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MEASUREMENT OF VIBRATION, FLOW AND ACOUSTIC CHARACTERISTICS OF A HUMAN LARYNX REPLICA

J. Horáček*, V. Bula*, V. Radolf*, T. Vampola, M. Dušková*****

Abstract: *The study presents results of in vitro measurements of voicing performed on the developed artificial larynx based on the CT images of human larynx taken during phonation. The measured phonation characteristics are in good agreement with the values found in human larynges. The knowledge of these characteristics for the vocal folds replica can be useful for experimental verification of developed sophisticated 3D computational finite element models of phonation due to relatively exactly defined input material and geometrical parameters, which is problematic to obtain reliably in humans.*

Keywords: Fluid-structure interaction, Flutter, Biomechanics of voice modeling, Phonation.

1. Introduction

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.

2. Model of the Human Larynx

The CT examination was performed for male trained singer (34 years old) after warm-up exercises. The subject was placed in a CT scanner in supine position and phonated a sustained vowel [a:] in a habitual pitch and comfortable loudness. The CT images were acquired by Toshiba–Aquilion CT machine with the time of the rotation 0.5 s and 510 slices of thickness 0.5 mm. The CT images were segmented and processed into volume model of the vocal tract (Vampola et al., 2014), which was used for preparation of the mould on a 3D printer, see Fig. 1.

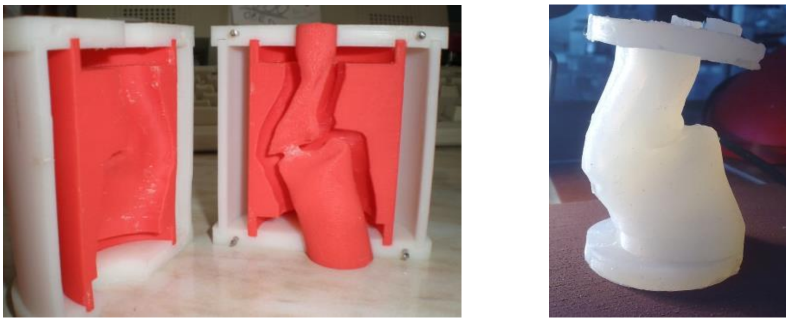

Fig. 1: The mould produced by 3D-printing and the casted larynx model made of silicone rubber.

* Ing. Jaromír Horáček, DrSc., Ing. Vítězslav Bula, Ing. Vojtěch Radolf, PhD., Institute of Thermomechanics, ASCR, Dolejškova 5, 18200 Prague, CZ, jaromirh@it.cas.cz, bula@it.cas.cz, radolf@it.cas.cz

** Assoc. Prof. Dr. Ing. Tomáš Vampola, Department of Mechanics, Biomechanics and Mechatronics, Faculty of Mechanical Engineering, Czech Technical University, Technická 4, 16607, Prague; CZ, Tomas.Vampola@fs.cvut.cz

*** Dr. Ing. Miroslava Dušková-Smrčková, Institute of Macromolecular Chemistry, ASCR, Heyrovského nám. 1888/2, 16206 Prague, CZ, m.duskova@imc.cas.cz

The dynamic viscoelastic properties of the silicone rubber were measured by oscillatory rheometer (Gemini HR Nano, Malvern, UK) as a frequency sweep in linear viscoelasticity region (LVR) in strain control mode. For dynamic measurement in lower frequency range: 0.1-10 Hz, standard plate-plate geometry was used. This test was performed with disc-like silicone rubber specimen of thickness 3 mm and diameter 25 mm. A rubber sheet of that thickness was casted from the same reactive mixture (Ecoflex 00-10) separately between two glasses with Teflon distance. After complete cure, the samples for dynamic mechanical analysis (DMA) were cut with a sharp puncher. For DMA measurement in a special high-frequency mode using so called piezzo-rotational vibration geometry (PRV attachment supplied by Malvern) that allows to reach loading frequencies of several kHz, thin rubber disks were made: their thickness was below 1 mm and the diameter was 40 mm (the dimension of specimen is varied due to increase of stiffness of tested material). In both tests, conventional DMA and high frequency DMA (using PRV) a shear dynamic oscillatory deformation was applied on the rubber and the force response was monitored in linear viscoelasticity region of the rubber that had to be determined separately prior to the DMA test. From the stress-strain ratio and rheometer response, the complex shear modulus $G=G'+iG''$ and loss factor tan δ were calculated as function of frequency, Fig. 2. The measurement was performed at laboratory temperature. The shear moduli of model silicone rubber Ecoflex 00-10 at frequency 100 Hz at PRV mode were G'=11 kPa, and G''=3.5 kPa with the loss angle around 20 degree. These values suggest the rubbery behavior and the material at frequencies close to phonation range reveals significant viscous response. At loading frequencies over 104 Hz, the model silicone starts approaching its vitrification (frequency) area.

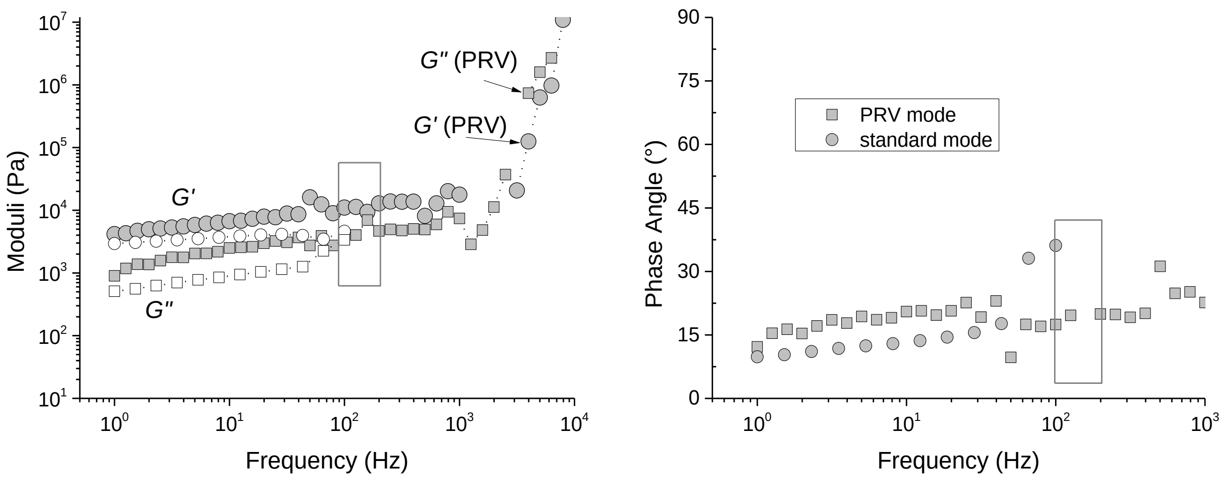

Fig. 2: Shear moduli of material for larynx model, G', G'' and the phase (loss) angle measured by dynamic mechanical oscillatory shear test. Two measurements combined in one plot: in low frequency range (1-100 Hz) by standard shear test - open symbols; and in high frequency range using special piezzo-rotational vibration mode (PRV, 1-10^4 Hz) – filled symbols.

The experiments with the artificial larynx were performed in a test rig that enables synchronous registration of the airflow induced vocal fold vibrations using a high speed camera, measurement of contact stress between the vocal folds during collisions, the subglottic dynamic and mean air pressure and the generated acoustic signal, see Horáček et al. (2013).

3. Results of the Phonation Measurement

Example of the simultaneously recorded time signals for the (*IS*) measured by a miniature pressure transducer, the subglottal pressure (P_{sub}) and the glottis opening (*GO*) evaluated from the images of the self-oscillating vocal folds are presented in Figs. 3 and 4. When the glottis was opened during the vibration period *T*, the contact sensor measured the intraglottal air pressure of about 2.5 kPa in the airflow between the vocal folds. As a result the maximum of contact (impact) stress was $MaxIS \cong 2.6$ kPa .

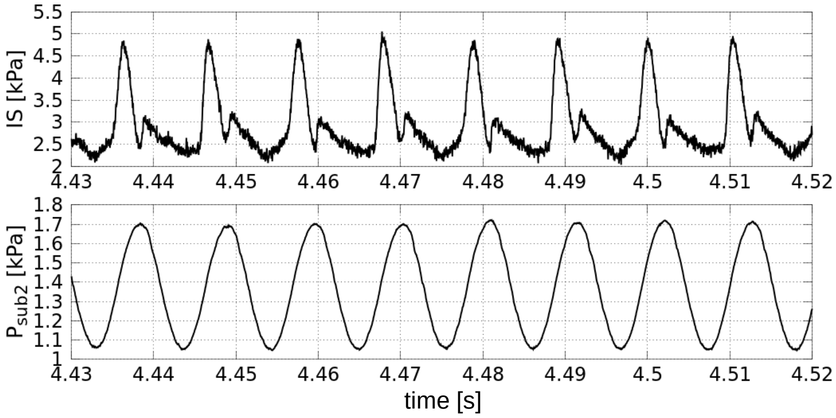

Fig. 3: Impact stress (IS) measured by the contact sensor during the vocal folds self-oscillations and the subglottic pressure (P_{sub}) measured by the pressure transducer mounted on the model of trachea for the mean flow rate Q=0.3 l/s and the mean subglottic pressure $\bar{P}_{sub}$ =1.47 kPa.

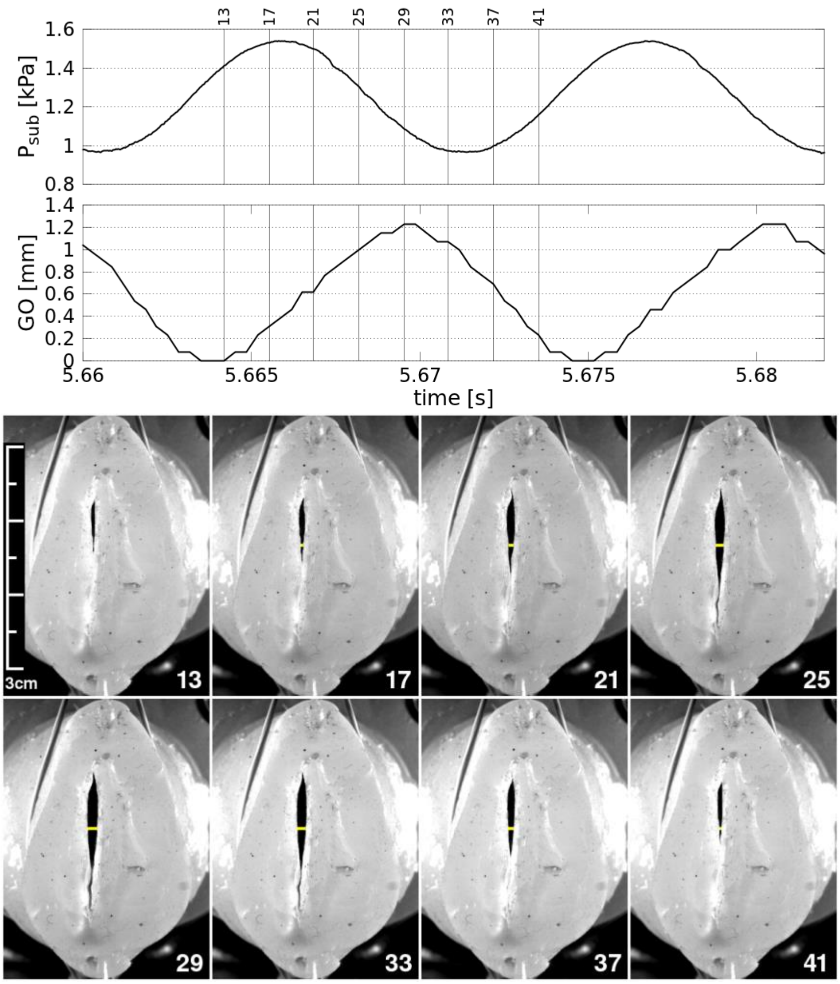

Fig. 4: The subglottic pressure (P_{sub}) and the glottal opening (GO) of the vibrating vocal folds evaluated from the images taken by the high speed camera at the time instants marked by numbers 13-41.

The maximum of $P_{sub} \cong 1.7$ kPa was delayed after the *MaxIS* of about *T*/5 (Fig. 3) and the maximum GO was delayed behind P_{sub} by about *T*/3, see Fig. 4, where the vibration pattern of the vocal folds is shown during one period. The results summary of the vibration and acoustic characteristics of the larynx in the measured phonation range is shown in Fig. 5. We note that the airflow rate was the controlled parameter in the experiments and the phonation onset, where $IS \approx 0$ and sound pressure level $SPL \approx 0$, was found at $Q \approx 0.15\, l/s$.

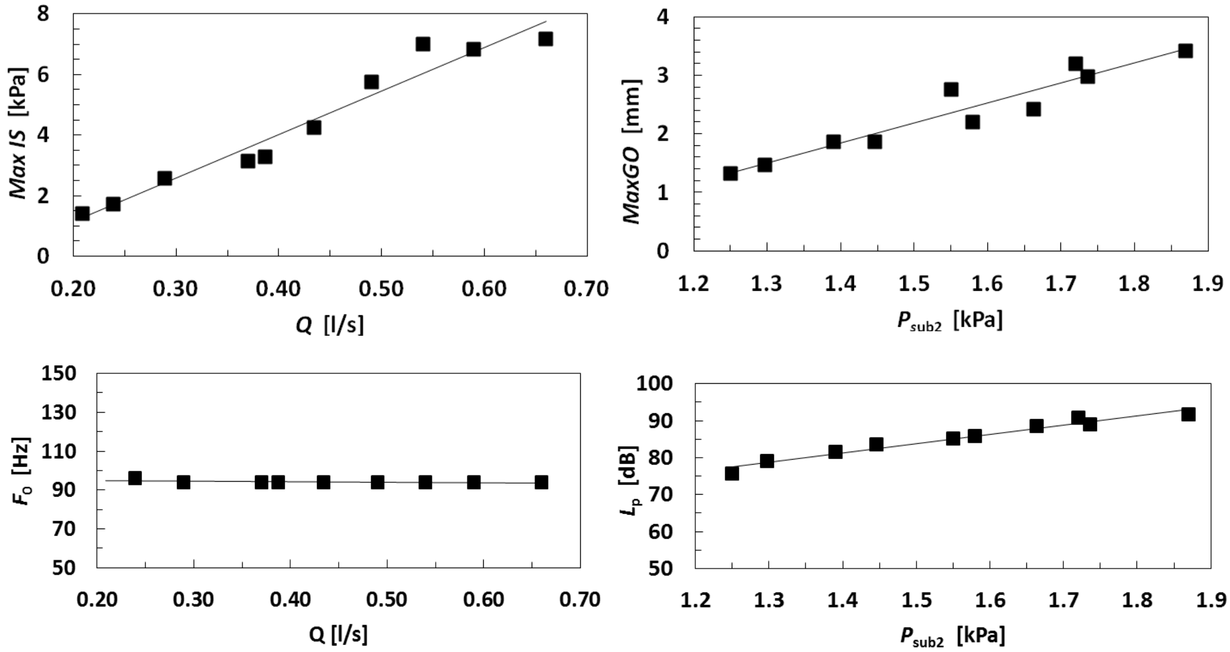

Fig. 5: Measured maxima of the impact stress (MaxIS) and the glottis opening (MaxGO), the fundamental phonation frequency (F_0) and peak sound level (L_p) as functions of the airflow rate (Q) and mean subglottic pressure (P_{sub}).

4. Conclusions

Depending on the mean flow rate Q=0.2-0.7 l/s the measured $MaxIS \cong 0-7.5$ kPa and the peak sound level $L_p \cong 75–92$ dB of the acoustic signal in a distance of 20 cm from the vocal folds were increasing approximately linearly. The mean subglottic pressure varied in the interval $\bar{P}_{sub} \cong 1.2–1.9$ kPa and the fundamental frequency of the vocal folds self-oscillations varied in the interval $F_0 \cong 94–96$ Hz.

The measured phonation characteristics are in good agreement with the values found in human or canine excised larynges, see e.g. Titze (2006). The knowledge of these characteristics for a vocal folds replica can be useful for experimental verification of developed 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.

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