Vol.2018-MUS-119 No.14
Vol.2018-SLP-122 No.14
2018/6/16

Regular Paper

Radiation Patterns and Changing Radiation Energy of the Singing Voice

Orie Takada[1,a)] Rolf Bader[1,b)]

Abstract: The previous studies on the radiation energy of singing voices have mostly been executed using an accelerometer with which the energy of each desired part of the body has been measured. However, in this investigation a microphone array of 121 microphones was in use. For this study, the sound energy of seven trained singers from four musical genres (classical, musical theatre, popular and Soul singing) was measured at fifteen parts of the body while the participants sang five vowels /a/e/i/o/u/ at different fundamental frequencies (90, 120, 180, 250, 380 and 500 Hz) in accordance with their voice classification. The gained information was analyzed using the Minimum Energy Method and Mathematica by which the radiating field and radiation patterns could be visualized. The results showed that the main energy source of the radiation energy of singing voices is the mouth, as expected, but strong energy can arise from other parts of the body as well. Furthermore, the research findings of this study indicate that the radiation patterns of singing voices change according to the vocal technique, the frequency analyzed, the vowel, and on the pitch that is sung.

Keywords: Radiation Energy, Singing Voice

1. Introduction

The vocal organ of singers is often described as a musical instrument, where the sound produced in the vocal folds is radiated both by the mouth and the singers body. A classical singer needs to pay special attention to his / her body to use it like a musical instrument, because classical singers rarely use electric amplification, even with large audiences. Furthermore classical singers, specially opera singers, have to compete against a loud orchestral accompaniment. Therefore a great physical effort is needed. In contrast, nonclassical singers usually use microphones, so that the physical force of the singer can be spared in contrast to classical singers, in regard to the use of the body as an instrument. 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 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 is still audible, even though singers are humming with closed lips. Obviously the sound energy is radiated not from the mouth in this case, otherwise the sound would not be audible. 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 a greater or smaller influence on the total energy of 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. In fact, 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 the factors "vocal technique", "pitch" and "vowel".

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. **?**, Fant et al. **?**, Sundberg **?**, Pawlowski et al. **?**, Sakakura et al. **?** and Takada **?**). These studies found out that the sound vibration depends on vowels because of mouth aperture size and on pitch. Furthermore, stronger vibration was also shown at loud vocal sound.

2. Method and Research Materials

There were two questions for this study:

- Is it true that the main sound energy of the singing voice only radiates from the mouth? Or are there other

[1] Institute for Systematic Musicology, University of Hamburg, Neue Rabenstrasse 13 20354 Hamburg, Germany
[a)] orietakada@gmx.de
[b)] R_Bader@t-online.de

body parts involved in the sound radiation of the singing voice?

- If so, are there recognizable differences in vocal music genres /singing techniques and vowels?

2.1 Method

This investigation was 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 to reconstruct sound pressure fields and to show an overall radiation directivity of a vibrating geometry. Both, this Acoustic Camera and the Minimum Energy Method, were developed at the Institute for Systematic Musicology (University of Hamburg), therefore a detailed description about the Acoustic Camera and the Minimum Energy Method as well as exemplary measurements can be found e.g. in **? ? ? ?**.

The array spacing is a regular grid with a grid constant of 3.9 cm. The construction of the microphone array using 121 microphones (11 x 11) enables to make a symmetric visualization of the radiating field (ca. 50 x 50 cm). 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 fifteen upper parts of the body (mouth / 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). This setting made it possible to show energy values of the voice radiation from the singer's upper body, including the phase angles. The received informations were reconstructed and visualized on a sketch of a photo of the human upper body from the head to the chest. At that, the radiated energies of all single frequencies were normalized to 0 dB at the mouth.

Furthermore, the strongest radiated area was color-marked: the radiation is adjusted up to -6 dB and the intensity of the radiation energy is visualized by colors (the brighter the color, the stronger the radiated energy)[*1].

2.2 Research Materials

Seven trained singers — three Classical (bass, alto and soprano), two musical theatre (male and female) and two popular singers (both female) — participated in this study. One popular singer's voice was recorded twice by means of popular singing technique and by means of Soul singing technique. 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 (bass), analyzed up to 1,3 kHz (15 partials)
- 120 Hz (males), analyzed up to 2,5 kHz (21 partials)
- 180 Hz (alto/mezzo), analyzed up to 3 kHz (17 partials)
- 250 Hz (all subjects), analyzed up to 4 kHz (16 partials)
- 380 Hz (tenor), analyzed up to 4,5 kHz (12 partials)
- 500 Hz (females), analyzed up to 5 kHz (10 partials)

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 singers, so that their mouth is positioned in the front of the center microphone (No. 61). Furthermore, the center microphone was placed 3 cm in front of the mouth.

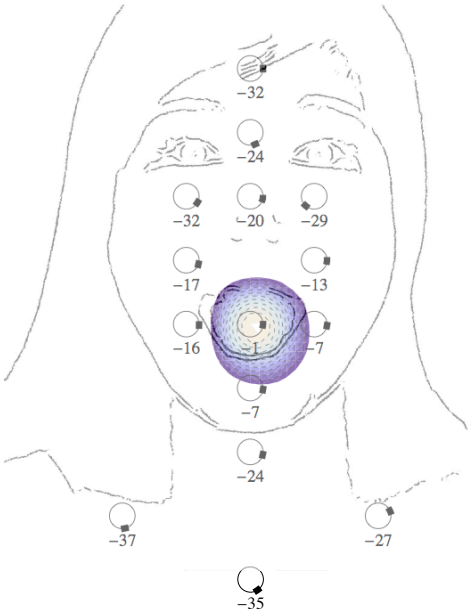

Fig. 1 Radiation of a female Pop singer at the fundamental for the vowel /a/ at 250 Hz.

3. Results

When singing at lower frequencies (90, 120, 180, 250, 380 Hz), it was observed at the fundamental that by far the strongest energy radiates from the mouth (see Figure **??**). This result was shown for all participants. However, in the case of 500 Hz, the radiation energy increased in total in comparison to that revealed from singing at lower pitches, so that strong radiation energy came from a large area of the lower part of the face (see Figure **??**). Therefore, by means of visualizing the strongest radiating area up to -6 dB that was marked in colors, it was clearly noticeable that the area of strong radiated energy shown at the fundamental became large with increasing fundamental frequency that was sung.

Furthermore, due to this increase, it was revealed that 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 expanding the strongest

[*1] Usually the radiation from the mouth is the strongest, so that the radiated energies of all single frequencies were therefore normalized to 0 dB at the mouth, but if there is a radiation point from which stronger energy value was 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. Furthermore, 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.

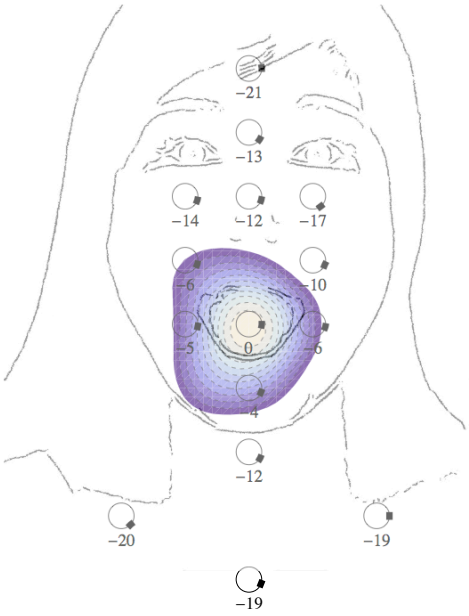

Fig. 2 Radiation of a female Pop singer at the fundamental for the vowel /a/ at 500 Hz.

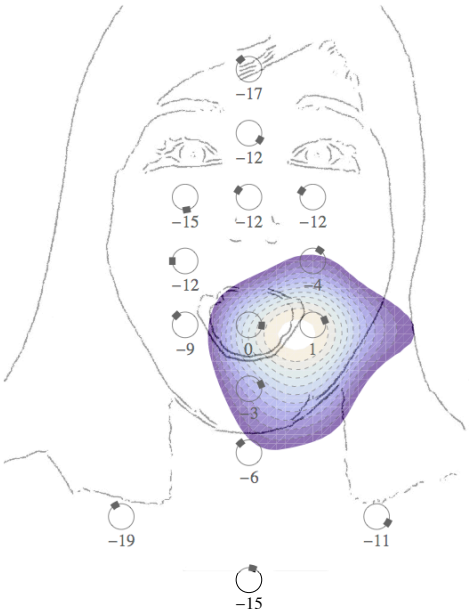

Fig. 3 Radiation patterns of a classical soprano at the 9. partial for the vowel /i/ at 500 Hz.

area radiated or by shifting the energy source that were often found in the case of 500 Hz (an example in Figure **??**.). This can be a temporary, but also as a continuing phenomenon.

Compared to the mouth radiation, the radiation from other parts of the body generally increased at ascending frequencies, up to 3 kHz, roughly (see Figures **??** and **??**). This means that the mouth radiation energy decreased in favor of the increased radiation of other parts of the body in total energy that was emitted while singing. However when it comes to the strength of the 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/ often

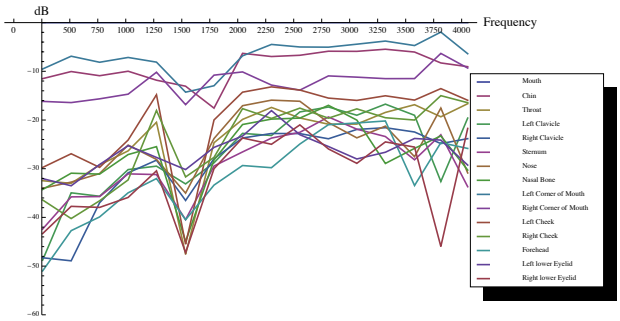

Fig. 5 Radiation energy of a male musical theatre singer at the fundamental for the vowel /o/ at 250 Hz.

showed a zigzag-like course (see Figures **??** and **??**). This motion was visible at all the parts of the body. This is probably because an air stream in the vocal tract occurs due to the narrowed mouth shape for these vowels. As mentioned above, the strength 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 at higher frequencies analyzed in comparison to the other subjects.

When it comes to differences in musical genre, the radiation patterns of nonclassical singers manifested that their strong energy occurs from the corners of the mouth and the chin for the vowels /o/ and /u/. 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, as shown in Figure **??** (Top three lines are the results from the corners of the mouth and the chin).

4. Conclusion

From the research findings, it was clarified that the mouth is usually the strongest energy source in singing, as expected. However, sufficiently strong radiation energy from other parts of the body, at least from the fourteen 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 all the parts of the body became smaller at high frequencies, even though the energy level showed rather changeable process for the vowel /u/ and sometimes also for the vowel /o/. This increase depends on the fundamental frequency that was sung. For the nonclassical 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 energy more widely distributed over the whole upper body measured for both vowels. Presumably that is because of the shape of their jaw / mouth while singing that changes not so much for all vowels in comparison to nonclassical singers. The mouth shape of classical singers almost

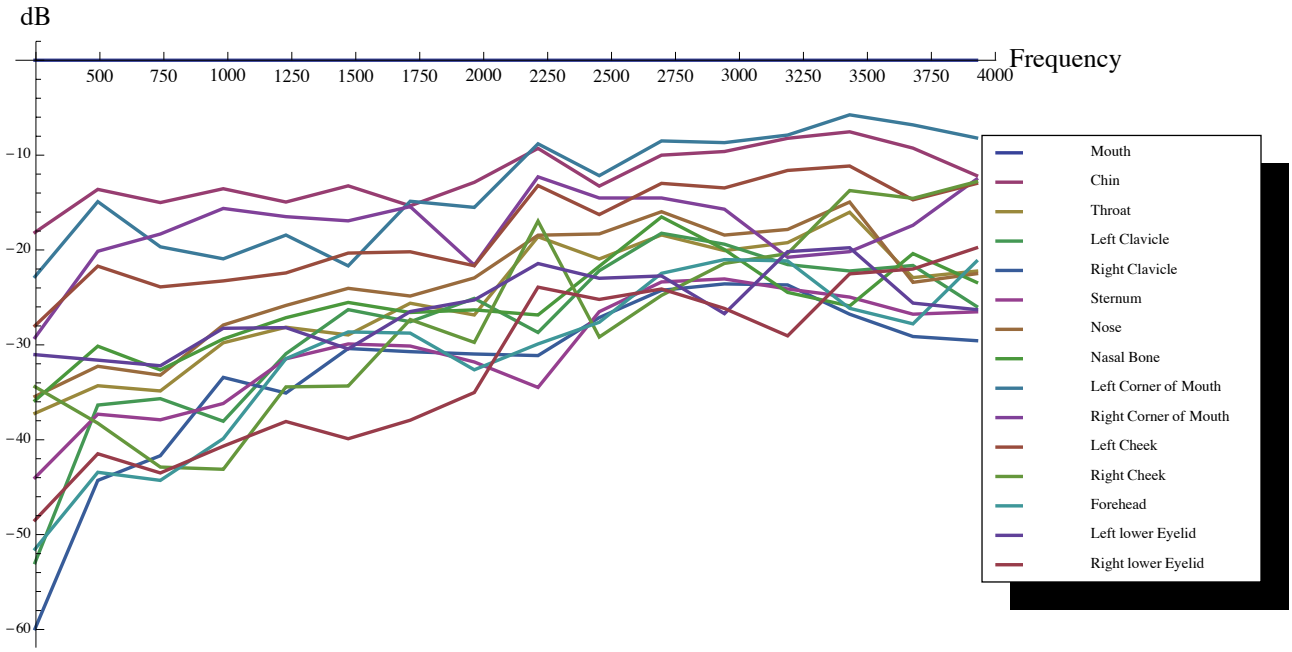

Fig. 4 Sound levels of fourteen measured upper parts of the body sung by a female musical theatre singer at the fundamental for the vowel /a/ at 250 Hz, compared to the sound level of the mouth. The energy from the mouth is shown at zero on the x-axis (dark blue line).

remains constant for each vowel.

References

[1] Kirikae, J., Sato, T., Oshima, H. and Nomoto, K.: Vibration of the body during phonation of the vowels, *Revue de Laryngologie, Otologie, Rhinologie*, Vol.85, pp.317–345 (1964).

[2] Fant, G., Nord, L. and Branderud, P.: A note on the vocal tract wall impedance, *Speech Transmission Laboratory Quarterly progress and status report*, Vol.4, pp.13–27 (1976).

[3] Sundberg, J.: Chest wall vibrations in singers, *Journal of Speech, Language, and Hearing Research*, Vol.26, No.3, pp.329–340 (1983).

[4] Pawlowski, Z., Pawloczyk, R. and Kraska, Z.: Epiphysis vibrations of singers studied by holographic interferometry, *Proc. SMAC-83*, Royal Swedish Academy of Music, Vol.28, (1983).

[5] Sakakura, A. and Takahashi, H.: Body wall vibration in trained and untrained voices, *Vocal Physiology: Voice Production, Mechanisms and Functions*, (Fujimura, O., ed.), Raven Press, New York, pp.391–401 (1988).

[6] Takada, O.: Radiation Pattern of Classical Singing Style, *Systematic Musicology: Empirical and Theoretical Studies*, (Schneider, A., v. Ruschkowski, A., ed.), Hamburger Jahrbuch für Musikwissenschaft, Peter Lang, Frankfurt/M, Vol.28, pp.163–173 (2011).

[7] Bader, R., Münster, M., Richter, J., and Timm, H.: Microphone Array Measurements of Drums and Flutes, *Musical Acoustics, Neurocognition and Psychology of Music*, (Bader, R., ed.), Hamburger Jahrbuch für Musikwissenschaft, Peter Lang, Frankfurt/M, Vol.25, pp.15–55 (2009).

[8] Bader, R.: Reconstruction of radiating sound fields using minimum energy method, *The Journal of the Acoustical Society of America*, Vol.127, No.1, pp.300–308 (2010).

[9] Bader, R.: Radiation characteristics of multiple and single sound hole vihuelas and a classical guitar, *The Journal of the Acoustical Society of America*, Vol.131, No.1, pp.819–828 (2012).

[10] Bader, R.: Microphone array, *Springer Handbook of Acoustics*, Springer, pp.1179–1207 (2014).