STUDY OF SOME ADVANCES OF THE TWO-MASS MODELS OF THE VOCAL FOLDS

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Abstract. *Low order non-linear mechanical models for vocal folds, in the phonation process, have been showed to be useful in the case of normal and disordered voice studies. Despite their relative simplicity, they are able to simulate the main features of the vocal fold dynamics. Good examples are the two-mass models (presented by Ishizaka and Flanagan or by Lous et al), which use few input parameters and have shown excellent results to understand phonation phenomena. The Ishizaka and Flanagan model is the oldest and it has been much explored by many researchers during more than thirty years. Other two-mass models appeared, but the Ishizaka and Flanagan model has shown to be better. Recently, Lous proposed another two-mass model to the production of the voiced sounds with some very interesting characteristics, including changings in the geometry and, mainly, in the airflow model through the glottis. Lous' model has presented good results but its comparison with the Ishizaka and Flanagan model is necessary, not only in the case of normal voices, but it is also interesting to explore their differences in pathological cases.It is the aim of this work to compare the two models using characteristics of the output radiated pressure and of the glottal signal, in the cases of normal voices and also in some cases of voices with pathological characteristics.*

Keywords: *Vocal Folds, Two-Mass Model, Ishizaka and Flanagan's model, Lous' model*

1. INTRODUCTION

Production of vowels by the phonatory system begins with the contraction of the diaphragm that leads to the creation of a controlled air flow in the larynx. Eventually, the vocal folds, contained by the larynx as showed on Fig. 1, start to auto-oscilate transforming the air flow into a serie of pulses, called glottal pulses. These acoustic pulses will then propagate in the upper phonatory system, or vocal tract, mainly composed by the oral and nasal cavities. The vocal tract acts as a frequency filter on the glottal pulses, favoring some frequencies, called formants, among the others. The resulting frequency distribution of the formants permits us to recognise the produced vowel.

During the phonation, the typical motion of the vocal folds presents an almost constant phase difference between the

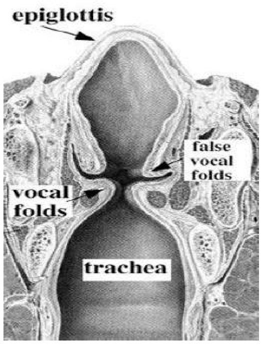

Figure 1. Frontal cut of the larynx.

lower part and the upper part of the vocal folds, as represented in Fig. 2.

Figure 2. Glottal cycle for modal voice, air flow from the lower to the upper end.

The numerical reproduction of the vocal folds dynamics by mechanical models started with Flanagan and Landgraf's (1968) model, where each vocal fold is represented by a single-degree-of-freedom lumped oscilator. Then, Ishizaka and Flanagan (1972) published the famous two-mass model for the vocal folds, a computationally light model yet describing well the dynamics of the vocal folds; a very efficient combination indeed. A comparison between these two last models is made in Cataldo et al. (2006). Since then, and after many studies on the physics of phonation, various authors have reformulated this model using more appropriate hypothesis. Nevertheless, Ishizaka and Flanagan's model still is the most used today. In this paper, we aim to understand why this model is the most used by comparing it to a more recent model proposed by Lous et al. (1998) through a description of the theories used to build each model and a comparison of some numerical simulations.

2. THEORETICAL DESCRIPTION OF THE MODELS

Although the physics of the phonatory system is complex, its modeling by two-mass models aims to be as simple as possible in order to lower the computational cost. Thus, the models to be presented, which may seem to be constructed with very crude approximations of the reality, represent a good compromise between the necessary simplification allowing easy computation and a realistic representation of the phonatory system.

2.1 Flow modelization

Flow description is the characteristic that mainly changed from Ishizaka and Flanagan's model to nowaday models. From Fig. 1 and now considering the flow going from left to right, the vocal folds are schematically represented as showed on Fig. 3. The flow is described along the x axis, going from the subglottal system (indicated by the $_{sub}$ subscript) to the supraglottal system (with $_{sup}$ subscript) through the glottis ($_g$ subscript), which is the opening in the vocal folds, a tubular region. The glottal flow separates from the vocal folds at a point x_s, indicated by a height h_s.

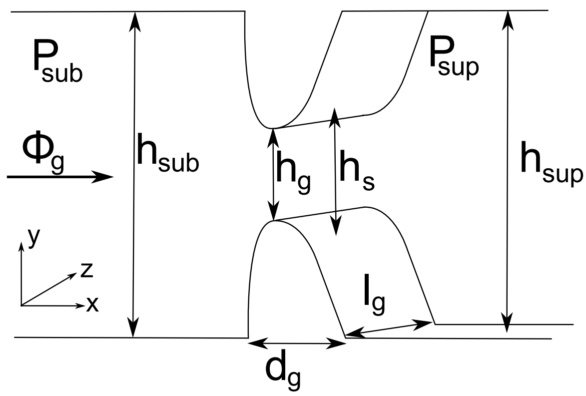

Figure 3. Sketch of the vocal folds

Some typical dimensions for flow calculation during phonation for a male speaker are presented in Tab. 1, they give a good idea of the peculiarities of the glottal flow. From these values, some dimensionless numbers associated to the flow were calculated by Pelorson (1994) and Vilain (2004) to describe the flow and to justify some of the simplifications made, like planar flow, incompressibility, etc. These numbers are described in the following:

Table 1. Typical values for flow determination during phonation for a male speaker (from Vilain (2004)).

Geometrical dimensions		
Vocal folds width	l_g	14 mm
Vocal folds length	d_g	3 mm
Mean glottal height at constriction	h_g	1 mm
Subglottal tract height	h_{sub}	2 cm
Supraglottal tract height	h_{sup}	2 cm
Flow dimensions		
Flow velocity at constriction	u_g	15-40 $m.s^{-1}$
Subglottal pressure$^{(1)}$	P_{sub}	100-1000 Pa
Fundamental frequency of oscillation	f_0	80-200 Hz

$^{(1)}$: relative to atmospheric pressure

Compressibility of the flow
The Mach number, expressed as $M = \frac{v_g}{c_0}$, where c_0 is the sound velocity, is lower than 10^{-2} in the glottis. Thus the flow can be considered incompressible in the glottis. Calculating then the Helmholtz number $He = \frac{d_g}{\lambda_0}$, where $\lambda = \frac{c_0}{f_0}$ is the acoustic wavelength, we are only considering the fluid locally incompressible from an acoustic point of view.

Two dimensional flow
As the width of the vocal folds in the z direction is 14 mm and its height h_g in the y direction 3 mm, the flow is considered two-dimensional in the (x, y) plane.

Steadiness of the flow
The Strouhal number calculated on the glottal length inform us on the influence of the vocal folds movement on the steadiness of the flow. Using the values of Tab.1, it can be seen that the Strouhal number, $S_r = \frac{f_0 d_g}{u_v}$, is of the order of 10^{-2}, telling us that the flow velocity is fast enough, in regard to the vocal folds frequency, not to be perturbed. The flow is then considered quasi-steady.

Viscosity of the flow
Calculating the glottis height related Reynolds number, $Re_h = \frac{u_g h_g}{\nu}$, where ν is the shear viscosity of the air, one can determine the relative importance of viscosity and inertia of the fluid. In the glottis, this number is typically 500, which means that the viscosity is only important near the vocal folds.

From all these hypothesis, we should then represent the flow as a two-dimensional, quasi-steady, non-viscous flow. But, as it has been pointed out by Pelorson (1994), the problem is not so simple. When the glottis closes, which is related to a diminution of h_g in the numbers described above, the effects of viscosity and fluid inertia can be neglected no more. On the other hand, as the purpose of a two-mass model is to be computationally cheap, a resolution of the problem describing well viscosity and inertia effects and with a good accuracy is not feasible since it would be too costly. As a compromise, and this is done in the models we present, the description of the flow is assumed unsteady and viscous even for large openning of the glottis.
Using Bernoulli's energy conservation law between section 1 and section 2 of the duct, we have:

$$(Energy)_2 = (Energy)_1 - Losses \tag{1}$$

where the energy is calculated for an unsteady, two-dimensional, incompressible flow, and losses due to viscosity.

2.2 Ishizaka and Flanagan's two-mass model

The vocal folds approximation made by Ishizaka and Flanagan (1972) is showed on Fig. 4.

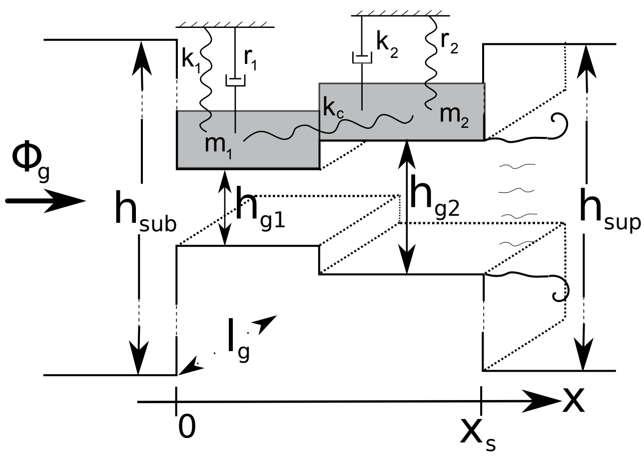

Figure 4. Schematic representation of the two-mass model proposed by Ishizaka and Flanagan.

An axial symmetry about the x axis is considered. A vocal fold is represented by a two-mass ensemble, permitting the reproduction of the phase difference between the lower and upper parts of the vocal fold as sketched in Fig. 2.

Mechanical description of the vocal folds

The dynamic of the two-masses is given by the equations:

$$m_i \frac{d^2 x_i}{dt^2} + r_i(y_i) \frac{dx_i}{dt} + s_i(y_i) + k_c(x_i - x_j) = f_i \, , \, i = 1, 2 \, , \, j \neq i, \tag{2}$$

where the force f_i is due to the pressure applied to the vocal folds and that can be computed only if the flow is known. The elasticity and damping, as showed in eqs. 3 and 4, are non-linear term. The parameters of elasticity were chosen to fit characteristics measured on fresh excised human vocal-folds [3].

$$\begin{cases} s_i(y_i) = k_i(y_i + \eta_i y_i^3) & y_i > -h_{g_i}/2, \\ s_i(y_i) = k_i(y_i + \eta_{k_i} y_i^3) + \kappa_i \left\{ \left(y_i + \frac{y_{0i}}{2}\right) + \eta_{\kappa_i} \left(y_i + \frac{y_{0i}}{2}\right)^3 \right\} & y_i \leqslant h_{g_i}/2, \end{cases} \tag{3}$$

where $h_{g_{0i}}$ is the initial glottal openning, y_{0i} the initial i^{th} mass position, y_i it position relative to the initial position and η_i, κ_i are constants.

$$\begin{cases} r_i(y_i) = 2\xi_i \sqrt{m_i k_i} & y_i > -h_{g_i}/2, \\ r_i(y_i) = 2(\xi_i + 1)\sqrt{m_i k_i} & y_i \leqslant h_{g_i}/2. \end{cases} \tag{4}$$

Counting all the parameters needed to implement the model, we see that it requires 12 constants to describe the mechanical properties of the vocal folds: $m_1, m_2, k_1, k_2, \xi_1, \xi_2, h_{g_{01}}, h_{g_{02}}, \eta_1, \eta_2, \kappa_1$, and $\kappa 2$.

Flow description in the glottis

The flow is calculated between the entrance of the glottis at $x = 0$, where the pressure is considered equal to p_{sub}, the lung's pressure, and the glottis end at $x = x_s$. It is assumed that a turbulent free jet separates from the vocal folds and the pressure is p_{sup}, the acoustic pressure at the entrance of the vocal tract. To describe the flow in a computationally light way, the following assumptions are made:

- The flow is quasi-steady, the pressure drop at each section discontinuity is described by Bernoulli equation $\Delta p_B = 1/2\rho\phi_g^2/l_g^2 \left(1/h_{\Lambda+1}^2 - 1/h_{\Lambda}^2\right)$, $i = 1, 2$, where the sections subscripts Λ are $\{sub, g_1, g_2, sup\}$.
- The unsteadiness of the flow within the glottis is taken into acount through the inertance of the air masses. For a duct of constant height it is given by: $\Delta p_I = \frac{\rho d_i}{h_{g_i} l_g} \frac{d\phi_g}{dt}$.
- Finally, the pressure drop due to viscosity is represented by an additional Poiseuille term expressed by $\Delta p_P = 12 \frac{\mu l_g^2 d_i}{(h_{g_i} l_g)^3} \phi_g$, $i = 1, 2$, in a canal of constant height and length d_i.

From these pressures in each section of the glottis we have the total pressure drop given by Eq. 5.

$$\Delta p = p_{sub} - p_{sup} = \Delta p_B + \Delta p_I + \Delta p_P. \tag{5}$$

As at the entrance of the vocal folds at $x = 0$ the height reduce from $h_0 = 2\ cm$ to $h_{g_1} = 0.1\ cm$, a *vena contracta* is produced according to van den Berg et al. (1957) which evaluated the loss figure at 0.37. The pressure at the entrance of the first mass is then given by Eq. 6.

$$p_{11}(t) = p_{sub} - \frac{1.37}{2} \rho \frac{\phi_g^2(t)}{l_g^2} \left(\frac{1}{h_{g_1}^2(t)} - \frac{1}{h_0^2} \right). \tag{6}$$

At the end of the first mass, on the left side of the gap and due inertance of the air and viscosity losses, the pressure is:

$$p_{12}(t) = p_{11}(t) - 12 \frac{\mu l_g^2 d_1}{(h_{g_1}(t) l_g)^3} \phi_g - \frac{\rho d_1}{h_{g_1}(t) l_g} \frac{d\phi_g(t)}{dt}. \tag{7}$$

On the right side of the gap, due to the section gap the pressur is:

$$p_{21}(t) = p_{12}(t) - 1/2\rho\phi_g^2(t)/l_g^2 \left(1/h_{g_2}^2(t) - 1/h_{g_1}^2(t)\right). \tag{8}$$

At the second mass outlet, on the left side, due inertance of the air and viscosity losses, the pressure is:

$$p_{22}(t) = p_{21}(t) - 12 \frac{\mu l_g^2 d_2}{(h_{g_2}(t) l_g)^3} \phi_g(t) - \frac{\rho d_2}{h_{g_2}(t) l_g} \frac{d\phi_g(t)}{dt}. \tag{9}$$

At the outlet, on the right side, it is assumed that the free jet reattaches to the vocal tract walls. The correspondent modified Bernoulli equation, taking into account a pressure recovery is showed in Eq. 10.

$$p_{sup}(t) = p_{22}(t) + \rho \left(\frac{\phi_g(t)}{h_{g_2}(t) l_g} \right)^2 \frac{h_{g_2}(t)}{h_{sup}} \left(1 - \frac{h_{g_2}(t)}{h_{sup}} \right). \tag{10}$$

Acoustic propagation in the vocal tract
The vocal tract can be described as an acoustic tube with variable transversal section. For the sake of simplicity, it is represented by a concatenation of cylindrical tubes. At the end of the acoustic tube a condition of radiation load equivalent to that of a circular piston moving on an infinite plan is imposed. This acoustic tube is coupled to the glottis flow model and thus it strongly affects the vocal folds dynamics. Calling $\phi_1(t)$ the volumetric flow in the first cylindrical tube of the vocal tract, the influence of the vocal tract on the vocal folds at time t is given by:

$$L_1 \frac{d\phi_g(t)}{dt} + R_1\phi_g(t) + \frac{1}{C_1}\int_0^t (\phi_g(t) - \phi_1(t))dt - p_{22}(t) = 0, \tag{11}$$

where C_1, R_1, and L_1 are its respectives acoustical capacitance, resistance, and inductance.

2.3 Lous et al. two-mass model

Since 1972, many changes have been done on Ishizaka and Flanagan's two-mass model for the vocal cords, leading to various derived models. We choose here to present the model proposed by Lous et al. (1998), because it includes most of these changes. The two-mass model for the vocal cords proposed by Lous et al. is showed on Fig. 5.

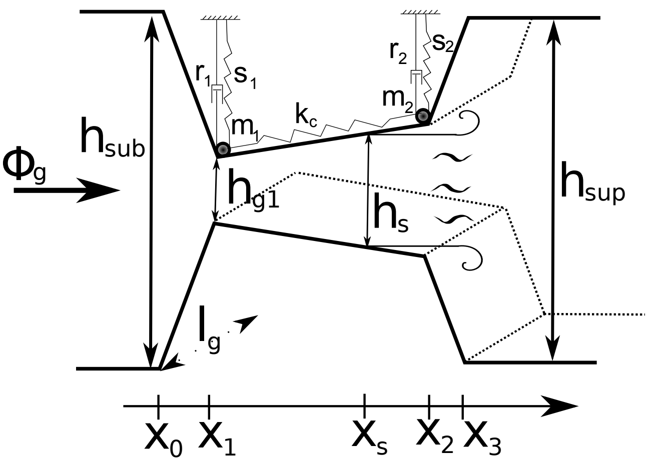

Figure 5. Schematic representation of the two-mass model proposed by Lous et al. (1998).

Rather than two rectangular mass, each vocal fold is now represented by three plates with point masses at their junctions. This different geometry permits a better representation of the pressure distribution in the glottis, thus of the forces acting on each oscilator, as we will see in the following.

Modified mechanical description of the vocal folds
As the model is a two-mass model, we can describe it by the system of equations 12.

$$m_i \frac{d^2x_i}{dt^2} + r_i(y_i)\frac{dx_i}{dt} + s_i(y_i) + k_c(x_i - x_j) = f_i \, , \, i = 1, 2 \, , \, j \neq i, \tag{12}$$

Nervertheless, two modifications are made compared to Ishzaka and Flanagan's model: one on the elasticity term and the other on the closing conditions.
Since many approximations are made and because the non-linearity of the elasticity is not of cardinal importance for result accuracy, the elasticity term is now piecewise linear as expressed in Eq. 13. Doing this, four coefficients are discarded from the mechanical representation of the vocal folds (κ_i and η_i, $i = 1, 2$).

$$\begin{cases} s_i(y_i) = k_i y_i & h_{g_i} > h_{min}, \\ s_i(y_i) = 4k_i y_i & h_{g_i} \leqslant h_{min}, \end{cases} \tag{13}$$

On the other hand, the closure phase has been improved. Pelorson et al. (1994) pointed out the fact that the contact does not occurs at once in the faces of the vocal folds, but start by the external parts of the folds (considering the z axis of Fig. 3) to end at the center. Then, as the contact is occurring, the flow is not totally stopped, only diminished. To modelize this phenomenon, the contact is anticipated and is considered to occur if $min(h_{g_i}) \leqslant h_{lim}$, where h_{lim} is generally set at 2.10^{-5} m.
The mechanical part is now described by 9 coeficients: $m_1, m_2, k_1, k_2, \xi_1, \xi_2, h_{g_{01}}, h_{g_{02}}$ and h_{lim}.

Modified flow description

The general description of the flow is again the one showed in Eq. 5, but is adapted to the new geometry of the glottis. The *vena contracta* phenomenon is discarded as it is not likely to occurs due to the vocal fold relatively smooth entrance (Pelorson, 1994). At the outlet, the pressure recovery (Eq. 10) is neglected since $h_{sup} \gg h_{g_2}$.

Although, as showed on Fig. 4, during the glottal closure (phase 5 of Fig. 2) where the channel is diverging, the free jet separate from the vocal folds before the end of the glottis (referenced as x_2). Calculate the position of this separation point can be done using a quasi-steady boundary layer theory as in Vilain and al. (2004), but as it is quite expansive numerically, the *ad-hoc* parameter a proposed by Liljencrants is used. This parameter sets the height at the separation point as a times the height at the minimum of the constriction ($h_s = ah_{min}$).

Finally, the pressure at each point is given by Eq. 14.

$$\begin{array}{lll} p(x) = & p_{sub} - \frac{\rho}{2}\left(\frac{\phi_g}{l_g(h(x)-h_{sub})}\right)^2 - 12\mu l_g^2\phi_g \int_{x_0}^{x} \frac{1}{l_g^3 h^3(x)}dx - \rho\frac{d\phi_g}{dt}\int_{x_0}^{x}\frac{1}{l_g h(x)}dx & , x < x_s \\ p(x) = & p_{sup} & , x \geqslant x_s \end{array} \quad (14)$$

The coupling between the vocal folds and the vocal tract is made through p_{sub}, which acts on the vocal folds from x_s to x_2.

3. NUMERICAL SIMULATIONS

A comparison of the models was done for the vowel $/a/$, representing the vocal tract, which is $175.10^{-3}\ m$ long, by a concatenation of eight tubes of equal length. Both models are implemented using finite differences. The sampling time of $64.10^{-6}\ s$ used for the simulation is imposed by the time taken by the acoustic wave to propagate in a vocal tract section. The values used for modelization of the larynx are the followings: $p_{sub} = 600$ Pa, $L_g = 1.4.10^{-2}\ m$, $m_1 = m_2 = 1.10^{-4}\ kg$, $k_1 = k_2 = 40\ N.m^{-1}$, $k_c = 25\ N.m^{-1}$, $\xi_1 = \xi_2 = 0.1$, $h_{lim} = 2.10^{-5}$, $\eta_1 = \eta_2 = 100$ and $\kappa_1 = \kappa_2 = 500$. The vocal folds length is set to $3.10^{-3}\ m$ for both models.

Due to the differences between the models we described in the last part, the models don't produce the same result for the same set of initial parameters. Though, in order to see why the results are so different, we applied some of the modifications proposed by Lous et al. on Ishizaka and Flanagan's model. We simulated the following cases where only one parameter is varied at each time, except for the last simulation. 1: original model; 2: we used eqs. 13 to obtain a piecewise linear elasticity; 3: the recovery of pressure at the outlet (eq. 10) is discarded; 4: it is considered that no *vena contracta* forms at the inlet; 5: the mechanical contact occurs before the glottis closes, for $h_{lim} = 2.10^{-5}$ m; 6: all the above modifications are made at the same time.

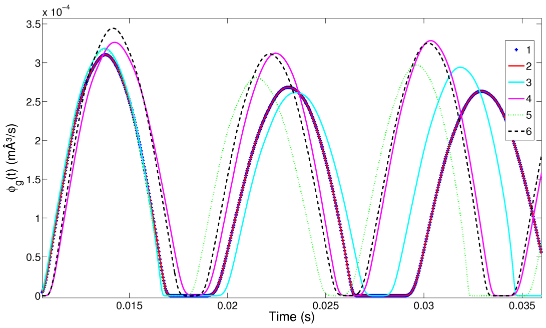

Figure 6. Effect of modification of the Ishizaka and Flanagan's model parameters. 1: original model, 2: piecewise-linear elasticity, 3: without pressure recovery, 4: without *vena contracta*, 5: anticipated contact, 6: with all the modifications at the same time.

From the results, showed on Fig.6, we can make some qualitative statements. It appears clearly that discard the non-linear terms of the elasticity brings a negligible change in the results. Pressure recovery at the outlet is quite relevant but depends on the vocal tract entrance area. Not considering the vena contracta at the inlet caused the most important change in the results, the correspondent result is almost similar to the results obtained when all modifications are made at the same time. These changes come from a large increase of the pressure forces applied to the first mass as the flow is no more contracted. Anticipating the contact, a non-negligible change is again observed, in the frequency as well as in the amplitude of the glotal pulses.

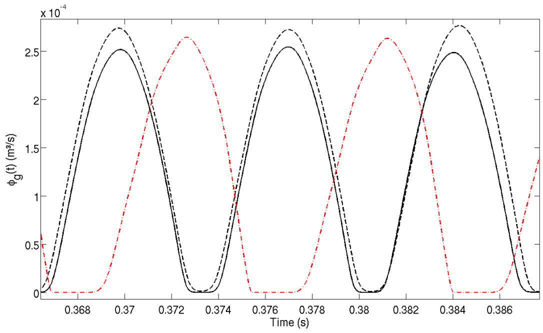

Figure 7. Volumetric flow obtained with the original Ishizaka and Flanagan's model, modified Ishizaka and Flanagan's model (dashed line), Lous model (dash dotted line).

Comparing now the original Ishizaka and Flanagan's model, its modified version, and Lous et al. model (Fig. 7), it appears that the three are quite different. While the original Ishizaka and Flanagan's model leads to an inferior volumetric flow compared to the Lous et al. model, the modified one leads to a superior volumetric flow. Nevertheless, the results are of the same order of magnitude and none of the models can be said to give the best result.

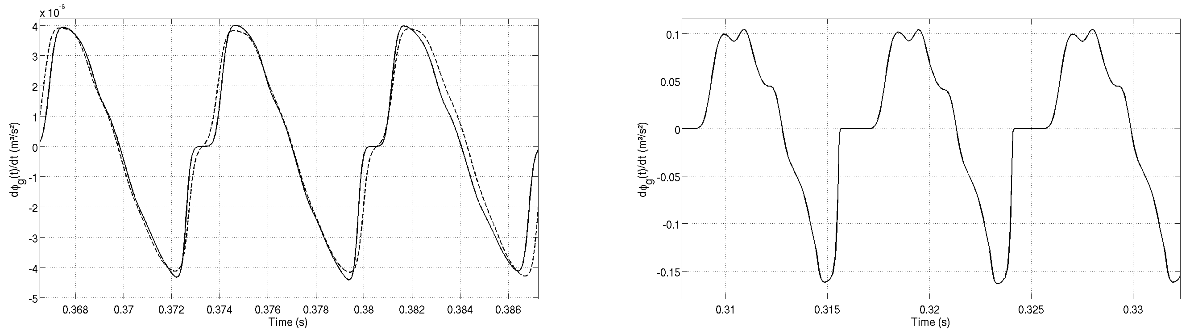

Figure 8. Volumetric flow derivative. On the left: original and modified Ishizaka and Flanagan's models (respectively solid line and dashed lines); on the right: Lous et al. model.

On the other side, a huge difference appears if we observe the volumetric flow derivative (Fig. 8): whereas the models based on Ishizaka and Flanagan's model estimate a maximum flow derivative of approximatelly $4.10^{-6}\ m^3.s^{-2}$, the Lous et al. model estimates is more than 10000 times higher. Furthermore, some higher frequencies clearly appear in the glottal flux derivative of Lous et al. model. These higher frequencies are caused by the acoustical coupling between the vocal cords and the vocal tract, which is best described by Lous et al. model.

The radiated voice corresponding to each model is showed on Fig. 9. We see that the frequency that perturbs the

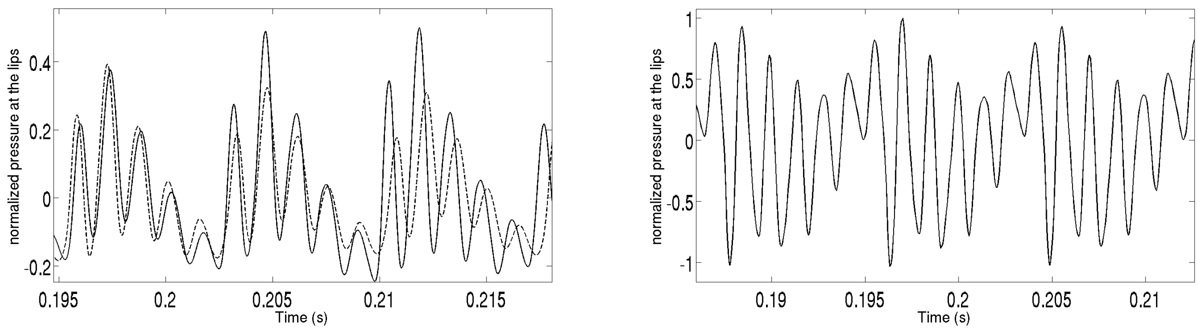

Figure 9. Normalized pressure radiated at the lips. On the left: original and modified Ishizaka and Flanagan's models (respectively solid line and dashed lines); on the right: Lous et al. model

volumetric-flow derivative corresponds to the first formant of the vowel. Even if Ishizaka and Flanagan's produces this formants, and if they are also present in the vocal tract, the coupling is significantly lower. This occurs because the Lous et al. model specific geometry allied to a moving separation point leaving the surface going from x_s to x_3 is more sensitive to vocal-tract-pressure variations.

4. CONCLUSIONS

We see from the results that the flow modeling modifications proposed along the years from Ihsizaka and Flanagan's model to Lous et al. model modifies significantly the predictions. Both model were shown to reproduce interesting dynamical features of the vocal cords, but it appears that Lous et al. model can produce some results that Ishizaka and Flanagan's model can not. The models are very sensitive to some of the parameters and for those parameters it will be important to do a stochastic modeling to gauge the corresponding sensitivity of the results. This study is under way and is object of a forthcoming paper.

5. ACKNOWLEDGEMENTS

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7. Responsibility notice