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Vocal-tract impedance at the mouth – from 1995 to today

A tribute to Joe Wolfe and John Smith

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ABSTRACT

The acoustic output signal of orators and singers contains information from the voice source as well as from the articulatory organs. The extraction of formants to achieve information about voice timbre and vocal-tract configuration is among the essential methods in speech and language processing as well as in singing-voice research. However, the validity of formant analysis is limited by voice features and analysis parameters. The measurement of the acoustic impedance of resonating structures allows one to obtain all relevant information from their resonances. The design of a method for impedance measurement at the human lips by Joe Wolfe and John Smith dates back to 1995, and since then variations of the concept have been applied in fundamental singing-voice research (high soprano and tenor voices, overtone singing), as well as for investigations in other domains such as voice rehabilitation. This review article collects methods and applications over the last 25 years, giving reference to the many colleagues and students who have contributed with theses and supporting work. The presentation is accompanied by a demonstration of the method.

1. INTRODUCTION

An innovative method for measuring wind-instrument and vocal-tract impedances was developed by Prof. Joe Wolfe and Prof. John Smith starting from 1995 [1, 2]. In the case of speech and singing, it allows the measurement of vocal-tract acoustical resonance properties without making any a priori assumptions about the glottal source. Earlier work of Osamu Fujimura and Jan Lindqvist has investigated the vocal tract transfer function [3] using external swept sine excitation at the larynx. This early research already revealed the significance of glottis, epiglottis and velum configuration on the resonance characteristics of the vocal-tract. In the last decade the investigation of the vocal tract acoustics using various other methods has been facilitated by the availability of MRI-based data and physical models produced with 3D printers [4, 5]. Their results demonstrate a

high comparability of resonance measurements using external excitation and formant frequencies derived from human voice signals.

The method presented here excites the vocal-tract externally with a sound wave. The development and applications of this method are detailed below.

The excitation of the vocal-tract using a broadband signal such as noise or a swept sine provides a high frequency resolution of the measurements in contrast to formant analysis methods that need to use the line spectrum of the voiced signal which – in case of high-pitched vowels – does not provide sufficient energy between the partials for an accurate formant analysis. On the other hand the determination of formants from the voice signal provides an average estimation of the vocal-tract’s filter function over time which corresponds to our perception of the filtered voice signal.

When the impedance at the mouth is measured during phonation the resulting signal not only contains the impedance function but also the voice signal. For a clear presentation of the impedance function the voice signal must be separated or suppressed to obtain resonance values that correspond to the formants during phonation.

Alternatively, the impedance can also be measured without phonation at all, resulting in undisturbed resonances. However, the glottal status of such measurements can be anything between open (higher resonances than average during phonation) and closed (lower resonances), resulting in a quite large variability of the impedance function and the derived resonance values [6]. Instructions to subjects to keep the glottis open or closed during measurements without phonation can help to define the glottal status but not necessarily provide the desired conditions. Trained subjects, however, can voluntarily open and close their glottis which provides valuable insight to the range of the vocal tract resonances for different open quotients. The position of the epiglottis can vary as well and is difficult to control voluntarily. However, the epiglottis movement would not have an equally fundamental effect on the resonance structure as the glottal status unless it is tilted back completely (as during swallowing). Further limitations of an external excitation at the lips of a speaker/singer can be the surprising sound of a noise or swept sine signal that might cause articulatory changes just before or during to the impedance measurement. To summarise, the impedance function derived at the mouth end of the vocal-tract can not provide the same information as the analysis of a voice signal but



Figure 1. VTMI device

allows insight into articulatory phenomena that are hard to obtain otherwise.

The method to measure the vocal-tract impedance was first developed for the study of musical instruments [1, 7] but also soon and successfully applied to the study of vowel formants in speech [8, 9] including applications to training of phonation as well as to the investigation of singing [10, 11]. We will first present the devices and their evolution in Section 2. Their application to the analysis of singing voice in different styles will then be reviewed. The nomenclature in this text follows the proposal given in [12].

2. METHOD

The measurement of the acoustic impedance requires the determination of two basic properties of the sound field: acoustic pressure $p(t)$ & acoustic velocity $v(t)$. The acoustic impedance $Z(f)$ is then determined by the quotient of the RMS values of both:

$$Z(f) = \frac{\text{FFT}(\tilde{p}(t))}{\text{FFT}(\tilde{v}(t))}. \quad (1)$$

The acquisition of acoustic pressure is far easier since sensors for acoustic velocity are, due to their small size, expensive, sensitive to damage, and of limited accuracy. Despite these problems, a prototype that captures both sound pressure and velocity has been developed in 2002. The installation of the sensors in a prototype is shown in Fig. 1. A graphic user interface for parallel evaluation of curves obtained by linear predictive coding (LPC) and vocal tract impedance at the mouth (VTMI) was developed in Matlab ([13], Fig. 2). Within the dissertation project of Julia Stoffers [14] the evaluation of the impedance curves was performed with respect to several parameters which were derived from the normalised magnitude of the impedance.

Candidates for the assessment of values for amplitude and bandwidth of each resonance were the steepness and the difference between maximum and minimum. It was

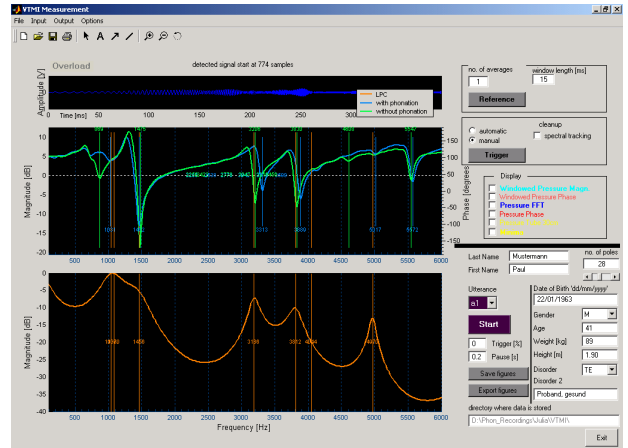


Figure 2. Applet for the VTMI device, impedance curves (top) and LPC curves (bottom) shown simultaneously for vowel /a:/

found that an absolute amplitude or bandwidth was difficult to obtain since these values do not seem to be constant with frequency [6].

2.1 One or two sensors?

Another device was developed at RWTH Aachen University in 2003 to provide both acoustic pressure and velocity values using miniature sensors in a small, portable set-up that allows mobile measurements, see Fig 3. The KE4-211-2 capsules by Sennheiser were used for pressure, and prototypes by Microflown were used for velocity. In Fig. 4 the set-up (right) and the velocity sensor (left) are shown.

By acoustic treatment of the propagation of the acoustic wave from the exciter to the exit of the measurement device, the acoustic velocity can be held approximately constant. This condition can be achieved by guiding the sound wave through a capillary wave guide or an inverse horn [15]. The use of a horn and additional damping material greatly reduces the feedback of an external impedance on the loudspeaker membrane. A constant sound velocity supply can be assumed. As a consequence, the relative impedance can be determined by simply measuring sound pressure $p(t)$ instead of also measuring sound velocity $v(t)$.

2.2 Calibration

The combined acquisition of sound pressure $p(t)$ and velocity $v(t)$ allows the direct calculation of the acoustic impedance by Eq. 1. If a change of the acoustic impedance is sufficient for characterisation of the resonances, and no absolute values are required, the measurement device can be calibrated against a constant impedance — such as the impedance Z_0 of the free field around the sensor, or the impedance of the closed mouth. Resonances of the vocal tract with an open mouth would then be shown as a deviation of the measured impedance from Z_0 .

Practically, the reference Z_0 is determined just prior to the measurement at the mouth and stored. After the acquisition of the sound pressure from the calibration ($p_0(t)$) and



Figure 3. Miniature VTMI set-up



Figure 4. Sensors of miniature VTMI set-up

the excitation at the mouth ($p_m(t)$), and subsequent Fourier transform, the relative impedance $Z_{\text{rel}}(f)$ of an ideal current source having uniform velocity is then calculated by the quotient of both measurements:

$$Z_{\text{rel}}(f) = \frac{Z_m}{Z_0} = \frac{\text{FFT}(\tilde{p}_m(t))}{\text{FFT}(\tilde{p}_0(t))}. \quad (2)$$

$Z_{\text{rel}}(f)$ is either visualised by its absolute value or phase (see Figs. 2 and 7-9).

2.3 Signal extraction

Methods for extraction of the acoustic impedance from a measurement during phonation have been developed from the beginning. Whereas early concepts used manual extraction of the resonances in the complete signal [8], signal processing was applied to separate the voice signal from the excitation signal of the measurement and the response of the vocal tract [16, 17]. A new method relying on multiple chirplet transforms has recently been proposed [18–20] which also investigates the effect of a distant microphone position.

2.4 Miniaturisation

Portable devices have been created in two institutions, the RWTH Aachen University in 2003, and the Singapore University of Technology and Design in 2018 [17, 21]. The device developed at RWTH Aachen can be worn with a holder around the neck and contains two sensors (see Figures 3 and 4). An application of the miniature device is shown in Fig. 5.

Following the successful implementation of the technique of broadband excitation at the speaker/singer’s lips and the estimation of vocal tract resonances from its corresponding relative acoustic impedance spectra [22], a modified, low-cost, portable, pocket-sized, and simplified version of

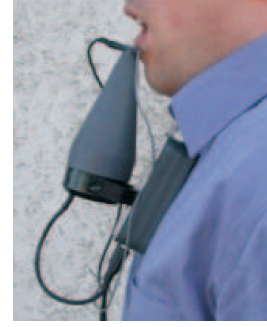


Figure 5. Use of the miniature VTMI device

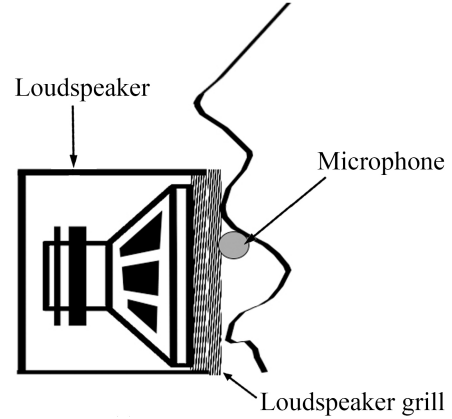


Figure 6. Schematic of the configuration of ACUZ-Lite during measurement (from [17])

this technique named “ACUZ-Lite” was developed [17] for estimating the vocal tract resonances non-invasively and thereby enabling an ‘ecological’ way of tracking phonation gestures. Whereas the predecessor version (from [22]) required a set of dedicated and high-performance equipment and laboratory conditions to perform the measurements, the ACUZ-Lite, on the other hand, is relatively simple in terms of the hardware and software design.

This compact device (<200 grams) is constructed with a small entry-level loudspeaker and a lavalier microphone, and it is meant for performing ‘quick and dirty’ field measurements outside the formal laboratory environment. The device is configured in a way that the speaker/singer’s lips touch the loudspeaker grill, and the loudspeaker radiates directly into the mouth opening during the measurements as shown in Fig. 6. Similar to the predecessor version, the measurement procedure of the ACUZ-Lite is a two-stage process: a calibration followed by the measurement during phonation. During the calibration process, the speaker’s mouth is kept closed, the device is held in the same way shown in Fig. 6, and a broadband noise signal is iteratively modified for this configuration to attain a uniform energy distribution over the appropriate frequency range (typically from 100 Hz to 4000 Hz). Thereafter, the measurement is performed by exciting the vocal tract with the modified broadband noise signal while the speaker phonates a target vowel. Since the loudspeaker drives with considerable power at low amplitude, and also the loudspeaker cone is

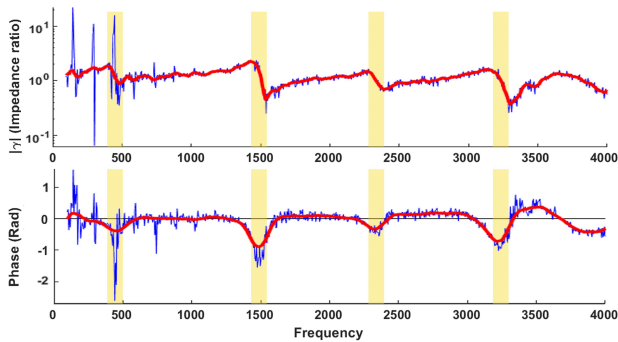


Figure 7. Relative acoustic impedance spectrum measured for the vowel /ə/ using ACUZ-Lite [17]: magnitude (top) and phase (bottom) plots

stiffer than the air, the acoustic velocity of the signal is approximated to be constant for the specified frequency range. Hence a relative acoustic impedance (Gamma) spectrum is evaluated between measured and calibrated reference loads by estimating the ratio of the corresponding pressure signals (assuming $\tilde{v}(t) = \text{constant}$). When plotting the Gamma spectrum, the vocal tract resonances are reflected as ‘steep negative slopes’ in the magnitude plot and the ‘sharp dips’ in the phase plot. Figure 7 shows a typical Gamma spectrum obtained for the vowel /ə/ (target word ‘herd’) that includes a raw (blue) and smoothed (red) version of the measurement. The first four resonance frequencies identified from both magnitude and phase spectra are highlighted.

According to a recent study on the device, tuning the physical configuration of the transducers and the implementation of acoustic foam is shown to improve the acoustic coupling between the device and the vocal tract and develop the sensitivity in low-frequency regions [21]. In order to investigate the optimal physical configuration of transducers, new parameters from the magnitude and phase domains are established in this study for quantitatively assessing the quality and sensitivity of vocal tract resonance detection.

Although the device relies on some approximations and ‘quick and dirty’ measurements, the resulting relative impedance spectra are comparable in performance with previous studies made under formal laboratory conditions. Despite the absence of acoustic flow information, the device is shown to detect vocal tract resonance frequencies reliably, especially the first resonance frequency, down to 350 Hz and possibly even lower by improving its low-frequency response, and the acoustic coupling with the vocal tract. This is expected to be further enhanced by implementing a more powerful loudspeaker and larger housing, as well as a short inverse horn for acoustic coupling between the device and the vocal tract in case of small mouth openings as in the vowel /u/. Even without further modifications, the device has extended the applicability of the impedance measurement at the mouth to a wide range of vowel articulations and singing styles under ‘field conditions’.

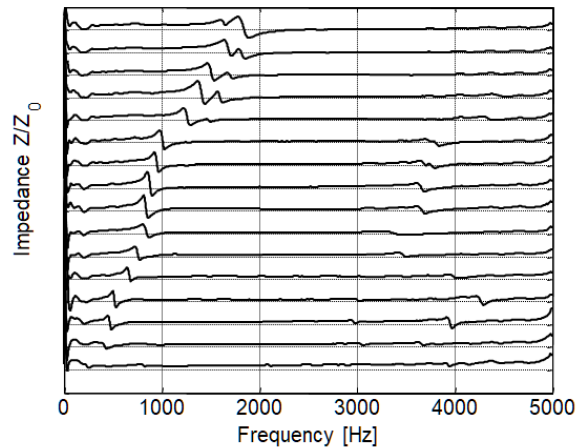


Figure 8. VTMI analysis of a sequence of rising overtones [23]

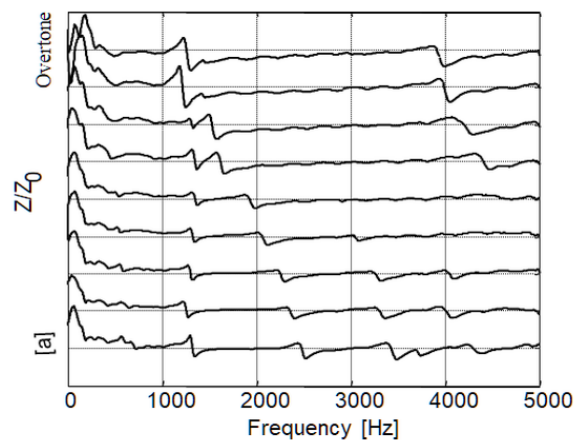


Figure 9. VTMI analysis of a morphed sound from /a:/ to an overtone sound [23]

3. APPLICATIONS

3.1 Analysis of overtone singing

The extraordinarily low bandwidth of the formant that occurs at the frequency of the melody pitch of singers who perform sygyt-style overtone singing, can be explained by focalisation, i.e. concentration of two resonances on one frequency [23]. The result from the impedance analysis of a rising overtone sequence is shown in Fig. 8 and demonstrates the presence of two resonances for some of the higher melody pitches. The impedance measurement of the vocal-tract has been used as a method to demonstrate the morphing of a sustained sound /a:/ to an overtone sound. The formant F_3 lowers its frequency from around 2 kHz to the frequency of F_2 around 1.2 kHz during the morphing process.

The resulting overtone formant has a lower bandwidth and therefore a higher selectivity than each of the formants alone. The transition of a vowel sound /a:/ to an overtone sound shown in Fig. 9 demonstrates the focalisation of two resonances that jointly create the strong overtone formant.

3.2 Resonance strategies in operatic singing

An active collaboration started in 2004 between an Australian and a French research team, receiving support from a French-Australian PHC funding program for scientific and technological exchanges (FAST, 2010-2011). Resonance-tuning strategies used by opera singers have been studied as a function of pitch, vocal intensity, and sung vowels. Several databases have been compiled:

- in 2004: 22 singers, from amateur to professional level (4 baritones, 8 tenors, 4 altos and 6 sopranos) [LYR2004 database]
- in 2005: 14 professional singers, mostly from the Sydney Opera House (2 baritones, 7 tenors, 5 sopranos) [LYR2005 database]
- in 2008: 12 singers from amateur to professional level (recorded by Maëva Garnier during her post-doctoral stay) [LYR2008 database]
- in 2010: 3 renowned professional singers, mastering yodeling technique

The analyses of these databases have revealed different resonance-tuning strategies in operatic singing. The frequencies of the first two vocal-tract acoustical resonances remained relatively constant throughout the singers' tessitura, as long as the sung note remains lower than the first-resonance frequency [24]. These resonance frequencies can sometimes increase with an increase in fundamental frequency, reflecting a movement of jaw opening as the singer sings higher in pitch. In cases where the first-resonance frequency (f_{R1}) joins the fundamental oscillatory frequency (f_o), for instance in the higher part of the tessitura or for closed vowels, a tuning $[(f_{R1}):f_o]$ is observed.

This phenomenon of resonance tuning is frequent in sopranos who sing at pitches where resonance and harmonics meet, whatever the training level of the singer. It is also found in other tessituras. Alto singers demonstrate $[(f_{R1}):f_o]$ tuning for vowels with a low-frequency first resonance. In the lower part of their pitch range, they may use a $[(f_{R1}):2f_o]$ strategy. Baritones and tenors demonstrate $[(f_{R1}):2f_o]$ and $[(f_{R1}):3f_o]$ tunings in part of their pitch range, or tuning with higher harmonics in low-pitch ranges. Inter-individual differences are great, especially for low-pitch voices.

First-resonance to first-harmonic tuning may be accompanied by an additional frequency tuning to the second resonance $[(f_{R2}):2f_o]$ for some singers. To produce their highest-pitch sounds, some of the singers extend their tuning range $[(f_{R1}):f_o]$ up to 1300-1500 Hz (E6-F#6). Other singers tune the second resonance near the first harmonic $[(f_{R2}):f_o]$ to 2350 Hz (D7).

3.3 Resonance strategies in Bulgarian women's singing

If lyrical singers sometimes present a (f_{R1}) resonance tuning to the second harmonic $2f_o$, the $[(f_{R1}):2f_o]$ tuning can be a systematic tuning strategy in other singing styles. For

example, Balkan songs, and in particular traditional Bulgarian women's singing, are particularly sonorous, with a predominance of acoustic energy in the voice second harmonic as a key feature [25, 26]. In collaboration with Mara Kiek (ACARMP Sydney Conservatorium of Music, The University of Sydney, Australia), the vocal behavior of an Australian singer who mastered traditional Bulgarian singing techniques was explored. Two distinct vocal qualities were assessed: the teshka (heavy) quality, which corresponds to a very sonorous vocal production, and the leka (light) quality, for which vocal production is softer, approaching in timbre the register of female head voice. The analysis of vowels sung in traditional Bulgarian style has shown the search for a tuning between the first resonance and the closest harmonic, either $2f_o$ or $1f_o$ depending on the vowel, no matter the technique used [27]. This systematic resonance-tuning strategy clearly distinguishes the vocal behavior in Bulgarian singing from the behavior in lyrical singing for the studied female singer. As shown in Figure 10, the resonance frequencies for vowels sung in head voice remain close to the resonance frequencies for the same vowels spoken.

3.4 Analysis of high tenor voices

The impedance measurement has been applied in a larger project for the analysis of potential register transitions in the high range of counter tenor singers. A comparison of the resonances during the performance of a sequence of sustained vowels allowed for grouping of the singers into one group that held the vocal tract configuration unchanged during the whole sequence, and another group that adopted vocal tract resonances to the frequencies of the first three partials. A publication of the work is pending.

4. CONCLUSIONS

The measurement method of vocal tract impedance, invented by Joe Wolfe and John Smith in 1995 has inspired research teams from various countries to further develop and apply it for investigations in speech and singing voice research. Different methods and their applications that had emerged from the technique of vocal tract impedance measurement at the human lips are presented in this review article. This included devices with both pressure and velocity sensors to measure the acoustic impedance, and relatively simple devices that include only a pressure sensor to estimate relative acoustic impedance. Whereas some of the devices are advanced for estimating the voice and resonance qualities for support of research on resonance phenomena in singing, a few have evolved in the direction of simple and portable use in field conditions. 25 years after the initial invention Matlab-based tool with instructions for a self-made device has been published on the UNSW web page of Joe Wolfe [28]. Further improvement of algorithms for the resonance analysis during phonation will enable the use of such devices for singing students outside acoustic laboratories.

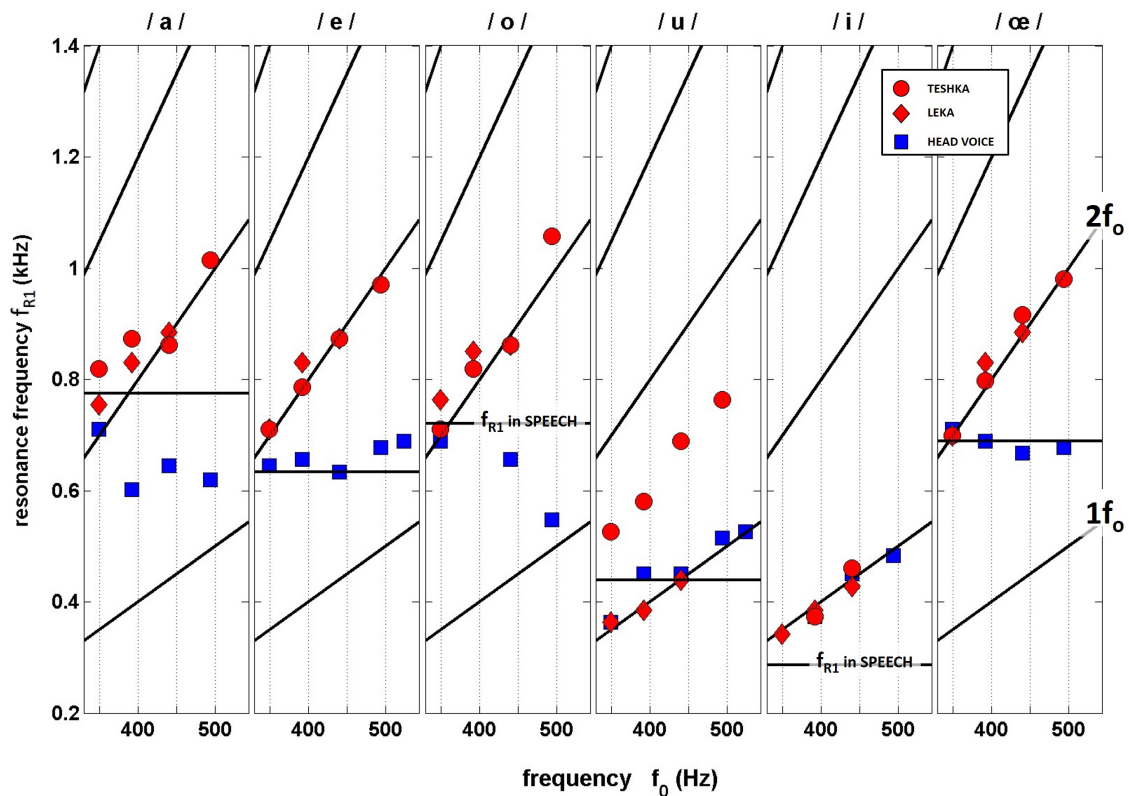


Figure 10. First-resonance frequencies for spoken vowels (horizontal black and sung vowels in bulgarian singing style (red markers) and classical female head voice (blue markers).

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