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EXPERIMENTAL INVESTIGATION OF FLUID-STRUCTURE-ACOUSTIC COUPLINGS BY STUDYING THE RESONANCE PROPERTIES OF VOCAL TRACT MODELS WITH YIELDING WALLS

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Abstract: *The novel experimental setup has been designed to study fluid-structure-acoustic interaction of the self-oscillating vocal folds model with vocal tract cavities and with a dynamical system originating in vibration of the soft tissue. The compliance of the vocal tract walls changes the phonation threshold so that a very small airflow is sufficient to vibrate the vocal folds. Comparing the same flow rates, the subglottal and radiated sound pressures are higher in the yielding-walled model. The shift of acoustic resonances towards higher frequencies due to the yielding wall corresponds to earlier experimental and numerical simulations.*

Keywords: Biomechanics of voice, vocal tract acoustics, artificial vocal folds, fluid-structure-acoustic interaction.

1. Introduction

Generation of voice is a complex process involving couplings between airflow coming from the lungs, self-oscillating vocal folds and acoustic resonances of the vocal tract. A primary sound, generated in the vocal folds (VFs), is modified in the acoustic cavities of the vocal tract (VT) above the VFs. The resulting sound thus includes acoustic resonances of the VT cavities, which occur as peaks in the envelope of the voice spectrum, referred to as formants, see e.g. Sundberg (1987). Formant frequencies define vowels and the voice timbre. The VT walls are not in reality acoustically hard but so-called yielding walls. This brings damping effects on the acoustic waves influencing the resulting sound radiated from the mouth. These effects were studied on an artificial laboratory model of voice production comprising the sound excitation by a silicone replica of self-oscillating VFs and a plexiglass VT model, where part of the VT wall was elastic.

2. Methods

First, the simplified vocal tract model was made of plexiglass. The base of its main geometric configuration was taken from a 3D volume model obtained from magnetic resonance images for the Czech vowel [u:], see Vampola et al. (2008). Cross-sectional rectangular areas of the model with hard walls corresponded to the areas of the human vocal tract. Second, the upper wall of the VT model, from the laryngeal part to the lips, was replaced with a soft membrane made of silicone rubber Ecoflex™ 00-50, see Radolf et al. (2020). The membrane of thickness 1 mm was slightly stretched during attachment to the VT model.

The developed simplified model of the human lungs, which includes splitting of the airways up to the fourth order branching, was built in the subglottic part of the experimental facility; see e.g. Horáček et al. (2017).

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The air was flowing through the model of the lungs to the trachea. Total trachea length was 23 cm and inner diameter 18 mm.

The measurements were performed with a 1:1 scaled three-layer vocal folds model (Horáček et al., 2017). The vocal folds were excited by airflow coming from the trachea. The airflow rate was increased step by step from the phonation onset up to the airflow rate and the subglottic pressure, which are in the range of physiologically relevant values for a normal human voice production. The sound level meter B&K 2239 was installed at a distance of 20 cm from the mouth of the vocal tract model. The pressure below the vocal folds (subglottal pressure) was measured by a special dynamic semiconductor pressure transducer developed in IT CAS. A Polytec OFV-505 laser vibrometer with an OFV-5000 controller was used for measuring vibration of the silicone membrane at the mouth cavity level, i.e. in the position of the cheek in the human vocal tract.

3. Results

The existence of a compliant wall caused the vocal folds start to oscillate at lower airflow rate $Q = 0.024$ l/s compared to 0.06 l/s for the hard-walled VT. The mean subglottal pressure and sound pressure level radiated from the mouth of the VT model increased for the compliant VT wall, see graphs in Fig. 1.

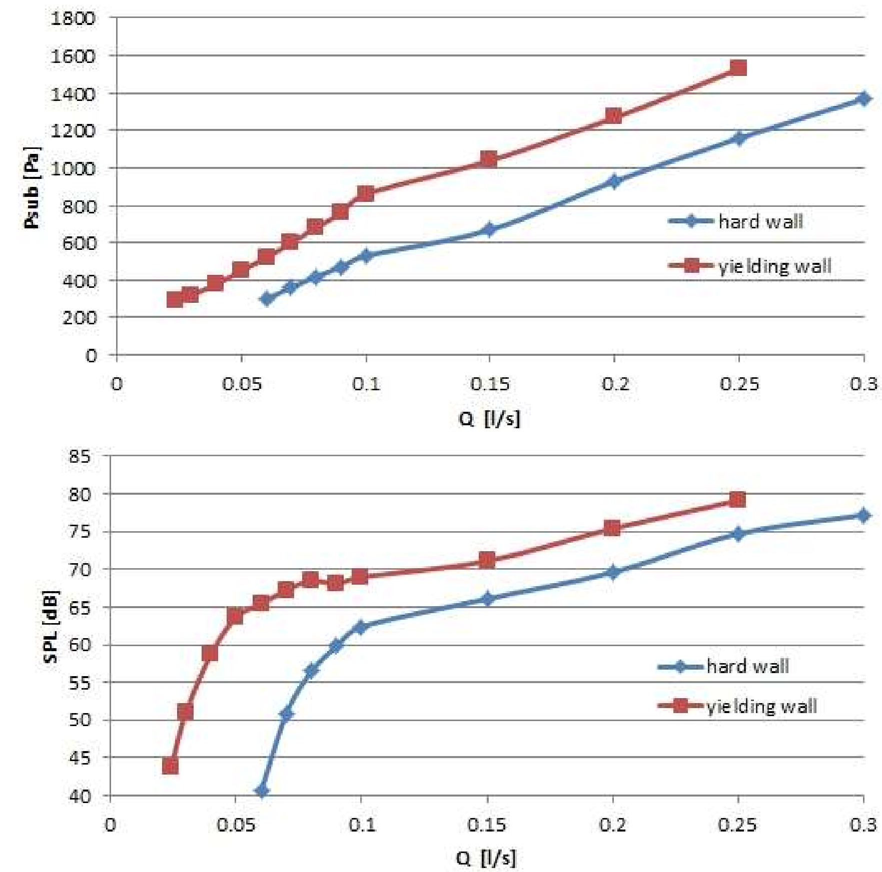

Fig. 1: Mean subglottal pressure (top) and sound pressure level radiated from the mouth (bottom) measured for hard-walled VT and yielding-walled VT.

Spectra of subglottal pressures for the mean airflow rate $Q = 0.1$ l/s are shown in Fig. 2. Harmonics in the spectra were filtered out (see e.g., Radolf et al., 2016) to better recognize their character and peaks. Interaction of the pressure oscillations with the compliant VT wall caused higher pressure levels, compared to hard-walled VT, in the frequency range from 200 Hz to 2 000 Hz and especially at the first subglottal resonance frequency at ca 700 Hz. Fundamental frequency of VFs oscillation was 82 Hz and 85 Hz for the hard-walled and yielding-walled model, respectively.

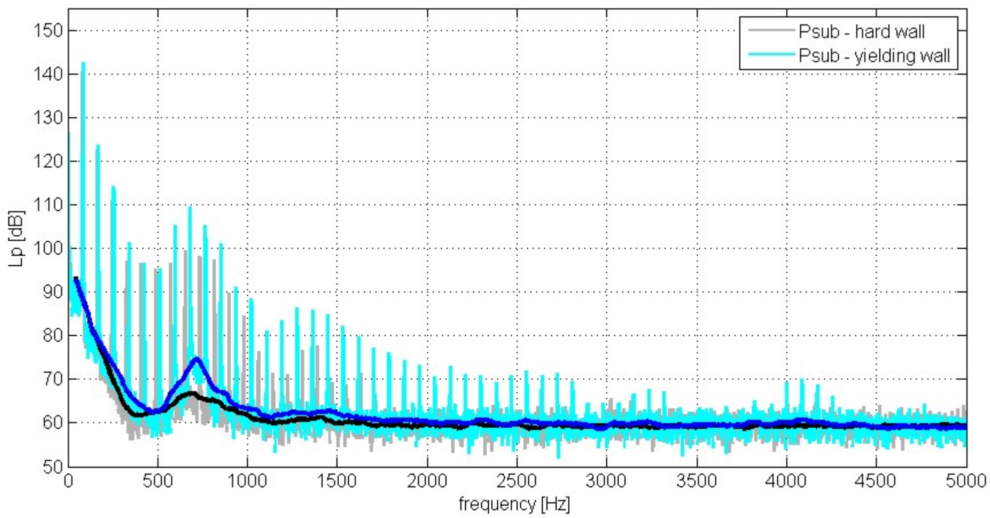

Fig. 2: Spectra of the subglottal pressure for hard-walled VT and yielding-walled VT, Q = 0.1 l/s.

Sound pressure levels measured outside the VT models show an even greater influence of the yielding wall. The energy of the sound waves increased significantly across almost the entire frequency band, see Fig. 3. All acoustic resonance frequencies increased in the case of the compliant-walled VT model compared to the model with the hard walls. The first and second acoustic resonances shifted significantly towards higher frequencies (F_1 from 440 Hz to 580 Hz and F_2 from 720 Hz to 780 Hz). The higher three resonance frequencies increased only negligibly. A new low resonance frequency at ca 230 Hz appeared for yielding walls in VT. This may have its origin in the weak resonance of the yielding wall in the epilaryngeal region, see the green curve in Fig. 4.

Spectra of the velocity of vibrating VT yielding wall show a sharp peak at about 40–50 Hz, which is the first mechanical resonance identified in the former study (Radolf et al., 2020), see the red curve in Fig. 3. Second peak at 780 Hz corresponds to the second acoustical resonance frequency.

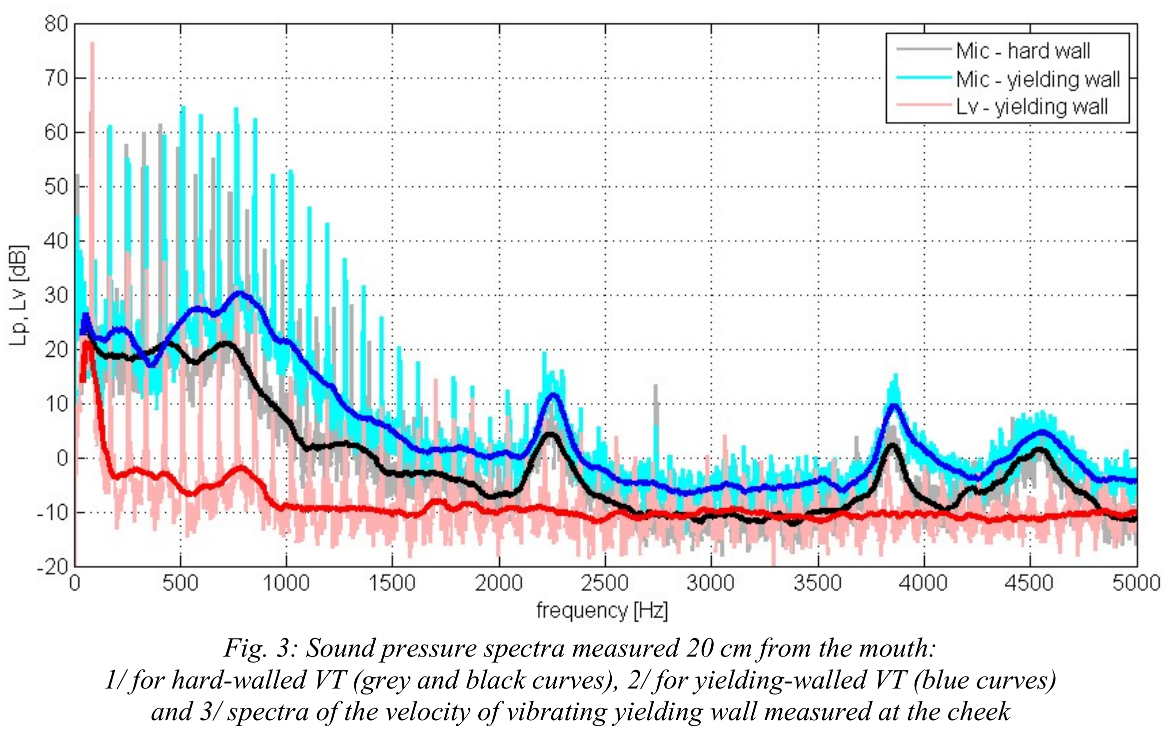

Fig. 3: Sound pressure spectra measured 20 cm from the mouth:
1/ for hard-walled VT (grey and black curves), 2/ for yielding-walled VT (blue curves)
and 3/ spectra of the velocity of vibrating yielding wall measured at the cheek
of the VT model (red curves), Q = 0.1 l/s.

The effect of the yielding wall shifting the acoustical resonances towards higher frequencies is qualitatively similar to the results of earlier measurements (Radolf et al., 2020), where the excitation of acoustic cavities of the VT model was realized by a small speaker placed instead of the vocal folds, see Fig. 4.

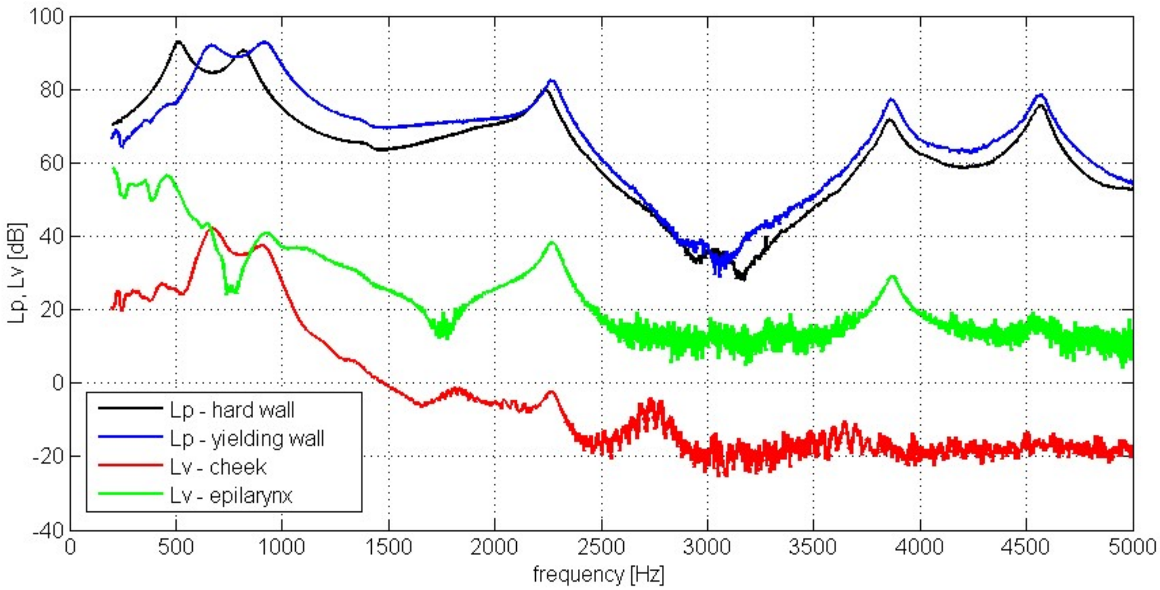

Fig. 4: a) Sound pressure spectra measured with microphone probe at the lips for hard-walled VT (black curve) and yielding-walled VT (blue curve), b) spectra of the velocity of vibrating yielding wall measured at the cheek of the VT model (red curve) and c) spectra of the vibrating yielding wall at the epilarynx position (green curve).

4. Conclusion

The compliance of the vocal tract walls significantly shifts the phonation threshold so that a very small airflow is sufficient to vibrate the vocal folds. Comparing the same flow rates, the subglottic pressures and SPL radiated from the mouth are noticeably higher in the model with a compliant wall. However, the phonation threshold subglottal pressure remains approximately the same for both models. The shift of acoustic resonances towards higher frequencies due to the compliant wall is consistent with previous experimental and numerical simulations (Radolf et al., 2016).

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