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EXPERIMENTAL INVESTIGATION OF AIR PRESSURE, ACOUSTIC CHARACTERISTICS AND VIBRATIONS OF VOCAL FOLDS ON A COMPLEX PHYSICAL MODEL OF PHONATION IN HUMANS

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Abstract: *The contribution aims to provide material that can be used in development of more realistic physical as well as theoretical models of voice production. The experimental set-up, methodology and the results of measurement of airflow rate, subglottal, oral and generated acoustic air pressures are presented together with the simultaneously measured flow-induced vibrations of a vocal folds replica, made of soft silicon rubber, and recorded by a high speed camera. The data were measured during a 'soft' phonation just above the phonation onset, given by the phonation threshold airflow rate, and during a 'normal' phonation for the airflow rate of about three times higher. A model of the human vocal tract in the position for production of vowel [u:] was used and the flow resistance was raised by phonating into a glass resonance tube either in the air or having the other end of the tube submerged under water, and by phonating into a narrow straw. The results for the pressures presented in time and frequency domain are comparable with the physiological ranges and limits measured in humans for ordinary phonation and for production of vocal exercises used in voice therapy.*

Keywords: ***Biomechanics of voice; subglottal, oral and transglottal pressure; flow resistance***

1. Introduction

Phonation under higher than normal supraglottic impedance is used in voice training and therapy (see e.g. Story et al. 2000; Titze et al., 2002; Laukkanen et al. 2012). This contribution compares *in vitro* measurements of phonation on [u:], phonation into a resonance tube and into a narrow straw for a 'normal' phonation and a 'soft' phonation at the phonation onset. The flow resistance of the vocal tract was furthermore increased by phonation through the tube into water making the phonation more difficult due to loading the human phonation system by the hydrodynamic pressure and bubbling.

2. Measurement set-up and measurement procedure

The measurements were carried out with silicon vocal folds replicas and with a simplified plexiglass vocal tract model for which the area cross-sections along its length corresponded to a male vocal tract during phonation on vowel [u:] (Horáček et al., 2011). The vocal tract was prolonged by a tube or straw, and also tube phonation into water having the other end submerged down to 10 cm below the water surface was studied. Tubes made of glass, e.g. like the resonance tube studied here: 27 cm in length and with inner diameter of 6.8 mm, have been used in Scandinavia for voice training and therapy, similarly like a plastic stirring straw (12.7 cm in length, inner diameter 2.5 mm) considered by Titze et al. (2002). The first set of measurements was performed for a 'normal' sustained phonation at the fixed airflow rate Q=0.4 l/s, and the second set at the phonation threshold defined by the airflow rate measured at a time instant when the flow was somehow gradually decreasing until the phonation with measurable acoustic pressure oscillations ended. The sound pressure level (SPL) inside the model of oral cavity was measured using the B&K special microphone probe designed for measurement of acoustic pressure in small cavities, and the mean oral pressure (P_{oral}) was measured by the digital manometer connected with the oral cavity by a small compliant tube. Generated acoustic signal outside the vocal tract model was recorded using a microphone (B&K sound level meter) installed at a distance of 20 cm from the lips. The recordings were made using 32.8 kHz sampling frequency by the PC controlled measurement system B&K PULSE 10 and synchronized with the high speed camera. The mean (P_{sub}) and peak-to-peak subglottal pressures were measured by special dynamic

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semiconductor pressure transducers. The fundamental vibration frequencies *F0* of the vocal folds and the formant frequencies (acoustic resonances of the vocal tract) were evaluated from the spectra of the pressure signals.

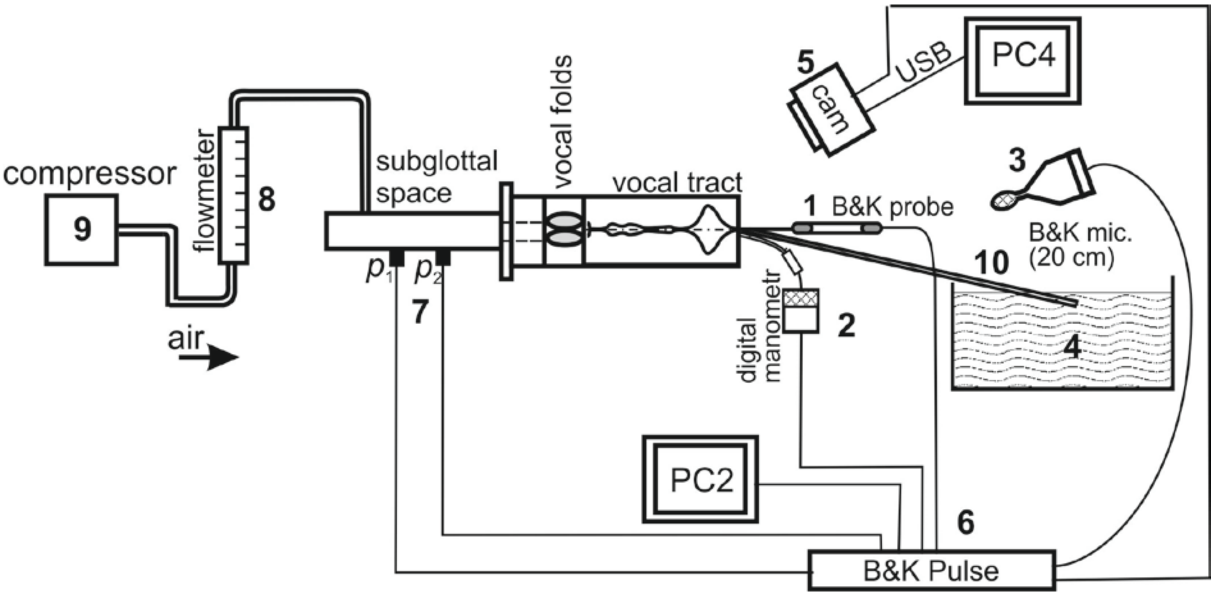

Fig. 1: Schema of the in vitro measurement set up: 1- B&K microphone probe 4182, 2 – digital manometer Gresinger Electronic GDH07AN, 3 – sound level meter B&K 2239, 4 – aquarium, 5 – high speed camera, 6 – B&K measurement system PULSE 10 with Controller Module MPE 7537 A, 7 – semiconductor pressure transducers, 8 – float flow meter, 9 – air compressor, 10 – resonance tube.

Fig. 2: Measurement set up with a detail of the model of supraglottal spaces.

The procedure for studying the pressure and vibration characteristics for a 'soft' phonation at the phonation threshold is demonstrated in Fig. 3 showing one measurement trial when the all measured signals were recorded by the measurement system B&K PULSE. The whole trial took exactly 20 s beginning with a fast manual increase of the airflow rate up to starting a sustained phonation for few seconds and followed by a slow decrease of the flow rate to a phonation threshold. Then the flow rate was fixed and the high speed camera was started – see the synchronization signal shown together with the subglottal pressure in Fig. 3 between about 14-16 s.

When a 'normal' phonation was studied, the same signals were recorded for 20 s as in the previously described procedure for a 'soft' phonation. However, just after starting the trial the flow rate was fixed and held constant with a prescribed value up to the trial end.

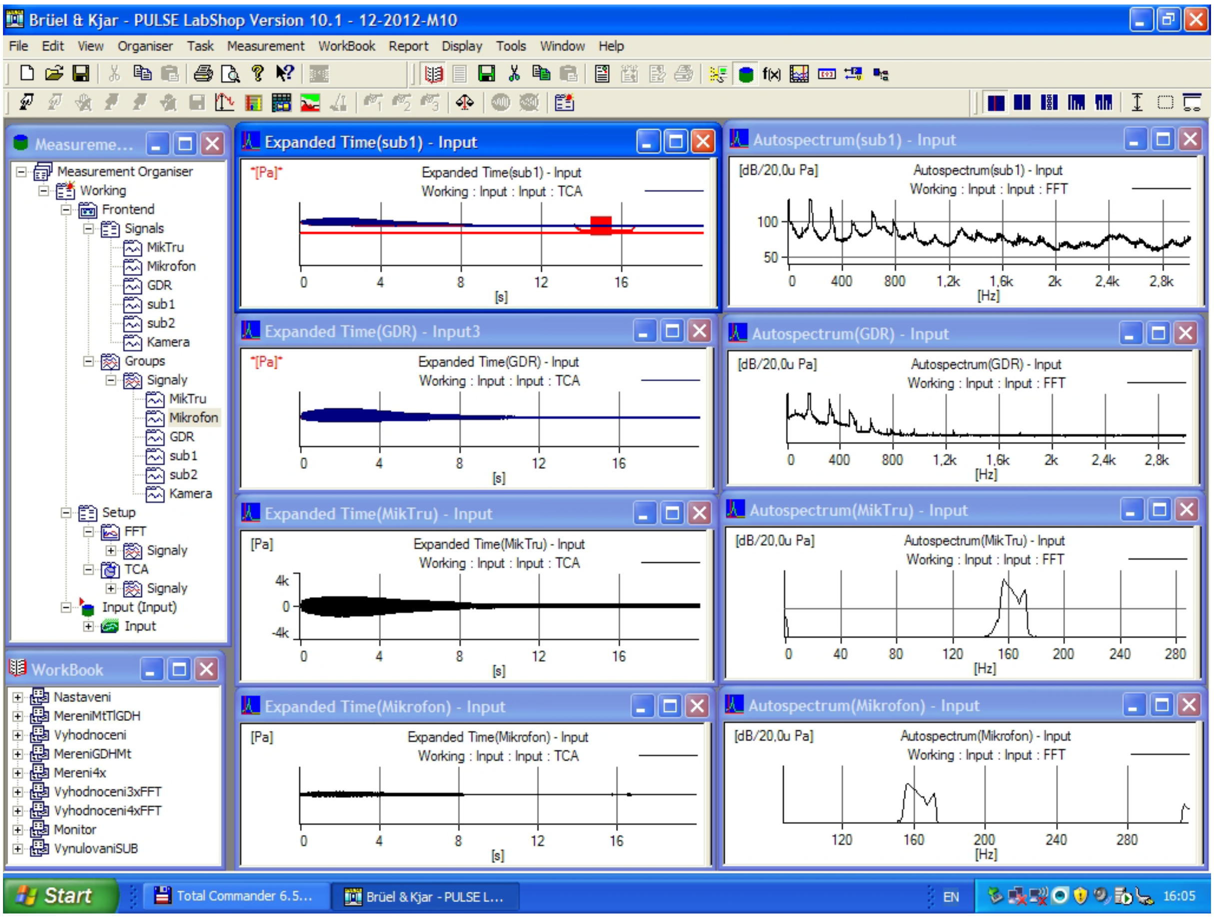

Fig. 3: Example of measured signals and their spectra by the B&K system PULSE during one trial for studying the case of a 'soft' phonation. From top: subglottal pressure, oral pressure measured by the digital manometer, oral pressure measured by the B&K probe, microphone signal.

3. Results

Figures 4–7 show measured signals and spectra for the subglottal pressure, the variation of the oral pressure and the radiated acoustic pressure for a „'soft'" phonation: on [u:], into the tube in air, into the tube 10 cm deep in water and into the straw, respectively.

Only the lowest resonance frequencies change substantially: from 16 Hz for bubbling in case of the tube in water (see the detailed spectrum of the oral pressure in Fig. 6) to about 80 Hz for straw (see the detailed spectrum of the oral pressure in Fig. 7) and up to about 100 Hz for phonation into the tube in air (see the spectrum of the oral pressure in Fig. 5). The first resonance frequency at about 260 Hz can be identified in the spectrum of radiated pressure shown in Fig. 4 for phonation on [u:]. The higher resonances at about 650 Hz, 1400-1450 Hz, 2300 Hz, 3950-4050 Hz and 4800-4850 Hz are nearly identical for all trials and visible practically in all of the spectra in Figs. 4–7. Thus these higher resonances are probably associated with resonances of the all joint acoustic cavities beginning from the model of the subglottal spaces to the open space at the end. It is caused by the fact that for all of the phonations there was no complete closure between the vocal folds and, consequently, the subglottal and supraglottal acoustic spaces were permanently joined during phonation.

Second important conclusion resulting from Figs. 4–7 is that for phonation into the tube submerged in water the most important part of the acoustic energy inside the oral cavity is associated with a bubbling effect at about the frequency 16 Hz where the resonance peak in amplitude is even higher than for the fundamental frequency $F0$ (see Fig. 6). The effect of bubbling can clearly be seen also on the subglottal pressure and on the vocal folds vibration in time domain when the low oscillation frequency of bubbling is superimposed on the higher fundamental frequency (see Fig. 9 hereinafter). Consequently the bubbling has an important effect on the vocal folds if this technique is used in the voice therapy. Similarly the sound pressure level in the oral cavity model in the frequency region of the lowest resonances for the vocal tract occluded by the tube or by the straw dominates in the spectra (see Figs. 5 and 7).

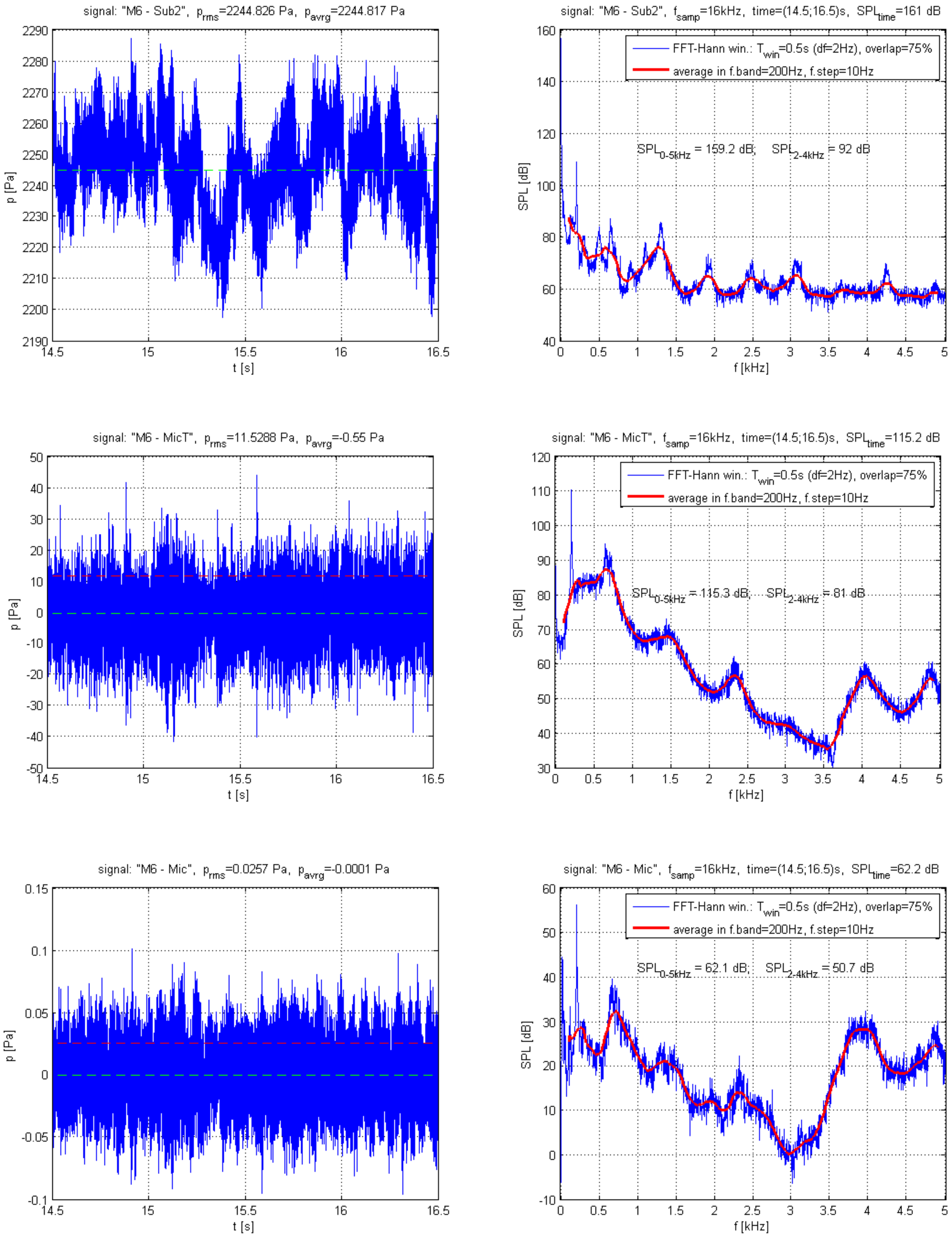

Fig. 4: Measured signals and spectra for the subglottal pressure (upper panel), the variation of the oral pressure (middle panel) and the radiated acoustic pressure (lower panel) for 'soft' phonation on [u:].

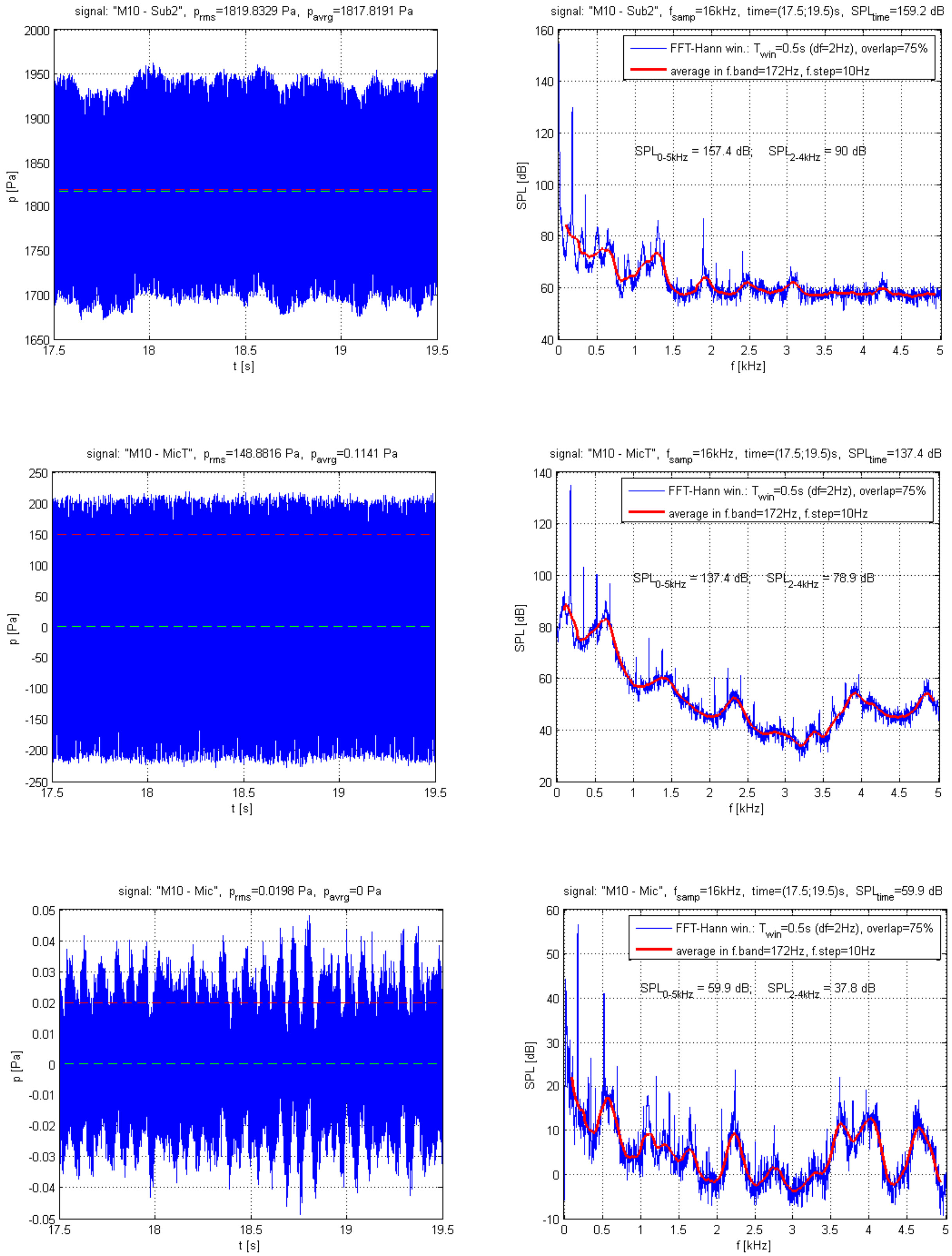

Fig. 5: Measured signals and spectra for the subglottal pressure (upper panel), the variation of the oral pressure (middle panel) and the radiated acoustic pressure (lower panel) for a ‘soft’ phonation into tube in air.

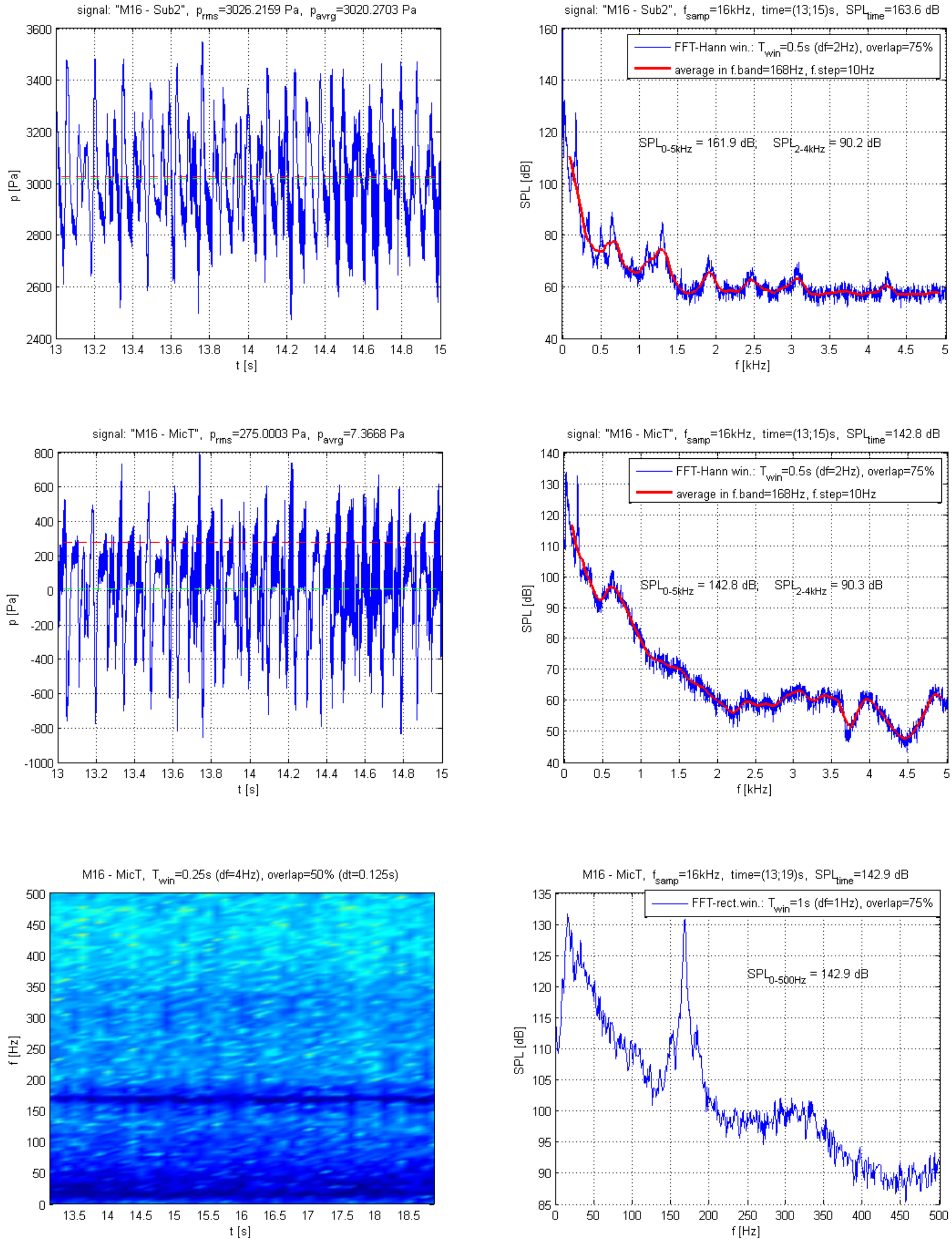

Fig. 6: Measured signals and spectra for the subglottal pressure (upper panel) and for the variation of the oral pressure (middle panel) and its spectrogram and the detail spectrum in the frequency range up to 500 Hz (lower panel) for a ‘soft’ phonation on tube with other end submerged 10 cm deep in water.

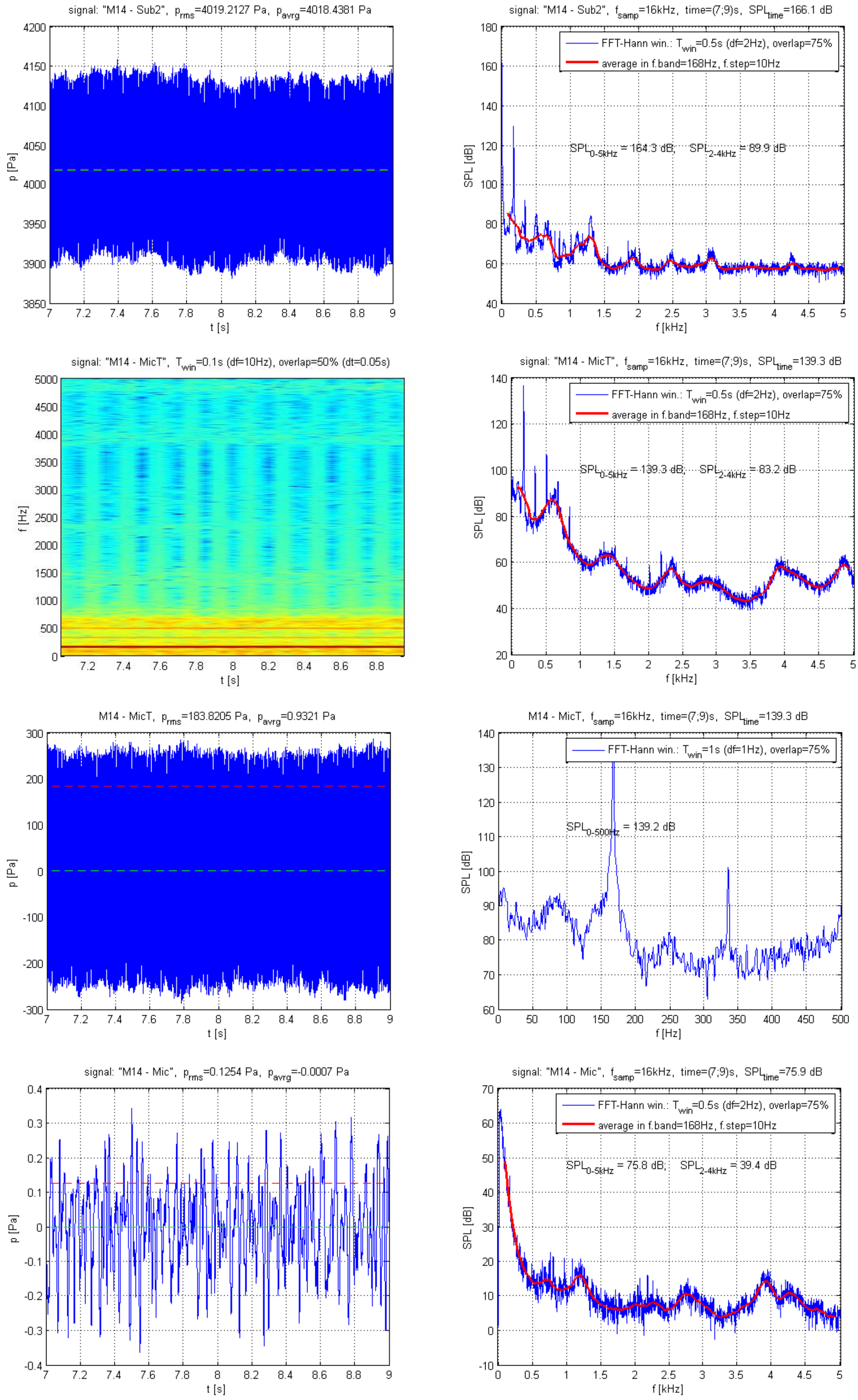

Fig. 7: Measured signals and spectra for the subglottal pressure (upper panel), the variation of the oral pressure, its spectrogram and the detail spectrum in the frequency range 0-500 Hz (middle two panels) and the radiated acoustic pressure (lower panel) for a 'soft' phonation into the straw.

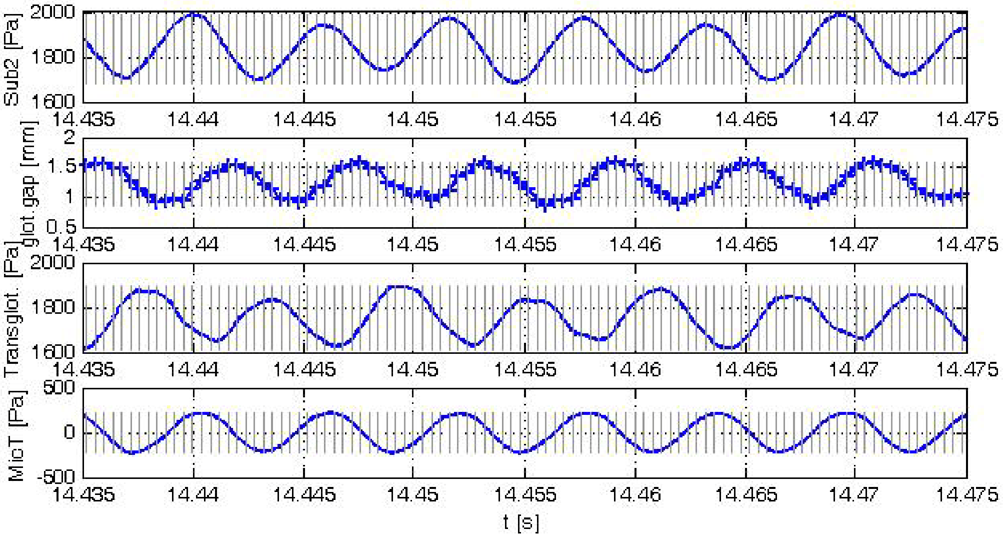

Fig. 8: Measured signals for subglottal pressure (first panel), glottis opening (second panel), transglottal (third panel) and oral pressure (lower panel) for a 'soft' phonation into the resonance tube (F0=172 Hz, Q=0.12 l/s).

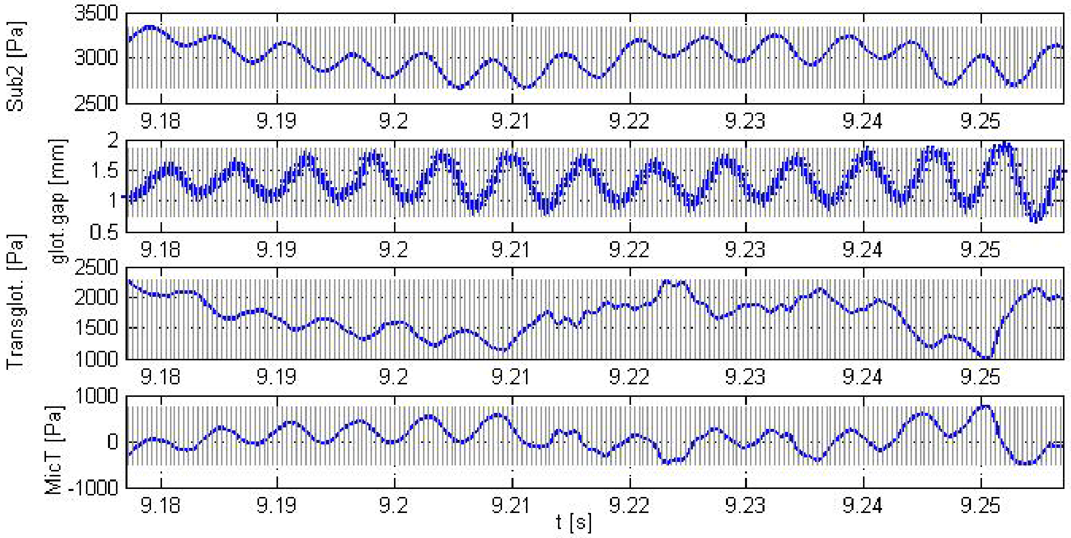

Fig. 9: Measured signals for subglottal pressure (first panel), glottis opening (second panel), transglottal (third panel) and oral pressure (lower panel) for a 'soft' phonation into the tube submerged 10 cm deep into water (F0=168 Hz, Q=0.12 l/s).

Figures 8-10 show the synchronously measured signals of the subglottal pressure, the peak-to-peak variation in the maximum glottal width (glottis opening), the evaluated transglottal pressure and the oral pressure for a 'soft' phonation into the resonance tube in air, into the tube submerged 10 cm into water and into the narrow straw. The maximum glottis opening is delayed after the subglottal pressure whereas between the subglottal and oral pressures is only a very small phase shift. The maximum of the transglottal pressure precedes the minimum of the glottis opening. The transglottal pressure for the tube phonation into water (see Fig. 9) is considerably influenced by the low bubbling frequency. The substantial difference between phonation into the tube and into the straw is in the mean value of the transglottal pressure which is much lower for the straw. However, the peak-to-peak variation of the transglottal pressure of about 300 Pa as well as the peak-to-peak values for the glottis opening are practically the same in both cases.

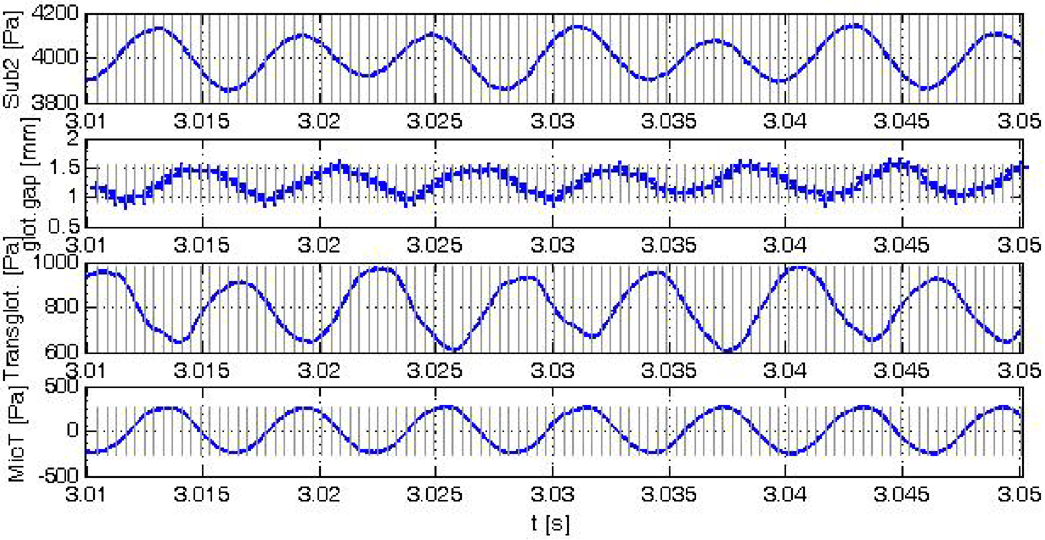

Fig. 10: Measured signals for subglottal pressure (upper panel), glottis opening (second panel), transglottal (third panel) and oral pressure (lower panel) for a 'soft' phonation into the narrow straw (F0=168 Hz, Q=0.12 l/s).

Figures 11 and 12 show the vibrating vocal folds recorded by the high speed camera for 'soft' and 'normal' phonation into the resonance tube in air. The different vocal folds replicas were used in both cases from technical reasons resulting mainly from the fact that a usable lifetime of the silicon models is restricted, especially, if they are loaded by excessive vibrations for a longer time. As mentioned above, during the experiments there was no complete closing of the vocal folds and the vibrations were in all cases studied without collisions.

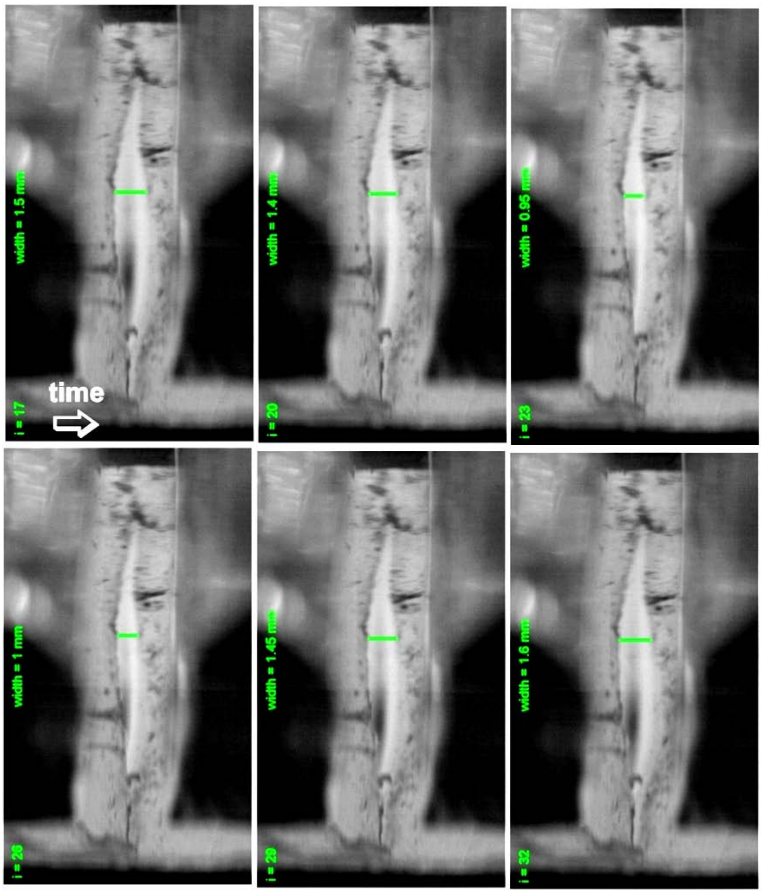

Fig. 11: Images of the vibrating vocal folds for a 'soft' phonation into the resonance tube taken by the high speed camera during one oscillation cycle. (F0=172 Hz, Q=0.12 l/s, speed of the camera 2500 images/s, images No 17, 20, 23, 26, 29, 32).

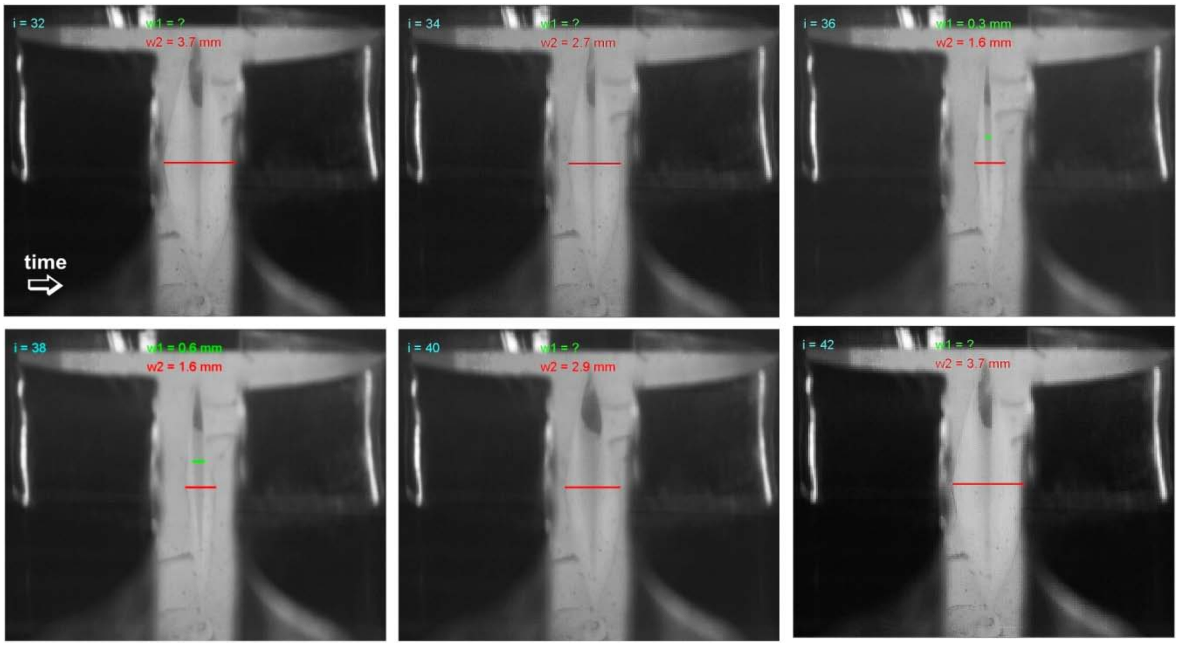

Fig. 12: Images of the vibrating vocal folds for a 'normal' phonation into the resonance tube taken by the high speed camera during one oscillation cycle (F0=198 Hz, Q=0.45 l/s, speed of the camera 2000 images/s, images No 32, 34, 36, 38, 40, 42).

4. Results - summary

The measured results are summarized for all studied cases in graphs presented in Figs. 13-17. We should note that the all results in the column graphs together for the 'soft' and 'normal' phonations are ordered according to the increasing values of the measured flow resistance, i.e. for phonations on: vowel [u:], tube in air, tube in water and straw.

Figure 12 shows the flow rates obtained as results for a 'soft' phonation at the phonation onset given by so-called phonation threshold flow rate (Q_{PT}), and for a completeness the prescribed constant flow rate Q=0.45 *l*/s for the studied 'normal' phonation is shown here as well. The higher Q_{PT}=0.22 *l*/s was found only for vowel [u:] and in all other cases measured for 'soft' phonation the phonation threshold flow rate was found lower: Q_{PT}=0.12 *l*/s. The measured flow resistance defined by the ratio of the mean subglottal pressure and the mean flow rate (P_{sub}/Q) is increasing from the case of phonation on vowel [u:] up to a maximum for the straw (see Fig. 12) for the 'soft' phonation as well as for the 'normal' phonation.

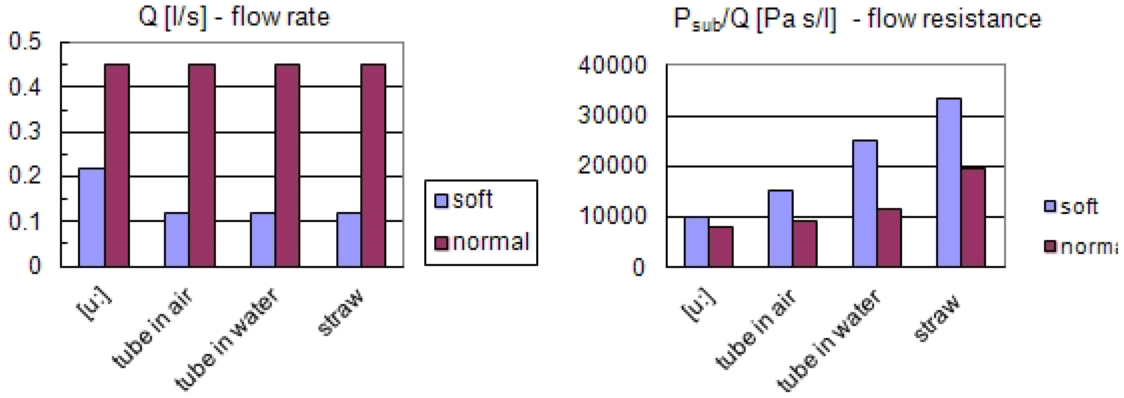

Fig. 12: Flow rate and flow resistance for 'soft' and 'normal' phonation on vowel [u:], into the resonance tube in air, into the tube submerged 10 cm deep in water and into the narrow straw.

The fundamental frequency of phonation was nearly constant (*F0*≈200 Hz) for all 'normal' phonations studied as well as for the 'soft' phonation on vowel [u:], but less (*F0*≈170 Hz) for the 'soft' phonations into the tube and straw (see Fig. 13).

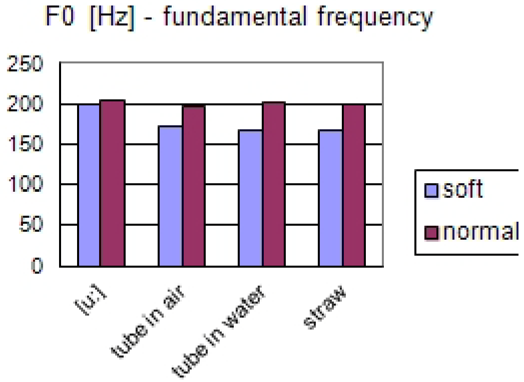

Fig. 13: Fundamental oscillation frequency of the vocal folds for ‘soft’ and ‘normal’ phonation on vowel [u:], into the resonance tube in air , into the tube submerged 10 cm deep in water and into the narrow straw.

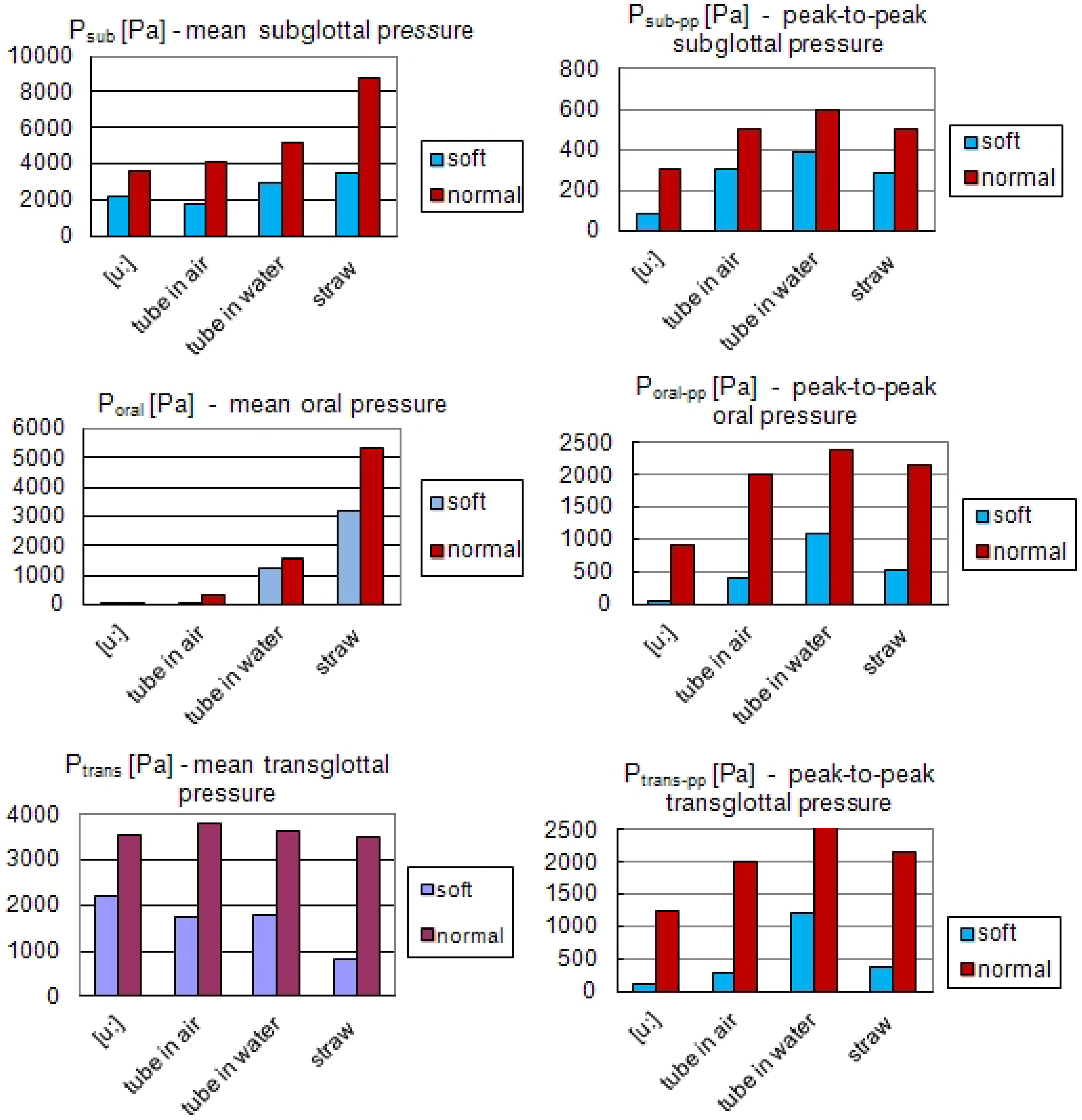

Fig. 14: Mean and peak-to-peak values of the measured subglottal, oral and transglottal pressures for ‘soft’ and ‘normal’ phonation on vowel [u:], into the resonance tube in air, into the tube submerged 10 cm deep in water and into the narrow straw.

Figure 14 shows the mean and peak-to-peak values of the subglottal, oral and transglottal pressures. Mean values of the subglottal and oral pressures are increasing approximately in accordance with the measured flow resistance being the lowest for [u:] and the highest for straw. However, the mean transglottal pressure for ‘soft’ phonation has an opposite tendency and is nearly a constant for ‘normal’ phonation. Peak-to-peak values of the all three pressures (subglottal, oral and transglottal) have a very similar tendency, being the highest for phonation into tube submerged 10 cm down into water, and having the lowest values for phonation on vowel [u:].

Figure 15 presents the sound pressure level values measured by external microphone and inside the oral cavity, where the *SPL* is much higher than outside the vocal tract. As expected the *SPL* is higher for the ‘normal’ phonation than for the ‘soft’ phonation. The *SPL* values in the oral cavity for the all cases of the occluded vocal tract by the resonance tube or by the straw are higher than measured for the open tract for vowel [u:]. This effect can be more important also from a point of view of a possible influence of the tube or straw prolongation of the vocal tract on a massage of the vocal folds in humans during the vocal exercises by the increased *SPL*, i.e. the pressure fluctuations, inside the vocal tract.

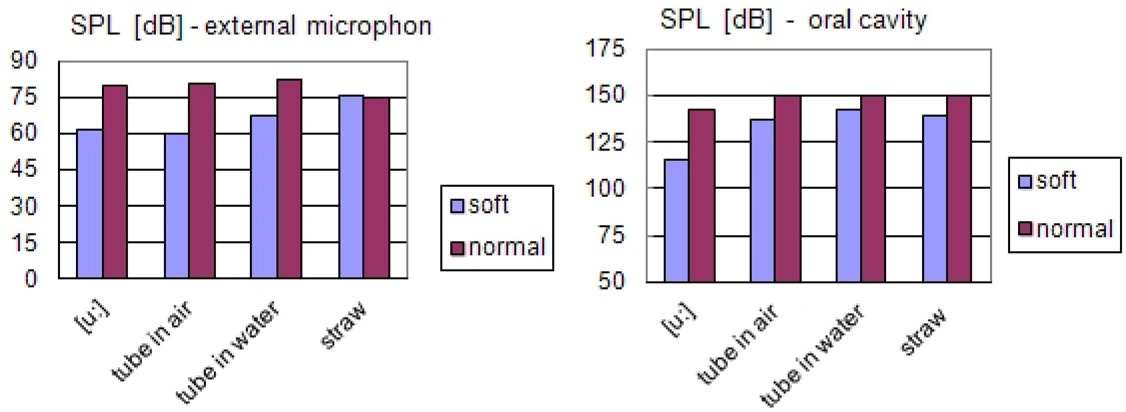

Fig. 15: Sound pressure level outside the vocal tract and inside the oral cavity for ‘soft’ and ‘normal’ phonation on vowel [u:], into the resonance tube in air , into the tube submerged 10 cm deep in water and into the narrow straw.

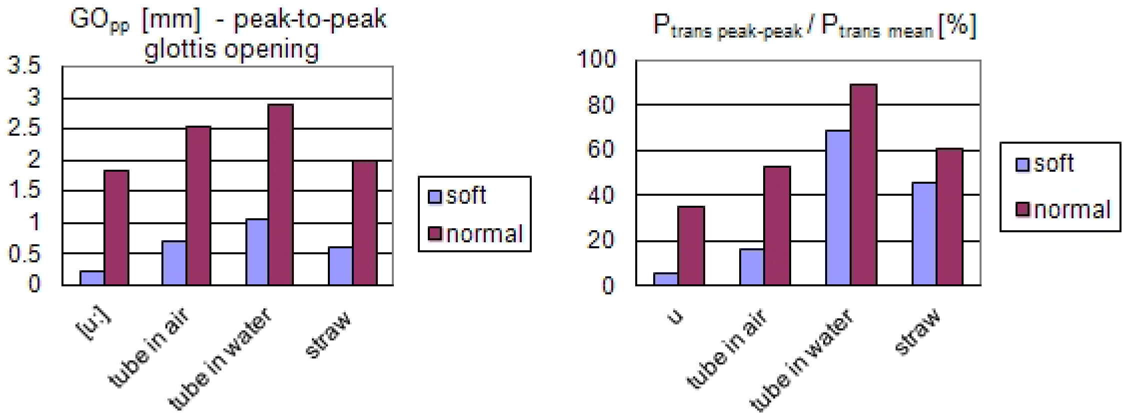

Fig. 16: Measured peak to peak glottis opening and related percentage variation of the transglottal pressure for ‘soft’ and ‘normal’ phonation on vowel [u:], into the resonance tube in air, into the tube submerged 10 cm deep in water and into the narrow straw.

Figure 16 shows the measured peak-to-peak vibration amplitudes (GO_{pp}) of the vocal folds vibration together with the percentage variation of the transglottal pressure calculated as the ratio of the peak-to-peak value of the transglottal pressure divided by the mean value of the transglottal pressure ($P_{trans-pp}$/ $P_{trans-mean}$). The tendencies for the ‘soft’ and ‘normal’ phonations are very well related in both graphs, i.e. for the glottal opening as well as for the percentage variation of the transglottal pressure. And also the very similar tendencies in relation between the glottal opening (GO_{pp}) and the transglottal pressure variation ($P_{trans-pp}$/ $P_{trans-mean}$) is nearly the same for the ‘normal’ and ‘soft’ phonations, having the values of GO_{pp} and $P_{trans-pp}$/ $P_{trans-mean}$ the lowest for vowel [u:], the highest for phonation into the tube submerged in water. An exception was found only for the'normal' phonation when GO_{pp} for the tube in air was higher than for the straw and while for the variation of the transglottal pressure it was found opposite.

5. Discussion and Conclusions

The flow resistance (P_{sub}/Q) increases with the tube and straw compared to vowel phonation in „normal" and 'soft' phonation, as expected, being higher for tube in air and even more in water, and the highest for straw. Similar tendency was found for the pressures P_{oral} and P_{sub}, especially for 'normal' phonation. However, completely different results were obtained for the transglottal pressure. In 'normal' phonation it stayed nearly a constant in all cases studied. In 'soft' phonation it decreased when flow resistance offered by the tube or straw increased, being lowest for straw. Fundamental frequency *F0* was between 170 and 200 Hz in all cases. The time variation amplitude of the subglottal pressure was comparable in both types of phonation: the smallest for [u:] and the highest for tube phonation into water. A same tendency was found for peak-to-peak variations of the transglottal pressure and of the maximum glottal width, measured at the midpoint of the glottis. The *SPL* values measured outside the vocal tract varied between 60-75 dB for 'soft' phonation and between 75-85 dB for 'normal' phonation. The *SPL* values measured inside the oral cavity were substantially higher in all cases with the prolonged vocal tract compared to vowel [u:]. In phonation into water a considerably high acoustic energy was generated by bubbling, whose dominant frequency in the spectrum varied between 16-19 Hz in 'soft' phonation and increased up to 40 Hz in 'normal' phonation.

The vibration amplitudes of the vocal folds perfectly correlate with the peak-to-peak transglottal pressure variation. The results for 'soft' phonation show that the phonation onset is given by the airflow rate which was found to be identical for tube, tube in water and straw even if the mean values of the subglottal, oral and transglottal pressures varied considerably. It confirms the theoretical conclusions found in previous studies (Horáček & Švec, 2002) that the fundamental controlling mechanism for phonation onset is given by a critical mass flow rate when the vocal folds start to vibrate due to the loss of aeroelastic stability of the system by flutter. Only exception was found for vowel [u:] where the flutter frequency *F0* was higher than for all other cases studied, which according to the theory resulted in a higher airflow rate needed for the loss of the system stability.

The results of the *in vitro* measurements did not confirm an influence of changing the acoustic impedance of the vocal tract by its prolongation on the phonation threshold given by the subglottal pressure as it was observed in humans (see e.g. Story et al. 2000; Titze et al., 2002; Laukkanen et al. 2012). The reason could be that in contrary to the model, the human phonation system can interactively react on the acoustic impedance changes, for example, by changing the geometry and volume of the supraglottal acoustic spaces and/or the fundamental phonation frequency related to the lowest formant frequency. The results also show that the effect of a considerable increase in the flow resistance can be more dominant than the effect of acoustic impedance, especially in cases of phonation into a very narrow straw or into a tube with the other end submerged in water.

Acknowledgement

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