PIV MEASUREMENTS OF VELOCITY FIELDS IN GLOTTIS ON A PHYSICAL VOCAL FOLD MODEL

P. Šidlof[1], Olivier Doaré[2], Olivier Cadot[2], Antoine Chaigne[2], Jaromír Horáček[1]
[1]Institute of Thermomechanics, Academy of Sciences of the Czech Republic, Prague, Czech Republic
[2]École Nationale Supérieure de Techniques Avancées, Paris, France

***Abstract*: The velocity fields along a self-vibrating physical model of vocal folds were studied experimentally. The shape of the vocal folds was specified according to data measured on excised human larynges in phonation position. The model was fabricated in 1:4 scale as a silicone body vibrating in the wall of a plexiglass wind tunnel. The model is not excited externally and oscillates only due to coupling with the flow. In addition to acoustic, subglottal pressure and impact intensity measurements, flow velocity fields were recorded in the coronal plane using particle image velocimetry, in the domain immediately above glottis. Analysis of the PIV images taken within 25 phases of one vibration cycle gives good insight into the dynamics of the supraglottal flow.**

***Keywords:* glottal flow, physical model, PIV**

I. Introduction

Despite the numbers of sophisticated mathematical models of vocal fold vibration and glottal flow developed in recent years, experimental approaches still play an important role in vocal fold research. The computational models can supply very useful data; nevertheless, it is necessary to keep in mind that many models are based on important simplifications and that the results cannot be extrapolated beyond the parameter limits, for which they were designed. The models often cannot avoid to include several ad hoc assumptions. Moreover, in vocal fold modeling one needs to enter many geometrical and tissue parameters, whose numerical values are often not well known. Therefore, the results from the mathematical models should always be verified using experimental data.

The most relevant data regarding vocal fold vibration originate from measurements on living human subjects. However, since the human vocal folds are hardly accessible, the majority of processes occuring during phonation cannot be measured directly in vivo. The second possibility is to perform in vitro investigations, i.e. measurements on excised human or animal larynges. This approach provides improved accessibility to measured structures and tissues in better controlled laboratory conditions; yet many drawbacks of experiments on living tissues persist – technical complications, poor measurement reproducibility and also ethical concerns. This is why several physical vocal fold models with well-defined and easily controllable parameters have been developed in recent years – like the self-oscillating latex-tube model of Pelorson, Deverge et al. [5, 1], static models of Shinwari, Scherer and Fulcher et al. [6, 3], Kob's or Erath's driven scaled models [4, 2] or the self-oscillating 1:1 vocal fold model of Thomson et al.[8].

Investigation of the supraglottal flow velocity field represents one of the cases, where both in vivo and in vitro measurements are hardly realizable. Therefore a self-vibrating mechanical model of human vocal folds was designed and fabricated at ENSTA Paris. The principal goal was to study the conditions, where flow-induced vibrations of vocal folds occur and to investigate the velocity fields in the supraglottal channel immediately upstream the narrowest glottal gap by means of Particle Image Velocimetry (PIV). The measured data were intended to be compared with the results from a FEM computational model.

II. Methods

The physical model was proposed as a vocal-fold-shaped element vibrating in the rectangular channel wall. A 4:1 scaled vocal fold model, oscillating only due to coupling with airflow, was designed (see Fig. 1). In current setup, the upper vocal fold is fixed to avoid difficulties with unsymmetric vocal fold vibration, the bottom one is supported by four flat springs. Best possible effort was made to keep the important dimensionless characteristics of the model close to the real situation. The shape of the vocal folds was specified according to measurements on excised human larynges, performed in the Institute of Thermomechanics [7].

The vocal fold model was mounted into a plexiglass wind tunnel. In addition to the PIV system installed to measure the supraglottal flow field, the model was also equipped with accelerometers, pressure transducers and microphones to measure and record vocal fold vibration.

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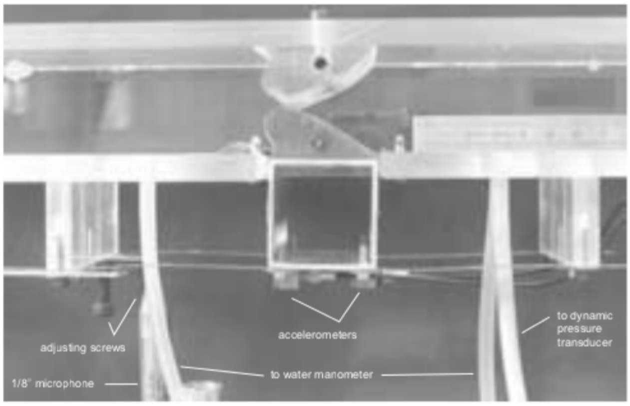

Figure 1: Design of the physical model of vocal folds (in configuration fixed upper - vibrating lower vocal fold). The vibrating elastic silicone rubber element is attached to an aluminum profile, supported by four adjustable brass flat springs.

To measure the mean flow in the channel, an ultrasonic flowmeter was mounted near the downstream end of the circular channel. Two accelerometers, fixed under the vibrating vocal fold, were used to record mechanical vibration. The 1:4 scale of the model allowed to use the relatively large, but very sensitive type B&K 4507C without affecting the system significantly.

III. Results

The primary purpose of the vibroacoustic measurements was to acquire supplementary data to the PIV records. Basically, the procedure consisted of setting the flow rate, taking one ten-second record of the accelerometer, pressure and acoustic signals, and performing a series of PIV measurements for approximately 25 phases of the vocal fold motion. This procedure was repeated for the flow rate values ranging from minimum flow able to sustain vocal fold vibration up to a maximum value, where either the vibrations ceased or became chaotic or irregular.

Fig. 3 shows the measured waveforms and their spectra for a sample flow rate value, where regular vibrations with impacts occur.

An extensive series of PIV measurements was performed on the vibrating vocal fold model. The flow rate was gradually increased from $Q = 5.33$ l/s (measurement No.001) to $Q = 25.61$ l/s (measurement No.044). Within each of the 44 measurements, approximately 25 PIV records, corresponding to 25 distinct phases of the vocal fold oscillation cycle, were taken. This was realized using the synchronization signal (accelerometer signal converted to TTL) and the time-delay function of the laser control software. Each PIV record consisted of ten PIV measurements of the same phase within ten successive vibration cycles.

Fig. 2 demonstrates the results of one sample measurement (out of 44 in total). This measurement was chosen as a representative case of medium flow rate, large-amplitude regular oscillations, which subjectively correspond the best to normal voice production.

It can be stated that the flow is not perfectly periodical in general. The turbulent structures, developing mainly due to presence of the boundary layer of the jet, interact mutually and with the jet in a disordered, stochastic way; this is why the flow fields of the same phase in successive oscillation cycles are not necessarily identical. The important flow structures, however, are generated periodically in accordance with the frequency of vibration: within each oscillation cycle, a new jet is created with one pair of large vortices propagating along the jet front. The jet attaches to the channel wall and during the closing phase it fades away and eventually disappears, leaving the turbulence to damp out.

The mathematical model, which was designed to calculate the 2D velocity and pressure fields in the proximity of the vibrating vocal folds, is based on the 2D incompressible Navier-Stokes equations in arbitrary Lagrangian-Eulerian formulation. The equations were discretized by the finite element method. The numerical scheme was completely programmed in the Fortran language, making use only of open-source libraries for the finite element discretization and for the numerical solution of the resulting linear system. The results of the numerical simulations show the development of the supraglottal jet and evolution of the recirculation vortices within one vocal fold oscillation cycle.

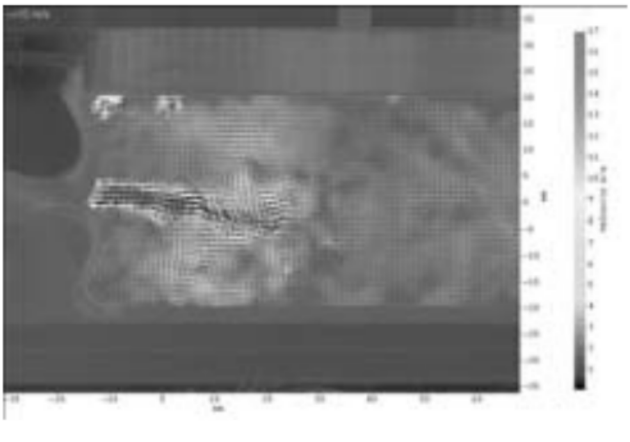

Figure 2: Instantaneous velocity field downstream the glottis. The vocal folds are on the left. The flow direction is from the left to the right. The velocity modulus is in color. A free jet with a maximum flow velocity of $U \approx 17$ m/s forms between the vocal folds. Two large-scale vortices develop at the sides of the jet front.

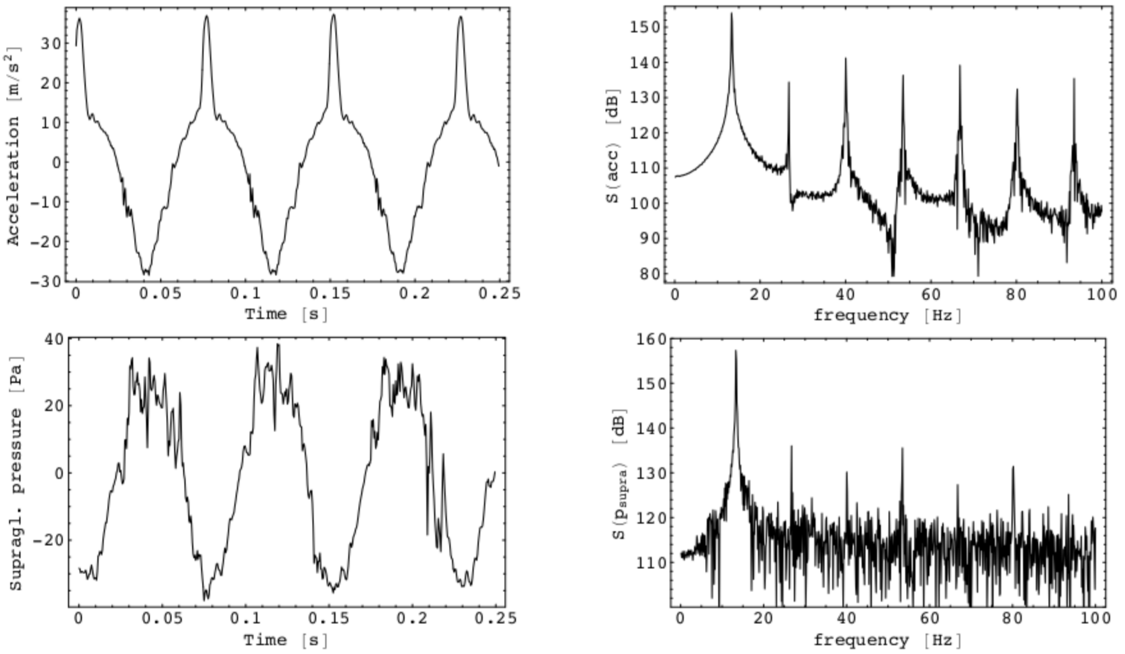

Figure 3: Waveforms and frequency spectra of the acceleration, and supraglottal pressure. Measurement No. 012 – medium flow rate $Q = 8.58$ l/s, ideal for regular vocal fold vibration with an impact in each cycle. Fundamental frequency 13.2 Hz. On the acceleration waveform, the impact is clearly visible as a peak on the positive half-wave.

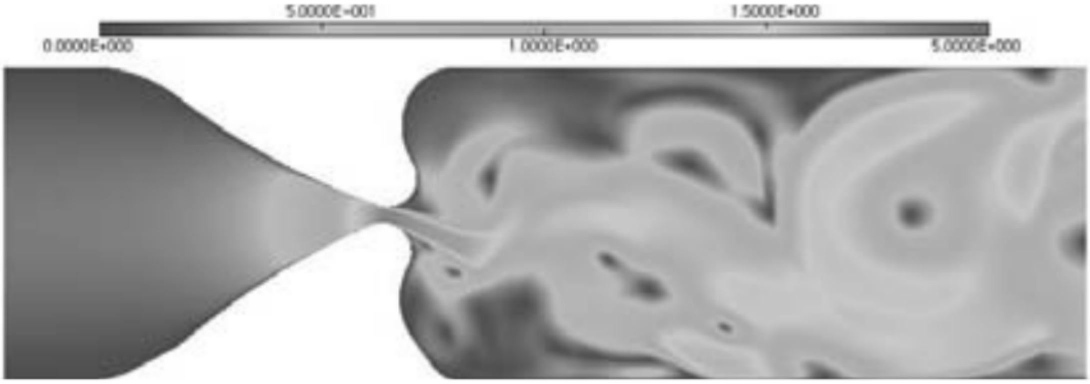

Figure 4: Sample velocity field during the vocal fold vibration cycle – velocity magnitude [m/s].

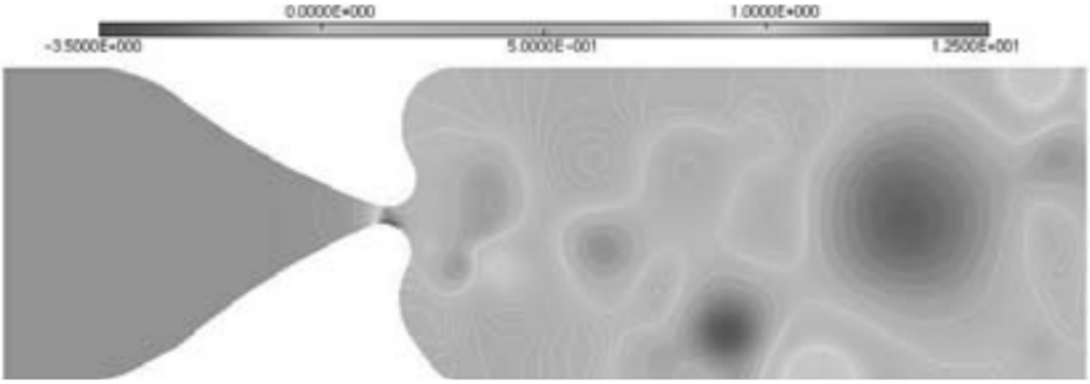

Figure 5: Sample pressure field during the vocal fold vibration cycle - dynamic pressure [Pa].

Figs. 4, 5 demonstrate the sample results calculated within a numerical simulation using typical values of input parameters. The channel geometry is the same as for the physical model. The mesh was triangular and consisted of 16537 Taylor-Hood (P^2/P^1) elements. The upper vocal fold was fixed, the motion of the bottom one was prescribed.

IV. Discussion

Neither the mathematical nor the physical model was primarily intended for direct comparison with real human vocal folds. The strategy was first to validate the mathematical model using results of the PIV measurements on the physical model; once a satisfactory correspondence between the computational and physical models will be achieved, the geometry and boundary conditions of the mathematical model can be modified in order to reflect the conditions occurring in real vocal folds. For the validation of the model, it was advantageous to use the configuration with one vocal fold moving and the other fixed.

The results from the mathematical and physical model obtained so far seem to correspond when compared visually. It should be noted that there are some aspects, which make a systematic comparison difficult for the time being – the main limitation is the fact that the vocal folds are not allowed to collide. The processes accompanying glottal closure are complex and from the algorithmic point of view, the separation of the computational domain into two, necessity to introduce additional boundary conditions and to handle pressure discontinuity when reconnecting the domains represent a very complicated problem. Yet it will be necessary to deal with this task in future, if the mathematical model should be employed to model regular loud phonation.

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