Measurement of the vocal-fold vibration behaviour in excised human larynges

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dedicated to the memory of Jw. van den Berg

Abstract

The contribution presents information on the experimental investigation of the glottal sound source with excised human larynges. The vocal fold vibrations were excited by airflow and monitored acoustically, electroglottographically as well as by means of laser vibrometry, pressure transducers, videokymography and stroboscopy techniques. The paper is focused on 1) presenting a method for monitoring non-linear vibration effects, when bifurcations appear during phonation by changing the tension of the vocal folds, and 2) on development of a method for casting laryngeal cavities using plaster and metal materials for determining the vocal fold shape in a defined phonation position.

Keywords: Non-linear dynamics, bifurcation phenomena, laryngoscopy, videokymography, chest-falsetto jumps, vocal fold shape

1. Introduction

A physical model the most similar to the real human voice source is an excised human larynx. Although not absolutely the same, the experiments with excised larynges reveal a lot about the properties of a real larynx. The first goal of the present study is to obtain more detailed information on the transition between different vibratory patterns of the vocal folds. Two of the authors have studied abrupt transition effects (jumps) during phonation on living subjects, and especially, the jumps between the chest and falsetto registers in voice were analysed [1,2]. The results of the study [2] were substantially supported by evaluation of old video records showing experiments done by Jw. van den Berg on human excised larynx [3,4]. The analysis revealed that the chest-falsetto jumps in frequency arise without any sudden change of the tension of the vocal folds. Such phenomena are important for understanding the mechanisms of the control of the fundamental frequency of the vocal folds and change between the different voice registers. The present study aims at verifying the validity of the results presented in [2] and further specifying the complex non-linear-dynamic nature of the vocal-fold vibration.

The second goal is to obtain more information on the shape of the human vocal folds in a phonatory position.

Recently published method on experiments with canine larynx [5] is further elaborated here. The shaping parameters, so-called bulging coefficients, play an important role in the quality of phonation or in modelling of the vocal fold vibration – see e.g. [6,7].

2. Measurement set-up

The framework originally developed by Vilkman [8] was used as a base for attachment of the excised larynges. Tested larynges (Fig.1) were fixed horizontally to a plate through which the airflow was delivered to the vocal folds. Adduction of the vocal folds was adjusted via a screw (SC) placed on a holder H. Rotation axis of the thyroid cartilage around the point S was given by holders N ended by needles pushed in the cricothyroid joint, and fixed to the base plate as well. Longitudinal tension of the vocal folds was increased or decreased manually and monitored by the force transducer F, which was fixed by a string to the thyroid cartilage at the point T. Electroglotography (EGG) electrodes were screwed on the thyroid cartilage at the vocal fold level. The larynx was fixed to the base plate by means of steel pins that were pushed through external tissue at the lower part of the larynx and pressed against the plate by a metal sheet to attain an air–tight junction. Air coming from a pressure vessel was warmed up to 37°C and humidified. The air passed
through an acoustically absorbent material to a tube, the dimensions of which correspond to the volume of human subglottal space. Subglottal pressure in the tube was measured by means of two pressure transducers. The air was blown through the tested larynx in an open space. The supraglottal space was not modelled. The airflow rate was adjusted within the range of 0.2-0.45 l/s and kept constant. The vocal folds were adducted so that the phonation was initialised. After that, the tension of the vocal folds was slowly smoothly increased or decreased and the changes of the fundamental phonation frequency $F_0$ (pitch) and of the vibration regimes were monitored.

The microphone, the pressure transducers, the electroglostograph and the laser vibrometer registered the phonation and vibration activities of the vocal folds. Furthermore the vocal fold oscillations were observed optically by means of strobovideoscopy and videokymography. All measured signals were recorded on the analogue tape recorder and/or on the s-VHS videorecorder. Afterwards using the B&K fronted controlled by a PC equipped by the B&K software measurement system PULSE 5.1 the signals were digitised and evaluated in the frequency range up to 3.2kHz. (For more detail, see [9,10]).

3. Examples of bifurcation phenomena

Results of a typical measurement of bifurcation phenomena are shown in Fig. 2. Spectrogram of the subglottal pressure $p_s$, EGG and microphone signals. Below these signals several samples of videokymographic images are presented, which were taken during the measurement for various phonation and vibration regimes. More detailed time records of the subglottal pressure $p_s$, EGG and microphone signals for two considerably different vibration regimes are shown in Fig. 2b.

The measurement shown in Fig. 2 was performed at a constant flow rate $Q=0.4l/s$ and the complete experimental procedure took about 130s. During this measurement time there were registered approximately 5 different regimes of phonation. After a transition time of about 5s duration in the beginning of the measurement the phonation started. While decreasing

![Diagram of larynx fixation](image)

Fig. 1 Scheme of the fixation of the tested larynx.

The longitudinal tension of the vocal folds, the pitch gradually decreased from about $F_0=900Hz$ down to $F_0=600Hz$. At the time instance of about $t=30s$ this 1st phonation regime (falsetto-like) changed abruptly into the 2nd regime (chest-like). The pitch frequency jumped from about $F_0=600Hz$ approximately to 200Hz, i.e. to $F_0/3$. Afterwards the tension of the vocal folds was gradually increased which caused gradual rise in pitch up to $F_0=300Hz$. By the time $t=60s$ the phonation stopped, followed shortly by the 1st vibration regime again, which was by $t=65s$ replaced by a 3rd regime with an indistinctive subharmonic fundamental frequency $F_0/2$. This 3rd regime abruptly changed back to the 2nd regime by $t=77s$ and the frequency jumped from $F_0=600Hz$ down to $F_0/3=200Hz$. By the time $t=85s$ a noisy 4th regime appeared with a low indistinctive subharmonic fundamental frequency ($F_0/2=100Hz$). This regime was followed again by the 1st and 2nd regimes in the time intervals $t=89-107s$ and $t=107-125s$, respectively. The 5th phonation regime is possible to see at the end of the measurement starting
Fig. 2a) Bifurcation phenomena during phonation
at about $t=125s$. The 5\textsuperscript{th} phonation regime was similar to the 4\textsuperscript{th} regime but without the noise.

The samples of videokymography and time records for $t=25s$ in Fig. 2a (below) and in Fig.2b show that during the 1\textsuperscript{st} phonation regime the glottis was not completely closed, there was practically zero EGG signal and the oscillations with relatively high frequency $F0$ were nearly harmonic. During the 2\textsuperscript{nd} phonation regime the glottis was closing completely, EGG signal and sound were much more intensive and the periodic oscillations contained higher harmonics – see the videokymography and time records for $t=40s$ in Figs.2a, b. The videokymography images for the 3\textsuperscript{rd}, 4\textsuperscript{th} and 5\textsuperscript{th} phonation regimes are shown in Fig. 2a (below) for $t=72s$, 87s and 125s, respectively.

Similar procedure with initialisation of the bifurcation effects was repeated several times for each tested larynx using alternatively videokymography or stroboscopy measurements.

4. Models of the glottal airways

3D models of the human laryngeal cavity were made in order to analyse the vocal fold shape in phonatory position and to specify morphological features (Fig. 3a). A cast procedure was developed for this purpose using special dental plasters. It enables to detect the shape of vocal fold tissue, to analyze the geometric asymmetries between left and right folds and to imprint tissue surfaces with a high accuracy.

Prior to casting, the phonation was initiated. While the larynx was fixed into the phonatory adjustment the airflow was stopped. Then a thin mixture of dental plasters (super stone) was slowly poured into the larynx from above. After the mixture hardened, the fixed larynx was turned upside down and the plaster was poured into the intralaryngeal space. Afterwards a plaster or metal bridge joined both parts in order to fix the exact position of the upper and lower parts of the airways casting. After hardening the plaster cast was broken into supraglottal and subglottal parts and removed from larynx. Then all plaster pieces were put back together in the correct position and fixed by fast-ticking glue. For making copies the plaster cast was submerged into a can containing mixture of a silicone material prepared for fabrication of the mould. An ADISIL compound was used as an embedding matrix with low polymerization shrinkage, long time stability, and great impressing properties. Vulcanization of the ADISIL results in conversion into elastic mass. Plaster
or Wood type low-fusing metal (77°C melting point) was used to create copies of the original plaster cast. The macro- and micromorphological changes of the vocal fold surfaces were examined at the tissue level by a SCAN microscopy, and their shape digitized by the optical topography using a method of projected line raster on the plaster cast (Fig. 3b).

Examples of the results of a typical measurement procedure are shown in Figs. 4-6 for larynx 7, \( Q = 0.45 \text{l/s} \), \( F_0 = 80.7 \text{Hz} \). The spectrum of the sound produced by the fixed larynx just before casting and the time records of signals characterizing the phonation and vibration of the vocal folds, are presented in Fig. 4. The vertical vibration velocity of the vocal folds is approximately in the phase with the subglottal pressure. During the opening phase of the glottis there was no signal in the vibrometer due to the lack of reflecting area for the laser beam. The corresponding vibration pattern during one period of oscillations is shown in Fig. 5.

![Image](image1.png)

**Fig. 3** Plaster casting of the glottal cavity and the area of investigation of the vocal fold shape with projected fringes for optical topography method.

![Image](image2.png)

**Fig. 4** Spectrum of the generated sound and time records of the subglottal pressure, the velocity of the vocal fold vibrations in the vertical direction, and the microphone signal produced by the larynx just before the casting.
The evaluated shape of the vocal fold is presented in Fig. 6. Preliminary results of the evaluated shapes of all the investigated human vocal folds in the phonation position suggest that the bulging of the vocal folds is smaller than usually assumed.

5. Conclusions

Sudden changes of fundamental frequency of vibration occurred while the longitudinal tension of the vocal folds changed gradually, which means the frequency jumps should be understood as bifurcation phenomena. The results substantiate the correctness of the previous analysis carried on the old cinematographic recording of the experiment of Jw. Van den Berg et al. [2].

The developed casting method makes possible to remove the material from the larynx without destroying the larynx itself. The method can thus be used for creating more than one cast from the same larynx and to study changes of geometry of specific vocal folds with different glottal configurations.

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