Towards full-scale three-dimensional larynx simulation

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Abstract

The present work describes a three-dimensional larynx simulation during phonation. Its modeling demands the use of pseudo-viscoelastic models to describe the larynx tissues in simplified way. The description of the airflow generated by the pressure drop between lung cavity and the region of epiglottis and mouth, the Navier-Stokes equations are used. Their solution requires sophisticated numerical methods because of its inherit nonlinear nature and the high Reynolds number in some places of the larynx (specially after the glottis).

Considering that the phonatory process produces true vocal fold closing in quasi-periodic way, a contact-impact model is used to determine the forces involved during the collision of the glottal surfaces.

The finite element method is used to numerically solve the problems described above because its ability to work with such physic domains and its acceptance for non-structure geometric meshes.

All these engineering problems were solved in a way to simulate the larynx tissue movements as well as analyze quantitatively and qualitatively the airflow. The results show that the variation of the lung pressure in relation to fundamental frequency is a function of viscoelastic properties of the tissues and it is approximately (in modulus) 3 Hz/(Kdyne/cm^2)).

Also it is clear that the simulated vocal folds produce laryngeal clefts during phonation as found in human being. This fact is important because it helps to qualitatively validate the presented 3D model.

1. Introduction

The larynx is the organ responsible for generating the glottal signal. The importance of this signal is that it will be modulated by the supraglottal tract in order to produce the human voice. The lack of such a signal results in difficulties of speech and even impossibility of speaking.

The aim of larynx modeling studies is to study the dynamic of several larynx components as well as to quantify the movements of laryngeal tissues and the aerodynamic aspects that take place during phonation.

One of the most important larynx models (used also in studies speech synthesis) is the two-mass model ([5]), in which two bodies of mass M are coupled by a spring K3 and individually connected to a rigid surface by two springs (K1 and K2) and two dampers (D1 and D2). A simplified version of Navier-Stokes equations is used to determine the airflow in function of the modeled "larynx" geometry and the aerodynamic force applied over the two bodies. Such forces moves the bodies according to the elastic energy stored in the springs and the energy loss produced by the dampers. All this system of second order partial differential equations (mathematical description of the tissues) is nonlinear and one the consequences is that the oscillatory sustained behavior of the simulated larynx is only achieved in specific viscoelastic and aerodynamic conditions.

The main advantage of the two-mass model is its simplicity and the its ability to produce movements in function of changes in its viscoelastic and geometric parameters. The authors also demonstrate that the subglotal pressure (or lung pressure) affects directly the glottal signal frequency in a rate of 3 Hz/cmH$_2$0.

[7] show that inclusion of false vocal folds and improvements in the airflow modeling allows that the larynx produces glottal signals with low subglottal pressures. Their results reinforce the idea that false vocal folds can act as a natural extension of the glottal channel for the airflow viewpoint.

[9] show that an adequate modeling of the glottal closing phase allows the simulated larynx to generate perceptually-realistic voice signals. The larynx models, according the authors, cannot cause abrupt closings but smooth ones, allowing the changing in the airflow volumetric velocity be smooth as well. It requires more sophisticated aerodynamic models, as proposed by them.

Toward more sophisticated models (with a large numer of "masses"), [1] proposes a two-dimensional larynx model (assuming larynx symmetry, they eliminate one of the true vocal folds) that conjugates viscoelastic and aerodynamic models (however, the authors simplify the collision forces by only avoiding that the true vocal fold movements mathematically surpass the larynx central line). The results show that a model with more granularity can represent more

Following this technique, the present work uses, by the first time, a three-dimensional model of the larynx. Using the finite element method, both tissues and airflow are mathematically described and numerically solved in order to obtain the movements of the larynx tissues, and the airflow velocities and pressures in several places of the laryngeal cavity. Methods based on solution of sparse systems are used

2. Material and Methods.

The first simulation step is the geometric description of the simulated tissues as well as the cavity where the air flows. According to [11], a set of hyper-ellipses is used to describe the simulated larynx. Table 1 shows the geometric description of the simulated larynx. The use of hyper-ellipses helps to describe the larynx because it allows to describe mathematically the peculiar geometry of the larynx like, for example, the glottal space where the so-called laryngeal cleft shows up.

Table 1: *Geometric description of the simulated larynx*

Section	Center (cm)	Radius R1, R2, R3, R4 (cm)
S0	0, 0, -2	0.7, 0.7, 0.7, 0.7
S1	0, 0, -1	0.7, 0.7, 0.7, 0.7
S2	0, 0, -0.8	0.7, 0.7, 0.7, 0.7
S3	0, 0, -0.61	0.7, 0.6, 0.7, 0.6
S4	0, 0, -0.47	0.7, 0.25, 0.7, 0.25
S5	0, 0, -0.40	0.7, 0.075, 0.7, 0.075
S6	0, 0, -0.33	0.7, 0.025, 0.7, 0.025
S7	0, 0, -0.26	0.7, 0.025, 0.7, 0.025
S8	0, 0, -0.19	0.7, 0.025, 0.7, 0.025
S9	0, 0, -0.12	0.7, 0.025, 0.7, 0.025
S10	0, 0, -0.05	0.7, 0.025, 0.7, 0.025
S11	0, 0, 0	0.7, 0.235, 0.7, 0.235
S12	0, 0, 0.03	0.7, 0.35, 0.7, 0.35
S13	0, 0, 0.07	0.7, 0.5, 0.7, 0.5
S14	0, 0, 0.10	0.7, 0.515, 0.7, 0.515
S15	0, 0, 0.23	0.7, 0.45, 0.7, 0.45
S16	0, 0, 0.35	0.7, 0.46, 0.7,0.46
S17	0, 0, 0.48	0.7, 0.6 0.7, 0.6
S18	0, 0, 0.60	0.7, 0.7, 0.7, 0.7
S19	0, 0, 1.30	0.7, 0.7, 0.7, 0.7
S20	0, 0, 2	0.7, 0.7, 0.7, 0.7

Tissue type	Thickness	Section
Cover	0.5 mm	S5 to S12
Ligament	0.5 mm	S5 to S12

The geometric elements that describes both the airflow and the laryngeal tissues are interpolated in the space defined by hyper-ellipses. Tetrahedrons are used as the geometric elements to obtain the numeric solution from the finite element method of both the dynamic of the tissues and airflow. Figure 1 shows a view of the simulated larynx.

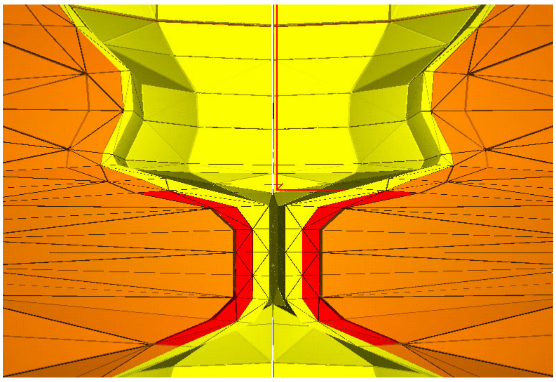

Figure 1: *Geometric description of the simulated larynx in transversal section*

Navier-Stokes equations for laminar, isothermal, incompressible and stationary flows are adopted to quantify the laryngeal airflow. The use of laminar flows is justified by the aerodynamic behavior of the air during a normal phonation although the Reynolds number be high in some portions of the larynx after the glottis. The airflow jet itself, formed during phonation, and the short length of the larynx after the glottal constriction allow the adoption of laminar airflow description (Millet et al. 1988). Inside the larynx cavity, the air is incompressible and the temperature variation is too small to change the airflow profile.

The only big simplification in the simulated airflow is the adoption of steady airflow description. Assuming non-steadiness would requires to take into account the airflow mesh movement during the airflow modeling. The key point in this difficulty is that during the glottal closing, the laryngeal air channel is closed. This increase the complexity of determining the airflow mesh movement during the this phonation cycle. To keep the solution stable, a denser airflow mesh would also be required if non-steadiness was adopted, something that used computational resources would not support.

The finite element method is used to solve Navier-Stokes equations. However several strategies are used ([11]) to stabilize the convective term of these equations because they are responsible for the formation of vortexes due to the transport of velocity components through the airflow, and for the difficulties of solving high Reynolds Navier-Stokes equations ([4]). The strategies are the use of first-order methods ([13]) and second-order methods ([12]), whose application is dependent of the local velocity gradient (Fidap, 1999) according to a Laplacian filter applied over all airflow mesh element.

To speed up the computation of the solution (which is iterative because the resulting equation system still are nonlinear), the method of reduced basis ([10]) is used. In this method, a base is obtained through the solutions of several airflow problems with reduced pressure drops. This base is used to project the estimated solution (in the desired pressure drop) that will be used as the first guest to iteratively achieve the final solution. The iterative process is the successive substitution method ([4]).

The airflow velocity in the walls of the laryngeal cavity is null and the pressure drop between both the subglottal and supraglottal cavities drives the flow - they are the boundary conditions of the problem.

The tissue modeling follows [1], only extending the concept to three dimensions and using the Newmark method ([2]) because of its inherit unconditional stability. It is assumed that the larynx tissue has elastic and viscous behaviors and is divided in three different tissues: cover (tissue in contact to the air), ligament (intermediate tissue and more rigid than the cover) and body (tissue more rigid than cover and ligament). It was adopted [14] to describe the elastic components in transversal direction - one of the few

The result of the mathematical formulation of the tissues is a system of second-order linear partial differential equations. After the discretization, using the finite element method, the system of equations still continues linear. The boundary conditions of the problem are a rigid support of the structure (null displacement) - Dirichlet condition - and the air pressure applied over the surface of the interface between the tissues and the airflow - Neumann condition.

The modeling of the contact between both true vocal folds during the glottal closing phase is defined according to [2] where physical restrictions are added to the system of equations of the laryngeal tissue to avoid body inter-penetration. The method proposed by [8] is used to efficiently solve this new system because it reduces the amount of calculation when new movement restrictions are included.

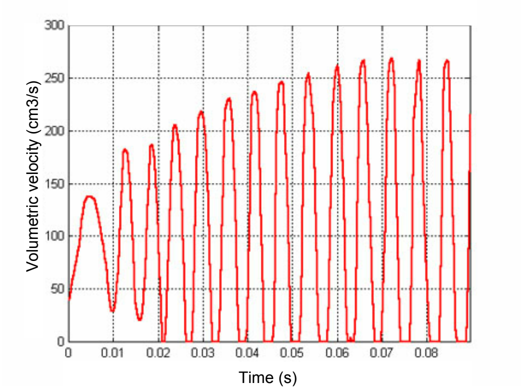

Figure 2: *Glottal signal for a pressure drop of 8 Kdyne/cm*^{2}

The tissue movement causes changes in the meshes. The tissue mesh is automatically updated because the solution of its equations produces the displacements that the mesh should perform. However, it is necessary to updating the airflow mesh in order to it follows the tissue one. Based on the displacement of the mesh nodes of the interface between both physical systems, the method of [6] is used to update the airflow mesh. It is important to note that there are cases where this method fails, producing elements with null or negative volumes. In this cases, the algorithm of mesh generation is used to reconstruct a new mesh for the airflow based on the laryngeal channel formed by the movement of the tissue mesh.

Considering the dimensions of the system of resulting linear equations (the iterative process to solve system of nonlinear equations produces a set of system of linear equations to be solved), the method of supernodes ([3]) is used.

The simulation is then solved by the following algorithm:

1) Solution of the airflow equations;
2) Gathering of airflow pressures in the tissue-airflow interface;
3) Solution of the laryngeal tissue equations;
4) Updating the tissue mesh
5) It there is collision between some parts of the laryngeal mesh:
5.1) Inclusion of mesh movement restrictions;
5.2) Go back to step 3;
6) Update the airflow mesh;
7) Go back to step 1;

In every cycle of the simulation algorithm, volumetric velocities and mean pressures along the airflow channel are calculated.

3. Results and Discussions

To simulate the larynx, a pressure drop between subglottal and supraglottal cavities of 8 Kdyne/cm^2 is used. The integration time step (necessary to solve the tissue dynamic equations) is 300 ms.

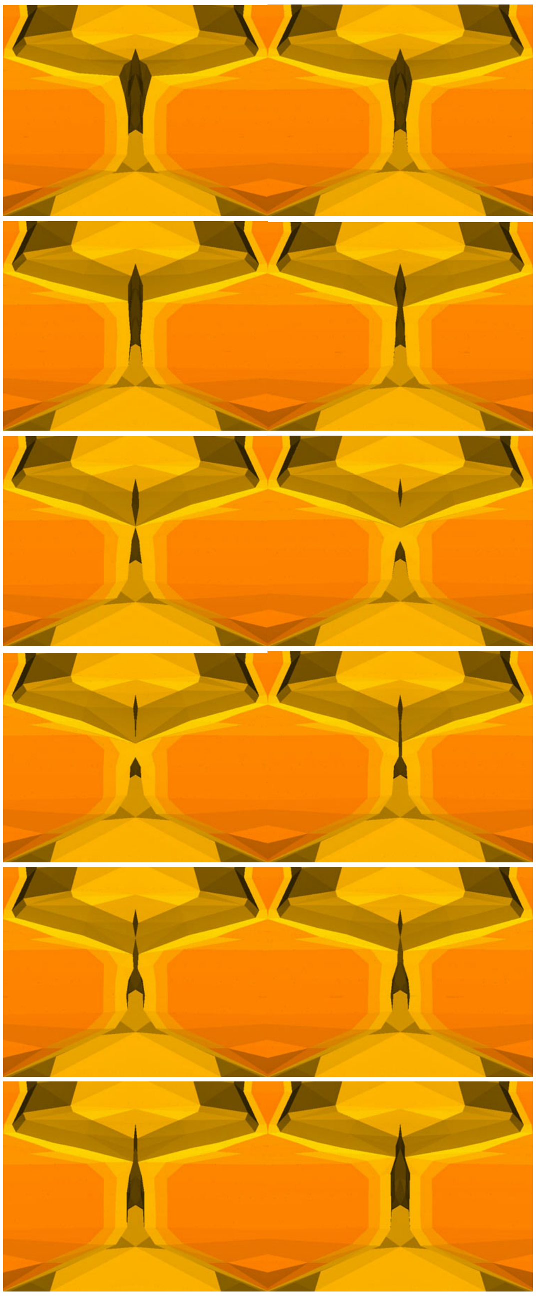

Figure 3: *Complete oscillation cycle of the larynx in transversal section - part 1.*

Figure 2 shows the glottal signal obtained by determining the volumetric velocity of the airflow in the laryngeal cavity. Note that the initial transient, after what the cover tissues of the true vocal folds reach a self-sustained oscillatory behavior. The frequency of this signal is 164 Hz and its open quotient is 0.6347 (these values are obtained from the last 9 cycles, where the steadiness is guaranteed).

A increase of 1 Kdyne/cm^2 in the pressure drop (=9 Kdyne/cm^2) produces a signal whose frequency is 161.3 Hz and open quotient is 0.6249. Note that such a frequency variation is equal to -3.4 Hz/(Kdina/cm^2), different from the one proposed by [5].

However, changing the elastic and viscous characteristics of the laryngeal tissues, a rate of +1.5 Hz/(Kdina/cm^2) - signal frequency from 188.8 to 190.3 Hz - when the pressure drop goes from 8 to 9 Kdyne/cm^2. This shows that the frequency of the glottal signal is function of the pressure drop between subglottal and supraglottal pressures, and of the viscoelastic characteristics of the laryngeal tissues.

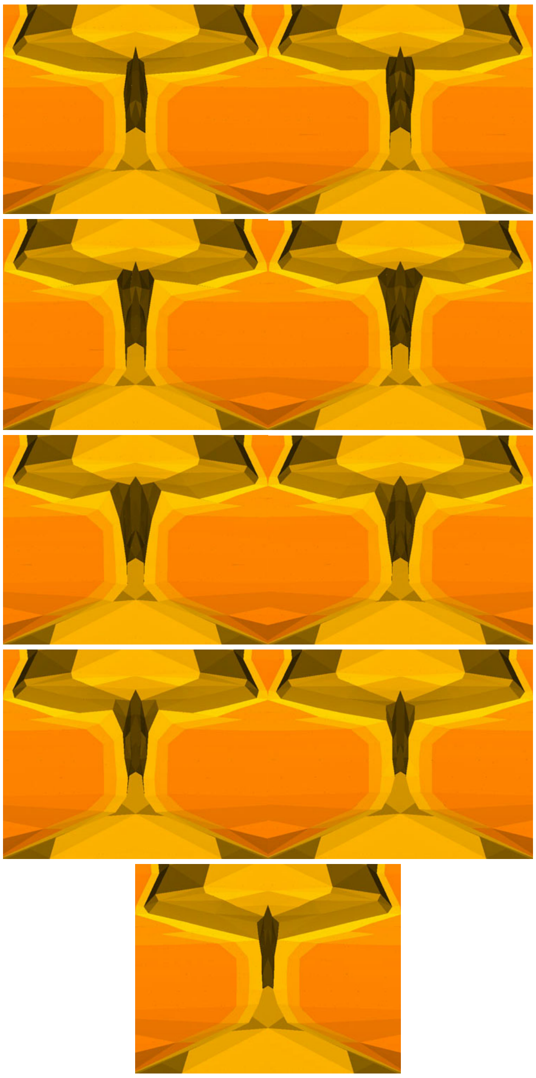

Figure 3: *Complete oscillation cycle of the larynx in transversal section - part 2.*

Figures 3 and 4 show a complete oscillation cycle of the larynx tissues during phonation. An analysis of the images shows that the larynx portion with the largest extension of movements is the superior portion of the cover tissue of the true vocal folds. Its movements are almost circular.

Observing the glottal surface, its is possible to see the formation of the material wave (commonly seen in laryngoscope exams): when the superior portion of the cover reaches its maximum opening, the medial portion of the cover produces a slight glottal closing, which is propagated in the following time steps to the superior region. This alternate movement is the one that originated the formulation of the two-mass model.

Note that the magnitude of the tissue movements that compose the ligament and the body are small or almost null. But these tissues (mainly the ligament) are the ones which gives support to the oscillatory movements of the laryngeal cover.

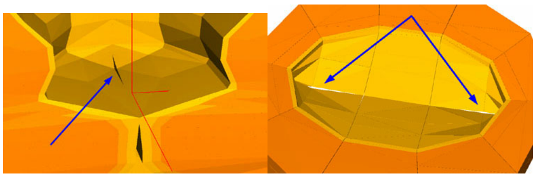

Figure 5: *Formation of laryngeal clefts*

The formation of the laryngeal cleft in the larynx is presented in Figure 5. Note that two clefts appear in the present model. This occurs because of the geometric description used here. In human beings, only one laryngeal cleft shows up, in the larynx anterior commissure; "posterior commissure" is the place where both arytenoids meet each other, approximating both true vocal folds during phonation. This formation allows that small quantities of air escapes during the glottal closing (depending on the geometric description and viscoelastic properties of the tissues, this quantity can be zero). [9] justifies that more realistic larynx models (from a perceptual viewpoint) are those that take into account this king of air escape, along with a smooth decaying of airflow volumetric velocity during the open-close glottal transition.

4. Conclusion

The three dimensional larynx model allows that qualitative and quantitative analyses can be performed in order to understand better the phonatory process. According to the results, the glottal signal frequency is dependent of the geometric and viscoelastic characteristics of the tissue, and the pressure drop between subglottal and supraglottal pressures.

The material wave observed in video-laryngoscope images is also reproduced, although its magnitude be lesser than the ones commonly seen in this kind of exam. Larynxes with more masses and elasticity will surely induce tissue movements with higher magnitude. The glottal signal frequency (164 Hz)

Another observed phenomenon barely discussed in works is the formation of the laryngeal cleft. According to [9], this kind of larynx characteristic can add perceptual naturalness to computer synthesized voices.

The natural next step of this work is direct: the study of larynx with some disease. In the future, simulations towards laryngeal pathologies would be performed, demonstrating the importance of this technique. Other studies like the effects produced by viscoelastic alterations of the larynx tissues are possible.

Acknowledgments

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5. References

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