Insight in vocal folds oscillation mechanisms is important in the understanding of phonation, the synthesizing of voiced sound and the study of voice disorders. In general, simplifications of the physical ongoing 3D fluid-structure interaction between the living tissues and the airflow are favoured. Several simple models (lumped models) are obtained by representing the vocal folds as a distribution of elastic mass(es). The mass-spring-damper system is acted on by a driving force resulting from the pressure exerted by the intraglottal airstream. The outcome of theoretical models is ‘in-vitro’ validated using rigid or deformable vocal fold replicas mounted in a suitable experimental set-up. Previous research focused on the prediction of the phonation pressure threshold and oscillation frequency of the ‘in-vitro’ replica in absence and presence of acoustical feedback whereas in the theoretical model a vocal fold is represented by one or two masses. The model yielded accurate prediction of the oscillation threshold and frequency. In this paper we present a new in-vitro set-up which allows to overcome some limitations of this previous study. Thanks to the use of a digital camera synchronised with a light source and pressure sensors this set-up allows 1) to measure the area of the vocal folds opening and 2) to impose independent initial conditions as e.g. height of the initial opening and internal pressure in the vocal fold replica. Preliminary results are presented and their impact on physical modelling are discussed.
model and the measured variables in the experimental set-up. Briefly, the replica is modeled as a one or two degree of freedom spring-mass-damper system driven by the pressure difference across the masses. This is schematically presented in Figure 1. The oscillation frequency $F_0$ and the minimum upstream pressure $P_{thres}$ required in order to maintain oscillations are derived by linearising the physical quantities and assuming that only small variations around the equilibrium position occur. This assumption is motivated in case only predictions about the onset and offset of self-sustained oscillations are aimed. In this case, applying linear stability analysis of the resulting system in state space representation allows to obtain $F_0$ and $P_{thres}$ from the eigenvalues of the system. In [2, 1, 3] an experimental procedure is applied in order to determine the values of the model parameters necessary for a theoretical simulation directly from the experiment. The parameters related to pressure are directly related to the pressure measured upstream (pulmonary pressure $P_1$) and downstream from the replica. The mechanical model parameters related to the spring and damper variables are obtained from measuring the mechanical response of the replica. And finally the initial total glottal opening at equilibrium, i.e. the total area $A_0$, is estimated from measuring the height between the two folds and assuming that the two folds are parallel and their width is known.

3 ‘In-vitro’ set-up

In the following improvements to the deformable replica and experimental set-up described in [2, 1, 3] are discussed. Although simulation results predict well experimental values changes are made in order to improve the direct relationship between physical model parameters and measured values. A major drawback of the previous vocal fold replica and experimental set-up is the reciprocal dependence of initial conditions and the assumption of parallel vocal folds in the replica made in order to estimate the total area $A_0$ at equilibrium.

3.1 Mechanical vocal fold replica

As in [2, 1, 3] the two vocal folds in the mechanical replica are represented by two connected latex tubes of 12mm diameter and thickness 0.3mm. The tubes are mounted on two metal cylinders with diameter 12mm for which the metal is removed over half the diameter for a length of 40mm. The latex tubes are filled with water supplied through a central duct of 3mm diameter connected to a water column. The height of the water column is controllable. This way the internal pressure $P_{in}$ in the latex tubes is controllable as well. The latex tubes are positioned in a metal block in order to prevent leakage. The positioning of the tubes in the block is a first important difference with the previous replica. In the replica described in [2, 1, 3] the metal block is a fixed entity leaving just one single manner to place the latex tubes. Obviously increasing the internal pressure by changing the water column is the only way to alter the initial aperture between the two folds. Consequently the internal pressure $P_{in}$ in the vocal folds and the initial aperture $h_0$ are no independent quantities. Since $P_{in}$ also determines the mechanical properties of the replica they also depend on $h_0$. In order to be able to vary $P_{in}$ and $h_0$ independently the mounting position of the tubes in the metal block can be changed by implementing fixation screws. The screws allow to vary $h_0$ from complete closure, $h_0 = 0mm$, to a maximal opening of $h_0 = 10mm$. This way different initial apertures $h_0$ can be assessed while the same $P_{in}$ value is maintained. So in the current replica $P_{in}$ and $h_0$ are independent. A second major improvement is the possibility to study non-parallel vocal folds configurations where $h_0(x)$. Firstly symmetrical configurations can be obtained by inclining each vocal fold according an angle with the same magnitude but opposite sign. Secondly asymmetrical vocal folds configurations of all kinds can be assessed. Figure 2 illustrates the possibilities with respect to different geometries of the vocal fold replica with in the top part 2(a) both tubes placed in parallel and in the bottom part 2(b) one of the tubes is shifted to an inclined position.

3.2 Experimental set-up and visualisation

The replica described in the previous subsection is placed in an experimental set-up. Except for a pressure tank, representing the lungs and enabling to supply an airflow with known upstream pressure, in the previous set-up an optical system consisting of a laser beam aligned with a photodiode allowed to quantify the initial height $h_0$ at equilibrium and the geometrical deformation during oscillation, i.e. $h(t)$. Since $h(x,t)$ and the total aperture area $A_0$ is of interest. Therefore the optical system is improved by replacing the photodiode with a camera (Philips Inca311) with a zoom objective and the

Figure 1: Schematic representation of low-dimensional one- and two-mass physical vocal folds models. $P_1$, $P$ and $h(t)$ denotes the pulmonary upstream pressure, the supraglottal pressure and the glottal opening.
laser beam by a flashlamp or a normal lightsource. Both the camera and the flashlamp can be controlled. In the present set-up image acquisition is triggered by the measured upstream pressure, this way stroboscopic images of the self-sustained oscillations can be obtained. The use of a normal light source is sufficient to measure $A_0$ and $h_0(x)$ at equilibrium. The optical set-up with the camera and the flashlamp is illustrated in Figure 3. A second visualisation issue concerns the use of a smoke machine in order to obtain qualitative information of the flow behaviour.

4 Results

Preliminary results for each of the suggested improvements are illustrated.

4.1 Visualisation

Constitutive images of exemplary visualisation of self-sustained oscillations on the deformable replica and of qualitative flow visualisation on a rigid diverging vocal fold replica are depicted in respectively Figure 4 and Figure 5. Remark in Figure 4 the almost parallel deformation during the auto-oscillation of the replica. Actually the behaviour of the current replica seems to approximate the behaviour of a theoretical one mass model, which might explain the good model outcome with such a simple model. The exemplary flow visualisation obtained by supplying smoke through a diverging rigid vocal flow replica illustrates qualitatively flow separation from the wall and so the formation of a jet and the formation of a vortex.

Figure 4: Consecutive images visualising the opening $A(t)$ between the two tubes of the deformable replica during auto-oscillation.

Figure 5: Consecutive images visualising a quasi-steady airflow through a diverging rigid vocal fold replica, illustrating the formation of a jet and consecutive vortex generation.
4.2 Equilibrium imaging

Exemplary results of image acquisition in order to measure the total area $A_0$ and height $h_0(x)$ during equilibrium for internal pressures $P_{in}$ ranging from 500Pa to 7500Pa and upstream pressures $P_l$ ranging from 0Pa up to 2000Pa are presented in Figures 6 and 7. Different screw fixations results in different initial apertures which are denoted as e.g. 0.0mm or 0.5mm. The values in mm correspond to the distance between the upper and lower tube taken at the tube boundaries. Remark the almost linear decrease in $A_0$ for increasing $P_{in}$ for mainstream $P_l$ values. Figure 7 illustrates additional details as the deformation $h_0(x, P_l)$ for each tube for the top curve corresponding with $P_{in} = 500Pa$ in Figure 6(b). The importance of detailed knowledge about the distribution of the replica opening $h_0$ along the $x$ dimension, and hence more general $h(x, t)$ is nicely shown in Figure 7(b). The difference between $h(x = 0)$ and e.g. $h(x = 1.5)$ yielding about 25%.

4.3 Phonation thresholds

The measured upstream pressure $P_{thres}$ required to maintain self-sustained oscillation and the resulting oscillation frequency $F_0$ are illustrated in Figure 8 for 4 different fixation positions denoted with 0.0mm, 0.5mm, 0.1mm and 0.2mm and for different values of $P_{in}$. The observed $P_{thres}$ show the expected hysteresis between on- and offset of the auto-oscillations. The same way as in [2, 1, 3] a minimum is obtained corresponding to the internal pressure $P_{in}$ for which oscillations are generated most easily. However the independence of $P_{in}$ and $A_0$ seems important since the measured $P_{thres}$ values are much increased compared to the values mentioned in [3] and influences the $P_{thres}$ values, e.g. the minimum $P_{thres}$ is shifting towards higher values. Interesting is the observed steep rise and fall of $P_{thres}$ before the minimum $P_{thres}$ is reached for small initial apertures between the tubes. This corresponds with [1], but not with [2, 3]. Further research seems appropriate. The same way the independence of $P_{in}$ and $A_0$ influence the observed oscillations frequencies as can be seen from Figure 8(b).
Figure 8: Measured $P_{\text{thres}}$ and $F_0$ in presence of a downstream resonator of 50cm and hence an acoustical resonance frequency of 170Hz.

5 Conclusion

The current paper presents experimental observations on an improved deformable vocal fold replica suitable to validate theoretical low-dimensional models. The importance of individual parameter variation is shown. Preliminary results of visualisation of deformation and flow are depicted. The results encourage further research.

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