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IMPACT STRESS IN A SELF-OSCILLATING MODEL OF HUMAN VOCAL FOLDS

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Abstract. *The impact stress is one of the possible loading factors in phonation and it is considered as the main traumatizing mechanism in voice production and the main cause of vocal fold nodules. The vocal folds are primary source of voice transferring the energy from the airflow coming from the trachea to the vocal folds oscillations and furthermore to the generated acoustic pressure which is frequency modified by passing through the supraglottal resonance spaces of the human vocal tract, and which results finally in voicing.*

The contribution presents in vitro measurement of impact stress in a vocal folds replica made of a silicon rubber excited by airflow with synchronous registration of the flow induced vocal fold vibrations using a high speed camera, measurement of the subglottal dynamic and mean air pressures and the radiated acoustic pressure. Special miniature contact sensor was used for measurement of the impact stress between the oscillating vocal folds during collisions. The sensor was mounted on a thin metal lamella and installed in the centre of the glottis between the vibrating vocal folds. The airflow coming to the 1:1 scaled model of trachea was increasing from the phonation threshold up to the airflow rate 0.6 l/s and subglottal pressure 2.3 kPa, which is in the range of physiologically relevant values for a normal human voice production.

Depending on the flow rate the maximum contact stress, so-called maximum of impact stress, was measured from about 1.7 to 2.75 kPa and the vibration amplitude of the glottis, so called maximum glottal opening, was found between about 2 and 3.7 mm. The fundamental frequency at the vocal folds self-oscillations was about 152 Hz.

The measured impact stress corresponds to the values 0.4 – 3.2 kPa found in human excised larynges as well as to the values numerically simulated by the authors previously developed aeroelastic model of the vocal folds for numerical simulations of their sustained oscillations with collisions.

1 INTRODUCTION

Voice production is a complicated and complex biomechanical process, which involves several basic factors: airflow coming from the lungs, vocal-fold vibration and acoustic resonance of the cavities of the vocal tract. Primary pressure fluctuations arise in the human larynx as a result of the airflow being modulated by the vibrating vocal folds. The acoustic resonant spaces, formed by the air cavities upstream the vocal folds, modify the sound and codetermine its quality [1,2]. The vocal folds, excited by the airflow, generate a primary laryngeal tone whose fundamental frequency corresponds to the vibration frequency of the vocal folds. In the airways above the vocal folds, i.e. in the vocal tract, the acoustic resonant phenomena modify the spectrum of the primary laryngeal tone, especially the higher harmonics.

Understanding the basic principles of voice production is important for better interpretation of clinical findings, detection of laryngeal cancers or other pathologies and treatment of laryngeal disorders. Considering the inaccessibility of the vocal folds in humans exact airflow or tissue measurements in vivo are very restrained or impossible. Therefore, the physical models of the voice production are important tools in development and validation of theoretical models of phonation.

The impact stress is one of the possible loading factors in phonation and it is considered as the main traumatizing mechanism in voice production and the main cause of vocal fold nodules. Titze [3] has estimated the magnitude of various stresses related to vocal fold vibration and discussed their potential detrimental effects. He considered the impact stress (*IS*) as the most detrimental stress for the vocal fold tissue. Vocal fold nodules appear in the upper part of the vocal folds [2], at the middle of the musculo-membranous portion where the amplitude of vibration is greatest [4].This suggests that the collision forces are an important cause of these traumas. The nodules appear within the striking zone below the superficial layer of the vocal folds. Piezoresistive transducer was used by Verdolini et al. [5] for studying the impact stress in humans and a special probe microphone was used by Chen and Mongeau [6,7] for studying the contact pressure in a silicon replica of the vocal folds.

The contribution presents measurement of contact stress by a miniature pressure transducer in the artificial vocal folds made of a soft silicon rubber excited by airflow. The experiments were performed using a laboratory test rig that enables also synchronous registration of the flow induced vocal fold vibrations using a high speed camera, measurement of subglottal dynamic and mean air pressure and the generated acoustic signal. The measured maximum impact stress, maximum glottal opening and sound pressure level are compared with data found in excised larynges as well as with the values numerically simulated by the aeroelastic model of vocal fold self-oscillations.

2 MEASUREMENT SET UP

The schema of the all instrumentation and of the test rig is shown in Figure 1. The arrangement of the experiment was similar as in the previous study [8]. The airflow was coming from a central pressure compressor. The mean airflow rate Q in the main measurement line was measured by the float flowmeter. Before entering the glottal region of the model with the mounted vocal folds the subglottal pressure P_{sub} in the model of the trachea was measured by the special dynamic semiconductor pressure transducers IT AS CR mounted on the channel wall. The trachea was modeled by a Plexiglas tube (length 23 cm and inner diameter 25.5 mm). The mean air subglottal pressure $\overline{P}_{\mathrm{sub}}$ was measured by the digital manometer Greisinger Electronic GDH07AN connected by a short compliant tube with the subglottic space of the glottal cavity at the entrance of the airflow to the vocal folds.

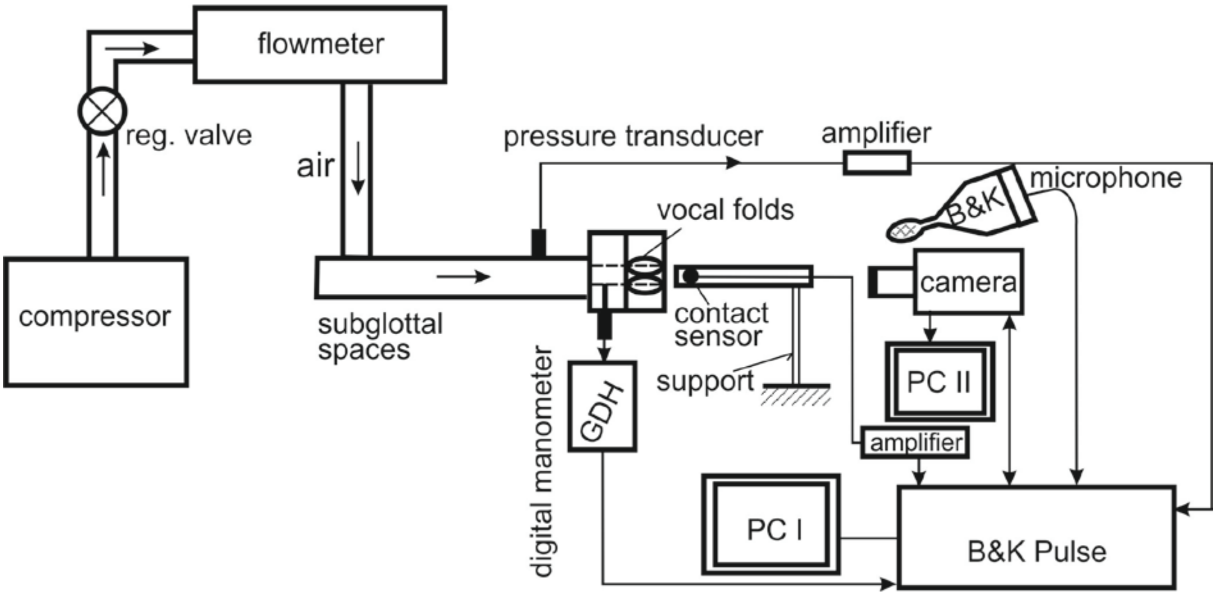

Figure 1: Schema of the measurement set up.

The personal computer (PC II) was used for recording the vocal folds model vibrations by the high-speed CCD camera NanoSense MkIII (maximal resolution 1280x1024 pixels) with the camera zoom lens Nikon AF micro Nikkor 60 mm. During the image recording using the frequency of 2500 frames per second the additional two intensive lights (2x500W) were focused on the vibrating vocal folds. The miniature pressure transducer (Precision Measurement Company, model 105S, range 60 psi, diameter 3.5 mm, thickness 0.4 mm) used for measurement of the contact stress was mounted on a thin metal lamella and installed in the centre of the glottis between the vibrating vocal folds. Figure 2 shows a detailed view on the construction of the complete contact stress sensor. The contact stress was amplified 10 000 times by an especially developed measurement amplifier. Acoustic signal was recorded by the sound level meter B&K 2239 installed at the distance of 20 cm from the vocal folds model.

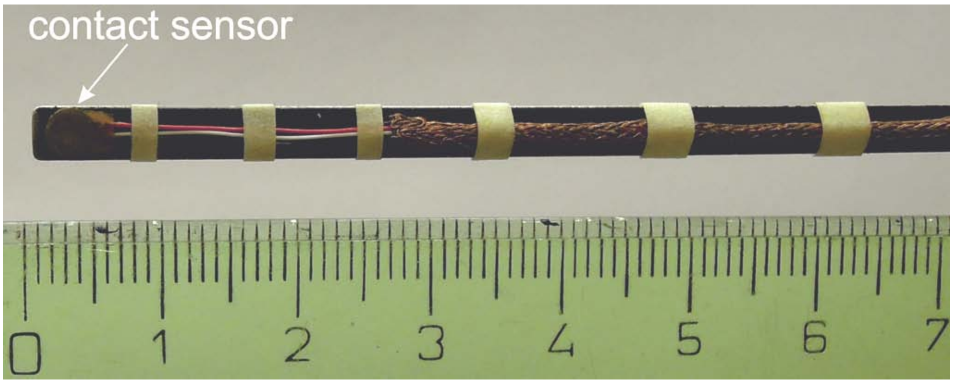

Figure 2: Impact stress probe with the mounted miniature contact sensor at the end.

The time signals from the pressure transducers and microphone were recorded in the personal computer (PC-I) using the measurement system B&K PULSE 10 with Controller Module MPE 7537A. The recording was made using 32.768 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.

The artificial vocal folds were made of a soft silicon rubber prepared from the Smooth-On Ecoflex Supersoft 0010 (parts A and B mixed in the ratio 1:1 by volume). The vocal folds model fixed in a Plexiglas frame was hermetically joined to the model of the subglottal spaces (see Fig. 1). A similar, one-layer isotropic model was used in previous study by Zhang et al. [9], and recently, some properties of layered silicone vocal fold models were investigated by Murray and Thomson [10], however, no impact stress was studied by these authors.

3 RESULTS OF THE MEASUREMENT

Example of the simultaneously recorded time signals for the contact stress, the subglottal pressure and the glottis opening evaluated from the images of the self-oscillating vocal folds is presented in Figure 3 for several oscillation periods. When the glottis was opened during the vibration period, the contact sensor measured the intraglottal air pressure of about 1.4 kPa in the airflow between the two vocal folds. As a result the maximum of the contact stress, so-called maximum of impact stress (*MaxIS*), was about *MaxIS* ≅ 4.0-1.4 =2.6 kPa. The maximum of the subglottal pressure (P_{sub}) of about 3 kPa was delayed after the maximum of impact stress of about ¼ of the vibration period. The delay of *MaxIS* behind the minimum of the glottis opening, given by a total thickness of the contact probe, was very small. The maximum of glottis opening (*maxGO*) was delayed behind the maximum of P_{sub} of about ½ of the vibration period.

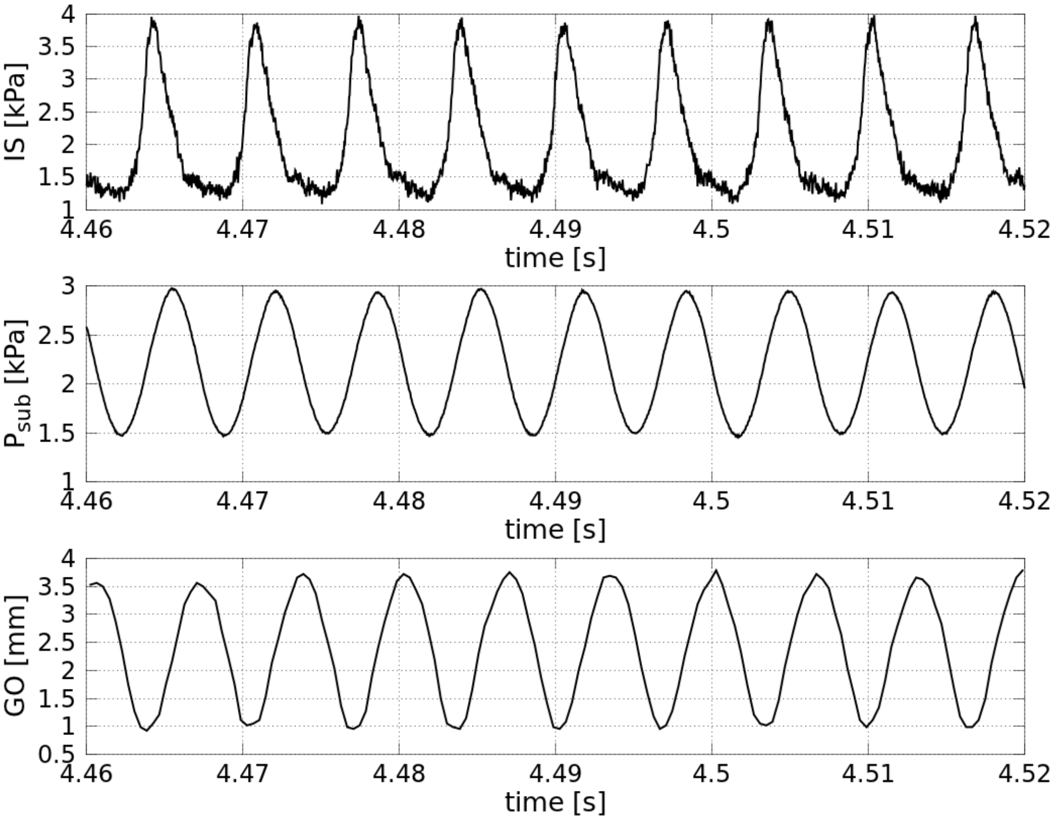

Figure 3: Example of the measured signals for the contact stress (upper panel), the subglottal pressure (middle panel) and the glottis opening (lower panel) for the mean flow rate Q=0.55 l/s and the mean subglottal pressure $\overline{P}_{\mathrm{sub}}$ =2.24 kPa. The fundamental frequency of the vocal folds self-oscillations was F_0 =152 Hz.

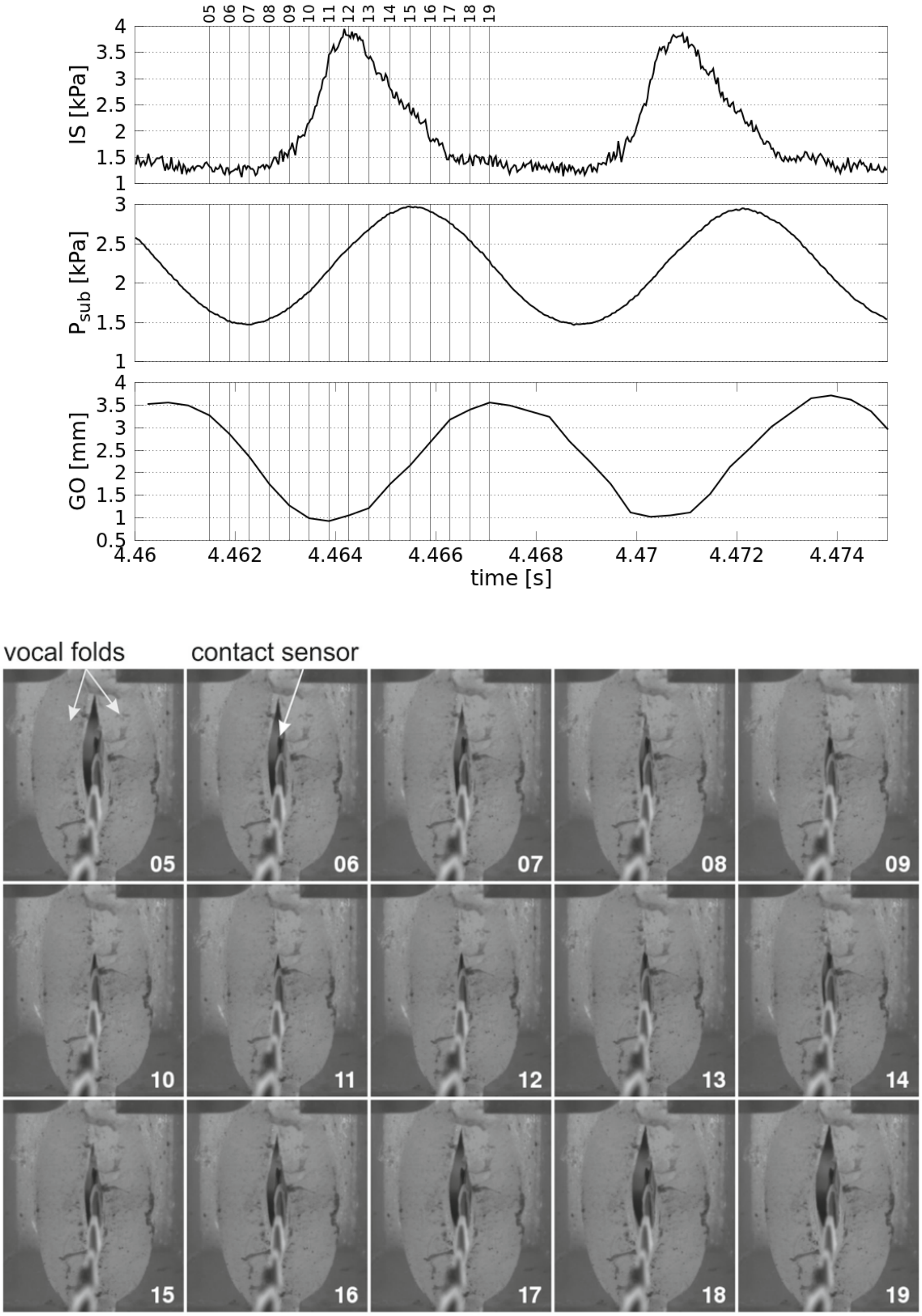

Figure 4: Detail of the measured signals for the contact stress (*IS*), the subglottal pressure (P_{sub}) and the glottis opening (*GO*) (upper panels). Vertical numbered lines 5-19 correspond to the time instants when the snapshots of the self-vibrating vocal folds (lower panel) were taken during one oscillation period. (The mean flow rate Q=0.55 l/s, the mean subglottal pressure $\overline{P}_{\mathrm{sub}}$ =2.24 kPa and the fundamental frequency F_0 =152 Hz.)

Figure 4 shows the simultaneously recorded images of the vocal folds vibration and the two time signals from the contact sensor placed between the vocal folds and the semiconductor pressure transducer positioned in the model of the trachea. The corresponding time instants are numbered on the vocal folds images (05-19) and marked by the same numbers on the time records during one oscillation cycle. The time instants marked by the numbers 05 – 08 belong to the open phase of the glottis. During this open phase the active side of the contact sensor measures the pressure in the air flowing in the glottis between the two vocal folds. At about the time instant denoted by number 09 the closing phase of the vocal folds vibrations starts and the left vocal fold starts to be in the contact with the contact sensor. At this moment the impact stress *IS* starts a fast increase reaching a maximum impact stress (*MaxIS*) at about the time instant numbered as 12. The closed phase of the glottis vibration period ends at about the time instant numbered as 14, but the *IS* value is still relatively high, because the subglottal pressure, which is loading the free active side of the contact sensor, still increases. Therefore, the decrease of the *IS* in the opening phase of the glottis is not as fast as in the closing phase. This phenomenon is the consequence of a phase delay of the subglottal pressure after the *IS* signal. It should be noted here that the impact stress is given by the difference between the maximum of the *IS* signal and the aerodynamic pressure measured by the contact sensor during the open phase and that the minimum glottis opening was not zero but it was about 0.93 mm given by the thickness of the stick holding the contact sensor.

Figure 5 shows the example of the spectrum of the microphone signal. In addition to the fundamental frequency F_0=152 Hz the acoustic signal generated by the artificial vocal folds vibration involves many higher harmonics (20 harmonics up to about 3 kHz). The sound is influenced in the higher frequency region by a noise originated in the air jet behind the glottis.

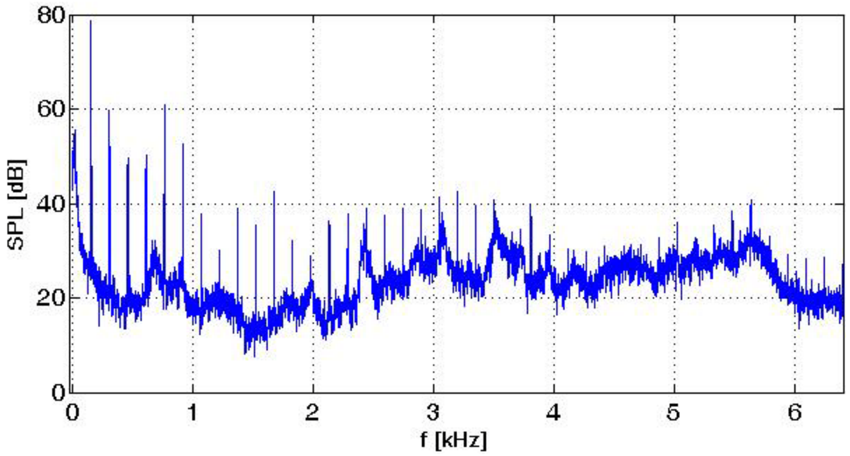

Figure 5: Spectrum of the microphone signal generated by the self-oscillating vocal fold model and measured for the mean flow rate Q=0.55 l/s, the mean subglottal pressure $\overline{P}_{\mathrm{sub}}$ =2.24 kPa and F_0=152 Hz.

Figure 6 shows the evaluated maximum of impact stress (*MaxIS*) depending on the preset mean airflow rate Q and on the measured mean subglottal pressure $\overline{P}_{\mathrm{sub}}$. The *MaxIS* increases with Q as well as with $\overline{P}_{\mathrm{sub}}$ approximately linearly. Below the airflow rate of about Q=0.39 l/s the level of the generated acoustic signal was very low as well as the contact stress, which was not possible to measure reliably. Therefore the so-called phonation onset flow rate was below 0.39 l/s.

Figure 7 shows the evaluated maximum of the glottis opening (*MaxGO*) measured from the images registered by the high speed camera, the sound pressure level (*SPL*) and the fundamental frequency F_0 for the same flow rate interval as the *IS* was measured. The *MaxGO* and as well as *SPL* increases with the flow rate *Q* approximately in a linear way while the fundamental frequency F_0 varied between 150 and 152 Hz.

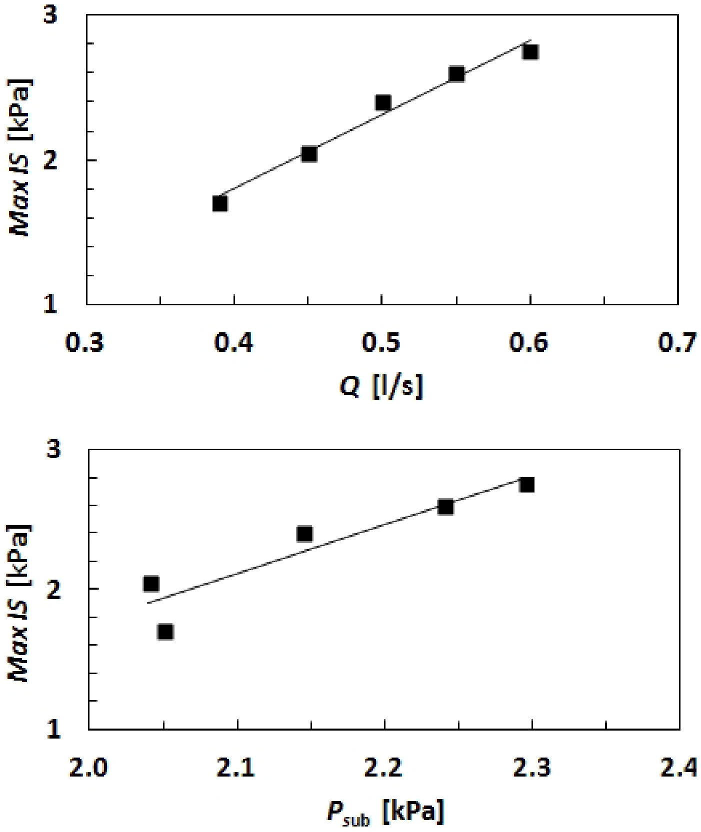

Figure 6: Measured maximum impact stress *versus* the mean flow rate (upper panel) and the mean subglottal pressure (lower panel).

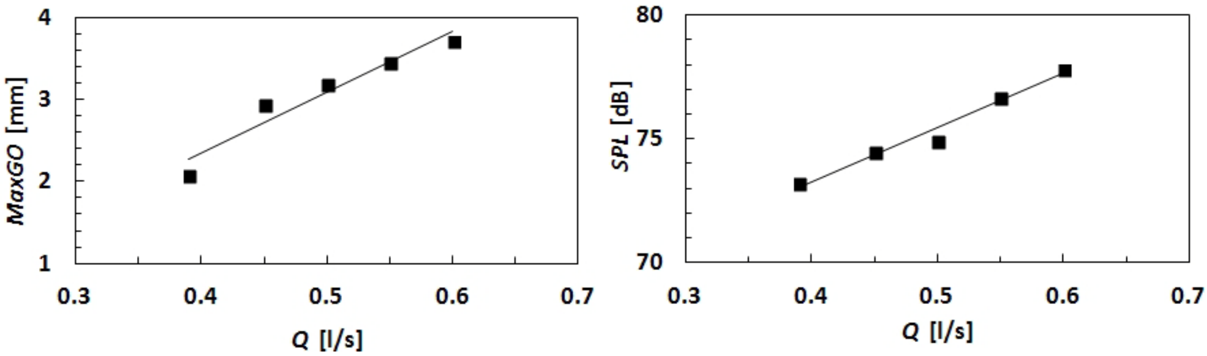

Figure 7: Measured maximum of the glottis opening (left) and the sound pressure level (right) *versus* the mean airflow rate.

4 COMPUTER SIMULATED IMPACT STRESS IN THE VOCAL FOLDS

The results for maximum impact stress can be compared with the values predicted by numerical simulations using an aeroelastic model of vocal folds self-oscillations [11]. The three-mass model (see Figure 8) is based on the equations of motion for the two-degrees of freedom dynamic system:

$$\bar{\mathbf{M}}\ddot{\mathbf{V}} + \bar{\mathbf{B}}\dot{\mathbf{V}} + \bar{\mathbf{K}}\mathbf{V} + \mathbf{F} = \mathbf{0}, \tag{1}$$

where $\bar{\mathbf{M}}, \bar{\mathbf{B}}, \bar{\mathbf{K}}$ are the structural mass, damping and stiffness matrices, ${}^{\mathrm{T}}\mathbf{V}(t) = [V_1(t), V_2(t)]$ is the vector for rotation and translation and the vector for nonlinear aerodynamic and collision forces can be expressed as

$${}^{\mathrm{T}}\mathbf{F}(t) = [F_1(t), F_2(t)], \qquad F_{1,2}(t) = \rho_t \sum_{i,j=0}^{2} \sum_{k,l=0}^{2} {}^{1,2}K_{i,j,k,l} \left[V_1^{(i)}(t)\right]^k \left[V_2^{(j)}(t)\right]^l, \tag{2}$$

where the superscripts above V_1 and V_2 denote the order of time derivatives and $K_{i,j,k,l}$ are complicated coefficients. The impact stress in the model is calculated as the maximum value during one oscillation period from the formula:

$$MaxIS = \frac{3}{2}\frac{F_{H,\max}}{\pi a^2}, \qquad a = \sqrt[3]{\frac{3}{4} r \frac{(1-\nu^2)}{E} F_{H,\max}}, \tag{3}$$

where r is the radius of the curvature of the vocal fold model at the contact point, E is the Young modulus, ν is the Poisson number, $F_H = k_H \delta^{3/2}$ is the impact Hertz force, where $k_H = 4/3\sqrt{r}\,E/(1-\nu^2) \cong 730\ \mathrm{N\,m^{-3/2}}$ was considered, and $\delta = (y_{max} - H_0)$ is a penetration of the vocal folds during contact.

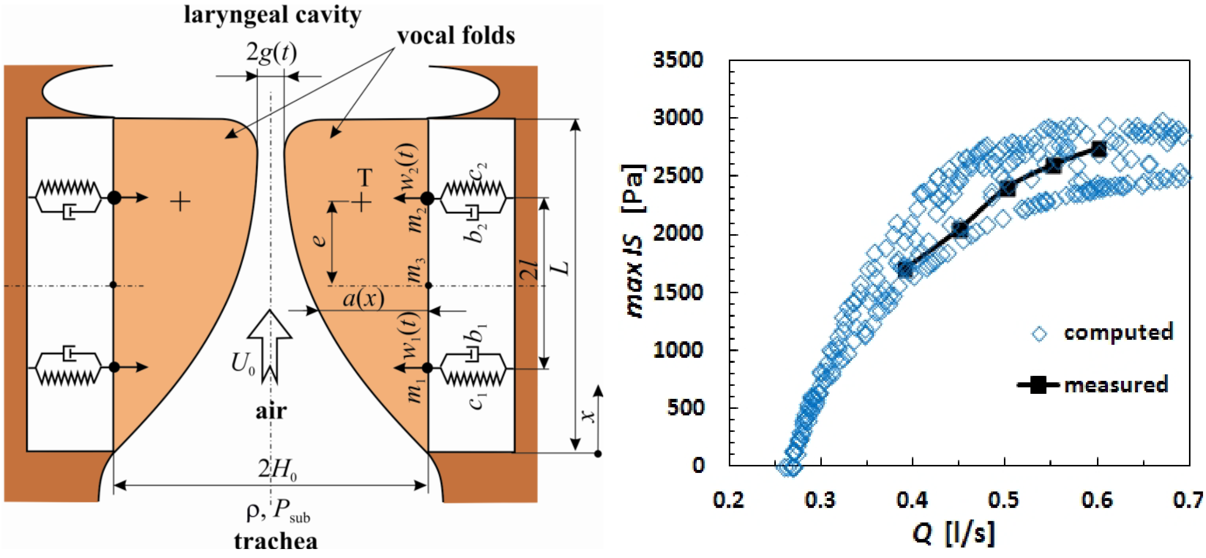

Figure 8: Schema of the aeroelastic model of the vocal folds (left) and the computed maximum impact stress *versus* the flow rate for $F_0 \approx 150$ Hz and the prephonatory glottal half gap $g = 0.375$ mm (right).

The results for computed and measured *MaxIS* are compared in Figure 8 as a function of the flow rate Q, which was a controlled parameter in the modeling as in the experiment. The data computed for *MaxIS* begin at the flow rate 0.27 l/s corresponding to the phonation onset, where no or a very slight impacts exist, and end at the flow rate 0.7 l/s, where the regular oscillations are changing to irregular regimes of vibration. The *MaxIS* increases rapidly just above the phonation onset, and reaches a plateau for higher Q values. A scattering of the online numerically simulated data is caused by the system nonlinearities both in the Hertz impact model as well as in the aerodynamic forces. The simulated data were obtained by numerical solution of Eq. (1) with flow rate automatically increased from 0.25 l/s to 0.7 l/s and then decreased back to the minimum. The initial conditions of each of the simulations were given by the final state of the previous simulation, i.e. random values within the vibration range.

5 DISCUSSION

Depending on the flow rate Q=0.39 - 0.60 l/s the measured maximum impact stress *MaxIS* on the vocal fold surface, the maximum glottal opening *MaxGO* and the sound pressure level *SPL* of the generated acoustic signal in a distance of 20 cm from the vocal folds were increasing approximately linearly in the intervals $MaxIS \cong 1.70 - 2.75\,\text{kPa}$, $MaxGO \cong 2 - 3.7\,\text{mm}$ and $SPL \cong 73.2 - 77.8$ dB (recall Figures 6 and 7). The mean subglottal pressure varied in the interval $\overline{P}_{\text{sub}} \cong 2.05 - 2.30\,\text{kPa}$ and the fundamental frequency of the the vocal folds self-oscillations varied in the interval $F_0 \cong 150 - 152$ Hz.

The values of the measured maximum impacts stress, the maximum glottis opening and *SPL* and the trends of their variation with the subglottal pressure are also in a good agreement with the results obtained by numerical simulations by Horáček et al. [12], where $MaxIS \cong$ 3 kPa and $MaxGO \cong$ 3 mm were found for the half-gap g=0.5 mm, $\overline{P}_{\text{sub}} \cong 2$ kPa and $F_0 \cong 100$ Hz . Later, the $MaxIS \cong$ 4 kPa resulted from the numerical simulations of soprano and bass voices for the prephonatory half-gap g=0.5 mm, see [13].

The measured results also fall well within the limits reported for excised human larynges. The values of the impact stress 1-5 kPa were found by Reed et al. [14] and 0.4-3.2 kPa by Verdolini et al. [5]. The maximum impact stress 0.59-0.63 kPa was measured in silicon replica of the vocal folds for Q=0.72-0.75 l/s, $\overline{P}_{\text{sub}}$=2.84-2.91 kPa and F_0=140Hz by Chen and Mongeau [6,7]. Maximum contact stress 3 kPa was measured in a canine hemilarynx for the $\overline{P}_{\text{sub}} \cong 2$ kPa and $F_0 \cong 145$ Hz, see [15].

6 CONCLUSIONS

The method for studying the impact stress in the physical models of the vocal folds with the synchronous registration of the vocal folds sustained vibrations with collisions, the acoustic and aerodynamic characteristics was developed and tested on a silicon replica.

The preliminary results showed that the measured maximum impact stress is in good agreement with the values 0.4 – 3.2 kP found in human excised larynges and corresponds well to the values and trends numerically simulated by the authors previously developed the aeroelastic model of vocal fold self-oscillations controlled by the airflow rate.

The knowledge of the impact stress for a vocal folds replica can be useful for experimental verification of developed more sophisticated 3D computational finite element models of phonation due to relatively exactly defined input material and geometrical parameters, which is problematic in case of real human vocal folds.

7 ACKNOWLEDGEMENTS

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