

## Study of the airflow through in-vitro oscillating pathological vocal folds.

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### Abstract and introduction

We present in this study experimental and theoretical results concerning the behaviour of the airflow through the glottis during phonation. This work follows our previous study on the behaviour of the flow in asymmetric models of vocal folds modelling pathologies ([6]). For sake of better control of the parameters, the vocal folds models were rigid but supplied with oscillating airflow. The measurements are now carried out on a more realistic set-up that reproduces the self-sustained oscillations of the vocal folds. It is inspired by previous works on brass player lips oscillations ([2]). By modifying asymmetrically the mechanical properties of the vocal folds models we can simulate pathologies. We then try to reproduce the measured phenomena by use of numerical simulation with a two-mass model inspired by Lous et al. ([3]).

In the first section, we describe the experimental set-up we use in this study, then we look at measurements with a special care to 'pathological' cases. Finally, after a brief description of the numerical model, we present numerical simulations that fit our experimental data.

### 1. Experimental set-up

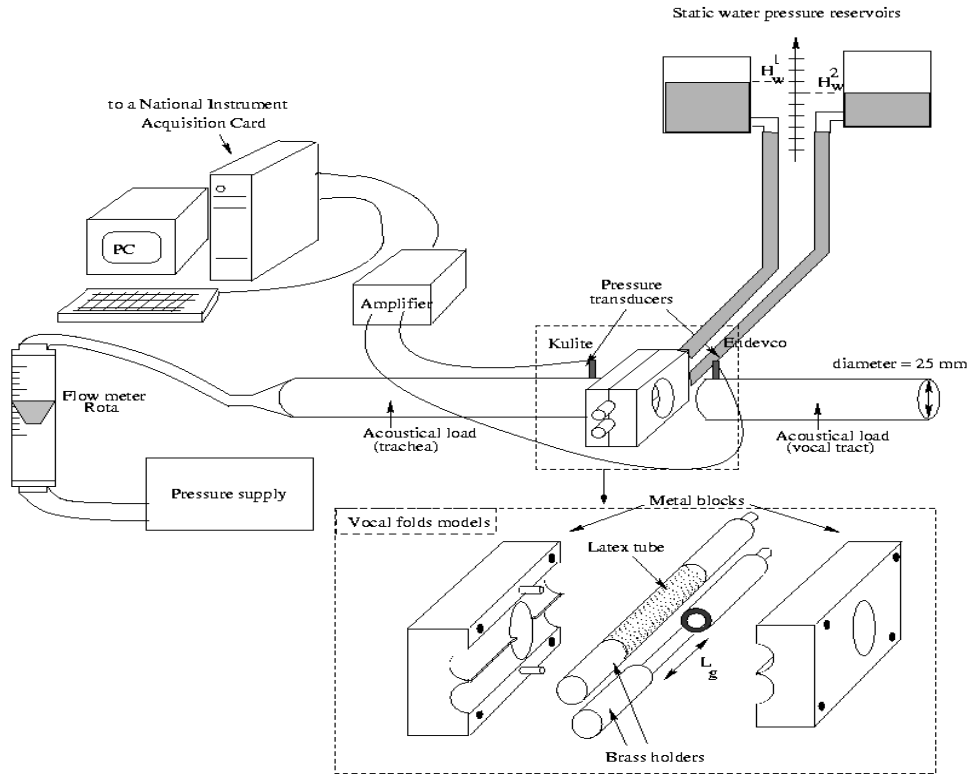
As proposed by Gilbert et al.([2]), the vocal folds are modelled by two rubber tubes of thickness 0.2 mm filled with pressurised

water and mounted on cylindrical brass holders of diameter 11 mm in which half of the metal has been removed over a length  $L_g = 30$  mm (see figure 1). The mechanical model is thus 3 times larger than in 'real life'. The water pressure in each vocal fold  $i$  is imposed by a water column of variable height  $H_w^i$ . In our experiment,  $H_w^i$  ranges between 0.8 and 1.6 meter of water ( $7.8 \cdot 10^3$  and  $15.7 \cdot 10^3$  Pa). We define  $Q$  as the ratio between water pressures in both vocal folds:  $Q = \frac{H_w^1}{H_w^2}$ .

$Q$  is an alternative asymmetry parameter similar to the one defined by Steinecke and Herzel ([5]).

During the experiments the water pressure inside the vocal folds is assumed to remain constant due to the small ratio between the volume of water in the vocal folds and the volume of water in the water reservoirs.

These mechanical models of vocal folds are clamped within two metal blocks screwed together. The distance between the two brass holders is equal to 0.2 mm. The metal blocks screwed together are coupled with 2 cylindrical pipes of diameter 25 mm. The pipe upstream (representing the trachea) has a length of 500 mm while the pipe downstream (representing the vocal tract) has a length of 290 mm. A flowmeter Rota E3-630-1 is placed between the pressure supply and the pipe upstream in order to measure the mean volume flow.



**figure 1:** Schematic view of the experimental set-up.

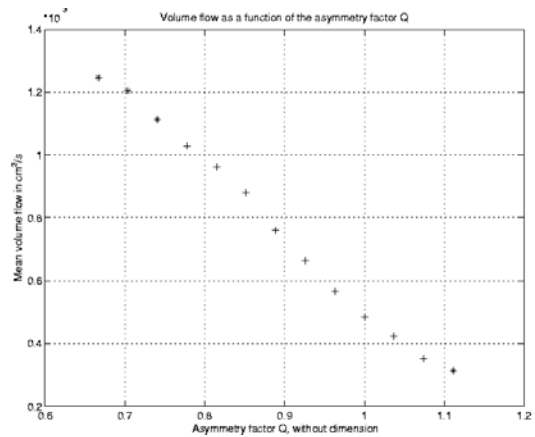
We also measure pressures at two locations: upstream the vocal folds (subglottal pressure  $p_{sub}$ ) and downstream the vocal folds (supraglottal pressure  $p_{supra}$ ) by using kulite XCS-093 and Endevco 8507C pressure transducers.

On this experimental set-up two types of experiments have been carried out. In the first one, the mean subglottal pressure is kept constant and the height  $H_w^i$  is varied systematically in order to impose variable  $Q$ . In the other type we keep constant heights  $H_w^i$  but variable subglottal pressures  $p_{sub}$ .

## 2. Experimental results

In the first kind of experiment, we measure the mean volume flow and the supraglottal pressure, for a constant mean subglottal pressure of about 2860 Pa, as a function of the asymmetry factor  $Q$ . The results are plotted in figure 2. We can observe a quasi-linear relationship between the asymmetry  $Q$  and the mean volume flow. For the given mean subglottal pressure, we can

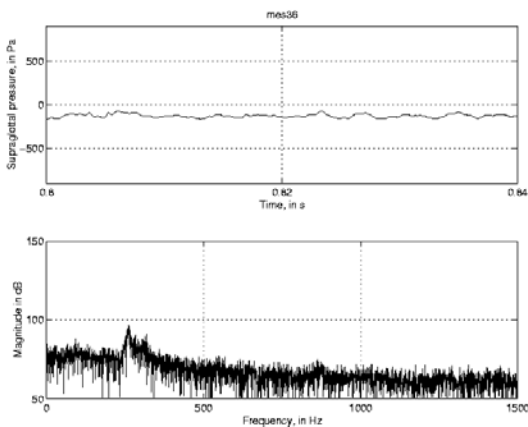
reach the upper and lower limits of the oscillation region. For an asymmetry factor  $Q$  superior to 1.12 or inferior to 0.75 we observe almost no oscillation.



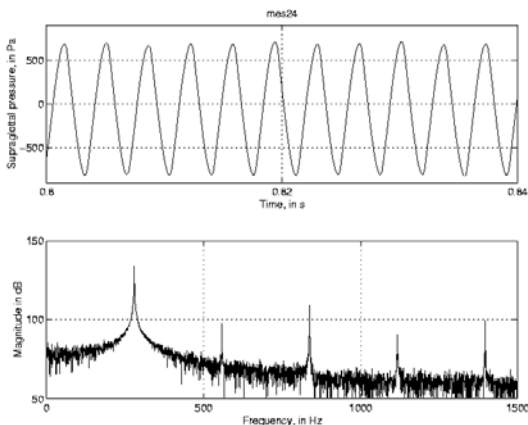
**figure 2:** Relation between the mean flow and the asymmetry parameter  $Q$  for a constant mean subglottal pressure equal to 2860 Pa. '\*' (resp. '+') represent cases without (resp. with) self-sustained oscillation.

Figure 3 gives the supraglottal pressure and the associated Fourier spectrum for  $Q = 0.67$  corresponding to the threshold of oscillations.

We can see on this figure that the spectrum is quite flat except in the region close to  $f = 280$  Hz where a peak of resonance is appearing. Within the oscillation region, the symmetric case  $Q = 1$  is the reference signal. It is plotted in figure 4. We can observe on this figure the quasi-sine waveform of the time signal with an amplitude of about 1000 Pa and a spectrum with well defined harmonics multiple of  $f_0 = 278$  Hz. One can notice that odd harmonics are attenuated. This effect is similar to the one observed on instruments with cylindrical resonator such as clarinets.

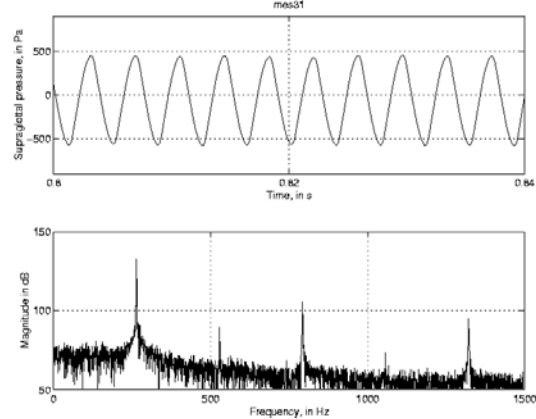


**figure 3:** supraglottal pressure in Pa (on top) and Fourier spectrum in dB (on bottom) in the case  $Q = 0.67$ .



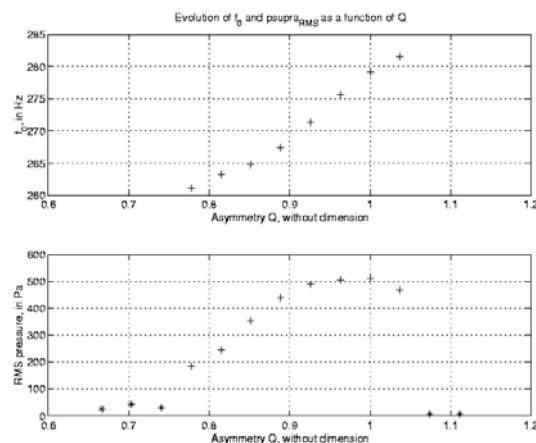
**figure 4:** supraglottal pressure in Pa (on top) and Fourier spectrum in dB (on bottom) in the symmetric case  $Q = 1$

For a small asymmetry with  $Q = 0.85$ , the result is surprisingly not so different than the symmetric case. Figure 5 gives an example of time signal and spectrum for  $Q = 0.85$ .



**figure 5:** supraglottal pressure in Pa (on top) and Fourier spectrum in dB (on bottom) in the asymmetric case  $Q = 0.85$

Except a small change in the fundamental frequency and the amplitude we have a signal similar to the previous one. The figure 6 shows more systematically the influence of the asymmetry  $Q$  on the fundamental frequency of oscillation and the amplitude of the supraglottal pressure. If we look at the fundamental frequency  $f_0$ , we can note once again a quasi-linear relationship between the two parameters. Like Steinecke and Herzl ([5]), we find that  $f_0$  decreases with the degree of asymmetry  $Q$ .

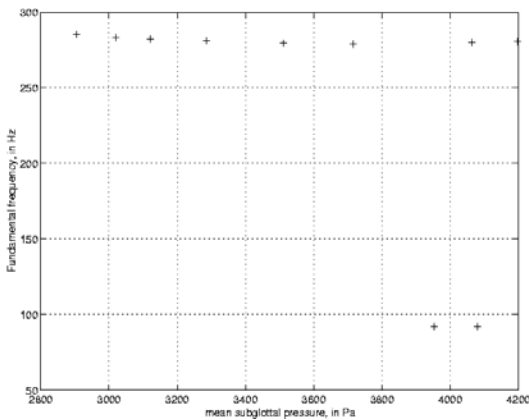


**figure 6:** On top, fundamental frequency as a function of  $Q$  in the region of oscillation; on bottom: RMS supraglottal pressure as a function of  $Q$ . '\*' (resp. '+') represent cases without (resp. with) oscillation.

Within the range of variation of  $Q$  the fundamental frequency varies of about 20 Hz

which corresponds to a variation of 8% of the mean fundamental frequency. If we consider now the amplitude of oscillation we can observe an asymmetric ‘bell-like’ curve which maximum corresponds to the symmetric case. In conclusion, it seems that the asymmetry has a strong influence on the fundamental frequency and the amplitude of oscillations.

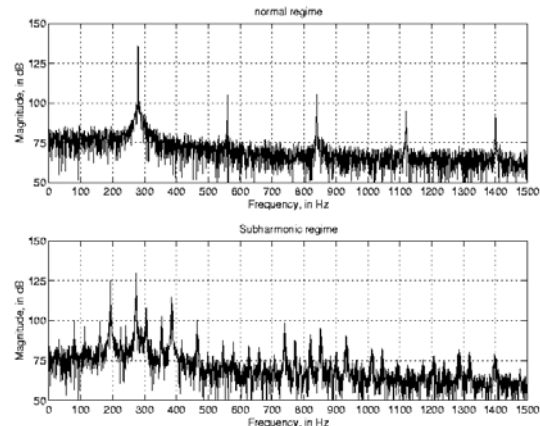
In the second set of experiments we impose fixed mechanical parameters of the vocal folds by keeping  $H_w^i$  constant. We take  $H_w^1 = 1.3$  m of H<sub>2</sub>O and  $H_w^2 = 1.5$  m of H<sub>2</sub>O which yields  $Q = 0.85$  which corresponds to a small asymmetry of the vocal folds. We then vary  $p_{sub}$  so that it spans the whole oscillation region. The result is plotted in figure 7. One can observe on this figure the lowering of the fundamental frequency when the subglottal pressure increases and a region where a subharmonic mode is appearing at a frequency of about 93 Hz corresponding to one third of the previous one.



**figure 7:** Relation between fundamental frequency of oscillation and mean subglottal pressure for a fixed geometry of the vocal folds.

We can see more precisely on figure 8 the Fourier spectra of two signals corresponding to the transition region where subharmonics appear. On top, we see a signal corresponding to a ‘normal’ regime with fundamental frequency  $f_0 = 280$  Hz. On bottom, we have a signal corresponding to a ‘subharmonic’ regime with  $f_0 = 93$  Hz. One can notice the irregular shape of the spectrum in this case,

which is similar to what was obtained by Steinecke and Herzel ([5]).



**figure 8:** Two examples of Fourier spectra: on top ‘normal regime’ with  $f_0 = 280$  Hz, on bottom ‘subharmonic regime’ with  $f_0 = 93$  Hz.

### 3. Numerical simulations

#### a) Order of magnitude of the in-vitro parameters

In order to compare our results with actual phenomena. We need to estimate mechanical and aero-acoustical parameters that are responsible for the measured oscillations.

The fluid at the level of the glottis can be characterised by the Reynolds and the Strouhal numbers. If we take for mean speed in the glottis a rough approximation given by

$$\text{Bernoulli's law } (U \approx \sqrt{\frac{2\Delta P}{\rho}}), \text{ we obtain } U \approx 70$$

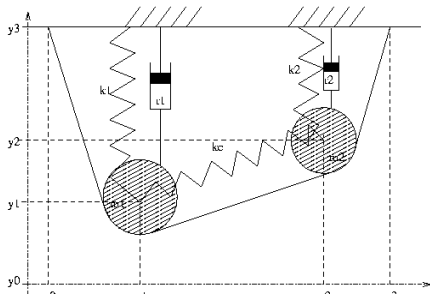
m/s. We take as characteristic length the mean glottal opening that we estimate equal to 1 mm. The viscosity of the air is equal to  $1.5 \cdot 10^{-5}$  m<sup>2</sup>/s. We thus obtain  $Re \approx 5000$ , which is in the same order of magnitude than in speech (see for example [4] for details). For the Strouhal number we take as a characteristic length the radius of curvature of the vocal folds equal to 5 mm. The frequency of oscillation is about 300 Hz. We thus obtain  $Sr \approx 0.02$  which is still in the same order of magnitude than in real speech. So we can assume that flow characteristics at the glottis in our set-up are close to actual ones.

The acoustical coupling in our set-up seems stronger than in ‘real life’. We can note that if we remove the acoustical load. The vocal folds oscillate with much more difficulties. Whereas this acoustical load effect is assumed to be of 2<sup>nd</sup> order in speech. One can refer to Cullen et all. ([1]) for a careful description of the interaction between mechanical and acoustical modes in the case of lips model coupled to a trombone.

Concerning the mechanical parameters, we can estimate the mass of water in the vibration area (‘effective mass’) as follows. The volume of the half-cylinder of length 30 mm and radius 6 mm is equal to 1.7 cm<sup>3</sup>, which gives a mass equal to 1.7 g. This is ten times superior to what is generally taken into account in two-mass models. The determination of the stiffness and the damping of the model is much more difficult. One way to proceed is to use a two-mass model coupled with 2 cylindrical resonators in order to fit the experimental data. We do this with a symmetric case then we modify the parameters in an asymmetric way to check if we can reproduce measured phenomena.

### b) Two-mass model simulation

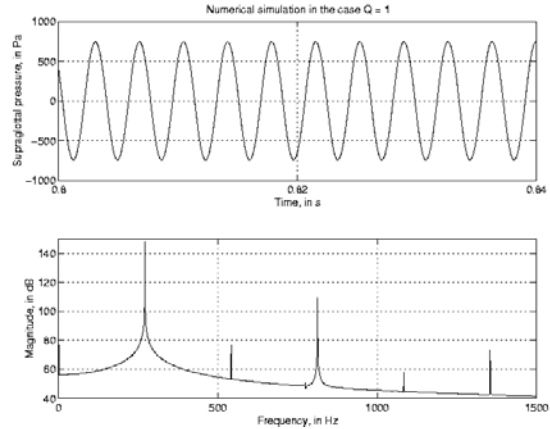
The numerical model we use is inspired from Lous et all. ([3]) but adapted in order to be compared to our experimental set-up. The mechanical parameters under control are given in figure 9.



**figure 9:** Mechanical parameters of the two-mass model for one vocal fold.

In a first step, we can fit the experimental data corresponding to the symmetric case. Figure 10 shows a result of simulation with  $m_1 = m_2$

$= 1.5$  g,  $k_1 = k_2 = 5300$  N/m,  $k_c = 3180$  N/m. As mentioned by Lous et all. ([3]), the damping coefficients  $r_i$  are given as functions of  $k_i$  and  $m_i$ :  $r_i = 0.2\sqrt{m_i k_i}$ . That yields in the present case  $r_1 = r_2 = 0.564$  Ns/m<sup>2</sup>. Moreover, it is important to note that vocal folds are assumed to be in contact at rest.



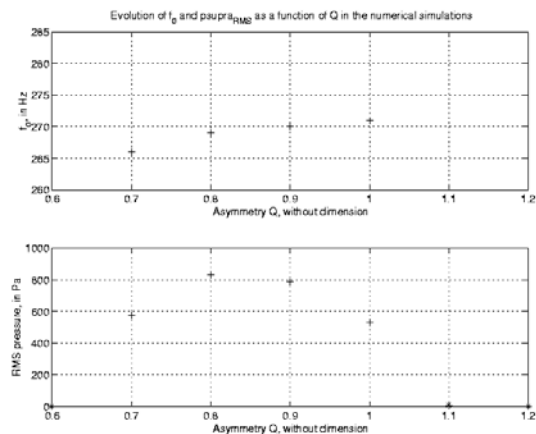
**figure 10:** Numerical simulation in a symmetric case fitting the measured amplitude of figure 4.

The parameters are fitted in order to reproduce measured amplitudes of oscillations. They also give an accurate fundamental frequency of 272 Hz (2% of difference with the measured  $f_0$  equal to 278 Hz). One can also notice that the odd harmonics are damped out in the numerical simulation which is consistent with the measurements. Thus, we can reasonably consider the values of the mechanical parameters as good order of magnitude. We can now investigate the influence of the asymmetry in the numerical simulation.

We make  $Q$  vary from 0.6 to 1.2 in order to span the same range than during the measurements. We keep  $m_1$  constant but we modify  $k_1$  and  $k_c$  with a factor  $Q$  in one of the two-mass. The evolution of  $f_0$  and the RMS supraglottal pressure as a function of  $Q$  is displayed in figure 11.

If we compare figures 11 and 6, we first note a very similar general behaviour. However we can see that the slope of the upper curve in figure 11 is smaller than in figure 6 and the maximum of the ‘bell-like’ lower curve in figure 11 is shifted to the left compared to

figure 6. This difference can be partly explained by the fact that when we modify experimentally the asymmetry of the vocal folds models, we also modify the opening at rest whereas in the numerical simulation, we always keep it equal to zero as we have no way of measuring it.



**Figure 11:** Results of the numerical simulation: On top (resp. on bottom) fundamental frequency (resp. RMS supraglottal pressure) as a function of Q. ‘\*’ (resp. ‘+’) represent cases without (resp. with) oscillation.

### Conclusions:

We have described a new and powerful experimental set-up able to reproduce vocal folds oscillations in normal or pathological conditions. The experimental results have been discussed and correlated to previous study of Steinecke and Herzel ([5]). A systematic numerical simulation based on a two-mass model inspired by Lous et al. ([3]) has been carried out. We have reproduced the experimental conditions in a symmetric case in order to obtain order of magnitude of mechanical parameters. Then we have modified the mechanical parameters in order to reproduce asymmetric experimental conditions. The results of numerical simulations have been shown to be very similar to experimental measurements. The difference can be explained by the influence of the asymmetry Q on the opening area at rest that we didn't take into account. An experimental set-up very similar to the one we use has been developed at Technical

University of Eindhoven with the possibility of measuring the dynamic vocal folds opening. The results obtained with this set-up will be very useful for further comparisons with numerical simulations.

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