The effect of resonance tubes on facial and laryngeal vibration – A case study

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ABSTRACT
The effects of resonant tubes of different lengths and diameters were measured by means of accelerometers placed on the subject’s larynx, forehead and cheek. The electroglottographic (EGG) and acoustical signals were also recorded. The aim of the study was to find the frequency at which the resonance tubes have maximal effect and to find, based on the analysis of the measured signals, the experimental method for the estimation of the resonance frequencies of the elongated vocal tract. The measured data were compared with transmission line modeling (TLM) and the yielding wall model (YWM). Our results show a better fit with the YWM modeled data than with TLM. The experimental data reveal two important kinds of measured maxima which can be identified as the maximum efficiency of the extended vocal tract (the maximum laryngeal vibration) and the correlation coefficient maximum (CCM) between laryngeal vibration and the EGG signal, that we assume to be above the resonance frequency of the extended vocal tract. The vibrational maximum frequency always lies below the CCM and their relative position does not differ by more than 25 Hz.

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1. Introduction

Semi-occlusion or significant narrowing of the vocal tract together with the extension of the vocal tract using resonance tubes is a method often applied in vocal pedagogy and therapy. This method is known as semi-occluded vocal tract (SOVT) exercises.

Apart from resonance tubes, SOVT exercises can also include the LaxVox methods, use of straws, lip and tongue trills, voiced bilabial fricatives and plosives [v; b:], hand-over-mouth, brumendo (humming) and their combinations [1–3]. These methods increase source-filter interaction by means of a resonant effect.

The effect of vocal tract and vocal fold vibration interaction has been described theoretically in several sources [3–5]. The effect is based on facilitating the vocal folds’ self-oscillation by vocal tract resonance.

Under normal conditions, the resonant frequencies of the vocal tract, typically expressed by the position of formant frequencies (F1-F4), are very distant from the fundamental frequency of vocal fold vibration. Prolongation (via a tube or pursing the lips) and the constriction of the vocal tract cause increased vocal tract impedance. As a result there is a significant reduction in the first formant frequency, which enters the frequency range of deep harmonics with which it interacts [6].

Setting the position of the fundamental frequency or some of the first harmonics just below the frequency of the first formant helps the vocal cords to move and the air to flow through the glottis. Inertive reactance is the most significant component of the feedback on the vocal fold vibration. The phase relations of acoustic pressure and airflow through the glottis are in such a state when the vocal fold oscillations are most enhanced.

Increasing the inertive reactance of the system results in a significant reduction of the phonation threshold pressure (PTP) [7], which corresponds to easier glottal vibration at a lower pressure. In addition, the intra-oral pressure increases. Model [8] shows how the mouth pressure increases up to three-times its the natural value just behind the lips when the resonance tube is used. Increased oral pressure results in an accentuation of the facial vibration sensation.

Nonlinear source-filter coupling is theoretically described in [9]. Interaction based on positive (inertive) vocal tract reactance skews the glottal flow pulse to the right; this produces new harmonics in the source spectra and raises the overall harmonic energy. Nonlinear interaction shows that collision of vocal folds (mainly near the glottal closing) is not essential for the production of source harmonics. The effect of nonlinear formant-harmonic coupling in the glottal flow is to distribute the acoustic energy over the entire spectrum rather than to accentuate it at the center of a formant.
The combination of compliant (negative) subglottal reactance and inertive (positive) supraglottal reactance provides the ideal reinforcement to vocal fold vibration in the modal register. Other effects of source-filter interaction when the dominant harmonics are close to formants are frequency jumps and instabilities such as subharmonics and non-random noise.

The effect of resonance tubes has also been monitored by means of electroglotography, where their influence on the contact quotient (CQ) of the vocal folds was assumed. Experimental studies have not demonstrated that SOVT has a consistent influence on the CQ yet. According to Gaskill and Ericsson [10] the effect was present with each subject, but the general trend (increasing or decreasing) could not be proven statistically. Singers have demonstrated the effect of SOVT on increasing CQ, flow, and SPL [2]. Study [11] divided SOVT exercises into two groups, measuring the CQ and the difference of F1–F0. The first group (named steady or single source) reduced the CQ and F1–F0 difference. This group included hand-over-mouth, humming, and straw exercises. The second group (fluctuating or dual source) resulted in greater variability of the CQ and F1–F0 difference. This group involved tongue and lip trills and LaxVox exercises.

The value of the estimated F1 frequency significantly varies in the literature [7,11–13]. There is still no simple and recognized method of measuring this parameter when resonance tubes are used. The influence of the tube length and diameter on the flow and pressure properties during the exercise has been discussed recently [14] without any clear therapeutic recommendation for specific targeted purposes.

The main goal of the present study is to measure the effect of resonance tube parameters (their length and diameter) on the vibration properties of the larynx, cheek and forehead surface and on intraoral pressure.

The study’s secondary aim is to determine the relationship between the measured signals and to find a method suitable for measuring experimentally the maximal effect of resonance tube exercises on the vocal fold vibration properties.

2. Material and methods

2.1. Theoretical part

Resonance frequencies for extended vocal tracts were modeled by two different methods. The first was the usual one dimensional transmission line modeling (TLM) [15], which deals with the vocal tract as if it were a set of cylindrical tubes, taking thermoviscous losses into account, but assuming the walls to be solid. The second approach was introduced by Radolf et al. [16]. A simplified

### Table 1

<table>
<thead>
<tr>
<th>Diameter (mm)</th>
<th>Length (cm)</th>
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<tbody>
<tr>
<td>14</td>
<td>60</td>
</tr>
<tr>
<td>12</td>
<td>80 70</td>
</tr>
<tr>
<td>10</td>
<td>60 50 40</td>
</tr>
<tr>
<td>8</td>
<td>60 50</td>
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</table>

Fig. 2. Examples of measured vibration amplitudes in glissandos with resonance tubes. The left column shows graphs for RTs with diameter 12 mm and different lengths (40, 50, 60, 70, and 80 cm, respectively). The right column displays the results for RTs with length 60 cm and different diameters (8, 10, 12, and 14 mm, respectively). The rows report the averaged amplitudes for A) larynx vibration B) cheek vibration C) forehead vibration, D) AC intra-oral pressure, and E) the correlation coefficient between the laryngeal and EGG signals.

Table 2
ANOVA results of the resonance tube length effect for the maximal amplitude, pitch position, SPL, CQ, EGG contact quotient, and EGG amplitude of the first and second maxima of laryngeal, cheek and forehead vibration and intraoral pressure. * depicts the level of significance above the Bonferroni correction 0.05/20.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>1st maximum</th>
<th>2nd maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Amp.</td>
<td>F0</td>
</tr>
<tr>
<td>Larynx</td>
<td>ns</td>
<td>1.17E-04</td>
</tr>
<tr>
<td>Cheek</td>
<td>1.31E-04</td>
<td>7.62E-04</td>
</tr>
<tr>
<td>Forehead</td>
<td>*0.0032</td>
<td>1.35E-04</td>
</tr>
<tr>
<td>Pintraoral</td>
<td>0.0259</td>
<td>2.35E-05</td>
</tr>
</tbody>
</table>

model consists of two tubes (a tube equivalent to the vocal tract and the resonance tube); this approach also takes into account the effects of yielding vocal tract walls (YWM). The model parameters were set the same way as in the cited study; these correspond to the length and cross-sectional surface of the female vocal tract and to the weight of female vocal folds. Both models estimate the resonant maxima of the different resonance tubes used in our experiment.

### 2.2. Experimental part

Only one subject (male, 38 years old) participated in the experiment. The subject performed upward and downward glissandos (twice for each measurement) using 11 types of attached resonance tubes (the parameters are shown in Table 1).

The subject's skin surface vibrations were measured using piezoelectric accelerometers (PCB Electronics 352C23 with sen-

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**Table 3**

ANOVA results of the resonance tube diameter effect for the maximal amplitude, pitch position, SPL, CQ, EGG contact quotient, and EGG amplitude of the first and second maxima of laryngeal, cheek and forehead vibration and intraoral pressure. * depicts the level of significance above the Bonferroni correction 0.05/20.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>1st maximum</th>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Amp.</td>
<td>F0</td>
</tr>
<tr>
<td>Larynx</td>
<td>2.11E-04</td>
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<td>Cheek</td>
<td>3.99E-07</td>
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<tr>
<td>Forehead</td>
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<tr>
<td>Pintraoral</td>
<td>*0.0034</td>
<td>ns</td>
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</tbody>
</table>

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**Fig. 3.** Box plots of the resonance tube length effect for the maximal amplitude (first column), pitch position (second column), SPL (third column), CQ - contact quotient (fourth column), and EGG amplitude (fifth column) of the first maximum of laryngeal vibration (the first row in the section), cheek vibration (the second row), forehead vibration (the third row) and intraoral pressure (the fourth row).
sitivity of 10.04, 9.66 and 10.13 mV/(m/s²). These were placed on the larynx, cheek and forehead, respectively. Glottal activity was synchronously recorded using a Laryngograph A-100 (EGG signal), while the acoustic signal was recorded at 10 cm distance from the free end of the measured resonance tube using an omnidirectional dynamic microphone (ME 2 Sennheiser). Intra-oral pressure was measured by the digital manometer Honeywell ASDXAVX001PD2A3. The measuring probe tip was placed in the mouth cavity just behind the incisors, next to the end of the resonance tube. Due to our measurement setup the length of the measuring probe was 34 cm.

All the signals (audio, EGG, and three accelerometer signals) were recorded synchronously (48 kHz, 24-bit). The analysis was performed on windows lasting 50 ms, in 25 ms steps. The data from the accelerometers were twice indefinitely integrated to obtain the displacement amplitude (both constants were set to zero).

All the displacement signals and the EGG signal were subject to a running average filter of 1/20 period length before analysis.

For each window the vibration amplitudes, SPL, intra-oral pressure, CQ were calculated. The resulting vibration amplitudes and the AC part of the intra-oral pressure were obtained average values of the peak-to-peak magnitudes for each window. The CQ was determined from the 1st derivative of the EGG signal [17].

Fig. 1 shows the measured parameters. Part A depicts the laryngeal amplitudes for four utterances of glissandi in mezzo-forte and forte dynamics, and their averages as a function of fundamental frequency. Part B shows in detail the first maximum vibration region and the local maxima for four utterances speaking loud voice. Parts C, E, and D, F show the averaged values normalized to maximal parameter values for the resonance tubes of diameter 12 mm and length 70 and 60 cm, respectively.

The vibration and pressure signals reveal two distinct maxima. We have assumed that these maxima are relevant for the extended vocal tract resonance frequencies, and therefore monitored them. The fundamental frequency positions F0 and skin vibration maxima for each accelerometer and intra-oral AC pressure were determined semi-automatically due to the high number of peaks in the analyzed data. The corresponding values of SPL, CQ and intra-oral pressure were detected automatically. First, for each of the measured signals the region of the given maxima (first or second) was manually selected. Second, the positions of the maxima (signal segment and its amplitude) were detected automatically for all utterances. Next, the amplitudes of the other signals (vibra-

Fig. 4. Box plots of the resonance tube length effect for the maximal amplitude (first column), pitch position (second column), SPL (third column), CQ - contact quotient (fourth column), and EGG amplitude (fifth column) of the second maximum of laryngeal vibration (the first row in the section), cheek vibration (the second row), forehead vibration (the third row) and intraoral pressure (the fourth row).
In order to investigate the relationship between the signals, the Pearson correlation coefficients between the EGG and laryngeal vibration signals were calculated.

The specific effect of the varied parameters (resonance tube length and inner diameter) was assessed by mean of a one-way ANOVA (the MATLAB statistics toolbox was used). The Bonferroni correction was applied for all coupled hypotheses.

### 3. Results

#### 3.1. Effect of resonance tube length

The left column of Fig. 2 shows the averaged amplitudes of the measured parameters (larynx, cheek and forehead vibration amplitudes, intra-oral pressure and the correlation coefficient between the EGG and laryngeal signals) for five resonance tubes of different lengths (40 to 80 cm), all with the same diameter of 12 mm. The

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right column shows the same parameters but for a constant tube length (60 cm) and different diameters (from 8 to 14 mm). The larynx, cheek and forehead vibration curves are of similar shape and the corresponding maxima are in similar frequency positions. The second maxima have smaller amplitudes than the first ones. Only the intra-oral pressure exhibits a different shape. Its first maximum is usually wider than for the other parameters, and the second maximum is comparable to the first one.

The results of ANOVA are presented in Table 2. The RT length mainly affected the F0 positions and the SPL of the first and the second measured maxima. The first maximal vibration amplitude was only affected in the vibration of the cheeks and forehead. These effects on the measured parameter values for the first and second maxima are summarized in the box plots given in Figs. 3 and 4, respectively.

Generally, the F0 position decreased with RT length for the first maximum (depicted in Fig. 3) and for all measured parameters except for cheek vibration.

The first maximal amplitude was only affected by RT length in cheek vibration, but without any trend. Cheek amplitude reached a local maximum at 50 cm RT length.

The results of the RT length effect on the second measured maximum are depicted in Fig. 4. The F0 significantly decreased with RT length. The maxima of other parameters were not affected. The cheek and forehead amplitudes show a similar trend. The highest amplitudes are reached for an RT 70 cm long. SPL was affected by the RT length: it decreased with the length with the exception of an RT 50 cm long.

When the F0 of the measured parameters first maxima were compared, significant differences were found for several couples. For an 80 cm long RT the F0 of the first Pio maximum significantly differed from the other parameters' maxima (for about 20 Hz). No difference was found for the second maxima. RTs 70 and 60 cm long did not result in any difference for the two maxima. For a 50 cm RT there were significant differences in the first measured maxima frequency position between intra-oral pressure and both larynx (14 Hz) and cheek (15 Hz) vibration, but no difference in the second maxima. The 40 cm RT differed in comparison to the other parameters only for the first cheek maximum frequency position (16 Hz for larynx, 19 Hz for forehead and 49 Hz for the Pio).

3.2. Effect of resonance tube diameter

The effect of the resonance tube diameter was tested for diameters 8, 10, 12 and 14 mm with an RT length of 60 cm using one-way ANOVA. The averaged amplitudes are shown as a func-
tion of the pitch in Fig. 2 (right column). The effect of diameter on the amplitude in the first maximum is evident for all the measured parameters; the effect on the F0 of the first maxima is evident mainly for larynx and cheek vibration.

The ANOVA results are displayed in Table 3. The main effect of the resonance tube diameter was observed in SPL for both maxima. Diameter only affected the first maximal amplitudes of all parameters. The F0 was affected for all parameters only for the second maxima.

Box plots of the measured parameters for the first and the second maxima are displayed in Figs. 5 and 6, respectively. The F0s for larynx and cheek only slightly decreased with increasing diameter. The maximal SPL was observed for an RT of 12 mm diameter. EGG amplitudes reached their minimum for a 10 mm diameter.

The CQ and EGG amplitudes were not affected in the second maxima of the observed parameters.

The second maximal amplitude was only affected for cheek vibration. The F0 was affected by the diameter for the second maxima only for laryngeal, cheek and forehead vibration.

The highest SPL was measured with a 12 mm diameter RT, but the maximal amplitudes varied without obvious trend. The F0 of the second maximum increased with increasing diameter.

3.3. Comparison of the modeled and measured data

Based on the TLM model, we calculated F0 positions for the first and the second resonance maxima for the different lengths and diameters as measured in the experimental part. The calculated vocal tract shape was set for the [u:] vowel (F1 ≈ 270 Hz, F2 ≈ 580 Hz).

The influence of yielding walls was only modeled for the neutral vowel (YWM model). The comparisons of the modeled and averaged measured data are depicted in Fig. 7 and listed in Table 4.

The YWM model provides first and the second maxima positions that are very close to both measured F0, for maximal laryngeal vibration amplitude and for maximal correlation coefficient positions between laryngeal vibration and EGG signals. The frequency positions of all the first vibration maxima were slightly below the position of the correlation coefficient maxima. The averaged differences between the first laryngeal vibration maxima and the first correlation coefficient maxima were usually less than 25 Hz (see Table 4–Diff F0) except for the narrowest tube (60 cm/8 mm). For the second maxima these differences were always less than 20 Hz but some vibration maxima were above the correlation coefficient maxima.

Student’s t-test reveals significant differences between the measured laryngeal vibration maxima and the correlation coefficient maxima for all of the first peaks; for the second maxima these differences were only found with the 50 cm/12 mm RT and 60 cm/8 mm RT. In both cases the laryngeal vibration maxima were found in higher F0 than the correlation coefficient maxima.

3.4. Correlation between EGG and laryngeal vibration signals

Fig. 8 shows the measured laryngeal vibration amplitudes for different dynamics and crescendo (gradually increasing volume). Part C depicts the calculated correlation coefficients between the EGG and laryngeal signals as a function of F0. For all dynamics, the correlation coefficients show two distinct maxima where the correlation is close to unity. Between these maxima there is a minimum of correlation (still above zero). Negative correlation occurs at very low or very high pitches. As shown in Table 4, the F0 position of the correlation coefficient maxima lay above the larynx vibration maxima for the first measured resonance (compare parts A and C of Fig. 8). This means that the segment with the maximum amplitude did not achieve the maximum correlation coefficient.
Fig. 8. A) Measured amplitudes of larynx vibration at different dynamics for RT 70 cm/12 mm. (mf normal, ff – loud, and Crescendo – gradual increase in volume. B) Comparison of the relative amplitudes of larynx, EGG and intraoral pressure with the values of the correlation coefficient (CC) between the EGG and laryngeal vibration signals. C) CC between the EGG and laryngeal vibration signals for different dynamics (as in part A). D–N Time series of laryngeal vibration (Larynx), EGG signal, and intra-oral pressure (Pio) signal of the segment with CC between EGG and laryngeal amplitude (the measured positions are depicted by the arrows in part B). Measured segment with: E) CC close
To explain the meaning of the correlation between the EGG and laryngeal signal, parts E-G-I-K of Fig. 8 depict a gradual increase in the calculated correlation coefficient from zero to a value close to unity in the first correlation coefficient maximum (CCM). A relative phase shift between the EGG and laryngeal signals is obvious. The phase shift decreases when the correlation coefficient approaches unity. On the other hand, when the intraoral pressure and EGG signals are compared, it seems that they are in opposite phases. When the EGG reaches its maximum (the vocal folds are totally closed) the pressure is minimal and vice versa, at minimum EGG (the glottis is maximally opened) intraoral pressure reaches its maximum. However, in our graphs there is only real time synchronicity in the measurements between the EGG and laryngeal signals. Due to the way our measurement was set up, the intraoral pressure is slightly time shifted. We are not able to specify this time shift exactly, because it depends on the distance between the glottis and the pressure sensor. This distance was close to 50 cm because the measuring probe tip was placed just behind the incisors (approximately 16 cm from the glottis) and the probe was 34 cm long. This means that the intraoral pressure is shifted by app. 0.00145 s, which is in the average frequency of the first correlation coefficient maxima (170 Hz) corresponds to a phase shift of π/2.

Nonetheless, from the relative positions of the EGG and intraoral pressure maxima we can see their approximation when the correlation coefficient increases. There is one specific disturbance in intra-oral pressure when the correlation coefficient is close to 0.5 (part G). The pressure signal differs from the EGG and the laryngeal signal, and there is a ripple in the decreasing pressure phase.

When the correlation coefficient between the EGG and laryngeal vibration decreases (parts K-M-D) the EGG and laryngeal maxima separate and where there is minimal correlation there are ripples in both laryngeal and intraoral pressure signals. This state occurs in a frequency position just above the minimal laryngeal amplitude.

In the case of the second correlation coefficient maximum the situation is similar. The higher the correlation coefficient the lower the phase shift between the EGG and laryngeal signals. When the correlation coefficient decreases after the second maximum, the shift increases and ripples appear in the pressure and laryngeal signals.

The first maximal correlation coefficient between the EGG and laryngeal vibration is depicted in part K of Fig. 8. In this case there was a minimal phase shift between the EGG and laryngeal vibration. We can assume that the maximal positive displacement of the laryngeal skin surface (outwards motion) corresponds to the local pressure maximum in the laryngeal cavity but with the phase shift depending on the laryngeal wall compliance. The maximum EGG signal corresponds to maximal closure of the glottis, therefore the maximal correlation coefficient between the EGG and laryngeal vibration indicates that the local laryngeal maximum displacement appears at the moment of maximum glottal closure, and vice versa, when the glottis is maximally open there is minimal displacement of the laryngeal surface.

In the minimal correlation case the situation is a bit different, as can be seen in parts D and L of Fig. 8. The laryngeal signal has very low amplitude (as seen in part A) with a ripple. This means that some higher harmonics start to dominate in the signal. The phase of the laryngeal signal at the instant of glottal closing is positive, but the amplitude and impact are very low. In the maximum closed phase of the glottal cycle there is a ripple; at the instant of glottal opening the positive displacement acts against it opening.

4. Discussion and conclusion

As Radolf et al. [16] had previously shown, the YWM model corrects the overly deep maxima predicted by the TLM model. Our data demonstrates the same behavior: the measured data are a better fit with the YWM model. The positions of the modeled first maxima were always placed between the positions of the laryngeal vibration maxima and the maxima of the correlation between the EGG and laryngeal signals. The second laryngeal and correlation coefficient maxima were also closer to the YWM model, although all the measured positions were above those predicted by the model.

The expected FO decrease with increasing RT length was fully confirmed. The TLM model predicts a more pronounced decrease in FO with the diameter than we measured. In this case the YWM is once again a more suitable model, despite the fact that a male subject (a tenor) was investigated and the YWM used female vocal tract parameters.

It can be concluded, as Radolf et al. previously stated using a single RT, that the coupling between acoustical parameters and vibration of the structure is the key factor in vocal tract modeling when RTs are used. Experiments using the TLM model on different vocal tract models show that vowel walls have a greater importance than vocal tract shape. The physical reason for this fact lies in increased intraoral pressure (both DC and AC components). Detailed discussion of this behavior remains, however, a subject for future research.

The present study shows the typical positions of two kinds of maxima: the maximum displacement and the maximum correlation coefficient between the EGG and laryngeal signals. The displacement maximum was always the lower of these two, and the difference between these maxima was always smaller than 25 Hz except in one case. Henrich et al. [18] state that a 25 Hz difference is the best formant tuning for classical singers. Based on this and on behavior modeled by Titze [4,6,9] we can identify the displacement maximum as the most effective vocal tract setting and we assume this point to be the maximum (inertive) reactance frequency.

The case of the correlation coefficient maximum is a little bit difficult to explain because there always is a real phase shift (time delay) between the force on the laryngeal wall caused by the pressure in the laryngeal cavity and the displacement amplitude on the laryngeal (neck) surface. The precise value of the phase shift is uncertain. We tentatively assume that the phonation FO is much higher than the resonant frequency of the neck tissue. Hence the phase shift is varying slowly and could be assumed as constant in the range of our experiment.

If there were no phase shift (infinitely stiff tissue) the measured data would suggest that the maximal displacement amplitude corresponds to maximum laryngeal pressure. Thus, the case of the maximal correlation coefficient (part K Fig. 8) could be explained as the state when the maximal pressure appears in the moment of maximal closure and minimal pressure when the glottis is maximally open. The pressure above and below the glottis becomes similar (or there is a minimal difference), so the trans-glottal pressure almost vanishes (is minimal). This helps the vocal folds to relax or close. When the vocal folds are maximally open there is minimal pressure above the glottis, which helps to open the glottis (by slight suction). The EGG and laryngeal vibration signal in Fig. 8 is consistent with Titze when the acoustic pressure phase helps the vocal folds to open and close at the instant of best vocal function. As a result glottal flow is enhanced in amplitude and overall steepness, which implies spectrum enrichment.
But since there is a certain phase shift and the driving (i.e. pressure) must be always ahead of the displacement, the correlation coefficient maximum lies above the resonance frequency. It is a matter of future research to determine an exact relation for the phase shift based on the key parameters (tissue stiffness and mass etc.).

The above described method for locating an interval in which the resonance and effective maxima are to be expected is simpler to apply practically than fitting the model (vocal tract combined with a resonance tube) for a specific person.

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