IN VITRO STUDY OF THE AIRFLOW IN ORAL CAVITY DURING SPEECH

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ABSTRACT

Although airflow/elastic structure interactions are the basis of speech production in human beings they are not really understood. We propose here experimental results obtained on a setup specially designed to study these interactions. They agree reasonably well whith a simple flow theory when using a rigid tongue. In the case of an elastic tongue, a strongly modified behavior is observed. The setup also exhibits self-sustained oscillations that can be linked to trills production. All these results incitate us to exploit further on our experimental setup.

INTRODUCTION

In the human respiratory tract, air flow commonly interacts with surrounding moving and deformable structures such as the vocal cords, the tongue, the velum or the lips. However, a strong interaction can only occur when the deformable structure induces a constriction in the flow. In such a case, flow exerts a strong hydrodynamical force, comparable to the elastic force naturally present in the structure. Under complex conditions this can result in a reshaping of the structure, inducing a complex feedback mechanism on the flow. Although this phenomenon is the basis for reproduction of most human sounds, the conditions of deformation appearance, the nature of this deformation and their consequences on the flow are still not clearly known.
The difficulty of studying such interactions mainly comes from the necessity to have simultaneously a realistic hydrodynamical description of the flow and a biomechanical description of the elastic structure considered. Previous works often favor one aspect, mainly the biomechanical description while overlooking the other one [1]. Hydrodynamical modelling involve dealing with instationarity, boundary layer modelling, and possibly turbulence, the latter implying a strongly modified flow structure and stability compared to the more usual laminar case.
Interactions involving vocal cords are the most investigated, as it is the basis of phonation. It is much less studied in the case of flow interacting with other articulatory structures, such as the tongue for instance. Recent investigations used a 2D biomechanical model of the tongue implemented on a computer interacting with a simplified but efficient flow description [2]. The results

obtained are quite interesting because they try to provide a rational explanation for the presence of some articulatory loops observed on the tongue when producing vowel plosive as the consequence of an airflow interaction.

Sleeping apnea or snoring is another spectacular example of such an interaction involving the tongue or the velum. It occurs mainly during sleep, when the muscular activity is low and the human body is lying, resulting in a reduction of the pharynx by the tongue. In a non-negligible percentage of the population air flowing in this constriction causes the tongue to close partially if not entirely the pharynx, preventing the patient from breathing. Apnea have been recently investigated using simplified numerical simulation [3] and allowed to get first insights of the phenomenon. In the case of apnea, the pressure variation characteristical time is that of a respiratory cycle which is of order of 1s, therefore a quasy-steady assumption can be made which greatly simplifies the problem. Further, when snoring is not present, we don't have to deal with flow/acoustic interaction. Therefore, although not directly related to speech production, studying this kind of interactions allow us to focus our attention on the complex fluid/elastic structure interaction. In this paper we present further works made on this subject, mainly the design and exploitation of a dedicated original[1] experimental setup.

EXPERIMENTAL SETUP

Our investigations are based on an experimental exploitation of a setup specially designed using caracteristical dimensions obtained through in-vivo data acquisition. In vivo data are obtained thanks to collaborations with hospital research laboratory[2]. Although they serve as a reference for model development, in vivo data are highly non reproducible and don't allow quantitative validation of theory, as many parameters are not controlled, or even not reachable. This underscores the interest of using an experimental setup where most of the parameters are under control.

In order to investigate precisely the interaction phenomenon, the elastical characteristics of the tongue must be reproduced with sufficient realism. To fulfill this requirement, the tongue is modelled by a latex cylinder filled with water under pressure. The modelled tongue is placed inside a squared rigid pipe (Fig.1) modelling the larynx and vocal tract. We thus assume that larynx walls are rigid compared to the tongue elasticity. Extremities of the latex are fixed and it is glued to the pipe with silicone. Pressure measurements can be performed at different positions : before (*Psub*), after the constriction, and at constriction (*Pgu*, *Pgd*), and dynamic sensor Kulite and E…. can be used. Complementary velocity measurements can also be made using a hot film (TSI, model 1210).

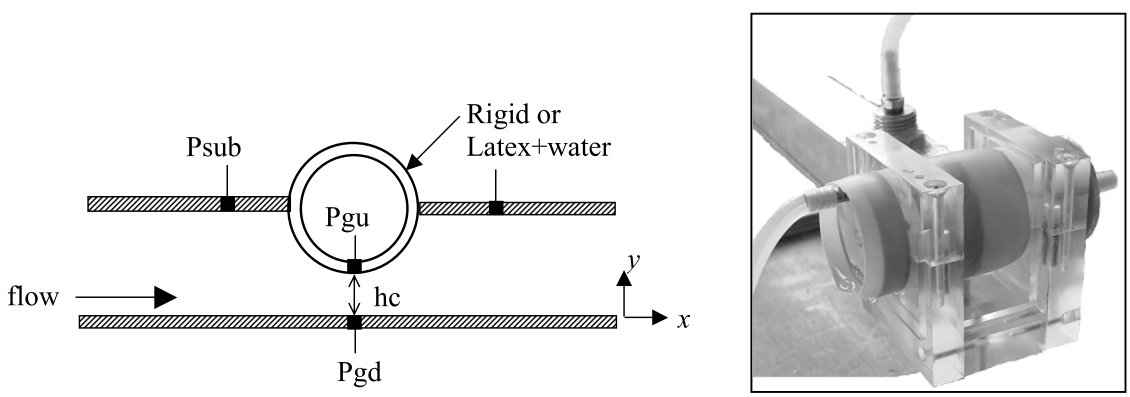

Fig. 1.- Schematic view and photography of the experimental setup used to study airflow/tongue interaction.

[1] This setup is original in speech research but has been used in musical acoustics research to model the lips of a brass player.

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Various parameters can be thus controlled : air flow conditions in order to simulate different aerodynamic conditions, constriction height *hc*. A rigid metal cylinder of similar dimensions can also be used, mainly for comparison in order to investigate the influence of elasticity. Elasticity influence can also be investigated qualitatively by stretching the latex.

INFLUENCE OF ASYMETRY

As can be noticed in figure 1, the constriction exhibits a strong geometrical asymmetry. We first investigate the consequences of such an asymmetry on the flow. Figure 2 presents the comparison of the upper and lower wall pressure evolution as a function of the pressure *Psub* for the rigid tongue with no pipe afterward.

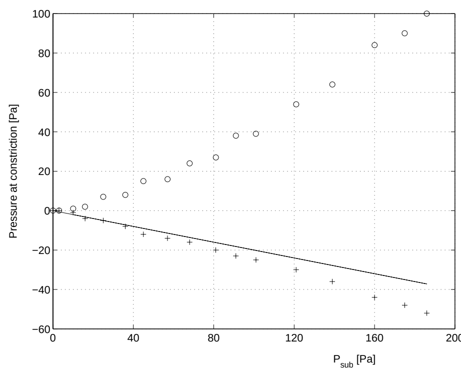

Fig. 2.- Pressure evolution at constriction, *hc*=1.63mm as a function of *Psub* (+) upper wall (o) lower wall.(+) experimental points (straight line) simple theory assuming a fixed separation point.

While the upper wall pressure is negative and is decreasing as *Psub* is increased (Bernoulli effect, see further), the lower wall pressure is positive and increasing. This indicates a strongly asymmetrical flow. Due to the diverging upper wall, the flow is strongly slowed down, inducing a negative pressure and causing the upper boundary layer to separate. The lower wall is straight, and the velocity seems not yet greatly influenced by what's happening on the upper border. The lower boundary layer is still sticking on the wall, inducing a positive pressure.

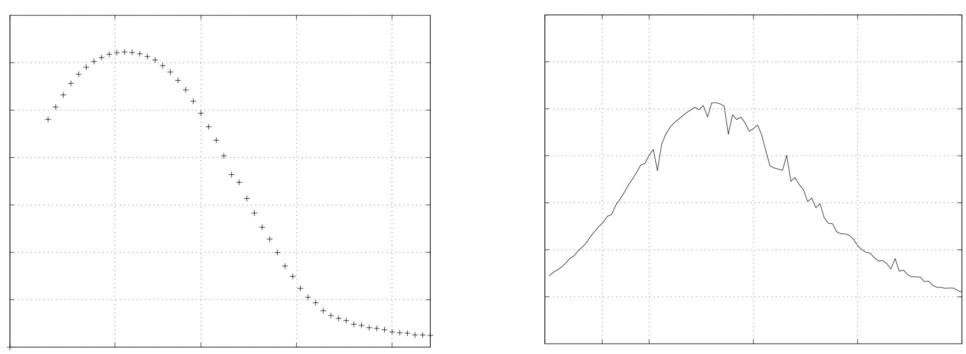

Fig. 3.- Velocity profiles obtained along the *y* axis (**left**) inside the channel, at approximately *x*=17mm from the constriction position (**right**) just outside the channel at approximately *x*=27mm from the constriction for a constriction height *hc*=1,11mm.

This flow asymmetry is confirmed by measuring the transverse velocity profiles (along the *y* axis). Two velocity profiles obtained using a hot-film placed inside and just outside the channel are presented figure 3. In order not to break the hot-film, measurements within the channel could only be performed starting at a finite distance from the wall. The offset position as been estimated to be *y*=0.2mm, *y*=0 corresponding to the lower rigid wall position. The constriction height being 1,11mm, the middle position, 0.55, is indicated on the axes for discussion.
Inside the channnel, at the lower wall, a zero velocity is expected due to the no-slip condition. On the upper half of the velocity profile, an inflexion point can be noticed which indicate that a free jet has formed [4]. Just outside the channel, which is around *x*=27mm further the constriction, the velocity profile shape has become symmetrical, except that the upper half is more chaotic than the lower one. This is likely to be due to turbulence raising more quickly on the upper jet boudary layer due to separation occurring earlier. The jet is deflected toward the diverging wall as it's maximum velocity is well upper the middle position of the constriction.
The conclusion that can be drawn for the moment on asymmetry influence is that the two halves of the flow seem to be mainly influenced by the wall nearest to it : diverging behavior on the upper half and straight one for the lower half. This is an interesting feature for further modelling of the flow.

RIGID TONGUE

Modification of the flow behavior compared to the rigid case is a good indicator of a deformation occurrence. Apnea for instance can be detected by flow decrease compared to what is expected. As a reference for further investigations, flow evolution as a function of *Psub* in the case of the rigid tongue is presented figure 4.

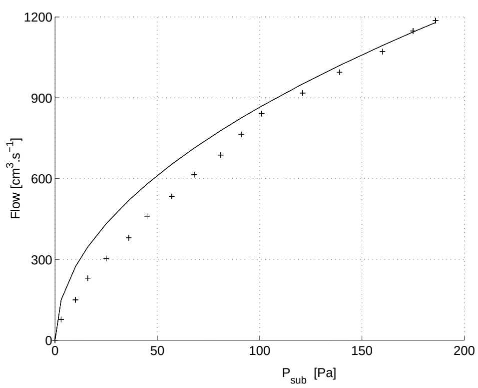

Fig. 4.- Flow evolution as a function of *Psub*. Rigid tongue, constriction height *hc*=1,63mm (**+**) experimental points (**straight line**) simple theory assuming a fixed separation point (see text).

The experimental results are compared with an empirically modified Bernoulli theory. For a steady laminar non-viscous flow, pressure *P* and flow *Φ* are connected along a stream line by Bernoulli's relationship [5] :

$$P + \frac{1}{2}\rho\left(\frac{\Phi}{A}\right)^2 = \text{constant} \qquad (1)$$

where ρ is the fluid density and *A* is the transverse flow area. Before the constriction, the pressure is *Psub* and the velocity can be assumed to be zero. At the channel exit, air flows in free space, pressure is thus assumed to be negligible, whereas velocity is not. In our case, viscosity can't be neglected as it is responsible for flow separation and jet formation after the constriction. This result in a greatly lower area *As* for the flow at the channel exit than expected in a non-viscous assumption. This area can not be easily obtained, as determining the separation point position precisely involve numerical simulation. However, for laminar flows where viscosity is limited to the vicinity of walls, assuming that the separation point position is not a function of *Psub*, Liljencraft [6] proposes a semi-empirical formula that links *As* and the constriction area *Ac* according to $As = 1{,}2 \times Ac$. Applying this relationship and Bernoulli formula we get a theoretical relationship between *Psub* and Φ that is :

$$\Phi_{th} = 1{,}2 \times Ac \times \sqrt{\frac{2Psub}{\rho}} \qquad (2)$$

This theoretical relationship is represented figure 4 as a straight line. The experimental results and theoretical ones are in fairly good agreement except for low *Psub*. In that case, viscosity is predominant everywhere in the flow, and the theory developped here is no longer valid. This semi-empirical formula also predicts that the constriction pressure *Pg* is related to *Psub* according to :

$$Pc = -0.2 \times Psub \qquad (3)$$

This theoretical formula is represented as a straight line in figure 2 and agrees fairly well with the constriction pressure at the upper wall. As a conclusion, the simple semi-empirical theory developped here seems sufficient to characterize the flow obtained in such a configuration.

ELASTIC TONGUE

Static measurements

Flow evolution as a function of the pressure *Psub* are presented figure 5.

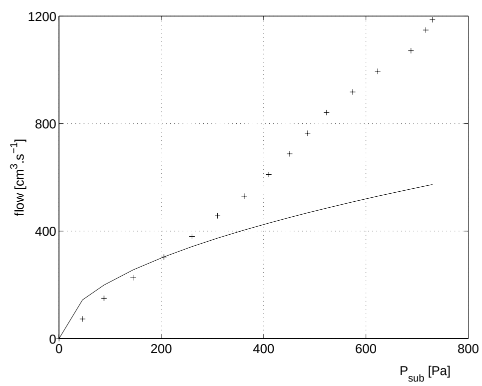

Fig. 5.- Flow evolution *Pgd* as a function of *Psub* for the latex tongue and a constriction height of *hc*=0.4mm.

The flow range between the rigid and the elastic case is the same, hence we get the same range of Reynolds number $\mathrm{Re} = \Phi / L_c \nu$, where *Lc* is the transverse dimension and ν is the air viscosity coefficient. The Reynolds number characterizes the relative importance of convective and viscous forces and ranges here from zero to ≈2300 which could be a transition position between a laminar flow and a turbulent one. In figure 5 we can observe that the flow evolution follows the theory only for alimentation pressure under 200Pa. Afterwards, experimental results and theory diverge quickly and flow increases with *Psub* at a much higher rate than theory.

This could be due to deformation occurring, resulting in a modification of the constriction area *Ac*. Therefore, if the proportionality relationship between *As* and *Ac* is still valid, the relationship between *Ac* and *Psub* need to be known in order to predict the flow. However, when increasing *Psub*, a decrease of *Ac* is rather expected due to the stronger hydrodynamical force and this should result in a lowering of the flow while we observe the opposite. This could be related to a turbulent flow appearing earlier than expected due to the channel deformation perturbating the flow. A turbulent flow is more stable and sticks much longer on the walls [7] resulting in a great increasing of the flow area at the channel exit *As.* The experimental points have a linear behavior, indicating that a constant proportionality between *As* and *Ac* may no longer be valid due to a separation point position varying greatly with the alimentation pressure *Psub*. All this facts should be further investigated.

Unsteady behavior

Under certain conditions, the same setup allows to generate self-sustained oscillations that produces sound. This can be related to trills production. Pressure measurements in that configuration are presented figure 6.

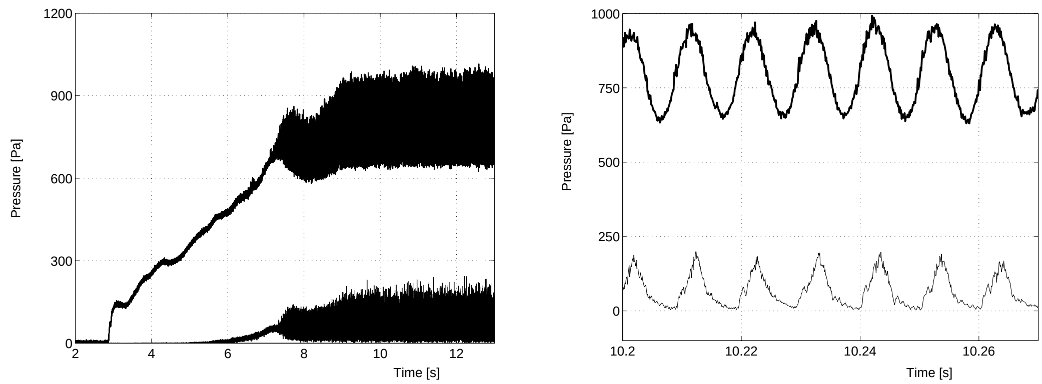

Fig. 6.- Self-sustained oscillations obtained with the experimental setup Upper curve :Psub, lower curve *Pgd*.

The right figure is a magnification of the left one, in order to see the details of the oscillation waveform. This shows the good concordance between the two signals. These are preliminary results but they indicate that our experimental setup displays behaviors encountered in speech production which are going to be further studied and modelled, especially the conditions of appearance of this oscillations.

CONCLUSIONS

Preliminary results obtained with our experimental setup show reasonable agreement between theory and measurements. It also displays interesting interaction phenomena such as self-sustained oscillation. This incitates us to exploit it further on in order to model fluid/elastic structure interaction. The flow modelization will have to take into account consequences of asymmetry of the channel, perharps by modelling separately the upper and the lower half of the flow. Suspicion of turbulence presence should be investigated further on, perharps using flow visualization, as it has a lot of consequences on flow modelization. Modelling turbulent boundary layer maybe necessary in order to get the precise separation point position. After validation, the flow model will have to be coupled with a biomechanical description of the tongue. As we need a refined elastic description, a finite element approach will have to be used. Complex and realistic tongue model are developped at ICP that will be used eventually. For the moment, a numerical simulation of the interaction using a simple elastic description of the latex cylinder is developped, in order to confront numerical and experimental results.

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