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Theoretical and experimental study of some aeroelastic phenomena during phonation

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ABSTRACT

Voiced sounds production involves interactions between an airflow coming from the lungs, elastic structures which form the vocal folds and acoustical resonators (lungs and oral and/or nasal tract). The study of the physics of these phenomena is of great importance, not only in order to improve our knowledge about these complex interactions, but also in order to model them, in particular for the purpose of bio-medical applications. In this paper we assess some physical phenomena which, although widely recognized as being essential from a production or a perceptive point of view as well as when considering some pathological cases, are poorly described or even completely overlooked in earlier studies. These phenomena are associated with the presence of an asymmetry either of anatomical or biomechanical nature and the complex inhomogeneous structure of the vocal folds. To study and to validate the theoretical models a specific experimental set-up has been built. It consists of a large pressure reservoir (representing the lungs) to which is connected a replica of the trachea, of the vocal folds and of the vocal tract. In order to mimic the internal structure of the human vocal folds, the self-oscillating replica is made of successive layers of material (such as water, silicone, latex…) each having its own mechanical properties. Asymmetrical configurations can be easily reproduced experimentally by either changing the geometry or by changing the internal structure of one fold of the replica. In addition to the acoustical pressure, the pressure upstream and downstream of the replica is measured as well as, using a laser device, the vibratory motion of the replica. A simple theoretical model (based on the well-known two-mass model of Ishizaka and Flanagan) to account for these effects will be presented and compared with the experimental data. Of particular interest are the oscillation threshold pressure and the fundamental frequency of vibration, which can both be extracted from a dynamic analysis of the theoretical equations. Some simulation results, including sound samples, will be presented to illustrate the effects of each phenomenon.

INTRODUCTION

While the advances of signal processing derived methods have been spectacular during the last decades of the twentieth century, in particular in the domains of speech coding and speech synthesis, there is a growing interest in the physical modeling of the phonation process. Besides increasing our knowledge about the complex mechanisms involved during speech, the motivation for such a study concerns speech synthesis using physical models (e.g. Koizumi et al., 1987 ; Pelorson et al., 1996 ; Imagawa et al. 2001 ; Kob 2002) and pathology. In the longer term, it is also often argued that many limits encountered by speech synthesis or coding, in terms of quality for instance, could be overcome by a better understanding of the production mechanisms (Flanagan et al., 1980). Concerning voice pathology, physical modeling is intended to provide tools for analysis and diagnostic (Mergell et al., 2000), for the prediction of surgery events or for the design of vocal folds prosthesis (de Vries, 2000). We aim at improving physical models of speech production by accounting for some specific effects which although known as important are often overlooked in the literature. In this contribution the effects of asymmetry of the vocal folds and/or of the glottal flow and the effect of inhomegeneity in the vocal fold structure will be addressed. Based on experiments on an in vitro experimental set-up the physical consequences of such phenomena will be evaluated and quantified. The experimental results will be compared with the predictions obtained with a simple physical model.

THEORETICAL MODEL AND EXPERIMENTAL SET-UP

A two-mass model of the vocal folds

Since van Den Berg et al. (1957) many researches have been devoted to the study and the modeling of vocal folds physics. This implies a theoretical work on either, or both, the fluid mechanics, the acoustics or the biomechanics of the vocal folds in normal or pathological configurations.

Direct numerical simulation of the vocal-folds self sustained oscillations is impossible at present time. From the fluid mechanical point of view, this would imply, indeed, the resolution of the full unsteady viscous compressible 3-D Navier-Stokes equations for the flow within a channel of rapidly changing shape. On the other hand, the biomechanics of the vocal folds cannot be simulated accurately either, mainly because of the lack of precise mechanical data (Young's modulus, Poisson's ratio…) and for each layer of the vocal fold structure. In addition, the description of the collision and of the deformation of the vocal folds is a formidable problem from a numerical point of view. Lastly, the huge computational times needed for such simulations, even for simplified configurations, makes them of little interest for practical applications such as synthesis or extensive pathology studies. Numerical simulation should be viewed therefore as an helpful tool for studying some specific simplified situations.

For these reasons, simplified theoretical models have become very popular. From our previous studies it was shown (Pelorson et al., 1994, Deverge et al. 2003) that for the main part of the flow (for Reh(h/L)>10), where the Reynolds number, Reh is defined as Reh = u.h/ν, with u a typical flow velocity, h the glottal minimum aperture and ν the kinematic viscosity coefficient, a boundary layer solution allows for a quite reasonable prediction of both the volume flow velocity and the pressure distribution along the glottis. Even simpler solutions based on a Bernoulli description coupled with a geometrical criterion or the model of Pelorson et al. (1994) to predict the position of the flow separation point can be used with a lesser accuracy but are easy to implement. This flow model will be used in the following.

Lumped mechanical models for the vocal folds, also called distributed or low-order models, have become a very popular alternative to continuous modeling. These models should be understood as a modal description of the vocal folds vibration, each mode being described by a degree of freedom. Theoretically two modes are necessary to explain the self-sustained oscillations of the vocal folds in absence of acoustical coupling. Experimentally, on the basis of numerical studies (de Vries, 2000) or on observations performed on excised larynx (Titze et al.,1993) or in-vivo (Svec et al. 2000) it has been shown that two or three modes were sufficient to describe globally the vocal folds behavior, at least for normal male voice in the chest register. We therefore adopt the simple two-mass description for the vocal folds as depicted in figure 1.

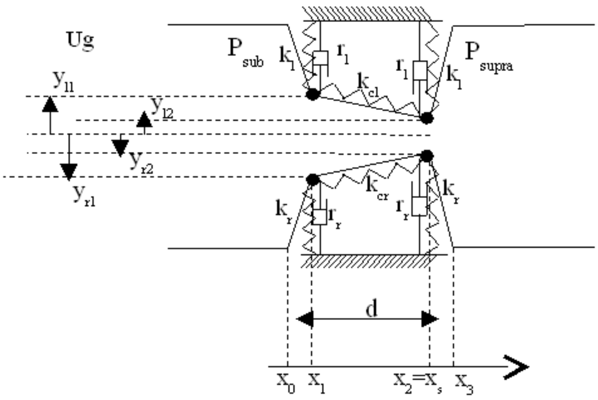

Figure 1. Two-mass model for the vocal folds

Lastly, the acoustics of the vocal tract and the sub-glottal tract is described by means of linear acoustics.

In summary, the theoretical model under test consist of a set of 5 coupled equations, two fluid mechanical equations (conservation of momentum and mass), two mechanical equations and one acoustical equation. More details, and detailed equations, can be found in Ruty et al. (2007).

A linear stability analysis can be performed. The 5 coupled are linearized around an equilibrium position. For a given set of parameters, we can determine whether or not the model is oscillating, and at which frequency. If the mechanical, acoustical and geometrical parameters are fixed, we can computes a variation of the subglottal pressure to obtain oscillation threshold pressure. Thus we obtain two relevant parameters in speech: fundamental frequency of oscillation and oscillation threshold pressure.

Experimental set-up

In order to test the relevance and the accuracy of the theoretical model for the vocal folds a specific experimental set-up has been built.

A mechanical replica of the vocal folds is mounted on a air reservoir whose pressure can be controlled. The pressure upstream and downstream of the replica are measured (using Kulite XCS093 pressure sensors) together with the mechanical displacement of the artificial folds thanks to a laser device.

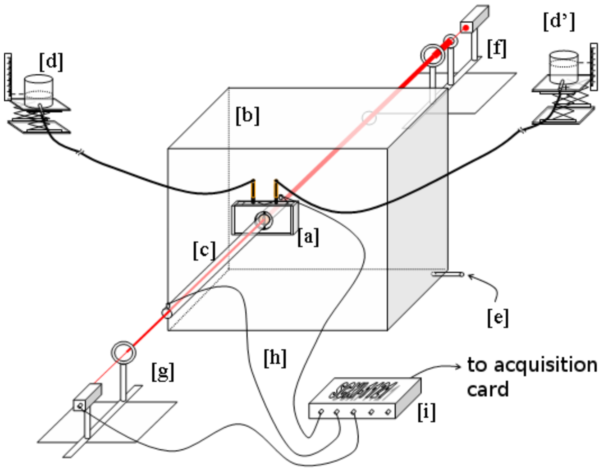

Figure 2. Experimental set-up: a: vocal folds replica, b: reservoir, c: acoustical resonator, d and d': water column, e: air supply, f: laser beam, g: photodiode, h: pressure sensors, i: daq.

Rigid vocal folds having a diverging shape with varying angles, or a rounded geometry are firstly used. These replica can be moved into a forced motion thanks to step-motors to simulate vocal folds vibrations. The advantage of such a replica is to have full a control of the oscillation rate, from 0 (static) up to 30 Hz.

A second replica consists of a self-oscillating structure made of various layers of water and latex with different mechanical properties. The elasticity of each layer can be controlled by changing the water column and hence the pressure of the water inside the vocal folds replica. A valve can be opened or closed which corresponds respectively to a constant pressure or a constant volume condition. Although very simplified such mechanical model is intended to replicate an inhomogeneous structure comparable to the human vocal folds one. A picture of one vocal fold replica is presented on figure 3.

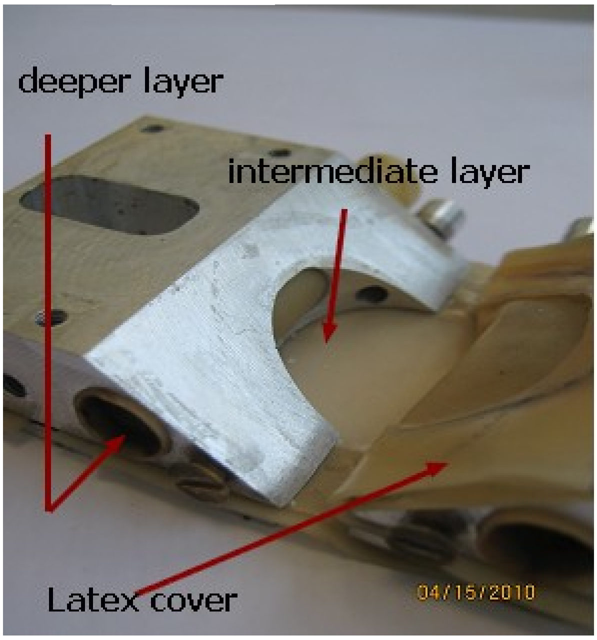

Figure 3. Internal structure of the inhomogeneous vocal fold replica. The deeper layer consists of a latex tube filled with water at pressure Pcin, the intermediate layer, filled with water at a different pressure, is covered by a thin latex cover. (removed for the picture)

Using an external acoustic excitation, one can record the frequency response of the self-oscillating vocal folds replica prior to the measurements. This allows to extract some important parameters (such as stiffness and damping) which will be used for the theoretical model simulations. An example of such measurement is presented on figure 4.

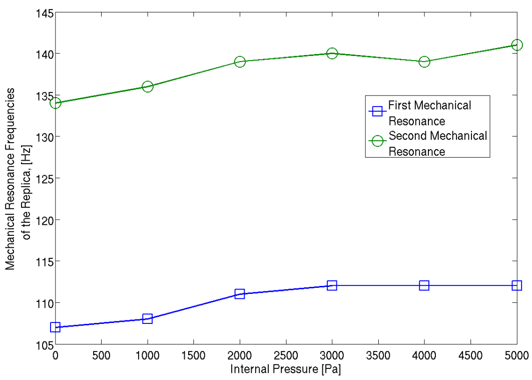

Figure 4. Extracted first and second resonance from mechanical frequency response. The internal pressure, Pcin is varied.

ASYMMETRY

Even in non-pathological configuration, the vocal folds are never perfectly symmetrical in shape nor in structure and thus in their mechanical characteristics, while an important number of pathology involve a strong asymmetry. Some studies have attempted to evaluate the consequences of slight or severe asymmetry but concentrate on some specific aspects like the fluid mechanics (e.g. Erath & Plesniak, 2006) or propose a modification of existing models to account for an asymmetrical mechanical behavior but neglect implicitly the effects of the asymmetry on the flow. (Ishizaka & Isshiki, 1976; Steinecke & Herzel, 1995).

Flow asymmetry

Even for a symmetrical glottal geometry an asymmetry of the flow can occur. This phenomenon known as the Coanda effect is illustrated on figure 5

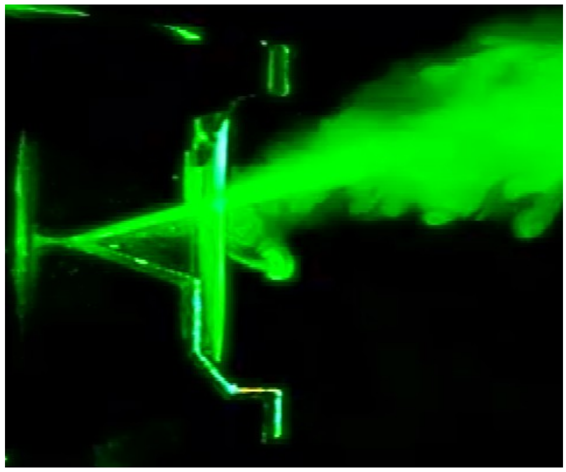

Figure 5. Visualization of the Coanda effect in the case of a steady flow through a rigid glottal replica having a 30° angle of divergence. Minimum glottal aperture is h=0.6mm and flow rate is 15l/min.

This spectacular asymmetry is however typical of steady flows, the Coanda effect needs time to establish, indeed. Under unsteady flow conditions it was observed that asymmetry remains limited as shown on figure 6.

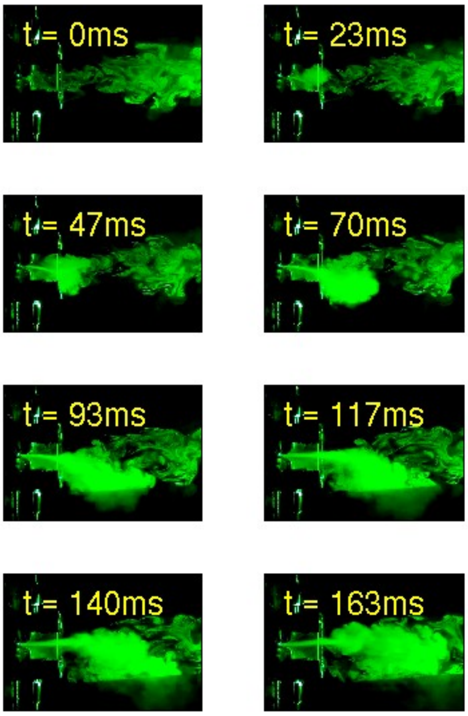

Figure 6. Visualization of the unsteady flow through a rigid rounded glottal replica in forced motion. An asymmetry is generated by moving only one replica while the other one stays steady.

A systematic study using different glottal geometry, symmetric or asymmetric reveals that under unsteady flow conditions, the asymmetry has little effect on the flow. Compared with the symmetrical case, typical pressure fluctuations induced by a geometrical asymmetry were within the range of 15 %.

Mechanical asymmetry

In this section we examine the effect of a mechanical asymmetry by controlling independently the water pressure inside each vocal fold replica (left or right). An example of results is presented on figure 7.

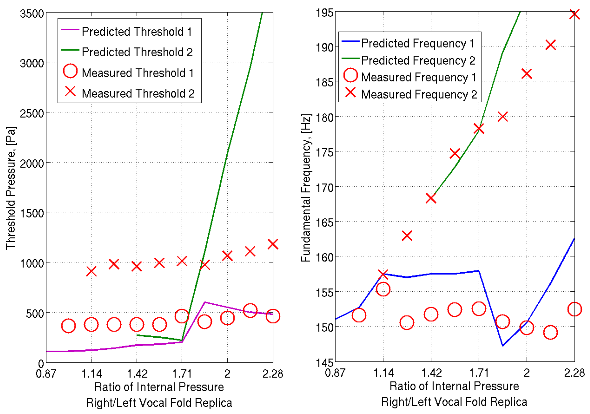

Figure 7. Measured (symbols) and predicted (lines) threshold pressure and frequency of oscillation as a function of the ratio of the water pressure inside each vocal fold replica (1 being the mechanically symmetric case)

As the difference of water pressure between the left and the right vocal fold replica increases, one rapidly observe the apparition of a secondary oscillation. In other words, each vocal fold vibrates with its own frequency.

The theoretical predictions, obtained using the two-mass model, is also represented in figure 7. As explained in the previous section, the effect of the asymmetry on the flow is neglected. While this uncoupling effect can be qualitatively predicted using the theoretical model, the agreement with the measured data is quantitatively poor, especially for the threshold pressure.

INHOMEGENEITY

As a first attempt to evaluate the physical consequences of the structural inhomogeneity we consider now the replica depicted in figure 3. In a very schematic way, the deeper layer mimics the vocalis muscle while the intermediate layer mimics the lamina propria. Although different materials were considered to fill each layers we only present here results obtained with a single material: water. The inhommogenity is thus generated but applying different pressures and boundary conditions for each layer.

In the first case both layers are maintained at a constant pressure. Figure 8 presents a typical example of results for the threshold pressure and the fundamental frequency when the pressure of the deeper layer is varied.

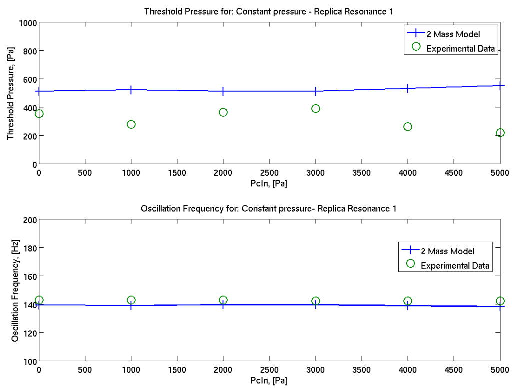

Figure 8. Measured (o) and simulated (+) onset threshold pressure [Pa] and associated oscillation frequency [Hz] in case the internal pressure (in the intermediate layer) is held constant.

As can be seen form figure 8, the deeper layer pressure, Pcin, has very little effect on the fundamental frequency and the threshold pressure. The theoretical model predicts well the frequency of oscillation but systematically overestimate the threshold pressure.

In the second experiment, the valve connected to the water column controlling the intermediate layer is kept closed providing a constant volume condition. This configuration seems indeed more plausible from a physiological point of view, since, for human vocal folds, the lamina propria has no direct elasticity control. The deeper layer is kept into constant pressure condition (opened valve).

An example of results is shown in figure 9 for both the threshold pressure and the fundamental frequency of oscillation.

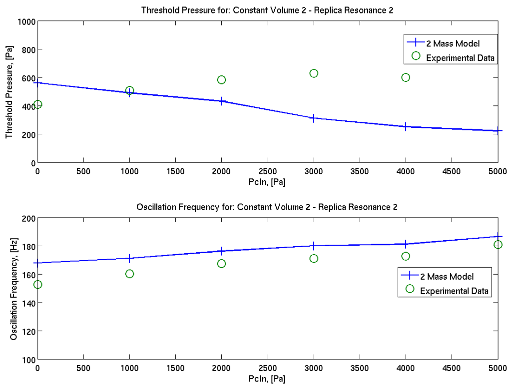

Figure 8. Measured (o) and simulated (+) onset threshold pressure [Pa] and associated oscillation frequency [Hz] in case the volume (in the intermediate layer) is held constant.

Compared with the results presented in figure 7, the results obtained show an important dependence of Pcin and significant changes in both the threshold pressure and the fundamental frequency. The two-mass model fits within 10 % the measured fundamental frequency but fails to explain the measured threshold. A decrease of the threshold pressure with Pcin is even predicted contrarily to what is observed,

CONCLUSIONS

The conclusions that can be drawn from this study are as follows:

- the asymmetry of the flow may be observed in steady flow conditions but is generally of little importance for unsteady (pulsatile) flow conditions even when the glottal channel is strongly asymmetrical in geometry or in motion.

- a mechanical asymmetry has a great influence on the oscillation characteristics. Bi-frequency oscillations can be observed which are to be related to pathological vocal folds behavior. A simple two-mass model can be used as a qualitative description for such a phenomenon.

- inhomogeneity of the replica leads also to important effects. Further systematic experiments, including more realistic materials are still needed to fully understand these changes in behavior. As one could expect from a lumped model, the two-mass model cannot explain the measured data. More complex theoretical models, including explicit in-deep structure, are obviously needed.

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