Experimental validation of some additional issues in physical vocal folds models

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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 intra-glottal 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.

1 Introduction

Physical vocal fold models intend to predict the vocal fold behaviour during phonation in terms of relevant physical quantities like the minimum pulmonary pressure P_{thres} necessary to sustain vocal folds oscillation, the oscillation frequency F_0, the vocal fold geometry and tissue properties. Recent publications on physical modelling of vocal folds behaviour during vowel production involve application of complex numerical as well as simplified theoretical models. Theoretical models, like lumped parameter models, aim to mimic the ongoing physiological flow-structure interaction with a limited number of model parameters. Validation of the model outcome on 'in-vivo' observations is difficult since the interpretation of 'in-vivo' data is hampered due to the complexity of the flow-structure interaction and the difficult or only indirect access to the vocal folds of living subjects. Hence 'in-vivo' data are not a first class choice to study the influence of individual physical parameters or a specific phenomenon and often present an indirect and incomplete estimation of the parameter set required for modelling. Therefore validation of theoretical models in terms of accuracy, reproducibility and sensitivity to varations of an individual parameter is performed on mechanical replicas in combination with a suitable experimental set-up. Moreover the use of an experimental set-up allows to focus on the modelling of specific physical issues involved in the oscillatory cycle, like acoustical feedback or vocal folds collision, which can hardly be attempted 'in-vivo' since 'in-vivo' phonation presents itself as an undividable natural entity which can not be split up into distinct separable and controllable events. To overcome the mentioned difficulties encountered considering 'in-vivo' measurements, mechanical replicas of the vocal apparatus with increasing degrees of complexity and reality are developed in order to study physical phonation models. In [2, 1] a deformable 'in-vitro' vocal folds replica and experimental set-up is presented in order to validate low-dimensional one or two-mass physical vocal folds models. The model yielded accurate prediction of the oscillation threshold P_{thres} and oscillation frequency F_0 in presence and absence of acoustical feedback. Further research showed that the measured physical quantities, like P_{thres} and F_0, were in the range observed on 'in-vivo' data [3]. Moreover the measured data were successfully applied to validate the outcome of a theoretical one-mass model in absence or presence of acoustical feedback. In the following some improvements to the deformable replica and experimental set-up described in [2, 1, 3] for the validation of low-dimensional physical vocal folds models are presented and motivated.

2 Physical model and set-up

In [2, 1, 3] physical modelling of the self-sustained replica is obtained by applying theoretical one- and two-mass physical models and exploiting the relationship between the input and output parameters in the physical 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 accross 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 osciallations 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 on- and offset of selfsustained 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_l) 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.

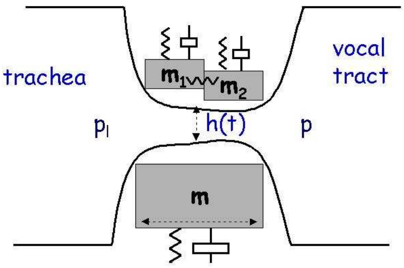


Figure 1: Schematic representation of low-dimensional one- and two-mass physical vocal folds models. P_l, P and $h(t)$ denotes the pulmonary upstream pressure, the supraglottal pressure and the glottal opening.

3 ‘In-vitro’ set-up

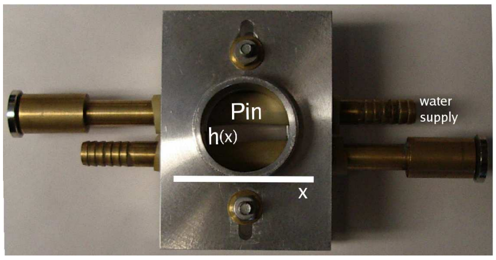
In the following improvements to the deformable replica and experimental set-up described in [2, 1, 3] are discussed. Although simulation results predict well experimental values changes are made in order to improve the direct relationship between physical model parameters and measured values. A major 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

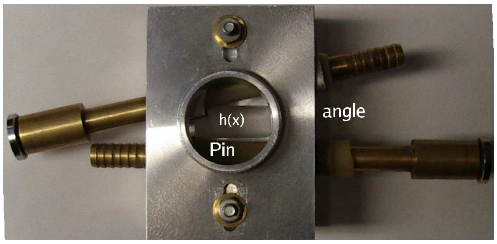
As in [2, 1, 3] the two vocal folds in the mechanical replica are represented by two connected latex tubes of 12mm diameter and thickness 0.3mm. The tubes are mounted on two metal cylinders with diameter 12mm for which the metal is removed over half the diameter for a length of 40mm. The latex tubes 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 postition 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 an camera (Philips Inca311) with a zoom objective and the



(a) symmetric



(b) a-symmetric

Figure 2: Exemplary symmetric and a-symmetric vocal fold replica configurations illustrating $h(x)$ and P_in with x the direction parallel to the metal tubes and perpendicular to the airflow. Remark the fixation screws for the tubes in the main metal block.

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 informtion of the flow behaviour.

(a) camera (b) flashlamp

Figure 3: Visualisation set-up with the alignment of camera and flashlamp on either side of the replica and the pressure tank observing a replica geometry at equilibrium and during deformation.

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 replcia are depicted in respectively Figure 4 and Figure 5. Remark in Figure 4 the almost parallell 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.

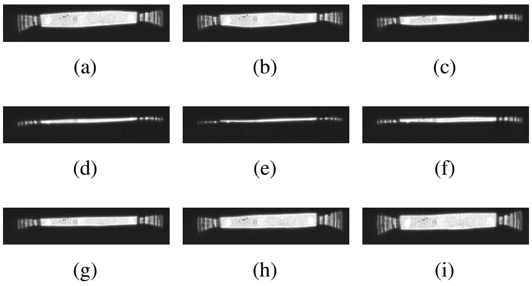


Figure 4: Consecutive images visualisating the opening $A(t)$ between the two tubes of the deformable replica during auto-oscillation.

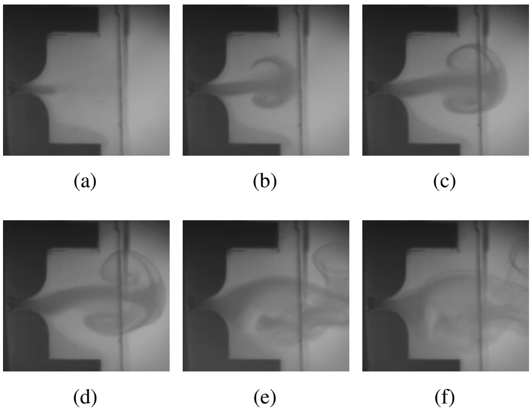
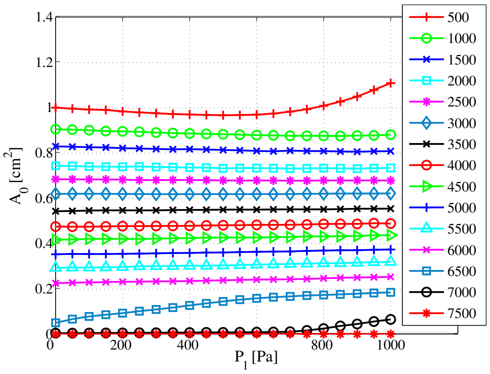
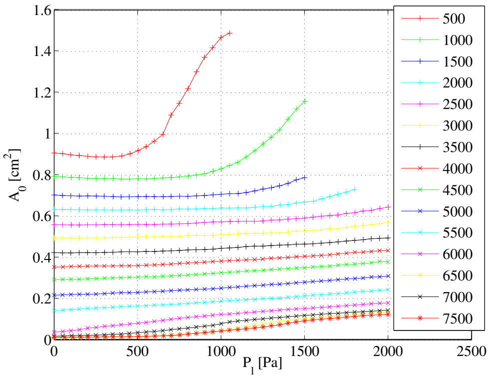


Figure 5: Consecutive images visualising a quasi-steady airflow through a diverging rigid vocal fold replica, illustrating the formation of a jet and consecutive vortex generation.



(a) 0.0mm

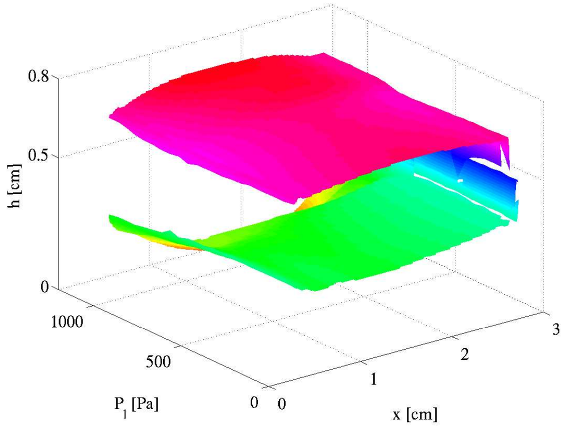


(b) 0.5mm

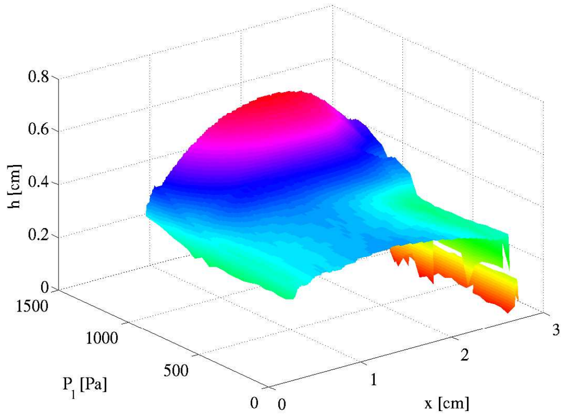
Figure 6: Equilibrium area A_0 $[cm^2]$ as a function of P_l and P_{in}.

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 wich are denoted as e.g. 0.0mm or 0.5mm. The values in mm correpond 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_{in} 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%.



(a) 0.5mm

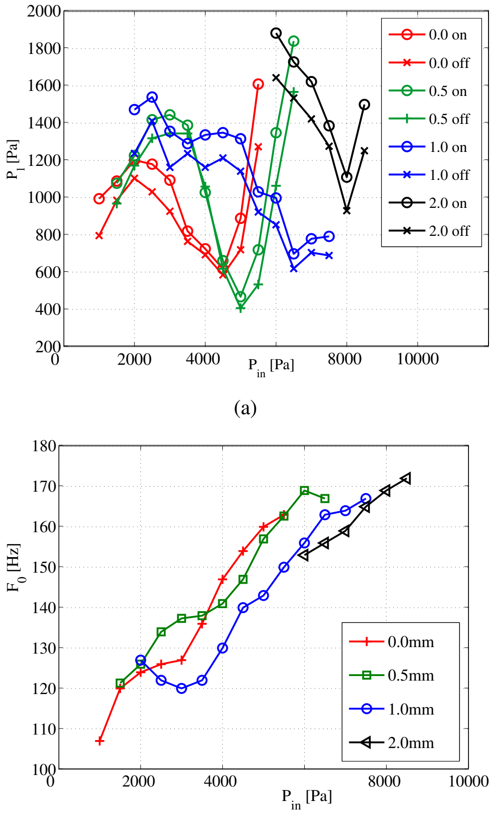


(b) 0.5mm

Figure 7: $h_0(x)$ for respectively both latex tubes and the total opening between both tubes for $P_{in} = 500Pa$.

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 is influence the observed oscillations frequencies as can be seen from Figure 8(b).



(a)

(b)

Figure 8: Measured P_{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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