belt, legit and Pop – we are able to clarify their characteristics. Various studies have identified that the differences in voice quality are decided by several factors, such as larynx position, glottal closed phase, subglottal pressure and vocal tract configuration. At the end of this chapter, I will display these characteristics again in condensed form in Table 3.2, including further research findings.

Style	Larynx position	CPQ	Ps	Freq. range	Characteristics in freq.	VT configuration	Acoust. CHARCS
1. Classical	Low to intermediate[15]		Moderate[16]		Strong fundamental[17], low F1[18], balanced energy at lower harmonic partials[20], strong in singer's formant cluster[22]	Widened vocal tract, moderate jaw and mouth opening,[19] shortening trachea[21]	Rather dark, covered sound with backward articulation
1a) Chest		>50 %[23]		Low			
1b) Falsetto/Middle		<40 %[24]		Middle to high			
2. Belt (chest)	High to very high[25]	>50%[26]	High[27]	Middle	Weak fundamental, strong second harmonic (/a/)[28] strong overtone (/a/, /i/)[29], high F1 and F2	Narrowed vocal tract, wide jaw opening, wider opened mouth[30], higher and more forward stretching tongue than classical singing[31], lengthening trachea[32]	Bright, shouted sound with speech-like articulation
3. Legit (falsetto)[33]	Low to intermediate[34]	<40 %[35]	Moderate[36]	Middle to high	Low F1, but close to second harmonic[37]	Reduced back cavity with avoiding over-high larynx[38]	Pretty, open sound with speech-like, but backward articulation
4. Pop[39]	Intermediate to high[40]	<40 %[41]	Moderate[42]	Low to middle	High F1[43]	Similar to legit: Reduced back cavity, but with elevated larynx[44]	Bright with speech-based natural articulation, similar in speech and singing

Table 3.2: Typical characteristics of the classical, belt, legit and the Pop singing style (abbreviations: CPQ = Closed phase quotient, Ps = Subglottal pressure, VT configuration = Vocal tract configuration, Acoust. CHARCS = Acoustical characteristics).

It is not so easy to pinpoint each character of each style because of various types of singing within each single singing style. For example, in classical singing style, there are few differences between operatic and other classical singing (e.g. baroque, lied singing), such as existence of a singer's formant in operatic style (see Section 2.6) or strength of formants in spectrum (see [82]). Also in the popular singing style, as already mentioned, not only the manner of singing that displayed for Pop in Table 3.2, but also belt singing technique is usually used, i.e., there are many variable ways of singing within a singing style. Therefore, I would like to mention that the data about the characteristics of the four singing styles, which is displayed in Table 3.2, is only a small excerpt of the data which exists at the present day. However, it is a fact that this information helps us to better understand the construction of each singing style and is also helpful for future research on singing voices.

[15] [61]
[16] [61] [72]
[17] [82]
[18] [74]
[19] [72]
[20] [82]
[21] [82]
[22] [82]
[23] [61]
[24] [61]
[25] [61]
[26] [61]
[27] [61]
[28] [82]
[29] [72] [28] [88]
[30] [74] [72]
[31] [51] [14]
[32] [82]
[33] [61]
[34] [61]
[35] [14]
[36] [61]
[37] [61]
[38] [61]
[39] This data is based on the statement by Schutte and Miller [61]. But as already mentioned, belt is also in popular music.
[40] [61]
[41] [14]
[42] [61]
[43] [12]
[44] [61]

4 Vibration and Radiation of the Singing Voice: Previous Researches

"To make music, an instrument needs three basic components: a sound source that vibrates in the air to generate a frequency that we perceive as pitch, together with higher frequencies that define the timbre (sound color); one or more resonators that reinforce the fundamental frequency by increasing its vibration strength; and a radiating surface or orifice that transfers the sound to free air space and, eventually, to a listener's ear."[80].

The previous chapters pointed out the way in which the human voice is produced, and how the differently perceived singing styles and techniques are produced physiologically. As shown in Titze's findings, thanks to much research on the singing voice, we have acquired a great knowledge about voice production with regard to acoustical, physiological and phonatory aspects. Among others, the topic "radiation of the human voice" has also been investigated as an interesting aspect of the research on voice, in speech as well as in the singing voice. Primarily, the subject "voice radiation" has been examined from two points of view: Firstly, can the vibration in the upper body, mostly generated in bony structures of certain locations like the sternum (chest) or the head, affect the volume of the radiated vocal sound? Research on this topic is important for vocal performance practice and has always been essential especially for research regarding in classical singing. The second point of view handled the directivity of the voice. Understanding this information is of great importance in various applications, such as microphone placement, room acoustics or acoustical design. Hence the research on voice radiation in singing is an important issue not only for voice researchers, but also for singers. Because of these facts, the vibration and radiation of singing voice will be discussed in the following in reference to the results of previous research for better understanding of the voice radiation in singing.

4.1 Observation of Body Vibration as a "Resonator" in Classical Singing Style

As already mentioned, the research on body vibration has always been of importance especially for the people who are concerned with the classical singing style. On the one hand, because vibration in the body during singing is often perceived and reported by singers themselves, and on the other hand, because cultivating an awareness of the vibration in the upper body is frequently advised by many singing teachers, in order for singers to produce a desired voice sound (e.g. singing in the mask to gain a bright sound). Their advice is based on the opinion that the vibration on the head, the nose, the chest etc., functions as "resonance generator" that is expected to change vocal sound quality, and thus, such vibration in singing has often been encouraged by vocal teachers. The terms "chest voice" and "head voice," which are often used in singing lessons, derived presumably from such perception of the vibration at these respective body parts [68]. Here I will introduce commonly used labels for perceived resonance and their localization in the body:

Label for resonance	**Localization**
Head resonance	Skullcap
Skull resonance	Neurocranium
Nasopharynx resonance	Mask
Mouth (oral cavity) resonance	Forefront
Chest resonance	Chest

Table 4.1: Labels for resonances and their localization in the body (from Fischer [31]).[1]

In a famous guidebook for classical singing written by voice pedagogues Frederick

[1]Translated in English by the author. The original in German (the label / the localization): Kopfresonanz/Schädeldecke, Schädelresonanz/Kuppel, Nasenrachenresonanz/Maske, Mundraum-resonanz/Vordersitz, Brustresonanz/Brust.

Husler and Yvonne Rodd-Marling, the phenomena of body vibration is singing is explained:

"The singer generates vibrations up in the head or in the forehead, at the root of the nose, the upper jaw, the teeth, etc., and calls this "placing the voice", giving the tone a "focal point", and so on. From the physical aspect, of course, a tone is much too fleeting to be "localized" anywhere, yet the typical sound phenomena that occur through "placing" are perfectly audible to the listener, as they are to the singer himself. Though research in vocal acoustics is undoubtedly right in denying that these vibrations themselves generate sound, it does not alter the fact that such phenomena exist. And a phenomenon must have a cause. What the voice trainer has to realize is that these vibrations are always effects produced by definite functions in the vocal organ, some of which can be determined fairly accurately. "Placing", therefore, is not a fiction, as science would have it. It is not purely "imaginary" (though singers may use fictive ideas, e.g., the frontal sinuses as resonators, while practicing it). By placing the tone in various ways the singer rouses (innervates) the inner and outer muscles of the throat, and it is the activity of these muscles that produces vibrations in the different localities mentioned above." [39].

This method of teaching the perception of such vibrations in a certain localization while singing seems to be valued by singing teachers. But, as Husler and Rodd-Marling already mentioned, it is also a subject of debate among voice specialists, mostly between voice pedagogues and voice researchers, because some voice pedagogues observe the vibrations occurring in the upper body parts as a "resonance generator." This implies that "vocal sound quality can be changed by the vibrations."

However in reality, the vibrations that singers sense in the body are an *"indication of effective conversion of aerodynamic energy to acoustic energy"* [79] and the "resonance" occurs from *"a reinforcement of vocal fold vibration"* [79] by which sound source will be boosted in the vocal tract (oral cavity, pharynx, nose cavity, paranasal sinuses) [62]. This means that only the vocal tract is the resonance chamber, therefore the "resonator," and the vibration in the body parts has no resonant effect and no effect on the change of vocal sound quality [31]. Titze also referred to these false interpretation of the vibration as a resonator;

"What is clinically known as resonant voice may indeed be based on a physical resonance, but the resonance is likely to be a reinforcement between vocal fold vibration and

supraglottal acoustic pressure, a nonlinear (feedback) phenomenon, rather than a facial resonance that "filters" the sound and boosts certain frequencies." [79].

I will explain in detail in the next section the nonlinearity of the voice production and the effect of the vibration on the vocal sound energy. However, as Titze's mentioned, resonance is produced by the reinforcement of vocal fold vibration, and the "resonator" is the vocal tract in which the sound source is boosted and various vocal sound qualities are produced. This means that these perceived vibrations in the body have no effect on vocal sound quality, although they can give singers useful information about the relation between the aerodynamic aspects and the acoustic energy in their singing.

4.2 Previous Studies about the Effect of Vibration on Vocal Sound Energy

In the previous section resonance was defined. It is easy to imagine that vocal sound energy is radiated mainly from the mouth and thus, the vocal tract contributes to boosting of this sound source. Nonetheless, it has not yet been clarified whether such facial or bodily vibrations, e.g. from the sternum or the clavicles, actually have no influence on overall vocal sound energy. According to Sundberg, vocal fold collisions of opening and closing of the glottis, responsible for phonatory vibration, must generate shock waves in the tissue (i.e. body tissue vibrations) and this vibration in the trachea and in the sternum is perceptible at a volume as low as 20 dB and up [68]. In addition he mentioned the origin of the body vibration following:

"Sufficiently loud sounds in an enclosure obviously bring walls to vibrate. The very strong sound pressures in the vocal tract and in the trachea cause adjacent tissues to vibrate. This is the origin of the phonatory vibrations in the skull, neck, and chest regions." [68].

However, vibrations from the surface of the tissues, such as wall vibration, probably have no amplifying functions and have no boosting effect on the radiated sound, because the energy produced will be absorbed: acoustic radiation from the surface of the tissues is very poor and viscous dissipation within the tissues is high [79]. Just like Fischer, Titze also notes that the maxillary, ethmoid and the sphenoid sinuses, which belong to the vocal tract (paranasal sinuses), do resonate, but for reasons already described above, these sinuses cannot produce an effective sound radiation [79] [31].

Nevertheless, investigations about a potential sound amplification by vibrations, mainly due to the sensations of (classical) singers, was executed by some voice researchers. In the past, the topic – whether the vocal sound energy is restricted to the mouth only – has been researched repeatedly (e.g. Kirikae et al. [45], Fant et al. [30], Sundberg [67], Pawlowski et al. [57], Sakakura et al. [60] and Takada [76]). In a book published in 1912, German physician Hermann Gutzmann sen, the founder of the medical research field "phoniatrics," described that the vibration of vowels /i/ and /u/ is produced in the whole vocal tract, the nape (behind the vocal tract) and the skull area and is much stronger than for the vowel /a/ [34]. However Kirikae et al. showed a different result from a measurement at the head of a male subject with the use of an accelerometer (see Figure 4.1). He pronounced the five vowels /a/e/i/o/u/ at 125 Hz and the results revealed that the head vibration is powerful for the vowels /a/ and /i/, and weaker in the case of the vowel /u/.

They also investigated the vibration at other body parts, the forehead, the cheek, the lower mandible, the larynx and the sternum, in the five vowels /a/e/i/o/u/ at 125 Hz respectively. The results showed that the vibration on the forehead, the cheek and the lower mandible was greatest for the vowels /i/ and /u/, lowest for the vowel /a/, while intermediate values were measured for the vowels /e/ and /o/ [45]. These findings conform with the result from Gutzmann's investigation. But the vibrations on the larynx and the sternum were equal for all vowels and showed the greatest level from values of all the measured body parts. This, according to Sundberg, is because the difference among vowels occur first in the supra- and the subglottis, where pulsating transglottal airflow is produced unchanged for all vowels. Its constant form is kept, so that the resonance characteristics stay equally for all vowels [68].
In the same way, using an accelerometer, Fant et al. recorded vibration of a male subject at vocal tract walls using low frequency sine tone induced through a thin tube. They determined that the vibration is greatest near vocal tract ends, the lips and the larynx at very low frequencies [30].

Pawlowski et al. gained the same result from measurements on two singers (soprano and bass) for the vowel /a/ using a laser technique. They found that the larynx vibrates rather vigorously for low tones while the greatest amplitudes appear in the lip region

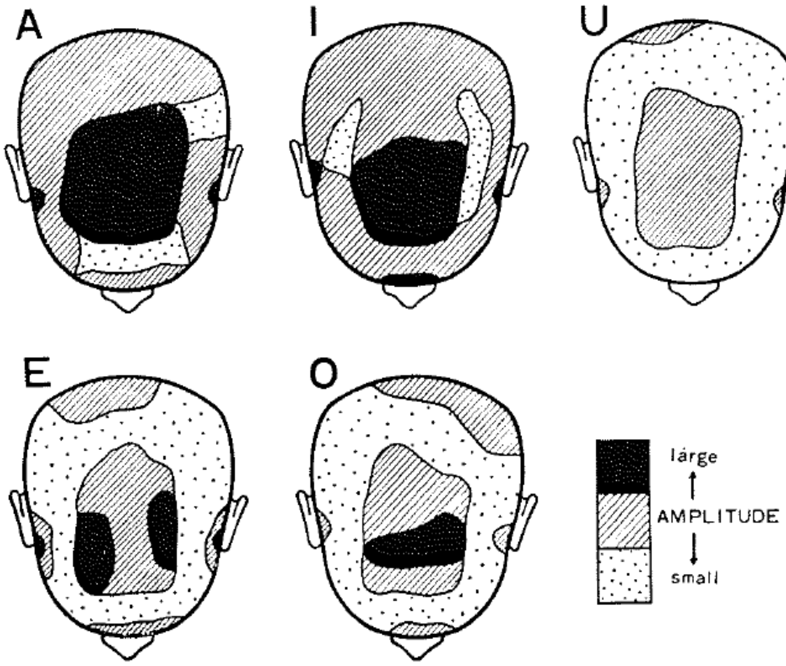


Figure 4.1: Allocation of the head vibration of speaking the five vowels /a/e/i/o/u/ at 125 Hz (from Kirikae et al. [45]).

for the highest pitches [57]. In regard to the comparison of the intoned voices between chest and head register, Kirikae et al. demonstrated that the voice of an alto vibrates clearly stronger in chest register than that in head register [45]. They measured vibration levels of the five vowels /a/e/i/o/u/ on the skull, the nasal dorsum, the mandible, the larynx and the sternum with the aid of an accelerometer at 250 Hz (in chest register) and 500 Hz (in head register) respectively and found that generally the voice in the chest register vibrates stronger than in the head voice, and that this tendency is shown more significantly at the nasal dorsum and the sternum (see Figure 4.2). With the same method they did a measurement of a baritone voice, showing its result is almost the same, except his vibration at the nasal dorsum and the larynx in head voice demonstrated a stronger vibration level than for the alto voice. By comparison between the vowels it becomes evident that the vibration of the vowels /i/ and /u/ at the head (vertex) is strong both in chest and head register. Sundberg expects a dependance of the lip opening and the vibration in the skull area:

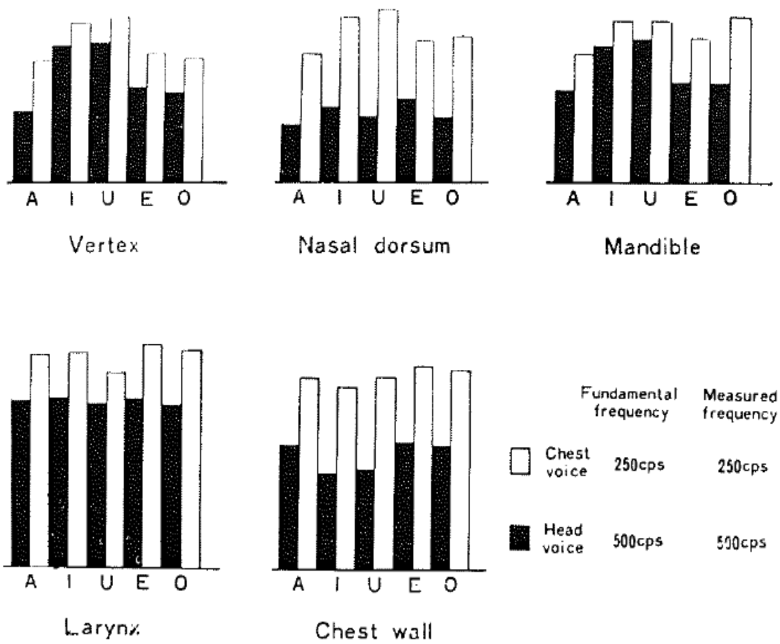


Figure 4.2: Body vibration of a baritone measured on the five vowels /a/e/i/o/u/ in the chest (at 250 Hz) and head voice (at 500 Hz) (from Kirikae et al. [45]).

"... formant frequencies are determined by the shape of the vocal tract, also including the termination represented by the lip opening. When the lip opening is widened, the first formant frequency is raised, other factors being equal. The frequencies of the formants are reflected in the sound pressure oscillations within the vocal tract. Therefore, the influence of the lip opening on the skull vibrations would merely reflect a dependance on the sound-pressure oscillations and, hence, on the first-formant frequency: the lower the first formant frequency, the grater the skull vibrations." [68].

When it comes to the results from the chest wall and the larynx, the vibration of the chest wall and the larynx showed almost equal levels for all vowels, because below the glottis there is basically no difference of the vibration levels among the vowels, as mentioned above.

Recently, I analyzed this topic using a microphone array of 121 microphones, called "acoustic camera," to investigate the difference of the radiation from the upper parts

of the body in both registers of classical singing voices [76]. For the study, the singing voice of a professional soprano singer was measured at the vowel /a/. I was able to show that the singing voice in both registers radiates not only from the mouth but also from other parts like the forehead, the nasal bone or the throat in higher frequency ranges.
Such dependencies of vibration levels on the frequency range were already confirmed by measurements on five body parts (forehead, cheek, right and left clavicles and sternum), as examined by Sakakura and Takahashi [60]. They also used the vowel /a/ for their measurement using accelerometers to investigate the vibration levels of a female singer and found out that the vibration levels on the forehead, the clavicles and the sternum become higher near 3 kHz, although the forehead showed low levels at the fundamentals[2]. They suggested a connection with singer's formant that occurs in around 3kHz. As shown, the topic has been explored for many years, mostly with the use of an accelerometer or a laser technique.

4.3 Radiation Directivity of Singing Voice

The topic "directivity of the human voice" has already been researched over 70 years. However, most of previous studies have addressed the investigation of the speech voice, even though there are few studies focused on singing voice over the last 30 years. The former studies did the measurements for various purposes and by diverse methods in order to

1. verify physical theories using physical models (dummy head) and speech simulators [32] [35] [42] [18] [64],

2. compare mathematical modeling techniques with physical modeling techniques [32] [46],

3. optimize microphone placement [22] [16] or architectural acoustical design [18],

[2] Actually, they also investigated the vibration level of the five vowels /a/e/i/o/u/ for three sopranos. However, Sundberg remarked that the analysis method of this study is critical, because the normalized vibration level was compared with the overall level of signals: *"The overall level of a complex tone, such as a vowel, is mostly determined by the levels of a quite small number of partials, viz. the very loudest one. This holds for both sound spectra and vibration spectra."* [68]. His argument is plausible and this is why only the investigation of the vowel /a/ with a female subject is introduced in this work.

4. gain more knowledge about singing performance practice [50] [16] [42] [44],
5. provide more precise data about voice production of speaker and singer [53] [13].

This thesis is about the radiation of the singing voice, however, in the following, I will introduce not only studies on the singing voice, but also a few on human speech voice. This is because of my research on singing voice of several musical genres and the fact that there are not yet much information about sound directivity of nonclassical singing that is based on speech-like singing technique, such as Pop.

4.3.1 Preliminary Research Methods and Subjects

Presenting an extract from former research on human speech voice, in 1939, Dunn and Farnsworth published one of the first studies about the directivity of the human voice. They measured the pressure field around a seated person who read a sentence repeatedly for 15 seconds and recorded data in the vertical and horizontal planes using a single "exploring" microphone that shifted its position around the talker at distances of 30 and 60cm [22].
Chu and Warnock also explored the sound field of the human speech, but they measured directional characteristics of 40 talkers (20 females and 20 males). The sitting subjects spoke a 40-second-text in English and French. Additionally, their conversational speech, in three voice levels (low, normal and high), was recorded by two microphone arrays with eight microphones positioned on two fixed orthogonal meridian arcs [18]. The chair where the talkers were sitting was shifted into six predefined positions which were set in increments of 15°. In the same manner, Halkosaari studied the radiation directivity of 13 talkers (5 females and 8 males) who spoke Finnish sentences, vowels and consonants using nine microphones that had been positioned near the chest and the cheek[3] [35].

With regard to the singing voice, Marshall and Mayer measured the vocal directivity of three professional singers (baritone, also, and soprano) who sang syllables with three vowels /a/o/e/ over a two octave range of notes (baritone G2 to G4, alto G3 to G5, soprano C4 to C6) in two sound levels either in "full voice" (*forte*) or in "half voice" (*piano*) [50]. The measurements (presumably using a single microphone) were generally

[3]For the purpose of telephonometry, this study focuses on directivity to few positions in the upper body.

done in 20° intervals in horizontal and vertical planes. Some were done in 10° intervals in the horizontal plane. To be able to measure in a 40° downward angle below the singer's mouth in the horizontal plane, the subjects stood during the recording.

Katz and d'Alessandro investigated the singing voice directivity of a professional counter tenor who sang vowels under following four different conditions: 1) simply vowels /a/i/o/, 2) vowel /a/ in various intensities (*piano, mezzo forte, forte, fortissimo*), 3) vowels /a/ and /o/ at the note "g1" with and without projection[4], and 4) the same process with and without focusing[5] on note "g1" [44]. They recorded simultaneously using a microphone array with 24 microphones attached to a displaceable semi-circular arch.

Cabrela et al. studied the long-term vocal directivity and the acoustic power of eight professional opera singers (six females and two males) who sang an Italian song in *Bel-Canto* style under three different conditions: in an anechoic room, in a reverberant room and in a recital hall [16]. This is different from the other studies introduced in this chapter, because most of them have been measured only in an anechoic room[6]. The number of microphones used and their placement varied depending on the purpose of the research in the rooms: 1) in the anechoic room a total of ten microphones were set around the room, nine of which were set at 15-degree intervals (0°, 15°, 30°, 45°, 60°, 90°, 120°, 150°, 180°, at a height of 1.5 m) in a distance of 1 m from the singers. The tenth microphone was a head-mounted microphone positioning in the corner of their mouth, 2) in the reverberant room five microphones were positioned between 1.9 and 3.9 m from the singer[7]. Furthermore, a head-mounted microphone was set at the corners of the mouth. Unlike the investigation in the anechoic room, there was no specific placement of the microphones in order to measure spatially integrated values of the singing voice radiated by a singer from all directions in the reverberant room, 3) in the recital hall

[4]Katz and d'Alessandro describe the term "projection" as a possibly adjuvant attitude for singing in a large concert hall in order to fulfill singer's maximal vocal energy till the last row of the concert hall.

[5]The term "focusing" is described by Katz and d'Alessandro as an attitude for singing with the most exquisite timbre and the most excellent nuance for performing in a relatively small room. For example singing Lieder or performing chamber music. There singers may pay more attention to their voice quality and vocal expression than singing in a large concert hall.

[6]Except the measurement by Dunn and Farnsworth, all studies referenced were executed in an anechoic room. Dunn and Farnsworth used a room for their experiments that was lined by multiple layers of cloth in order to approach a free field condition as closely as possible.

[7]In fact, seven microphones have been set, but because of technical difficulties only five of them were used for the analysis.

there were two surveys: firstly, with eight microphones positioning at 0°, 15°, 30°, 60°, 90°, 120°, 150°, and 180° at a distance of 1.8m from the singer respectively. Secondly, eight omnidirectional measuring microphones, set in two arcs with four microphones each, were situated at a distance of 10 and 15m from the singer's standing position in the audience area. Under these three different conditions, the subjects sang in following four ways: (1) with attention to intonation, (2) with attention to all the emotional connection which is signified by composer, (3) with an attitude of singing in a large auditorium (so-called "projection" by some voice researchers), (4) and with an attitude of singing in a small theatre (so-called "focusing").

Monson et al. surveyed the directivity of both speech and singing voice, particularly the directivity of its high-frequency energy, and they measured the singing voice of fifteen singers (8 females and 7 males) with different background of singing style (classical, opera, choral, Jazz, Pop and musical theater) [53]. For the research on speech voice, all the subjects spoke 20 "six-syllable low-predictability phonetically representative phrases with alternating syllabic strength"[8] in three different intensities (normal, soft and loud). For the research on singing voice each of them sang in three different intensities (normal, *pianissimo* and *fortissimo*) in his/her favored singing style. The directivity was examined in a horizontal plane using thirteen microphones that were set up at 15-degree intervals from 0° to 180° in a semicircular radius, and another microphone stood at a distance of 60 cm from the subject's mouth at a 0° angle.

Boren and Roginska investigated the speech voice as well as the singing voice of two musical styles, musical theater singing and opera singing. Monson et al. did also an experiment with singing voices from different musical styles, but they focused on a comparison between directivity of speech voice and that of singing voice. The research by Boren and Roginska is the first to measure vocal sound directivity including nonclassical singing voice and comparing three kinds of human voice. In the first experiment, all the subjects, two male singers (a professional opera singer and a musical theater singer) and two actors (a female and a male), spoke five vowels /E/A/o/O/OO/ intoned on C4, for two seconds each [13]. Secondly, the singers performed a prepared song for 30 seconds using the three singing methods of "back" (singing in the rear of the mouth), "forward" (singing in the front of the mouth) and "in the mask" (singing in the sinus

[8]This phrases were cited by Monson et al. from Appendix A of Spitzer, S. M., Liss, J. M., Mattys, S. L., Acoustic cues to lexical segmentation: A study of resynthesized speech, Journal of Acoustical Society of America, Vol. 122, pp 3678-3687, 2007.

cavities), whereas the actors performed a monologue also for 30 seconds. They were required to speak using four different speech voices/methods of "chest" (speaking in the front of the speaker's chest), "mask" (speaking in the front of the mouth), "head" (speaking with a feeling of resonance producing at the top of the speaker's head) and "back resonance" (speaking with resonance generated in the rear of the torso)[9]. For the measurements, thirteen microphones were spaced at 15-degree intervals from 0° to 180° in a semicircular radius in the horizontal plane and positioned at the height of the center of each test person's mouth. The microphones shifted in front of the subjects (at 0°) had been placed 60 cm from their mouth. Due to presuming vocal symmetry, they showed the obtained data in a form of 360-degree radiation patterns in the horizontal plane.

4.3.2 Findings from the Investigations

These studies achieved informative and very significant results. In the research on human speech voice, Dunn and Farnsworth found that the directivity patterns change at high frequencies and these depend on the size of the mouth opening [22]. Below 1000 Hz in the horizontal plane, the directivity radiates strongest directly from the lips, while at 5600 Hz the strongest radiation was measured at an downwards angle of about 45° in the front. With regard to the changing of the sound directivity at increased frequencies, Chu and Warnock showed a similar finding, namely that the directivity at high frequency emits downward. Furthermore, their study revealed no significant differences between female and male subjects, while there were differences in the spectra between the genders. The forward directivities of both normal and loud speech were also similar, and for the low voice speech a backward directivity behind the talkers was observed. The investigation by Halkosaari came to the conclusion that the mouth (aperture) size has an influence on the directivity as well [35]. Besides the measurement with human voices, he also experimented with a head and torso simulator (HATS) and detected the same results as Dunn and Farnsworth, namely that the radiation directivity depends on mouth aperture size. This finding is also confirmed by the study with Speech Transmission Index (STI), which was executed by Stewart and Cabrera [64].

In their research on the human singing voice, Marshall and Meyer found that the

[9]The details in the brackets originate from the paper written by Boren and Roginska.

directivity of the singing voice generally points downward, about 40° below the singer's mouth in both horizontal and vertical planes. They referred this phenomenon to the "singer's formant," but their observations would differ from some of the other voice researchers due to the existence of singer's formant in soprano voice, as discussed in Section 2.6. Nonetheless, this perception of a downward radiation of the singing voice is consistent with the findings by Dunn and Farnsworth and by Chu and Warnock that came from their measurements of the speech voice. Furthermore, by the measurements of the sung vowels /a/o/e/, Marshall and Meyer determined that the directivity of all the vowels appeared to be similar in frequencies up to 500 Hz, while from 500 to 2000 Hz there was a significant difference, which became less obvious above 4000 Hz again: at 2000 Hz, the 40° sideways directional pattern occurred for the vowels /a/ and /o/ in the horizontal plane, while such appearance was missing for the vowel /e/. In the vertical plane, the vowel /e/ radiated more weakly forward than the vowels /a/ and /o/. By the measurement with two vocal projections "full and half voice," there was a small reduction in the sideways directivity for the half voice (*piano*) above 1000 Hz.

As already introduced, Katz and d'Alessandro conducted four experiments, including different sung vowels and sound intensities similar to the studies by Marshall and Meyer. In the research with the vowels /a/i/o/, singing in *forte* at the note "a," Katz and d'Alessandro found significant differences from 800 Hz to 1000 Hz, at 2500 Hz, and (weaker) at 4000 Hz: in the frequency range between 800 Hz and 1000 Hz, the vowels /a/ and /i/ radiated more forward than the vowel /o/, although the result at 2500 Hz showed a inverse finding [44]. At this frequency, the directivity of the vowel /a/ registered the weakest in the analyzed frequency range up to 4000 Hz. In comparison with the directivities of the different sound intensities measured with the vowel /a/, there was no significant difference in general, except that loud singing showed more power. From both studies on vocal projection and forcing, in fact, with and without these conditional requirements employed depending on performing music style and size of room, there were also no significant differences, with the only exception being that with the projection it was more vigorously in the high frequency range than without the projection. The reason why there were similar results from both measurements on sound intensities and vocal projection, is because singers need more power, i.e., high vocal sound intensity, when they have to sing in a large room (e.g. concert hall, opera house etc.). In other words, singers sing with a certain vocal projection in such a case automatically. That implies, according to the study by Katz and d'Alessandro, that the vocal loudness has no or only little effect on radiation patterns. This finding differs from the observations by Chu and Warnock on speech voice, where a less backward pointing directivity (behind the talker) for low voice level was shown than for normal and loud voice levels. Presumably that is because they analyzed the radiation patterns of a conversational speech voice for 40 seconds in three voice levels, although Katz and d'Alessandro only used the vowel /a/ for such a comparison of directivities of different sound intensities. Furthermore, the different research objects, speech voice and singing voice, might be a reason for this distinctive results.

Cabrela et al. also came to the conclusion from their measurements in a small and a large hall that there is no directivity effect whether singers sing with or without vocal projection [16]. Like the results by Katz and d'Alessandro, a slight difference was described here, but not with regard to the sound directivity: the frequency range from 2 kHz to 4 kHz showed more energy than that from 0 Hz to 2 kHz for the large-hall projection, although such difference in singer's projection which had been measured in the audience area, seems to depend rather on the singer than on the singer's vocal projection. Cabrela et al. assumed the reason why the directivity in the frequency range between 2 kHz and 4 kHz does not change: They concluded that it would be important to change the mouth aperture strong enough, when changing singer's directivity [16]. They guessed that the changing of oral aperture between the singing projections are not significant enough to gain significant results from this measurement. Even by the comparison of both modes – with attention to intonation (viz. technical singing) and with all of the emotions intended by the composer (viz. emotional singing) – only little or no significant effect on directivity was found. Therefore, at least from the studies by Katz and d'Alessandro and by Cabrela et al. on singing voice, it is clear that there are generally wider differences in sound power levels than that in the directivity. However, Cabrela et al. emphasize the effect of the singing projection on vocal directivity;

"... Singing projection did have an observable effect on voice directivity, because the singers shifted the spectral distribution of energy as they changed projection. Shifting energy to a higher-frequency range yields greater directivity, because the voice is more directional at higher frequencies." [16].

This implies that the singer's formant region is more directional than the lower-frequency range [16]. In other words, the fact that opera singers shift energy into the higher-frequency ranges means that this is the characteristic of operatic vocal directivity which differs from that of other singing styles, such as Pop or musical theater singing.

The investigation on speech and singing voice by Monson et al. revealed that there are no or only slight significant directivity differences between speech and singing voices, and between genders [53]. With regard to the former, its result probably bases on the size of the mouth opening, and the mouth shape varies depending on the singing style. The fact that the mouth aperture plays an important role for vocal sound directivity was already mentioned by Cabrera et al.. The latter results are consistent with the findings of Chu and Warnock, although the male speech voice showed slightly more directional radiation for octave bands below the 8 kHz octave than that for female speech voice in researches by Monson et al. Even in measurements on various sound intensities, this difference was only slightly recognizable, thus this result agrees with the results of Katz and d'Alessandro and differs from the finding of Chu and Warnock.

In comparison with the directivity of four vocalists (actress and actor, musical theater and operatic singers) in the different vocal projections – chest/mask/head/back resonance for speech voice and back/forward/mask for singing voice – Boren and Roginska found a lot of difference between the investigated voices. They observed the radiation patterns in two ways – normalized (analyzed that without influence on sound spectrum) and absolute (analyzed the loudest of the vocal projections) [13]. Based on the analysis about the normalized radiation patterns of the intoning vowels on C4, normalized overall levels at 251 Hz showed only slight difference among the vocalists as well as vocal projections, although the actress's voice that was analyzed in normalized third-octave bands (251 Hz, 1995 Hz and 10000 Hz) revealed wider difference between the vocal projections at 251 Hz. But this difference always became smaller in higher frequency ranges. Likewise, the opera singer's song directivity indicated great variation at 1995 Hz, while the radiation patterns of all the vocal projections became slightly more uniform at 10000 Hz. In a comparison between the musical theater singer's vowels and song data in normalized radiation patterns analyzed at 10000 Hz, the intoned spoken vowels demonstrated a great variation in radiation pattern between the vocal projections – "mask" radiates most powerfully and "back resonance" was most feeble – whereas there was no significant difference in radiation pattern between the vocal projections of his singing voice.
Unlike this finding, the opera singer's radiation patterns of all the vocal projections, for both vowels and song, showed extremely similar results. This is, assumed by Boren and Roginska, because a sung opera aria has more notes with long vowels and fewer

fricatives compared to the musical theater singer's song [13]. Based on the analysis about the absolute radiation patterns of the intoning vowels on C4, the absolute overall levels revealed wide differences between the vocalists as well as the vocal projections: The directivity of the musical theater singer for the intoned vowels and the song was almost equal, likewise for each projection, although that of the opera singer's "forward" mode for the intoned vowels and the song was not so strong compared to other vocal projections. The directivity of both "forward" voices showed not only a weaker radiation than that of other projections, but also it does not direct to the front, as expected. Surprisingly the "back" voice radiated even more strongly forward than the "forward" and "mask" voices. The analysis of opera singers song directivity in absolute third-octave bands (251 Hz, 501 Hz and 1000 Hz) showed a similar result, namely that the radiation of opera singing voice changes largely at each analysis band, and that this is independent of the vocal projection: at 251 Hz and 1000 Hz the directivity of each vocal projection radiated almost identically, while that of the voices focused on "forward" and "mask" at 501 Hz decrease dramatically. Only the directivity of the "back" singing showed no such change. Therefore, it can be claimed that the vocal projection "back" has most the powerful directivity from all the investigated vocal projections. Even in the same way, measured on intoned spoke vowels of both actor and actress in four vocal projections, chest/mask/head/back resonance, the absolute radiation patterns of the actor showed that his chest and "back resonance" voices radiate most powerfully. His head voice was most feeble, whereas the actress's head voice radiated more strongly than her chest and "back resonance" voices (her speech voice in the projection "mask" was the most powerful).

When it comes to the simulation of the directivity of the singing voice, in comparison of the directivity patterns of human singers (a female and a male) with an artificial singer which was developed by Kob, the results showed that the artificial singer (artificial torso) can simulate directivity patterns similar to that of human singers [46]. However, he found differences of frequency-dependance among the singers as well as between the human and artificial singers.

4.4 Radiation of Singing Voice (Executive Summary from Previous Studies)

Previous researches on human speech voices as well as on human singing voices has been introduced in this chapter. Most studies have focused on the speech voice in comparison to the singing voice. However a comparison of the speech voice may help with the understanding of the radiation of singing voices. In order to comprehend the current state of research in the topic "radiation of singing voices," a summary of the presented research results will be given in the following:

Measured Objects in Terms of Body Vibration

- Vowels: Sound vibration depends on vowels because of mouth aperture size – the closer the lip opening, the greater the skull vibrations. But the vibration level of body parts situated below the glottis, is basically not affected by any vowels.
- Register: In comparison with chest and head voices the sternum vibration is greater in the chest register [45]. However, this vibration also depends on pitch.
- Loudness: Stronger vibration at loud vocal sound.
- Pitch: Vibration in the larynx is greatest for the low pitch and in the lip region for the high pitch [57].

Measured Objects in Terms of Vocal Sound Directivity

- Frequency: Radiation directivity of human voice changes depending on frequency. Furthermore, all the human voices, whether speech or singing voices, radiate in the horizontal plane equally backward (behind talker or singer) as well as in a forward direction to the mouth in the low frequency range, but the directivity becomes more forward in the higher frequency ranges (the backward directivity decreases) [22] [18]. In the vertical plane, the forward directivity becomes more clearly measurable at higher frequencies and will also be more downward from the mouth [50] [18].
- Gender: No significant or only slight differences in the speech voice [53] [18].

- Sound intensity: Only slight differences between sound levels both in speech and singing voices [53]. Low-level speech has greater directivity than that of other sound levels [18]. A noticeable variation between *fortissimo* and other intensities (*piano/mezzoforte/forte*) at 800-1000 Hz – presumably because of the mouth geometry for *fortissimo* which differs from that for the others [44]. But unlike the research by Monson et al. on the voices of 15 subjects, both studies by Chu and Warnock and by Katz and d'Alessandro were executed on a single subject, therefore, more measurements would be needed for the verification.

- Mouth aperture size: The size of mouth opening influences on radiation directivity of the human voice [22] [16] [64] [35] [44]. Large mouth size radiates more directionally [64], and the dependence of the mouth aperture size on the vocal directivity is confirmed by research results of the investigation on the voiceless fricatives [53]. But in comparison of the singing voice with the speech voice, no directivity differences in regard to the size of mouth opening was detected. Nevertheless, the result changes depending on the singing style used [53].

- Singing technique: Measured on a classical singing voice, no wider differences had been detected in the research on the directivity, with and without the vocal projection, and among the various modes used [16] [44]. Individual differences among singers were observed significantly in comparison with the singer's vocal projections sung in the audience area of the recital hall [16]. Directivity of the opera singing showed a variation between the measured vocal projections (back/forward/mask), while that of the musical theater singing had no such differences [13].

5 Research on Sound Radiation of Singing Voice: Methods and Materials

Voice scientist Ingo Titze describes that the human vocal system is similar to some string and wind instruments, such as violin and trumpet: In the case of a violin, the strings make the fundamental frequency and the harmonic frequencies, just as the vocal folds create the sound source of the voice. The top plate works to reinforce and amplify all these frequencies, similar to the vocal tract, and finally the sound will be radiated from the f-holes in the top plate. In the case of a trumpet, it is the same thing: the vibration by a player's lips as the sound source, the metal tubes as the resonators, and the horn as the sound radiator [80]. In the field of instrumental acoustics, many researchers have already measured the sound of musical instruments. They have determined by their experiments that the radiation patterns of musical instruments change with materials used, pitches played, and other factors (e.g. [4] [84] [56] [89]). Indeed, while the human vocal system operates in the way that is similar to some musical instruments, as asserted by Titze, it would seem possible that a singing voice would also have radiation patterns similar to the instruments. But when it comes to radiating surfaces, there is a vast difference between musical instruments and a singing voice. The human body is covered by soft skin compared to the rigid body of musical instruments. As already mentioned in Chapter 4, Titze asserts that only very poor radiation comes from tissue surfaces and high viscous dissipation is occurred within tissues [79]. However, as results by Kirikae et. al. and Sakakura & Takahashi revealed (see Section 4.2), radiation from tissue surfaces is possible, even if this effect on total sound energy of singing voice would have been relatively small.

In the previous chapter, the methods and results from studies of the radiation of singing voices were introduced in two ways: body vibration and vocal sound directivity, thus we know about the importance of the size of mouth opening and dependence on frequency for radiation directivity, as well an influence of sound level on body vibration.

The topic of my research is also directed at vocal sound radiation from the body, in other words, radiation properties of the singing voice, which are measured close to the body in the near field. Yet this investigation differs from the previous studies in following respects;

- Research method: microphone array with 121 microphones and the Minimum Energy Method,
- Subjects: 7 singers (8 voices) from various musical genres (not only classical singers),
- Measured location: 15 parts of the upper body.

This setting made it possible to investigate:

- Radiation patterns of singing voice in general,
- Radiation patterns of singers from various musical genres,
- Grasp of sound source of singing voice,
- Sound radiation from the measured parts of the body related to that from the mouth,
- Comparative analyses e.g. among the musical genres.

Therefore, this method offers a number of opportunities to expand the knowledge about the singing voice.

5.1 Recording and Analysis Technique

As already introduced in Chapter 4, until now accelerometer and laser technique have usually been in use for measurements of the vibration of singing voice. However, this investigation is executed using a microphone array with 121 microphones, the so-called "Acoustic Camera." Finally, the data obtained by the array were used to back-propagate the sound field to the radiating source surface by means of a Minimum Energy Method. This method enables us to reconstruct sound pressure fields and to show an overall radiation directivity of a vibrating geometry. Both, the Acoustical Camera and the Minimum Energy Method, are developed at the Institute of Systematic Musicology of Hamburg University, and all information about these recording and analysis technique can be found in the publications of the developer Rolf Bader[1]. Therefore, most descriptions about these, introduced in the following, will be quoted from Bader's publications which are mentioned as footnote.

5.1.1 Acoustic Camera

For recording of sound pressure fields, many microphones will be used and these are often arranged as a microphone grid or array [4]. The method by means of a microphone array is usually used in musical instrumental acoustics nowadays, however in vocal acoustics, the use of microphone grid seems to be standard and the research method using an acoustic camera is still new. A recording using a microphone array has two advantages [4]:

- It enables us to see the radiation field of the radiating source.
- The recorded data can be used to back-propagate the sound field to the surface of the radiating source.

The microphone array, which was employed in my investigation, consists of 121 microphones (11 x 11), and this construction enables to make a symmetric visualization of radiating field later (see Figure 5.1)[2]. The microphones record simultaneously with a sampling frequency of 48 kHz, thus the whole human hearing range up to 20 kHz is covered. This is a very important factor for measurements of musical instruments including singing voice, because musical instruments often radiate high frequency and initial transients are often the most important part of the sound [4].

As already mentioned, the microphone array used here was developed at the Institute of Systematic Musicology in Hamburg and the developer Rolf Bader notes in his publication how this array is built:

[1]Detailed description about the Acoustic Camera and the Minimum Energy Method as well as exemplary measurements can be found e.g. in [4] [1] [3] [2] [54]. Furthermore, there is a DVD about the Acoustic Camera: Bader, R., Acoustic Camera, Systemata Musika, 2010.

[2]In the original, the microphone array consists of 128 microphones. However for perfectly symmetric visualization only 121 microphones were used.

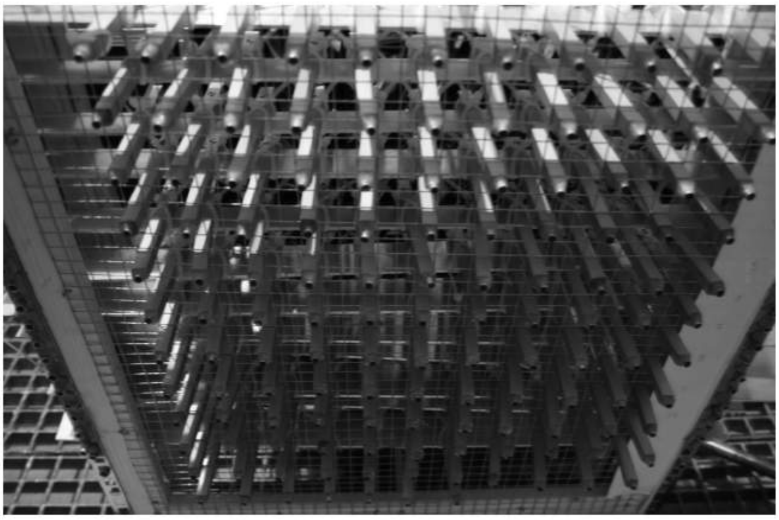


Figure 5.1: Microphone array with 128 electret microphones (from Bader et al. [4]).

"The hardware used is a microphone array consisting of 128 electret MCE-4000 omnidirectional microphones with a frequency range 20 Hz–20 kHz and a S/N ratio of <58 dB. They are driven by a 9 V external battery voltage supply. The array is flat and equally spaced 11x11 plus an additional row of seven microphones. All microphones are spaced 3.9 cm apart in x- and y-direction. The amplification and digitalization equipment is a RME system of 128 microphone preamplifiers synchronized by a word clock and streamed by a Multichannel Audio Digital Interface (MADI) protocol. Two 64 channel MADI signals are streamed into a Personal Computer (PC) using two Peripheral Component Interconnect (PCI) cards, respectively, and again synchronized by a world clock. The signal is recorded using a Steinberg ASIO driver code written for this purpose. The used sample frequency is 48 kHz with 24 bits/sample for each channel. As the MADI protocol uses 32 bits/sample, a data flow of 128 X 48 000 X 32 bits/ s is processed. These data are analyzed and statically and dynamically visualized by a WINDOWS C# code, including a Graphical User Interface (GUI)" [1].

Before recording, all the microphones were calibrated by a continuous sine wave which was generated from a source with quasi-monopole radiation characteristic at distance of 30 cm in front of the array. At first, as displayed left in Figure 5.2, the microphones show differently strong signals and this must be adjusted, so that all the signals become equal strong. Therefore, the recorded monopole radiation will be firstly divided by the theoretically calculated monopole radiation and then this difference will be multiplied by the measured value in the propagation (see right in Figure 5.2).

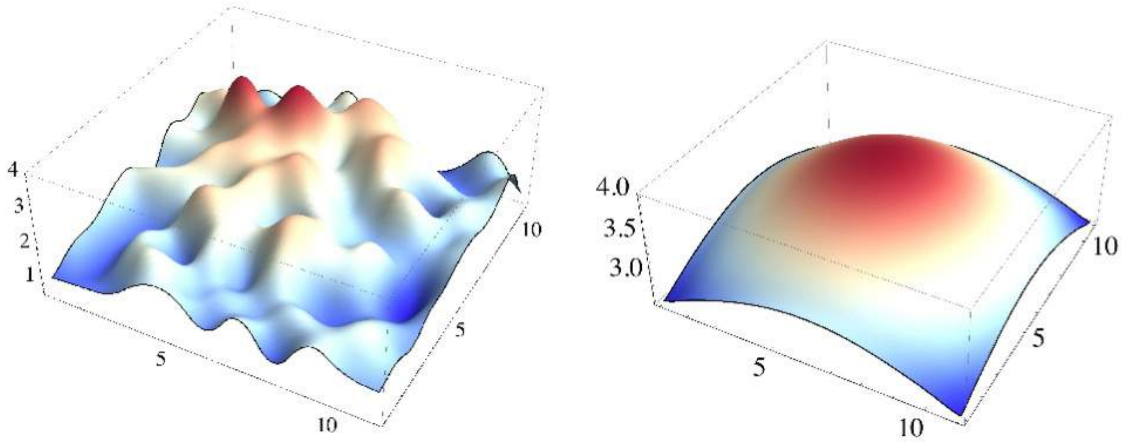


Figure 5.2: Calibration of the array: before (left) and after (right) the calibration.

5.1.2 Minimum Energy Method

In this investigation, the radiated sound fields were reconstructed by a Minimum Energy Method, as already introduced. The Minimum Energy Method is a near-field research method for reconstructing a sound pressure field at a radiating surface of musical instruments including the human body for voice research. It samples the source plane by as many the so-called *equivalent sources* as microphones present in the Acoustic Camera. The principle is illustrated in Figure 5.3. Each equivalent source radiates into each microphone. The main feature of this method is that the directivity of equivalent sources in the radiating plane is assumed to be intermediate between a monopole and a beam or ray. This directivity is tuned by a parameter α. The "correct" directivity is the one that needs minimum energy to create exactly the recorded sound pressure distribution [1].

This parameter can broaden as well as narrow the overall radiation directivity, and the directivity value is determined by a radiation matrix, which describes the sound propagation from each equivalent source to each microphone. The matrix looks different for each value of α. For example, if $\alpha = 0$, this means a perfect monopole, whereas $\alpha = \infty$ denotes rays, connecting each equivalent source with one microphone only. By means of this method not only monopole radiation, but also dipole or higher pole radiation

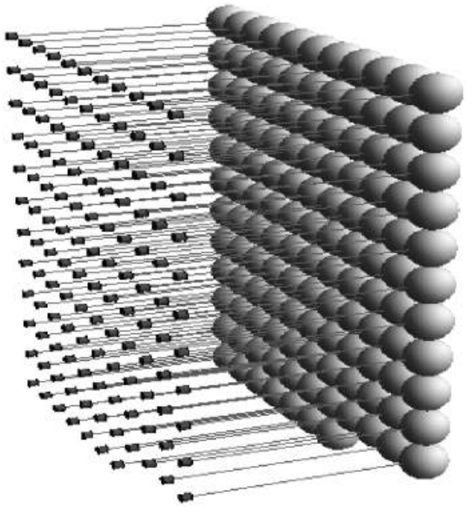


Figure 5.3: Structure of the microphone array built on the basis of the relations between 128 radiating points (monopole radiators, right) and the corresponding microphones (left) (from Bader et al. [4]).

on the radiating surface can be shown, if there is a phase difference between radiation points. Dipoles or quadrupoles are examples of such complex radiation patterns which directivity value mostly shows $\alpha > 0$. In general: the higher α, the narrower the radiation is [4].

Furthermore, the angle between the microphones and the radiating point, i.e. the radiation angle from the radiation position, is also important for the reconstruction process and is shown using the parameter β [1]. Thus, the radiating field can be reconstructed using both parameters α and β as a set. The following information can be gained according to the revealed value of α and β;

- The case of $\alpha > 0$ and $\beta = 1$ means *maximum radiation* and this is always in the normal direction.

- The case of $\alpha > 0$ and $\beta = 0$ means *minimum radiation* and this is always in a direction orthonormal to the normal direction [1].

In the case that a different value of α is shown for complex radiation patterns, a linear equation solver back-propagates measured sound pressure to the radiation points on the

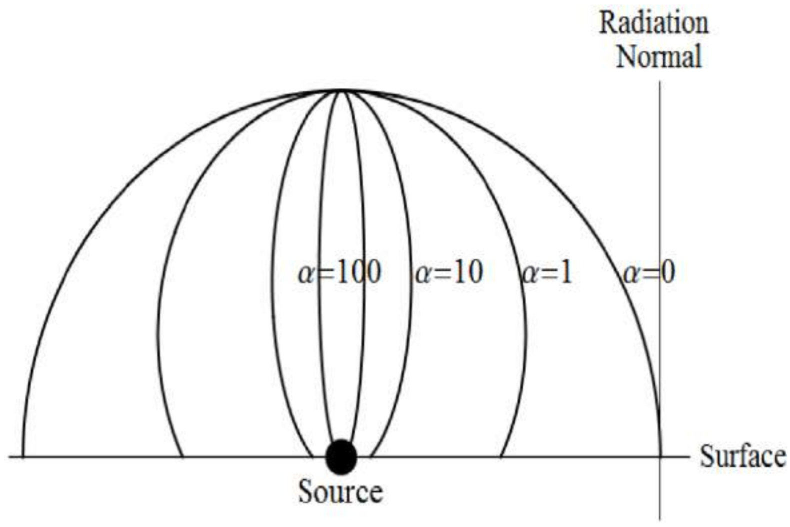


Figure 5.4: Radiation pattern for different values of α. The value $\alpha = 0$ means a perfect monopole, the value $\alpha = \infty$ would be a ray (from Bader [1]).

radiating surface using the radiation matrix. The value α is correct, when cumulated energy of the equivalent sources is at minimum. The correct value for α is found iteratively. Firstly, α is set to 0 and a linear equation system is solved to receive the radiation energy of the equivalent sources. Then, α is increased by 1 and the equation system is solved, again. This is done until a clear inflection point with a relative minimum can be observed, when plotting the cumulated energy over α. In the next iteration, α is altered in steps of 0.1 around the minimum, to find a new minimum with a precision of a higher order [4]. The Minimum Energy Method is similar to the method of Acoustic Holography developed by Earl G. Williams: measurement, analysis of the holographic reconstruction and visualization of data [86]. However, the Minimum Energy Method solves the problem which occurs in the method of the Acoustic Holography that the cancellation by phase differences of neighboring radiating points leads to an exponential decay of the amplitude in the radiating direction [1].

5.1.3 Visualization with Phase Angle

For the analysis, code written in Mathematica was applied to all the data and by means of this the vibrations were analyzed on a total of the 15 upper parts of the body (see more detailed information in the following section). This setting made it possible to show energy values of the voice radiation from the singer's upper body, including the phase angles, and all statical procedures, which will be shown in the following chapters, are based on that visualized results. The data are reconstructed and visualized on a photo of the human upper body from the head to the chest[3]. Three aspects of the complex results can be visualized: real part, imaginary part and absolute value, as shown in Figure 5.5.

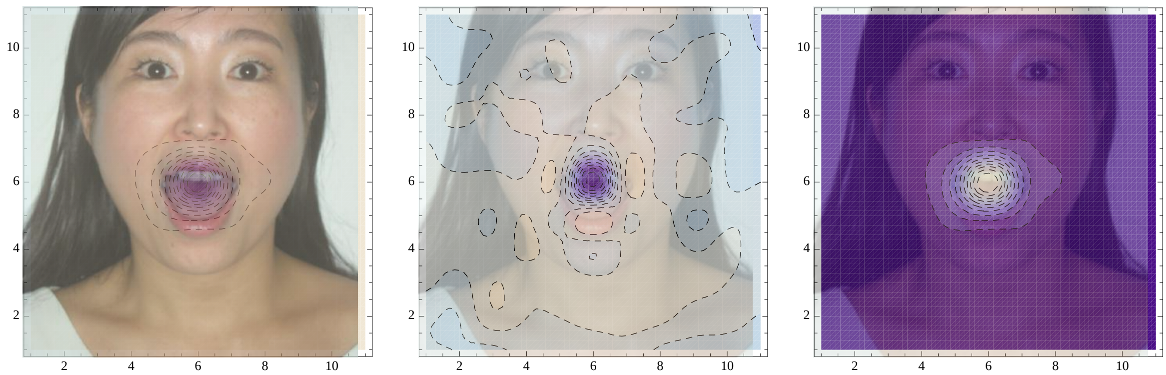


Figure 5.5: Process of a visualized mode of singing voice (from left to right: real part, imaginary part and absolute value). The mouth is adjusted to the middle of the picture where "6" (6th microphone of 121 microphones (11 x 11)) is on the x- and y-axis.

The reconstructed amplitudes include the phase of the amplitude from the real and the imaginary parts. The plotted real and imaginary parts of the reconstruction show the different phases of the radiated points. Phase is a physical parameter by which vibrational state is defined and gives a information about a particular point in a circle of periodic wave process. The position on the circle can be determined by a phase angle. As shown in Figure 5.6, the wheel rotates counterclockwise in the circle and the phase of wave can be defined as followed:

$$y = A \sin(\omega t + \phi)$$

(y = relative sound pressure, A = sine function of amplitude, ω = angular frequency, t = time, ϕ = phase angle).[4]

[3]Later in Chapter 6 where radiation patterns of a singer's voice are presented, a sketch of this photo is in use instead of the photo.

[4][85]

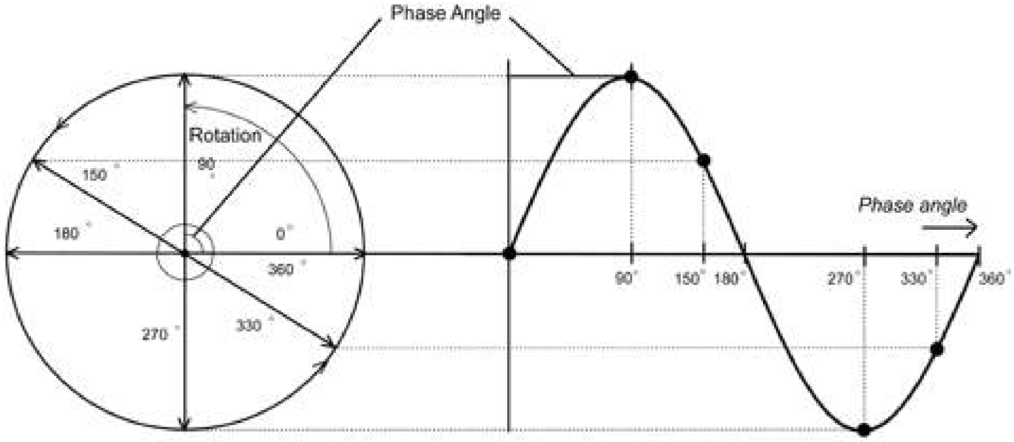


Figure 5.6: Interaction of the phase of a wave with phase angle.[5]

The absolute value shows the amplitude strength and the parameter of the complex number reveals the phase [4], so only the absolute value with phase information will be shown as ultimate results in the following chapters. The radiated energies of all single frequencies are normalized to 0 dB at the mouth[6], so the ultimate result of the absolute part with phase angle looks like Figure 5.7. Furthermore, as shown there, the radiation is adjusted up to -6 dB and the intensity of the radiation energy is visualized by colors. The phase of the 15 parts of the body is indicated by a little square on a unit circle. Usually the mouth radiation is the strongest, so that the radiated energies of all single frequencies are therefore normalized to 0 dB at the mouth, but if there is a radiation point from which stronger energy value is observed than from the mouth (i.e. more than 0 dB, normalized value to the mouth), the color scale of radiation energy will be changed: for example, 1 dB is measured at a radiation point and in this case, the radiating fields that show more than -5 dB are marked in colors.

Figure 5.7 shows that all the phases are equiphase (i.e. all at 90 degree angle in clockwise direction). If a phase angle is similar to that of the mouth, which always displays a 90 degree angle in clockwise direction, its radiation energy is stronger than the radiation energy shown with an opposite (270) degree angle in clockwise direction. But the modes of the real and imaginary part also have an influence on the strength of

[5]Downloaded from http://www.jiscdigitalmedia.ac.uk/guide/the-physical-principles-of-sound (last visited: 14/5/2015).

[6]Nevertheless there are some figures where energy value at the mouth is resulted in -1 dB. This means that the revealed energy value is not quite 0 dB, so somewhat stronger than 0 dB.

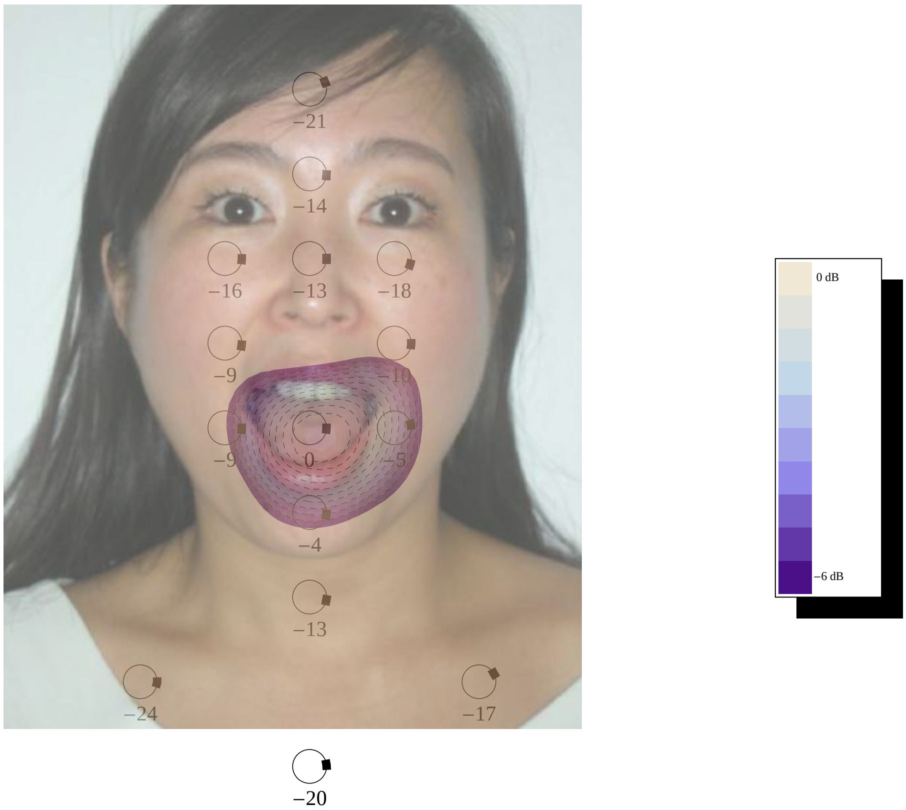


Figure 5.7: Standardized color scale of the radiation (from -6 dB to 0 dB).

the radiation energy.

5.2 Research Materials

5.2.1 Experimental Subjects

Seven trained singers — three Classical (bass, alto and soprano), two musical theater (tenor and mezzo soprano) and two popular singers (both mezzo soprano) — participated in this study, as shown in Table 5.1. Five of them (CH, SE1, TF, SE2 and VS) finished their study in vocal music at a music educational institute, and the remaining two singers (JR and SS) had singing lessons for over three years and various experiences on stage. In addition, one popular singer's voice (VS) was recorded twice by means of popular singing technique and by means of Soul singing technique, because she claimed that she uses her voice to adapt musical genre in her performance.

	Subject	**Sex and Age**	**Trained Musical Genre**	**Voice Category**	**Repertoire**
1	CH	Female, 37 years old	Classical	Alto	Lieder/Oratorio/Opera
2	SE1	Female, 29 years old	Classical	Soprano	Lieder/Oratorio/Opera
3	JR	Male, 49 years old	Classical	Bass	Lieder/Opera/Pop
4	SS	Female, 28 years old	Musical	Mezzo Sop./Alto	Musical/Pop
5	TF	Male, 25 years old	Musical	Tenor/High Baritone	Musical/Pop/Jazz/ German Schlager music/Folk music
6	SE2	Female, 26 years old	Pop	Mezzo Sop./Soprano	Pop/Jazz/Bossa Nova/ Turkish folk music
7	VS	Female, 25 years old	Pop/Rock	Mezzo Sop.	Pop/Soul/Rock/ Classical/Bossa Nova

Table 5.1: List of information about the participants.

In the beginning, all participants were asked to fill in a questionnaire, stating their musical education, duration of singing career, musical genres of singing and vocal health, i.e., whether they have ever had voice disorders. The duration of their musical education (except JR and SS) ranges from years to eight years and has a mean value of five years. For the question that addresses to all subjects, how long they have totally sung in their life, they stated the duration from six years to 37 years, so that the arithmetic mean is 17,8 years. When it comes to the question of the vocal health, only one subject, CH had had a vocal fold nodule.

Besides the questions mentioned above, a self-report questionnaire was also conducted where participants stated their voice category including vocal range and information regarding singing techniques they had learned. As expected, there were different statements about singing techniques among musical genres and also between the singers. The classical singers stated that they have learned following techniques: "singing in the mask," "abdominal respiration," "openness in the nasopharynx," "lifting of the soft palate," "lowering of larynx," "singing with diaphragmatic support," and "attention to position of the lips, the chin and the tongue," These are the most common techniques taught in classical singing lessons. However, some of these singing techniques, such as "abdominal respiration" or "attention to position of the lips, the chin and the tongue," are also used for musical theater and popular singing, therefore all the subjects declared that they were taught these singing techniques. But the popular singers also stated that they have learned to pay attention to "singing in the mask," and "lifting of the soft palate," beside attention to speech-based natural articulation in singing and nasal sound production. This is not because one of them (VS) has also classical singing in her repertoire, but both singers have actually learned these techniques in their musical education. For the musical theater singers, I marked that both subjects are differently trained, although they stated both to use the common musical theater singing technique "belting" for singing. One singer (SS) has learned traditional "belting" technique, while another one (TF) was taught a mixed technique from classical and belting singing methods. According to his statement, this "belting" voice is built on classical voice leading.

5.2.2 Vowels and Tones

For the study, after a short warming-up vocal exercise, each subject sang five vowels a/e/i/o/u at following notes;

- 90 Hz (approx. F2#, sung by a bass singer)
- 120 Hz (approx. B2, sung by male singers only)
- 180 Hz (approx. F3#, sung by alto/mezzo soprano singers only)
- 250 Hz (approx.B3, sung by all subjects)
- 380 Hz (approx. F4#, sung by a tenor singer)
- 500 Hz (approx. B4, sung by female singers only)

This means that two notes were measured at three different pitches. Each vowel was recorded separately and max. 2 seconds of phonation. In order to get good data, the vowels were repeatedly measured two or three times in the order of a-e-i-o-u, respectively.

As already mentioned, all singers were asked before which vocal technique they have learned and usually use for their singing, but it was not indicated that they must apply that for the measurement. They were also not asked which singing technique that were used during the recording. I left the technique to subjects' discretion. They were only requested that during the measurement they were to sing as if they were singing in a large concert hall. This suggestion was meant to be helpful for the singers singing so closely in front of the acoustic camera, so that they would sing as naturally as possible, but simultaneously with a certain physically present posture. In addition, vocal registers, such as chest or head voice, were also not taken into consideration. Because for this study I used no electroglottogram or a similar measuring instrument by which voice scientists can easily determine vocal register change, and also because of various use of the definitions in the term "vocal register" (see Chapter 2), it is purposely avoided here, to determine and to show, for example, how the "chest voice" radiates. But, in fact, for the simple reason that the ultimate goal of this research project is to gather information about the production of sound energy of singing voice from the singer's body which is finally perceived as total sound energy by listeners in distance.

5.2.3 Measured Body Parts

In order to see the sound radiation of the singing voices, the energy was measured at 15 parts of the upper body, as shown in Figure 5.7;

- Mouth
- Chin
- Throat
- Left and and right clavicles
- Sternum
- Nose
- Nasal bone
- Left and right corners of the mouth
- Left and right cheeks
- Forehead
- Left and right lower eyelids

The measurement was executed in an anechoic chamber. For the recording, the microphone array was attached to the front of a stand and adjusted for the height of the singer, so that their mouth is positioned in the front of the center microphone (No. 61). As already mentioned, the Minimum Energy Method is a near-field method, so that *"The closer the microphones are to the geometry, the better the condition of the radiation matrix R, as the relative lengths of neighboring radiation points for each microphone become larger"* [1]. Therefore the center microphone was placed 3 cm in front of the mouth. The recording condition was constructed as normally as possible, so that the subjects were normally dressed for the measurement[7].

[7] I would like to add the information that there was nobody who wore glasses among the subjects. If there had been, I would have requested them to take off their glasses because of acoustic reflection.

5.2.4 Analyzed Frequency Range

For analyses of the data, the frequency ranges were examined carefully, whereby noises occur as low as possible and these are the following ones (analyzed partials in brackets);

- 90 Hz: up to 1,3 kHz (15 partials)
- 120 Hz: up to 2,5 kHz (21 partials)
- 180 Hz: up to 3 kHz (17 partials)
- 250 Hz: up to 4 kHz (16 partials)
- 380 Hz: up to 4,5 kHz (12 partials)
- 500 Hz: up to 5 kHz (10 partials).

6 Result 1: Radiation Patterns of the Singing Voices

In this chapter it will be displayed in a visual form how the measured voice of the singers radiates, particularly whether, and how the sound radiation changes according to frequency and fundamental frequency that is sung. Here, the main question deals with individual results from each of the subjects and these will be shown in the following as an example from repeated recordings.

At this place, I would like to point to two important things: Firstly, for this study, only one sketch of the upper body and the face is used for all the illustrations of resulted radiation patterns, where the middle of the mouth is adjusted to the center microphone (6 x 6 in x- and y-direction), as mentioned in Subsection 5.1.3 of the previous chapter. Although the recording was executed several times and singers were reminded to sing to the centre microphone, there are some plots where the radiation source displayed using colors is not exactly located at the middle of the mouth in the sketch. Because configuration of the mouth and the lip which affects angle of sound radiation pretty much, and opening of interspace between the maxillary and the mandibular teeth have great influence on the sound radiation of singing voice. Such a configuration of the mouth region changes according to vowels, vocal technique and the habit of each singer how she/he usually moves her/his mouth region while singing. Furthermore, the bony structure of the face, for example size and length as well as precise placement of the parts of the face are also somewhat different for each person. Nonetheless the color-coded radiation comes at low partials from the mouth, even though these may not exactly occur from the centre of the mouth position of the sketch.

It is also possible that the singer's mouth was not precisely enough adjusted to the front of the center microphone where the strongest radiation is usually expected. A slightly oblique angle, which may happen unconsciously through slight head movements or by breathing while singing, has an influence on radiation direction, even though there is a spacing of 3.9 cm to each of neighboring microphones, as already mentioned in

Subsection 5.1.1 of the previous chapter.
Thus, the condition for recording the "vocal instrument" using the acoustical camera somewhat differs from measurements of other musical instruments.

All the results of radiation energy displayed in the following chapters are shown in relation to the mouth radiation in order to compare the sound level of the mouth to that of the other measured parts of the body, due to the fact that the strongest radiation is usually expected from the mouth.

6.1 Radiation Patterns of Classical and Nonclassical Singing Voices — Case Study of All Subjects at Tone 250 Hz (approx. B3)

The results of all the singers measured at 250 Hz will be shown here in two ways: in the first part, the radiation of the fundamental of the sung the vowel /a/ is displayed on the sketch in Subsection 6.1.1, representing research findings from all the vowels. However, generally, the section also discusses findings from all the vowels measured. Each of the results comes from only a single recording, as already pointed out.
In the second part, the radiation energy from singing the same vowel (/a/) is exhibited up to 4 kHz in Subsection 6.1.2 where the radiations from all the body parts and their change in the course of frequency can be observed at a glance. Each of the figures shows an average of all the results from the repeated (maximal three times) recording[1]. Beside the display of the results in this plot, changing radiation patterns are also illustrated[2]. Because this pitch is the only one on which all the subjects sang, the results from this pitch will be more detailed, compared to all the other pitches measured.

[1]In spite of repeated recording there were some data which are not good enough, but only the results that are usable for this research will be shown and analyzed in the following chapters.

[2]The results from the fundamental of these radiation patterns will be displayed in Subsection 6.1.1. As already mentioned, the research findings that are displayed on the sketch arose from a single recording, therefore, the further (changing) radiation patterns shown in Subsection 6.1.2 are not an average of the results from repeated recordings, but also from a single recording.

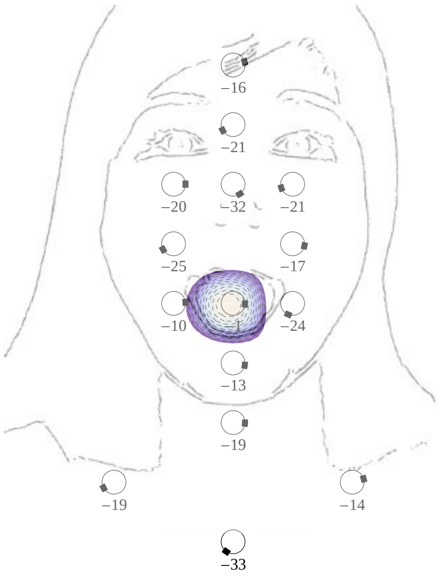
6.1.1 All Singers at the Fundamentals

The results from the fundamental of the vowel /a/ sung by all subjects are shown in the following (see Figures 6.1 and 6.2).
For a moment it seems for all the subjects that the strongest radiation energy of their singing voice (color-coded area) came uniformly from the mouth at the fundamentals. It is not difficult to imagine that the mouth is generally the strongest radiation source of the singing voice, and that the corners of the mouth often vibrate strongest of all the measured parts except the mouth due to the near localization from the mouth, in fact independent of vowel. In general, it seems to be that the closer to the mouth the measured part of the body, the stronger the radiation energy. Hence, powerful energy was emitted also from the chin, but interestingly, this was sometimes even stronger than that from the corners of the mouth. Of course, the energy values of the measured parts were different for each subject: CH (alto, classical) had a characteristic feature for all vowels, in that that the radiation from the forehead was stronger than that from the nose. Otherwise none of the other subjects showed such a characteristic. Furthermore, when it comes to the radiation of her voice, radiation from the sternum was weaker in comparison to that of other singers. Looking through the results of all vowels, it was found that the vowel /i/ generally radiates most weakly among all the vowels.
The voice of SE1 (soprano, classical), TF (musical, male) and SE2 (Pop, female) strongly emitted from the chin, sometimes even more powerfully than from the corners of the mouth. In these cases, the radiated area of the vowels /a/ and /e/ was strong around the mouth in comparison to all the other vowels. In relation to all the other singers, the voice of both female classical singers (CH and SE1) came strongly from the measured body parts for the vowels /e/i/o/u/ which are located in the area between the throat and the sternum (i.e. the throat, the clavicles and the sternum). In other respects, for the vowel /e/ sung by a female Pop singer (SE2), her radiation energy from the mouth area was most powerful among the singers.
The intensity of the radiation energy seems to depend on vowels, respectively on mouth opening: for the vowels /o/ and /u/, the energy value of the musical singers (SS and TF) and the Soul singing of VS decreased at the cheeks, although for other vowels, there were no large differences in the radiation energy between the corners of the mouth and the cheeks. A presumed reason for this difference between classical and nonclassical singers is, as mentioned in Chapter 3, that classical singers usually open their mouth in a round shape, as equal as possible for each vowel, thereby providing evenness of the

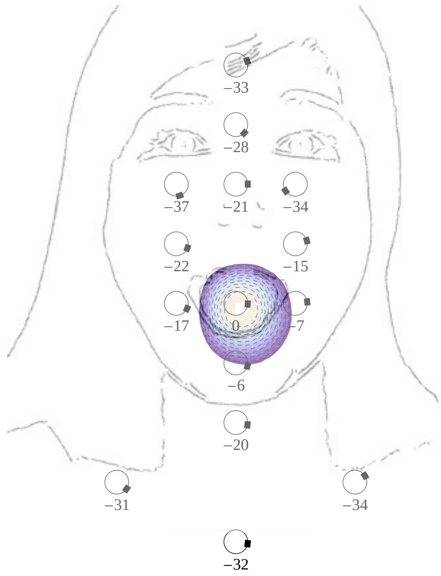
voice sound – "instrumental beauty of the singing voice." Of course, this argument is not true for nonclassical singers, thus, also for the singers involved in this research.

When it comes to the phase, no subject showed uniform phase angles. But the radiation of SE1, JR and SE2 from the area where the corners of the mouth, the chin and the cheeks are located was in phase with that at the mouth, while for CH, TF and VS (Pop) this was opposite in phase.

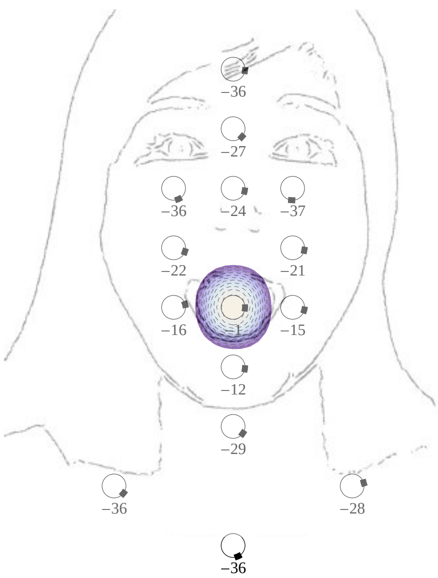
In total, when considering all the displayed energy values given at the fundamentals, it was observed that CH is strongest and SS is weakest from all the subjects. Furthermore, looking at the results from each part of the body, stronger energy arose by SE1, TF, SE2 and VS than by CH, JR and SS at the chin. No significant difference was observed in the results among musical genres.



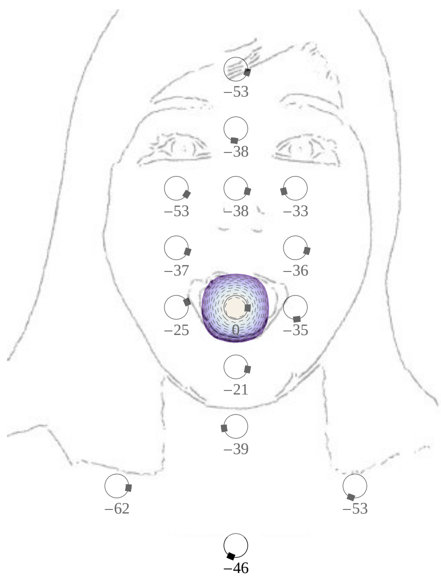
(a) CH (classical, alto)



(b) SE1 (classical, soprano)

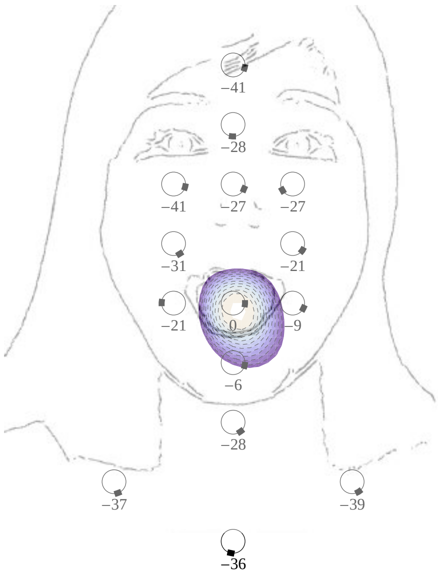


(c) JR (classical, bass)

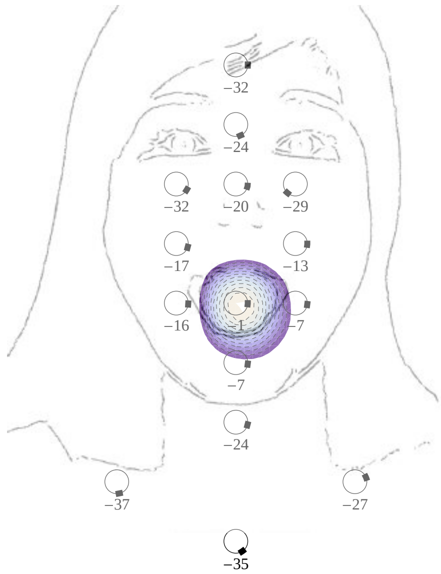


(d) SS (musical, female)

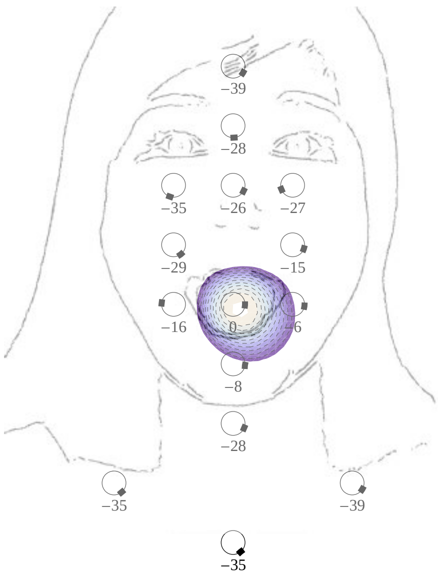
Figure 6.1: Radiation of three classical singers (a, b and c) and a female musical theater singer (d) at the fundamental of 250 Hz for the vowel /a/.



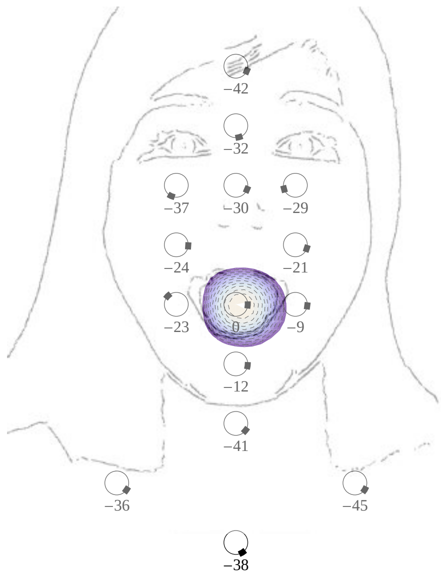
(a) TF (musical, male)



(b) SE2 (pop, female)



(c) VS (pop, female)



(d) VS (soul, female)

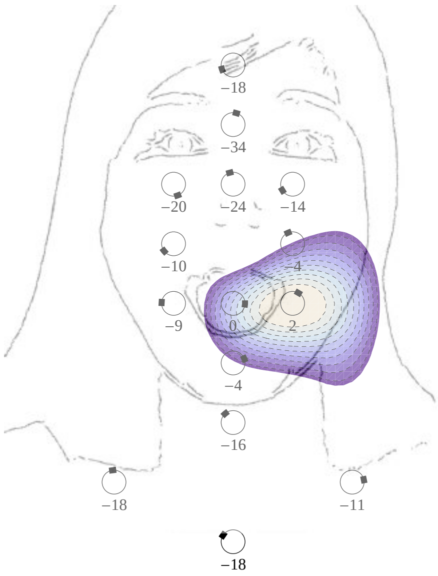
Figure 6.2: Radiation of a male musical theater singer (a), two Pop singers (b and c) and Soul singing (d) of the fundamental of 250 Hz for the vowel /a/.

6.1.2 Changing Radiation of the Singing Voice

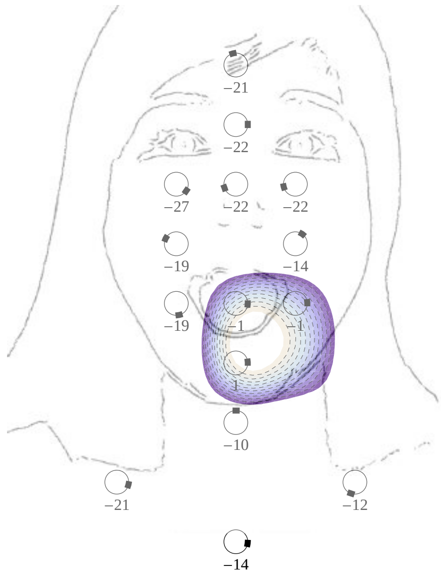
At the fundamental frequency, the strongest sound energy of the singing voice radiated from the mouth, as explained in the previous subsection. The radiation energy, however, was intrinsically changeable depending on frequency, although there were differences in the radiation pattern among singers. Therefore, this subsection addresses changing radiation patterns of the singers in the frequency range analyzed, up to 4 kHz.

First of all, we see an average of the results from all the vowels in this subsection. It can be seen in the results how the sound radiation of the singing voice changed at high frequencies. Like the results shown at the fundamental frequency (see Subsection 6.1.1), the energy from the corners of the mouth and the chin was powerful. The fact that these parts of the body were usually the second and third strongest radiated parts next to the mouth remained unchanged till the end of the analyzed frequency range. The radiation energy from the left corner of the mouth was often stronger than that from the right corners, and in some cases, this was even stronger than the radiation from the mouth in the frequency range from around 3 kHz. As already mentioned, such a result might arise from subject's standing slightly to the left.
When it comes to a comparison of the overall energy level of the measured 14 parts with mouth radiation energy, it showed that SE1 (classical) has strongest radiation energy relating to her mouth radiation and her overall energy was, for example in the case of the vowel /a/, between about - 5 and - 30 dB (see Figures 6.7, 6.8, 6.9 and 6.10). Such a high energy level from certain parts of the body was also observed for other subjects, but in the case of SE1, in general, all her parts radiated strong energy.
Looking through all the findings of the measurement at 250 Hz, it can be seen for classical singers that energy levels gained from all the parts of the body were relatively close to each other for all the vowels, so that the difference of these energy levels was smaller among the measured parts in comparison to the nonclassical singers.

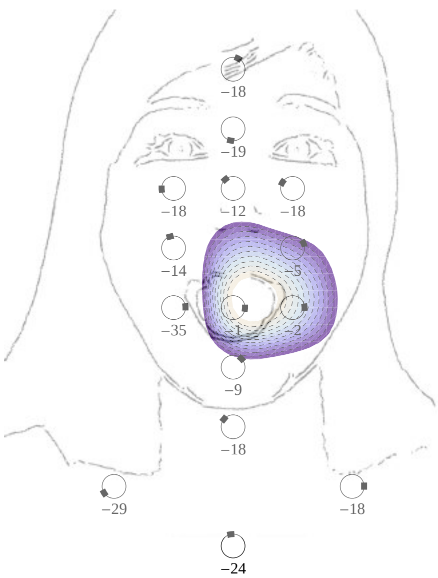
The sound radiation changed steadily in the frequency range, independently of any factor such as the vowel or the musical genre, and this mostly increased at advancing frequency in comparison to the fundamental frequency. At this point, we look briefly at the radiation patterns that we saw in the previous section partially, namely the radiation patterns of the fundamental frequency. These radiation patterns can clearly reveal radiation energy, which changed according to frequency. At advancing frequencies,



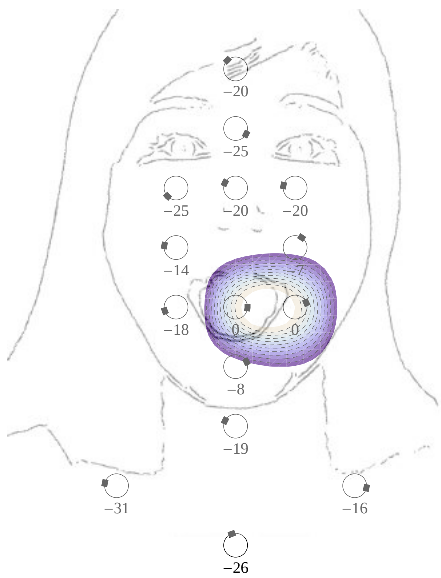
(a) 16. Partial (classical, soprano)



(b) 13. Partial (pop, female)

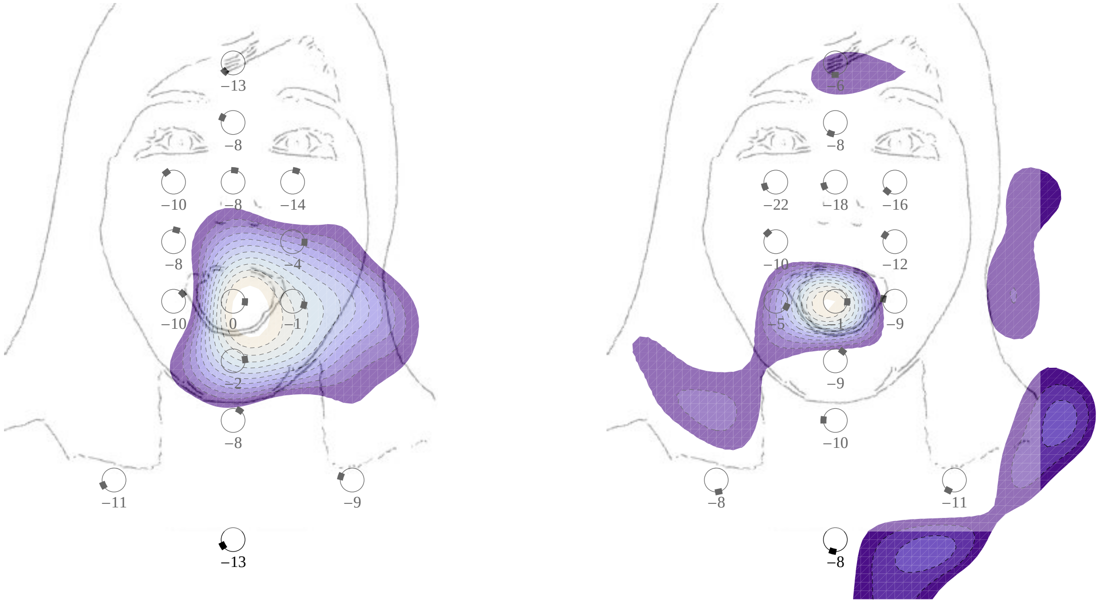


(c) 14. Partial (pop, female)



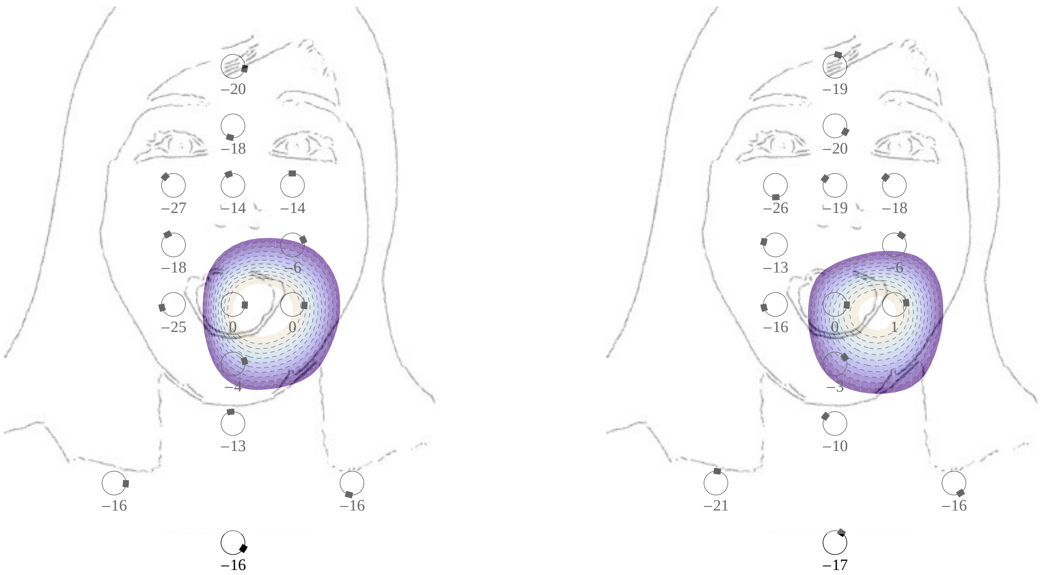
(d) 16. Partial (pop, female)

Figure 6.3: Radiation of SE1 (a) and VS of popular singing (b, c, d) for the vowel /a/ at 250 Hz.



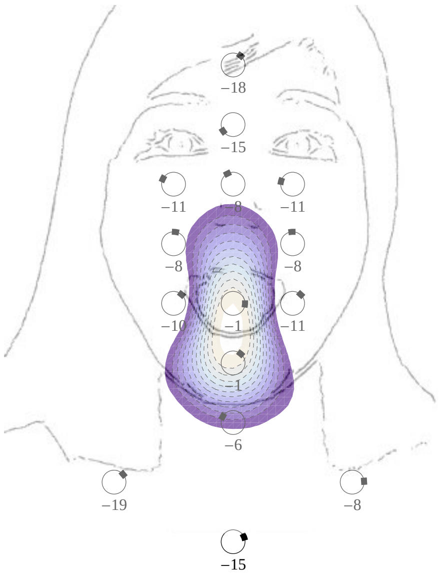
(a) 10. Partial (classical, soprano) (b) 15. Partial (classical, bass)

Figure 6.4: Radiation of SE1 (a) and JR (b) for the vowel /e/ at 250 Hz.

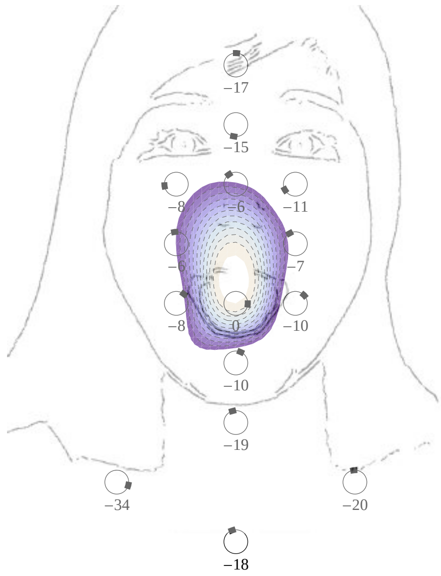


(a) 12. Partial (b) 16. Partial

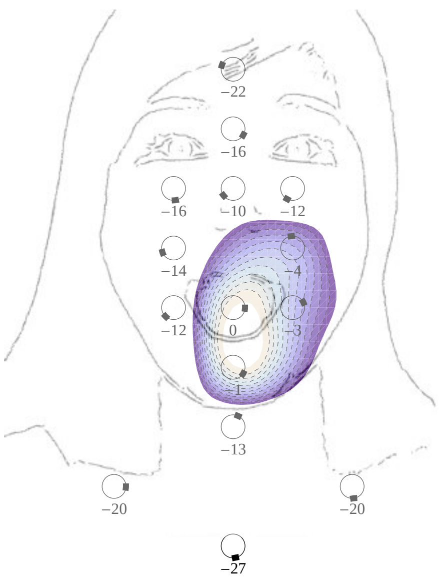
Figure 6.5: Radiation of SE1 for the vowel /i/ at 250 Hz.



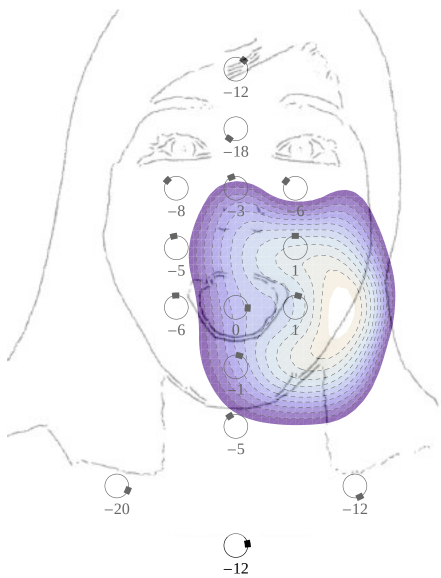
(a) 15. Partial (pop, female)



(b) 16. Partial (pop, female)



(c) 14. Partial (musical, male)



(d) 13. Partial (pop, female)

Figure 6.6: Radiation of SE2 for the vowel /e/ (a, b) and TF for the vowel /i/ (c) as well as SE2 (d) for the vowel /o/ at 250 Hz.

the color-coded area often spread and strong radiation energy also occurred from the chin approximately from the 10. partial (2500 Hz). In some cases, the radiation energy arose from other parts of the body, too, as displayed in Figures 6.3, 6.4 and 6.6. The figures show the radiation energy of the vowel /a/: the radiation was getting stronger and the strongest radiating point (middle) of her radiation that actually came from the center of the mouth at the fundamental frequency (see in Figure 6.1) shifted towards the right corner of the mouth at the 16. partial. This partial's radiation was stronger than from her mouth and indicated an energy value of 2 dB. A similar finding was observed in the case of TF singing the same vowel, in that his radiation energy from the corner of the mouth was equal to that from the mouth (0 dB), due to shifting of the strongest radiating point to the right side. The results of VS shown in popular singing was actually also similar to both findings, however, her radiating area was often in a fluctuation from the 13. partial to the 16. partial – the middle of the radiation source moved downward, in the direction of the chin at the 13. partial, so that the energy from there became stronger than the mouth radiation (1 dB from the chin), but at the 14. partial, the strong radiating area was located rather in the upper area of the mouth. Finally, at the 16. partial, her strong energy emitted from the mouth as well as from the right corner of the mouth, therefore the energy value of the latter also indicated 0 dB.

For the vowel /e/, the strong radiated (color-coded) area seems to be generally more widespread than for the vowel /a/: the radiation of SE1 that was getting broader in the frequency range seems to have reached the maximum of her radiation energy at the 10. partial, not only because of the size of her strong radiated area, but also because her whole radiated energies increased there (see energy values displaying in Figure 6.4). After that, at the 16. partial, her radiation energy from the right corner of the mouth indicated 0 dB (just like the mouth radiation) due to the shifting of the strongest radiating point to the right side (similar to the result gained from the vowel /i/ displayed in Figure 6.5). Also in the case of SE2, her emitted strong energy became broader at increasing frequency, but its ever-changing radiation patterns shown at high frequencies are similar to the radiation patterns of VS that was observed in her popular singing for the vowel /a/. The singing voice of SE2 that came directly from the mouth at the fundamental radiated from the area between the throat and the nose, in oblong form, at the 15. partial, however, at the 16. partial, this occurred from the area around the upper lip. Unlike SE1 and SE2, JR's energy always radiated directly from the mouth until the 14. partial spread at this partial. At the 15. partial, his radiation energy was radiated from the chest region including the shoulder and the forehead, additionally from the mouth and the corners of the mouth (this pattern however went back to the original form at the 16. partial).

For the vowel /i/, the radiation patterns of SE1 were similar to that of the vowel /e/ – an ever-growing area from where strong energy radiated (at the 12. partial), and shifting of the strongest radiating point to the right side at high partials, so that the energy from the right corner of the mouth became the most powerful radiation part there (see Figure 6.5). The radiation energy of TF spread most of all at the 14. partial and was emitted from the chin, the right corner of the mouth and the right cheek, as shown in Figure 6.6.

For the vowel /o/, some subjects revealed somewhat extensive radiation at higher frequencies (for example: SS at the 9. partial), but the radiating area was restricted to the area around the mouth. The only exception was observed at the 13. partial of SE2: Her strong radiation energy was a large-area (from the nose, chin, right cheek and the right corner of the mouth) and the strongest radiation point was located at the right cheek, however, a little further away from the measured point (see Figure 6.6). This seems to occur from the outline of the face on the sketch, but in fact, it is uncertain because everyone looks somewhat different, as already mentioned. However, this radiation pattern went back to the form from the 14. partial, as it was before.

For the vowel /u/, the results gained by all the singers except for TF seem similar to these shown in the case of the vowel /o/: from the 9. partial, his strongest radiation point moved to the right similar to the radiation patterns of SE1 displayed in Figure 6.3. This way, the energy value from the right corner of the mouth surpassed that from the mouth or these parts of the body are equivalent.
In addition to the findings that are mentioned above, I would like to point out that a strong radiation energy of CH always came from the mouth in all results from singing at 250 Hz and this fact remained the same in the frequency range analyzed.

However, such increase of the sound energy can be better seen in the process of radiated energy shown in Figures 6.7, 6.8, 6.9 and 6.10 is especially clearly recognizable in nonclassical singing styles. The reason is that in classical singing style its radiation from all the measured parts of the body did not increase much or, in other words, was rather less in a fluctuation at the whole frequencies analyzed (except for the vowels /o/

and /u/), particularly for CH and SE1. The parts of the body that are located far apart from the mouth showed a remarkable increase, so that the difference between all the measured parts became smaller at higher frequencies. This implies that the difference of both sound levels, from the mouth and from all the others, also became smaller there.
Furthermore, looking at the results yielded by each vowel, it was found that all the radiated energies from the measured parts, in comparison with the mouth radiation, mostly remain stable about from approx. 1.5 – 2 kHz for the vowels /a/e/i/, although for the vowels /o/ and /u/, such stability was much less observable. Presumably there were complicated air motions in the vocal tract due to narrowing mouth opening and configuration changes of the vocal tract for these vowels.

When it comes to the increase of the sound energy mentioned above, I have to add one more point: Generally, the dimension of such increase seems to differ from subject to subject, i.e., this is due to individual singing manners rather than musical genres. For example, the fluctuations of the energy shown in the cases of SE1 and SE2, classical and Pop singer, respectively, were very similar for the vowels /a/e/i/, so that its sound energy level in comparison with its mouth radiation stayed firm in the whole frequency range analyzed.
However, one significant difference among the musical genres was clearly recognizable for the vowels /o/ and /u/: For the musical theater and popular singers, a wide difference of the energy between the mouth area (the corners of the mouth and the chin) and rest of the parts of the body was revealed, whereas no such phenomenon for the classical singers occurred (see Figure 6.11). In other words, the radiation energy from all the measured parts was relatively similar in energy value for the classical singers, compared to the musical theater and popular singers. Presumably, this is due to different mouth/lip opening – as repeatedly mentioned, classical singers usually hold the shape of their mouth/jaw opening as constant as possible for all vowels in order to keep certain vocal loudness and beauty of the voice, independently of changing pronunciation of vowel sound.

For the rest of the results, looking at all the results of each subject separately, it showed clearly that there were only slight differences in the radiation energy of some singers among the vowels: The singing voice of SE1, JR and TF radiated similarly in each vowel, whereas that of CH, SS, SE2 and VS in both singing techniques (Pop and Soul) differed consistently for each vowel. However, in most cases, the results of the latter subjects looked alike among the vowels /a/e/i/, thus only the results of both vowels /o/ and /u/ differed from those of all the other vowels due to instability in the motion of the radiation energy, as mentioned above.

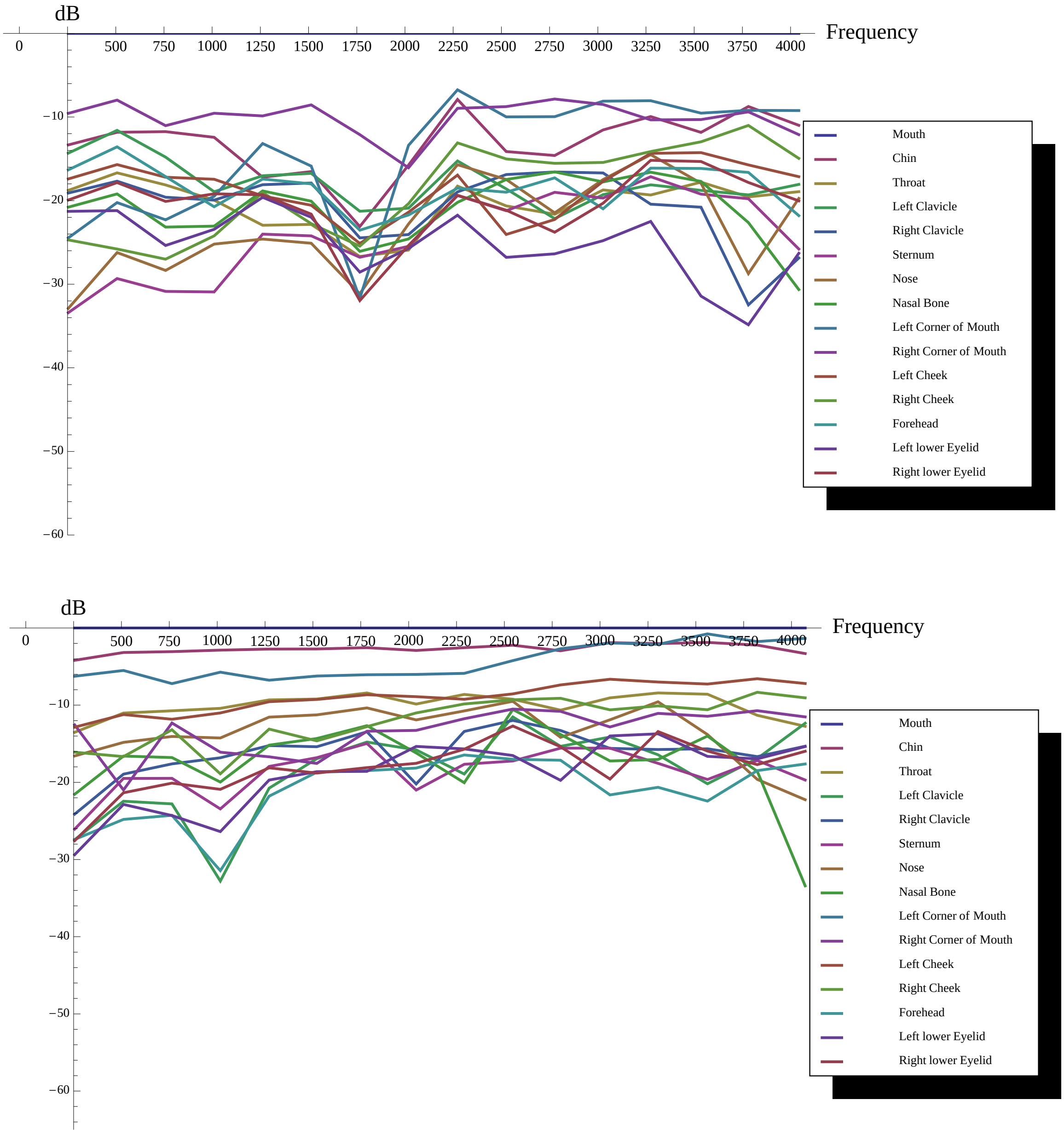
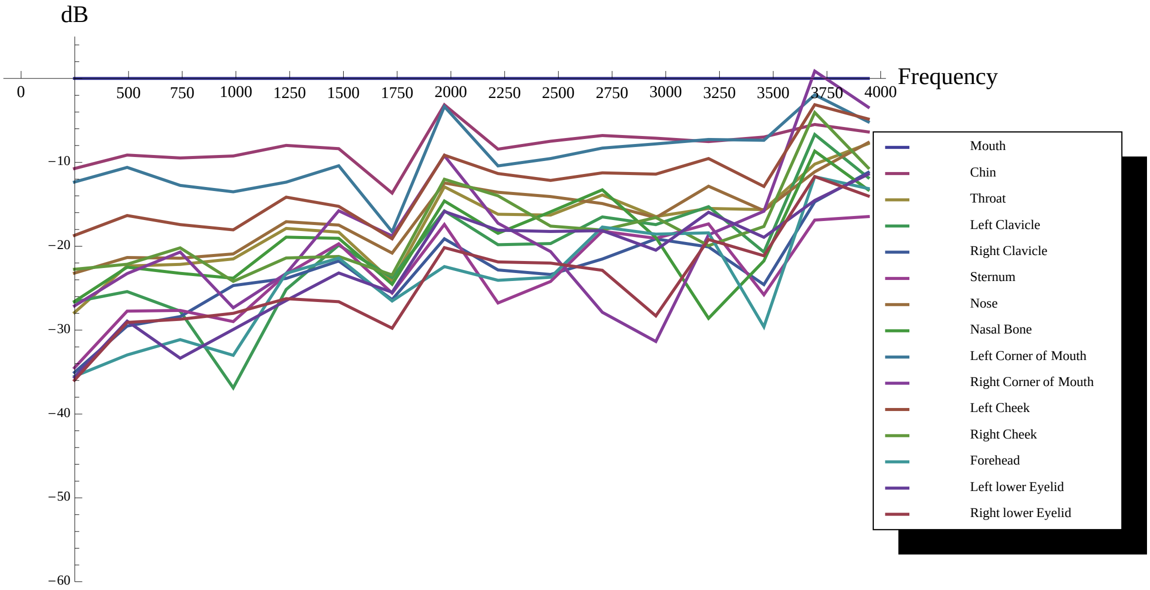


Figure 6.7: Sound levels of 14 measured upper parts of the body sung by two female classical singers (above: CH, below: SE1) at the fundamental frequency of 250 Hz for the vowel /a/, compared to the sound level of the mouth. The energy from the mouth is shown at zero on the x-axis (dark blue line).



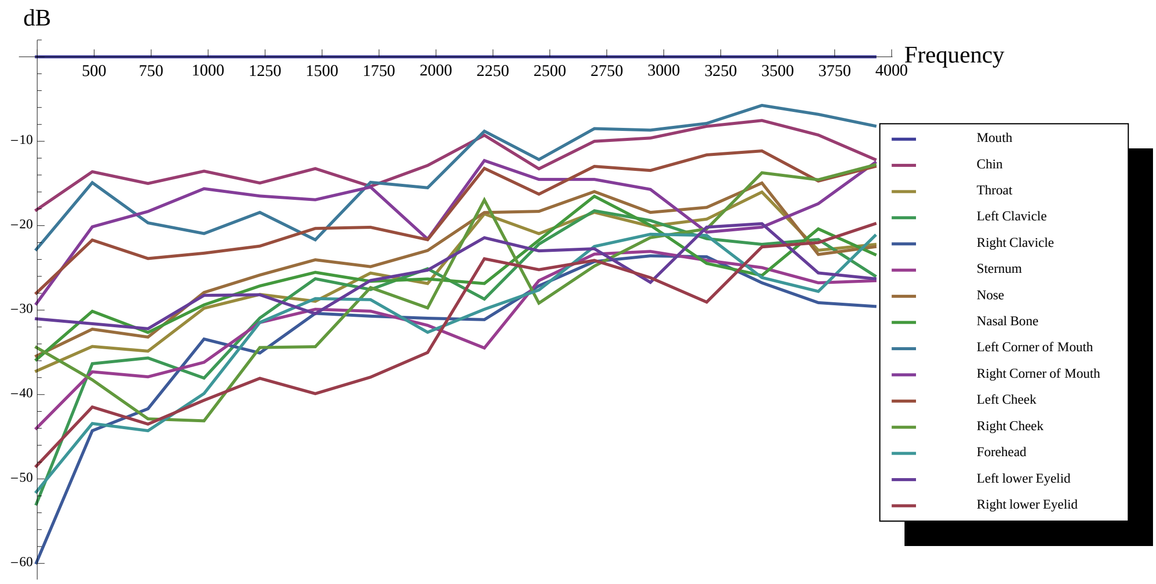


Figure 6.8: Sound levels of 14 measured upper parts of the body sung by a male classical singer (above, JR) and a female musical theater singer (below, SS) at the fundamental frequency of 250 Hz for the vowel /a/, compared to the sound level of the mouth. The energy from the mouth is shown at zero on the x-axis (dark blue line).

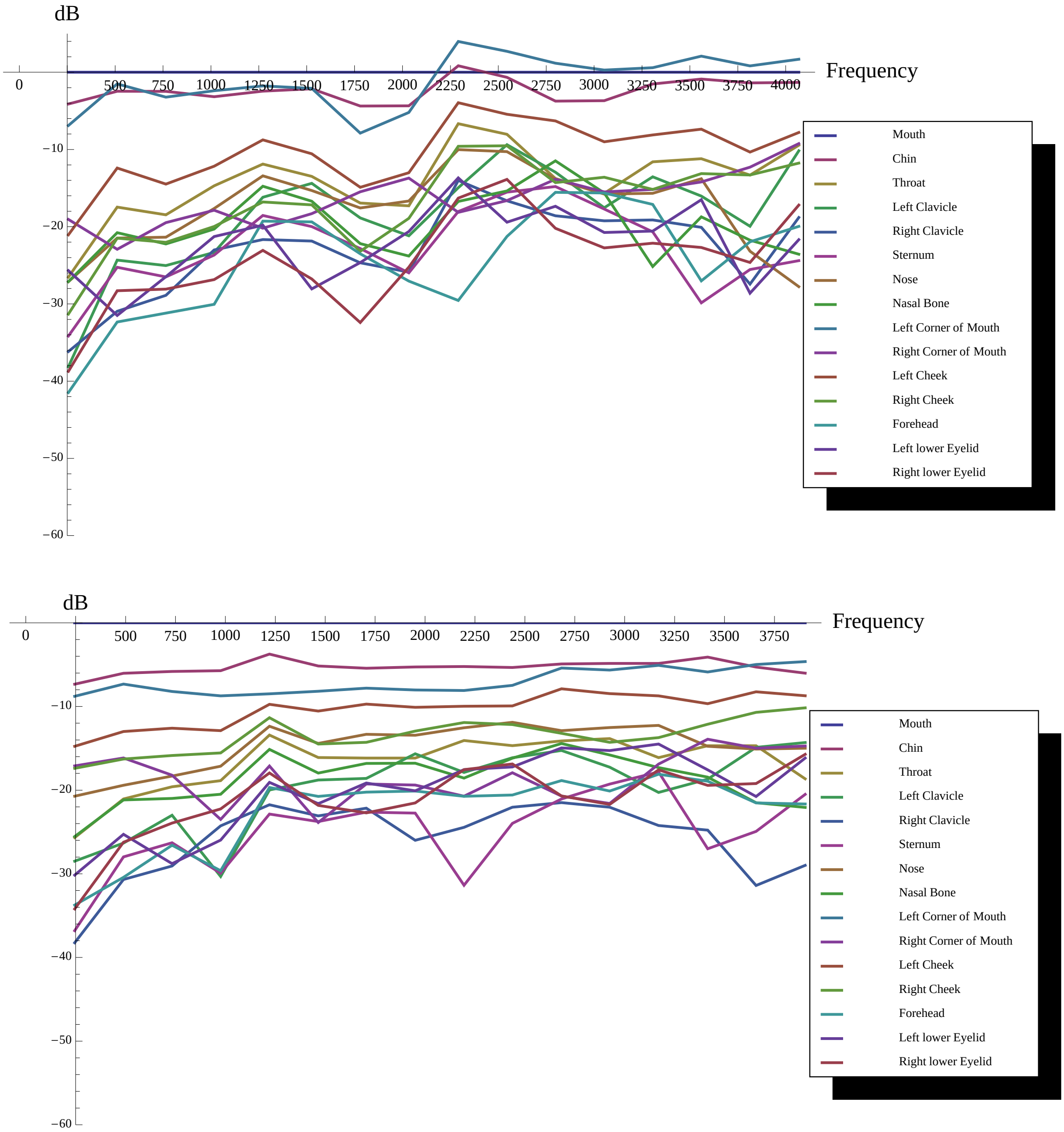


Figure 6.9: Sound levels of 14 measured upper parts of the body sung by a male musical theater singer (above, TF) and a Pop singer (below, SE2) at the fundamental frequency of 250 Hz for the vowel /a/, were compared to the sound level of the mouth. The energy from the mouth is shown at zero on the x-axis (dark blue line).

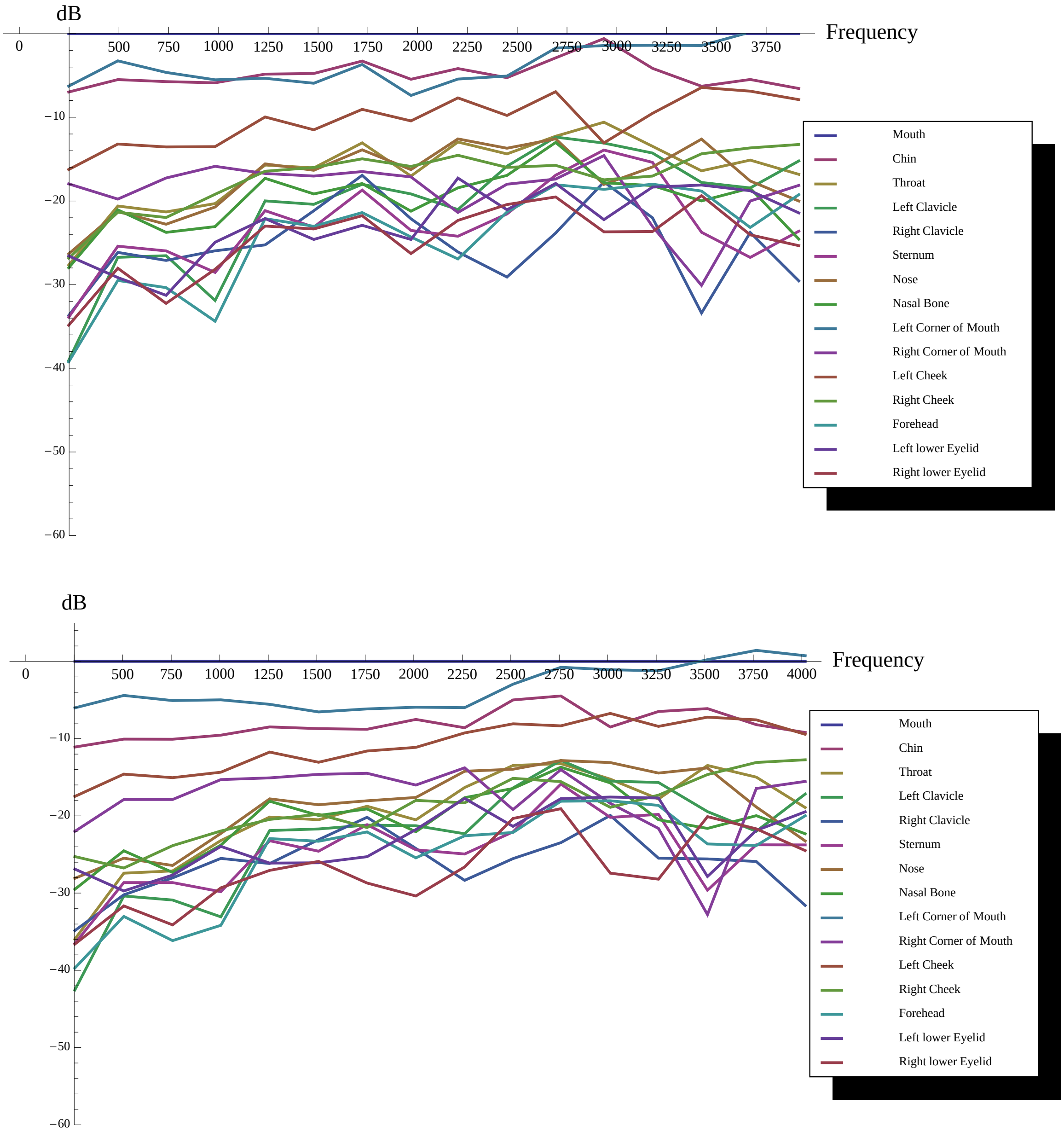


Figure 6.10: Sound levels of 14 measured upper parts of the body from Pop singing and Soul singing (both VS, above: Pop singing, below: Soul singing) at the fundamental frequency of 250 Hz for the vowel /a/, were compared to the sound level of the mouth. The energy from the mouth is shown at zero on the x-axis (dark blue line).

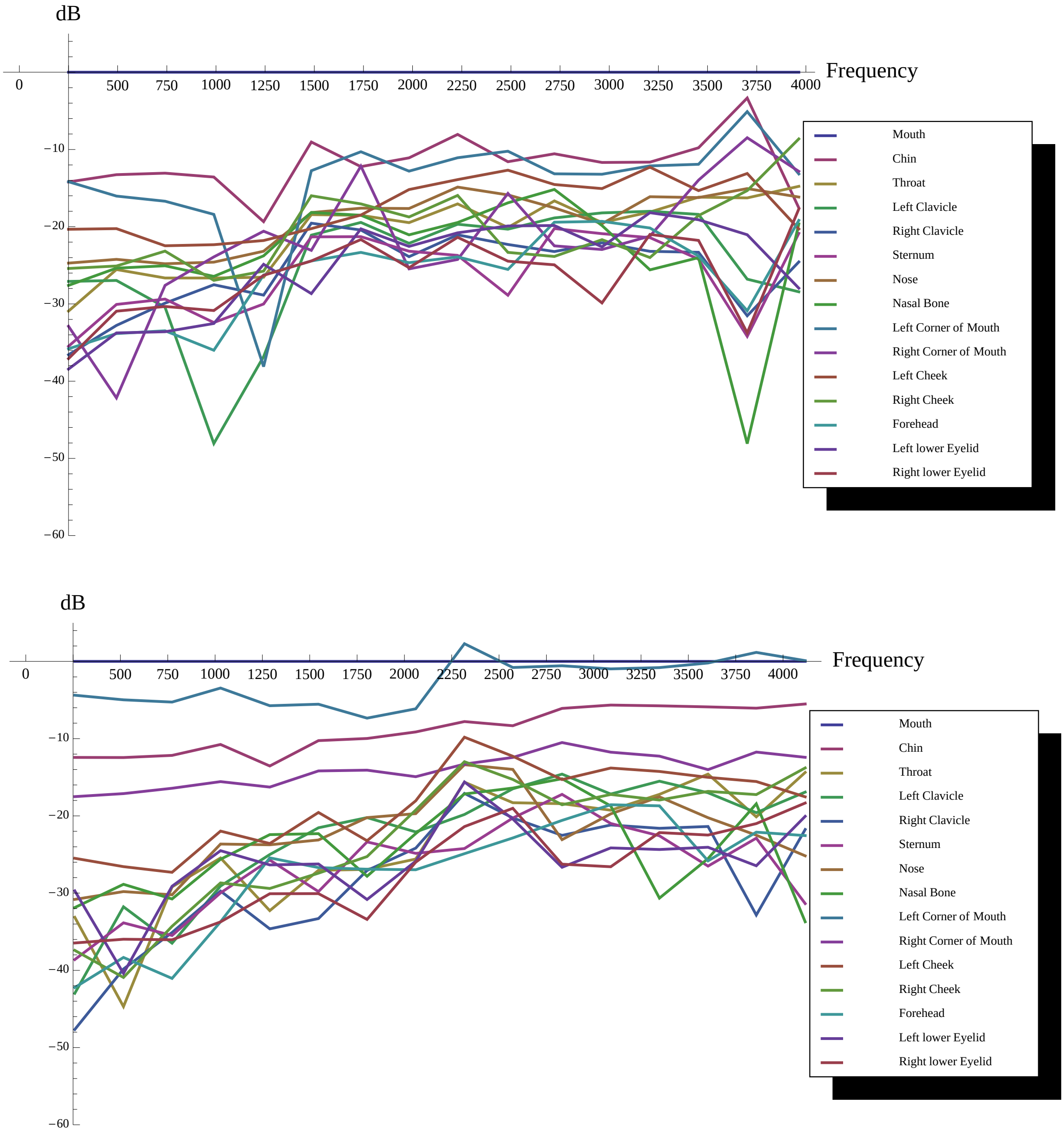


Figure 6.11: Sound levels of 14 measured upper parts of the body sung by a male classical singer (above, JR) and a male musical theater singer (below, TF) at the fundamental frequency of 250 Hz for the vowel /u/, were compared to the sound level of the mouth. The energy from the mouth is shown at zero on the x-axis (dark blue line)

6.2 Radiation Patterns Related to the Pitch of Fundamental Frequency

In the previous section we saw that sound radiation of singing voices varies and increases in the course of the frequency range analyzed, even though there are certain differences in the dimension of this increase among singers. This section will address the question of whether and how sound radiation of the singing voice changes depending on sung pitch (fundamental frequency). In order to clarify these questions, three comparative studies were undertaken, where female and male subjects sang in various pitch according to their voice classification or vocal range (self-declared): the radiation of the female singers was measured at 500 Hz (approx. B4) and 180 Hz (approx. F3#), and at 120 Hz (approx. B2) for the radiation of the male voices. In addition, two separate studies are also included: the measurement of the sound radiation of both sung pitches, 90 Hz (approx. F2#) sung by a bass singer (JR) and 380 Hz (approx. F4#) sung by a tenor/high baritone singer (TF). Therefore, research findings from three different pitches of tone F# (F2#, F3# and F4#) and tone B (B2, B3 and B4) will be presented in the following. This makes it possible to check, compare, and analyze the results from various pitches.

6.2.1 Case Study of Female Subjects at 500 Hz (approx. B4)

Here, the results from all the female singing voices measured at 500 Hz will be presented and analyzed in the frequency range up to 5 kHz[3].

In general, in comparison to the radiations of the fundamental frequency researched at 250 Hz that were already shown in Subsection 6.1.1, the findings from the sung vowel /a/ at 500 Hz by female singers revealed a somewhat broader radiation (see Figures 6.12 and 6.13). This was clearly perceivable for SE1 and SE2, whereas for CH and SS, it seemed unchanged in their results at between 250 Hz and 500 Hz arisen from fundamental frequency (VS showed slight differences in her Pop and Soul singing). But in fact, this occurrence with broader radiation (compared to the measurement of 250 Hz) almost holds true for the whole analyzed frequency range, up to 5 kHz. It was even observed in

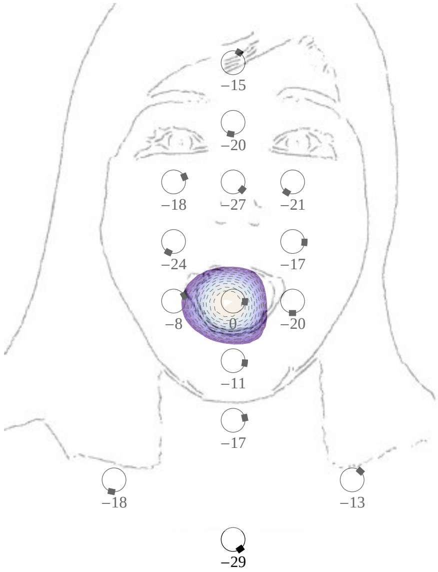
[3] As in the previous case study, the results from the fundamental frequency to the 5. partial and from the highest partial analyzed are displayed in general. Furthermore, when a change is observed in the color-coded radiation area, their results are also shown. The results of the VS measured at the vowel /u/ in both singing techniques (Pop and Soul) are eliminated due to lack of recording quality.

this case study (at 500 Hz) that strong sound radiation comes not only from the mouth, but also from other body parts, such as the results shown in Figures 6.14, 6.16, 6.17, 6.18, 6.19, 6.20, 6.21 and 6.23[4]. Such a radiation from outside of the mouth area was also found at 250 Hz, and considerably more at 500 Hz. However, this occurrence is not accidental, for example, the sound spectrum shows overdriven data based on high sound pressure level from singing at a higher pitch, or there are many similar peaks at the partials in the analyzed frequency range up to 5 kHz (see the spectra of SE2 in Figure 6.22 yielded by singing the vowels /a/ and /u/, as an example).

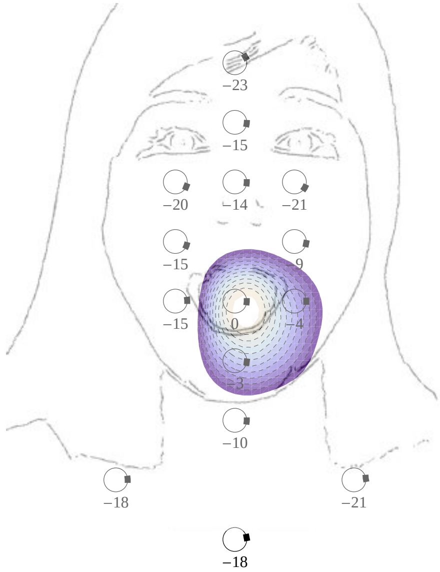
Now let's return to the research findings of this case study. As mentioned above, the radiation was generally broader than that of 250 Hz, but, besides mouth radiation that was actually strongest radiation source, we could also see autonomous radiation sources here, like the finding of JR shown at 250 Hz (see Figure 6.4). However, at 500 Hz, these was 0 dB (thus equivalent to mouth radiation) or above this value in some results.
The occurrence of such radiation patterns of the singing voice seems to be independent of vowels but dependent on frequency. The reason is that all results revealed such a sound radiation mainly at highest partials which were analyzed, often at the 9. and 10. partials (approx. 4,5 – 5 kHz).
Looking at the radiation patterns per vowel displayed on the sketch, the vowel /a/ of the singing voice of SE1 that was broadly emitted from the beginning including the chin, showed its strongest energy source between the mouth, the right corner of the mouth and the chin. All those three measured points revealed 0 dB (maximum energy) at the 7. partial. This radiation energy moved towards the right side of the face at the 8. and 9. partials, so that the maximum energy point was not longer located at the mouth. Ultimately, at the 10. partial, almost all the measured parts showed stronger radiation than that from the mouth (see Figure 6.14). However, when it comes to the radiation pattern observed at the 10. partial, the sound pressure level was very low at this partial, as shown in Figure 6.15, so that undesired sound (noise) could be resulting and also emitted there[5]. Furthermore, it was not easy to locate a clearly recognizable peak at this partial due to low sound energy and all these factors could be the reason for such a radiation.

[4] In some cases, strong sound radiation, which is color-coded, can be seen outside of the body on the plot. This is presumably due to sound reflection, although this recording was excited in an anechoic chamber.

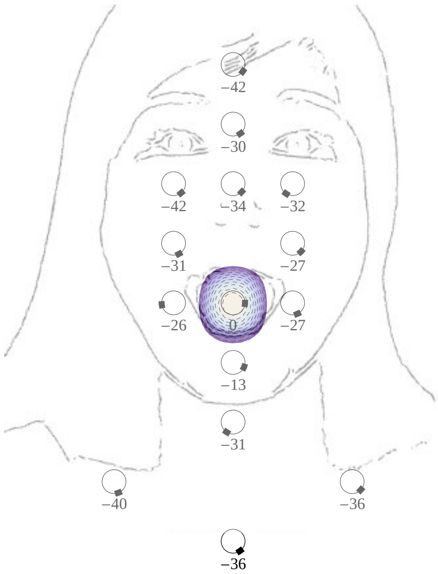
[5] As already mentioned in Section 6.1, in general, only the results that are free from anomalies are analyzed and discussed here. This result is included as an example of an interesting radiation pattern originating from a frequency range where sound energy is reduced.



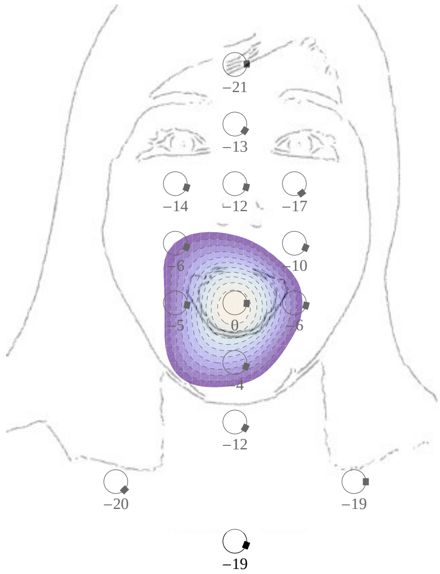
(a) CH (classical, alto)



(b) SE1 (classical, soprano)

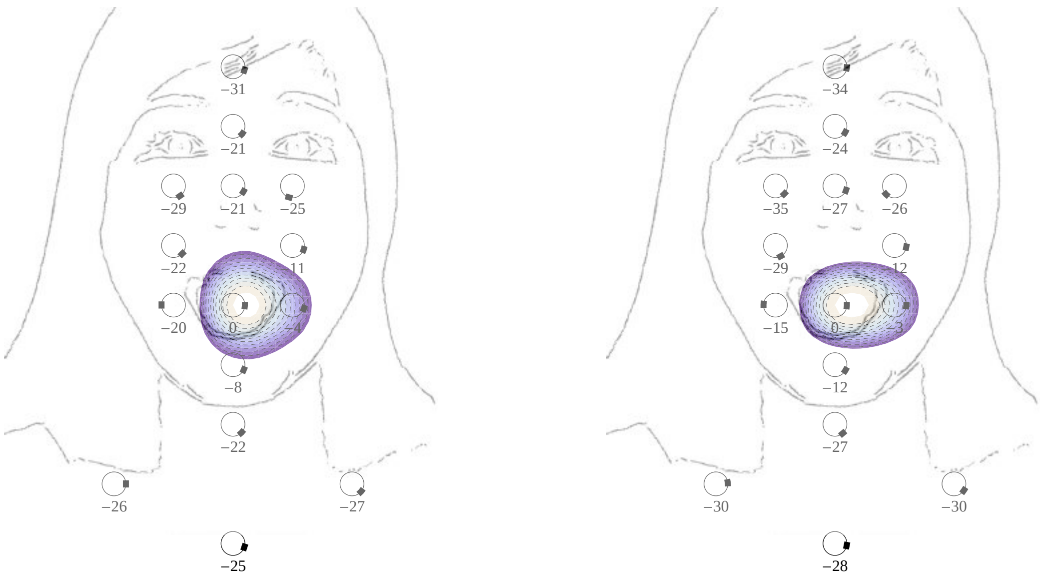


(c) SS (musical, female)



(d) SE2 (pop, female)

Figure 6.12: Radiation of two classical singers (a and b), a female musical theater singer (c) and a female Pop singer (d) at the fundamental frequency of 500 Hz for the vowel /a/.

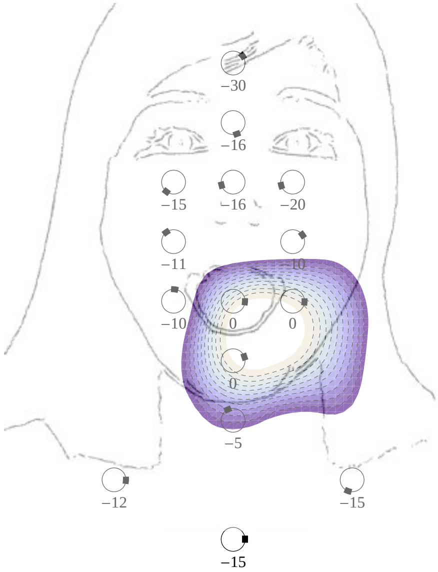


(a) VS (pop) (b) VS (soul)

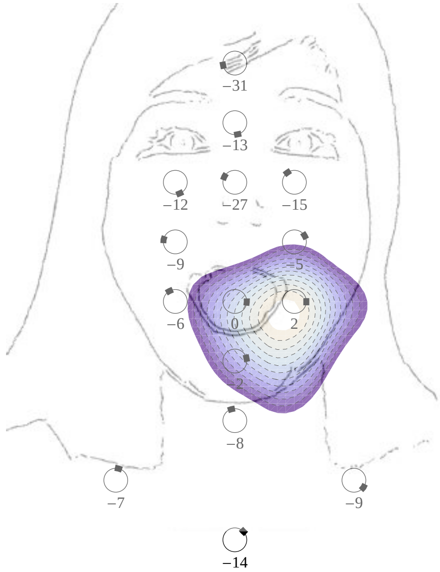
Figure 6.13: Radiation of Pop singing (a) and Soul singing (b) of the fundamental frequency of 500 Hz for the vowel /a/.

But this is just a single case and for all other results, there is nothing to worry about such interference factors possibly arising. The strong radiated area of SE2 gained from the vowel /a/ expanded lengthwise now and at the 3. partial, occurred from almost the whole of the face and also from the neck, as shown in Figure 6.16. After that, her strong radiated area went back to a lengthwise pattern as before, but at the 8. and 9. partials, strong energy was also emitted from a large area of the face, such as from the cheek, chin, nose and the throat (the last two at the 9. partial only).
Both cases of VS (popular and Soul singing) singing the vowels /a/ and /e/ revealed that the strongest radiating point, which was the mouth at the fundamental frequency, shifted towards the right side of the mouth at the 10. partial (also at the 9. partial in popular singing, see Figure 6.27). The radiation energy admittedly already showed a slightly right directional tendency at the 4. partial for the vowel /a/ where the strong radiating area became widened, however after that, this was getting smaller and centering again as before.

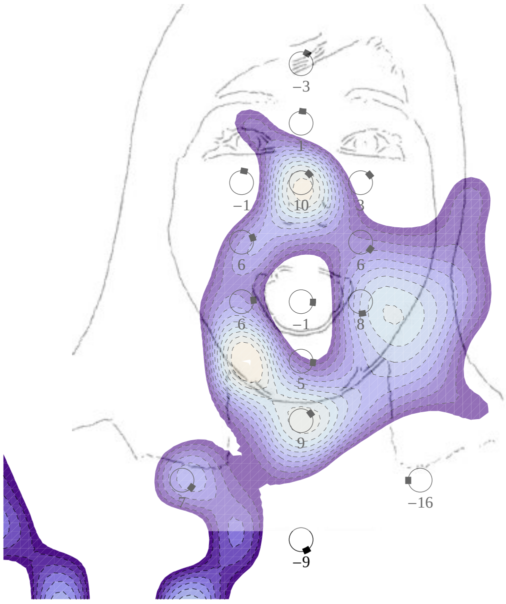
Additionally, when it comes to the results of the vowel /e/, two autonomous radiation sources were observed in the result of SE2 beside a strongest radiation from her mouth:



(a) 7. Partial (classical)



(b) 9. Partial (classical)



(c) 10. Partial (classical)

Figure 6.14: Radiation patterns of subject SE1 (classical) for the vowel /a/ at 500 Hz.

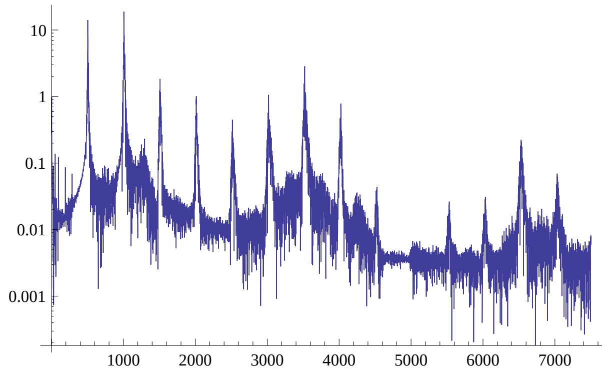
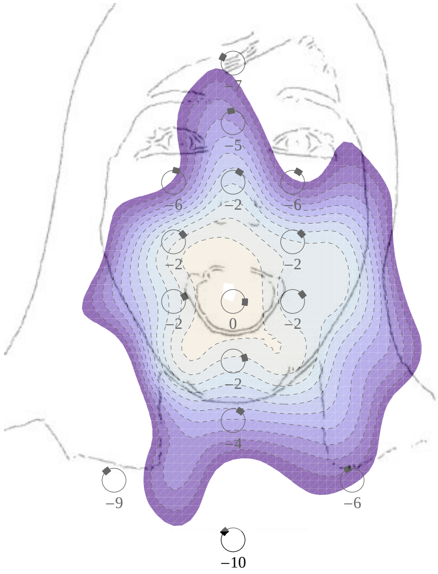


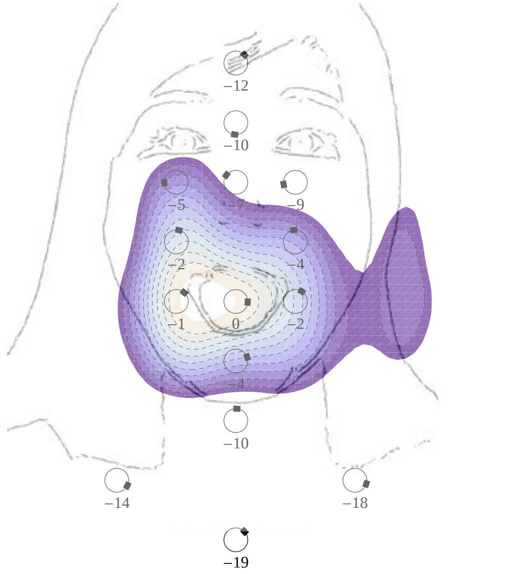
Figure 6.15: Sound spectra of subject SE1 singing the vowel /a/ at 500 Hz.

her lengthwise radiation pattern changed gradually from the 7. partial, as shown in Figure 6.17. Firstly at the 8. partial, strong radiation energy came from a large area of the face (the corners of the mouth, chin, cheeks, nose and the lower eyelids), thus spreading throughout the face, and at the 9. partial, the radiation changed cross-sharped, in the directions of the nose, chin and the right and left corners of the mouth. Ultimately, at the 10. partial, additionally, two other radiation sources framed on the right and left sides of the face and the energy value from both sources was identical to that from the mouth (0 dB). Although this case revealed three equally strong energy sources, a similar radiation pattern was observed at the same partial in each result from three recordings (see Figure 6.18). In fact, such a radiation (with widespread color marking on the sketch) was already observed for the vowel /a/, but something similar, meaning several radiation sources at a partial, has been not found there.

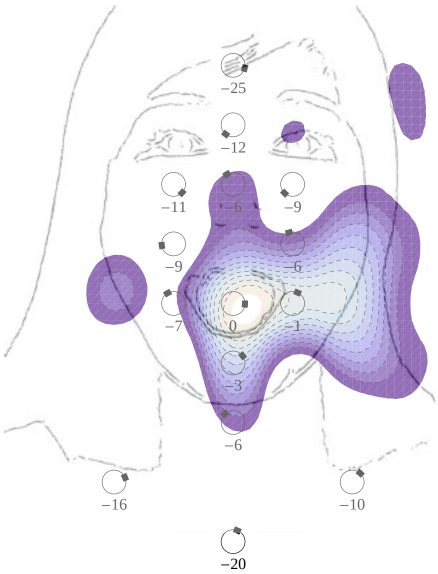
The radiation pattern of the vowel /i/ was relatively similar to that of the vowel /e/, primarily with autonomous, sometimes equipollent radiation source in addition to the radiation source from the mouth. For example, in the case of SE2, her radiation was firstly getting more and more oblong in the frequency range, and after that, this changed into a cross-like pattern at the 9. partial (see see the result of SE2 in Figure 6.19). This change in the patterns looked like the case of the vowel /e/ shown in Figure 6.17. The further radiation pattern of SE2, observed at the 10. partial, was also similar to that of the vowel /e/, even though there was shown only one similar strong radiation source as the mouth radiation.
The popular singing voice of VS that sang the vowel /i/ also emitted similar to that for the vowel /e/. For example, her strong radiation area was getting wider until the chin at the 4. partial but smaller again at the next partial (5. partial), and finally,



(a) 3. Partial (pop)

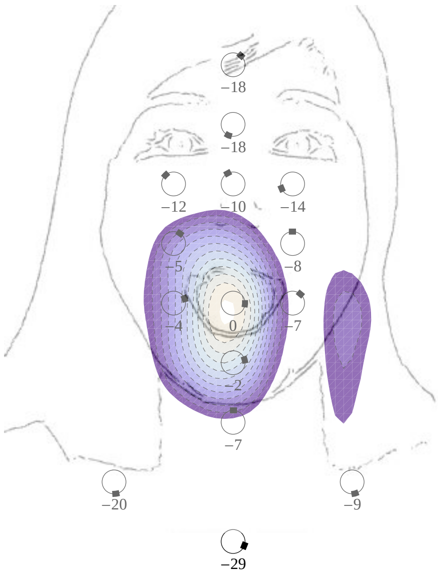


(b) 8. Partial (pop)

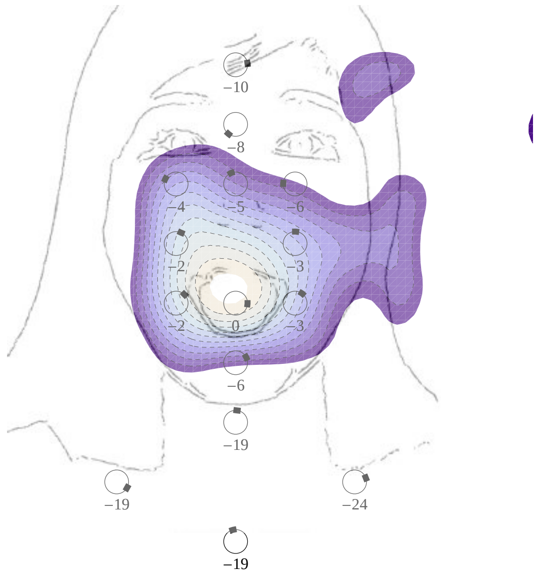


(c) 9. Partial (pop)

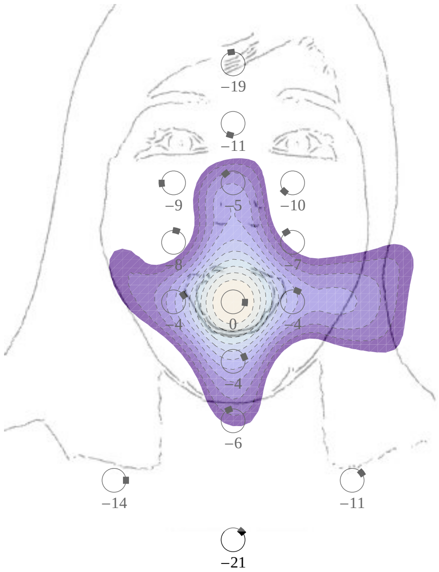
Figure 6.16: Radiation patterns of subject SE2 (Pop) for the vowel /a/ at 500 Hz.



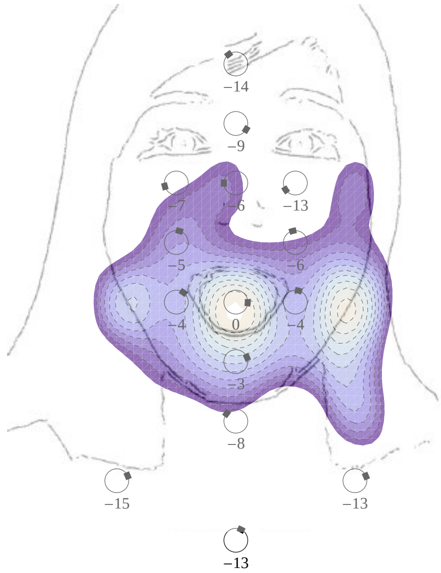
(a) 7. Partial (pop)



(b) 8. Partial (pop)



(c) 9. Partial (pop)



(d) 10. Partial (pop)

Figure 6.17: Radiation patterns of subject SE2 (Pop) for the vowel /e/ at 500 Hz.

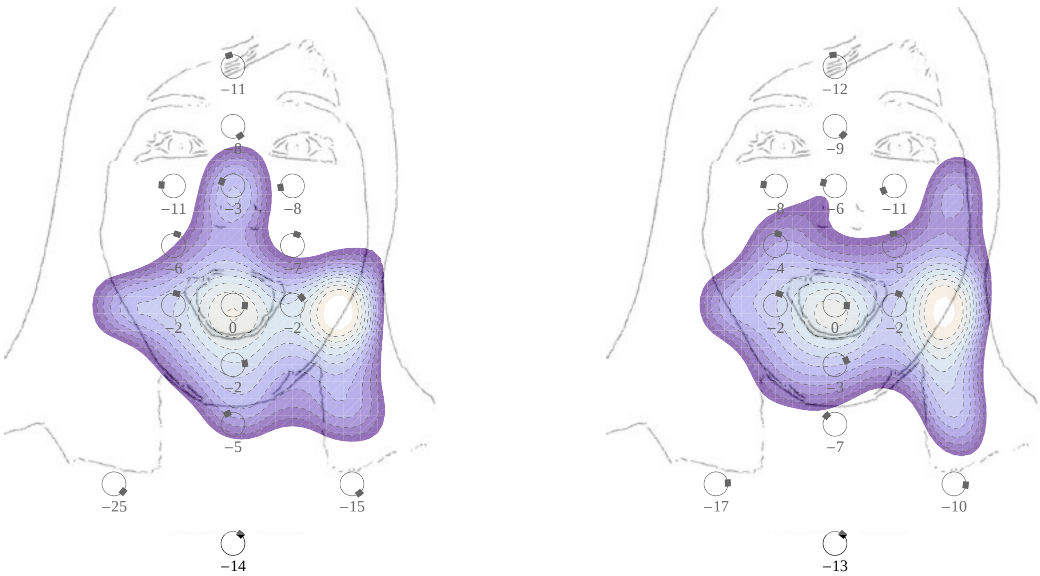
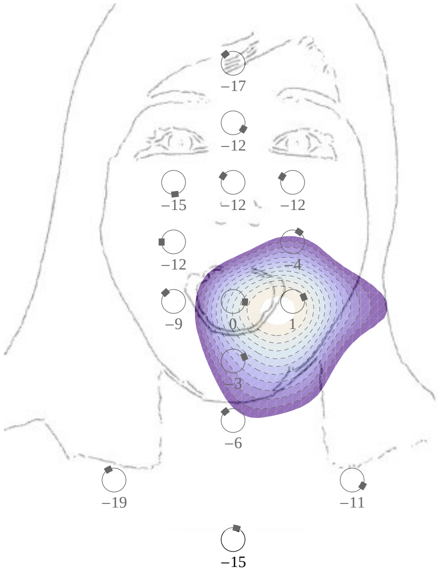


Figure 6.18: Radiation patterns of subject SE2 (Pop) shown at the 10. partial for the vowel /e/.

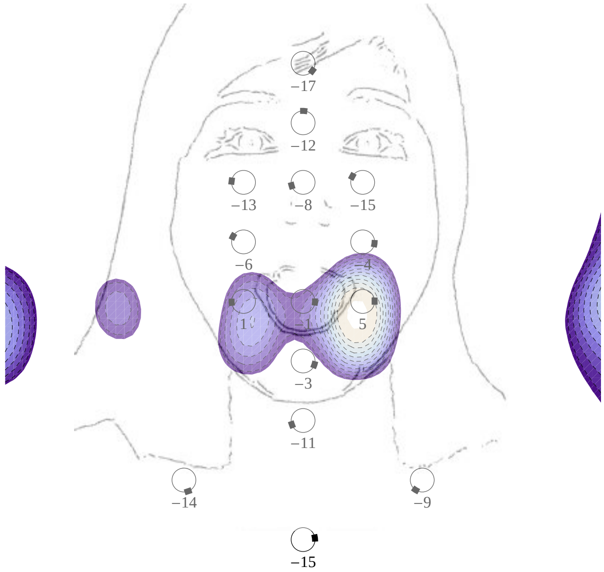
at the 10. partial, the strongest radiation source shifted towards the right side of the face (therefore the energy value from the right corner of the mouth was higher (1 dB) than that from the mouth). However, what differed here from the result shown for the vowel /e/ was the radiation pattern of the 9. partial (see the result of VS in Figure 6.20) – with a strongly radiated point located at the bottom of the right corner of the face in addition to the strong radiation from the mouth. In fact, this radiation energy came from around the face, but, as already mentioned, each body is built more or less differently, therefore it is uncertain whether this radiation source is located on the face or the neck.

The research finding of SE1 also revealed two strong radiation sources for this vowel, as displayed in Figure 6.19: her radiation source from the right side of the face at the fundamental gradually shifted towards the right side of the face from the 7. partial, so that the radiation energy from the right corner of the body was getting stronger than that from the mouth[6]. Finally, at the 10. partial, it was found that another strong

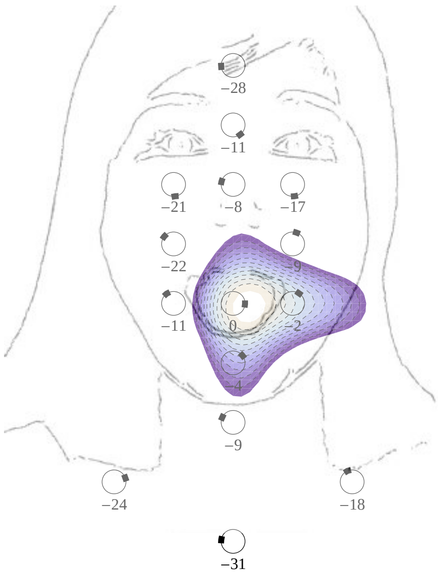
[6]It seems that the middle of this radiation is located between both measured points, the mouth and the right corners of the mouth. The distance between the arrays is 3,9 cm and therefore a little movement, for example head movement, can change radial direction which may happen e.g. by respiration or change of attitude, as repeatedly mentioned in this work. This fact shows the difficulty



(a) 9. Partial (classical)

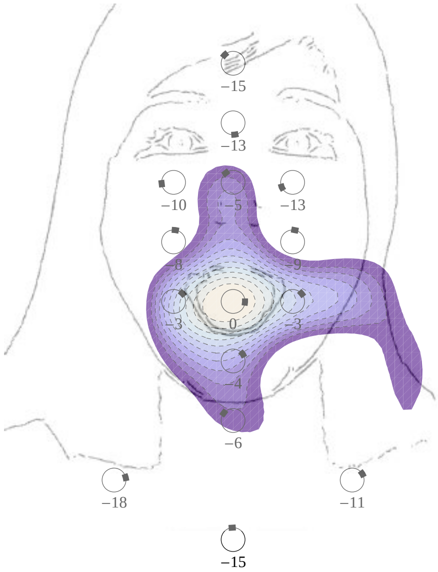


(b) 10. Partial (classical)

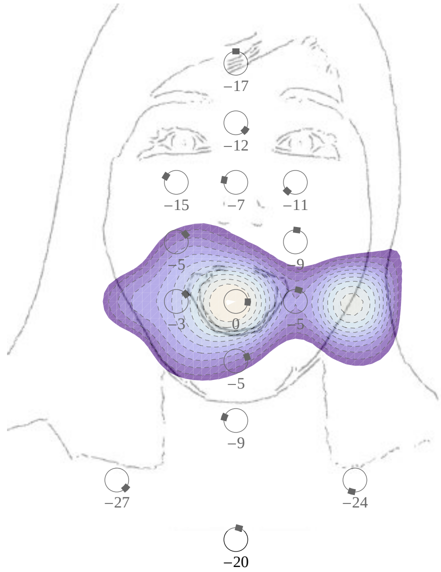


(c) 9. Partial (musical)

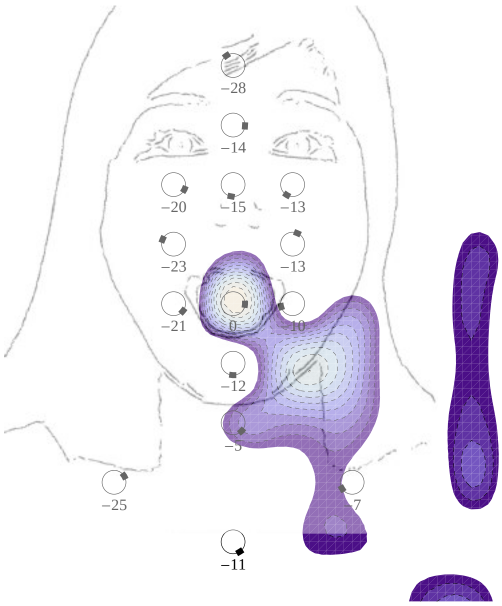
Figure 6.19: Radiation patterns of subject SE1(classical, a,b) and subject SS (musical, c) for the vowel /i/ at 500 Hz.



(a) 9. Partial (SE2, pop)

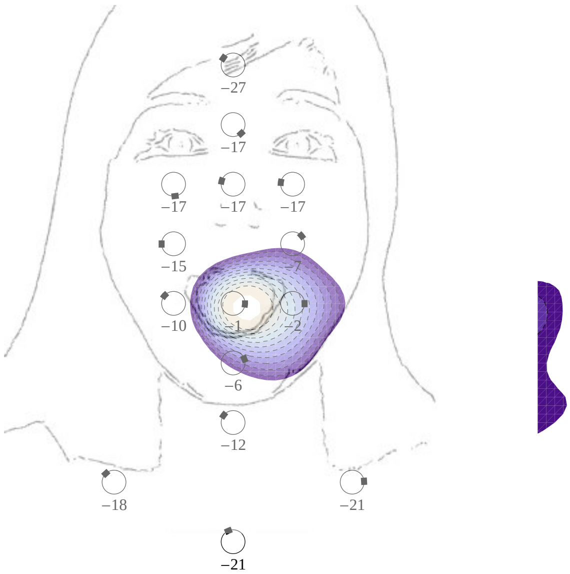


(b) 10. Partial (SE2, pop)

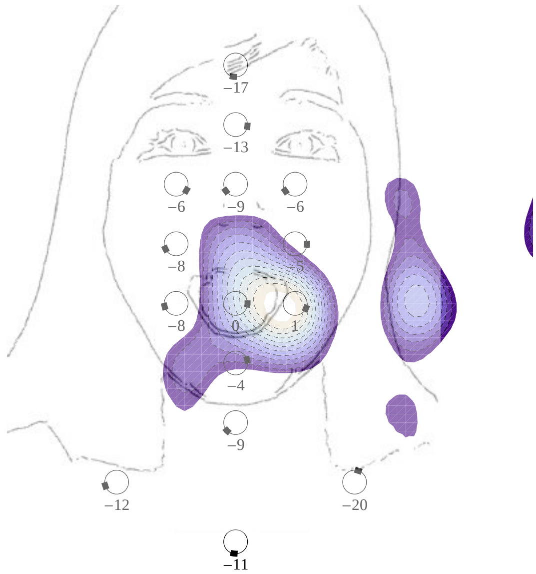


(c) 9. Partial (VS, pop)

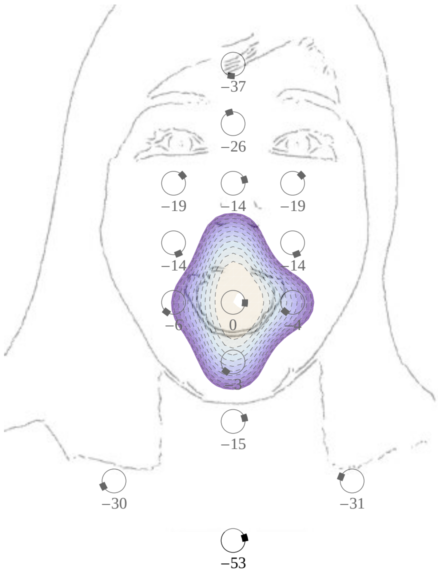
Figure 6.20: Radiation patterns of subject SE2 (Pop, a, b) and subject VS (Pop, c) for the vowel /i/ at 500 Hz.



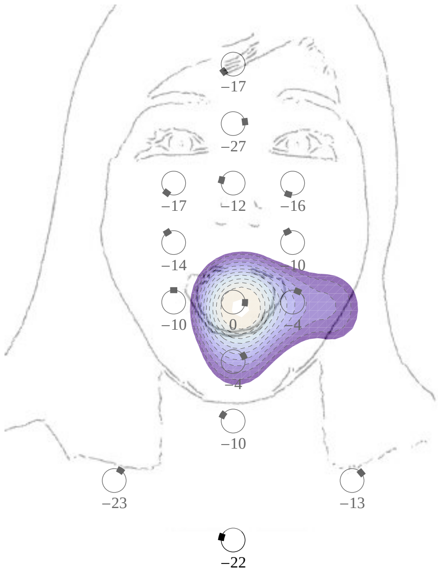
(a) 9. Partial (classical)



(b) 10. Partial (classical)

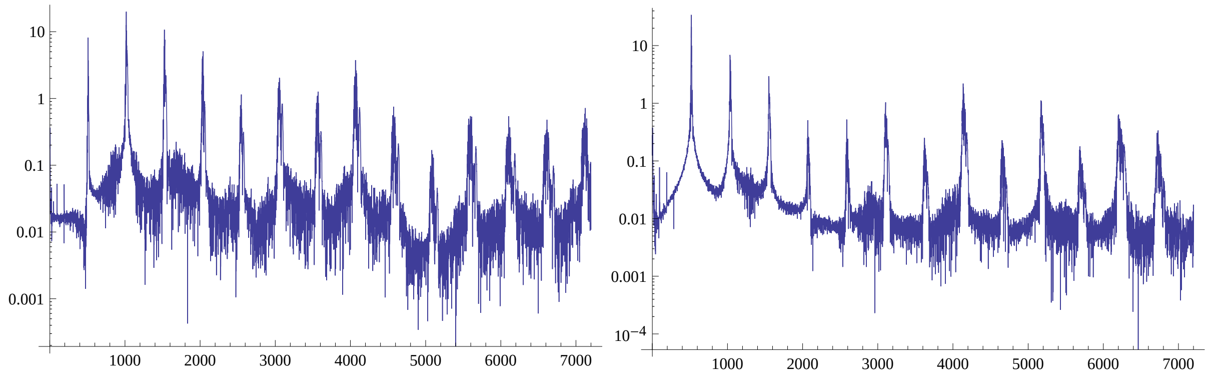


(c) 5. Partial (musical)



(d) 9. Partial (pop)

Figure 6.21: Radiation patterns of subject SE1 (classical, a,b) SS (musical, c) and subject SE2 (Pop, d) for the vowel /o/ at 500 Hz.



(a) Vowel /a/

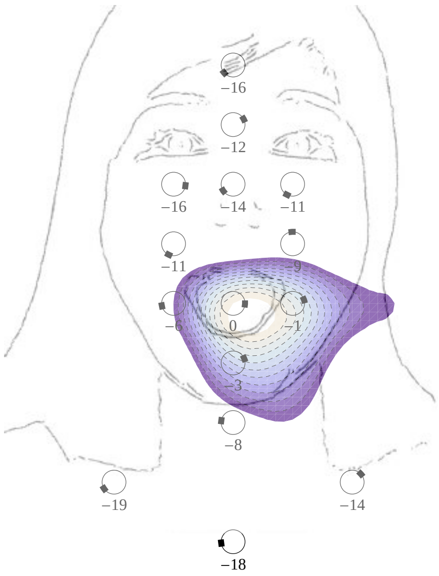
(b) Vowel /u/

Figure 6.22: Sound spectra of a Pop singer (subject SE2) singing the vowels /a/ (a) and /u/ (b) at 500 Hz.

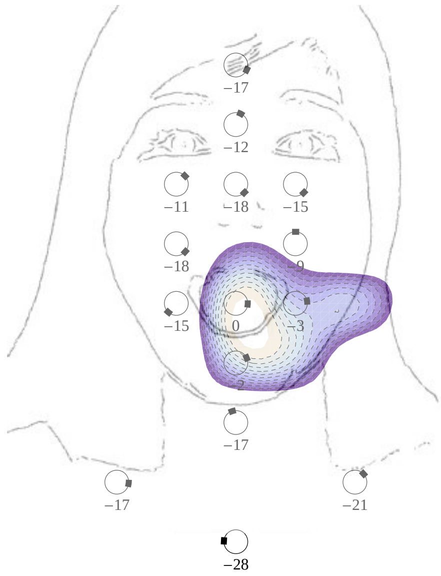
radiation source also appeared on the left side. This is a similar finding as the results of SE1 (for the vowel /e/) and SE2 (for the vowel /e/ and /i/).
In addition, in the case of the vowel /i/, a significant enlargement of strong radiated area was also observed at the 9. and 10. partials of SS, as displayed in Figure 6.19.

When it comes to results of the vowel /o/, a strong radiated area of SS revealed a cross-like pattern at the 5. partial, as shown in Figure 6.21. Actually, this area had already increased at the 3. partial, but became smaller once again at the 4. partial, before increasing to the size of the area at the 5. partial. Such a decrease of the strong radiated area was also found in the result of SE1, SE2 and VS for popular singing (also in the results of the vowel /a/ for VS and the vowel /u/ between the 3. – 5. partials for SE1).
There was no large difference in the results of SE1 and SE2 between both vowels /o/ and /u/: at the fundamental frequency, the strong radiated area of SE1 seems to be slightly away from the right side of the face, as with the vowel /i/, but this changed at the 3. and 4. partials with decrease in size of her radiated area. The strongest radiated point shifted towards the right side of the face from the 5. partial, so that her

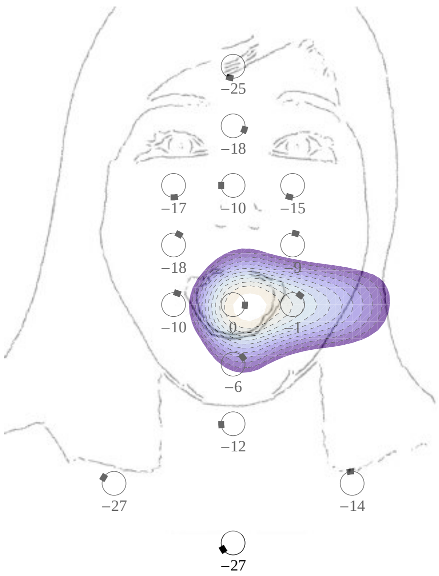
of measuring the singing voice by means of this microphone array. But it is uncertain whether such a radiation pattern occurred from involuntary changes of that kind in direction, because the strongest radiation source appeared also from the mouth at some partials (e.g. the 2. partial of SE1 for the vowel /i/) and/or at the fundamental frequency (e.g. VS for the vowel /e/), even though its location moved at higher frequencies. For that reason, I decided to include this results of SE1 shown at 500 Hz.



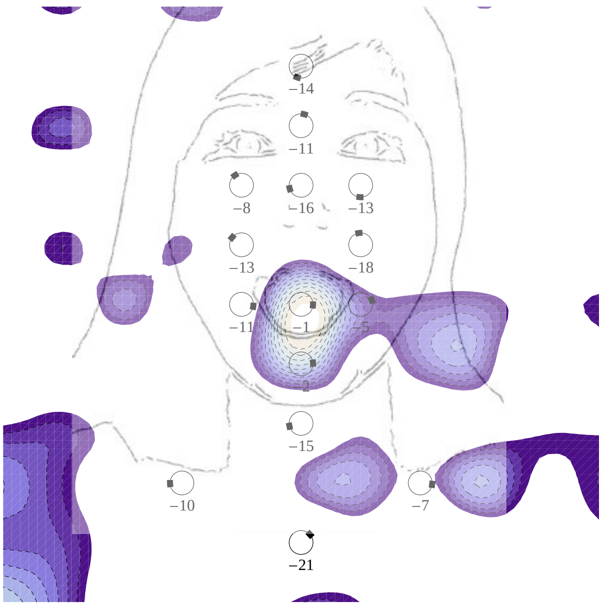
(a) 9. Partial (classical)



(b) 10. Partial (classical)

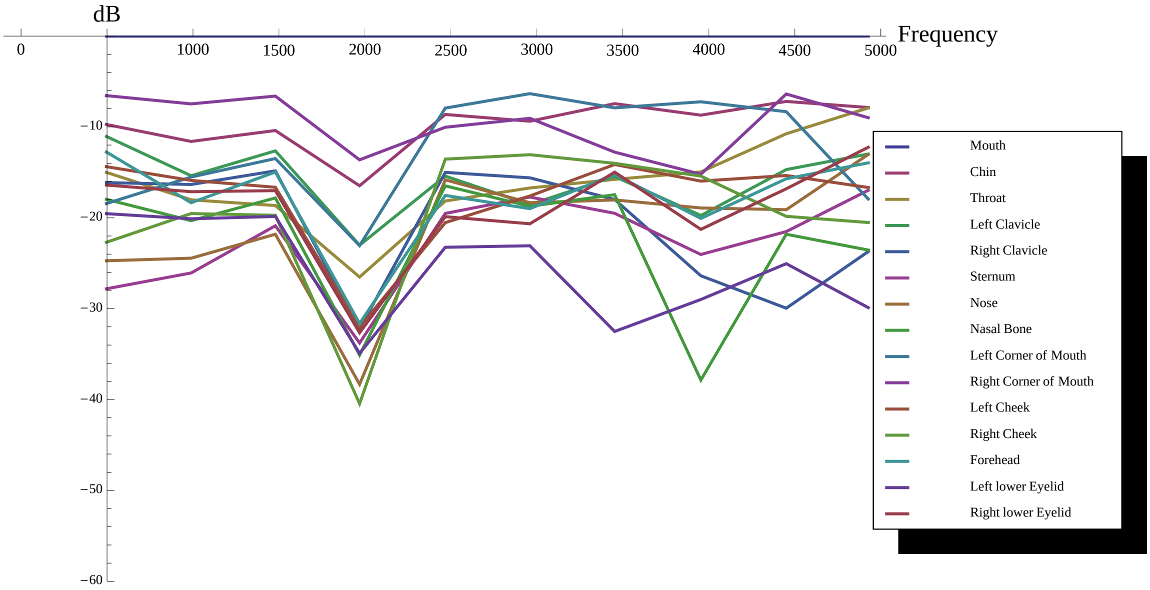


(c) 9. Partial (pop)



(d) 10. Partial (pop)

Figure 6.23: Radiation patterns of subject SE1 (classical, a,b) and subject SE2 (Pop, c,d) for the vowel /u/ at 500 Hz.



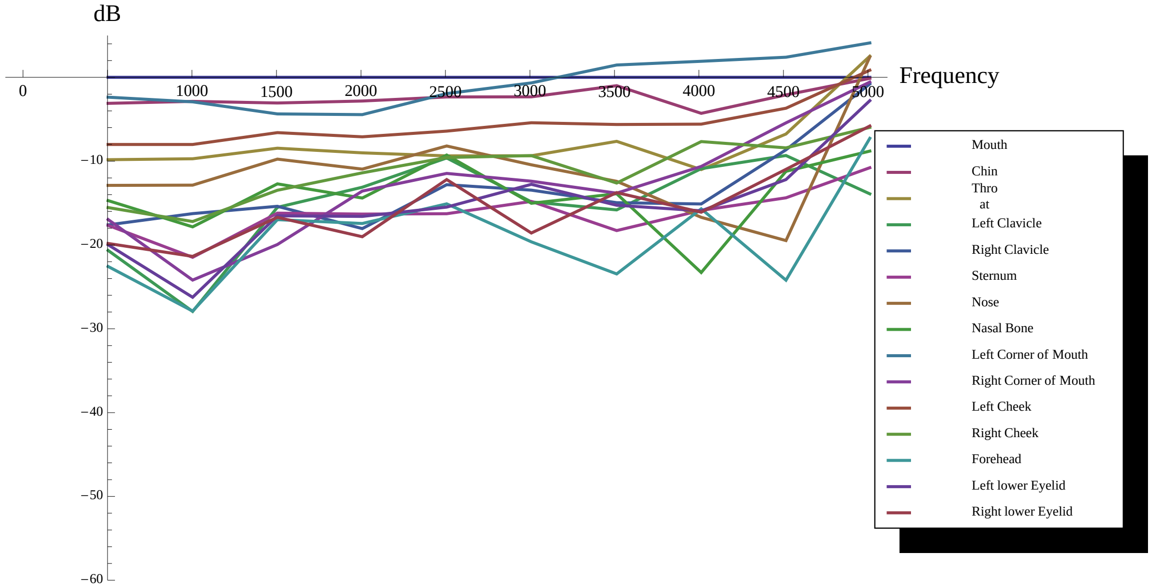
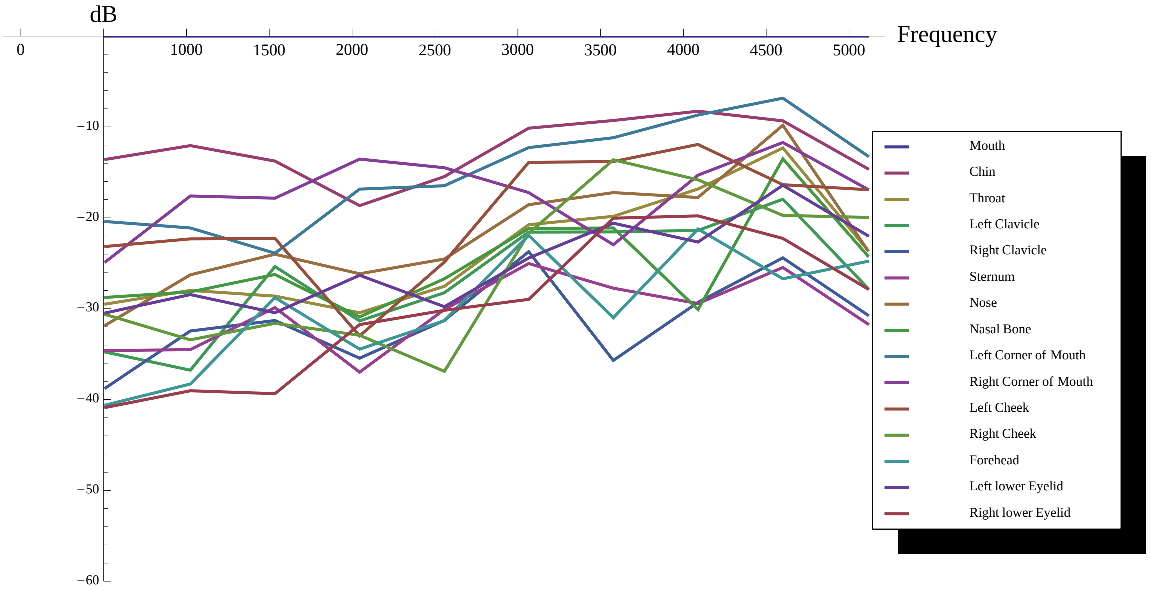


Figure 6.24: Sound levels of 14 measured upper parts of the body sung by two classical singers (above: CH, below: SE1) relating to the radiation from the mouth (0 dB) at the fundamental frequency of 500 Hz for the vowel /a/.



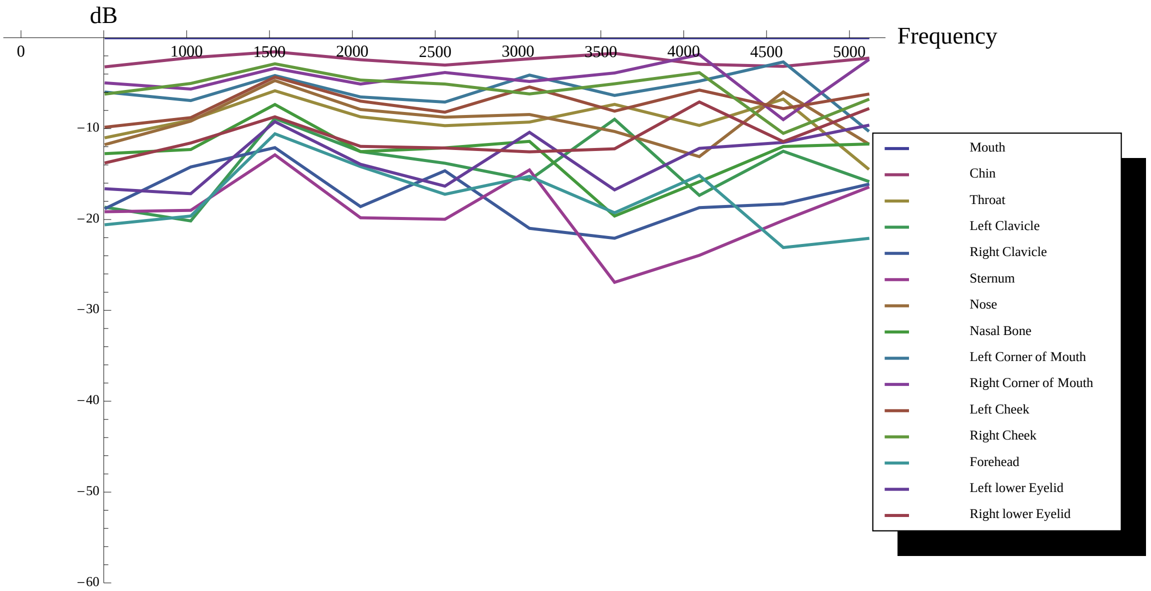


Figure 6.25: Sound levels of 14 measured upper parts of the body sung by a female musical theater singer (above, SS) and a Pop singer (below, SE2) relating to the radiation from the mouth (0 dB) at the fundamental frequency of 500 Hz for the vowel /a/.

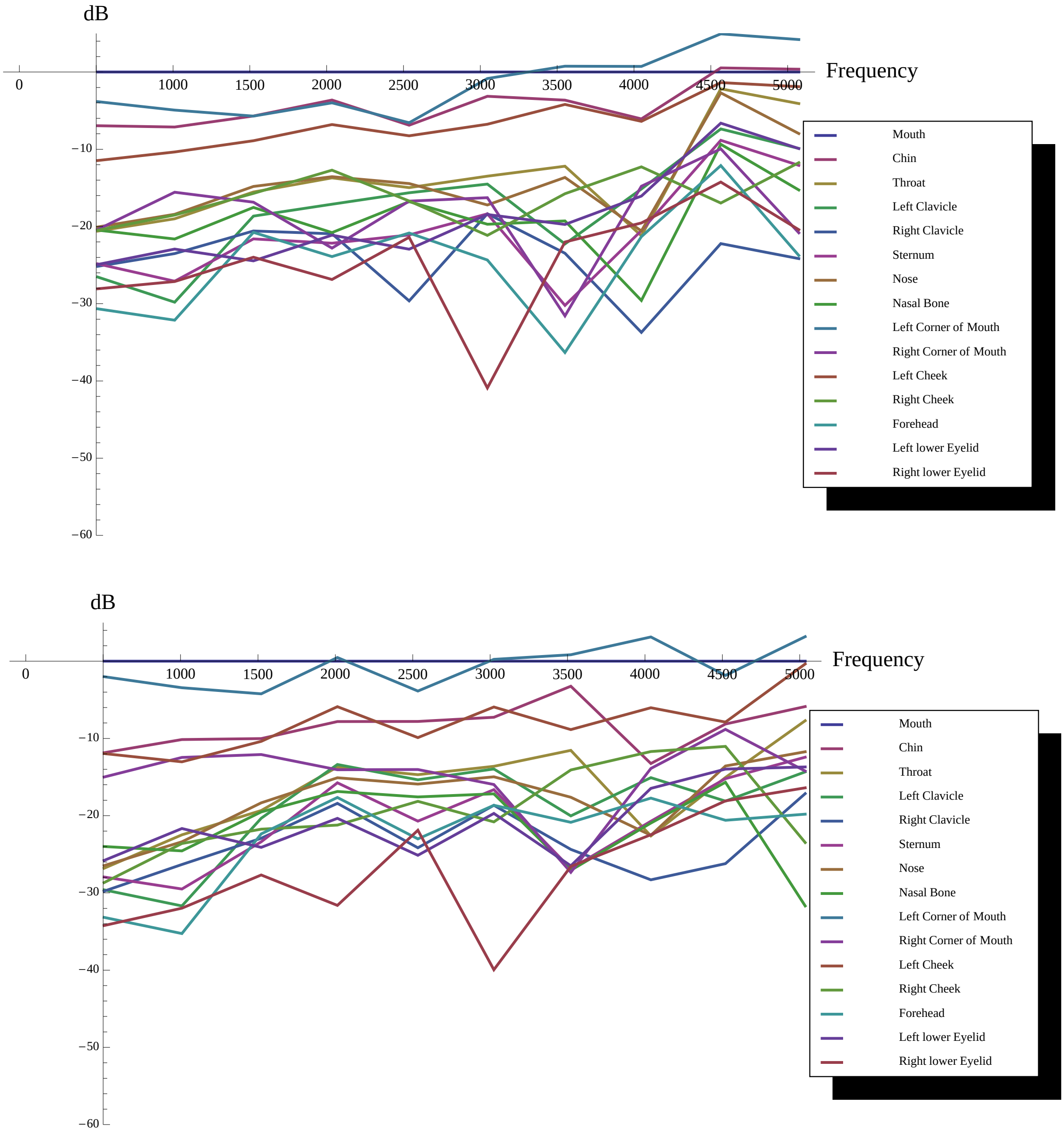
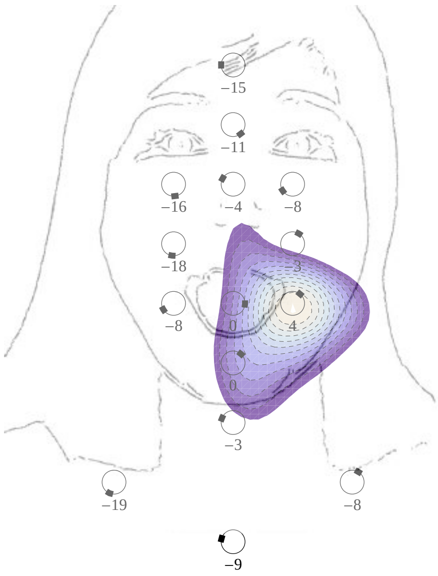
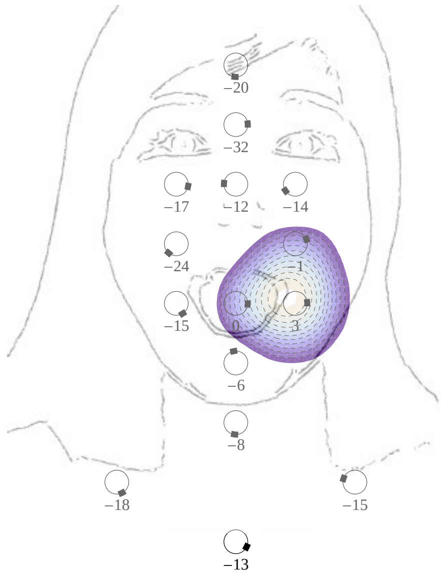


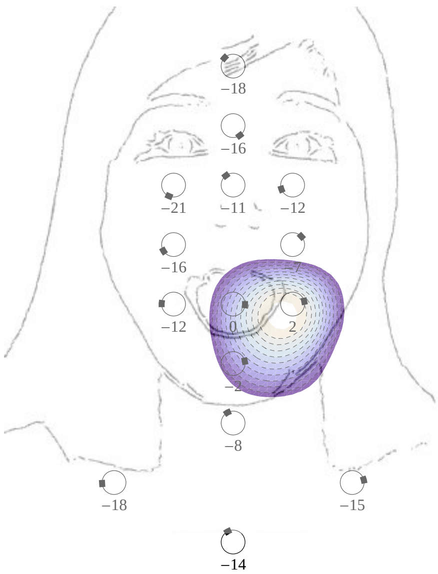
Figure 6.26: Sound levels of 14 measured upper parts of the body from Pop singing and Soul singing (both VS, above: Pop singing, below: Soul singing) relating to the radiation from the mouth (0 dB) at the fundamental frequency of 500 Hz for the vowel /a/.



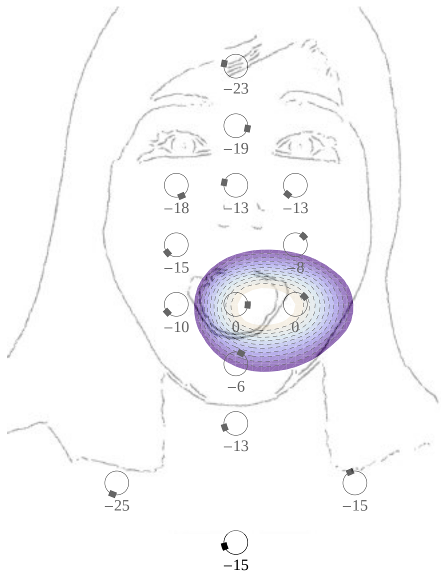
(a) 9. Partial (pop)



(b) 10. Partial (soul)



(c) 9. Partial (pop)



(d) 9. Partial (soul)

Figure 6.27: Radiation patterns of subject VS in Pop (a) and Soul (b) singing for the vowel /a/ and in Pop (c) and Soul (d) singing for the vowel /e/ at 500 Hz.

radiation energy from the right corner of the body was getting stronger than that from the mouth, although this point went back into the mouth at the 9. partial in the case of the vowel /o/ (this became wider for the vowel /u/). Her radiation patterns of both vowels appeared at the 9. and 10. partials are more or less similar to the findings of SE2 shown at the same partials (see the results of the vowel /u/ in Figure 6.23 as an example), even though we could also see strong radiated sources from many locations of the body and from the outside observed at the 10. partial for the vowel /u/ sung by SE2. I suggest that such a radiation pattern deals with air flow that comes through the lips (this topic will be discussed in the following subsection). Apart from this recognition, it was found in the results of SE2 that her strongest radiated area becomes ever greater in the frequency range measured.
Concerning research findings of CH and VS of Soul singing voice, these have not been addressed, because I ascertained that their radiation patterns hardly changed at the pitch of 500 Hz, independent of the vowel.

At this point, let's review the radiated sound levels from the 14 measured parts of the body, compared to mouth radiation, results which were obtained from singing the vowel /a/ shown in Figures 6.24, 6.25 and 6.26. These results revealed that SE1 and SE2 are the subjects who radiated the strongest energy at 500 Hz in total. Generally, the course of the sound radiation measured at 500 Hz seems more stable than that of 250 Hz, i.e. there was no steep energy increase, although the unstable fluctuation of the radiated energy was also exhibited there for the vowels /o/ and /u/. Furthermore, there were fewer differences in energy levels among the measured parts of the body in this case study and when it comes to the radiation of Pop and Soul singing by VS, no large differences were found in the plot (Figure 6.26) between both results for the vowels /a/ and /e/ as well as the vowel /i/. Even though the strongest radiating illustrated color-coded area on the sketch revealed more or less varying radiation patterns, as mentioned above and displayed in Figure 6.27, as an example.

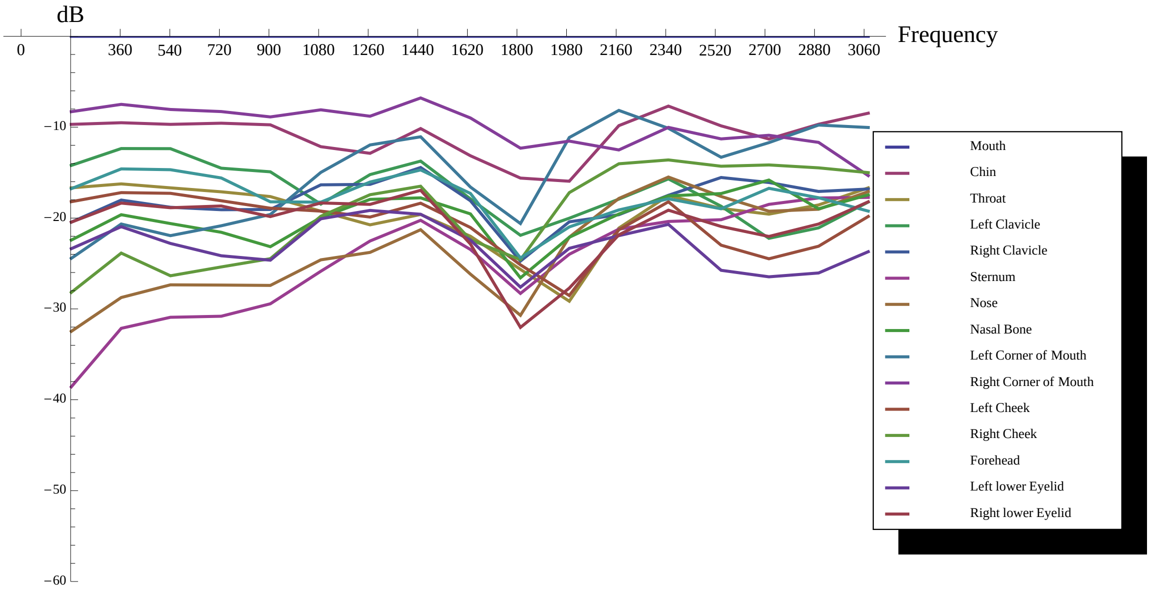
For the rest, the difference in radiation energy between the mouth area and the rest of the parts of the body that was recognized among the various musical genres in the results of both vowels /o/ and /u/ shown at 250 Hz was also observed in the case of 500 Hz (see 6.1.2). However, there was no large difference in the sound spectrum among the subjects.

6.2.2 Case Study of Female Subjects at 180 Hz (approx. F3#)

In the following, the results of female singing voices measured at 180 Hz will be presented and analyzed up to 3 kHz[7]. In this case study a classical alto (CH) and all the female nonclassical singers were involved. This means that the classical soprano (SE1) is excluded because analyzed tone is too low for her vocal range, thus it exists very rarely in her singing repertoire. When looking at the sound levels of all the 14 parts of the body shown for the vowel /a/ in Figure 6.28 and 6.29 it was observed for all the female singers involved, except for the classical alto (CH), that their radiated energy strongly increases in the frequency range analyzed. Such a result was also shown in the case study of 250 Hz, and it was likely due to different singing techniques among musical genres. Actually, there was generally no large difference in the results between both measurements at 180 Hz and 250 Hz, which was presumably because both frequencies are located close to each other: the fluctuation of the radiation energy became stable from around 1,5 – 2 kHz for the vowels /a/e/i/, whereas the energy was very unstable in the whole frequency range for the vowels /o/ and /u/. The results shown by the musical theatre and popular singers for the vowels /o/ and /u/ in the case studies of 250 Hz and 500 Hz – a wide difference in radiation energy between the mouth area (the corners of the mouth and the chin) and the residual parts of the body – was also observed at 180 Hz.

Concerning the strongest radiated area shown at the fundamental frequency, all the measured singing voices occurred uniformly from the mouth, as displayed in Figure 6.30. In changing radiation patterns with increasing frequency, it was found for some subjects singing all the vowels that the area with strong radiating energy became spreading at higher frequencies and that this was not restricted to the mouth, as also found in all the previous case studies (see the results in Subsections 6.1.2 and 6.2.1). This occurrence was usually visible from around the 9. partial (approx. 1600 Hz) in this case – for example, in the case of the vowels /a/e/i/, SE2 and VS showed such a pattern where the chin was also included in the area (VS at the 8. partial for the vowel /a/, SE2 at the 17. partial for the vowel /e/, SE2 at the 9. and 13. partials for the vowel /i/).
A peculiar finding was found for the vowel /i/ in the case of SS: Her singing voice

[7] As in the previous case studies, the results of the fundamental to the 5. partial and of the highest partial analyzed are displayed in general. Furthermore, when changing the color-coded radiation area, its results are also involved. At that, results of CH singing the vowel /u/ are eliminated due to a lack of recording quality.



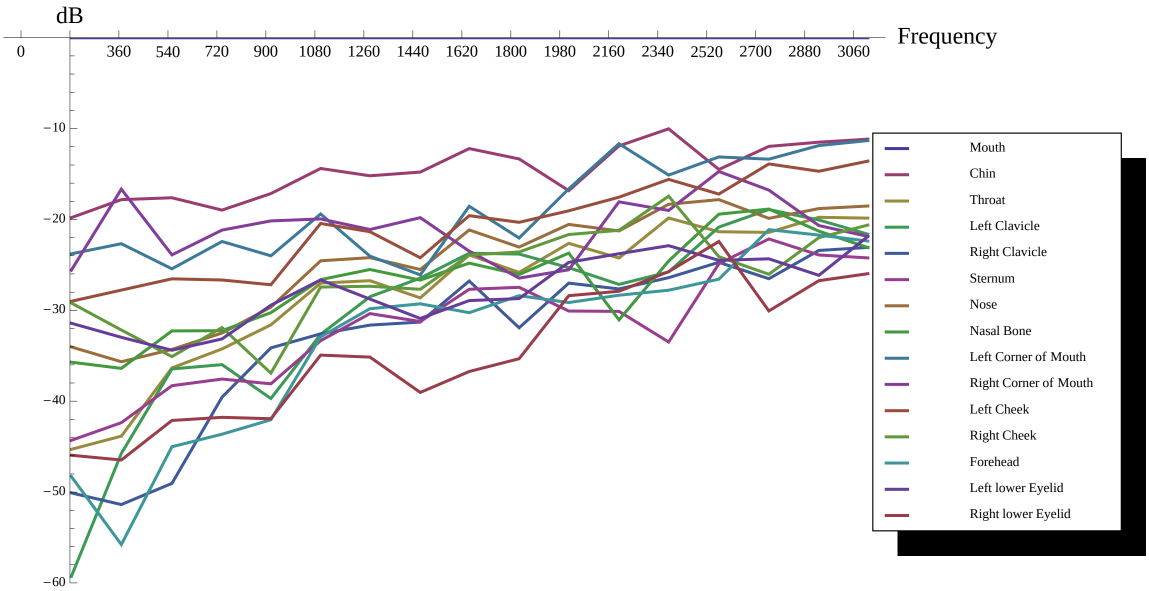


Figure 6.28: Sound levels of 14 measured upper parts of the body sung by a classical singer (above, CH) and a female musical theater singer (below, SS) relating to the radiation from the mouth (0 dB) at the fundamental frequency of 180 Hz for the vowel /a/.

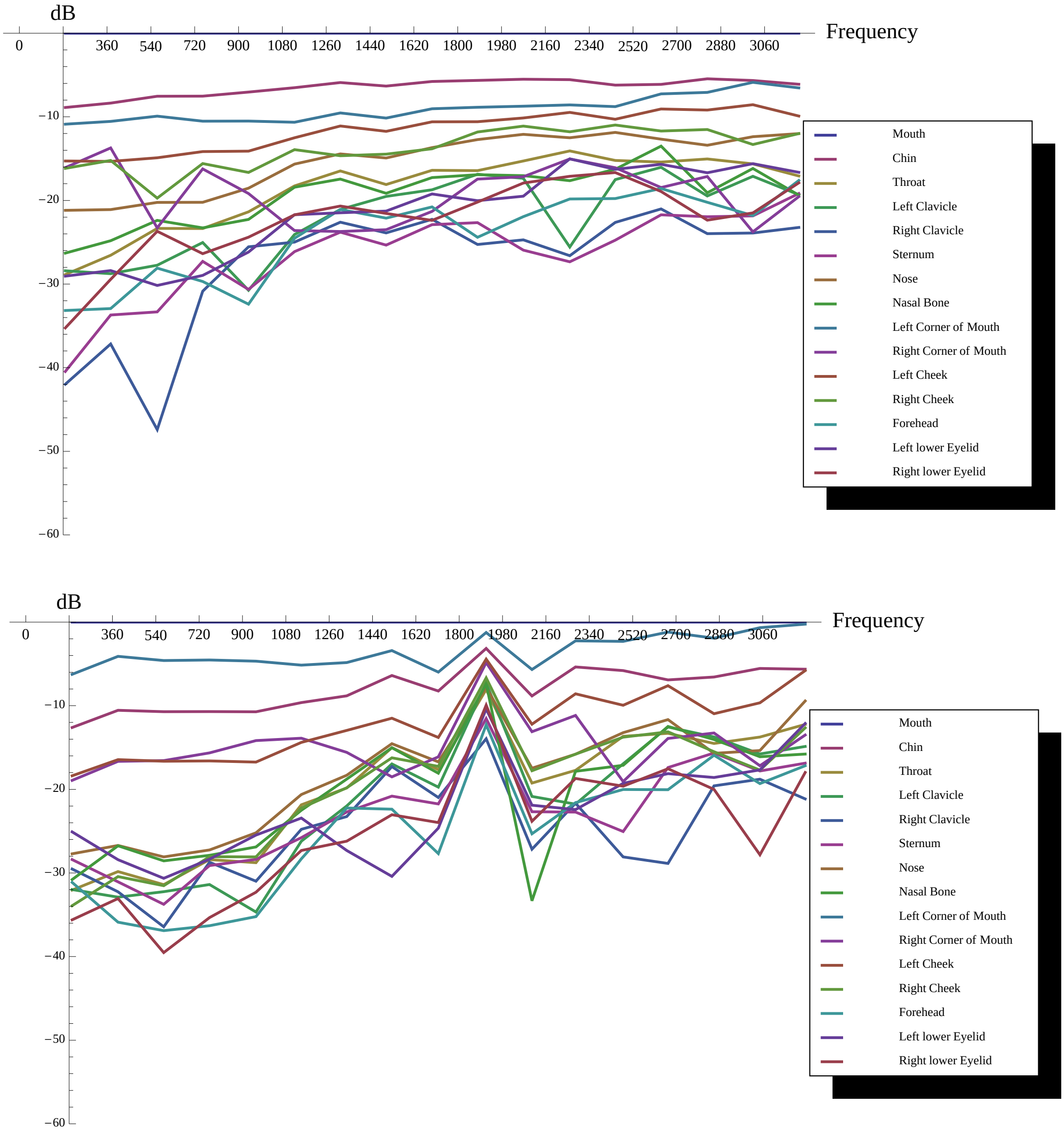


Figure 6.29: Sound levels of 14 measured upper parts of the body sung by two Pop singers (above: SE1, below: VS) relating to the radiation from the mouth (0 dB) at the fundamental frequency of 180 Hz for the vowel /a/.

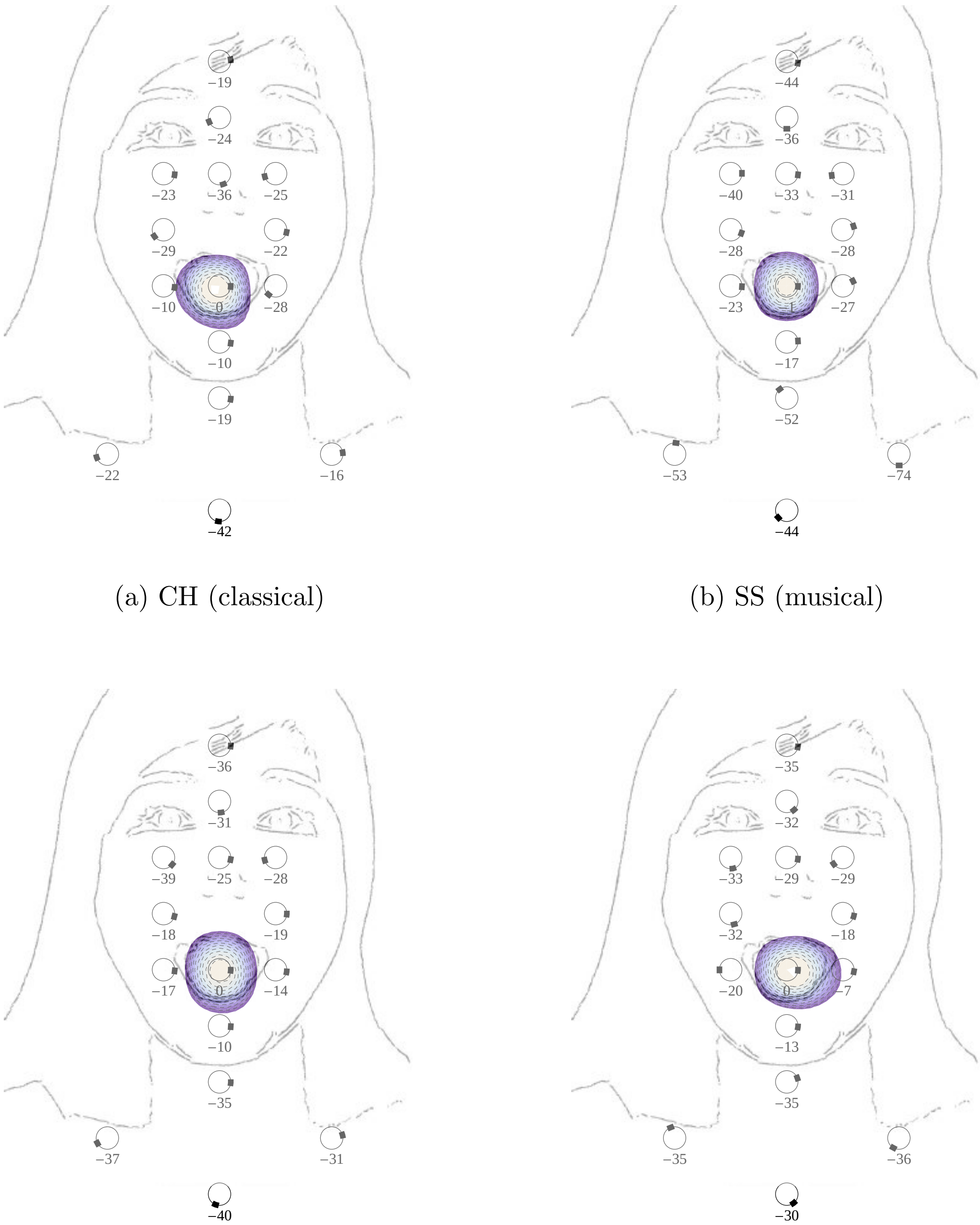
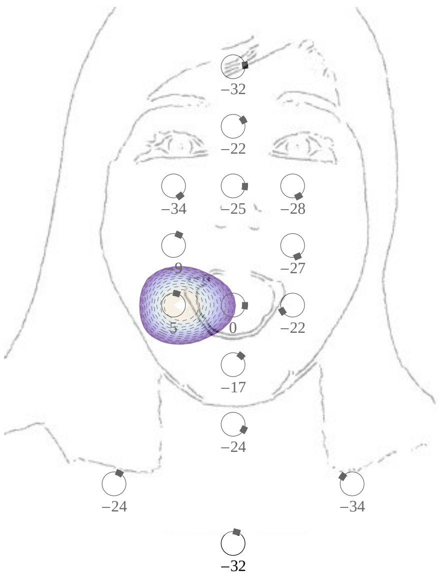
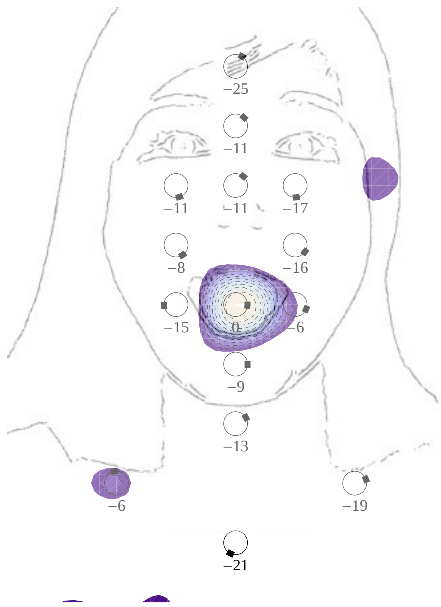


Figure 6.30: Radiation of a classical singers (a), a female musical theatre singer (b) and two female Pop singers (c and d) at the fundamental frequency of 180 Hz for the vowel /a/.



(a) 5. Partial (musical)



(b) 9. Partial (pop)

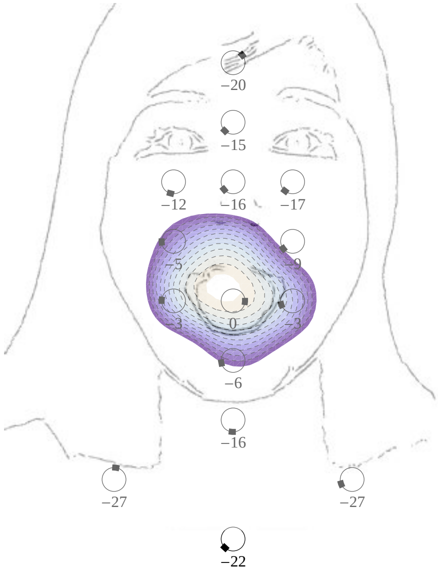
Figure 6.31: Radiation pattern of subject SS (musical, a) for the vowel /i/ and subject VS (Pop, b) for the vowel /o/ at 180 Hz.

emitted the strongest from the mouth, although this seems to be directed slightly to the left. At the 3. and 4. partials, the strong radiation energy occurred from the middle of the mouth, but shortly after, the radiation source shifted towards the left side at the 5. partial, so that the radiation energy from the left corner of the mouth was getting stronger (5 dB) than from the mouth (see Figure 6.31). After that, the strongest radiation source went back into the mouth again. Such a relocation was also observed at the 10. partial.
These changing radiation patterns are like those of the vowel /u/ shown in Figure 6.32, although the radiation area of the vowel /i/ was much smaller at high frequencies than other vowels.

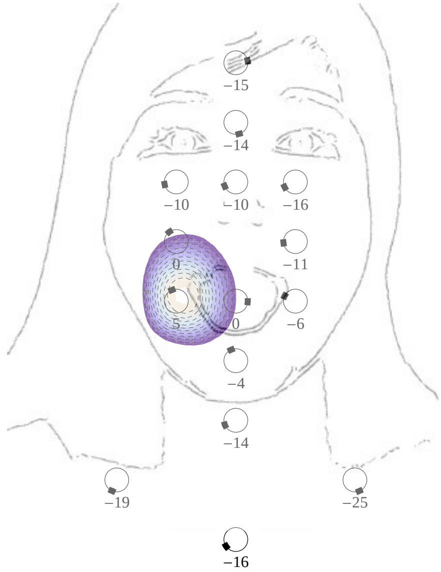
For the vowels /o/ and /u/, strong radiation energy occurred from another body area too, as shown in Figures 6.31, 6.32, 6.33, 6.34 and 6.35. The radiation of VS appeared from the left clavicle and the chest area (shown at the bottom of the sketch) at the 9. partial for the vowel /o/ (see right in Figure 6.31) was a single case for this vowel, however, for the vowel /u/, all the subjects except for CH revealed such results with radiation from other body area. The radiation energy of SS was first restricted only

from the mouth at the fundamental frequency, but her strong radiating area spread up to the left cheek and enveloped surrounding the mouth at the 12. partial. After that, at the 13. partial, the strongest radiating point moved from the mouth to left where both measured parts of the body, the left corner of the mouth and the left cheek, are located (see Figures 6.32 and 6.33). This means that the mouth was not the main energy source there. For that reason, the energy value of the former was measured 5 dB higher and that of the latter was of equal value, compared to the mouth radiation, respectively. The fact that the radiation from the left corner of the mouth (and the chin at the 16. partial) was stronger than the mouth radiation remained unchanged until the 16. partial, means that the mouth was the strongest sound source at the 17. partial again. Such results of the vowel /u/ were observed not only in one case but also at second time, that was each time in the case of SS.
When it comes to research findings of SE2, also for the vowel /u/, strong radiation initially occurred only from her mouth, however it changed at higher frequencies, such as the radiation of SS. From the radiation pattern displayed at the 9. partial, it can be seen in Figure 6.34 that strong energy also radiated from the thoracic region and this spread in this region at the 10. partial. The radiation of VS showed similar results from the 9. partial, so that her radiation also came from the shoulder and the thoracic regions (at the 9. and 15. partials). Interestingly, the radiation pattern from the mouth region was diamond-like, as shown at the 9., 15. and 16. partials in Figure 6.35. But such a pattern was already observed, for example, in the case of SS measured at 180 Hz and 500 Hz (see Figures 6.32, 6.33 and 6.21). The reason behind such findings could be a narrow mouth opening for these vowels, especially for the vowel /u/, because acoustical energy of singing voice concentrates inside of the mouth (in oral region) by narrowing the mouth/lip opening.

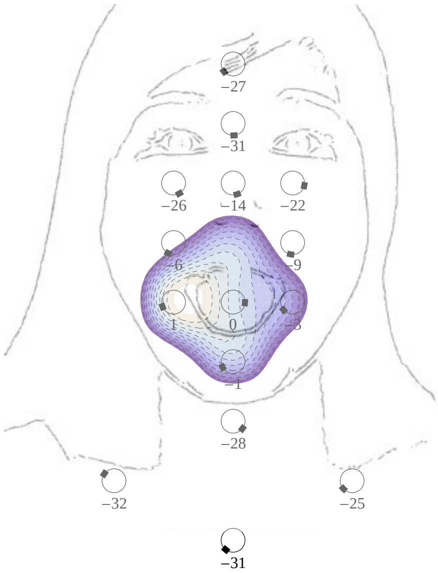
In the case study measured at 180 Hz, strong radiation energy was frequently observed outside of the body on the plot in a higher frequency range. As mentioned in Subsection 6.2.1, this is probably a sound reflection, however, the occurrence may deal with air that is contained in the singing voice and emitted from the mouth while singing. Because, at least in this work, such radiation was generally found more often for the vowel /u/ than for other vowels, especially at the low pitch that was measured. Actually, research of radiation energy of the sung vowel /u/ by means of the acoustical camera was difficult, and also made data analysis difficult due to the fact that the singing voice often contained a large amount of the air which leads to deaden generation of overtones. As shown in the research findings of the previous case studies, the singing voice of nonclassical singers often showed such a tendency, especially when they sang on low pitch.



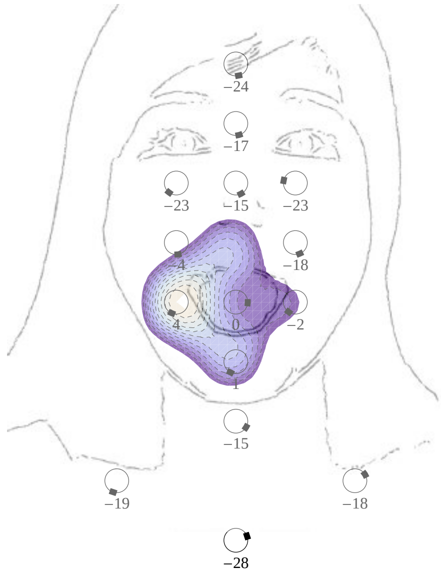
(a) 12. Partial (musical)



(b) 13. Partial (musical)

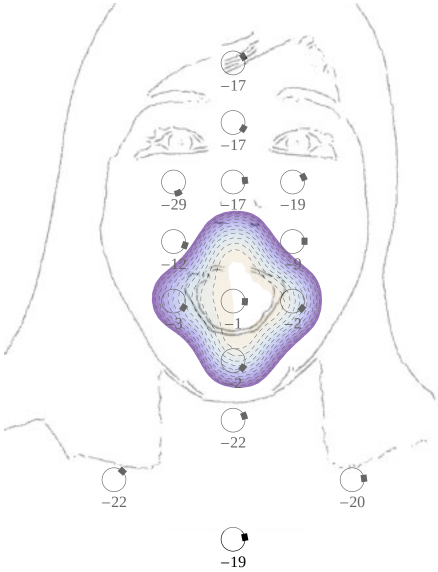


(c) 14. Partial (musical)



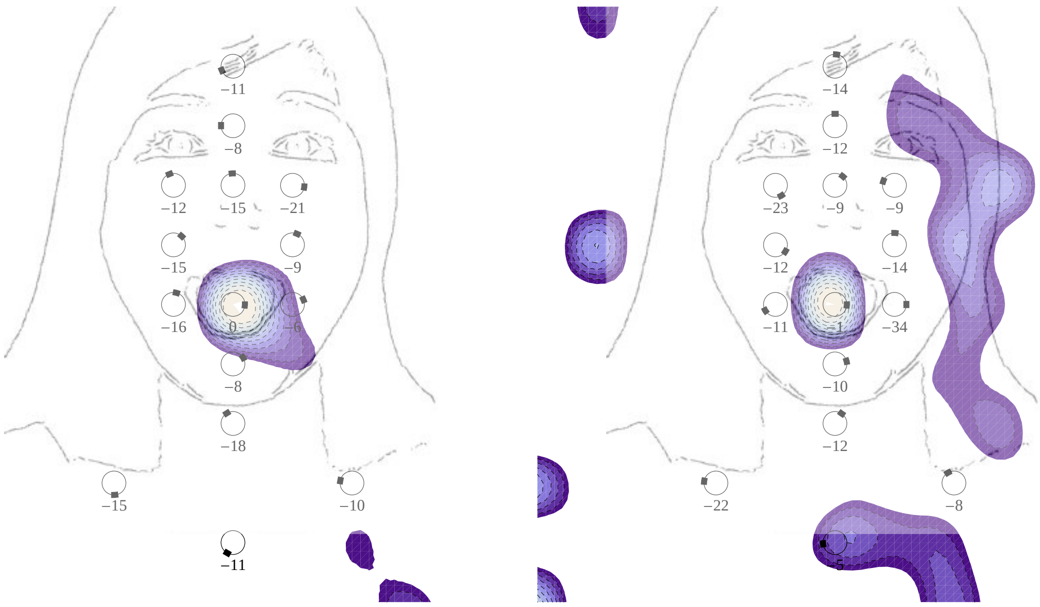
(d) 16. Partial (musical)

Figure 6.32: Radiation patterns of subject SS (musical) for the vowel /u/ at 180 Hz.



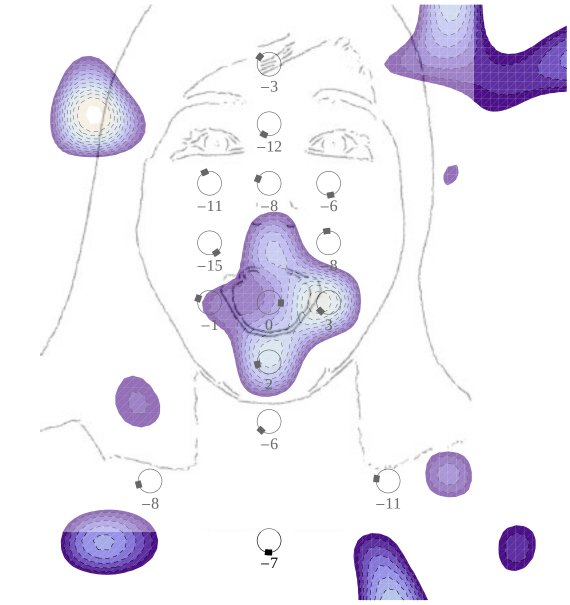
(a) 17. Partial (musical)

Figure 6.33: Radiation pattern of subject SS (musical) for the vowel /u/ at 180 Hz.

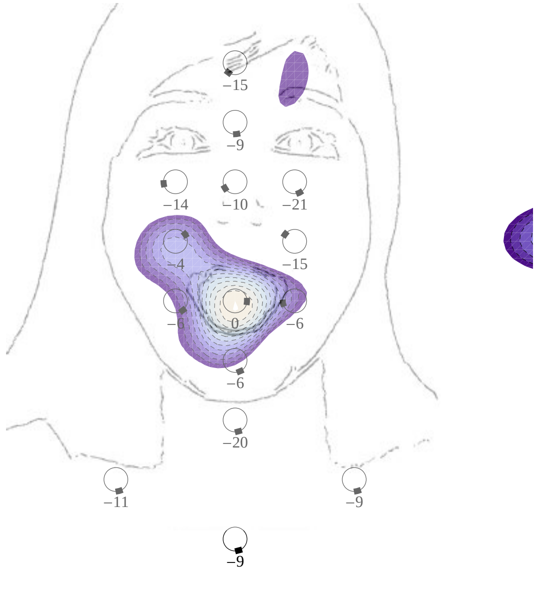


(a) 9. Partial (pop) (b) 10. Partial (pop)

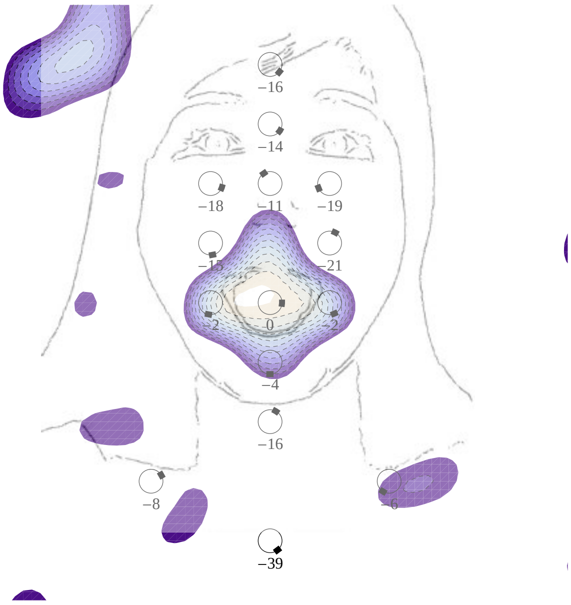
Figure 6.34: Radiation patterns of subject SE2 (pop) for the vowel /u/ at 180 Hz.



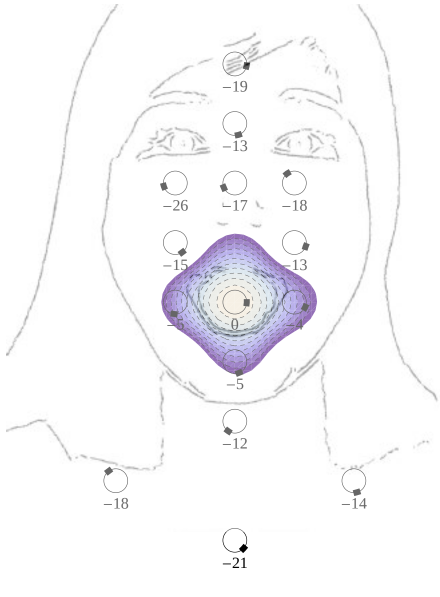
(a) 9. Partial (pop)



(b) 14. Partial (pop)



(c) 15. Partial (pop)



(d) 16. Partial (pop)

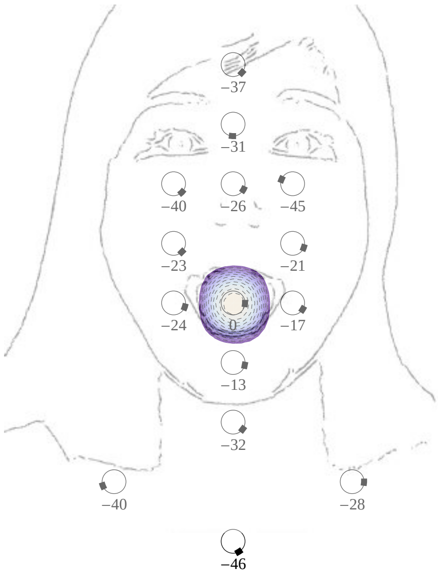
Figure 6.35: Radiation patterns of subject VS (pop) for the vowel /u/ at 180 Hz.

6.2.3 Case Study of Male Subjects at 120 Hz (approx. B2)

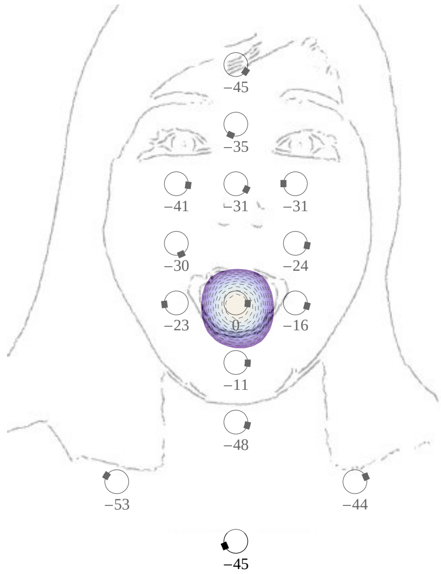
In this subsection, the results of the male singing voices of JR and TF measured at 120 Hz will be shown and analyzed up to 2,5 kHz.

In the previous sections we saw three research findings in each of the previous case studies presented that indicated 1) the radiation energy of singing voice generally increases at increasing frequency, that 2) this is unstable for the vowels /o/ and /u/ and that 3) for the nonclassical singers, there is a large difference in the energy level between the mouth area (the corners of the mouth and the chin) and all the others of the measured parts of the body. The results shown in this case study (examined at 120 Hz) were similar to those of the previous case studies in my work, so that all the fact findings, that were mentioned just now, are actually existing here (see Figures 6.38 and 6.39). However, as shown in Figures 6.38 and 6.39, the unstable fluctuations observed for both vowels /o/ and /u/ seem to be somewhat diminishing in this case study in comparison to all the other case studies that we have seen yet. This is possibly due to the singers who were involved in this study. The radiation energy of both male singers did not change dramatically in the experiment at 250 Hz either (see Section 6.1).

Looking at the energy level gained from the fundamental of the sung vowel /a/ that is shown on the sketch in Figure 6.36, it is clear that the strongest radiation generally occurred only from the mouth at 120 Hz and that this phenomenon was independent of vowel and singer. The only exception which relates to both singers was nevertheless observed at the higher frequency for the vowel /o/ (at the 18. partial for JR and at the 17. partial for TF, see in Figure 6.37), so that their voice strongly radiated also from the chin. This means that the radiation of both singers was similar in this case study despite different voice types, when it comes to the strongest radiating area.

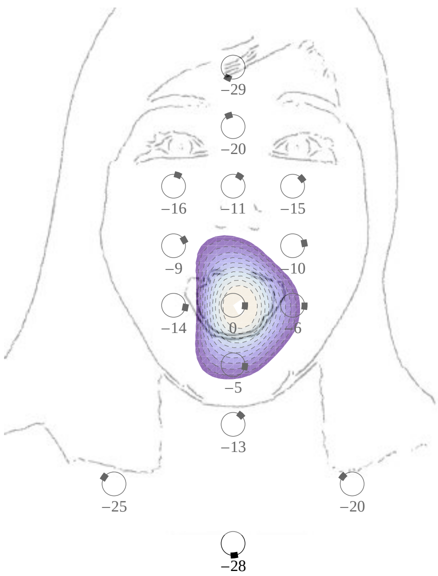


(a) JR (classical)

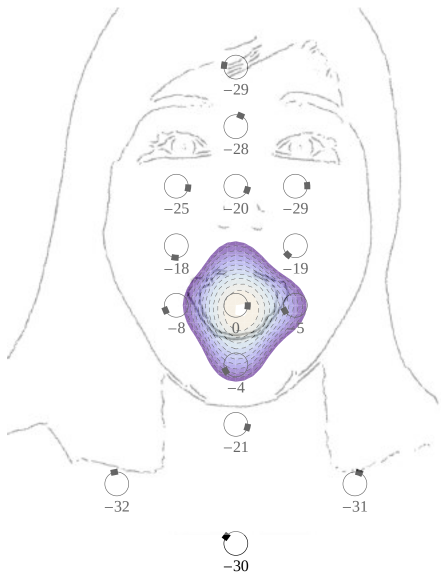


(b) TF (musical)

Figure 6.36: Radiation of a male classical singer (a) and a male musical theatre singer (b) at the fundamental frequency of 120 Hz for the vowel /a/.



(a) 18. Partial (JR)



(b) 17. Partial (TF)

Figure 6.37: Radiation of a male classical singer (a) and a male musical theatre singer (b) for the vowel /o/ at 120 Hz.

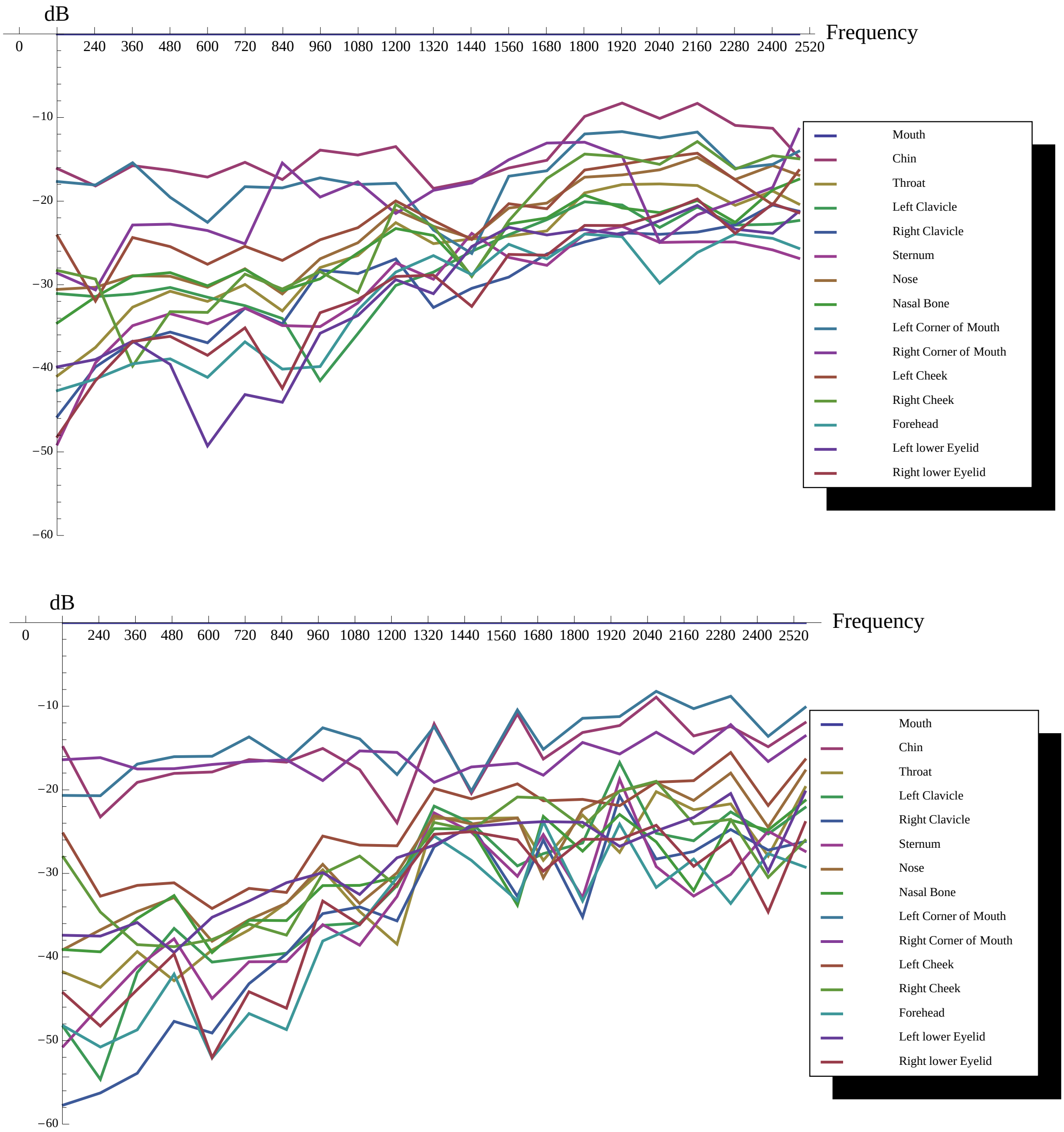


Figure 6.38: Sound levels of 14 measured upper parts of the body sung by a male classical singer (above, JR) and a male musical theater singer (below, TF) relating to the radiation from the mouth (0 dB) at 120 Hz for the vowel /o/.

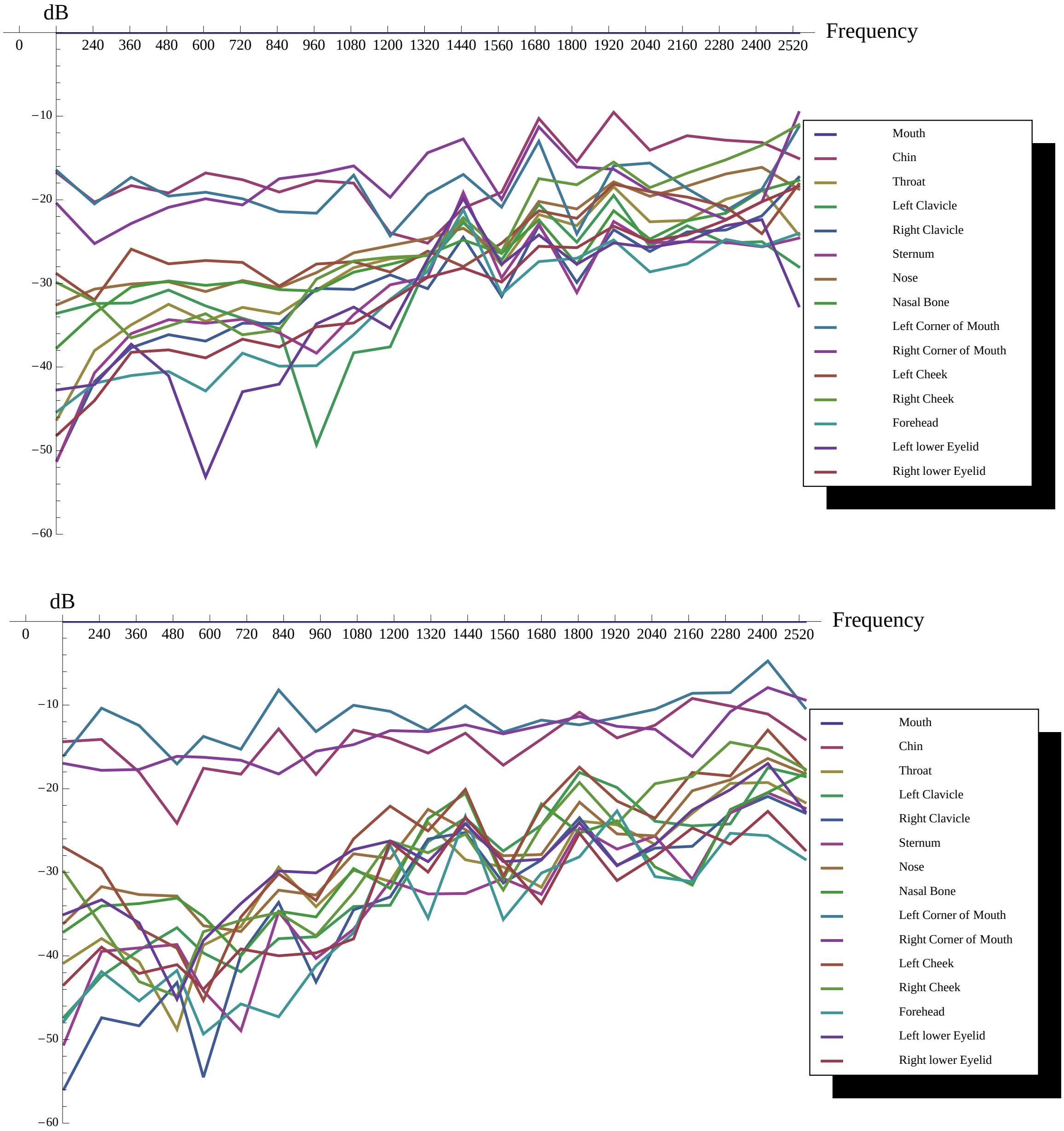


Figure 6.39: Sound levels of 14 measured upper parts of the body sung by a male classical singer (above, JR) and a male musical theater singer (below, TF) relating to the radiation from the mouth (0 dB) at 120 Hz for the vowel /u/.

6.2.4 Two Single Case Studies Measured at 90 Hz (approx. F2#) and 380 Hz (approx. F4#)

Furthermore, sound radiation from singing at 90 Hz by a classical bass singer (JR) and singing at 380 Hz by a male musical theater singer (TF) will be also examined carefully, as mentioned above. Each of these experiments is a single case study and the results were analyzed up to 1,3 kHz and 4,5 kHz, respectively[8].

The research findings of both measurements revealed increasing radiation energy in each frequency range analyzed, which became stable around 1 kHz in the case of JR and around 1,5 kHz in the case of TF. Concerning fluctuation in their radiation energy, no wide difference was found among the vowels in total, just like at 120 Hz (see Figure 6.40).

Looking at the results gained from JR, we can also observe the distinction of the radiation energy between the mouth area and all the other parts of the body which was heretofore found only in the results of nonclassical singers, including from singing at 380 Hz by TF.

When it comes to the results gained from TF, his energy increase up to 1,5 Hz was steep, such as his radiation energy measured at 250 Hz. Furthermore, it seems that his radiation energy decreased somewhat from approx. 3800 Hz, which could also be seen in the case of 500 Hz sung by female singers. But at this point, it is difficult for us to determine exactly whether there were actually decrease in energy in this frequency range, and if so, how strong this was and which part of the body was concerned. We will address these questions in the next chapter.

Concerning the strongest radiating area displayed on the sketch, at first view, we could possibly get the impression that for all research findings for JR, that these results would all be the very same due to the uniformly appearing radiation from the mouth only (see the results left in Figure 6.41). Unlike this, the results of TF showed changes in his strongest radiating area – radiation energy of each vowel revealed gradual extension of this area from around the 4. partial (approx. 1500 Hz, but some cases only from

[8] As in the previous case study, the results of the fundamental frequency to the 5. partial and from the highest partial analyzed are displayed in general. Furthermore, when changing the color-coded radiation area, the results are also involved. At that, results of TF singing the vowel /u/ are eliminated due to the lack of recording quality.

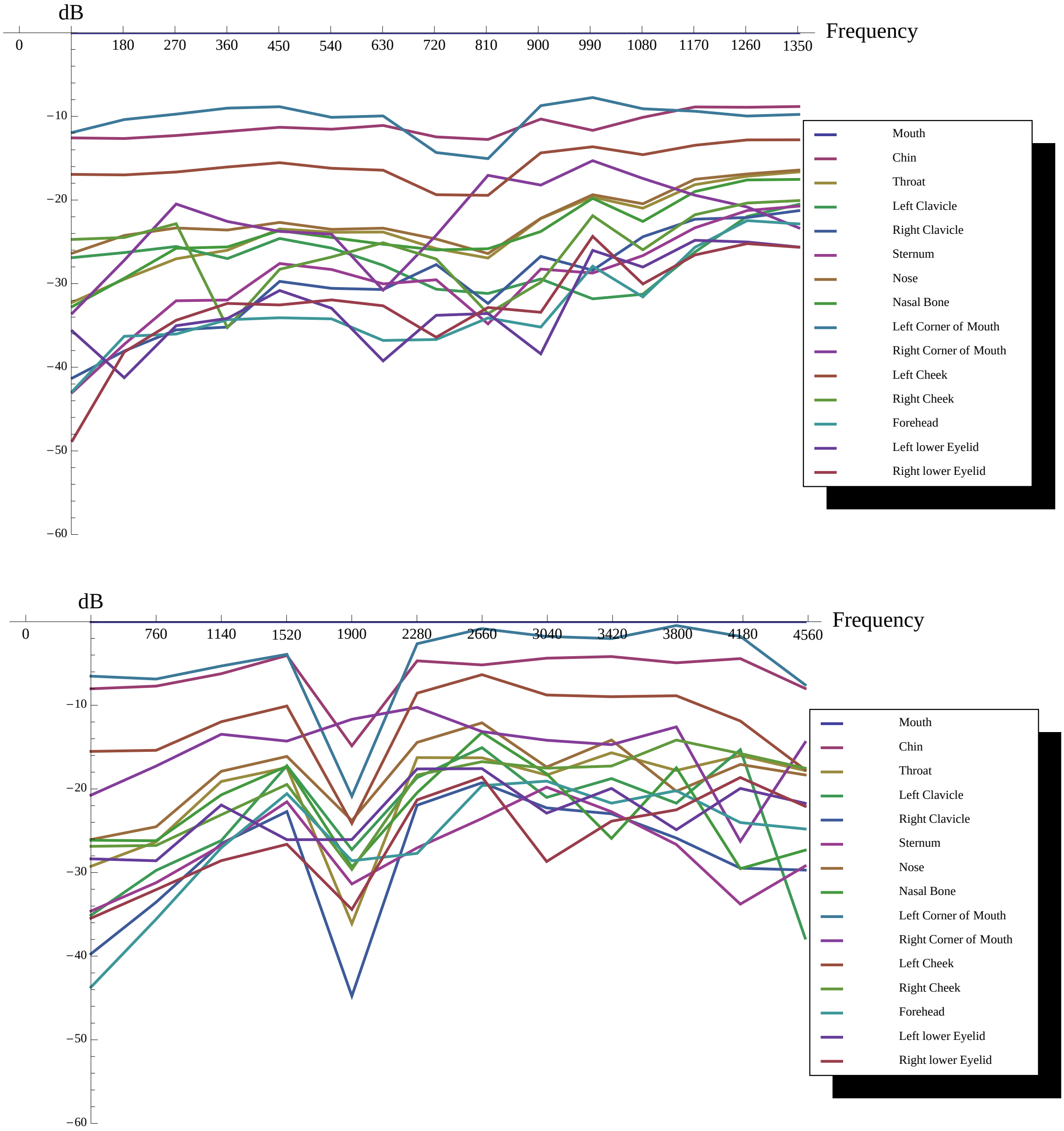
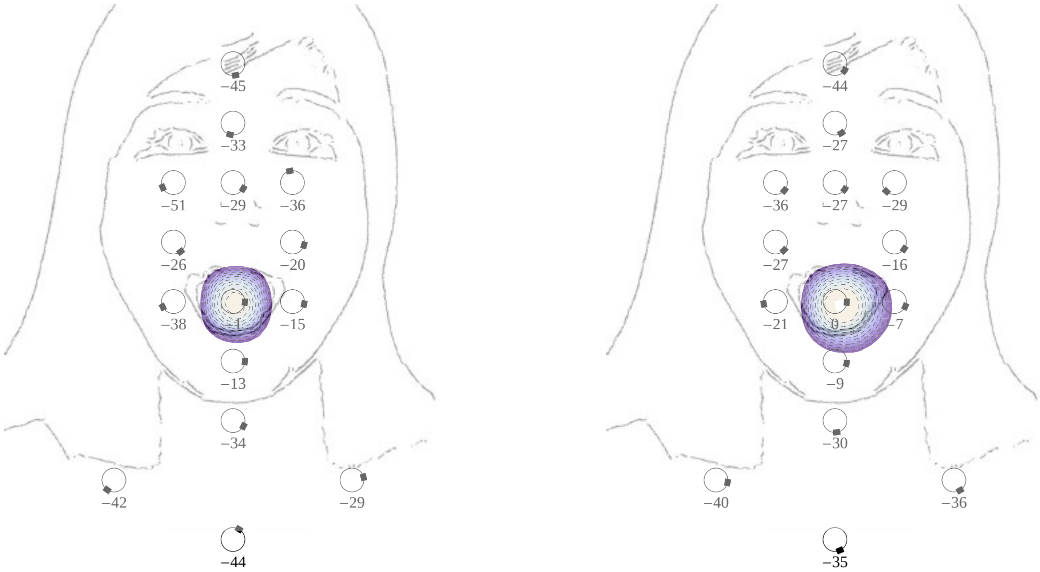


Figure 6.40: Sound levels of 14 measured upper parts of the body sung by a male classical singer (above, JR) at 90 Hz and a male musical theater singer (below, TF) relating to the radiation from the mouth (0 dB) at 380 Hz for the vowel /a/.

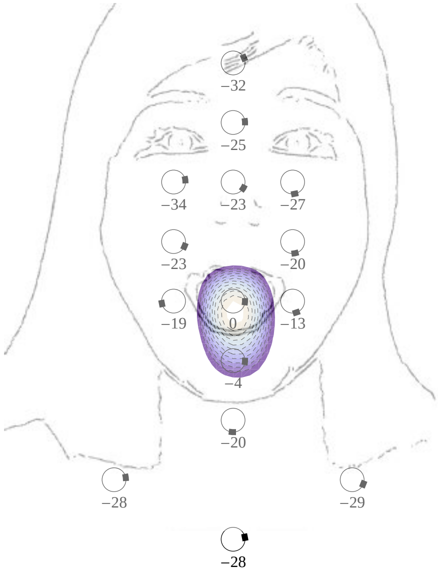


(a) JR (classical) (b) TF (musical)

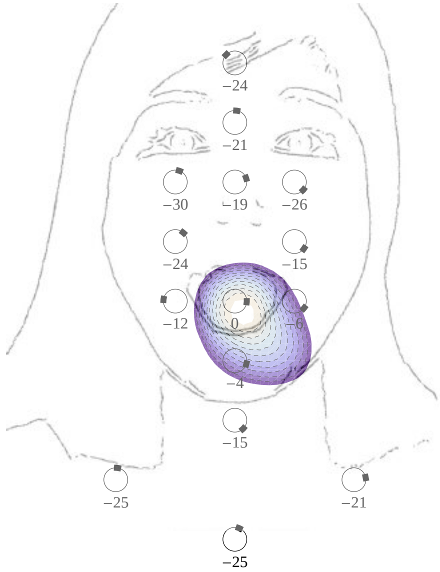
Figure 6.41: Radiation of a male classical singer (a) at 90 Hz and a male musical theater singer (b) at 380 Hz for the vowel /a/.

the 6. partial). A few times, the energy from this area became even stronger at higher frequencies than that from the mouth. The radiations of the vowels /i/ and /o/ observed at the 12. partial are such examples, so that the strongest radiation did not come from the mouth but from the chin (+ 1 dB, compare to the mouth radiation) for the vowels /i/ and from the right corner of the mouth (+ 3 dB, compare to the mouth radiation) for the vowel /o/ (see Figures 6.42 and 6.43).

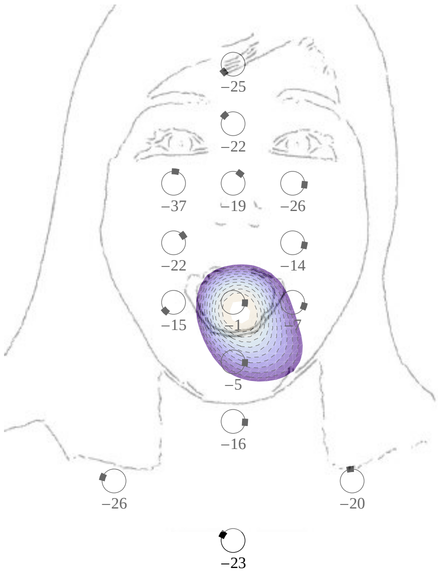
Apart from these findings, there was an interesting insight in the case of TF: his strong radiation around the mouth became reduced, briefly, for example at the 5. partial for the vowels /a/ and /i/ (such results was found for the vowel /o/). It is not clear why such a thing happens, but similar findings were also shown in the case study of 500 Hz (see Subsection 6.2.1).



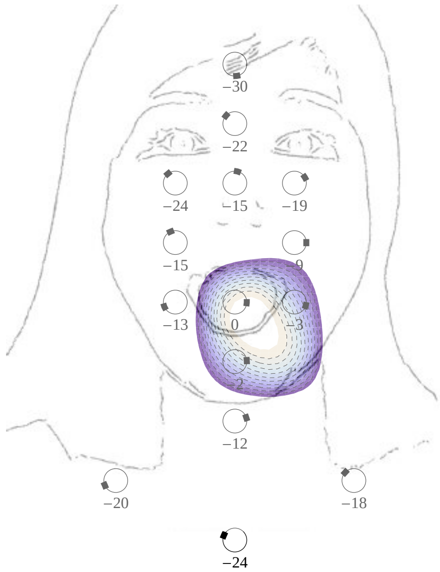
(a) 3. Partial



(b) 4. Partial

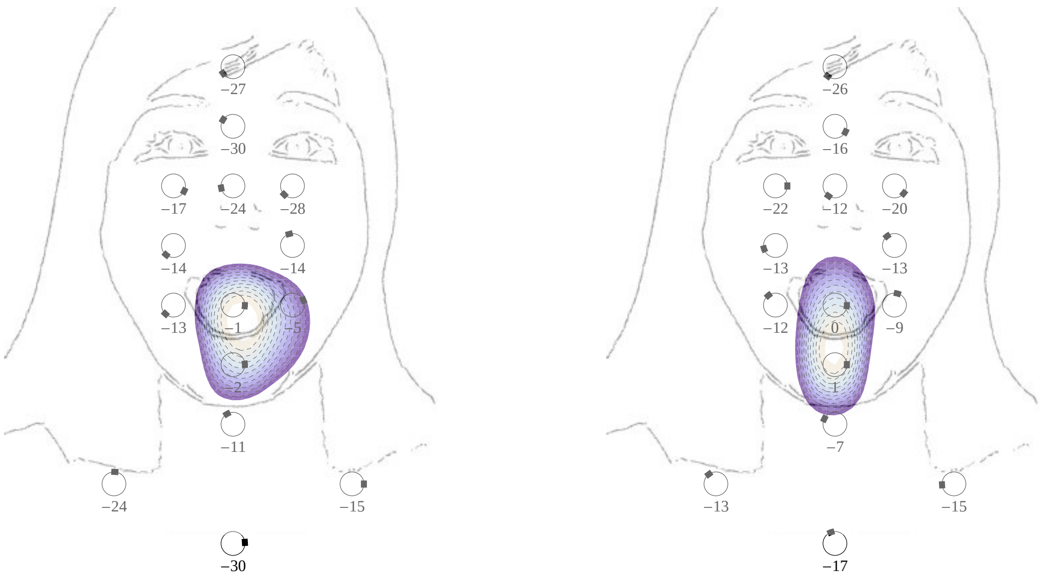


(c) 5. Partial



(d) 6. Partial

Figure 6.42: Radiation patterns of a male musical theater singer (Subject: TF) for the vowel /i/ at 380 Hz (at the 3., 4., 5. and 6. partial)



(a) 11. Partial

(b) 12. Partial

Figure 6.43: Radiation patterns of a male musical theater singer (Subject: TF) for the vowel /i/ at 380 Hz (at the 11. and 12. partial).

6.3 Conclusion 1

1. General findings presented in this chapter

- **Sound radiation of singing voice comes not only from the mouth**
  The results showed that sound radiation of the singing voice is not restricted to the mouth but also comes from other parts of the body, although the maximum radiation mainly radiates from the mouth. It is easy to imagine that the strongest energy source is the mouth and a powerful energy value can be measured at both corners of the mouth due to their localization near the mouth, but the experiments presented revealed an occurrence of strong energy from the chin (relatively frequently) and other parts measured, mostly from the facial area. Such an occurrence and its rate however strongly depend on frequency and pitch that is sung.

- **Increase of radiation energy from other parts of the body**
  Compared to the mouth radiation, the radiation from other parts of the body gen-

erally increased at ascending frequency, up to 3 kHz, roughly. This means that the former radiation energy decreased recognizably there in favor of the latter energy increase in total energy that was emitted while singing. Here is the percentage rate of the total radiation energy of subject SE2 (popular singing) singing the vowel /a/ at 250 Hz that was shown in Figure 6.9 as an example (dark blue line at the top of the figure is the mouth radiation and for the identification of all the other color-coded lines see Figure 6.9).

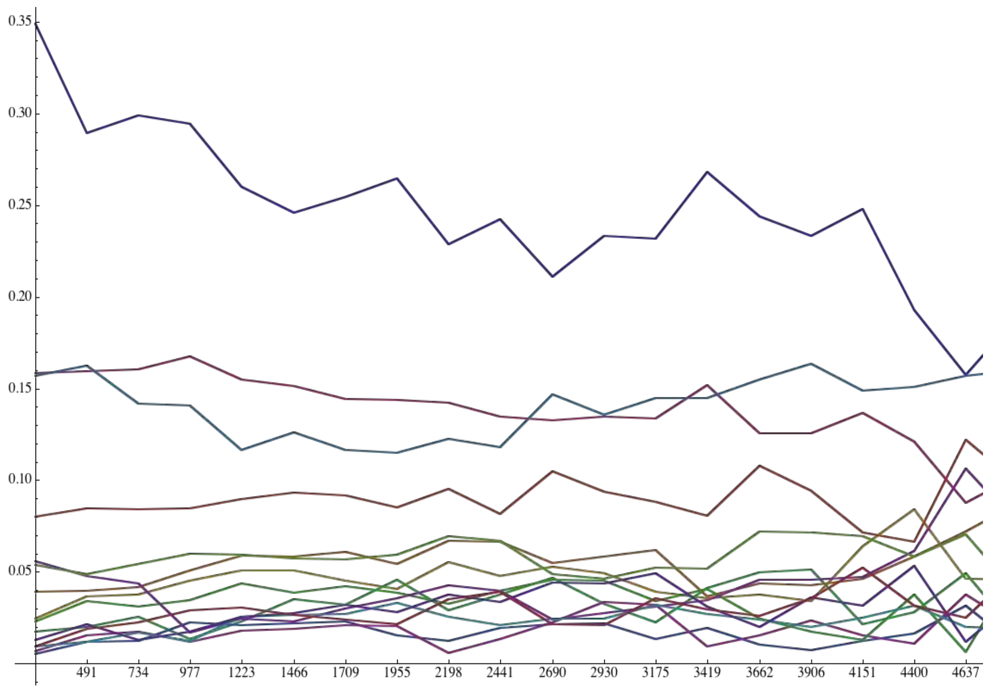


Figure 6.44: Percentage rate of the total radiation energy of SE2 singing the vowel /a/ at 250 Hz (y-axis: percentage, x-axis: frequency)

- **Radiation energy from some parts of the body can be stronger than that from the mouth**
  Due to this increase, the radiation energy of some parts of the body can be stronger than that of the mouth at high frequencies, i.e. above the adjusted value of 0 dB to the radiation from the mouth. Such radiation energy was observed by shifting the energy source or emergence of multiple energy sources that were often found in the case of 500 Hz. This can be a temporary, but also as a continuing phenomenon.

- **The higher the sung tone the stronger the radiation energy measured at the fundamental frequency**
  By means of visualizing the strongest radiating area up to -6 dB that was marked in color, it is clearly noticeable that the area of strong radiated energy shown at the fundamental became large with increasing pitch that was sung (the question whether total energy radiated increased with pitch or not will be clarified in the next chapter).

- **Radiation patterns of singing voice change depending on the frequency**
  The radiation patterns displayed in this chapter revealed that the sound radiation changes depending on the frequency, and that the energy from the region of the body outside of the mouth increases up to about 3 kHz, as mentioned above. However when it comes to dimension of energy increase, there were large differences among the vowels and individuals (so from subject to subject). While the progress of the vowels /a/e/i/ were a smooth increase, that of the vowels /o/ and /u/ showed a strong zigzag-like course. This fluctuation was visible at all the parts of the body. This is probably because an air stream in the vocal tract occurs due to the constructed mouth shape for these vowels. As mentioned above, the dimension of the energy increase was also different in each individual case. Some subjects showed a strong energy value from the beginning, i.e., from the fundamental frequency, so that their energy only slightly increased in comparison to the rest.

- **Radiation energy of nonclassical singing techniques for the vowels /o/ and /u/ strongly origins from the mouth area**
  For the vowels /o/ and /u/, the radiation patterns of nonclassical singers manifested that their strong energy occurs from the corners of the mouth and the chin. This is clearly noticeable when looking at the progress of the radiated energy, because there was a large difference in the energy level between these parts of the body and rest of the parts measured.

2. **Further findings related to the topic in this chapter**

- **No cognition of special increase of radiated energy from the measured parts excluding the mouth in formant frequencies**
  By reference to this utterance by Sundberg *"In a vowel spectrum where the first formant frequency is well above the fundamental, an overtone is normally the loud-*

est partial. In vowel spectra with the fundamental close to the first formant, on the other hand, the fundamental is the loudest partial" [68], I viewed all the sound spectra of the subjects, in particular, to find out whether the frequency range is influenced in some way by radiated energy of the measured parts, except the mouth, when the overall energy increases there. The increased energy level of the frequency range is shown in the sound spectrum such as formant frequencies or the fundamental frequency.

When it comes to the sound energy level, the sound spectrum gained by the subjects showed that the strongest partial is located between the fundamental frequency and the 6. partial, according to the sung pitch. In this study, the lowest pitch that was sung is 90 Hz and the highest pitch is 500 Hz, and it was shown in general that the lower the sung pitch the higher the partial which showed the strongest energy level in the sound spectrum. For example, in the case of 250 Hz, the fundamental frequency mostly demonstrated the strongest level for the vowels /e/i/u/, whereas such an energy level was shown rather at a higher partial for the vowels /a/ and /o/. But in the case of 120 Hz, nearly one octave lower, it looks different to the previous case, so that the strongest level was located at a higher partial for all the vowels. That is because of the location of the first formant frequency: the first formant frequency of the vowels /e/i/u/ is located, depending on voice classification, at approximately 300 – 400 Hz, while that of the vowels /a/ and /o/ can be found in a higher frequency range (for the vowel /o/ 400 – 500 Hz and the vowel /a/ 700 – 1000 Hz, approximately, see Section 2.2 as a reference). This means that the fundamental frequency of the vowels /e/i/u/ is close to the first formant frequency, so that the fundamental frequency is the loudest partial, whereas this is not the case for the vowels /a/ and /o/ whose first formant is located far away from the fundamental frequency at this pitch, as mentioned by Sundberg.

However, it doesn't matter whether the sound level is highest at the fundamental frequency or at the first formant frequency, no causal relation of the radiated energy from the measured parts of the body excluding the mouth to the formant frequency, in other words, no special increase from these parts at the formant frequency was recognized there, and this holds true also for the second and third formant frequencies. This implies that such an increase at these formant frequencies is effected by the radiation from the mouth.

- **No relevant change of sound level and fluctuation of radiated energy from the measured parts excluding the mouth**
  Furthermore, I also examined whether the process in sound spectrum, i.e., change of sound level, has an influence on the fluctuation of the radiated energy. The reason for that is, as already demonstrated, that a large difference among the subjects was shown in the fluctuation of their radiated energy for the vowels /o/ and /u/, so the energy from the measured parts (except the mouth) moved up-and-down. However, there was no finding of a relevant change of the sound level and fluctuation of the radiated energy from these measured parts of the body.

3. Comparison with previous research findings

- **Relation of pitch to radiation of singing voice**
  In fact: The higher the fundamental frequency, i.e., sung pitch, the more powerful the radiation energy from the body. As shown, this holds true not only for the radiation from the mouth, but also for the radiation from all the measured parts of the body. Although a stronger radiation energy was observed at a higher pitch, it seems that in total there was no large difference in sound level, except that a slightly higher level was observed in a high frequency range. This is why only a small difference was given in the sound level, because the sound energy is controlled in the recording to avoid overdriving. However, according to Fant and Cleveland, partials at high frequencies show a higher sound level than partials at lower frequencies, when vocal loudness is increased [29] [19]. Furthermore, it is possible that the increased sound pressures were certainly at a higher pitch than at a lower pitch due to the fact that the stronger radiation energy from other parts of the body was observed at 500 Hz than at lower sung pitch such as 250 Hz. And that increased sound pressure in the vocal tract and in the trachea is the source of vibrations in the skull, neck, and chest regions, as mentioned by Sundberg (see Section 4.2). Therefore, this occurrence could depend on loudness of vocal sound rather than on pitch, however, this is consistent with the assertion by Sundberg that the radiation energy is dependent of pitch, and also with the insight that radiation directivity of human voice changes depending on the frequency (see Section 4.4).

7 Result 2: Radiation Energy of the Singing Voices (Statistical Acquisition)

In the previous chapter we see how the sound radiation of singing voices changes and the fact that strong radiation energy comes not only from the mouth but also from other parts of the body. So far, the main focus has been on these fact findings. For this purpose, the results of the radiation patterns were illustrated using a sketch of the upper body where all the measured parts of the body were located. This method of presentation is an optimal way to understand the radiating area of the singing voice and the strength of its radiation energy, however, as we already know, only a single case can be presented using this method, so that another method is needed for further data analyses.
Therefore, a mean from all the data which are acquired by two or three time repeated measurements, this means that not only the results which were already presented in the previous chapter, but also the results that are not yet shown in this work, will be exhibited in the following chapter. The mean of the results will be gathered according to requirements and used for a statistical task to consider the results from different angles.

Furthermore, the resulting energy value of each measured part of the body will be presented according to various frequencies, vowel and pitch. This allows a summary of the energy values from the parts of the body, but also a method to follow the motion of the radiation energy at frequencies. This chapter is about the following questions:

- How strong is the radiation energy of each part of the body?
- Where is the frequency range in which the energy was distinctly increased or decreased and where is located its maximum and minimum?
- How large is the difference between these maximum and minimum energies?

In oder to clarify such questions, the motion of radiation energy that was presented in the previous chapter, will be carefully examined here by separate observations of each part.

At the end, I would like to introduce some abbreviated terms, because of a lack of space in the lists:

- left and right clavicle = LC and RC
- nasal bone = N.Bone
- left and right corner of the mouth = LCoM and RCoM
- left and right cheek = LCh and RCh
- left and right lower eyelids = LLE and RLE

7.1 Energy Values and Fluctuation of Radiated Energy

Firstly, we will focus on the energy values gained from the singers here once again and after that it will be shown how the radiated energy changes in the course of the frequency range analyzed.
Beside the clarification of existing radiation energy from the area outside of the mouth, the results of the previous chapter revealed that the difference between the radiation energy from this area and that from the mouth decreases in the high frequency range, because the radiation energy from the area outside of the mouth increases there. It seems that the energy from the area outside of the mouth increases up to a certain frequency, even though the dimension of such an increase differs from vowel to vowel that was sung (for example, in the case of the vowels /o/ and /u/, we saw the results with unstable fluctuation of the radiated energy in the previous chapter). Therefore, the question here is where the energy distinctly increases or decreases in general. Now let's take a look at the results arranged according to pitch that was measured.

In the upcoming tables, I would like to suggest to the energy values, which increase or decrease more than 10 dB compared to the energy value at the previous or subsequent frequency. The energy values will be shown in yellow. In the same way, if an energy value from any part of the body is higher than from the mouth, its value is written in red.

7.1.1 Case of 250 Hz (B3)

First of all we will see the results of the measurement at 250 Hz, where all the subjects are involved (see Tables 7.1, 7.2, 7.3, 7.4, 7.5, 7.6, 7.7, and 7.8). At this point, all the results are analyzed at five frequencies of 250 Hz, 1000 Hz, 2000 Hz, 3000 Hz, and 4000 Hz.

Radiated Energy Value

As the measured radiation energy values show in the tables for all the subjects, the strongest radiation energies arise from the chin and the corners of the mouth (in most cases from the left corner of the mouth). When it comes to the most powerful radiated part, it seems that there is little difference among the musical genres and vowels.
However, when looking at the energy values gained from singing all the vowels by each subject, we can notice that there are often large differences between the vowels /a/e/i/ and the vowels /o/ and /u/ (or between the vowel /u/ and all the others). Only subject JR (classical, male) showed no such difference, but the fact finding actually holds true for each subject: The energy values of subject CH (classical, female) are generally weaker for /o/ and /u/ than for all other vowels, especially at the chin, throat, clavicles and the sternum. Subject SE1(classical, female) also yielded a similar result for the vowel /u/, even though the difference among the vowels is small in comparison to that of CH. In her case the radiation from the throat was much weaker there than for all the others. Energy values of subject SS (musical, female) was very weak in total in comparison to all other participants, particularly at the chin for the vowel /i/ and at the throat for the vowels /o/ and /u/ (the strongest vowels are /a/ and /e/ in her case). The vowel /a/ was also the strongest vowel of subject TF (musical, male) in total and additionally, it was found that his voice radiates generally weaker from the chin for the vowels /o/ and /u/ and also from the forehead for the vowel /o/ at 250 Hz. The results of SE2 (Pop, female) in popular singing and VS (Pop and Soul, female) in Soul singing were similar so that its radiation energy revealed the weakest value for the vowel /u/. The difference

Subject CH: Fundamental 250 Hz

	Chin	Throat	LC	RC	Sternum	Nose	N.Bone	LCoM	RCoM	LCh	RCh	Forehead	LLE	RLE
/a/														
250 Hz	-13	-18	-14	-19	-33	-32	-20	-24	-9	-17	-24	-16	-21	-19
1000 Hz	-12	-19	-18	-19	-30	-25	-23	-19	-9	-17	-24	-20	-23	-19
2000 Hz	-15	-25	-20	-24	-25	-22	-24	-14	-16	-21	-20	-21	-25	-25
3000 Hz	-11	-18	-19	-16	-19	-17	-17	-8	-8	-17	-15	-20	-24	-20
4000 Hz	-10	-18	-18	-26	-25	-19	-30	-9	-12	-17	-14	-21	-26	-20
/e/														
250 Hz	-13	-19	-15	-19	-33	-34	-21	-27	-10	-17	-25	-17	-21	-20
1000 Hz	-12	-21	-19	-21	-32	-27	-25	-23	-10	-19	-26	-22	-24	-21
2000 Hz	-14	-25	-17	-19	-20	-21	-19	-11	-9	-21	-16	-18	-22	-27
3000 Hz	-12	-20	-18	-17	-20	-18	-19	-7	-7	-17	-14	-21	-22	-22
4000 Hz	-11	-18	-21	-28	-22	-18	-41	-8	-10	-18	-11	-18	-26	-22
/i/														
250 Hz	-11	-18	-14	-20	-39	-31	-21	-23	-8	-19	-28	-16	-22	-20
1000 Hz	-11	-21	-21	-19	-30	-27	-25	-20	-9	-23	-24	-22	-24	-19
2000 Hz	-13	-27	-20	-20	-22	-22	-21	-12	-9	-27	-16	-21	-23	-27
3000 Hz	-9	-19	-18	-17	-21	-18	-20	-10	-7	-21	-14	-26	-22	-23
4000 Hz	-7	-16	-16	-26	-27	-21	-32	-24	-14	-21	-17	-23	-35	-21
/o/														
250 Hz	-26	-26	-22	-27	-42	-38	-29	-24	-19	-28	-30	-23	-29	-28
1000 Hz	-31	-29	-27	-25	-36	-31	-28	-21	-16	-30	-28	-28	-27	-26
2000 Hz	-23	-30	-24	-34	-34	-42	-34	-27	-13	-27	-37	-28	-37	-33
3000 Hz	-11	-21	-23	-20	-22	-17	-19	-9	-5	-20	-21	-22	-22	-23
4000 Hz	-24	-24	-24	-33	-33	-25	-40	-21	-13	-22	-24	-21	-34	-23
/u/														
250 Hz	-21	-25	-21	-26	-41	-35	-28	-22	-15	-26	-29	-23	-28	-26
1000 Hz	-19	-28	-32	-44	-49	-34	-57	-19	-17	-24	-28	-34	-39	-31
2000 Hz	-28	-39	-28	-51	-34	-42	-50	-27	-19	-35	-38	-30	-36	-59
3000 Hz	-11	-20	-22	-20	-22	-17	-20	-9	-6	-22	-20	-25	-22	-21
4000 Hz	-18	-21	-23	-37	-35	-24	-33	-18	-16	-22	-25	-21	-43	-20

Table 7.1: Process of the sound energy of subject CH (classical) singing at 250 Hz (in dB).

among the vowels is clearly recognizable at the throat and chin, especially in the case of subject VS (Soul). Her energy value from the vowel /u/ measured at the chin is almost three time lower than from the vowel /a/ at 250, 1000 and 2000 Hz. On the other side, in popular singing, subject VS (Pop) revealed such a weak energy value for the vowel /o/ at the fundamental frequency in comparison to the results gained from the vowel /a/, particularly at the throat. Maybe such a finding could have been seen for the vowel

Subject SE1: Fundamental 250 Hz

	Chin	Throat	LC	RC	Sternum	Nose	N.Bone	LCoM	RCoM	LCh	RCh	Forehead	LLE	RLE
/a/														
250 Hz	-4	-13	-27	-24	-26	-16	-21	-6	-12	-12	-16	-27	-29	-27
1000 Hz	-2	-10	-32	-16	-23	-14	-19	-5	-16	-11	-18	-31	-26	-20
2000 Hz	-2	-9	-15	-20	-21	-11	-16	-6	-13	-8	-11	-18	-15	-17
3000 Hz	-1	-9	-14	-15	-15	-11	-17	-1	-12	-6	-10	-21	-13	-19
4000 Hz	-3	-12	-12	-15	-19	-22	-33	-1	-11	-7	-9	-17	-15	-15
/e/														
250 Hz	-3	-12	-26	-23	-24	-15	-20	-5	-15	-12	-16	-26	-28	-27
1000 Hz	-2	-8	-25	-15	-21	-12	-17	-3	-18	-8	-16	-27	-28	-20
2000 Hz	-1	-7	-11	-16	-14	-9	-13	-1	-16	-4	-11	-16	-13	-18
3000 Hz	-1	-7	-12	-13	-14	-10	-15	0	-17	-5	-11	-20	-12	-19
4000 Hz	-3	-9	-12	-15	-16	-16	-23	0	-16	-7	-9	-16	-16	-16
/i/														
250 Hz	-4	-12	-22	-23	-23	-15	-18	-3	-27	-10	-21	-24	-26	-27
1000 Hz	-3	-9	-14	-8	-13	-11	-18	-2	-11	-10	-13	-15	-15	-11
2000 Hz	-2	-7	-10	-17	-16	-8	-11	-1	-16	-4	-11	-16	-12	-16
3000 Hz	-2	-9	-13	-14	-14	-11	-15	0	-20	-5	-14	-18	-12	-22
4000 Hz	-4	-10	-12	-17	-17	-15	-23	1	-18	-7	-10	-16	-15	-19
/o/														
250 Hz	-4	-15	-30	-25	-27	-19	-22	-6	-17	-16	-19	-29	-30	-31
1000 Hz	-3	-12	-38	-18	-25	-17	-22	-5	-21	-13	-19	-36	-29	-24
2000 Hz	-1	-9	-13	-13	-14	-11	-15	-5	-10	-9	-10	-19	-18	-18
3000 Hz	-2	-9	-13	-13	-14	-12	-15	0	-11	-7	-10	-20	-14	-18
4000 Hz	-4	-11	-14	-15	-19	-21	-25	-2	-10	-11	-8	-17	-24	-15
/u/														
250 Hz	-6	-21	-30	-30	-29	-22	-25	-7	-16	-19	-26	-31	-32	-34
1000 Hz	-28	-29	-31	-25	-31	-28	-28	-16	-14	-26	-34	-31	-36	-28
2000 Hz	-9	-25	-28	-23	-34	-24	-20	-8	-9	-20	-22	-26	-20	-22
3000 Hz	-6	-18	-18	-17	-23	-21	-28	-8	-6	-11	-15	-18	-16	-27
4000 Hz	-6	-14	-17	-22	-20	-24	-33	-5	-17	-11	-14	-20	-31	-24

Table 7.2: Process of the sound energy of subject SE1 (classical) singing at 250 Hz (in dB).

/u/ also in this case, but unfortunately no results can be demonstrated for this vowel due to poor quality of the recorded data. The vowel /a/ is the strongest radiated vowel of subject VS, both in Pop and Soul singing.
Thus, it can be concluded that the radiation energy of both vowels /o/ and /u/, especially the vowel /u/, is often weaker than all the others, and it seems that this difference is felt at the chin and the throat.

Subject JR: Fundamental 250 Hz

	Chin	Throat	LC	RC	Sternum	Nose	N.Bone	LCoM	RCoM	LCh	RCh	Forehead	LLE	RLE
/a/														
250 Hz	-10	-27	-26	-35	-34	-23	-26	-12	-27	-18	-22	-35	-35	-35
1000 Hz	-9	-21	-36	-24	-28	-20	-23	-13	-27	-18	-24	-33	-29	-28
2000 Hz	-3	-12	-15	-19	-17	-12	-14	-3	-9	-9	-12	-22	-15	-20
3000 Hz	-7	-16	-17	-20	-19	-16	-18	-7	-31	-11	-16	-18	-20	-28
4000 Hz	-6	-7	-11	-11	-16	-7	-13	-5	-3	-4	-10	-13	-11	-14
/e/														
250 Hz	-14	-33	-29	-37	-37	-26	-29	-23	-14	-27	-22	-38	-36	-39
1000 Hz	-15	-30	-46	-30	-34	-26	-28	-32	-23	-30	-31	-37	-30	-33
2000 Hz	-9	-18	-21	-25	-25	-16	-20	-16	-17	-17	-15	-27	-22	-24
3000 Hz	-10	-17	-21	-20	-20	-18	-19	-18	-20	-19	-14	-19	-26	-24
4000 Hz	-8	-16	-15	-15	-13	-14	-18	-16	-8	-14	-18	-14	-17	-30
/i/														
250 Hz	-12	-30	-27	-35	-34	-24	-26	-17	-18	-23	-20	-35	-35	-35
1000 Hz	-10	-24	-49	-25	-31	-23	-25	-18	-19	-22	-27	-36	-32	-30
2000 Hz	-10	-21	-22	-25	-24	-18	-22	-13	-17	-17	-20	-27	-22	-25
3000 Hz	-12	-21	-21	-23	-22	-19	-22	-14	-14	-16	-21	-22	-23	-24
4000 Hz	-9	-18	-16	-15	-14	-20	-14	-9	-9	-17	-14	-14	-19	-22
/o/	Nrs.													
250 Hz														
1000 Hz														
2000 Hz														
3000 Hz														
4000 Hz														
/u/														
250 Hz	-14	-30	-27	-36	-35	-24	-27	-14	-32	-20	-25	-35	-38	-37
1000 Hz	-13	-26	-48	-27	-32	-24	-26	-18	-23	-22	-26	-35	-32	-30
2000 Hz	-11	-19	-22	-23	-23	-17	-21	-12	-25	-15	-18	-24	-22	-25
3000 Hz	-11	-19	-18	-22	-20	-19	-19	-13	-22	-15	-21	-19	-22	-29
4000 Hz	-17	-14	-28	-24	-20	-16	-19	-13	-12	-20	-8	-19	-27	-17

Table 7.3: Process of the sound energy of subject JR (classical) singing at 250 Hz (in dB, Nrs.= No results).

As we already know, there are parts of the body which were measured in pairs, symmetrically on the left and right, namely at the clavicles, corners of the mouth, cheeks and the lower eyelids. Their energy value from both sides sometimes revealed very different results at the fundamental frequency, particularly, at the corners of the mouth. Possible reasons for such an occurrence are covered in the previous chapter (see Chapter 6). However, although both energy values could be different at the fundamental

Subject SS: Fundamental 250 Hz

	Chin	Throat	LC	RC	Sternum	Nose	N.Bone	LCoM	RCoM	LCh	RCh	Forehead	LLE	RLE
/a/														
250 Hz	-18	-37	-52	-59	-43	-35	-35	-22	-29	-27	-34	-51	-31	-48
1000 Hz	-13	-29	-38	-33	-36	-27	-29	-20	-15	-23	-43	-39	-28	-40
2000 Hz	-12	-26	-25	-30	-31	-22	-26	-15	-21	-21	-29	-32	-25	-35
3000 Hz	-9	-20	-19	-23	-23	-18	-19	-8	-15	-13	-21	-21	-26	-26
4000 Hz	-12	-22	-25	-29	-26	-22	-23	-8	-12	-12	-12	-21	-26	-19
/e/														
250 Hz	-20	-38	-51	-51	-41	-33	-34	-27	-16	-28	-24	-47	-30	-47
1000 Hz	-15	-30	-37	-34	-34	-28	-27	-19	-7	-20	-21	-34	-26	-36
2000 Hz	-14	-24	-25	-29	-30	-22	-27	-16	-12	-17	-29	-32	-25	-32
3000 Hz	-14	-22	-20	-24	-23	-19	-21	-12	-14	-14	-26	-21	-25	-29
4000 Hz	-11	-21	-27	-29	-26	-20	-23	-8	-15	-11	-13	-21	-29	-21
/i/														
250 Hz	-32	-39	-52	-55	-44	-39	-37	-26	-17	-40	-29	-49	-34	-54
1000 Hz	-27	-33	-41	-47	-41	-33	-36	-25	-11	-32	-25	-36	-30	-34
2000 Hz	-24	-26	-32	-34	-34	-25	-29	-17	-11	-24	-33	-37	-27	-30
3000 Hz	-15	-22	-22	-24	-24	-20	-21	-13	-11	-16	-29	-23	-25	-29
4000 Hz	-14	-24	-26	-28	-31	-22	-24	-8	-13	-13	-16	-20	-25	-21
/o/														
250 Hz	-26	-52	-54	-57	-48	-42	-42	-24	-22	-42	-44	-56	-39	-52
1000 Hz	-23	-34	-43	-40	-42	-34	-36	-22	-15	-35	-34	-44	-33	-47
2000 Hz	-5	-15	-22	-21	-22	-15	-25	-6	-4	-11	-13	-27	-15	-18
3000 Hz	-12	-22	-21	-25	-25	-21	-20	-11	-8	-19	-26	-24	-25	-27
4000 Hz	-22	-27	-27	-30	-31	-24	-28	-15	-14	-18	-18	-24	-27	-22
/u/														
250 Hz	-23	-53	-53	-63	-47	-38	-41	-22	-24	-37	-43	-54	-38	-48
1000 Hz	-18	-34	-40	-41	-40	-33	-37	-20	-14	-30	-29	-44	-34	-42
2000 Hz	-8	-26	-29	-20	-25	-21	-26	-7	-6	-16	-16	-37	-15	-20
3000 Hz	-13	-20	-23	-25	-26	-20	-21	-14	-8	-18	-27	-23	-21	-25
4000 Hz	-16	-24	-24	-21	-27	-23	-26	-13	-16	-19	-18	-28	-23	-21

Table 7.4: Process of the sound energy of subject SS (musical) singing at 250 Hz (in dB).

frequency, it seems in most cases that differences in the left and right energy values diminish at higher frequencies (just at a certain frequency or thenceforward). In order to understand such an occurrence we focus now on the results in which the energy values show a wide difference at both measured points (see results from those which showed a difference of more than 10 dB in the energy values at the clavicles, corners of the mouth, cheeks and the lower eyelids).

Subject TF: Fundamental 250 Hz

	Chin	Throat	LC	RC	Sternum	Nose	N.Bone	LCoM	RCoM	LCh	RCh	Forehead	LLE	RLE
/a/														
250 Hz	-4	-26	-38	-36	-34	-27	-27	-6	-19	-21	-31	-41	-25	-38
1000 Hz	-3	-14	-23	-23	-23	-17	-20	-2	-17	-12	-19	-30	-21	-26
2000 Hz	-4	-17	-21	-25	-25	-16	-23	-5	-13	-13	-18	-27	-20	-25
3000 Hz	-3	-15	-17	-19	-17	-15	-15	0	-15	-9	-13	-15	-20	-22
4000 Hz	-1	-9	-10	-18	-24	-27	-23	-1	-9	-7	-11	-19	-21	-17
/e/														
250 Hz	-5	-30	-44	-46	-36	-29	-30	-5	-17	-22	-35	-42	-27	-38
1000 Hz	-4	-20	-28	-27	-28	-22	-24	-7	-16	-18	-25	-33	-25	-33
2000 Hz	-2	-14	-18	-21	-24	-15	-19	-2	-17	-10	-15	-25	-22	-24
3000 Hz	-2	-15	-17	-21	-19	-18	-17	0	-14	-10	-14	-18	-23	-24
4000 Hz	-2	-10	-13	-22	-32	-23	-24	-2	-7	-6	-10	-20	-22	-15
/i/														
250 Hz	-6	-34	-42	-43	-38	-29	-31	-15	-23	-27	-30	-42	-31	-36
1000 Hz	-5	-22	-30	-27	-28	-23	-26	-14	-25	-19	-21	-34	-28	-31
2000 Hz	-4	-16	-19	-23	-25	-17	-21	-7	-16	-11	-18	-27	-23	-26
3000 Hz	-3	-17	-20	-21	-22	-19	-20	-4	-15	-10	-16	-20	-25	-26
4000 Hz	-1	-10	-16	-20	-27	-25	-24	-5	-9	-15	-14	-24	-32	-19
/o/														
250 Hz	-11	-32	-48	-48	-42	-34	-34	-9	-16	-29	-36	-50	-32	-43
1000 Hz	-9	-26	-30	-30	-31	-25	-27	-7	-14	-24	-32	-34	-25	-35
2000 Hz	-6	-19	-22	-23	-26	-17	-20	-6	-10	-14	-17	-29	-23	-23
3000 Hz	-5	-20	-19	-21	-21	-23	-20	-4	-11	-15	-17	-20	-27	-28
4000 Hz	-9	-16	-19	-23	-33	-30	-30	-6	-9	-15	-16	-25	-29	-21
/u/														
250 Hz	-12	-33	-42	-47	-38	-30	-31	-4	-17	-25	-37	-42	-29	-36
1000 Hz	-10	-25	-29	-29	-29	-23	-25	-3	-15	-21	-28	-33	-24	-33
2000 Hz	-9	-25	-22	-24	-24	-19	-22	-6	-14	-18	-19	-26	-25	-25
3000 Hz	-5	-19	-17	-21	-20	-19	-18	0	-11	-13	-17	-18	-24	-26
4000 Hz	-5	-14	-16	-21	-31	-25	-33	0	-12	-17	-13	-22	-20	-18

Table 7.5: Process of the sound energy of subject TF (musical) singing at 250 Hz (in dB).

In many cases regarding four subjects – CH, JR SS and TF – the differences between both radiated energies will be reduced from around 2 kHz, even though there are small variations among the vowels and subjects. Likewise, the results of subject VS (both in Pop and Soul singing) showed a similar approximation of both energy values at 1–2 kHz, but after that, the difference of the radiation energy values from both corners of the mouth, which was diminishing, becomes bigger again. Such an occurrence can

Subject SE2: Fundamental 250 Hz

	Chin	Throat	LC	RC	Sternum	Nose	N.Bone	LCoM	RCoM	LCh	RCh	Forehead	LLE	RLE
/a/														
250 Hz	-7	-25	-28	-38	-36	-20	-25	-8	-17	-14	-17	-33	-30	-34
1000 Hz	-5	-18	-30	-24	-29	-17	-20	-8	-23	-12	-15	-29	-25	-22
2000 Hz	-5	-16	-15	-26	-22	-13	-16	-8	-19	-10	-12	-20	-20	-21
3000 Hz	-4	-13	-17	-22	-19	-12	-15	-5	-21	-8	-14	-20	-15	-21
4000 Hz	-6	-18	-14	-28	-20	-14	-22	-4	-14	-8	-10	-21	-16	-15
/e/														
250 Hz	-7	-22	-24	-39	-34	-18	-24	-6	-15	-12	-20	-30	-29	-27
1000 Hz	-6	-17	-32	-26	-30	-15	-17	-10	-24	-13	-15	-22	-27	-17
2000 Hz	-3	-13	-13	-25	-21	-11	-14	-6	-15	-8	-10	-17	-17	-17
3000 Hz	-2	-11	-16	-22	-16	-11	-13	-4	-16	-6	-13	-18	-13	-20
4000 Hz	-5	-12	-18	-23	-16	-9	-14	-4	-7	-6	-6	-18	-11	-9
/i/														
250 Hz	-8	-24	-24	-38	-32	-18	-23	-9	-13	-14	-14	-29	-26	-26
1000 Hz	-6	-18	-15	-13	-22	-15	-12	-11	-14	-14	-9	-16	-16	-14
2000 Hz	-5	-14	-12	-19	-17	-10	-10	-5	-17	-6	-8	-11	-12	-15
3000 Hz	-4	-13	-16	-21	-18	-12	-14	-5	-15	-9	-15	-20	-15	-21
4000 Hz	-6	-19	-16	-29	-19	-14	-20	-5	-16	-10	-11	-22	-17	-14
/o/														
250 Hz	-9	-28	-26	-39	-33	-21	-25	-5	-24	-13	-19	-32	-29	-31
1000 Hz	-6	-17	-29	-20	-27	-15	-18	-4	-21	-10	-13	-28	-22	-21
2000 Hz	-5	-16	-14	-27	-20	-14	-16	-4	-14	-8	-10	-13	-15	-18
3000 Hz	-6	-14	-14	-20	-16	-13	-13	-2	-24	-8	-16	-16	-15	-24
4000 Hz	-8	-21	-15	-27	-19	-20	-21	-2	-11	-10	-10	-21	-19	-15
/u/														
250 Hz	-13	-35	-29	-39	-35	-26	-29	-10	-25	-19	-22	-35	-33	-33
1000 Hz	-13	-27	-43	-28	-33	-23	-26	-11	-31	-18	-20	-35	-26	-27
2000 Hz	-8	-17	-18	-22	-21	-15	-16	-10	-17	-14	-16	-23	-21	-20
3000 Hz	-10	-16	-15	-22	-21	-16	-15	-5	-19	-12	-24	-21	-20	-28
4000 Hz	-10	-22	-13	-23	-18	-24	-19	-3	-16	-12	-13	-23	-24	-19

Table 7.6: Process of the sound energy of subject SE2 (Pop) singing at 250 Hz (in dB).

be also seen at the corners of the mouth in the results of subjects SE1, SE2 and TF. Furthermore, in the case of subjects SE1, TF and VS, the energy measured at the corners of the mouth reached the energy level from the mouth (0 dB) or even surpassed it at a higher frequency (see Tables 7.2, 7.5, 7.7, and 7.8).
As shown in the previous chapter, such appearances are presumably due to the fact that strong radiated area became small or was centered at a certain frequency for a while

Subject VS Pop: Fundamental 250 Hz														
	Chin	**Throat**	**LC**	**RC**	**Sternum**	**Nose**	**N.Bone**	**LCoM**	**RCoM**	**LCh**	**RCh**	**Forehead**	**LLE**	**RLE**
/a/														
250 Hz	-6	-27	-39	-33	-33	-26	-27	-6	-17	-16	-26	-39	-26	-34
1000 Hz	-5	-20	-31	-25	-28	-20	-23	-5	-15	-13	-19	-34	-24	-28
2000 Hz	-5	-17	-19	-22	-23	-16	-21	-7	-17	-10	-15	-24	-24	-26
3000 Hz	0	-10	-13	-17	-13	-18	-17	-1	-14	-13	-17	-18	-22	-23
4000 Hz	-6	-16	-15	-29	-23	-20	-24	0	-18	-7	-13	-19	-21	-25
/e/														
250 Hz	-9	-31	-40	-34	-35	-26	-28	-8	-20	-18	-25	-38	-28	-35
1000 Hz	-7	-22	-31	-25	-30	-23	-26	-8	-15	-17	-21	-37	-24	-31
2000 Hz	-6	-18	-21	-24	-24	-16	-22	-8	-16	-12	-16	-26	-22	-24
3000 Hz	-5	-15	-17	-20	-19	-16	-18	-4	-16	-10	-19	-21	-19	-29
4000 Hz	-5	-16	-16	-31	-24	-22	-26	-2	-18	-11	-14	-21	-24	-24
/i/														
250 Hz	-11	-33	-37	-34	-35	-27	-28	-14	-26	-23	-22	-37	-29	-35
1000 Hz	-9	-23	-30	-23	-36	-23	-23	-17	-16	-24	-19	-28	-26	-24
2000 Hz	-7	-19	-27	-27	-26	-18	-22	-13	-14	-14	-16	-21	-25	-27
3000 Hz	-6	-16	-17	-21	-21	-17	-20	-7	-17	-12	-20	-21	-21	-28
4000 Hz	-7	-17	-22	-38	-25	-20	-23	-5	-24	-14	-15	-20	-25	-23
/o/														
250 Hz	-13	-39	-40	-38	-35	-30	-32	-7	-18	-21	-36	-41	-29	-37
1000 Hz	-11	-26	-35	-28	-32	-25	-27	-8	-17	-21	-24	-38	-26	-32
2000 Hz	-17	-26	-25	-34	-27	-26	-28	-11	-9	-19	-26	-27	-25	-26
3000 Hz	-8	-14	-15	-19	-18	-16	-17	-3	-18	-11	-19	-19	-21	-25
4000 Hz	-10	-17	-17	-30	-25	-23	-20	0	-12	-11	-12	-20	-24	-23
/u/	Nrs.													
250 Hz														
1000 Hz														
2000 Hz														
3000 Hz														
4000 Hz														

Table 7.7: Process of the sound energy of subject VE (Pop) singing at 250 Hz (in dB, Nrs.= No results).

when the parts of the body, which were measured in pairs (i.e., symmetrically on the left and right, such as the corners of the mouth) show a reducing difference in its energy values. Furthermore, that is also because there is a relocation of the strongest energy source or an occurrence of severally equal energy sources when the higher energy value was observed from a part of the body than 0 dB.

Subject VS Soul: Fundamental 250 Hz

	Chin	Throat	LC	RC	Sternum	Nose	N.Bone	LCoM	RCoM	LCh	RCh	Forehead	LLE	RLE
/a/														
250 Hz	-11	-35	-42	-34	-36	-28	-29	-6	-21	-17	-25	-39	-26	-36
1000 Hz	-9	-23	-33	-25	-29	-22	-23	-4	-15	-14	-21	-34	-23	-29
2000 Hz	-7	-20	-21	-24	-24	-17	-22	-5	-16	-11	-17	-25	-21	-30
3000 Hz	-8	-15	-15	-19	-20	-13	-15	-1	-18	-6	-18	-18	-17	-27
4000 Hz	-9	-18	-17	-31	-23	-23	-22	0	-15	-9	-12	-19	-19	-24
/e/														
250 Hz	-13	-41	-45	-36	-38	-30	-31	-8	-18	-19	-32	-42	-28	-39
1000 Hz	-13	-28	-32	-25	-33	-25	-23	-10	-15	-18	-26	-32	-25	-29
2000 Hz	-9	-20	-21	-23	-24	-18	-23	-8	-16	-12	-18	-27	-23	-26
3000 Hz	-7	-15	-15	-19	-20	-17	-18	-3	-16	-11	-22	-20	-22	-28
4000 Hz	-10	-19	-21	-37	-25	-22	-21	-2	-16	-13	-13	-20	-23	-23
/i/														
250 Hz	-14	-43	-40	-27	-37	-31	-31	-15	-19	-25	-27	-40	-31	-41
1000 Hz	-15	-26	-28	-17	-25	-24	-25	-15	-14	-26	-23	-28	-25	-29
2000 Hz	-9	-19	-20	-23	-26	-17	-18	-13	-16	-16	-16	-29	-24	-21
3000 Hz	-9	-17	-17	-21	-23	-17	-19	-6	-13	-12	-24	-22	-21	-32
4000 Hz	-10	-19	-23	-32	-23	-21	-22	-4	-18	-13	-15	-19	-26	-26
/o/														
250 Hz	-14	-42	-43	-36	-37	-31	-31	-4	-19	-22	-31	-41	-28	-38
1000 Hz	-11	-24	-33	-25	-29	-23	-25	-3	-14	-19	-24	-37	-25	-31
2000 Hz	-12	-31	-17	-21	-22	-23	-21	-5	-12	-20	-21	-22	-27	-27
3000 Hz	-7	-14	-14	-18	-17	-15	-16	0	-17	-11	-18	-18	-20	-25
4000 Hz	-11	-15	-17	-24	-23	-19	-18	0	-11	-19	-11	-22	-21	-18
/u/														
250 Hz	-30	-48	-46	-41	-41	-35	-35	-10	-15	-30	-37	-44	-32	-43
1000 Hz	-27	-34	-44	-37	-36	-33	-36	-12	-14	-29	-37	-36	-28	-33
2000 Hz	-23	-24	-19	-25	-41	-21	-22	-10	-12	-19	-18	-26	-26	-21
3000 Hz	-11	-23	-16	-21	-17	-20	-18	-3	-12	-10	-26	-19	-21	-36
4000 Hz	-18	-23	-25	-23	-16	-28	-22	-2	-7	-13	-11	-14	-18	-27

Table 7.8: Process of the sound energy of subject VS (Soul) singing at 250 Hz (in dB).

However, in total, we can recognize that the radiated energy is always in a fluctuation and that such a distinction may occur at a higher frequency also in the cases where no large difference in the energy value was shown at the fundamental frequency.

Fluctuation of Radiation Energy in Frequency Range

When looking at the results of all the subjects singing the vowels /a/o/u/e/i/ at a glance, the findings of most of the subjects revealed that the radiated energy varies strongly at the throat, sternum, clavicles and the forehead (see results with yellow marks. As already mentioned, only the locations, where great fluctuations of more than 10 dB were found, are color-coded). Of course, concerned parts where such powerful fluctuations happen differ more or less from vowel to vowel. But it seems that strong changes of radiated energy often occurred rather at the parts of the body which are located far from the mouth than at the parts near the mouth.
However, this fact is independent of vowels that are sung. By focusing on the parts concerned, we can see for the vowels /o/ and /u/ that the parts of the body which are located near the mouth are also involved and that a distinction among the subjects is clearly recognizable there, when it comes to the parts concerned and the intensity of the fluctuation occurring. For example, the findings of subjects CH and SS as well as subject VS (Soul singing) for the vowels /o/ and /u/ (VS for the vowel /u/ only) differ widely from that of all the other subjects. In their cases, almost all of the parts of the body are involved, although the affected frequencies are different between them (this topic will be discussed later). Therefore, the results for the vowels /o/ and /u/ differ strongly from those for the vowels /a/e/i/. For the rest, there was no large difference among vowels and singers at that point. Therefore, the results for the vowels /a/ and /o/ of subject TF are a little bit different than for the other vowels which he sang.

By the energy value with color marks we can understand thus far that the radiation energy is inconstantly in a fluctuation, especially for the vowels /o/ and /u/, but it is not yet clear whether the changes are caused from an increase or a decrease of the energy. In conclusion, in most cases, the radiated energy increases between 250 Hz and 3000 Hz and decreases between 3000 Hz and 4000 Hz for all the vowels. This holds true particularly for the subjects TF, SE2, VS (both in Pop and Soul singing), but for the rest there are small variations: In the case of the vowels /o/ and /u/, the results of three female singers, CH, SE1 (for the vowel /u/ only) and SS, showed a mix of increase and decrease between 250 Hz and 3000 Hz. But in the frequency range between 3000 Hz and 4000 Hz, their results indicated a decrease of the radiated energy, just like the other subjects. The latter finding is applicable to what was already predicated above. But the research finding of subjects JR and SS (for the vowels /e/ and /i/ only) revealed just increasing energy in the whole frequency range that was analyzed. This is an interesting result.

In the tables displayed, the energy values which increase or decrease more than 10 dB compared to the energy value at the previous or subsequent frequency are color-coded in yellow, but in fact, there are also the fluctuations of the radiated energy which increased or decreased more than 20 dB. Such a finding exists in the case of the vowel /u/ between 2000 Hz and 3000 Hz sung by CH (at the right clavicle, nose, nasal bone and the right lower eyelid) as well as in the cases of the vowels /o/ and /u/ at some parts (most of them are located between 1000 Hz and 2000 Hz). This is noteworthy, however, because these are usually the parts from where weaker radiation energy comes, compared to the chin or the corners of the mouth.

As shown in the results of this case study, radiation energy of the singing voice is always in a fluctuation. It is interesting to note that the difference of the radiated energy among the subjects was decreasing at higher frequencies, even though a low energy value was shown at the fundamental frequency, for example at the throat. Such a phenomenon occurs whereby the radiated value of the subjects such as SS and JR, who actually revealed low energy values at the fundamental frequency, powerfully increased in the higher frequency range, as the sound levels measured at 14 parts of the upper body showed in the previous chapter (see the results of SS and JR in Figure 6.8 as an example). When it comes to the range of the radiated energy, it will be shown in Chapter 7.3.

7.1.2 Case of 500 Hz (B4)

Secondly, the results of the measurement at 500 Hz sung by all female singers will be displayed here (see Tables 7.9, 7.10, 7.11 ,7.12, 7.13, and 7.14). The results are analyzed at six frequencies – 500 Hz, 1000 Hz, 2000 Hz, 3000 Hz, 4000 Hz and at 5000 Hz.

Radiated Energy Value

The measured parts of the body which displayed the strongest radiation energy are the chin and the corners of the mouth (except for the vowel /u/ of CH), so just as in the

Subject CH: Fundamental 500 Hz

	Chin	Throat	LC	RC	Sternum	Nose	N.Bone	LCoM	RCoM	LCh	RCh	Forehead	LLE	RLE
/a/														
500 Hz	-9	-15	-11	-16	-27	-24	-17	-18	-6	-14	-22	-12	-19	-16
1000 Hz	-11	-18	-15	-16	-26	-24	-20	-15	-7	-15	-19	-18	-20	-17
2000 Hz	-16	-26	-23	-32	-33	-38	-35	-23	-13	-32	-40	-31	-34	-32
3000 Hz	-9	-16	-18	-15	-17	-18	-18	-6	-9	-17	-13	-18	-23	-20
4000 Hz	-8	-14	-19	-26	-24	-18	-37	-7	-15	-15	-15	-20	-28	-21
5000 Hz	-7	-7	-12	-23	-16	-13	-23	-17	-8	-16	-20	-13	-29	-12
/e/														
500 Hz	-10	-16	-11	-17	-29	-26	-19	-16	-10	-14	-24	-13	-20	-18
1000 Hz	-9	-18	-16	-19	-30	-25	-23	-13	-8	-15	-23	-20	-22	-19
2000 Hz	-12	-24	-15	-18	-20	-21	-19	-10	-9	-19	-16	-18	-21	-26
3000 Hz	-12	-19	-19	-17	-17	-20	-20	-8	-8	-19	-15	-19	-24	-24
4000 Hz	-15	-27	-20	-24	-25	-18	-21	-15	-5	-17	-13	-19	-28	-19
5000 Hz	-8	-10	-13	-29	-18	-17	-21	-13	-9	-14	-23	-17	-29	-19
/i/														
500 Hz	-9	-15	-10	-16	-28	-24	-18	-19	-7	-14	-24	-12	-20	-17
1000 Hz	-10	-18	-19	-20	-32	-26	-24	-26	-8	-17	-27	-22	-23	-19
2000 Hz	-9	-23	-15	-19	-20	-20	-20	-9	-9	-18	-14	-19	-20	-25
3000 Hz	-7	-17	-18	-16	-18	-19	-20	-8	-7	-17	-12	-22	-20	-24
4000 Hz	-8	-13	-15	-25	-19	-17	-28	-9	-11	-14	-10	-16	-31	-20
5000 Hz	-5	-10	-14	-31	-18	-15	-20	-12	-7	-17	-18	-16	-26	-15
/o/														
500 Hz	-14	-20	-14	-20	-20	-31	-22	-24	-11	-22	-27	-16	-24	-21
1000 Hz	-14	-21	-22	-21	-32	-28	-25	-23	-11	-24	-26	-23	-25	-21
2000 Hz	-15	-20	-17	-24	-24	-24	-28	-12	-11	-21	-19	-22	-25	-23
3000 Hz	-14	-20	-20	-17	-19	-20	-18	-11	-8	-23	-18	-19	-24	-22
4000 Hz	-13	-17	-13	-21	-23	-25	-30	-11	-9	-17	-18	-24	-26	-17
5000 Hz	-12	-18	-17	-32	-23	-21	-26	-17	-11	-16	-25	-19	-24	-18
/u/														
500 Hz	-33	-25	-19	-24	-37	-37	-26	-21	-17	-29	-29	-21	-28	-25
1000 Hz	-15	-27	-26	-27	-41	-42	-32	-19	-10	-24	-33	-29	-32	-25
2000 Hz	-21	-30	-39	-42	-41	-31	-40	-22	-21	-26	-27	-39	-33	-32
3000 Hz	-30	-28	-28	-35	-30	-36	-37	-34	-20	-36	-43	-29	-39	-37
4000 Hz	-23	-31	-40	-39	-39	-32	-40	-23	-23	-30	-30	-39	-34	-33
5000 Hz	-24	-23	-25	-40	-27	-30	-33	-33	-20	-26	-32	-23	-44	-25

Table 7.9: Process of the sound energy of subject CH (classical) singing at 500 Hz (in dB).

case of 250 Hz. However, when it comes to radiated energy, there was a great difference among the singers. For example, the energy values of subject SE2 are everywhere clearly

Subject SE1: Fundamental 500 Hz

	Chin	Throat	LC	RC	Sternum	Nose	N.Bone	LCoM	RCoM	LCh	RCh	Forehead	LLE	RLE
/a/														
500 Hz	-3	-9	-20	-17	-17	-12	-14	-2	-16	-8	-15	-22	-19	-19
1000 Hz	-2	-9	-27	-16	-21	-12	-17	-2	-24	-8	-17	-27	-26 -	-21
2000 Hz	-2	-9	-13	-18	-16	-10	-14	-4	-13	-7	-11	-17	-16	-19
3000 Hz	-2	-9	-14	-13	-14	-10	-15	0	-12	-5	-9	-19	-12	-18
4000 Hz	-4	-10	-10	-15	-15	-16	-23	1	-10	-5	-7	-15	-15	-16
5000 Hz	0	2	-13	0	-10	2	-8	4	0	0	-5	-7	-2	-5
/e/														
500 Hz	-3	-11	-23	-20	-20	-15	-17	-2	-34	-10	-20	-25	-24	-23
1000 Hz	-2	-9	-30	-19	-25	-14	-21	-3	-31	-9	-17	-32	-29	-22
2000 Hz	-1	-7	-11	-17	-15	-10	-14	-2	-19	-6	-12	-16	-15	-19
3000 Hz	-1	-8	-13	-13	-13	-11	-14	0	-23	-6	-13	-19	-13	-22
4000 Hz	-4	-11	-13	-18	-20	-16	-29	0	-19	-6	-10	-17	-18	-18
5000 Hz	-1	-11	-19	-16	-17	-10	-16	2	-3	-3	-11	-15	-14	-15
/i/														
500 Hz	-3	-10	-20	-18	-17	-13	-15	0	-21	-7	-18	-22	-21	-21
1000 Hz	-5	-11	-38	-22	-27	-14	-24	-6	-20	-8	-20	-28	-23	-22
2000 Hz	-2	-8	-11	-16	-15	-10	-13	0	-21	-4	-13	-16	-14	-20
3000 Hz	-2	-9	-14	-14	-14	-11	-15	0	-19	-4	-14	-18	-12	-23
4000 Hz	-5	-11	-13	-18	-17	-15	-22	1	-16	-6	-9	-16	-15	-20
5000 Hz	-3	-16	-10	-16	-14	-9	-13	1	-3	-2	-8	-18	-12	-13
/o/														
500 Hz	-4	-13	-23	-20	-20	-16	-17	0	-24	-9	-20	-20	-25	-23
1000 Hz	-4	-14	-35	-19	-25	-16	-21	-1	-23	-10	-20	-36	-25	-24
2000 Hz	-7	-17	-20	-21	-22	-16	-21	-5	-18	-12	-17	-23	-22	-22
3000 Hz	-3	-11	-15	-13	-15	-12	-14	0	-17	-6	-13	-18	-14	-22
4000 Hz	-7	-11	-12	-19	-20	-20	-22	1	-13	-7	-9	-16	-17	-20
5000 Hz	-3	-11	-15	-15	-12	-10	-12	0	-14	-6	-11	-15	-9	-11
/u/														
500 Hz	-4	-12	-21	-19	-18	-15	-16	0	-31	-9	-20	-23	-23	-22
1000 Hz	-4	-13	-33	-18	-25	-15	-21	-1	-27	-10	-19	-36	-26	-23
2000 Hz	-7	-15	-16	-21	-20	-16	-19	-4	-10	-15	-17	-20	-22	-23
3000 Hz	-3	-10	-14	-13	-14	-12	-14	0	-20	-6	-13	-17	-14	-23
4000 Hz	-7	-12	-11	-16	-17	-27	-24	1	-12	-7	-9	-16	-18	-22
5000 Hz	-1	-12	-17	-14	-25	-14	-11	0	-12	-4	-17	-25	-11	-10

Table 7.10: Process of the sound energy of subject SE1 (classical) singing at 500 Hz (in dB).

much stronger than those of subject SS.

The difference of the radiated energy value between both vowels, /o/ and /u/, and the

Subject SS: Fundamental 500 Hz

	Chin	Throat	LC	RC	Sternum	Nose	N.Bone	LCoM	RCoM	LCh	RCh	Forehead	LLE	RLE
/a/														
500 Hz	-13	-29	-34	-38	-34	-31	-28	-20	-24	-23	-30	-40	-30	-40
1000 Hz	-12	-27	-36	-32	-34	-26	-28	-21	-17	-22	-33	-38	-28	-39
2000 Hz	-18	-30	-31	-35	-36	-26	-30	-16	-13	-33	-32	-34	-26	-31
3000 Hz	-10	-20	-21	-23	-25	-18	-21	-12	-17	-13	-21	-21	-24	-28
4000 Hz	-8	-16	-21	-29	-29	-17	-30	-8	-15	-11	-15	-21	-22	-19
5000 Hz	-9	-17	-22	-21	-18	-15	-11	-5	-10	-7	-17	-18	-16	-12
/e/														
500 Hz	-13	-33	-36	-43	-36	-30	-30	-27	-24	-23	-32	-41	-34	-41
1000 Hz	-12	-26	-39	-32	-35	-25	-29	-21	-19	-22	-30	-38	-27	-38
2000 Hz	-11	-24	-23	-30	-33	-20	-24	-16	-19	-18	-22	-29	-26	-31
3000 Hz	-9	-20	-21	-23	-25	-18	-21	-13	-16	-13	-23	-22	-23	-31
4000 Hz	-8	-16	-21	-29	-29	-15	-32	-7	-20	-11	-18	-21	-20	-20
5000 Hz	-9	-17	-22	-21	-18	-15	-11	-5	-10	-7	-17	-18	-16	-12
/i/														
500 Hz	-12	-31	-33	-43	-34	-27	-27	-19	-24	-19	-30	-38	-34	-37
1000 Hz	-14	-36	-52	-41	-42	-28	-39	-14	-15	-25	-28	-39	-26	-48
2000 Hz	-9	-21	-22	-28	-29	-18	-23	-15	-19	-15	-19	-28	-24	-26
3000 Hz	-10	-20	-22	-24	-26	-17	-21	-11	-14	-13	-23	-23	-22	-26
4000 Hz	-8	-16	-21	-29	-31	-16	-30	-8	-21	-11	-17	-20	-22	-21
5000 Hz	-7	-14	-17	-24	-17	-11	-15	-5	-12	-10	-15	-19	-11	-19
/o/														
500 Hz	-30	-39	-44	-50	-44	-42	-38	-26	-18	-38	-37	-50	-39	-52
1000 Hz	-27	-34	-46	-39	-42	-35	-37	-23	-17	-36	-35	-45	-35	-43
2000 Hz	-25	-31	-33	-35	-37	-29	-33	-29	-34	-29	-30	-36	-33	-32
3000 Hz	-9	-18	-22	-24	-25	-17	-20	-8	-9	-17	-20	-23	-25	-23
4000 Hz	-16	-26	-28	-31	-34	-25	-27	-12	-16	-18	-21	-24	-39	-23
5000 Hz	-28	-36	-35	-36	-33	-30	-30	-23	-22	-28	-27	-33	-33	-30
/u/														
500 Hz	-21	-42	-45	-54	-45	-40	-40	-22	-18	-44	-34	-51	-42	-53
1000 Hz	-23	-32	-46	-38	-41	-32	-35	-19	-17	-39	-35	-42	-31	-46
2000 Hz	-14	-24	-30	-32	-34	-23	-29	-14	-15	-19	-22	-33	-27	-27
3000 Hz	-14	-22	-21	-24	-25	-21	-21	-13	-10	-18	-23	-23	-27	-27
4000 Hz	-19	-26	-28	-30	-33	-22	-26	-13	-16	-17	-20	-23	-30	-22
5000 Hz	-25	-29	-32	-28	-28	-25	-21	-20	-20	-21	-22	-28	-29	-26

Table 7.11: Process of the sound energy of subject SS (musical) signing at 500 Hz (in dB, female subject).

other vowels, which was clearly recognizable in the case of 250 Hz, cannot be found for each of the subjects singing at 500 Hz. Only singers CH and SS radiated distinctly

Subject SE2: Fundamental 500 Hz

	Chin	Throat	LC	RC	Sternum	Nose	N.Bone	LCoM	RCoM	LCh	RCh	Forehead	LLE	RLE
/a/														
500 Hz	-3	-10	-18	-18	-19	-11	-12	-5	-4	-9	-9	-20	-16	-13
1000 Hz	-2	-9	-20	-14	-18	-9	-12	-6	-5	-8	-5	-19	-17	-11
2000 Hz	-2	-8	-12	-18	-19	-7	-12	-6	-5	-6	-4	-14	-13	-11
3000 Hz	-2	-9	-15	-20	-14	-8	-11	-4	-4	-5	-6	-15	-10	-12
4000 Hz	-2	-9	-17	-18	-23	-13	-15	-4	-1	-5	-3	-15	-12	-7
5000 Hz	-2	-14	-15	-16	-16	-11	-11	-10	-2	-8	-6	-22	-9	-7
/e/														
500 Hz	-3	-11	-17	-21	-19	-10	-12	-3	-8	-7	-8	-19	-16	-14
1000 Hz	-2	-9	-21	-15	-20	-9	-12	-6	-8	-8	-6	-20	-17	-12
2000 Hz	-2	-9	-11	-20	-17	-8	-11	-5	-8	-6	-6	-13	-12	-13
3000 Hz	-2	-8	-14	-20	-14	-8	-10	-3	-7	-5	-7	-16	-10	-14
4000 Hz	-2	-12	-14	-16	-15	-9	-13	-2	-3	-4	-4	-15	-10	-8
5000 Hz	-1	-5	-11	-18	-12	-4	-8	-2	-2	-5	-4	-12	-10	-8
/i/														
500 Hz	-3	-12	-16	-22	-19	-11	-13	-3	-9	-8	-8	-19	-16	-15
1000 Hz	-3	-11	-26	-18	-24	-10	-15	-7	-9	-10	-7	-22	-20	-13
2000 Hz	-2	-9	-10	-20	-16	-8	-10	-4	-7	-5	-6	-13	-12	-13
3000 Hz	0	-6	-13	-17	-12	-8	-10	-3	-8	-5	-9	-16	-10	-15
4000 Hz	-4	-15	-16	-22	-19	-13	-19	-6	-8	-9	-8	-20	-16	-11
5000 Hz	-2	-7	-18	-20	-13	-4	-7	-2	0	-5	-2	-13	-7	-9
/o/														
500 Hz	-3	-13	-18	-21	-20	-13	-14	-3	-9	-9	-9	-22	-17	-17
1000 Hz	-2	-10	-22	-16	-20	-10	-13	-5	-8	-8	-7	-21	-18	-13
2000 Hz	-5	-13	-15	-27	-24	-12	-18	-11	-13	-11	-10	-17	-21	-17
3000 Hz	-3	-11	-15	-21	-16	-10	-13	-5	-8	-7	-9	-17	-13	-16
4000 Hz	-5	-16	-17	-23	-20	-17	-20	-6	-12	-9	-11	-22	-16	-13
5000 Hz	-2	-12	-16	-22	-26	-13	-15	-2	-6	-6	-8	-26	-23	-16
/u/														
500 Hz	-6	-16	-19	-26	-22	-15	-16	-5	-11	-10	-11	-22	-21	-19
1000 Hz	-5	-15	-26	-19	-24	-13	-16	-7	-11	-10	-9	-23	-20	-16
2000 Hz	-4	-13	-13	-19	-20	-10	-14	-7	-10	-8	-8	-15	-15	-14
3000 Hz	-5	-12	-15	-22	-15	-10	-13	-4	-9	-7	-11	-15	-13	-16
4000 Hz	-6	-15	-17	-22	-21	-15	-20	-5	-12	-10	-13	-20	-15	-14
5000 Hz	-1	-14	-8	-10	-18	-14	-12	-7	-6	-13	-9	-14	-8	-6

Table 7.12: Process of the sound energy of subject SE2 (Pop) singing at 500 Hz (in dB).

weaker for the vowels /o/ and /u/ (CH for the vowel /u/ only) than for the rest of the vowels. For example the energy value of CH, measured at the chin for the vowel /u/, is

Subject VS Pop: Fundamental 500 Hz

	Chin	Throat	LC	RC	Sternum	Nose	N.Bone	LCoM	RCoM	LCh	RCh	Forehead	LLE	RLE
/a/														
500 Hz	-6	-20	-26	-25	-24	-20	-20	-3	-20	-11	-20	-30	-24	-28
1000 Hz	-7	-19	-29	-23	-27	-18	-21	-4	-15	-10	-18	-32	-22	-27
2000 Hz	-3	-13	-17	-20	-22	-13	-20	-3	-22	-6	-12	-23	-21	-26
3000 Hz	-3	-13	-14	-18	-18	-17	-19	0	-16	-6	-21	-24	-18	-40
4000 Hz	-6	-21	-15	-33	-20	-20	-29	0	-14	-6	-12	-21	-16	-19
5000 Hz	0	-4	-9	-24	-12	-7	-15	4	-20	-1	-11	-23	-9	-20
/e/														
500 Hz	-9	-26	-29	-29	-27	-24	-24	-4	-18	-14	-27	-32	-31	-32
1000 Hz	-10	-24	-35	-27	-32	-23	-27	-8	-15	-15	-25	-35	-23	-31
2000 Hz	-4	-16	-18	-20	-20	-14	-18	-3	-16	-8	-13	-23	-20	-24
3000 Hz	-7	-16	-16	-20	-20	-16	-18	-3	-15	-8	-22	-22	-20	-33
4000 Hz	-9	-20	-18	-33	-24	-18	-22	0	-17	-8	-13	-19	-18	-20
5000 Hz	-5	-11	-16	-27	-22	-11	-15	0	-20	-4	-28	-23	-14	-29
/i/														
500 Hz	-9	-24	-27	-28	-26	-22	-22	-4	-19	-13	-24	-30	-32	-30
1000 Hz	-12	-27	-38	-30	-32	-24	-31	-10	-15	-14	-25	-34	-22	-32
2000 Hz	-3	-14	-19	-19	-21	-12	-18	-1	-13	-7	-11	-24	-16	-21
3000 Hz	-6	-16	-17	-19	-21	-15	-18	-2	-18	-8	-20	-21	-19	-33
4000 Hz	-11	-15	-19	-30	-19	-14	-23	-1	-14	-12	-11	-19	-14	-17
5000 Hz	-3	-8	-15	-24	-16	-10	-15	1	-21	-3	-16	-28	-11	-22
/o/														
500 Hz	-13	-29	-31	-29	-29	-28	-25	-2	-14	-12	-32	-35	-24	-34
1000 Hz	-12	-23	-31	-26	-29	-24	-24	-3	-11	-13	-27	-34	-21	-31
2000 Hz	-20	-33	-34	-33	-50	-32	-32	-23	-10	-16	-24	-36	-21	-30
3000 Hz	-4	-14	-12	-17	-18	-14	-16	1	-22	-4	-17	-17	-19	-28
4000 Hz	-12	-28	-17	-28	-20	-24	-20	1	-12	-8	-11	-19	-17	-21
5000 Hz	-8	-11	-16	-25	-31	-23	-30	-2	-20	-11	-42	-23	-26	-26
/u/	Nrs.													
500 Hz														
1000 Hz														
2000 Hz														
3000 Hz														
4000 Hz														
5000 Hz														

Table 7.13: Process of the sound energy of subject VS (Pop) singing at 500 Hz (in dB, Nrs.= No results).

up to four times weaker in comparison to the other vowels. But for the other subjects, as already mentioned, there was no such wide difference in sung vowels, so that all the

VS Soul: Fundamental 500 Hz

	Chin	Throat	LC	RC	Sternum	Nose	N.Bone	LCoM	RCoM	LCh	RCh	Forehead	LLE	RLE
/a/														
500 Hz	-11	-26	-29	-29	-27	-26	-23	-2	-14	-11	-28	-33	-25	-34
1000 Hz	-10	-22	-31	-26	-29	-23	-24	-3	-12	-13	-23	-35	-21	-31
2000 Hz	-7	-13	-13	-18	-15	-15	-16	0	-14	-5	-21	-17	-20	-31
3000 Hz	-7	-13	-13	-18	-16	-14	-17	0	-15	-5	-20	-18	-19	-39
4000 Hz	-13	-22	-15	-28	-20	-22	-20	3	-13	-6	-11	-17	-16	-22
5000 Hz	-5	-7	-14	-17	-12	-11	-31	3	-14	0	-23	-19	-13	-16
/e/														
500 Hz	-13	-31	-33	-32	-31	-29	-27	-7	-16	-17	-31	-36	-31	-36
1000 Hz	-14	-26	-36	-28	-33	-26	-28	-8	-14	-17	-26	-37	-24	-33
2000 Hz	-10	-21	-20	-24	-24	-18	-22	-8	-13	-11	-19	-26	-22	-27
3000 Hz	-13	-20	-19	-22	-22	-18	-18	-5	-11	-10	-25	-20	-21	-39
4000 Hz	-11	-17	-27	-28	-26	-16	-21	-3	-16	-18	-16	-22	-25	-26
5000 Hz	-11	-17	-21	-29	-29	-18	-19	-5	-14	-11	-26	-26	-22	-30
/i/														
500 Hz	-15	-35	-35	-35	-33	-33	-29	-11	-16	-22	-33	-38	-34	-39
1000 Hz	-19	-36	-39	-35	-38	-33	-36	-14	-13	-22	-35	-40	-24	-42
2000 Hz	-10	-22	-22	-25	-25	-19	-24	-9	-13	-13	-19	-27	-23	-28
3000 Hz	-13	-20	-19	-22	-22	-18	-18	-5	-11	-10	-25	-20	-21	-39
4000 Hz	-11	-17	-27	-28	-26	-16	-21	-3	-16	-18	-16	-22	-25	-26
5000 Hz	-11	-17	-21	-29	-29	-18	-19	-5	-14	-11	-26	-26	-22	-30
/o/														
500 Hz	-15	-31	-32	-32	-30	-30	-27	-3	-15	-17	-33	-36	-28	-36
1000 Hz	-16	-26	-34	-28	-32	-25	-26	-4	-12	-16	-27	-36	-23	-32
2000 Hz	-15	-23	-21	-28	-20	-20	-25	-1	-8	-13	-21	-25	-27	-30
3000 Hz	-10	-15	-14	-19	-18	-14	-15	0	-15	-7	-20	-17	-20	-29
4000 Hz	-13	-25	-19	-34	-22	-27	-20	0	-10	-9	-11	-19	-20	-22
5000 Hz	-9	-11	-17	-24	-20	-14	-21	0	-17	-6	-26	-21	-17	-21
/u/	Nrs.													
500 Hz														
1000 Hz														
2000 Hz														
3000 Hz														
4000 Hz														
5000 Hz														

Table 7.14: Process of the sound energy of subject VS (Soul) singing at 500 Hz (in dB, Nrs.= No results).

energy measured at a point (frequency) revealed almost a similar level for all the vowels.

In addition, when it comes to the comparison of the radiated energy gained from both measurements at 250 Hz and 500 Hz, the radiated energy measured at 500 Hz was stronger in total than the results of 250 Hz. This phenomenon was shown for all subjects, vowels and parts of the body, but especially the radiation energy of SE2 surged strongly. Such an increase of the radiation energy appeared strongly at the parts of the body which are locate rather far from the mouth, such as the throat, clavicles, sternum, nose, nasal bone and the forehead. Of course, the parts concerned vary a lot from vowel to vowel as well as from singer to singer, however, the energy values of these parts often show an increase of more than 10 dB in comparison to the radiated energy measured at 250 Hz.

When it is about the difference in the energy value of the two points where the energy was measured separately at the left and right side (the clavicles, corners of the mouth, cheeks and the lower eyelids), we can also see here a reduction of the difference between their energy values at higher frequencies (in most cases from around 2–3 kHz, just like the results of 250 Hz, see Subsection 7.1.1). The radiation energy level from the corners of the mouth was occasionally even stronger than that from the mouth (see red marked energy values in Tables 7.10, 7.13, and 7.14). In the case of VS, both in Pop and Soul singing, the middle of her radiated energy shifted to the left side of the mouth, as shown in Subsection 6.2.1 of the previous chapter. But in the case of SE1, there was a similar finding with a shifting (see Figure 6.21) plus a number of strong energy sources that showed higher radiation energy than at the mouth, such as the results shown in Figures 6.14 and 6.19 – for example, from the throat and the nose of SE1 measured at 5000 Hz for the vowel /a/ (see Table 7.10). However, in fact, all measured parts of her body revealed extreme high energy levels at this partial.

Fluctuation of Radiation Energy in Frequency Range

When we take a look at the color-coded energy values in the tables, it can be seen that there were large variations in the radiated energy of most of the singers also at 500 Hz. The parts involved are often, as the parts in the results at 250 Hz, the throat, clavicles, sternum, nose, nasal bone and the forehead. Especially in the case of both vowels /a/ and /u/ sung by CH as well as for the vowels /i/ and /o/ sung by SS and VS (Pop), their radiated energy paced up and down at many parts of the body at certain frequencies, but some of these radiation energies measured are continually in a fluctuation in the whole frequency range analyzed. For example, VS (Pop) often revealed up-and-down movements with a difference of about 20 dB or more than this value in radiated energy for the vowel /o/.

Looking at individual results, the only subject who hardly showed such a change in radiation energy is SE2, and this is presumably because her radiated energy at 500 Hz was very strong everywhere, so that her weakest value was still under 30 dB, whereas it was measured between around 30 dB and 55 dB for all the rest of the subjects. Generally, when radiated energy is high at the fundamental, such a great fluctuation was not shown in this study. For this reason, no large fluctuation of radiated energy over 10 dB was less observed at the chin and the corners of the mouth than at all the other parts of the body. This is also why the radiated energy value of SS, who showed no high energy level at the fundamental frequency, will be ranked similar as the radiation energy of SE2 at higher frequencies.

In terms of the question where an increase and a decrease of each of the radiated energy happen in the frequency range, in the case of the sung pitch at 500 Hz, it is somewhat difficult to give a precise answer, because several differences exist in the results of 500 Hz in comparison to the results of 250 Hz. But in summary, it can be said that for the vowels /a/e/i/o/, in most cases (i.e., except CH for the vowel /a/ and SS for all vowels), the radiation energy first decreased in the frequency range 500 Hz – 1000 Hz. But after that, this energy increased in the frequency range 1000 Hz – 2000 Hz, whereas the energy of the vowel /u/ only decreased in both frequency ranges. In the frequency range between 2000 Hz and 3000 Hz all the results were more or less different among the subjects, as well as among the vowels for each person. This means that one revealed an increase but the other one showed decreasing energy, even though the difference of energy values between 2000 Hz and 3000 Hz was actually small in either case. In both frequency ranges, 3000 Hz – 4000 Hz and 4000 Hz – 5000 Hz, the fluctuations in the result seem to be rather consistent again: decreased values in the former frequency range (except SE2 for the vowels /a/e/i/ and VS (Soul) for all vowels, because their results indicated a mix) and increased values in the latter frequency range (except SS and VS (Pop) for the vowel /o/).

7.1.3 Case of 180 Hz (F3#)

The results of the measurement at 180 Hz sung by alto and mezzo soprano singers will be displayed here (see Tables 7.15, 7.16, 7.17, and 7.18). In this case study, subject VS sang just using one singing technique which was self-defined as "Pop."
All the results are analyzed here at five frequencies – 180 Hz, 1000 Hz, 2000 Hz, 2500 Hz, and at 3000 Hz.

Radiated Energy Value

The fact that the chin and the corners of the mouth are the strongest points of radiation energy holds true for this study case as well. When it comes to the question "which singer radiates most strongly," in this case, the answer is subject CH, even though there are a few exceptions. The difference between her radiation energy and the energy of all the others can be clearly found at the chin, throat, clavicles and at the forehead, but just as in the previous case studies, such a difference among the singers became smaller at higher frequencies.

When we look at the results gained by each subject individually, the following differences in the results occur: the vowel /o/ sung by CH radiated remarkably weakly everywhere at the fundamental frequency (180 Hz) compared to the other vowels. The radiated energy of SE2 also showed distinctly low energy at the chin and the throat for this vowel. When it comes to the results for SS, it can be seen that her radiation energy of the vowel /e/ is strongest at the fundamental frequency, but, for all the other vowels, each part of the body indicated similar energy values, except that there was a difference in energy value at the chin, throat and at the clavicles (weak for the vowel /u/). Likewise for subject VS, no large difference in vowels was shown at each part of the body, so that such a difference was recognized only at the chin, throat and at the corners of the mouth (low values) for the vowel /i/ as well as at the sternum and the forehead (strong values at the fundamental frequency, however hardly any difference at higher frequencies) for the vowel /a/.

From all these results of the case of 180 Hz, we can see that there are more differences in the results among the sung vowels at lower pitch than at higher pitch. In the case of 250 Hz, it was shown that both vowels /o/ and /u/ radiate generally more weakly

Subject CH: Fundamental 180 Hz

	Chin	Throat	LC	RC	Sternum	Nose	N.Bone	LCoM	RCoM	LCh	RCh	Forehead	LLE	RLE
/a/														
180 Hz	-9	-16	-14	-20	-38	-32	-22	-24	-8	-18	-28	-16	-23	-20
1000 Hz	-12	-19	-18	-16	-25	-24	-19	-14	-8	-19	-19	-18	-20	-18
2000 Hz	-15	-29	-20	-20	-23	-22	-22	-11	-11	-28	-17	-20	-23	-27
2500 Hz	-9	-18	-18	-15	-20	-17	-17	-13	-11	-22	-14	-18	-25	-20
3000 Hz	-8	-16	-18	-16	-17	-17	-17	-10	-15	-19	-15	-19	-23	-18
/e/														
180 Hz	-9	-16	-14	-20	-40	-33	-22	-27	-8	-18	-28	-17	-23	-20
1000 Hz	-14	-23	-24	-19	-28	-25	-23	-14	-10	-22	-20	-27	-21	-22
2000 Hz	-11	-25	-16	-18	-21	-21	-20	-11	-9	-23	-16	-19	-23	-28
2500 Hz	-11	-19	-18	-16	-20	-18	-18	-12	-10	-26	-16	-20	-26	-22
3000 Hz	-10	-18	-18	-18	-18	-18	-17	-9	-9	-20	-17	-20	-24	-20
/i/														
180 Hz	-8	-16	-14	-20	-37	-33	-23	-26	-7	-20	-27	-17	-24	-21
1000 Hz	-8	-19	-15	-18	-27	-30	-25	-18	-7	-24	-22	-21	-25	-19
2000 Hz	-9	-26	-24	-20	-22	-21	-22	-10	-10	-25	-14	-21	-24	-27
2500 Hz	-7	-19	-20	-15	-20	-19	-17	-17	-10	-23	-13	-19	-25	-22
3000 Hz	-6	-18	-19	-16	-19	-19	-21	-13	-11	-21	-13	-20	-23	-20
/o/														
180 Hz	-24	-29	-25	-31	-46	-40	-32	-26	-20	-32	-30	-27	-32	-31
1000 Hz	-16	-26	-30	-30	-40	-36	-33	-19	-12	-23	-27	-32	-37	-27
2000 Hz	-22	-26	-21	-34	-26	-32	-33	-21	-16	-29	-34	-25	-37	-33
2500 Hz	-12	-19	-23	-25	-26	-17	-21	-11	-7	-25	-15	-23	-21	-21
3000 Hz	-11	-20	-22	-20	-21	-18	-20	-9	-5	-23	-20	-22	-22	-22
/u/	Nrs.													
180 Hz														
1000 Hz														
2000 Hz														
2500 Hz														
3000 Hz														

Table 7.15: Process of the sound energy of subject (classical) singing at 180 Hz (in dB, Nrs.= No results).

than all the others, whereas only a few differences among the vowels were recognized in the case of 500 Hz. The reason could be that a singer generally tends to open their mouth widely in order to produce a sufficiently loud voice at high pitch and this is often independent of the vowel, so that the shape of the mouth will be similar for each vowel at high pitch.

Subject SS: Fundamental 180 Hz

	Chin	Throat	LC	RC	Sternum	Nose	N.Bone	LCoM	RCoM	LCh	RCh	Forehead	LLE	RLE
/a/														
180 Hz	-19	-45	-59	-50	-44	-34	-35	-23	-25	-28	-29	-48	-31	-45
1000 Hz	-17	-31	-39	-34	-38	-29	-30	-23	-20	-27	-36	-42	-29	-41
2000 Hz	-16	-22	-25	-27	-30	-20	-23	-16	-25	-19	-21	-29	-24	-28
2500 Hz	-14	-21	-20	-24	-24	-17	-19	-13	-14	-17	-24	-26	-24	-22
3000 Hz	-11	-19	-20	-23	-23	-18	-21	-11	-20	-14	-21	-21	-26	-26
/e/														
180 Hz	-14	-36	-40	-35	-39	-27	-29	-22	-18	-24	-25	-35	-29	-36
1000 Hz	-14	-29	-37	-31	-34	-26	-29	-27	-17	-24	-22	-35	-28	-30
2000 Hz	-9	-20	-25	-27	-28	-18	-24	-14	-21	-14	-19	-28	-22	-27
2500 Hz	-9	-17	-20	-27	-26	-15	-19	-14	-19	-14	-20	-24	-20	-22
3000 Hz	-9	-20	-21	-22	-24	-17	-19	-11	-20	-13	-20	-21	-24	-27
/i/														
180 Hz	-26	-38	-40	-38	-43	-35	-30	-26	-2	-39	-15	-41	-32	-41
1000 Hz	-10	-17	-27	-18	-21	-17	-15	-16	8	-22	-3	-26	-20	-29
2000 Hz	-15	-21	-25	-35	-30	-22	-24	-20	-2	-18	-11	-29	-23	-29
2500 Hz	-18	-21	-23	-27	-29	-17	-20	-17	-8	-19	-15	-25	-21	-22
3000 Hz	-14	-21	-22	-24	-25	-19	-21	-14	-13	-17	-22	-23	-24	-26
/o/														
180 Hz	-24	-45	-44	-39	-44	-36	-36	-25	-25	-39	-30	-44	-38	-46
1000 Hz	-22	-33	-45	-37	-42	-32	-33	-23	-22	-31	-32	-42	-32	-42
2000 Hz	-10	-15	-25	-26	-23	-16	-15	-12	-9	-13	-14	-25	-15	-17
2500 Hz	-9	-13	-18	-21	-22	-14	-15	-9	-7	-10	-11	-16	-14	-18
3000 Hz	-12	-17	-23	-26	-24	-16	-20	-12	-12	-16	-19	-21	-21	-21
/u/														
180 Hz	-26	-55	-60	-56	-44	-36	-39	-21	-19	-45	-24	-46	-35	-47
1000 Hz	-23	-33	-39	-35	-42	-32	-32	-10	-21	-31	-27	-40	-31	-41
2000 Hz	-13	-25	-25	-30	-25	-28	-19	-10	-18	-18	-21	-24	-20	-27
2500 Hz	-6	-22	-25	-21	-20	-13	-16	-7	3	-13	-2	-19	-18	-15
3000 Hz	-1	-16	-18	-17	-23	-18	-16	-1	0	-14	-9	-25	-25	-24

Table 7.16: Process of the sound energy of subject SS (musical) singing at 180 Hz (in dB).

When it comes to the approach of energy values, which were measured separately at the left and right side of a part of the body, there was nothing new here, so that the difference decreased from around 1000 – 2000 Hz and was usually smallest at around 2000 Hz (except for the case of SE2). But there were also findings in the case of SE2 and VS where such a difference became wider again, even though it was temporarily getting smaller at a certain frequency. This also occurred in the case where no large

Subject SE2: Fundamental 180 Hz

	Chin	Throat	LC	RC	Sternum	Nose	N.Bone	LCoM	RCoM	LCh	RCh	Forehead	LLE	RLE
/a/														
180 Hz	-8	-28	-28	-41	-40	-21	-26	-10	-16	-15	-16	-33	-29	-25
1000 Hz	-7	-21	-30	-25	-30	-18	-22	-10	-19	-14	-16	-32	-26	-24
2000 Hz	-5	-15	-17	-24	-25	-12	-17	-8	-17	-10	-11	-21	-19	-17
2500 Hz	-6	-15	-17	-22	-24	-11	-16	-8	-16	-10	-10	-19	-16	-16
3000 Hz	-5	-15	-17	-23	-21	-12	-16	-5	-23	-8	-13	-21	-15	-21
/e/														
180 Hz	-7	-24	-26	-41	-49	-20	-25	-9	-22	-15	-17	-31	-28	-31
1000 Hz	-6	-20	-33	-35	-37	-18	-21	-11	-25	-16	-16	-25	-25	-18
2000 Hz	-4	-14	-15	-25	-25	-13	-16	-8	-19	-10	-11	-19	-18	-18
2500 Hz	-4	-13	-14	-22	-21	-11	-15	-7	-19	-10	-12	-19	-17	-16
3000 Hz	-3	-12	-15	-23	-18	-11	-14	-5	-17	-7	-13	-21	-14	-20
/i/														
180 Hz	-10	-29	-24	-42	-38	-21	-26	-10	-18	-15	-17	-31	-28	-31
1000 Hz	-9	-18	-16	-12	-18	-16	-15	-14	-9	-14	-9	-21	-16	-11
2000 Hz	-7	-18	-18	-23	-20	-12	-21	-7	-25	-8	-10	-17	-15	-20
2500 Hz	-4	-12	-15	-20	-21	-10	-14	-7	-20	-8	-12	-18	-16	-16
3000 Hz	-6	-16	-18	-25	-19	-13	-16	-6	-22	-9	-15	-21	-15	-20
/o/														
180 Hz	-18	-54	-30	-38	-39	-28	-34	-9	-30	-18	-27	-36	-27	-42
1000 Hz	-16	-28	-41	-30	-36	-24	-26	-10	-24	-18	-23	-36	-27	-29
2000 Hz	-13	-26	-15	-23	-23	-19	-22	-7	-23	-15	-13	-15	-23	-19
2500 Hz	-12	-21	-17	-20	-20	-15	-17	-6	-23	-12	-18	-18	-22	-20
3000 Hz	-12	-19	-18	-24	-21	-14	-18	-4	-23	-9	-18	-18	-16	-23
/u/														
180 Hz	-14	-33	-28	-48	-42	-24	-28	-8	-27	-16	-22	-32	-27	-35
1000 Hz	-15	-27	-36	-29	-35	-24	-27	-9	-24	-17	-22	-36	-26	-29
2000 Hz	-8	-17	-14	-19	-22	-13	-17	-7	-21	-13	-15	-21	-19	-25
2500 Hz	-11	-17	-14	-19	-16	-13	-15	-5	-20	-10	-14	-15	-21	-18
3000 Hz	-10	-23	-15	-24	-15	-17	-16	-4	-11	-10	-18	-18	-16	-22

Table 7.17: Process of the sound energy of subject SE2 (Pop) singing at 180 Hz (in dB).

gap was shown at the fundamental frequency (180 Hz). But as mentioned above, such a phenomenon was also found in the cases of 250 Hz and 500 Hz.

For the vowels /i/ and /u/ sung by SS, her energy from the right corner of the mouth was partly stronger than that from the mouth (see the results written in red in Table 7.16). That is because a shift of the strongest energy source was sometimes shown for these vowels, as shown in Subsection 6.2.2 of the previous chapter.

Subject VS: Fundamental 180 Hz

	Chin	Throat	LC	RC	Sternum	Nose	N.Bone	LCoM	RCoM	LCh	RCh	Forehead	LLE	RLE
/a/														
180 Hz	-12	-32	-31	-29	-28	-27	-30	-6	-18	-18	-33	-31	-25	-35
1000 Hz	-10	-28	-34	-30	-28	-25	-26	-4	-14	-16	-28	-35	-25	-32
2000 Hz	-3	-8	-7	-13	-11	-7	-7	-1	-4	-4	-6	-12	-10	-9
2500 Hz	-5	-13	-16	-28	-25	-13	-17	-2	-19	-9	-13	-20	-19	-19
3000 Hz	-5	-13	-15	-18	-17	-15	-16	0	-17	-9	-17	-19	-17	-27
/e/														
180 Hz	-17	-45	-42	-37	-43	-33	-35	-11	-17	-24	-34	-43	-29	-42
1000 Hz	-15	-33	-32	-28	-30	-30	-30	-8	-13	-22	-27	-47	-29	-33
2000 Hz	-11	-21	-23	-26	-24	-18	-23	-9	-13	-14	-19	-28	-23	-24
2500 Hz	-10	-17	-18	-26	-23	-15	-17	-6	-14	-11	-17	-23	-23	-20
3000 Hz	-10	-19	-18	-24	-19	-18	-17	-4	-10	-11	-21	-20	-19	-30
/i/														
180 Hz	-23	-49	-44	-40	-42	-33	-34	-30	-20	-36	-30	-40	-33	-43
1000 Hz	-22	-25	-32	-17	-35	-26	-20	-27	-13	-24	-26	-19	-25	-16
2000 Hz	-13	-22	-26	-22	-25	-18	-29	-15	-11	-19	-20	-21	-17	-25
2500 Hz	-14	-19	-22	-28	-26	-18	-20	-13	-13	-16	-23	-26	-23	-23
3000 Hz	-12	-20	-20	-25	-22	-20	-19	-10	-10	-16	-27	-22	-20	-28
/o/														
180 Hz	-18	-37	-34	-35	-42	-30	-36	-10	-18	-30	-36	-34	-28	-42
1000 Hz	-16	-24	-28	-22	-20	-21	-24	-8	-19	-19	-18	-16	-18	-21
2000 Hz	-9	-10	-33	-26	-19	-13	-11	-11	-7	-9	-11	-15	-13	-17
2500 Hz	-10	-14	-12	-20	-19	-12	-13	-5	-17	-12	-9	-22	-19	-16
3000 Hz	-4	-10	-19	-18	-21	-13	-20	-2	-17	-9	-13	-20	-14	-23
/u/														
180 Hz	-12	-40	-44	-40	-42	-33	-37	-15	-13	-25	-23	-40	-36	-43
1000 Hz	-10	-32	-26	-24	-25	-39	-22	-8	-12	-26	-24	-25	-33	-22
2000 Hz	-7	-9	-13	-7	-9	-21	-14	-7	-5	-7	-11	-13	-8	-17
2500 Hz	-13	-19	-17	-19	-19	-15	-14	-19	-14	-15	-9	-19	-22	-20
3000 Hz	-2	-10	-12	-11	-25	-9	-13	0	-1	-10	-9	-13	-13	-12

Table 7.18: Process of the sound energy of subject VS (Pop/Soul) singing at 180 Hz (in dB).

Fluctuation of Radiation Energy in Frequency Range

Generally, when it comes to the fluctuation of radiated energy shown in the tables, it was found that SS and SE2 revealed similar findings to their result from the case study at 250 Hz. A small difference was shown for SS, in that her radiation of the vowel /i/ was also strongly in a fluctuation (there were only the vowels /o/ and /u/ in case of 250

Hz) and for all the vowels involved. Almost all the parts of the body changed in certain frequency range analyzed. This change localized between 180 Hz and 1000 Hz for the vowel /i/ as well as between 1000 Hz and 2000 Hz for the vowel /o/.
CH revealed remarkably less fluctuation in comparison to her results in the case studies of 250 Hz and 500 Hz, but the finding of VS proved the opposite, so that her energy changed most vigorously in the case of 180 Hz in relation to her results from other case studies.

All these fluctuations mostly happened in the frequency range between 180 Hz and 2000 Hz (sometimes to 2500 Hz for the vowels /o/ and /u/). In this case study, it was found for all the subjects that, in most cases, their energy only increased in the frequency range between 180 Hz and 2500 Hz, even though a few exceptions were observed in the frequency range between 1000 Hz and 2000 Hz. For example, the result of the vowel /i/ showed a mix of increase and decrease in the latter frequency rage (that however holds true for all the vowels in the case of CH). Likewise, the result in frequency range between 2500 Hz and 3000 Hz was different among the singers, so this is a mix of increase and decrease.

When it is a question which part of the body is strongly in a fluctuation, the following results were shown: In the case of CH, the sternum is involved for all the vowels and in the case of SE1, the clavicles and the sternum as well as the forehead (except the vowel /e/) are involved. In latter case, the throat is also strongly in a fluctuation for the vowels /i/o/u/. For VS there are more parts of the body involved: the throat, clavicles, sternum, nasal bone and the forehead. SS showed strong fluctuations at most parts of the body, as already mentioned.

The fact that the radiation energy from singing at 180 Hz increased completely in the result of each subject except CH was already mentioned in Subsection 6.2.2 of the previous chapter. The reduction of the difference in energy values that occurred at higher frequencies was also observed in this case study, independent of whether a high energy value was shown at the fundamental frequency or not.

7.1.4 Case of 120 Hz (B2)

The results of the measurement singing at 120 Hz by two male singers (classical bass and musical theater tenor/high baritone) will be displayed here (see Tables 7.19 and 7.20). All the results are analyzed for the five frequencies, 120 Hz, 1000 Hz, 1500 Hz, 2000 Hz, and 2500 Hz.

Subject JR: Fundamental 120 Hz

	Chin	Throat	LC	RC	Sternum	Nose	N.Bone	LCoM	RCoM	LCh	RCh	Forehead	LLE	RLE
/a/														
120 Hz	-13	-32	-28	-40	-46	-26	-30	-15	-26	-19	-25	-38	-42	-43
1000 Hz	-11	-24	-34	-27	-31	-24	-26	-14	-19	-20	-30	-37	-35	-31
1500 Hz	-14	-23	-24	-29	-26	-22	-24	-22	-18	-18	-31	-26	-29	-33
2000 Hz	-5	-15	-18	-19	-20	-13	-17	-5	-10	-11	-12	-23	-17	-19
2500 Hz	-8	-17	-20	-20	-26	-15	-16	-8	-11	-12	-12	-25	-22	-19
/e/														
120 Hz	-16	-38	-30	-44	-49	-29	-34	-19	-25	-23	-26	-41	-40	-46
1000 Hz	-15	-30	-35	-32	-31	-30	-30	-17	-16	-24	-34	-38	-30	-33
1500 Hz	-14	-22	-24	-27	-25	-22	-23	-18	-15	-19	-34	-25	-30	-33
2000 Hz	-11	-21	-22	-26	-24	-19	-22	-13	-17	-16	-21	-26	-25	-27
2500 Hz	-11	-18	-19	-24	-23	-16	-16	-12	-18	-14	-24	-23	-20	-23
/i/														
120 Hz	-18	-36	-31	-45	-48	-29	-33	-22	-19	-25	-23	-40	-40	-41
1000 Hz	-15	-33	-35	-31	-34	-31	-28	-22	-11	-27	-21	-36	-38	-33
1500 Hz	-15	-24	-28	-26	-26	-22	-23	-22	-16	-21	-32	-26	-29	-31
2000 Hz	-13	-22	-23	-27	-24	-19	-22	-16	-18	-17	-23	-26	-25	-27
2500 Hz	-14	-20	-21	-24	-24	-17	-16	-18	-16	-16	-23	-23	-21	-23
/o/														
120 Hz	-16	-40	-31	-45	-49	-30	-34	-17	-28	-24	-28	-42	-39	-48
1000 Hz	-13	-27	-41	-28	-35	-26	-29	-17	-19	-24	-28	-39	-35	-33
1500 Hz	-16	-24	-24	-29	-26	-20	-22	-17	-15	-20	-22	-25	-23	-26
2000 Hz	-10	-17	-23	-23	-24	-16	-21	-12	-24	-14	-15	-29	-22	-21
2500 Hz	-14	-20	-22	-21	-26	-16	-17	-14	-11	-16	-14	-25	-21	-21
/u/														
120 Hz	-16	-46	-33	-51	-51	-32	-37	-16	-20	-28	-29	-45	-42	-48
1000 Hz	-17	-30	-49	-30	-38	-28	-30	-21	-16	-27	-29	-39	-34	-35
1500 Hz	-20	-22	-22	-24	-19	-23	-24	-16	-12	-27	-22	-21	-19	-28
2000 Hz	-14	-22	-25	-26	-25	-19	-24	-15	-18	-19	-18	-24	-25	-24
2500 Hz	-15	-24	-28	-17	-24	-18	-17	-11	-9	-18	-11	-24	-32	-18

Table 7.19: Process of the sound energy of subject JR singing at 120 Hz (in dB).

Subject TF: Fundamental 120 Hz

	Chin	Throat	LC	RC	Sternum	Nose	N.Bone	LCoM	RCoM	LCh	RCh	Forehead	LLE	RLE
/a/														
120 Hz	-8	-38	-40	-52	-43	-28	-32	-14	-31	-21	-26	-42	-29	-37
1000 Hz	-7	-22	-31	-28	-30	-23	-25	-13	-21	-18	-24	-36	-26	-32
1500 Hz	-5	-20	-19	-24	-24	-18	-20	-11	-18	-16	-21	-25	-33	-36
2000 Hz	-8	-19	-21	-27	-29	-19	-22	-14	-15	-17	-19	-27	-27	-26
2500 Hz	-4	-16	-16	-22	-20	-15	-18	-8	-14	-13	-18	-24	-21	-21
/e/														
120 Hz	-9	-42	-44	-47	-45	-31	-34	-13	-17	-22	-37	-42	-30	-43
1000 Hz	-7	-23	-31	-26	-29	-24	-25	-11	-15	-20	-29	-34	-27	-27
1500 Hz	-8	-23	-25	-25	-26	-22	-24	-16	-13	-20	-28	-32	-30	-35
2000 Hz	-6	-19	-20	-26	-28	-18	-23	-11	-16	-14	-19	-28	-24	-26
2500 Hz	-7	-18	-19	-24	-22	-16	-18	-10	-15	-13	-19	-25	-22	-22
/i/														
120 Hz	-8	-40	-40	-48	-45	-30	-33	-13	-19	-24	-32	-41	-31	-39
1000 Hz	-8	-22	-32	-24	-30	-22	-25	-13	-16	-20	-25	-33	-29	-29
1500 Hz	-7	-17	-23	-21	-24	-18	-18	-13	-14	-16	-20	-20	-21	-28
2000 Hz	-5	-18	-20	-25	-25	-18	-23	-10	-17	-14	-19	-28	-24	-27
2500 Hz	-4	-15	-16	-25	-19	-16	-20	-8	-15	-13	-19	-26	-22	-24
/o/														
120 Hz	-14	-41	-48	-57	-50	-39	-39	-20	-16	-25	-28	-48	-37	-44
1000 Hz	-15	-29	-36	-34	-36	-28	-31	-12	-18	-25	-30	-38	-29	-33
1500 Hz	-20	-23	-23	-24	-25	-24	-24	-20	-17	-21	-24	-28	-24	-25
2000 Hz	-12	-27	-16	-20	-18	-20	-22	-11	-15	-21	-20	-24	-26	-25
2500 Hz	-11	-19	-22	-26	-27	-17	-21	-10	-13	-16	-26	-29	-20	-23
/u/														
120 Hz	-14	-40	-47	-55	-50	-36	-37	-16	-16	-27	-29	-47	-35	-43
1000 Hz	-18	-34	-37	-43	-40	-32	-35	-13	-15	-33	-37	-41	-30	-39
1500 Hz	-17	-29	-27	-31	-30	-28	-30	-13	-13	-30	-32	-35	-28	-28
2000 Hz	-12	-26	-23	-27	-25	-25	-29	-10	-12	-23	-19	-30	-26	-28
2500 Hz	-14	-21	-18	-22	-22	-18	-18	-10	-9	-17	-17	-28	-22	-27

Table 7.20: Process of the sound energy of subject TF (musical) singing at 120 Hz (in dB).

Radiated Energy Value

The chin and the corners of the mouth are strongest of all, just as all the results of the previous case studies (measured at 250Hz, 500 Hz and 180 Hz) showed. However, the energy from the chin here seems slightly stronger than from the corners of the mouth. By comparing all the results, it was found that there is no large difference in the radiation energy among the vowels, except that the energy from the throat sung by JR for the the vowel /u/ as well as that from the nose sung by TF for the vowel /o/ are weakest of all. In this case study, the gap of measured energy values between the left and right side also became smaller from around 1000 Hz (see the results from the clavicles and the corners of the mouth in Tables 7.19 and 7.20).

Compared to the case of 250 Hz, the radiated energy singing at 120 Hz showed distinctly weaker values at certain parts of the body – for example, in the case of JR, at the sternum for all the vowels, and at the throat, clavicles, nose, and nasal bone as well as at the forehead for the vowel /u/. Likewise for TF, his radiated energy was also obviously weaker at the throat and the sternum when he sang the vowels /a/e/o/.

Fluctuation of Radiation Energy in Frequency Range

When it comes to the fluctuation of radiated energy and the question of which parts of the body are involved, it seems that there are no wider differences in the result between 250 Hz and 120 Hz. The parts are mostly located far from the mouth, in particular the throat, clavicles, sternum, forehead and the lower eyelids.

Great changes of radiated energy, which are color-coded in yellow, mostly existed in the frequency range between 120 Hz and 1500 Hz and these revealed almost all increasing energy (except the right cheek for the vowel /i/ and the left clavicle for the vowel /u/). This is related to the fact that the radiated energy singing at 120 Hz increased to 2000 Hz at all parts of the body. In the frequency range between 2000 Hz and 2500 Hz, a mix of increase and decrease of the energy was observed.
However, the radiated energy increased in the whole frequency range, as mentioned in Subsection 6.2.3 of the previous chapter.

7.1.5 Two Single Cases: 90 Hz (approx. F2#) and 380 Hz (approx. F4#)

Here I would like to display the results achieved by male singers who also participated in the previous case study. Here, classical bass singer (JR) sang at 90 Hz and the singing voice of musical theater tenor/high baritone singer (TF) was measured at 380 Hz.

The results were analyzed at four frequencies of 90 Hz, 500 Hz, 1000 Hz, and at 1300 Hz for the former as well as at six frequencies of 380 Hz, 1000 Hz, 1500 Hz, 2000 Hz, 3000 Hz, and at 4000 Hz for the latter (see Tables 7.21 and 7.22).

Subject JR: Fundamental 90 Hz

	Chin	Throat	LC	RC	Sternum	Nose	N.Bone	LCoM	RCoM	LCh	RCh	Forehead	LLE	RLE
/a/														
90 Hz	-12	-32	-26	-41	-42	-26	-32	-11	-33	-16	-24	-42	-35	-48
500 Hz	-11	-23	-25	-30	-28	-23	-24	-10	-24	-16	-26	-34	-32	-31
1000 Hz	-11	-19	-31	-28	-28	-19	-19	-7	-15	-13	-21	-27	-26	-24
1300 Hz	-8	-16	-20	-21	-20	-16	-17	-9	-23	-12	-20	-22	-25	-25
/e/														
90 Hz	-11	-34	-28	-39	-40	-28	-31	-12	-28	-24	-27	-43	-35	-40
500 Hz	-10	-29	-27	-34	-30	-26	-26	-8	-24	-23	-29	-35	-35	-34
1000 Hz	-10	-24	-30	-23	-25	-22	-22	-10	-17	-20	-29	-30	-34	-26
1300 Hz	-9	-24	-23	-25	-22	-20	-20	-9	-16	-18	-27	-24	-28	-28
/i/														
90 Hz	-15	-38	-29	-53	-50	-29	-32	-18	-26	-24	-26	-41	-37	-47
500 Hz	-16	-32	-29	-34	-31	-29	-27	-18	-20	-26	-27	-41	-41	-34
1000 Hz	-16	-26	-38	-25	-30	-26	-24	-21	-14	-28	-32	-27	-27	-45
1300 Hz	-15	-22	-31	-27	-27	-22	-22	-15	-14	-19	-36	-25	-25	-25
/o/														
90 Hz	-18	-40	-30	-41	-41	-30	-33	-14	-28	-20	-28	-47	-41	-46
500 Hz	-16	-28	-28	-33	-31	-26	-26	-11	-23	-18	-33	-36	-37	-35
1000 Hz	-16	-26	-39	-27	-31	-25	-26	-12	-17	-19	-28	-36	-30	-32
1300 Hz	-12	-20	-22	-26	-22	-20	-22	-13	-20	-17	-25	-25	-36	-31
/u/														
90 Hz	-15	-35	-31	-42	-43	-30	-34	-16	-26	-23	-27	-43	-43	-46
500 Hz	-13	-26	-27	-34	-30	-25	-26	-13	-23	-20	-29	-35	-37	-33
1000 Hz	-14	-24	-37	-29	-31	-22	-23	-12	-17	-19	-25	-30	-28	-27
1300 Hz	-14	-18	-20	-25	-21	-19	-19	-19	-21	-18	-26	-20	-21	-27

Table 7.21: Process of the sound energy of subject JR (classical) singing at 90 Hz (in dB).

Case of 90 Hz Sung by Classical Bass Singer

Compared to the results of the case of 120 Hz, the case of 90 Hz showed almost similar results in all analyses: the chin and the corners of the mouth are strongest of all, and the parts of the body, which are located far from the mouth, were often strongly in a fluctuation. In addition, it was observed that energy from all these parts increased

Subject TF: Fundamental 380 Hz

	Chin	Throat	LC	RC	Sternum	Nose	N.Bone	LCoM	RCoM	LCh	RCh	Forehead	LLE	RLE
/a/														
380 Hz	-8	-29	-35	-39	-34	-26	-26	-6	-20	-15	-26	-43	-28	-35
1000 Hz	-6	-19	-26	-26	-26	-17	-20	-5	-13	-11	-23	-27	-21	-28
1500 Hz	-4	-17	-17	-22	-21	-16	-17	-3	-14	-10	-19	-20	-26	-26
2000 Hz	-14	-36	-27	-44	-31	-23	-29	-20	-11	-24	-29	-28	-26	-34
3000 Hz	-4	-18	-21	-22	-19	-17	-18	-1	-14	-8	-17	-19	-22	-28
4000 Hz	-4	-16	-15	-29	-33	-17	-29	-1	-26	-11	-15	-24	-19	-18
/e/														
380 Hz	-5	-27	-34	-44	-33	-26	-28	-6	-18	-18	-29	-41	-28	-35
1000 Hz	-5	-21	-27	-30	-28	-20	-22	-5	-13	-14	-25	-27	-21	-34
1500 Hz	-2	-11	-14	-19	-18	-13	-14	0	-20	-7	-15	-17	-20	-22
2000 Hz	-3	-15	-17	-24	-20	-14	-17	-3	-17	-9	-17	-21	-22	-31
3000 Hz	-3	-15	-17	-19	-20	-15	-17	0	-14	-8	-15	-18	-20	-24
4000 Hz	-5	-11	-12	-22	-26	-16	-35	-1	-11	-7	-11	-18	-17	-16
/i/														
380 Hz	-3	-27	-35	-45	-34	-29	-29	-11	-21	-24	-29	-43	-29	-36
1000 Hz	-4	-19	-27	-26	-26	-21	-23	-10	-17	-17	-22	-30	-24	-31
1500 Hz	-4	-11	-16	-19	-20	-13	-15	0	-16	-8	-16	-19	-20	-22
2000 Hz	-3	-12	-15	-21	-18	-14	-16	-1	-21	-8	-17	-19	-21	-30
3000 Hz	-2	-13	-17	-17	-18	-14	-16	0	-14	-7	-15	-18	-19	-23
4000 Hz	-2	-11	-13	-23	-30	-22	-29	-1	-12	-12	-13	-23	-24	-18
/o/														
380 Hz	-7	-25	-30	-36	-30	-23	-24	-2	-21	-13	-25	-37	-25	-31
1000 Hz	-11	-15	-23	-25	-25	-13	-17	-6	-21	-7	-17	-23	-21	-19
1500 Hz	-10	-25	-21	-34	-27	-20	-25	-8	-13	-18	-29	-25	-25	-35
2000 Hz	-6	-20	-20	-26	-23	-18	-24	-6	-13	-15	-22	-26	-21	-27
3000 Hz	-3	-13	-15	-18	-15	-15	-16	2	-17	-5	-14	-17	-18	-26
4000 Hz	-4	-11	-13	-23	-32	-20	-26	0	-14	-14	-12	-20	-19	-22
/u/	Nrs.													
380 Hz														
1000 Hz														
1500 Hz														
2000 Hz														
3000 Hz														
4000 Hz														

Table 7.22: Process of the sound energy of subject TF (musical) singing at 380 Hz (in dB).

uniformly at frequencies marked in yellow, due to the occurrence of an increase in the radiation energy at whole frequencies analyzed, from 90 Hz to 1300 Hz. This is maybe because both fundamental frequencies measured (90 Hz and 120 Hz) are not far apart from each other.

Case of 380 Hz Sung by Musical Theater Tenor/High Baritone Singer

Unlike the previous case study of 90 Hz by the classical bass singer, in this case study there were some changes in the results in comparison with other cases in which the musical theater singer also participated, namely 120 Hz and 250 Hz.
One of them involves many parts of the body – almost all parts were strongly in a fluctuation, even though the chin and the corners of the mouth were distinctively less affected. Especially the vowel /a/ showed strong changes in the radiation energy, but in general, the singer's radiated energy has never been before so much in a fluctuation as in this case. Interestingly, when it comes to the question whether the radiated energy was altogether increased in the measurement at 380 Hz in comparison to that from the measurement at 250 Hz, we can see that the energy actually rose there, but only for the vowel /o/, in particular at the clavicles, sternum, nose and at the nasal bone. For this vowel, the energy from the left corner of the mouth radiated more strongly than that from the mouth at 3000 Hz (see the energy value written in red, in Table 7.22). As already shown in the Section 6.2 of the previous chapter, strong radiation energy of singing voice can occur from other parts of the body (i.e., not from the mouth) at high frequencies, especially when the fundamental frequency that is sung is high. In this case, it seems that the middle of the energy source is shifted to the left side of the mouth.

It is also interesting that the sternum and the nasal bone also showed strong changes in the radiated energy in the frequency range between 3000 Hz and 4000 Hz, whereas most of the other parts of the body revealed such a fluctuation often only in the frequency range between 380 Hz and 1500 Hz. But in fact, such finding that strong fluctuation in the radiation energy from these parts occurs firstly in the higher frequency range between 3000 – 5000 Hz was shown not only in this case and for this singer, but also in the results of some singers achieved from the measurements at 500 Hz and 250 Hz (see the results of both case studies). Such a result could not be obtained in the case of 180 Hz, because its energy was analyzed only up to 3000 Hz. It is conceivable that radiation energy from the sternum, nasal bone, and potentially also from the throat and the clavicles is often constantly changing at higher frequencies while singing.

When it is about the question of increased and decreased energy, which are well recognizable at the frequencies color-coded in the table, it was found that the energy increases between 380 Hz and 1000 Hz independent of vowel. But for the rest, the fluctuation of energy, whether it increases or decreases, depends on the vowels: the energy of the vowels /a/e/i/ still increased also in the frequency range between 1500 Hz and 2000 Hz, whereas that of the vowel /o/ showed a decrease, and vice versa between 1500 Hz and 2000 Hz (i.e. decrease for the former and increase for the latter). In the frequency range between 2000 Hz and 3000 Hz, all the vowels revealed an increasing energy value. This energy is, however, blended in the frequency range between 3000 Hz and 4000 Hz – decreasing energy at the sternum, nose, nasal bone and the forehead, but increasing at all the other parts of the body.

7.2 Minimum and Maximum Values

We observed fluctuation of radiated energy of the singing voice in the frequency range analyzed and ascertained that the radiated energy changes depending on the frequency. There it was shown where increasing and decreasing points are located in the frequency range, but because of the steady fluctuation, it was not so easy to realize the location of a minimum and maximum of the radiated energy. Therefore, I would just like to list where these points of each involved subject are located. The minimum and maximum numbers are shown in red and blue, respectively. There it is possible that there are several color-coded numbers in the tables, when multiple minimums or maximums result therein. But in the case of spread results where all the subjects showed different results, there is either a minimum nor a maximum number and none of the numbers are color-coded.
Furthermore, the large difference between the minimum and the maximum energy values is noted. This provides an information about the dimension of the changing energy that was radiated from the parts of the body.

7.2.1 Localization of Minimum Energy

First of all we, see the result of the case of 250 Hz, in which all the subjects participated (see Table 7.23). Here, most of the subjects showed their minimum energy at

[1]The number of the participating subjects is displayed in the left column beside the sung vowel.

Fundamental 250 Hz /a/e/i/o/u/

	Chin	Throat	LC	RC	Sternum	Nose	N.Bone	LCoM	RCoM	LCh	RCh	Forehead	LLE	RLE
/a/ n = 8														
250 Hz	7	7	4	7	8	7	6	6	3	7	5	7	7	7
1000 Hz			3					2	2	1	4	1		
2000 Hz	2	1	1					3	1	1		1		1
3000 Hz									1					
4000 Hz	1			1		2	2		1			1	1	
/e/ n = 8														
250 Hz	6	7	5	6	8	7	6	4	4	5	6	6	7	7
1000 Hz	2		2					5	3	2	3	1	1	
2000 Hz	1	1						1	1	1	1	1		1
3000 Hz														
4000 Hz	1		1	2		1	2					1	1	
/i/ n = 8														
250 Hz	6	7	6	5	7	8	6	4	4	5	5	6	6	7
1000 Hz	1		2		1			4	2	4	1	1		
2000 Hz	1	1							1	1	1			1
3000 Hz	1										1	1		
4000 Hz	1			3		1	2	1	1				2	
/o/ n = 7														
250 Hz	5	6	4	6	7	5	4	4	6	6	6	5	6	6
1000 Hz	1		3						1	2	1	2		
2000 Hz	1	1		1		1		3			1	1	1	1
3000 Hz									2					
4000 Hz	1					1	2							
/u/ n = 7														
250 Hz	4	5	3	6	5	5	3	1	4	4	3	6	4	6
1000 Hz	2	1	4		1	2	2	4	1	2	3	4	1	
2000 Hz	1	1		1	2	1		2	1	1	1			1
3000 Hz											1			
4000 Hz	1						2		1				1	

Table 7.23: Localization of the minimum of the radiated sound energy for all the vowels singing at 250 Hz (shown by the number of participating subjects).[1]

the fundamental frequency, and this is independent of the part of the body as well as the vowel. The minimum energy of some singers was also found at 1000 Hz and in the higher frequency range, but seldom at 3000 Hz.
Looking at the results from the corners of the mouth and the cheeks, it can be seen that their locations of the minimum are divided at two frequencies among the singers, namely at 250 Hz and 1000 Hz. On the other hand, there was barely any variance at

Fundamental 500 Hz /a/e/i/o/u/

	Chin	Throat	LC	RC	Sternum	Nose	N.Bone	LCoM	RCoM	LCh	RCh	Forehead	LLE	RLE
/a/ n = 6														
500 Hz	1	1		2		3			1	3	2	1	3	2
1000 Hz	1		5		3			3	2	2	2	3	2	1
2000 Hz	2	2	1	2	2	1	1	2	2	2	1	1	1	1
3000 Hz				1					1		1			2
4000 Hz	2	2		1	1	3	5		1					
5000 Hz	1	1					1	1				1		
/e/ n = 6														
500 Hz	2	4		4	1	5		2	5	2	5	1	3	3
1000 Hz	2		5		5		3	4	1	2		5	2	
2000 Hz								1	1	1				1
3000 Hz										1				3
4000 Hz	2	3	1	1		1	3		1	1				
5000 Hz		1		1					1		1		1	
/i/ n = 6														
500 Hz				3		1		1	4	1	1		3	1
1000 Hz	5	3	6	3	6	4	4	5	1	5	4	6	2	2
2000 Hz		1							1	1				1
3000 Hz											1	1		3
4000 Hz	2	1		2		2	2		2				1	
5000 Hz		1		1					1					
/o/ n = 6														
500 Hz	1	2		1	1	3	2	1	2	2	4	2	3	4
1000 Hz	1	1	5		3			1	1	1	1	2	1	1
2000 Hz	4	2	1	3	1	1	1	4	3	3		1		2
3000 Hz									1					
4000 Hz	2	1		1		2	3				1	1	1	
5000 Hz				1	1				2		1	1	2	
/u/ n = 4														
500 Hz	2	2		2	1	2	1	1	1	1	1	1	2	2
1000 Hz			3		3	1		1			1	2	1	1
2000 Hz	1	1		2	1		1	2		1		1		1
3000 Hz								1		1	1			2
4000 Hz	1	1	1			2	3		2		1	1		
5000 Hz					1			1	1	1			1	

Table 7.24: Localization of the minimum of the radiated sound energy for all the vowels singing at 500 Hz (shown by the number of participating subjects, all females).

Fundamental 180 Hz /a/e/i/o/u/

	Chin	Throat	LC	RC	Sternum	Nose	N.Bone	LCoM	RCoM	LCh	RCh	Forehead	LLE	RLE
/a/ n = 4														
180 Hz	3	3	1	3	4	4	4	4	1	3	3	2	3	3
1000 Hz			2	1	1			2			2	1	1	
2000 Hz	1	1	1	1			1			1		1		1
2500 Hz									1				1	
3000 Hz									2					
/e/ n = 4														
180 Hz	3	3	2	4	4	4	3	2	1	2	4	2	3	3
1000 Hz	2		2				2	2	2	2		3		
2000 Hz		1							1					1
2500 Hz									1	1			1	
3000 Hz														
/i/ n = 4														
180 Hz	3	3	3	4	4	4	3	3	1	3	3	3	3	3
1000 Hz							1	1				1	1	
2000 Hz	1	1	1	1					1	1		1		1
2500 Hz													1	
3000 Hz									2		1			
/o/ n = 4														
180 Hz	4	4	1	3	4	4	3	2	3	4	2	3	3	3
1000 Hz			3				1	1	1	1	1	2	2	
2000 Hz				1			1	1			1		1	1
2500 Hz														
3000 Hz														
/u/ n = 3														
180 Hz	1	3	2	3	3	2	3	1	1	1	1	2	3	3
1000 Hz	1		1			2		1	1	2	3	1		
2000 Hz														
2500 Hz	1							1	1					
3000 Hz														

Table 7.25: Localization of the minimum of the radiated sound energy for all the vowels singing at 180 Hz (shown by the number of participating subjects, both alto and mezzo soprano singers).

the throat and the sternum, although this is somewhat less true for the vowel /u/.

When it comes to the localization of the minimum energy, the findings of the cases of 180 Hz and 120 Hz seem very similar, as shown in Tables 7.25 and 7.26. Not only because the minimum energy was also measured at the fundamental frequency in these

Fundamental 120 Hz /a/e/i/o/u/

	Chin	Throat	LC	RC	Sternum	Nose	N.Bone	LCoM	RCoM	LCh	RCh	Forehead	LLE	RLE
/a/ n = 2														
120 Hz	1	2	1	2	2	2	2	1	2	1	1	2	1	2
1000 Hz			1							1				
1500 Hz	1						1	1			1		1	
2000 Hz	1							1						
2500 Hz														
/e/ n = 2														
120 Hz	2	2	1	2	2	1	2	1	2	1	1	2	2	2
1000 Hz			1			1				1	1			
1500 Hz								1			1		1	
2000 Hz														
2500 Hz														
/i/ n = 2														
120 Hz	2	2	1	2	2	1	2	2	2	1	1	2	2	2
1000 Hz	1		1			1		2		1				
1500 Hz								2			1			
2000 Hz														
2500 Hz														
/o/ n = 2														
120 Hz	1	2	1	2	2	2	2	2	1	2	1	2	2	2
1000 Hz			1					1	1	2	2			
1500 Hz	2							2						
2000 Hz														
2500 Hz														
/u/ n = 2														
120 Hz		2	1	2	2	2	2	1	2	1	1	2	2	2
1000 Hz	1		1					1		1	2			
1500 Hz	1													
2000 Hz														
2500 Hz														

Table 7.26: Localization of the minimum of the radiated sound energy for all the vowels singing at 120 Hz (shown by the number of participating subjects, all males).

cases, but also because of the fact that the localization of the minimum was almost consistent for all subjects at the throat and the sternum. These results also look like the case of 250 Hz, but such a uniform result was also shown at the nose (except for the vowel /u/) in the case of 180 Hz and at the nasal bone, forehead and partly at the lower eyelids in the case of 120 Hz. But in the case study of 120 Hz, only two male singers participated, so that it is easy to yield a coherent result in the statistical procedure. For the rest, in terms of the measurement at 180 Hz, there was wide variance in the result of the corners of the mouth and the cheeks for the vowel /u/. The single study measured at 90 Hz sung by JR (bass singer) also revealed the existence of the minimum energy at the fundamental frequency[2].

Unlike the previous case studies mentioned, the finding achieved from the measurement at 500 Hz looks somewhat different (see Table 7.24), because the weakest energy values were not categorically located at the fundamental frequency, but rather at higher frequencies and their localization differed from vowel to vowel: the minimum of the vowels /i/ and /e/ was situated at 500 Hz and 1000 Hz (very clearly for the vowel /i/) whereas that of all other vowels was also at 2000 Hz. The minimum energy was sometimes found at 3000 Hz and 5000 Hz, but interestingly between both frequencies, at 4000 Hz, this was located and can be often seen at the chin, throat, nose and the nasal bone. The minimum energy from the sternum does not seem to be affected so much by vowel, so that this occurred at 1000 Hz for all the vowels, even if there was somewhat at variance for certain vowels.
Likewise, the single study measured at 380 Hz sung by TF (tenor / high baritone singer) showed split results in terms of the minimum and this also depends on the vowels: his weakest energy was clearly found at the fundamental frequency for the vowels /e/ and /i/, whereas that was located at two different frequencies for other vowels – at the fundamental frequency and 2000 Hz for the vowel /a/ as well as at the fundamental frequency and 1500 Hz for the vowel /o/[3].

7.2.2 Localization of Maximum Energy

Earlier, we were concerned with the localization of the minimum energy and know that the minimum is mostly located at the fundamental frequency and additionally also at 1000 Hz in the case of singing at 500 Hz.

When it comes to the localization of the maximum energy, it can be seen in the results shown in Tables 7.27, 7.28, 7.29, and 7.30 (see numbers of participating singers written in blue in the tables) that the maximum energy is usually at higher frequencies, mostly from 2000 Hz. The result that the maximum is found in the higher frequency range

[2]Because this is a single case, see the results shown in Table 7.21 of the previous section.
[3]This is also a single case, therefore see the results shown in Table 7.22 of the previous section.

Fundamental 250 Hz /a/e/i/o/u/

	Chin	Throat	LC	RC	Sternum	Nose	N.Bone	LCoM	RCoM	LCh	RCh	Forehead	LLE	RLE
/a/ n = 8														
250 Hz	1	1								1		1	1	1
1000 Hz								1	1					1
2000 Hz	2	1				2	1	1				1	1	
3000 Hz	4	6	3	6	7	6	6	4	2	4		5	4	1
4000 Hz	2	3	4	3	1	1	1	4	6	6	7	3	2	6
/e/ n = 8														
250 Hz			1						1	1		1	1	1
1000 Hz									3					
2000 Hz	2	1	2	1	2	3	2	1		1		1	2	2
3000 Hz	5	4	1	7	7	4	6	4	1	4	1	4	4	1
4000 Hz	5	4	3	1	2	3	1	6	3	4	7	5	3	6
/i/ n = 8														
250 Hz			1						1	1		1	1	
1000 Hz				3	1				2			1		3
2000 Hz	2	1	2		1	5	3	1	2	2	1	1	3	
3000 Hz	4	4	3	3	5	4	4	3	3	4	1	2	5	
4000 Hz	4	3	2	2	2		1	6	3	1	4	3	2	6
/o/ n = 7														
250 Hz			1											
1000 Hz				1										
2000 Hz	3	2	2	2	2	3	2	1	3	3	2	1	3	1
3000 Hz	4	5	6	6	6	4	7	5	1	5	1	4	5	1
4000 Hz		1	1					3	4	1	5	3		6
/u/ n = 7														
250 Hz			1											
1000 Hz														
2000 Hz	3			2	1	2	1	2	1	2	1		2	3
3000 Hz	5	4	3	6	3	5	6	2	3	6	1	5	4	
4000 Hz	2	4	3	1	4	1	1	4	3	3	5	3	2	4

Table 7.27: Localization of the maximum of the radiated sound energy for all the vowels singing at 250 Hz (shown by the number of participating subjects).

is actually clear due to the finding of the minimum at low frequencies. Unlike in the case of the minimum energy, the localization of the maximum seems to depend rather on the frequency range analyzed than on the pitch that is sung, because, in most cases, the maximum emerged at highest frequencies of each of the case studies that are shown here[4]. In other words, the higher the analyzed frequency the higher the localization of

[4]For the results of the measurement at 90 Hz, see in Table 7.21 of the previous section.

Fundamental 500 Hz /a/e/i/o/u/

	Chin	Throat	LC	RC	Sternum	Nose	N.Bone	LCoM	RCoM	LCh	RCh	Forehead	LLE	RLE
/a/ n = 6														
500 Hz			1				1		1	1		1	1	
1000 Hz	1			1					1					
2000 Hz	1	1	2			1	1					2		
3000 Hz	1		2	2	1		1	2		1	1			
4000 Hz	1	1	2					3	3	1	3	2		2
5000 Hz	6	4	1	3	5	5	4	3	1	4	2	2	5	5
/e/ n = 6														
500 Hz			1	1			1			1		1	1	1
1000 Hz				1					1					
2000 Hz	3	1	2	1	1	1	2				1			
3000 Hz	1		3	4	4		2	1	2	1		1	3	
4000 Hz	1	2	1			2		3	1	1	5	1	1	3
5000 Hz	3	4	2	1	2	5	3	4	3	4	2	3	3	3
/i/ n = 6														
500 Hz			1	1			1		1	1		1	1	
1000 Hz														
2000 Hz	3	1	1	1			1		1	1	1	2	1	
3000 Hz	2	1	1	6	4		1	1	2	2		1	3	
4000 Hz		1			1	1		2		1	3	2		2
5000 Hz	3	4	3	1	3	5	4	4	4	4	3	2	4	4
/o/ n = 6														
500 Hz												1	1	
1000 Hz	1	1		1		1	1				1			1
2000 Hz			1						2			1	1	
3000 Hz	3	2	4	5	5	5	5	4	2	3	2	4	3	1
4000 Hz		2	2					4	1		4		1	4
5000 Hz	4	3			1	2	1	2	1	4		1	3	2
/u/ n = 4														
500 Hz			1	1			1					1	1	1
1000 Hz	1							1	1	1				1
2000 Hz	1					1			1		2		1	
3000 Hz	1	3	1	2	3	3	1	2	1	1		1	1	
4000 Hz			1					2		1	2	2		1
5000 Hz	1	1	1	1	1	1	3		1	1		1	2	3

Table 7.28: Localization of the maximum of the radiated sound energy for all the vowels singing at 500 Hz (shown by the number of participating subjects, all females).

Fundamental 180 Hz /a/e/i/o/u/

	Chin	Throat	LC	RC	Sternum	Nose	N.Bone	LCoM	RCoM	LCh	RCh	Forehead	LLE	RLE
/a/ n = 4														
180 Hz		1							1	1		1		
1000 Hz									1				1	1
2000 Hz	2	2	2	1	1	1	1		1	1	2	1	2	1
2500 Hz		1	3	2		3	3		2		2	1	1	2
3000 Hz	3	3	2	1	3	1	2	4		2	1	1	1	1
/e/ n = 4														
180 Hz	1	1	1						1	1		1		1
1000 Hz									1				1	
2000 Hz	1										3	1		
2500 Hz	2	2	3	2		4	2			1	1	1	1	3
3000 Hz	3	1	1	2	4	2	4	4	2	3		2	2	1
/i/ n = 4														
180 Hz		1	1						1	1		1		
1000 Hz	1	1		3	3	1	1		3		2	1	1	3
2000 Hz						1		1		1	1	1	2	
2500 Hz	1	2	1	1		4	2			2	1			1
3000 Hz	2		2		2	1	1	3	1	2	1	1	2	
/o/ n = 4														
180 Hz														
1000 Hz										1				
2000 Hz		1	2		1		2		2	1	1	2	1	2
2500 Hz	2	2	2	2	3	3	2	1	2	1	3	1	2	2
3000 Hz	3	2		2	1	1	1	3	2	3		1	1	
/u/ n = 3														
180 Hz														
1000 Hz														
2000 Hz	1	2	1	2	1	1				1		1	1	
2500 Hz		1	1	1	1	2	2		1	2	3	2	1	2
3000 Hz	2	1	2	1	1	1	2	3	2	1	1	1	1	1

Table 7.29: Localization of the maximum of the radiated sound energy for all the vowels singing at 180 Hz (shown by the number of participating subjects, both alto and mezzo soprano singers).

the maximum energy in these case studies. For example, in the measurement at 120 Hz which is the lowest measured pitch in this work, its maximum energy was mostly observed at 2500 Hz, thus at the highest frequency analyzed in this case study.

In addition, it is noted that the results of the vowels /a/e/i/ are often rather more

Fundamental 120 Hz /a/e/i/o/u/

	Chin	Throat	LC	RC	Sternum	Nose	N.Bone	LCoM	RCoM	LCh	RCh	Forehead	LLE	RLE
/a/ n = 2														
120 Hz														
1000 Hz														
1500 Hz														
2000 Hz	1	1	1	1	1	1		1	1	1	1	1	1	1
2500 Hz	1	1	1	1	1	1	2	1	1	1	2	1	1	2
/e/ n = 2														
120 Hz														
1000 Hz														
1500 Hz									2					
2000 Hz	2										2			
2500 Hz	1	2	2	2	2	2	2	2		2	1	2	2	2
/i/ n = 2														
120 Hz														
1000 Hz									1		1			
1500 Hz				1			1		1			1	1	
2000 Hz	1				1			1			1			
2500 Hz	1	2	2	1	2	2	1	1		2	1	1	1	2
/o/ n = 2														
120 Hz														
1000 Hz														
1500 Hz												1		
2000 Hz	1	1	1	1	2	1		1		1	1	1		1
2500 Hz	1	1	1	1		2	2	1	2	1	1	1	2	2
/u/ n = 2														
120 Hz														
1000 Hz														
1500 Hz		1	1		1							1	1	
2000 Hz	2	1						1						
2500 Hz		1	1	2	1	2	2	2	2	2	2	1	1	2

Table 7.30: Localization of the maximum of the radiated sound energy for all the vowels singing at 120 Hz (shown by the number of participating subjects, all males).

at variance between the subjects than those of the vowels /o/ and /u/, so that the maximum of all the measured parts of the body is mostly centralized between 2000 Hz and the highest frequency analyzed for the vowels /o/ and /u/[5]. A sole exception is the finding from the measurement at 500 Hz where no such difference among the vowels was

[5]For the results of the measurement at 380 Hz, see the results shown in Table 7.22 of the previous section. The musical theater singer's maximum is located from 1500 Hz for the vowels /a/e/i/.

shown (the results are widely dispersed in the whole frequency range). It seems that the individual singing technique used was clearly reflected in the result.

The difference among singers was shown to be the least at the sternum, nose and at the nasal bone, so that most of the singers revealed their maximum at the same frequency for these parts of the body. But such a finding was more distinctly observable in the localization of the minimum energy, as we have already noted.

7.3 Dimension of the Difference between the Minimum and Maximum Energy

In the following I would like to show results from two further analyses, which also help to grasp the dimension of the changing radiation energy, particularly between the minimum and maximum energy.

7.3.1 Analyzing of Each Part

The first analysis is about the magnitude of the difference between the minimum and the maximum energy of each measured part of the body. The localization of the minimum and the maximum of the radiated energy has been discussed, but at this point, I will display the dimension between these energy points of each subject analyzed from three aspects – among the parts of the body and among the vowels, as well as among the subjects. For this analysis the results shown in Section 7.1 are employed.

All following findings presented may seem to be already presented in Section 7.1, but in fact, so far, just general dimensions of change in the radiated energy were mentioned. In other words, that was not such a comparative analysis of the minimum and maximum energy, but rather it was about where the radiated energy was strongest in a fluctuation, more preciously, where the energy was increasing or decreasing more than 10 dB in the results.
However, this analysis actually yielded results similar to the analysis about general dimensions of change in the radiated energy, therefore the results from this analysis

Fundamental 250 Hz /a/e/i/o/u/

	Chin	Throat	LC	RC	Sternum	Nose	N.Bone	LCoM	RCoM	LCh	RCh	Forehead	LLE	RLE
/a/														
CH	5	7	6	10	14	15	13	16	8	4	10	5	5	6
SE1	3	4	20	9	11	11	17	5	5	6	9	14	16	12
JR	7	20	15	24	18	16	13	10	28	14	14	22	24	21
SS	9	17	33	36	20	17	16	14	17	15	31	30	6	29
TF	3	17	28	18	17	12	12	6	10	14	20	26	5	21
SE2	3	12	16	16	17	8	10	4	6	6	7	13	15	19
VS Pop	6	17	26	16	20	10	10	7	4	9	13	21	5	11
VS Soul	4	20	27	15	16	15	14	6	6	11	13	21	9	12
/e/														
CH	3	7	6	11	13	16	22	20	3	4	15	5	5	7
SE1	2	5	15	10	10	7	10	5	3	8	7	11	16	11
JR	6	17	31	22	24	12	11	16	15	16	17	24	19	15
SS	9	18	31	27	18	14	13	19	9	17	16	26	5	26
TF	3	20	31	25	17	14	13	7	10	16	25	26	5	23
SE2	5	11	19	17	18	9	11	6	17	7	14	13	18	18
VS Pop	4	16	24	14	16	10	10	6	5	8	11	17	9	11
VS Soul	6	26	30	18	18	13	13	8	5	8	19	22	6	16
/i/														
CH	6	11	7	9	18	13	12	14	7	8	14	10	13	8
SE1	2	5	12	15	10	7	12	4	16	6	11	9	14	16
JR	3	12	11	20	20	6	12	9	10	7	13	22	16	13
SS	18	17	30	27	20	19	16	18	6	27	17	29	9	33
TF	5	24	26	23	16	12	11	11	16	17	16	22	9	17
SE2	4	11	12	25	15	8	13	6	4	8	7	18	14	22
VS Pop	5	17	20	17	15	10	8	12	12	12	7	17	8	12
VS Soul	6	26	23	15	14	14	13	11	6	14	12	21	10	20
/o/														
CH	20	9	5	14	20	25	21	18	14	10	16	7	12	10
SE1	3	6	25	12	13	10	10	6	11	9	11	19	16	16
SS	21	37	33	36	26	27	22	18	18	31	31	32	24	34
TF	6	16	29	27	21	17	14	5	7	15	20	30	9	22
SE2	3	14	15	19	17	8	12	3	13	5	9	19	14	16
VS Pop	9	25	25	19	17	14	15	11	9	10	24	22	8	14
VS Soul	7	28	29	18	20	16	15	5	8	11	20	23	8	20

Table 7.31: Maximum and minimum of the sound energy from the measured parts of the body for all the vowels singing at 250 Hz (in dB, all subjects).

about the difference between the minimum and maximum energy could emphasize the findings displayed in Section 7.1.

Fundamental 250 Hz /a/e/i/o/u/

	Chin	Throat	LC	RC	Sternum	Nose	N.Bone	LCoM	RCoM	LCh	RCh	Forehead	LLE	RLE
/u/														
CH	17	19	11	31	27	25	37	18	13	13	18	13	21	39
SE1	22	15	14	13	14	7	13	11	11	15	20	13	20	12
JR	6	16	30	14	15	8	8	6	20	7	18	16	16	20
SS	15	33	30	43	22	18	20	15	18	21	27	31	23	28
TF	7	19	26	26	18	11	15	6	6	12	24	24	9	18
SE2	5	19	30	17	17	11	14	8	15	7	11	14	13	14
VS Soul	19	25	30	20	25	15	18	10	8	20	26	30	14	22

Table 7.32: Difference between the maximum and the minimum of the sound energy from the measured parts of the body for all the vowels singing at 250 Hz (in dB, all subjects).

From the measurement at 250 Hz it can be seen that the energy from the chin was least in a fluctuation compared to the other parts. In addition, the difference among singers was also smallest there, however this difference occurred widely in the sung vowel /o/ for CH and SS as well as in the sung vowel /u/ for CH, SE1, SS and VS (Soul singing). This is caused by the strong change in the radiation energy for these vowels, as shown in Section 6.2. The evidence that the parts of the body located far away from the mouth revealed a strong change in the energy can be also confirmed by the results from certain parts, for example from the throat, clavicles and the forehead. The difference between the minimum and maximum energy was frequently more than 20 dB, although the affected parts were more or less different according to the vowel.
However, this wide difference relates to the fact that the radiation energy from such parts of the body was mostly weak at the fundamental frequency, but usually showed a drastic increase at higher frequencies. As already shown, all parts radiated strong energy at high frequencies compared to the fundamental frequency, however the dimension of such an increasing energy seems to depend on the singer, because the difference between the minimum and the maximum can be up to 20 Hz among the subjects, too (e.g. in the case of the vowel /o/, SE1 revealed a difference of 6 dB at the throat, whereas a difference of 37 dB was measured there for SS). But, as already mentioned, such a drastic energy change seems unlikely to happen at the chin, with the exception of some cases, such as for the vowels /o/ and /u/, probably because of their high energy value already radiated at the fundamental frequency.

Apart from that, the results of SS showed in total a remarkably large difference

Fundamental 500 Hz /a/e/i/o/u/

	Chin	Throat	LC	RC	Sternum	Nose	N.Bone	LCoM	RCoM	LCh	RCh	Forehead	LLE	RLE
/a/														
CH	9	21	12	17	17	25	20	17	9	18	27	19	15	20
SE1	2	7	16	10	9	9	7	5	17	3	10	15	16	10
SS	9	14	15	17	18	16	19	16	14	26	18	22	14	28
SE2	1	6	8	6	9	6	4	6	4	4	6	8	8	6
VS Pop	7	17	20	15	15	13	14	8	8	10	10	11	15	21
VS Soul	8	19	18	12	17	15	15	6	3	13	17	18	12	23
/e/														
CH	7	17	9	12	13	9	4	8	5	5	11	7	9	8
SE1	3	4	19	7	12	6	15	5	31	7	10	17	16	8
SS	5	17	18	22	18	15	19	22	14	16	15	23	18	29
SE2	2	7	10	6	8	6	5	4	6	4	4	8	7	6
VS Pop	6	15	19	13	12	13	12	8	5	11	15	16	17	13
VS Soul	4	14	17	10	11	13	10	5	5	8	15	17	10	13
/i/														
CH	5	13	9	15	14	11	10	18	4	4	17	10	11	10
SE1	3	8	28	8	13	6	11	7	18	6	12	12	11	10
SS	7	17	35	19	25	17	24	14	12	15	15	20	23	29
SE2	4	9	16	5	12	9	12	5	9	5	7	9	13	6
VS Pop	9	19	23	11	13	14	16	11	8	11	14	15	21	16
VS Soul	9	19	20	13	16	17	18	11	5	12	19	20	13	16
/o/														
CH	3	4	9	15	13	11	12	13	3	8	9	8	2	6
SE1	4	6	23	8	13	10	10	6	11	6	11	21	16	13
SS	21	21	24	26	19	25	18	21	25	21	17	27	14	29
SE2	3	6	7	11	10	7	7	9	7	5	4	9	10	4
VS Pop	16	22	22	16	32	18	16	24	12	12	31	19	9	13
VS Soul	7	20	20	15	14	16	12	4	9	11	22	19	11	15
/u/														
CH	18	8	21	18	14	12	14	15	13	12	16	18	16	12
SE1	6	5	22	8	11	15	13	5	21	11	11	20	15	13
SS	7	20	25	30	20	19	19	9	10	27	15	28	15	31
SE2	5	4	18	16	9	5	8	3	6	6	5	9	13	13

Table 7.33: Difference between the maximum and the minimum of the sound energy from the measured parts of the body for all the vowels singing at 500 Hz (in dB, female subjects).

between her minimum and maximum, and CH, SE1 as well as SE2 revealed the least difference. This large difference occurred because of the parts of the body that showed

Fundamental 180 Hz /a/e/i/o/u/

	Chin	**Throat**	**LC**	**RC**	**Sternum**	**Nose**	**N.Bone**	**LCoM**	**RCoM**	**LCh**	**RCh**	**Forehead**	**LLE**	**RLE**
/a/														
CH	7	13	6	5	21	15	5	14	7	10	14	2	5	9
SS	8	26	39	27	21	17	16	12	11	14	15	27	7	23
SE2	3	13	13	19	19	10	20	5	7	7	6	14	14	9
VS	9	24	27	17	17	20	23	6	15	14	27	23	15	26
/e/														
CH	5	7	10	4	22	15	6	18	2	8	12	10	5	8
SS	5	19	20	13	15	12	10	16	4	11	6	14	9	14
SE2	4	12	19	19	31	9	11	6	8	9	6	12	14	15
VS	7	28	24	13	24	18	18	7	7	13	17	27	10	22
/i/														
CH	3	10	10	5	18	14	8	16	4	5	14	4	2	8
SS	16	21	18	20	22	18	15	12	21	22	19	18	12	19
SE2	6	17	9	30	20	11	12	8	16	7	8	14	13	20
VS	11	30	24	23	20	15	15	20	10	20	10	21	16	27
/o/														
CH	13	10	9	14	25	23	13	17	15	9	19	10	16	12
SS	15	32	27	18	22	22	21	16	18	29	21	28	24	29
SE2	6	35	26	18	19	14	17	6	7	9	14	21	11	23
VS	14	27	22	17	23	18	25	9	12	21	27	19	15	26
/u/														
SS	25	39	42	39	24	23	23	20	24	32	25	27	17	32
SE2	7	16	22	29	27	11	13	5	16	7	8	21	11	17
VS	11	31	32	33	33	30	24	19	13	19	15	27	28	31

Table 7.34: Difference between the maximum and the minimum of the sound energy from the measured parts of the body for all the vowels singing at 180 Hz (in dB, classical alto and popular singers).

a great growth in the radiation energy at increasing frequencies.
Furthermore, it is noteworthy for some classical singers, namely CH and SE1, that their difference was mostly very small at the throat and the forehead (especially for CH).

The results of the measurement at 500 Hz are similar to that from the research at 250 Hz: the smallest change in the radiated energy shown at the chin and when it comes to a comparison among the singers, it was observed that the change was smallest for SE2 and largest for SS. However, compared to the measurement at 250 Hz, the difference between the minimum and the maximum was generally smaller everywhere, also among the singers. This is caused by a general increase of the radiation energy at 500 Hz

Fundamental 120 Hz /a/e/i/o/u/														
	Chin	**Throat**	**LC**	**RC**	**Sternum**	**Nose**	**N.Bone**	**LCoM**	**RCoM**	**LCh**	**RCh**	**Forehead**	**LLE**	**RLE**
/a/														
JR	8	17	16	21	26	13	14	17	16	9	19	15	25	24
TF	4	22	24	30	23	13	14	6	17	8	8	18	12	16
/e/														
JR	5	20	16	20	26	14	18	7	10	10	13	18	20	23
TF	3	24	25	23	23	15	16	6	4	9	18	17	8	21
/i/														
JR	5	16	14	21	24	14	17	6	8	11	11	17	9	18
TF	4	25	24	27	26	14	15	5	5	11	13	21	10	15
/o/														
JR	6	23	19	24	25	14	17	5	17	10	14	17	18	27
TF	9	22	32	37	23	22	18	10	5	9	10	24	17	21
/u/														
JR	6	24	27	34	32	14	20	10	11	10	18	21	23	30
TF	6	19	29	33	28	18	8	6	7	16	20	19	13	16

Table 7.35: Difference between the maximum and the minimum of the sound energy from the measured parts of the body for all the vowels singing at 120 Hz (in dB, male subjects).

Fundamental 90 Hz /a/e/i/o/u/														
	Chin	**Throat**	**LC**	**RC**	**Sternum**	**Nose**	**N.Bone**	**LCoM**	**RCoM**	**LCh**	**RCh**	**Forehead**	**LLE**	**RLE**
/a/	4	16	11	20	22	10	15	4	18	4	6	20	10	24
/e/	2	10	7	16	18	8	11	4	12	6	2	19	7	14
/i/	1	16	9	28	23	7	10	6	12	9	9	16	16	22
/o/	6	20	17	15	19	10	11	3	11	3	8	22	11	15
/u/	2	17	17	17	22	11	15	7	9	5	4	23	22	19

Table 7.36: Difference between the maximum and the minimum of the sound energy from the body for all the vowels singing at 90 Hz by JR (bass singer, shown in dB).

in relation to the measurement at 250 Hz, as already mentioned in Section 7.1. The minimum energy was generally higher there than that of 250 Hz, thus the difference between the minimum and the maximum would be smaller.

The results of all the other measurements, namely at 180 Hz (females only), 120 Hz (males only), 90 Hz (bass singer JR only) and at 380 Hz (high baritone / tenor singer TF only) also revealed the smallest difference between the minimum and maximum energy at the chin. But in comparison to the findings from 120 Hz where a little difference was

Fundamental 380 Hz /a/e/i/o/u/														
	Chin	**Throat**	**LC**	**RC**	**Sternum**	**Nose**	**N.Bone**	**LCoM**	**RCoM**	**LCh**	**RCh**	**Forehead**	**LLE**	**RLE**
/a/	10	13	20	17	15	10	12	19	15	16	14	24	9	17
/e/	3	16	22	25	15	13	21	6	9	11	18	24	11	19
/i/	2	16	22	28	16	16	14	11	9	17	16	25	10	18
/o/	8	14	17	18	17	10	10	10	8	13	17	20	7	16
/u/	Nrs.													

Table 7.37: Difference between the maximum and the minimum of the sound energy from the measured parts of the body for all the vowels singing at 380 Hz by TF (tenor / high baritone singer, shown in dB, Nrs.= No results).

shown at the chin among the subjects and the vowels, those from 180 Hz were split, so that their difference was definitively smaller for the vowels /a/ and /e/ than for the other vowels. However, this wide difference in the results between both vowels, /o/ and /u/, and the other vowels is actually what we found almost at all the measured pitches. This phenomenon actually occurred at many parts and is caused by enormous fluctuation of radiated energy for both vowels, as often mentioned in the previous chapters.

In other respects, when it is about the case of 180 Hz, the difference among the singers was often more than 20 dB at certain parts such as the throat, clavicles and the forehead, just like in the case of 250 Hz. But also in both cases with a single person respectively (measured at 90 Hz and 380 Hz) a large difference of more than 20 dB was observed at the clavicles (TF only), sternum (JR only) and the forehead (see Tables 7.21 and 7.22).

7.3.2 Analyzing among the Parts of the Body

The next analysis is also a comparative one about the dimension of the difference between the minimum and the maximum of the radiated energy, however this analysis is about the approximation of radiation energies from all the measured parts of the body. The question arose from the evidence, discussed above, that the radiation energy of the singing voice mostly increases everywhere until 2 kHz or higher and its maximum emerges there. Actually we have already seen the results in Chapter 6 (for example in Figure 6.7 and 6.8) that the difference in the radiation energy among the parts is getting smaller. Therefore, at this point I would like to analyze the dimension of the convergence of radiation energies from the measured parts of the body.

Fundamental 250 Hz								
	CH	SE1	JR	SS	TF	SE2	VS(p)	VS(s)
/a/								
250 Hz	24	25	25	41	37	31	33	33
1000 Hz	18	30	27	30	28	25	29	30
2000 Hz	11	19	19	23	23	21	21	25
3000 Hz	16	20	24	18	22	18	23	26
4000 Hz	21	32	13	21	26	24	29	31
/e/								
250 Hz	24	25	25	35	41	33	32	37
1000 Hz	22	26	31	30	29	26	30	23
2000 Hz	18	17	18	20	23	22	20	19
3000 Hz	15	19	16	17	24	20	25	25
4000 Hz	20	23	22	21	30	19	29	35
/i/								
250 Hz	31	24	23	38	37	30	26	29
1000 Hz	21	16	39	36	29	16	27	15
2000 Hz	18	16	17	26	23	14	20	20
3000 Hz	19	20	12	18	23	17	22	23
4000 Hz	28	24	13	23	31	24	33	28
/o/								
250 Hz	23	27	-	35	41	34	34	40
1000 Hz	20	35	-	32	28	25	30	36
2000 Hz	29	18	-	23	23	23	25	12
3000 Hz	18	20	-	19	23	22	22	22
4000 Hz	27	23	-	17	27	25	30	25
/u/								
250 Hz	28	25	24	41	43	29	-	38
1000 Hz	40	28	35	30	30	32	-	35
2000 Hz	40	14	14	31	20	15	-	23
3000 Hz	19	11	18	19	26	23	-	17
4000 Hz	27	21	20	15	33	21	-	19

Fundamental 120 Hz		
	JR	TF
/a/		
120 Hz	33	44
1000 Hz	26	29
1500 Hz	19	31
2000 Hz	18	21
2500 Hz	18	20
/e/		
120 Hz	33	38
1000 Hz	23	27
1500 Hz	20	27
2000 Hz	16	22
2500 Hz	13	18
/i/		
120 Hz	30	40
1000 Hz	27	25
1500 Hz	16	21
2000 Hz	14	23
2500 Hz	10	22
/o/		
120 Hz	33	43
1000 Hz	28	26
1500 Hz	14	11
2000 Hz	19	16
2500 Hz	15	19
/u/		
120 Hz	35	41
1000 Hz	33	30
1500 Hz	16	22
2000 Hz	12	20
2500 Hz	19	19

Table 7.38: Difference between both parts of the body which showed the minimum and maximum energy measured at 250 Hz and 120 Hz. The smallest difference is marked in green.

The results of all the pitches measured are listed in Tables 7.38 and 7.39. As already mentioned, the results shown are a difference in the radiation energy from the parts of the body which showed the minimum and the maximum. This is calculated in the following way – for example, when it comes to the case of 250 Hz with the sung vowel /a/ by CH, her minimum and maximum values (compared to the mouth) gained from

Fundamental 500 Hz

	CH	SE1	SS	SE2	VS(p)	VS(s)
/a/						
500 Hz	21	21	27	17	27	32
1000 Hz	19	26	27	18	28	32
2000 Hz	27	16	23	17	23	31
3000 Hz	17	19	18	18	40	39
4000 Hz	30	23	22	22	33	31
5000 Hz	22	19	17	20	28	34
/e/						
500 Hz	19	32	30	18	28	29
1000 Hz	22	29	27	19	27	29
2000 Hz	17	19	22	18	21	19
3000 Hz	16	23	22	18	30	34
4000 Hz	23	29	25	14	33	25
5000 Hz	21	21	17	17	29	25
/i/						
500 Hz	21	22	31	19	28	28
1000 Hz	24	33	38	23	28	29
2000 Hz	16	21	20	18	23	19
3000 Hz	17	23	16	17	31	34
4000 Hz	20	23	23	18	29	25
5000 Hz	26	19	19	20	29	25
/o/						
500 Hz	20	25	24	19	33	33
1000 Hz	21	25	29	20	31	33
2000 Hz	17	18	12	22	40	25
3000 Hz	16	22	17	18	28	28
4000 Hz	21	23	27	18	28	31
5000 Hz	21	15	14	24	40	23
/u/						
500 Hz	20	31	36	21	-	-
1000 Hz	32	32	29	21	-	-
2000 Hz	21	19	20	16	-	-
3000 Hz	23	23	17	18	-	-
4000 Hz	17	28	20	17	-	-
5000 Hz	24	25	12	17	-	-

Fundamental 180 Hz

	CH	SS	SE2	VS
/a/				
180 Hz	30	40	33	29
1000 Hz	17	25	25	31
2000 Hz	18	14	20	12
2500 Hz	16	13	18	26
3000 Hz	15	15	18	27
/e/				
180 Hz	32	26	42	34
1000 Hz	18	23	29	39
2000 Hz	19	19	21	19
2500 Hz	16	18	18	20
3000 Hz	15	18	20	26
/i/				
180 Hz	30	41	32	29
1000 Hz	23	37	12	22
2000 Hz	18	33	18	15
2500 Hz	18	21	17	15
3000 Hz	17	13	19	18
/o/				
180 Hz	26	22	45	32
1000 Hz	28	23	31	20
2000 Hz	21	17	19	26
2500 Hz	18	15	17	17
3000 Hz	18	14	20	21
/u/				
180 Hz	-	41	40	31
1000 Hz	-	32	27	31
2000 Hz	-	20	18	16
2500 Hz	-	28	16	11
3000 Hz	-	25	20	25

Table 7.39: Difference between both parts of the body which showed the minimum and maximum energy measured at 500 Hz and 180 Hz. The smallest difference is marked in green.

the fundamental frequency were found at the sternum (-33 dB) and at the right corner of the mouth (-9 dB), respectively (see the results at the fundamental shown in Table 7.1). The difference from both parts is therefore 24 dB, as written in Table 7.38 for CH at 250 Hz.

Now, let's see the results shown in Tables 7.38 and 7.39, especially at the frequencies where the smallest difference is marked in green. It is obvious that the difference is usually small in the frequency range between 2000 Hz and 3000 Hz and this holds true for all the pitches measured (except for both single cases, 90 Hz[6] and 380 Hz[7]), even though there is a variance in the results of the measurement at 500 Hz.

When considering the results according to pitch, at three pitches, 250 Hz and 120 Hz as well as 500 Hz, the difference is smallest for classical singers (CH, SE1 and JR) at the fundamental frequency (although that of SE2 is also small at 500 Hz). In the case of 250 Hz, the widest difference was shown by musical theater singers, especially the male musical theater singer (TF) often revealed a strong reduction of the difference between the fundamental frequency and the second frequency analyzed in all the cases where he was involved (at 120 Hz, 250 Hz and 380 Hz). Furthermore, it also appeared that the results can differ from vowel to vowel, as resulted in the cases of 500 Hz and 180 Hz – the results of SE1 and SS from the measurement at 500 Hz, as well as the results of SS and SE2 from the measurement at 180 Hz, revealed a difference of that kind at the fundamental frequency and the second frequency, which is in Tables 7.38 and 7.39. This means that the differences among the singers and the vowels often became smaller in the higher frequency range analyzed, in most cases, no matter how large these were.
This is caused by the fact that a wide difference of the radiation energy value among singers, which is often shown at the fundamental frequency, will generally diminish at higher frequencies, as displayed in Section 7.1. Because such a difference, which is usually shown at the fundamental frequency and occurs from various singing techniques, is mostly noticeable at the parts located far away from the mouth (e.g. the clavicles, sternum and the forehead). But the energy from those parts increases in the higher frequency range, even though low energy value was originally observed at the fundamental frequency by certain singers.

[6]The singing voice measured at 90 Hz was analyzed here only up to 1300 Hz, so that the smallest difference was found at the highest frequency analyzed, namely at 1300 Hz.

[7]In the case of 380 Hz, the localization of the smallest difference varied from vowel to vowel: for the vowels /a/e/i/ at 1500 Hz and for the vowel /o/ at 1000 Hz as well as for the vowel /u/ at 3000 Hz.

Therefore, in conclusion, as the results of this analysis revealed, not only the difference among singers but also among the parts of the body obviously became smallest, in most cases, in the frequency range between 2000 Hz and 3000 Hz due to a dynamic radiation energy increase in the higher frequency range.

7.4 Conclusion 2

1. General findings presented in this chapter

- **Dramatical energy increase at the parts located far away from the mouth**
  The chin and the corners of the mouth were the parts showing the strongest radiation of energy of the 14 measured parts of the body (except for the mouth radiation), as already shown in the previous chapter. The radiation from the chin remained almost unchanged in the whole frequency range analyzed, so that the difference between its maximum and minimum was quite small. However, it was found that the radiation energy of the parts of the body, that are located far away from the mouth, increases dramatically and is strongly in a fluctuation compared to the parts which are in the place near the mouth. This sometimes resulted in a difference of more than 20 dB between the maximum and minimum energies at these parts.

- **Change in radiated energy**
  The fact finding introduced in the previous chapter shows that the vowels /o/ and /u/ were much stronger in a fluctuation than the other vowels was emphasized by the analyses in this chapter. That is probably because a turbulent air flow occurred by the configuration of the vocal tract or/and narrow mouth opening. This appeared rather at low pitch than at high pitch that is sung, likely due to a wider mouth opening at higher pitch.

- **Relation of pitch and localization of the minimum and maximum energy**
  This investigation revealed a correlation between sung pitches and the change of the frequency range where the minimum of the radiated energy was located. In the cases of 90 Hz, 120 Hz, 180 Hz and 250 Hz, the minimum energy was located at the fundamental frequency, unlike the measurements at 380 Hz and 500 Hz where

this was not the case.
In contrast, the maximum of the radiated energy was mostly located in the frequency range from 3 kHz and this was almost unchanged at each pitch, even though the frequency range analyzed varied according to the pitch that was sung. However, this localization differs slightly from vowel to vowel.

- **Convergence of radiated energy values from all measured parts of the body**
From the analysis of the minimum and maximum energy of the measured parts, it was found that there is a convergence of radiated energy values from all these parts in the frequency range between 2 kHz and 3 kHz. This means that the difference among the parts is smallest there due to its energy increase compared to the mouth radiation.

- **Difference among the singers**
The difference among the singers was found to be smallest at the chin, even though there was a variance in the results of the measurement at the vowels /o/ and /u/. In the case of 250 Hz, CH, SE1 and SE2 revealed the smallest difference, whereas the largest difference was observed for SS. For the rest, a notable fact is that the difference shown at the chin and the forehead was generally very small for both female classical singers CH and SE1. In the case of 500 Hz, SE2 displayed the smallest difference in total.
But, in general, the difference of the radiated energy among the singers shown at the fundamental frequency becomes smaller at higher frequencies, even though a low energy value was shown at certain parts of the body in the beginning. Such a phenomenon is caused by a powerful energy increase of the subjects in the higher frequency range who actually revealed low energy values at their fundamental frequency.

- **Individually different sound radiation**
However, sound radiation of the singing voice seems to be very individual, as the sound of the singing voice itself is so individual, and depends rather on the singing technique of each singer than on musical genre. The singing technique is affected by the shape of the vocal tract and of the vocal folds, as well as how singer usually uses their voice while singing. Therefore, no certain characteristic in the radiation

pattern of each investigated singing technique which may systematically assign to a musical genre was found, although some small differences between classical and nonclassical singing styles were shown in the radiation energy, namely for the vowels /o/ and /u/ (see Section 6.3 of the previous chapter).

2. Comparison to previous research findings

- **Relation between vowel and radiation level**

  The results of my study on vowels were consistent with the findings by Gutzmann [34] and by Kirikae et al. [45] as well as the claim by Sundberg [68] that were introduced in Chapter 4, indicating the vibration/radiation level of the singing voice depends on the vowel that is sung. These findings are also identical with the results by Dunn & Farnsworth [22], Cabrera et al. [16], Stewart & Cabrera [64], Halkosaari [35], and Katz & d'Alessandro [44], who revealed the relation of vocal sound directivity to vowels.

  However, the assertion by Sundberg that the chest and throat vibration are unchanged for all vowels was not always confirmed by the findings of my investigation. For example, the results for the vowels /o/ and /u/ generally differed from the other vowels at these parts of the body, and popular singing also got different findings for each vowel.

  Furthermore, this claim by Sundberg "The closer the lip the stronger the vibration" was only verified for singing at 380 Hz by TF (tenor/high baritone, musical theater singing), thus not for every subject. However, this assertion "the narrower the lip opening, the stronger the skull vibration" (see Section 4.2) held true for my findings from the measurement at the forehead, although this occurred only a little bit for the vowels /o/ and /u/.

8 Result 3: Dimension of Total Radiation Energy from Measured Parts of the Body

The results of the measurement of the radiation energy of the singing voices and of the analyses presented in the last two chapters clearly showed that the sound energy of the singing voice also emits strongly from other parts of the body and that the radiation energy from certain parts is not as weak as expects.

For the analyses in this chapter, all the radiated energy measured at the 14 parts of the body (chin, throat, left and right clavicles, sternum, nose, nasal bone, left and right corners of the mouth, left and right cheeks, forehead, left and right lower eyelids), that were used for the statistical acquisition presented in Chapter 7, will be examined for another purpose. These radiation energies will be complied, in other words, to compare the total energy measured to that of the mouth.
By means of this comparative method, we can answer these questions:

- How strong is the sum of the radiated energy from all the measured parts of the body in relation to the mouth radiation?
- What about the radiation energy excluding the corners of the mouth?

The reason for the second analysis arose from the fact findings shown in the previous chapters that the radiation energy originated from the corners of the mouth has a strong influence on the total energy, not only because of the location of these parts close to the mouth, but also because of some strong, unbalanced results in the energy value from the corners of the mouth, so that the sides of the mouth showed stronger radiation energy than that from the mouth, as displayed heretofore. In fact, the radiation from the body locations, that were measured in pairs (on the left and the right), often revealed similar findings, but none other has such a huge influence on total energy due to high radiation energy from as the corners of the mouth. Therefore, additionally I would like to examine the total energy excluding the radiation energy from the corners of the mouth.

This comparison enables us to recognize how strong radiated energy from these parts affects the total energy emitted into the air and perceived by the listener.

8.1 Total Radiation Energy of the Measured Parts of the Body in Relation to the Mouth Radiation

Indeed, the mouth is usually the strongest power source of the singing voice, as expected. But conversely, the results showed in the previous chapter that the difference of both energy values, from the mouth and from the other parts measured, decreases in high frequencies. Therefore my questions are the following:

- How strong are the energies from other parts, if they will be added together?
- Can these be stronger than that from the mouth?
- If so, how strong is the energy?
- Is this added radiation energy still stronger than the energy from the mouth, even though the energy from the corners of the mouth, where strong energy value was measured, is not added to that?

Not all results will be displayed in this chapter, due to a large amount of data. Please see appendixes, which are referred to in each subsection.

8.1.1 Case Study 1: 250 Hz (B3)

Firstly, the results gained from all subjects singing at 250 Hz (B3) are discussed. Figures 8.1 and 8.2 show the relation between the total radiation acquired from all 14 measured parts of the body and the mouth radiation. It shows the results of the sung vowel /a/ displayed on the x-axis. All the results are compared to the mouth radiation, thus, this line above zero point means that the total radiation energy is stronger than the mouth radiation energy.

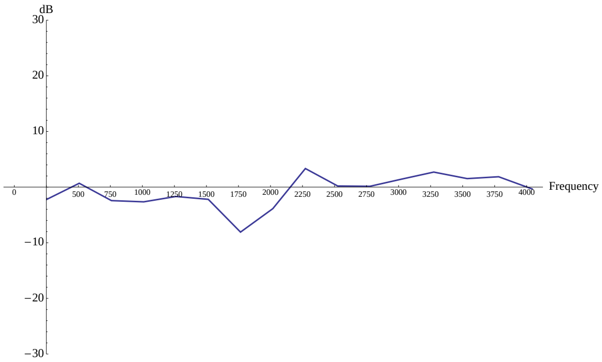
Looking at the results of this case study (see Figures 8.1 and 8.2), it is clear that the total radiation energy can generally exceed the mouth radiation energy, and each subject obtained this result (sole exception: JR for the vowel /i/). The duration of the course, how long this takes, and the starting point (frequency), where this state occurs, differ strongly from subject to subject: the total radiation of SE1, TF (for the vowels /a/ and /e/) and SE2 (for the vowels /e/i/o/) often showed exceeding or same energy values as the mouth radiation (i.e., at zero point on the x-axis) already from the fundamental frequency, whereas all the others revealed such a condition later, at a higher frequency. In most cases, the total radiation became stronger than the mouth radiation at around 2 kHz.

In other respects, we can see clearly here the process of the change in the energy value which was shown and discussed in the previous chapters. For example, the steep progress of the radiated energy by JR and SS in comparison to the mouth radiation, displayed in Figure 6.8, is here easily recognizable. Furthermore, the zigzag course for the vowels /o/ and /u/ was also distinctly shown in this analysis.

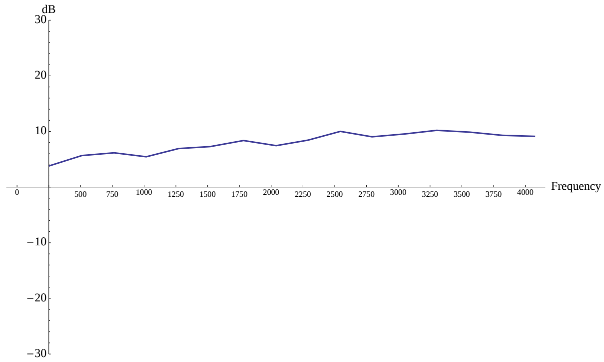
The total energy from the 14 parts of the body can indeed be stronger than the energy from the mouth. This implies that a great portion of the total sound energy of the singing voice which is radiated into the air comes from outside of the mouth. This occurrence nevertheless differs from subject to subject and also among the vowels, as shown above.

This finding is noteworthy and relevant to understanding the origin of the sound energy of the singing voice. However, I would like to point out that the energy from the corners of the mouth is included here where a strong energy value was measured, as shown in the previous chapters. Therefore, I will now show another analysis of the total radiation energy values from only 12 parts of the body, excluding the corners of the mouth.

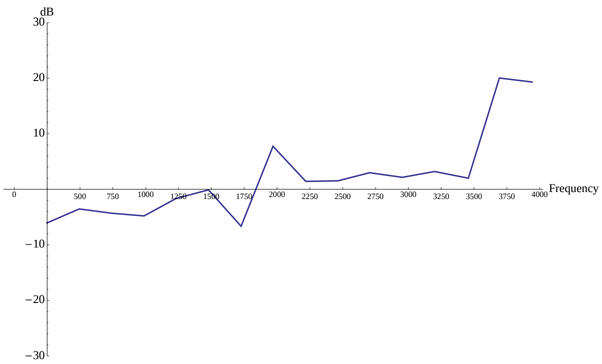
The results of this analysis revealed that the total radiation energy can still surpass the mouth radiation, although its energy value is distinctly reduced in comparison to the analysis including the corners of the mouth.



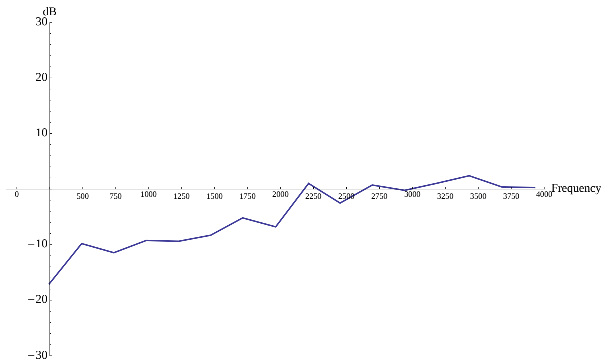
(a) CH (Alto)



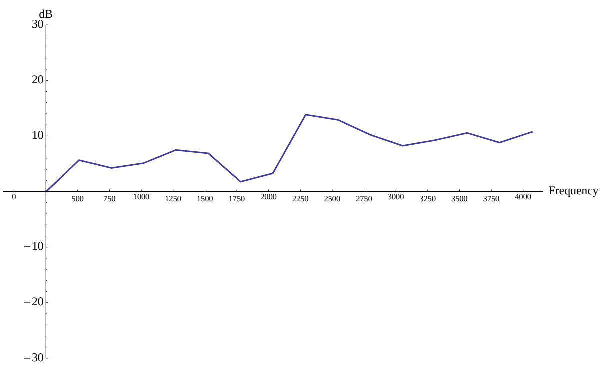
(b) SE1 (Soprano)



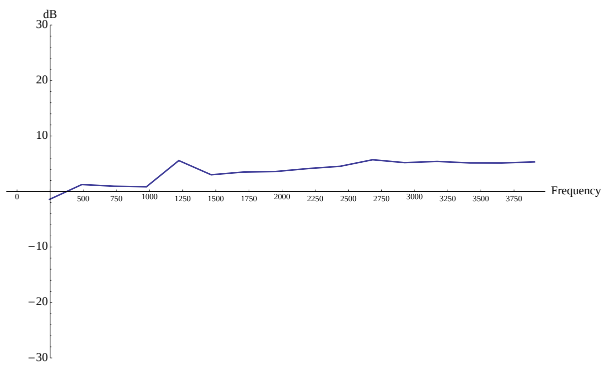
(c) JR (Bass)



(d) SS

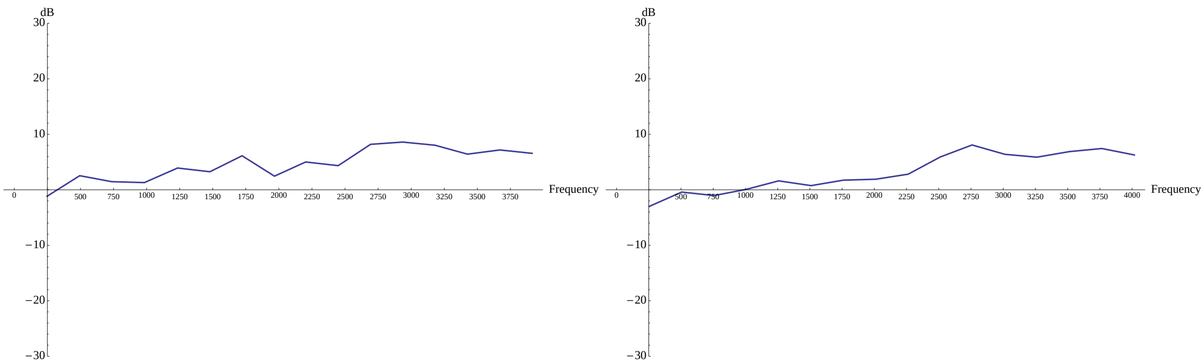


(e) TF



(f) SE2

Figure 8.1: Total radiation energy from 14 measured parts of the body compared to the mouth radiation for the vowel /a/ at 250 Hz.

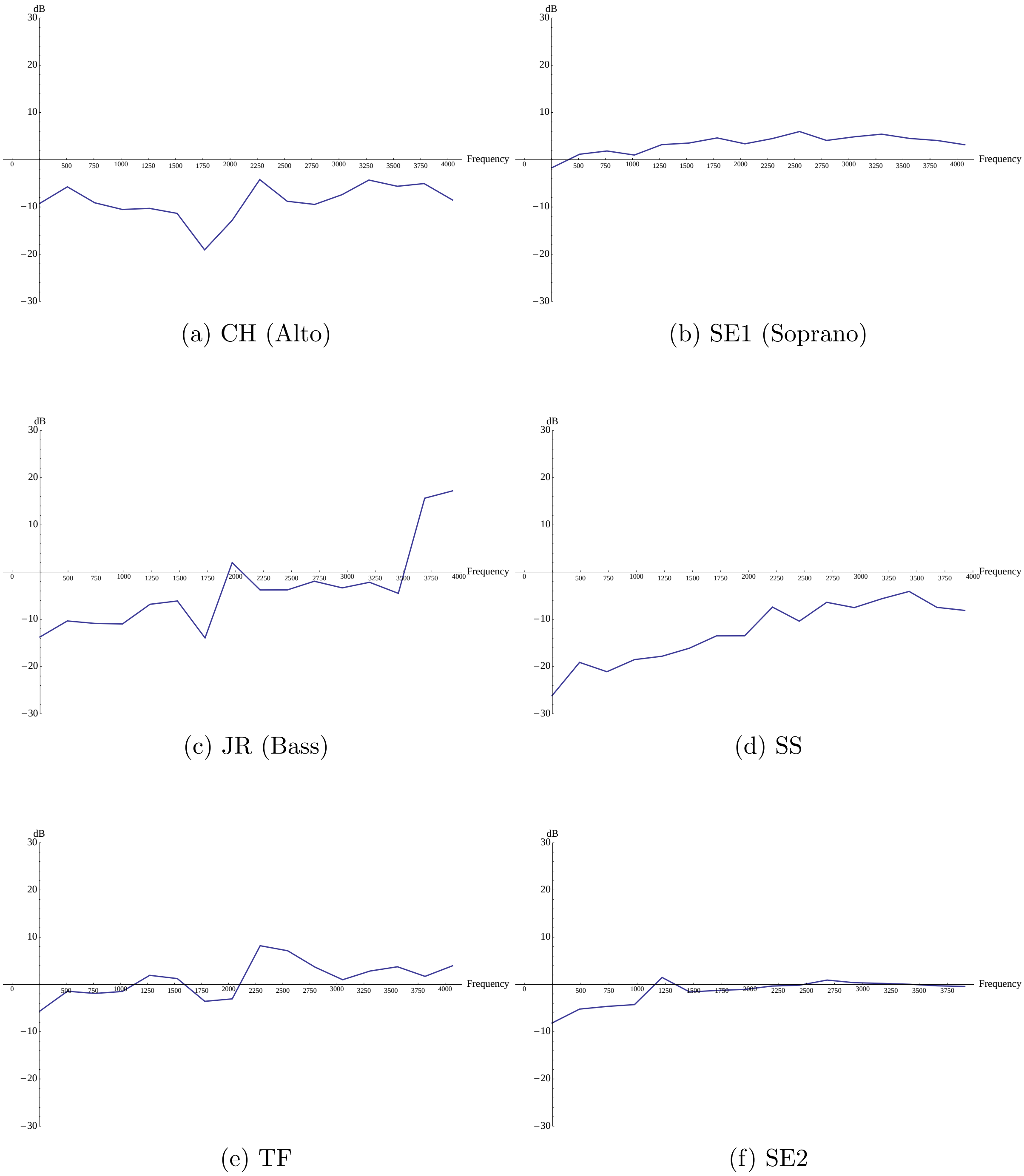


(a) VS (pop) (b) VS (soul)

Figure 8.2: Total radiation energy from 14 measured parts of the body compared to the mouth radiation for the vowel /a/ at 250 Hz.

At the fundamental frequency, it was observed that the radiation energy of the singing voice is dominated by the mouth radiation, because just SE1 reached the zero point, namely for the vowel /i/ only, unlike in the previous analysis. This indicates a strong influence of radiation energy from the corners of the mouth on the total radiation energy. This effect continues in the whole frequency range analyzed, so that the total energy remained generally weaker than that in the analysis which included the corners of the mouth. For this reason, only the total energy of the subjects, SE1 and TF (for the vowels /a/e/i/) as well as SE2 (except for the vowel /u/) exceeded their radiation energy from the mouth somewhere at a higher frequency. This energy remains relatively stable around zero point (see Figures 8.3 and 8.4). These subjects already revealed a strong total energy in the previous analysis (including the corner of the mouth). For all the other subjects, such an exceeding was seen at some frequencies (only briefly), or no exceeding is happened (for CH).

From all previous results, it is clear how the total radiation energy bears a relation to mouth radiation. In order to provide an overview, I would like to display the results from both analyses by subject in a list format here once again. At this point the results of three measured points (frequencies) – fundamental, minimum and maximum – from each analysis as well as the differences of both achieved energies will be drawn up the table.



(a) CH (Alto) (b) SE1 (Soprano)

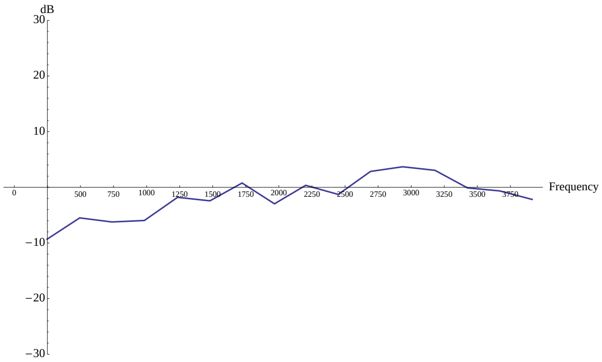
(c) JR (Bass) (d) SS

(e) TF (f) SE2

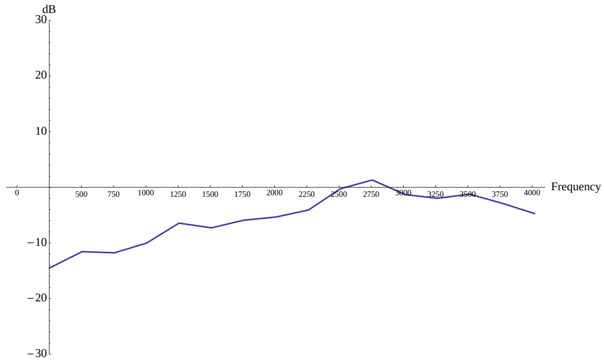
Figure 8.3: Total radiation energy excluding the energy from the corners of the mouth compared to the mouth radiation for the vowel /a/ at 250 Hz.

		With CoM			Without CoM			Difference		
Subject	Vowel	FF	Min	Max	FF	Min	Max	FF	Min	Max
CH	a	-2	-8	3	-9	-19	-4	7	11	7
	e	-3	-4	3	-10	-12	-2	7	8	5
	i	-1	-9	1	-9	-17	-4	8	8	5
	o	-14	-18	1	-23	-30	-7	9	12	8
	u	-11	-27	1	-21	-37	-8	10	10	9
SE1	a	3	3	10	-1	-1	5	4	4	5
	e	4	4	12	-1	-1	8	5	5	4
	i	4	4	11	0	0	7	4	4	4
	o	2	2	10	-3	-3	5	5	5	5
	u	-1	-11	4	-8	-27	-1	7	16	5
JR	a	-6	-6	20	-13	-13	17	7	7	3
	e	-11	-15	10	-20	-23	5	9	8	5
	i	-7	-8	4	-15	-15	-1	8	7	5
	o	-	-	-	-	-	-	-	-	-
	u	-10	-12	4	-18	-19	-2	8	7	6
SS	a	-17	-17	2	-26	-26	-4	9	9	6
	e	-12	-14	2	-25	-27	-7	13	13	9
	i	-17	-18	0	-39	-39	-8	22	21	8
	o	-22	-22	17	-38	-38	14	16	16	3
	u	-22	-22	10	-36	-37	4	14	15	6
TF	a	0	0	13	-5	-5	8	5	5	5
	e	0	0	9	-7	-7	3	7	7	6
	i	-6	-6	10	-9	-10	3	3	4	7
	o	-6	-10	4	-18	-20	-4	12	10	8
	u	-2	-3	8	-18	-19	-2	16	16	10
SE2	a	-1	-1	5	-8	-8	1	7	7	4
	e	1	-1	9	-6	-6	6	7	5	3
	i	0	0	10	-6	-6	7	6	6	3
	o	0	0	13	-10	-10	11	10	10	2
	u	-7	-9	3	-17	-19	-1	10	10	4
VS Pop	a	-1	-1	8	-9	-9	3	8	8	5
	e	-4	-4	4	-13	-13	1	9	9	3
	i	-8	-9	4	-15	-15	0	7	6	4
	o	-5	-5	10	-19	-19	6	14	14	4
	u	-	-	-	-	-	-	-	-	-
VS Soul	a	-2	-2	8	-14	-14	1	12	12	7
	e	-6	-6	8	-19	-19	4	13	13	4
	i	-11	-11	1	-21	-22	-4	10	11	5
	o	-3	-3	8	-21	-21	1	18	18	7
	u	-11	-11	6	-38	-38	0	27	27	6

Table 8.1: Table of the total radiation energy measured at the fundamental frequency (FF), the minimum (Min) and maximum (Max) energy points from both analyses including (with CoM) and excluding the energy from the corners of the mouth (without CoM) as well as the differences at 250 Hz (shown in dB).



(a) VS (pop)



(b) VS (soul)

Figure 8.4: Total radiation energy excluding the energy from the corners of the mouth compared to the mouth radiation for the vowel /a/ at 250 Hz.

From Table 8.1, it can be seen that the total energy of SE1 is the strongest in comparison to the mouth radiation and, by contrast, that of SS is the weakest. Otherwise in the case of VS, her Pop singing voice emitted more powerful total energy from outside of the mouth region than her Soul singing voice.

From the results shown in Figures 8.1, 8.2, 8.3 and 8.4, we already know that the total radiation energy can surpass the mouth radiation. However, when looking at the results given at the maximums, it is clear how strong the total energy can be in comparison to the mouth radiation: the fact findings of many subjects manifest that the total energy can be more than 10 dB louder than the mouth radiation at the maximums in the analysis including the energy from the corners of the mouth.

When it is comes to the difference in the results yielded from the two analyses (including and excluding the energy from the corners of the mouth), in total, the smallest difference was observed for SE1, everywhere at the fundamental frequency and the minimum, but also SE2 showed the smallest difference at the maximum (see Table 8.1). The process of change in the radiation energy by SE1 is quite stable except for the vowel /u/, as shown in Figures 8.1 and 8.3, so that no wide difference between the minimum and the maximum was found there.

In contrast to SE1 and SE2, SS and Soul singing of VS revealed a large difference between both analyses. When it comes to the results of SE1 and SE2, there was no large difference among the vowels, except for the vowel /u/, at the fundamental frequencies and the minimums in the analysis including the energy from the corners of the mouth (also at the maximums of SE1). For the vowel /u/, TF revealed the strongest energy value at his fundamental frequency and minimum, but this is a special case and all the other subjects usually showed distinctly weaker energy values for this vowel than for all the other vowels, especially in the cases of CH and SS, as shown in Table 8.1. Such energy intensity naturally differs from singer to singer independent of the vowel, in other words, it is different due to a singer's own singing technique. But it seems that the total radiation energy of the vowel /u/ and often also the vowel /o/ strongly depends on the radiation energy from the corners of the mouth. This can be clearly perceived when looking at the difference given by both analyses, including and excluding the energy from the corners of the mouth, at their fundamental frequencies and minimums: for both vowels /o/ and /u/, the decrease of the total energy excluding the energy from the corners of the mouth is considerably larger than for all the other vowels and the difference is often more than 10 dB. Such large difference was observed almost nowhere at the maximums, surprisingly.

The radiation energy of the sung vowels /o/ and /u/ is generally weaker than all the other vowels, as we already saw in the previous chapters. But at this point, it became clear that the total energy of both vowels is strongly affected by the radiation from the mouth area. The fact that their radiation energy is often steadily in a fluctuation can be seen in the results shown in Table 8.1. The difference between the minimum and the maximum is very large in both analyses, particularly for the vowel /u/ (for example, in the analysis including the energy from the corners of the mouth, the total energy of the sung vowel /u/ by CH, compared to the mouth radiation, is -27 dB at the minimum but 1 dB at the maximum). In particular, the process of SS changed dramatically in energy value, so that her total radiation energy showed very high energy values at the maximums, when singing both vowels, although the total energy was very low at the fundamental frequency and the minimum. For all the other vowels, her findings also revealed a wide change in the radiated energy, but nothing as extreme as these.
Interestingly, in total, such difference between the analyses, including and excluding the energy from the corners of the mouth, among the vowels was hardly recognizable at the maximum energy point.

Table 8.1 shows the results from both analyzed points, the fundamental frequency and the minimum, separately, but in fact, the minimum values were mostly found at the fundamental frequency, as already mentioned in Subsection 7.2.1 of the previous chapter. Only in the case of CH, different results were observed.

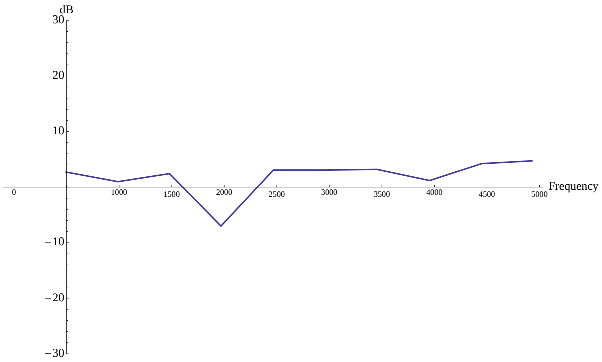
8.1.2 Case Study 2: 500 Hz (B4)

We will see the results gained from the measurement at 500 Hz (B4) where only female singers took part. First of all, it shows the whole process of the total radiation energy including the energy from the corners of the mouth, when singing the vowel /a/, compared to the mouth radiation (see Figure 8.5).

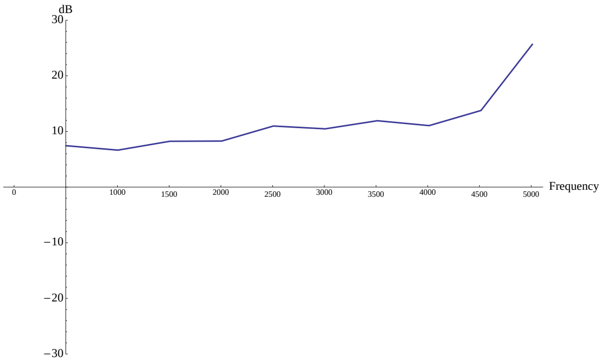
When looking at the results of the vowel /a/ from the measurement at 500 Hz and comparing these with those from the measurement at 250 Hz, it seems that the total radiation energy of the former is stronger than that of the latter, especially at the fundamental frequency. Most of the subjects, except for SS, showed their total radiation above zero point on the x-axis already from the fundamental frequency for nearly all the vowels.
Otherwise, the total energy of SE2 is distinctively stronger here than in the case of 250 Hz and the fluctuation of the total radiation energy measured at 500 Hz generally proceeded similar to the case of 250 Hz – for example, the stable process of the radiation energy observed in the case of SE1 and SE2 and the dynamic change in the total radiation energy shown for the vowel /u/ sung by CH and SS.

When looking at the results of the analysis excluding the energy from the corners of the mouth, the total energy compared to the mouth radiation energy was stronger than in the case of 250 Hz, just as the analysis including the energy from the corners of the mouth (see Figure 8.6). This implies that this increasing total energy, which is occurred for singing at higher pitch, did not come particularly from the corners of the mouth. Otherwise, the results of this analysis would show a change in ratio between the total radiation energy and the mouth radiation energy, in other words, a distinct decrease would be given in the total energy due to the absence of the energy from the corners of the mouth.

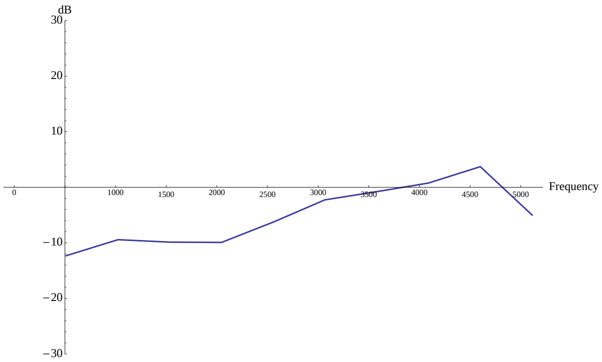
As mentioned above, the total energy excluding the energy from the corners of the



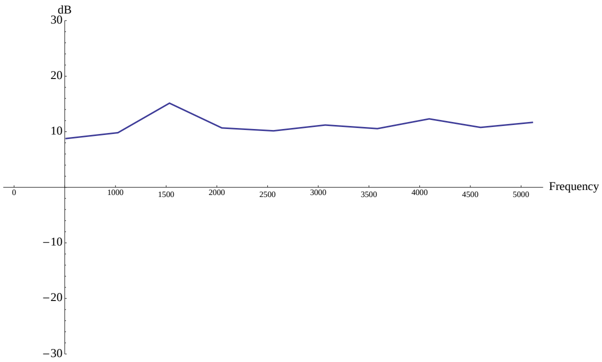
(a) CH (Alto)



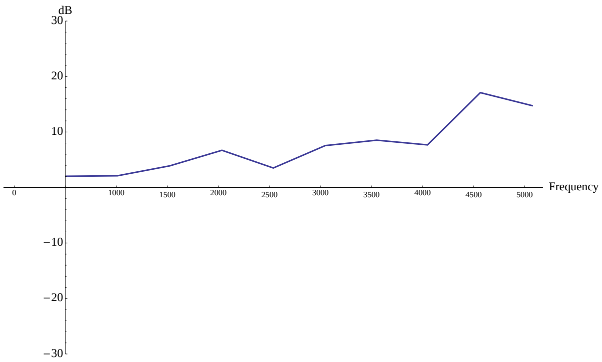
(b) SE1 (Soprano)



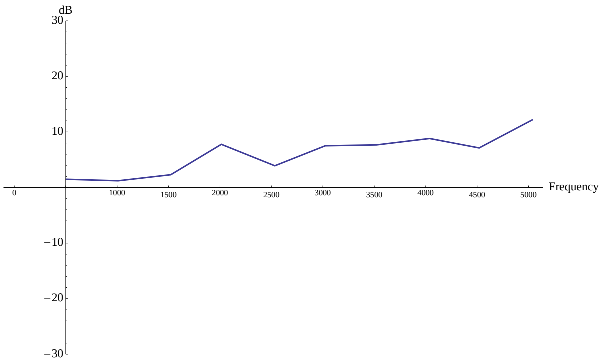
(c) SS



(d) SE2

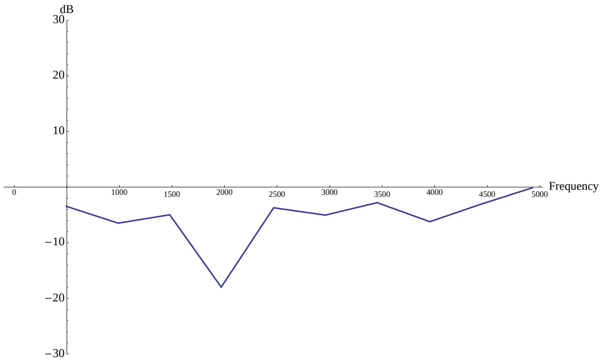


(e) VS (pop)

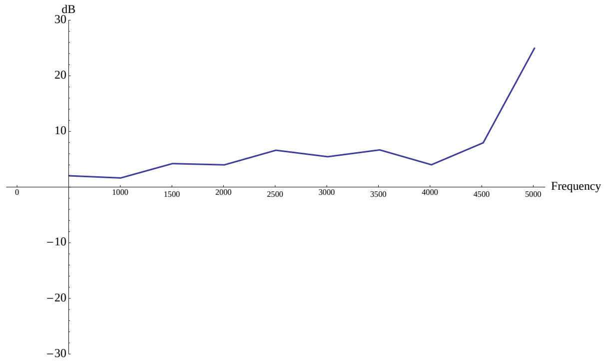


(f) VS (soul)

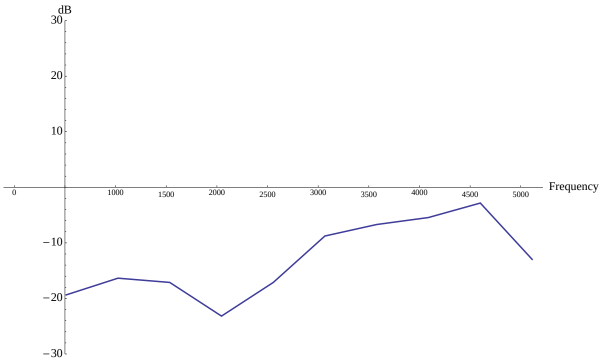
Figure 8.5: Total radiation energy from 14 measured parts of the body compared to the mouth radiation for the vowel /a/ at 500 Hz.



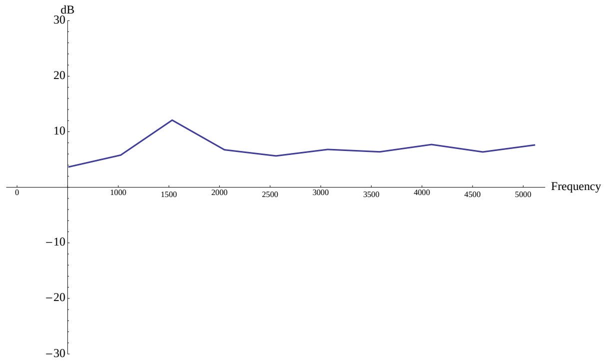
(a) CH (Alto)



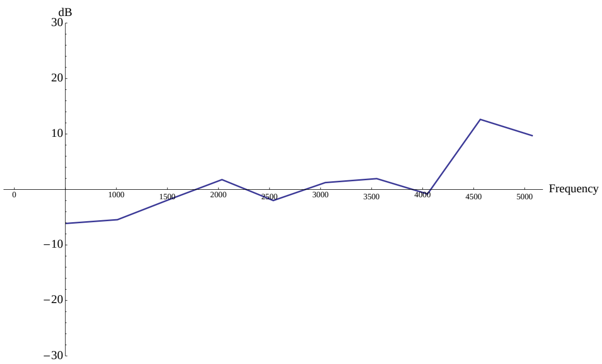
(b) SE1 (Soprano)



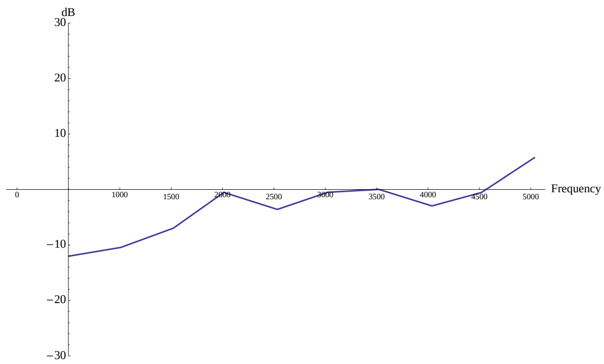
(c) SS



(d) SE2



(e) VS (pop)



(f) VS (soul)

Figure 8.6: Total radiation energy excluding the energy from the corners of the mouth compared to the mouth radiation for the vowel /a/ at 500 Hz.

		With CoM			Without CoM			Difference		
Subject	Vowel	FF	Min	Max	FF	Min	Max	FF	Min	Max
CH	a	2	-7	4	-3	-17	0	5	10	4
	e	0	0	2	-5	-10	-3	5	10	5
	i	2	-2	5	-3	-9	0	5	7	5
	o	-4	-20	5	-11	-32	0	7	12	5
	u	-11	-23	3	-21	-34	-5	10	11	8
SE1	a	7	6	25	2	1	24	5	5	1
	e	5	5	13	0	0	6	5	5	7
	i	7	3	13	2	-1	6	5	4	7
	o	6	1	12	-1	-5	7	7	6	5
	u	6	-2	11	0	-9	6	6	7	5
SS	a	-12	-12	3	-19	-23	-2	7	11	5
	e	-13	-13	6	-19	-19	1	6	6	5
	i	-9	-9	7	-15	-18	2	6	9	5
	o	-20	-20	2	-40	-40	-5	20	20	7
	u	-18	-18	-3	-34	-34	-10	16	16	7
SE2	a	8	8	15	3	3	12	5	5	3
	e	8	8	14	3	3	10	5	5	4
	i	8	6	14	3	1	10	5	5	4
	o	6	3	10	1	0	6	5	3	4
	u	4	4	11	-2	-2	7	6	6	4
VS Pop	a	2	2	17	-6	-6	12	8	8	5
	e	0	-2	12	-11	-11	5	11	9	7
	i	0	-4	10	-9	-13	4	9	9	6
	o	0	-8	9	-13	-20	2	13	12	7
	u	-	-	-	-	-	-	-	-	-
VS Soul	a	1	1	12	-11	-11	5	10	10	7
	e	-4	-4	9	-17	-17	3	13	13	6
	i	-9	-10	6	-22	-25	0	13	15	6
	o	2	1	11	-13	-13	2	15	14	9
	u	-	-	-	-	-	-	-	-	-

Table 8.2: Table of the total radiation energy measured at the fundamental frequency (FF), the minimum (Min) and maximum (Max) energy points from both analyses including (with CoM) and excluding the energy from the corners of the mouth (without CoM) as well as the differences 500 Hz (shown in dB).

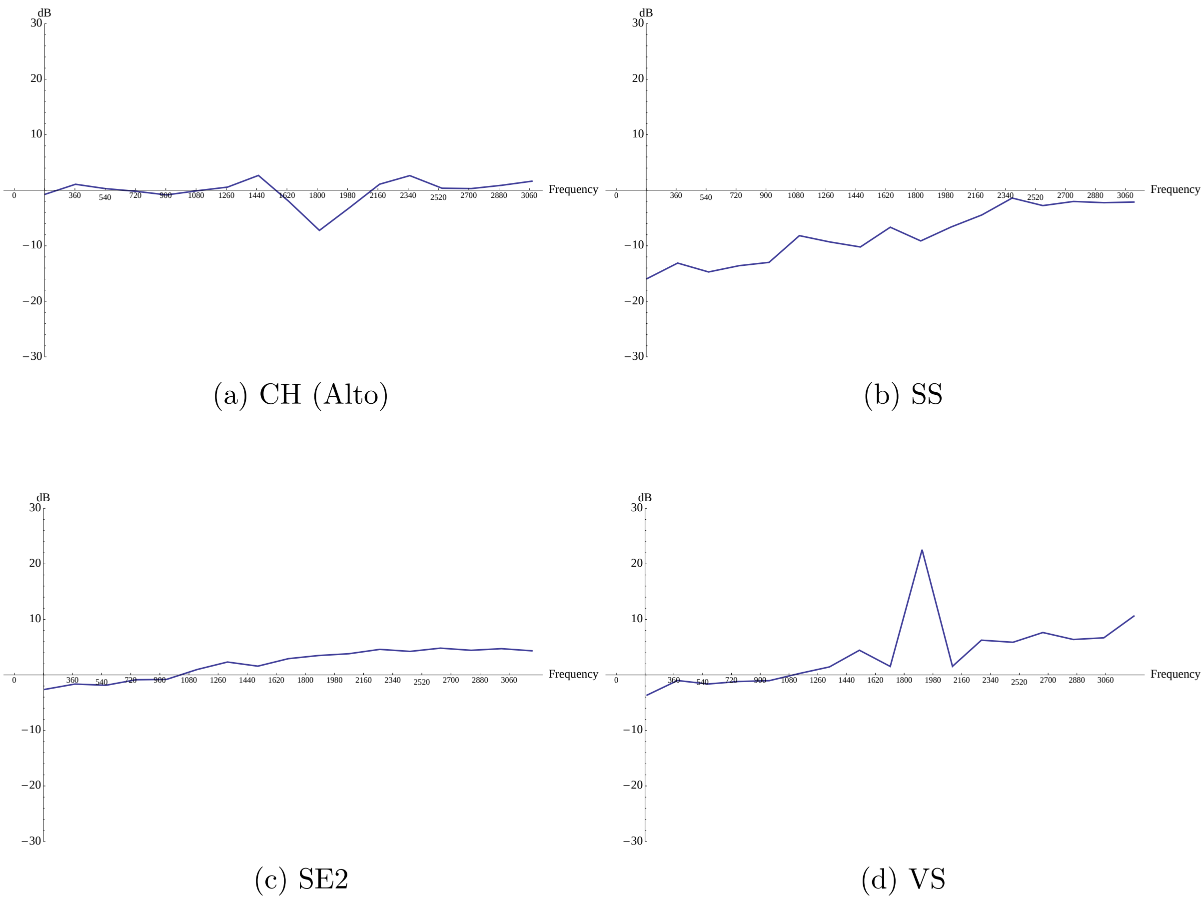
mouth is stronger than that from 250 Hz, even though a great influence of the energy from the corners of the mouth on the total energy was also observed here. However, the total radiation exceeded the mouth radiation already from the fundamental frequency in the cases of SE1 (except for the vowel /o/) and SE2 (except for the vowel /u/). The total energy of most of the other subjects also reached a higher energy value than that from the mouth radiation, but only at higher frequencies – in most cases, briefly at around 2000 – 3000 Hz or/and from 4500 Hz, as shown in Figure 8.6. The presence of such a strong total energy in the high frequency range was already noticed in the case of the 500 Hz, as shown in Subsection 6.2.1 of the previous chapter.

But we can best detect such differences in the results of both measurements (250 Hz and 500 Hz) in Table 8.2, where the total energy values are shown, measured at the fundamental frequency, the minimum and the maximum. The strongest total energy was observed for SE1 and SE2 in both analyses (including and excluding the corners of the mouth) and these analyses reveal that the maximum total energy is overall more powerful than that in the case of 250 Hz, particularly in the case of SE1 (for the vowel /u/), SS (for the vowel /i/) and SE2 (for the vowels /a/ and /u/). On the other side, the results of the vowels /o/ and /u/ sung by SS revealed a decrease at her maximum in comparison to her results of the measurement at 250 Hz in both analyses.
Furthermore, a large dependence of the total energy on the radiation from the mouth region for the vowels /o/ and /u/, which was observed in the case of 250 Hz, seems to be reduced here, as shown in Table 8.2, so that only SS yielded such a result for these vowels.

Additionally, the following subjects showed a change in the total energy value between both measurements: CH (for the vowel /o/), SE1 (for the vowel /u/), SS (for the vowel /i/), VS in Pop singing (for the vowels /i/o/u/) and in Soul singing (for the vowels /o/ and /u/). In short, some differences were observed for the vowels /i/ and /o/ as well as /u/, rather than for the vowels /a/ and /e/, and in all these cases, the energy only increased. Particularly the increase revealed by SS for the vowel /i/ was striking: for example at the fundamental frequency, from -17 dB to -9 dB in the analysis including the energy from the corners of the mouth and from -39 dB to -15 dB in another analysis.

8.1.3 Case Study 3: 180 Hz (F3#)

In the following, the results of the measurements at 180 Hz (F3#) sung by alto or mezzo sopranos will be discussed. These results do not differ widely from those given at 250 Hz, probably because of the closeness of the two frequencies. Concerning the differences in the results between both measurements, the total energy of this case was generally somewhat weaker and the change in the radiated energy was more recognizable for the vowel /i/ than in the case of 250 Hz, just like for the vowels /o/ and /u/ (see Figures 8.7 and 8.8). For this vowel, SS revealed an increase in comparison to her energy value shown at 250 Hz, whereas SE1 and VS displayed a decreasing energy in this case study.

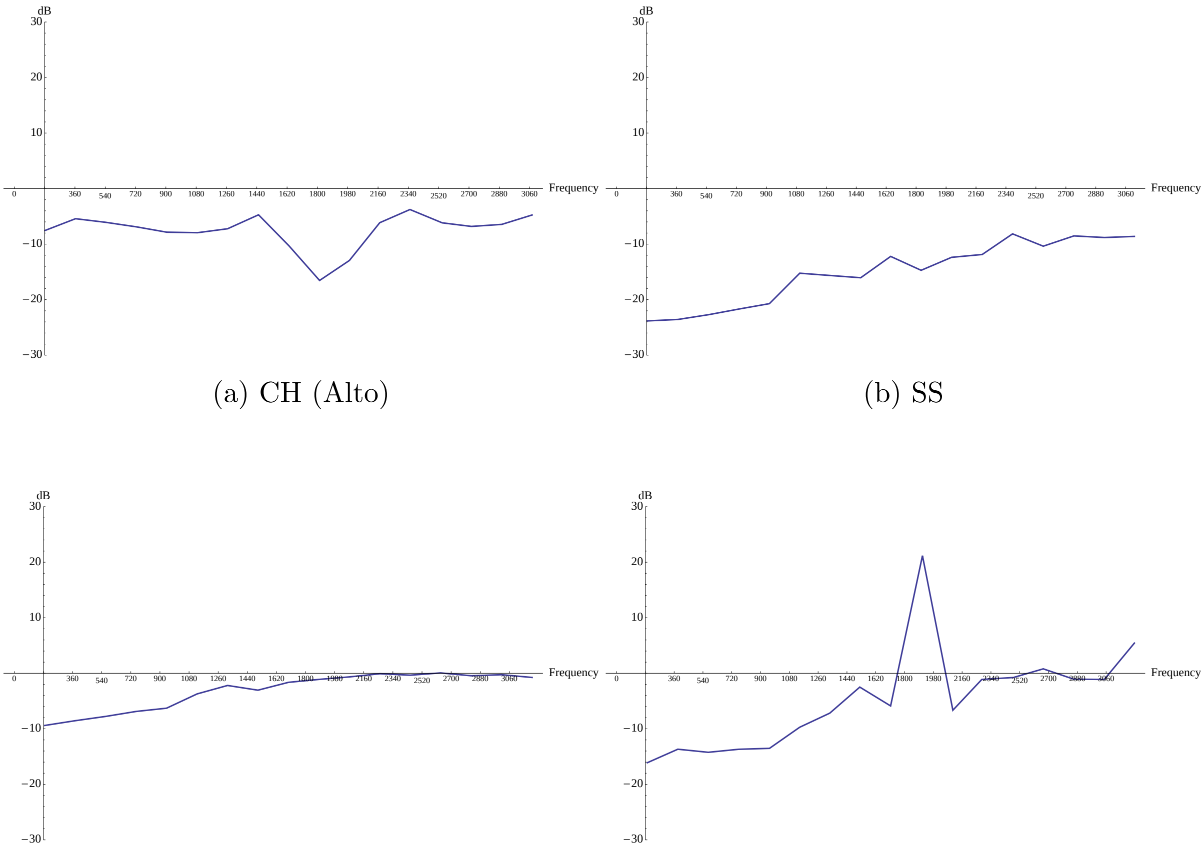


(a) CH (Alto) (b) SS

(c) SE2 (d) VS

Figure 8.7: Total radiation energy from 14 measured parts of the body compared to the mouth radiation for the vowel /a/ at 180 Hz.

Analyzing the results. in the case including the energy from the corners of the mouth, the total energy mostly exceeded the mouth radiation energy at any point, even though CH was the only one who showed equal energy values both in total radiation energy and in mouth radiation energy starting from the fundamental frequency (for the vowels /a/ and /i/). The total radiation of the other subjects, in many cases, became stronger than their mouth radiation from around 1 kHz, as displayed in Figure 8.7.



(a) CH (Alto)

(b) SS

(c) SE2

(d) VS

Figure 8.8: Total radiation energy excluding the energy from the corners of the mouth compared to the mouth radiation for the vowel /a/ at 180 Hz.

In another analysis, only some cases, SE2 (for the vowels /a/e/i/) SS as well as VS (both subjects for the vowel /u/), revealed stronger total energy than the mouth radiation at the zero point on the x-axis for a while, but for the rest, the total energy surpassed the mouth radiation just infrequently or not a bit (see Figure 8.8) in the whole

		With CoM			Without CoM			Difference		
Subject	Vowel	FF	Min	Max	FF	Min	Max	FF	Min	Max
CH	a	0	-7	2	-7	-16	-3	7	9	5
	e	-1	-3	1	-7	-11	-7	6	8	8
	i	0	-2	3	-7	-10	-2	7	8	5
	o	-17	-21	11	-27	-32	8	10	11	3
	u	-	-	-	-	-	-	-	-	-
SS	a	-15	-15	-1	-23	-23	-8	8	8	7
	e	-10	-14	0	-19	-21	-6	9	7	6
	i	-1	-9	17	-19	-22	4	18	13	13
	o	-22	-22	7	-34	-34	2	12	12	5
	u	-18	-23	12	-32	-38	3	14	15	9
SE2	a	-2	-2	4	-9	-9	0	7	7	4
	e	-2	-2	6	-8	-8	2	6	6	4
	i	-4	-4	17	-11	-11	13	7	7	4
	o	-8	-8	2	-21	-21	-4	13	13	6
	u	-6	-6	9	-16	-16	6	10	10	3
VS	a	-3	-3	22	-16	-16	21	13	13	1
	e	-10	-10	7	-25	-25	1	15	15	6
	i	-18	-18	5	-30	-30	1	12	12	4
	o	-11	-11	9	-29	-29	5	18	18	4
	u	-5	-11	15	-12	-25	11	7	14	4

Table 8.3: Table of the total radiation energy measured at the fundamental frequency (FF), the minimum (Min) and maximum (Max) energy points from both analyses including (with CoM) and excluding the energy from the corners of the mouth (without CoM) as well as the differences at 180 Hz (shown in dB).

frequency range analyzed.

When looking at the results shown at the fundamental frequency and the minimum as well as the maximum of both analyses in Table 8.3, it can be seen in many cases that the total energy excluding the energy from the corners of the mouth still reached stronger values at the maximum than the mouth radiation energy, just like in the case of 250 Hz. Interestingly, the total energy of CH is the strongest of all the subjects at the fundamental frequency, especially in the analysis excluding the energy from the corners of the mouth, but surprisingly weak at the maximum energy point. That is because her radiation energy remained almost unchanged in the whole frequency range (except for the vowel /o/), while the energy of all the other singers increased and were also in strong fluctuation (see Figures 8.7 and 8.8).

For the rest, the difference found in the results of both analyses also revealed, for the vowels /o/ and /u/ in this case study, that the total radiation strongly depends on the radiation energy from the mouth region (by the mouth and the corners of the mouth), as the total radiation measured at the fundamental frequency and the minimum displayed under the category “difference” in Table 8.3 which indicates the difference of the energy values between both analyses. Such a difference among vowels was not observed at the maximum. But the singing voice of VS seems to be mostly radiated from the mouth region for each vowel, because her difference was very large there in comparison with all the other singers.

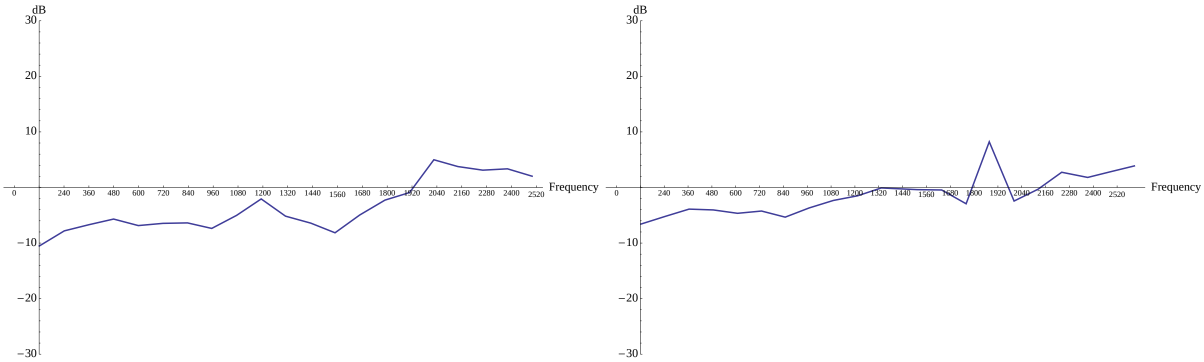
8.1.4 Case Study 4: 120 Hz (B2)

Now the results of the measurement at 120 Hz (B2) in which the male subjects took part will be discussed here. It is already clear from the former chapters as well as from the previous case studies shown in this chapter that the radiation energy level generally depends on the pitch that is sung, as the comparison of the results from the various pitches shows. Concerning this case study, because both male subjects sang at the pitch (120 Hz), that is about one octave lower than that in the case of 250 Hz, the total radiation energy yielded from this measurement is thus also weaker than that from the case study of 250 Hz (see Figure 8.9).

When looking at the results of the total radiation, we see that none of the resulting total radiation energies exceeded the mouth radiation energy or is in line with that from the beginning of singing, but often not until around 2 kHz (see Figure 8.9). The total energy of the vowels /o/ and /u/ revealed a strong fluctuation, as often shown in this work.

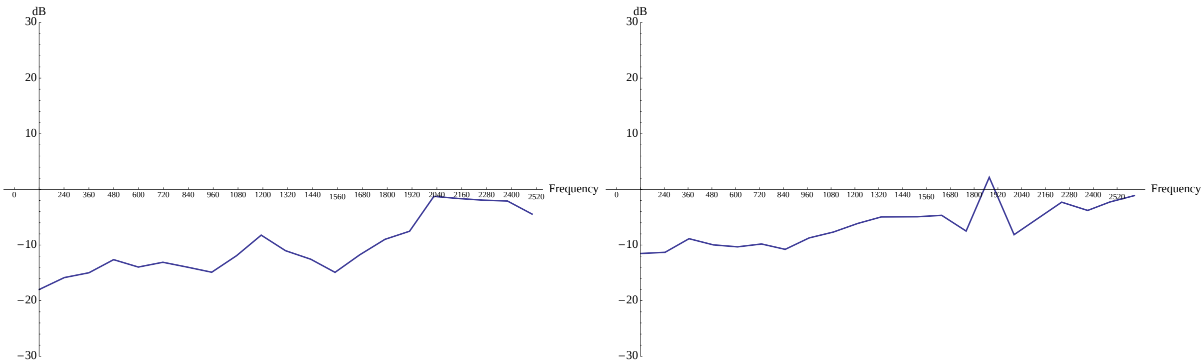
Regarding the analysis excluding the energy from the corners of the mouth, only the total energy of the vowels /a/ and /i/ sung by TF exceeded the mouth radiation at a frequency in the whole frequency range analyzed (the total energy of the vowel /a/ sung by JR and the vowel /u/ by TF reached zero on the x-axis, see Figure 8.10).

For most of the results introduced in this case study, we can see clearly in Table 8.4: the radiated energy is, yielded in both analyses, much weaker than that of 250 Hz in comparison to the mouth radiation. In particular, the total radiation of TF is



(a) JR (Bass) (b) TF

Figure 8.9: Total radiation energy from 14 measured parts of the body compared to the mouth radiation for the vowel /a/ at 120 Hz.



(a) JR (Bass) (b) TF

Figure 8.10: Total radiation energy excluding the energy from the corners of the mouth compared to the mouth radiation for the vowel /a/ at 120 Hz.

		With CoM			Without CoM			Difference		
Subject	Vowel	FF	Min	Max	FF	Min	Max	FF	Min	Max
JR	a	-10	-10	4	-17	-17	0	7	7	4
	e	-13	-13	-1	-21	-21	-7	8	8	6
	i	-13	-14	-2	-22	-23	-10	9	9	8
	o	-13	-14	1	-22	-22	-3	9	8	4
	u	-12	-14	0	-22	-24	-6	10	10	6
TF	a	-6	-6	8	-11	-11	2	5	5	6
	e	-6	-8	1	-13	-15	-3	7	7	4
	i	-6	-7	5	-13	-13	1	7	6	4
	o	-6	-15	3	-15	-32	-5	9	17	8
	u	-10	-12	6	-20	-30	0	10	18	6

Table 8.4: Table of the total radiation energy measured at the fundamental frequency (FF), the minimum (Min) and maximum (Max) energy points from both analyses including (with CoM) and excluding the energy from the corners of the mouth (without CoM) as well as the differences at 120 Hz (shown in dB).

reduced about 10 dB for the vowels /o/ and /u/ at the minimum energy point in the analysis excluding the energy from the corners of the mouth. Furthermore, the fact that his difference in the total energy between both analyses, shown at the fundamental frequency and the minimum under the category "difference," is larger for both vowels than for the other vowels emphasizes a strong dependence on radiation energy from his mouth region for these vowels.

8.1.5 Case Study 5: 90 Hz (approx. F2#) and 380 Hz (approx. F4#)

I will show the results gained from two experiments where JR (bass) sang at 90 Hz (F2#) and TF (high baritone/tenor) sang at 380 Hz (F4#), respectively.

When it comes to the results of the analysis including the energy from the corners of the mouth, the total energy level of JR was somewhat stronger than that at 120 Hz (see Figure 8.11). Such a finding, that the radiation energy from singing at lower pitch may be stronger than that at higher pitch due to a small distance of both frequencies, also ascertained in a few cases measured at 180 Hz, when comparing these results with the results shown in the case of 250 Hz.

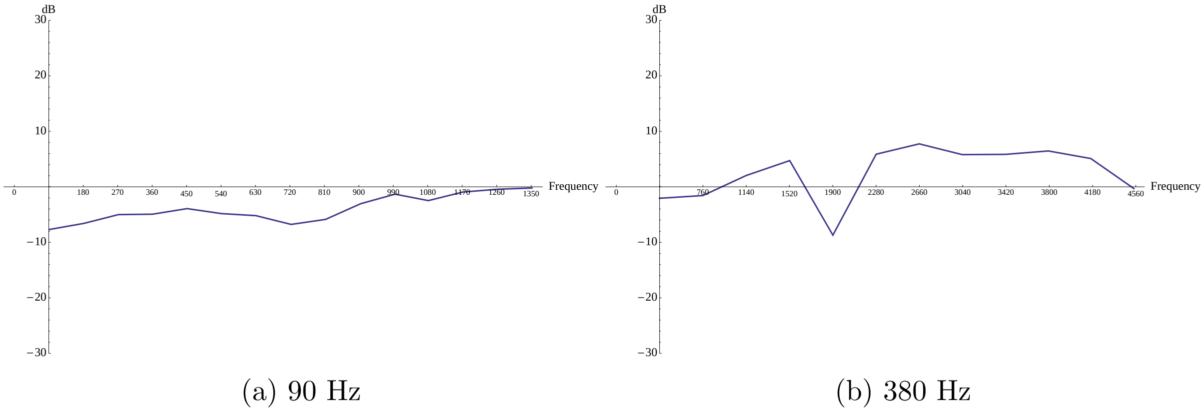
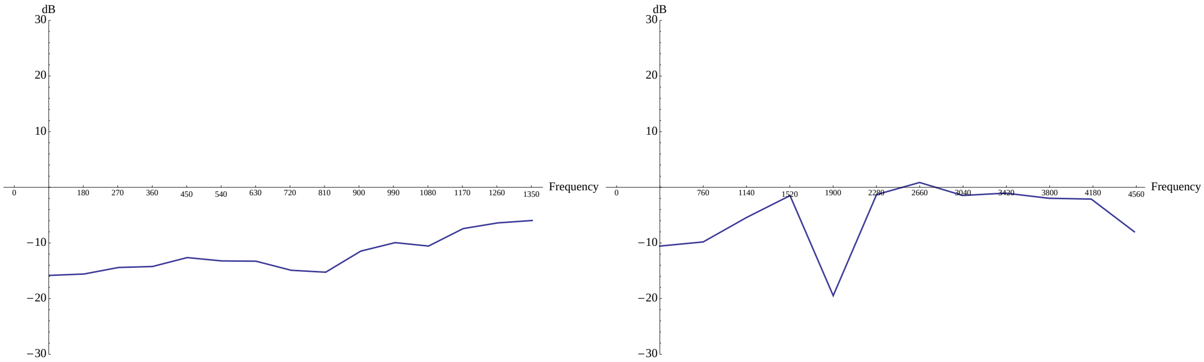


Figure 8.11: Total radiation energy from 14 measured parts of the body compared to the mouth radiation for the vowel /a/ sung at 90 Hz by a classical bass singer (JR) and sung at 380 Hz by a high baritone/tenor musical theater singer (TF).

In other respects, the vowel /i/ was the only one where his total radiation clearly exceeded the mouth radiation, although the total energy of the vowels /a/ and /e/ also surpassed the zero point or is close to that at some frequencies. The fact that the total radiation energy measured at 90 Hz is weak, compared to the other pitches analyzed, can be also recognized in the results shown left in Table 8.5.

Just as the outcomes for JR, in total, TF revealed a distinctively stronger total radiation at 380 Hz (except for the vowel /a/) than in the other case studies where his singing voice was also examined carefully. His total radiation exceeded his mouth radiation well, although this did not occur at the fundamental frequency, as shown in Table 8.6 (see also Figure 8.11).

When analyzing the findings from another study (excluding the energy from the corners of the mouth), the total energy of JR remained weaker than his mouth radiation energy in the whole frequency range, whereas that of TF was generally stronger than his mouth radiation, namely mostly for a while (see Figure 8.12). As shown in Table 8.6, the total radiation of TF is higher than the mouth radiation at the maximum for all the vowels. When comparing the results of the total energy measured at the fundamental frequency, the minimum and the maximum shown in the table, it was determined that



(a) 90 Hz　　(b) 380 Hz

Figure 8.12: Total radiation energy excluding the energy from the corners of the mouth compared to the mouth radiation for the vowel /a/ sung at 90 Hz by a classical bass singer (JR) and sung at 380 Hz by a high baritone/tenor musical theater singer (TF).

the outcome of the vowel /i/, sung by JR at 90 Hz, is often 10 dB stronger than that from the measurement at 120 Hz. But on the other hand, for the vowels /a/ and /e/, the outcome was up to 20 dB weaker at the maximum in comparison to the findings in the case of 250 Hz (see Tables 8.4 and 8.1).

When it comes to the case of TF, when excluding the energy from the corners of the mouth, analysis of his results of the vowel /o/ at 380 Hz shown that this is 10 dB stronger than his result given at 250 Hz. Furthermore, the results were also more powerful for the vowels /i/ and /o/ in relation to the total radiation energy measured at 120 Hz, in both analyses including and excluding the energy from the corners of the mouth.

		With CoM			Without CoM			Difference		
Subject	Vowel	FF	Min	Max	FF	Min	Max	FF	Min	Max
JR	a	-7	-7	0	-15	-15	-5	8	8	5
	e	-7	-7	0	-15	-16	-9	8	9	9
	i	-4	-7	12	-14	-15	0	10	8	12
	o	-10	-10	-3	-20	-20	-9	10	10	6
	u	-12	-12	-1	-21	-21	-6	9	9	5

Table 8.5: Table of the total radiation energy measured at the fundamental frequency (FF), the minimum (Min) and maximum (Max) energy points from both analyses including (with CoM) and excluding the energy from the corners of the mouth (without CoM) as well as the differences at 90 Hz (shown in dB).

		With CoM			Without CoM			Difference		
Subject	Vowel	FF	Min	Max	FF	Min	Max	FF	Min	Max
TF	a	-2	-8	7	-10	-19	0	8	11	7
	e	0	0	9	-7	-7	4	7	7	5
	i	-1	-1	11	-4	-5	5	3	4	6
	o	1	-2	12	-8	-12	6	9	10	6
	u	-	-	-	-	-	-	-	-	-

Table 8.6: Table of the total radiation energy measured at the fundamental frequency (FF), the minimum (Min) and maximum (Max) energy points from both analyses including (with CoM) and excluding the energy from the corners of the mouth (without CoM) as well as the differences at 380 Hz (shown in dB).

8.2 Conclusion 3

- **Total energy from all the measured parts of the body can exceed the energy from the mouth**
  All the subjects showed that total energy of their singing voices can exceed the energy from the mouth. But the energy level strongly depends on the frequency analyzed, the vowel and the pitch that was sung. The facts are generally that 1) the higher the frequency, the stronger the total radiation energy from the parts of the body in comparison to the energy from the mouth, and that 2) the higher the sung pitch, the stronger the total radiation energy from the parts of the body. The energy of the vowels /o/ and /u/ seems to be mostly radiated from the mouth.

- **Total energy of singing voice is strongly affected by the corners of the mouth**
  Comparing the radiated energy from the mouth with the total energy from all the parts excluding the energy from the corners of the mouth, it was clear that the energy from the corners of the mouth has a strong influence on the total energy of the singing voice. But this varied among the vowels, so that this influence seems to be strong particularly for the vowels /o/ and /u/.

- **Total energy from the parts of the body excluding the energy from the corners of the mouth can nevertheless be stronger than the mouth radiation**
  In spite of the absence of the radiation energy from the corners of the mouth, it was shown that the total energy can also exceed the energy from the mouth. Such an appearance was mostly not obvious at the fundamental frequencies, but often at the maximum energy point. This emerged either as a temporary occurrence or as a continuing phenomenon at higher frequencies.

- **Hardly any changes in the energy difference among the pitches in both analyses between including and excluding the energy from the corners of the mouth**
  In the analyses including and excluding the energy from the corners of the mouth, when looking at the individual results of each subject at all the pitches measured (shown under the category "difference" in the tables), there were no large energy

differences among the pitches everywhere as a result. This means that the relation between the total radiation energy and the mouth radiation generally remains the same, independent of the pitch that is sung. Additionally, this relation was independent of whether the total energy is generally strong or weak, i.e. the energy level has no significant influence on the relation.

- **Difference of the analyses between including and excluding the energy from the corners of the mouth given at the maximum energy point is hardly recognizable among the vowels as well as the singers**
  Furthermore, when comparing the outcome including the energy from the corners of the mouth with that excluding these parts that was shown at the maximum in the tables (standing under the category "difference"), there was no large difference among the sung vowels and the singers, so that the numerical values of all the energy differences yielded look alike. This implies that the relation of the total radiation energy to the mouth radiation energy remains almost unchanged at the maximum, whereas the relation shown at the fundamental frequency and the minimum energy point changes according to the vowels that are sung and also among the singers.

- **Energy level of the total radiation is independent of the voice classification but dependent of the singer's own singing technique**
  The energy level of the total radiation was different from singer to singer, however characteristic attributes of each voice classification or musical genre was not significant in the analyses. Therefore, the radiation of the singing voice seems to be individual and determined by the singer's own singing technique and style.

9 Summary and Discussion

The characteristics of each kind of singing voice are made in the trachea and in the vocal tract, more precisely, involving larynx position, closed phase quotient, subglottal pressure, and vocal tract configuration, and the outcome is reflected in the frequency, thus, in acoustical characteristics. As introduced in Chapter 3, the research findings on these factors show quite large differences among singing techniques, but surely the characteristics also vary from singer to singer, individually.
In comparison to research on such inner activities in the body while singing, research on radiation energy of the singing voice from the body into the air, is still relatively small. However, previous studies on radiation energy of the singing voice have yielded some important findings.

Here, my study deals with the question of radiated energy of the singing voice from the body in general. In order to find out whether most of the radiation energy comes from the mouth or not, an experiment was undertaken with seven singers from four various musical genres, and their singing voices were measured at 15 parts of the body by an acoustic camera with 121 microphones. The data gained from the measurement was analyzed from various points of view and displayed in different forms, so that many questions have been answered thereby.

Nevertheless, some difficulties attended my study. In comparison to a common measuring method with an accelerometer, which was often used in the previous studies on the singing voice, my method using a microphone array was not easy for a measurement with human singers (i.e., except an artificial singer's body/torso), especially when it comes to exactly symmetrical measurements. Because even a small angle change of the standing position or facial direction affects the energy level at the measured points, one of the two symmetrically-set points shows a higher level than that of another one. Such a result was often presented in the research findings measured at the corners of the mouth. But a measurement taken with the body or head immobilized would have prevented the natural posture of the subjects while singing, even if such a method had been used in favor of more exact results.

Another problem was that back-propagation of radiated energy from some unevenly located parts of the body, such as the throat, caused the low energy level shown in the results. In opposition to this, the nose is located nearer to the microphone array. But this differs more or less from person to person because of individual bony structure of the body. For example, when it comes to radiation from the facial parts, individuals have varying shape and size of the face, but also vary in opening the jaw/mouth while singing, further individualized by certain factors such as their habit for singing, or adjusted singing technique for making of desired vocal sound, all of which made it difficult to measure radiation energy at accurate points and to do back-propagation uniformly to these points. The latter mainly changes the position of the chin and the corners of the mouth, so that measuring of an accurate energy level will be somewhat prevented.

In order to yield an accurate result, a measurement using an accelerometer is certainly a suitable research method, but despite of all that, research by means of a microphone array and the Minimum Energy Method provides a number of opportunities to consider the data from various points of view as well as to display the research results in a visual form.

From the research findings shown in Chapter 6, it was clear that the mouth is usually the strongest sound source in singing, as expected. However, sufficiently loud sound pressures from other parts of the body, at least from the 14 parts measured, were also observed in this investigation. In most cases, an increase of the energy from these parts was shown up to about 3 kHz for all the vowels, so that the difference of the radiated energy among the parts of the body became smaller at high frequencies, even though the energy level showed a rather changeable process at all the pitches for the vowel /u/ (and sometimes also for the vowel /o/). This increase depends on the pitch that was sung. When analyzing and comparing all the findings gained from different sung pitches, it was revealed that the strongest energy of the singing voice is usually located at around 3 kHz, independent of the singing technique.

Because of this increase, in some cases, a few of the parts of the body revealed even higher energy values than the mouth radiation at high frequencies and surprisingly, the total energy from the 14 parts even surpassed the radiation energy values from the mouth, as shown in Chapter 6. This depends strongly on frequency, but this fact is a remarkable finding for a better understanding about the origin of radiation energy of the singing voice.

Furthermore, it was clarified that the energy from the corners of the mouth has strong influence on the total radiated sound energy level by comparing the energy from the mouth with the total energy from the other parts excluding the energy from the corners of the mouth. This influence was expected, due to the localization near the mouth. In particular, the difference was appreciably shown for the vowels /o/ and /u/ and largely among subjects, in fact, independent of the musical genre. This recognizable difference was distinctive in the progress of the radiated energy analyzed at three partials, at the fundamental frequency and at the partials where the maximum and minimum energy was measured.

In other aspects, it was found that total radiation energy of the singing voice is strongly supported by the enhanced energy from the body regions that are located far from the mouth, because the energy values from the body regions of the chin, the corners of the mouth and the cheeks, did not change as much. However, it was displayed in Chapter 6 that for the vowels /o/ and /u/, the radiation energy of nonclassical singers is strongly supported by the chin as well. For the singers, the difference in the radiation energy level between the region of the mouth (i.e. the corners of the mouth and the chin) and the rest of measured parts of the body was much larger than for classical singers. This finding indicates that the singing voice of a classical singer emits rather from the whole upper body region measured for both vowels.

In conclusion, the results of my study revealed that radiation energy of the singing voice depends on vowels, frequency, pitch and person who sings. All the results of the radiated sound energy of the singing voices are nothing more than the end products created by all the factors, such as by the height of larynx position, by the level of closed phase quotient and the subglottal pressure, and by the condition of the vocal tract configuration. Particularly the latter factor, which changes depending on the vowel, pitch and the singer, plays a crucial role for the radiation characteristics.
But the finding that for singing at high pitch, radiation of the singing voices became stronger at high frequencies, is presumably caused by a high lung volume and high-speed opening and closing of vocal folds at the pitch, so that strong sound pressure will be

produced by these factors. This is just what Sundberg asserted, even though the body regions concerned are not confirmed by his recognition (introduced in Chapter 4): very strong sound pressures in the vocal tract and in the trachea generate the phonatory vibrations in the skull, neck and chest region [68].

In addition, the strong radiation energy from the measured parts of the body at high frequencies is presumably related to the fact that the partials at high frequencies radiate forwards, whereas there at low frequencies emit almost equally in all directions, as reported by Marshall and Meyer (see in Section 4.3 of the previous chapter) [50]. Their findings relate to my study because the radiation energy was measured just in front of the singer's body there.

Even though it is difficult to say how the typical radiation pattern of each singing technique will look, I hope that has provided more detailed information about the source of sound radiation energy of the singing voice, and that more unresolved issues in research of vocal acoustics will be sorted out in the near future.

10 Kurzfassung der Ergebnisse

Für die Feststellung der abgestrahlten Schallenergie von Singstimmen wurde die abgestrahlte Energie von sieben ausgebildeten Sängern und Sängerinnen aus verschiedenen Musikgenres – Klassik, Musical und Pop (inkl. Soul) – anhand eines Mikrofonarrays mit 121 Mikrofonen untersucht. Diese Methode ermöglicht die Energie an gewünschten Körperstellen zu messen, sodass diese an fünfzehn verschiedenen Stellen – Mund, Kinn, Kehle, linkem und rechtem Schlüsselbein, Brust, Nase, Nasenbein, linkem und rechtem Mundwinkel, linker und rechter Wange, Stirn, linkem und rechtem Unterlid – aufgenommen wurde. Dabei sang jeder Teilnehmer fünf Vokale /a/e/i/o/u/ in verschiedenen Tonhöhen zwischen 90 und 500 Hz, je nach deren Stimmlage.

Die Ergebnisse dieser Untersuchung haben bewiesen, dass die Abstrahlung der Singstimmen nicht auf den Mund beschränkt ist, jedoch diese Partie, wie vermutet, die Hauptquelle der gesamten abgestrahlten Energie ist. Dennoch ist diese Energiestärke aus dem Mund abhängig von dem Frequenzbereich, dem Vokal, der Tonhöhe und auch vom Sänger. In einer Vergleichsanalyse zwischen der Energie aus dem Mund und der Gesamtenergie aus den restlichen gemessenen Körperstellen, zeigte die Gesamtenergie eine Steigerung der Energie ungefähr bis zu 3 kHz bei allen gesungenen Vokalen und Tonhöhen, sodass der Unterschied zwischen den beiden Energiewerten immer kleiner wurde. Im hohen Frequenzbereich zeigte diese Gesamtenergie sogar oft einen höheren Energiewert als die Energie aus dem Mund. Vor allem eine starke Energiezunahme an den Körperstellen, die weit entfernt vom Mund lagen, wurde im analysierten Frequenzbereich beobachtet. Beim Vokal /u/ und manchmal auch beim Vokal /o/ zeigte sich ein Zickzack-Kurs von abgestrahlter Energie, während diese bei den anderen Vokalen eine relativ glatte Kurve im analysierten Frequenzbereich hatte.

Wenn es um die Analyse der verschiedenen Gesangstechniken ging, trat ein Unterschied bei den Vokalen /o/ und /u/ unter den Sängern auf, sodass bei den nichtklassischen Sängern mehr Energie von dem Kinn abgestrahlt wurde, während dies bei den klassischen Sängern nicht zu sehen war. Dieses Ergebnis zeigt, dass bei nicht-klassischen Sängern die Energie vom Kinn einen großen Anteil der Gesamtenergie hat, im Gegensatz zu der Energie von klassischen Sängern, welche eher ausgeglichen am Körper entsteht.

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List of Publications Resulting from the Dissertation

Takada, Orie, *Sound Radiation Patterns in Classical Singing Styles*, in Albrecht Schneider/Arne von Ruschkowski (Ed.), *Systematic Musicology: Empirical and Theoretical Studies*, Hamburger Jahrbuch für Musikwissenschaft 28, Peter Lang, Frankfurt am Main, 2011, S. 163 – 173.

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Hamburg, im September 2019