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PHONATION CHARACTERISTICS OF SELF-OSCILLATING VOCAL FOLDS REPLICA WITH AND WITHOUT THE MODEL OF THE HUMAN VOCAL TRACT

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Abstract: *The experimental study presents in vitro measurements of phonation characteristics performed on the developed 1:1 scaled replica of human vocal folds. The aerodynamic, vibration and acoustic characteristics measured with and without the model of the human vocal tract for vowel [u:] are compared.*

Keywords: Fluid-Structure-Acoustic Interaction, Biomechanics of Voice, Modelling of Phonation.

1. Introduction

Voice production is a complex physical process, which involves airflow coming from the lungs, self-oscillating vocal folds and acoustics of the resonance cavities of the human vocal tract. The vocal folds, excited by the airflow, generate a primary sound which propagates in the airways of the vocal tract modifying its spectrum and producing the final acoustic signal radiated from the mouth (Titze, 1994). Understanding basic principles of voice production is important for detection of laryngeal pathologies and treatment of laryngeal disorders. The physical models of voice production are important tools for experimental verification of developed theoretical models of phonation and in the development of the vocal folds prosthesis (Verkerke & Thomson, 2014).

2. Methods

The design of the geometry (size and shape) of the vocal folds replica was based on computer tomography (CT) measurement of the subject during phonation. The replica is made of ca 1 mm thin silicon cover filled by water (Horáček et al. 2015). The fundamental frequency of the self-oscillations can be controlled by changing the hydrostatic pressure inside the vocal folds and by their slight static pretension in the anterior - posterior direction. A simplified plexiglas model of the human vocal tract was developed from the 3D finite element (FE) model designed from the CT images of the subject taken during phonation (Vampola et al. 2015). To ensure the correspondence with reality the straight model of the vocal tract of the circular shape has the same areas in the 47 cross-sections along the vocal tract as the 3D FE model. The model begins with a simple model of the laryngeal cavity near the ventricular folds and ends at the lips by modelling the oral cavity.

The vocal folds were excited by the manually controlled airflow rate with synchronous measurement of the subglottic and oral air pressures (the fluctuating compound and the mean values) and the radiated sound. A general scheme of the measurement set up is shown in Fig. 1. The airflow is coming from the compressor through the float and orifice flowmeters to the model of subglottal spaces created by a simplified model of the human lungs and trachea (diameter 18 mm), then enters the glottal region with the vocal folds and finally the vocal tract model for the vowel [u:]. 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.

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The personal computer (PC I) was joint to the measurement system B&K Pulse with the Controller Module MPE 7537A, where all time signals measured by the pressure transducer, the two digital manometers, the contact sensor and two microphones were synchronously recorded using 16.384 kHz sampling frequency. The fundamental frequencies F_0 of the vocal folds vibration were analyzed using the FFT spectra of the time signals in the frequency range 0 - 6.4 kHz.

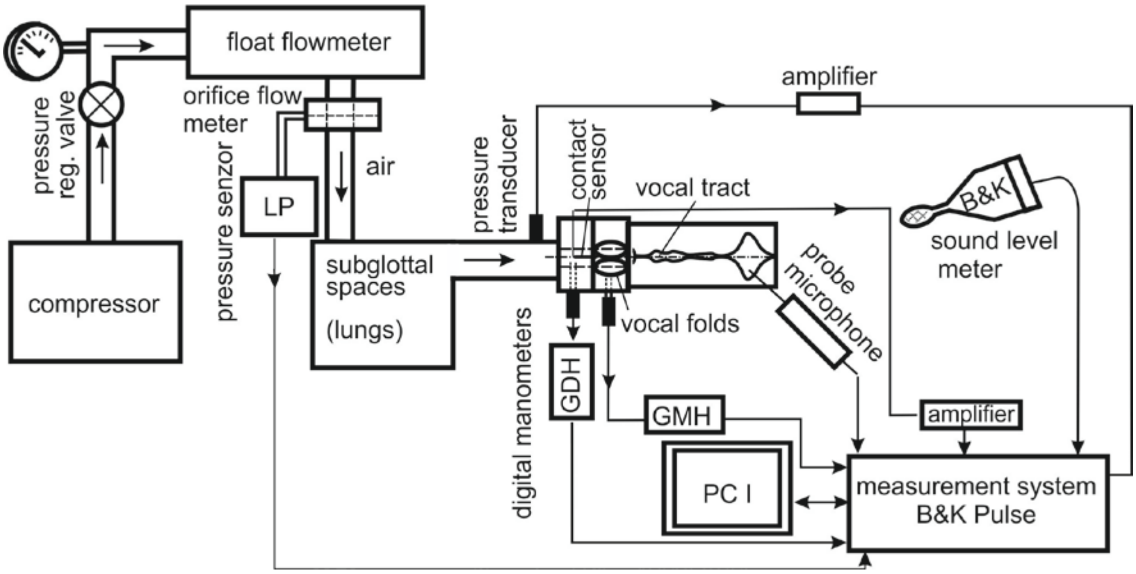

Fig. 1: Scheme of the measurement set up.

The miniature pressure sensor (Precision Measurement Company, model 060, range 0-350 kPa, diameter 1.5 mm, thickness 0.3 mm) used for measurement of the contact stress was mounted on a thin metal lamella and installed freely in the center of the glottis between the vibrating vocal folds. When the glottis is opened, the sensor measures the intraglottal pressure. The signal was amplified by an especially developed measurement amplifier. The acoustic signal was recorded by the sound level meter B&K 2239 installed at the distance of 30 cm from the vocal folds model or from the end of the oral cavity.

3. Results

Before starting the measurements, the vocal folds setting was tuned in order to obtain the regular phonation in the airflow range Q=0.2-0.4 *l*/s both for the vocal folds with and without the vocal tract. The original length (20 mm) of the vocal folds was prolonged by 8.25% (1.65 mm) and the hydrostatic pressure of water inside the vocal folds was adjusted to 1.75 kPa.

Several examples of the measured time signals are shown in Fig. 2 and the spectra of the generated sound measured by the external microphone placed outside the vocal tract are presented in Fig. 3. The peak sound level of the generated acoustic pressure signal (P_{out}) at the distance 30 cm from the lips is higher than the peak sound level measured without the vocal tract (see Fig. 2), however, the most of the energy of the microphone signal for the vowel [u:] is concentrated in the region of the first and second formant frequencies, i.e. the acoustic resonances of the vocal tract: $F_1 \simeq 350$ Hz and $F_2 \simeq 550$ Hz, while the primary signal generated by the vocal folds contains many higher harmonics up to 6 kHz, see Fig. 3. The maximum of the impact (contact) stress *IS* is evaluated from the intraglottal pressure $P_{intraglot}$ measured by the miniature pressure sensor in the glottis taking into account a time delay between the *IS* and the synchronously measured subglottal pressure P_{sub} , see Fig. 2. The relatively high fluctuation amplitudes (peak-to-peak values) of the P_{sub} were reduced by the acoustic-structure interaction of the vocal tract joint to the self-oscillating vocal folds.

Figure 4 shows the effects of acoustic-structural interaction on the vibration, acoustic and airflow characteristics measured with and without vocal tract in the whole region of the flow rates Q=0.2-0.4 *l*/*s*. The fundamental vibration frequency F_0 for the joint system (vocal tract and vocal folds) increased by cca 5-10 Hz and similarly as expected increased the P_{sub} by ca 0.3 – 0.75 kPa and the flow resistance P_{sub}/Q, see Fig. 4. On the other hand the following positive changes can be concluded. The vocal tract decreased the *IS* by ca 0.3-0.6 kPa and peak-to-peak amplitudes of the subglottal pressure from cca 50% for the lower flow rates Q and up to 100% for the higher values of Q. The difference in the sound pressure level SPL of the acoustic signal are smaller.

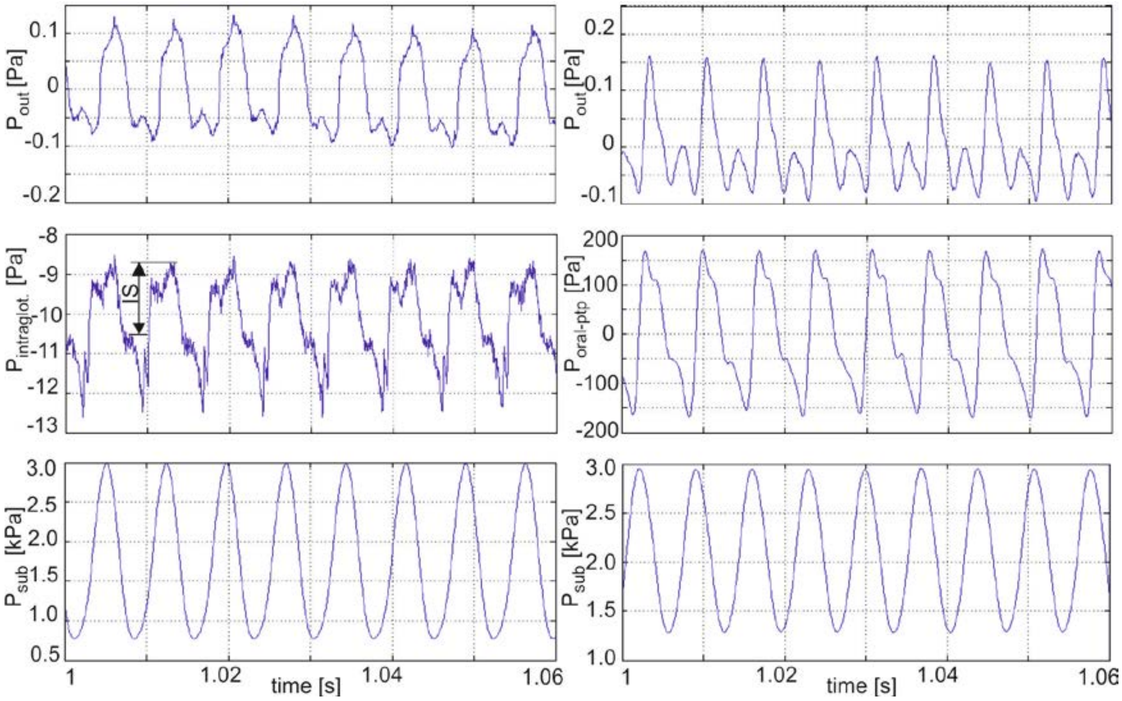

Fig. 2: Measured time signals for the airflow rate Q=0.25 l/s: a) without the vocal tract (left column), and b) with the vocal tract model for the vowel [u:] (right column). P_{out} - the generated acoustic signal measured by external microphone, $P_{intraglot}$ - the intraglottal pressure measured by the miniature pressure transducer in the glottis, $P_{oral-ptp}$ - fluctuations of the oral pressure and P_{sub} - the subglottal pressure.

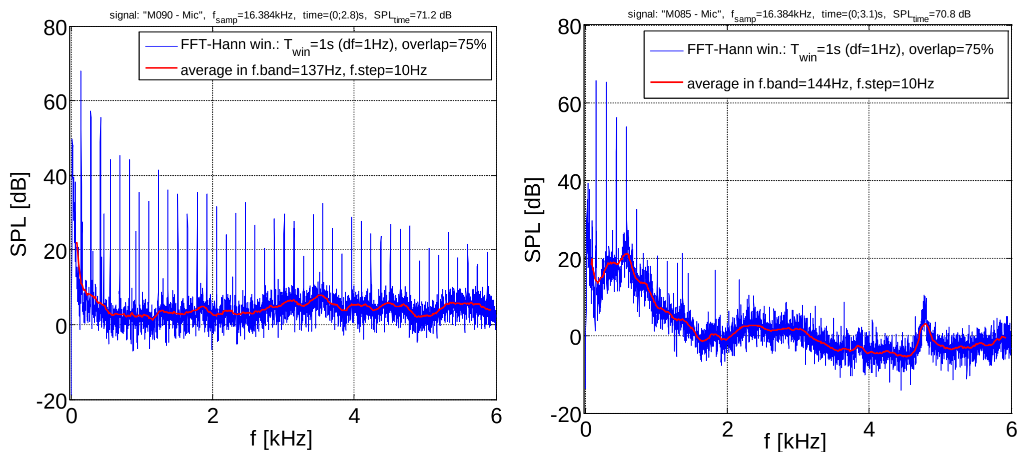

Fig. 3: Spectra of the generated sound measured by the external microphone for the airflow rate Q=0.25 l/s: a) without the vocal tract (left), and b) with the vocal tract model for the vowel [u:] (right).

4. Conclusions

The study was focused on modelling the effects of interaction of the supraglottal acoustic cavities with the self-oscillating vocal folds. The vocal fold model created by the silicon cover filled by water phonated in the intervals of the airflow rates Q=0.2-0.4 l/s and subglottic pressure $P_{sub} \cong 1.5 - 2.75\,\mathrm{kPa}$ that are realistic values in humans. The fundamental frequency F_0 which corresponded to a tenor voice increased when the vocal tract was joint system with the vocal folds. The highest impact (contact) stress during the vocal folds collisions was found ca $IS \cong 3.5\,\mathrm{kPa}$, which is also in the range of values measured in humans (Jiang & Titze, 1994). Important finding is that the vocal tract decreased the *IS* and peak-to-peak amplitudes of the subglottal pressure. A high contact stress is one of the most detrimental factor causing nodules and other pathologies in the vocal fold tissue. The influence of the vocal tract on the sound pressure level of the acoustic signal was found small. The measured aerodynamic, vibration and acoustic characteristics are in good agreement with the values found in humans.

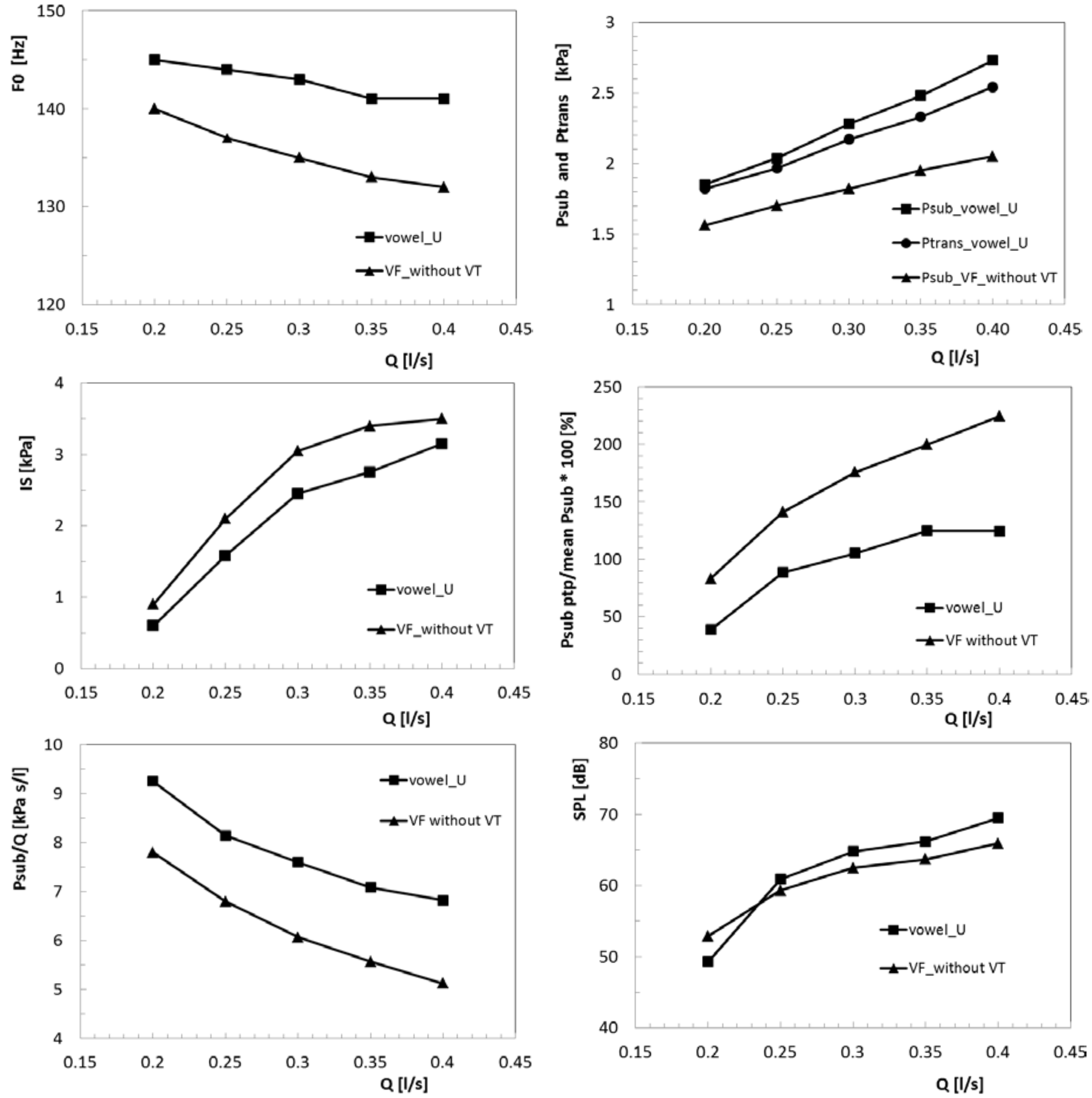

Fig. 4: Comparison of the vibration, acoustic and airflow characteristics of phonation measured on the vocal folds replica without and with the vocal tract model for the vowel [u:].

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