An approach for numerical calculation of glottal flow during glottal closure

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Introduction

Accurate numerical simulation of voice signals have always been challenging problems in acoustics since voiced phonation is the result of a complex interaction of air flow, moving phonatory and articulatory organs, and therewith of various forces acting on the surface and inside the tissues.

To solve this problem, a couple of finite-element (FE) models have been presented in the last years [1, 2, 3, 4], which include a number of numerically difficult solver algorithms.

The here presented model represents a coupled two-dimensional model of VF movement including fluid-structure interaction (FSI) effects. As solvers ANSYS was chosen for the structure and CFX for the fluid. A special problem is handling the stop of the airflow in the closed phase of the glottal cycle. Since the fluid elements in the glottal gap channel would have to be zero-volume elements, a special modeling strategy is necessary. In this model a loss coefficient is introduced when the glottal gap falls below a certain control volume.

Methods

The fluid-structure interaction simulation model consists of two separate sub-models which exchange their results iteratively. The structural model, which represents the laryngeal tissues, is a FE model and the fluid model, which represents the airflow from the lungs, is a finite-volume (FV) model.

Since the modeled continua differ essentially in their physical behavior, both of the domains are idealized by unlike formulations. Structure is described by a *Lagrangian* approach, fluid by an *Eulerian* approach. The Lagrangian approach describes the displacement of the continuum while the Eulerian approach controls the particles which enter and exit a control volume.

The initial driving force of the coupled model is a constant intraglottal pressure difference between 800 Pa and 1200 Pa. This pressure drop leads to an air flow from sub- to supraglottal and excites self-sustained oscillation of the vocal folds. Oscillation of the vocal folds (structure) as well as pressure and velocity fields of the airflow (fluid) are analyzed as a function of the vocal fold shape/geometry used.

For calculation time reasons, the model is limited to a two-dimensional description of the vocal fold oscillation. However, the air flow simulation uses a volumetric approach. Hence, a 0.25 mm thick slice is modeled, which can be interpreted two-dimensional due to boundary conditions of symmetry.

Structure: Vocal fold tissues

The vocal fold tissues are supposed to be a structure which undergoes large displacements as well as large strain. The calculation of displacements and strains is done transient with simulation times of normally around 50 ms.

The structure of the vocal fold tissue is divided into a cover layer and a body layer. The chosen material parameters are listed in table 1. The structural model is shown in Figure 1.

	Body layer (orthotropic)	Cover layer (isotropic)
Poisson's ratio	$\nu_{xy} = 0.4$ $\nu_{yz} = 0.4$ $\nu_{xz} = 0.4$	$\nu = 0.4$
Young's modulus	$E_x = 7\ kPa$ $E_y = 20\ kPa$ $E_z = 20\ kPa$	$E = 5\ kPa$
Shear modulus	$G_{xy} = 5\ kPa$ $G_{yz} = 5\ kPa$ $G_{xz} = 5\ kPa$	
Density	$\rho = 1040\ kg/m^3$	$\rho = 1020\ kg/m^3$

Table 1: Material parameters of the structural FE model

On the one hand, during the coupled sequential solving process it has to be assured that the FVs of the fluid model are not distorted to an almost zero or negative volume. On the other hand, the collision forces of the vocal folds have to be considered. Therefore, the model includes two contact element pairs. On each vocal fold a contact area is implemented with a target area in the glottal gap. Both of the target areas form a parallel channel of 0.35 mm width between the vocal folds which is always open. To compensate for the missing complete closure, a variable loss coefficient K_l has been introduced.

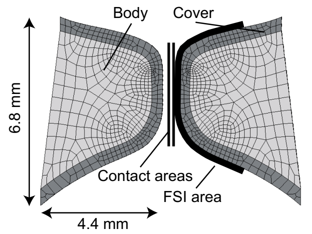

Figure 1: Structural FE model with two layers (body and cover), contact areas and fluid-structure interaction (FSI) areas.

Fluid

For the description of the fluid, the governing linearized equations [5] are:

$$V\left(\frac{\rho-\rho^{t^-}}{\Delta t}\right) + \sum_{ip}\dot{m}_{ip} = 0$$

(Continuity)

(1)

$$V\left(\frac{\rho\underline{v}_i-\rho^{t^-}\underline{v}_i^{t^-}}{\Delta t}\right) + \sum_{ip}\dot{m}_{ip}(\underline{v}_i)_{ip} = \sum_{ip}(p\underline{n}_i)_{ip} + \sum_{ip}\left(\mu\left(\frac{\partial \underline{v}_i}{\partial x_j}+\frac{\partial \underline{v}_j}{\partial x_i}\right)\underline{n}_i\right)_{ip} + \sum_{ip}(S_M V)_{ip}$$

(Momentum)

(2)

$$V\left(\frac{\rho h_{tot}-h_{tot}^{t^-}}{\Delta t}\right) - V\left(\frac{p-p^{t^-}}{\Delta t}\right) + \sum_{ip}\dot{m}_{ip}h_{tot,ip} = \sum_{ip}\left(\mu\left(\frac{\partial \underline{v}_i}{\partial x_j}+\frac{\partial \underline{v}_j}{\partial x_i}\right)\underline{v}_i\underline{n}_i\right)_{ip} + \sum_{ip}(S_M V\underline{v}_i)_{ip}$$

(Energy)

(3)

with discrete mass flow through a surface of the control volume

$$\dot{m}_{ip} = (\rho\ \underline{v}_i\ \underline{n}_i)_{ip}$$

and

- V = control volume
- ρ = density
- $^{t^-}$ = superscript indicating the previous time step
- Δt = time step size
- $\sum_{ip}$ = Summation over integration point
- $\underline{v}_i$ = velocity vector component
- p = pressure
- μ = dynamic viscosity
- S_M = momentum source
- h_{tot} = total enthalpy
- $\underline{n}_i$ = normal vector of volume surface i

The air is modeled as compressible fluid with density of 1.185 $\frac{kg}{m^3}$ and dynamic viscosity of $1.831\cdot10^{-5}$ $\frac{kg}{m\ s}$. While a constant relative pressure of 0 Pa was applied to the downstream end the relative pressure is 800 Pa at the upstream end. The interaction areas are movable walls which get their displacement information from the structural model (see Figure 2).

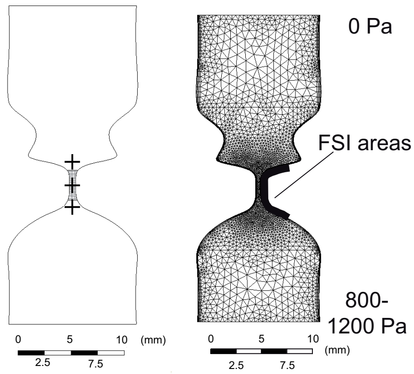

Figure 2: Fluid FV model. Left-hand side: Sketch of the fluid model. The striped zone is the zone where the loss coefficient K_l is introduced when a control distance is undercut. The crosses mark nodes where velocity and pressure is read off for the diagrams and are referred to as "top", "middle", and "bottom". Right-hand side: FV net with FSI areas and pressure boundary conditions.

The effects related to the glottis closure are modeled indirectly in two ways: First, The contact elements are introduced to the structure. Second, the volume elements of the fluid must not be distorted to an near-to zero or negative volume. To prevent this, an artificial momentum source (as in equation 2 and 3) is introduced. Therefore a loss coefficient K_l is set up, when the vocal folds come closer to each other than a minimum lateral distance of 0.35 mm. The momentum source then is calculated as follows:

$$S_{M,i} = -\frac{1}{2}K_l\ \rho\ |v|\ v_i \quad (4)$$

with $|v|$ being the norm of the velocity vector. The loss coefficient is defined in dependence on the lateral distance d_{vf} between the vocal folds:

$$K_l = \begin{cases} 0 & \text{for } d_{vf} \geq 0.35\ mm \\ 1.0\cdot10^8\frac{kg}{m^{-4}} & \text{for } d_{vf} < 0.35\ mm \end{cases}$$

Coupling of the domains

The Lagrangian and the Euler formulation is adapted to a so called Arbitrary Lagrangian Eulerian (ALE) formulation by including both, the deformed fluid mesh and the velocities of the interacting walls [5].

Results

Eigenmodes and eigenfrequencies of the structure

The model underwent a modal analysis to calculate the eigenfrequencies and the eigenmodes. Each of them

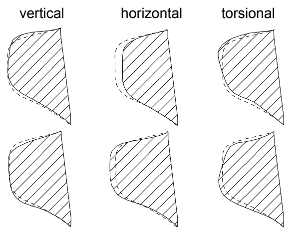

Figure 3: First three eigenforms of the structural model. The dashed line marks the original shape of the model while the lined shape shows the two extrema (minimum/maximum) of the eigenform.

showed the first eigenmode in vertical direction and the second in horizontal direction. The third eigenmode turned out to be a rotational one. The eigenfrequencies are 114 Hz (vertical), 189 Hz (horizontal), and 247 Hz (rotational) and are shown in Figure 3.

Oscillation forms and frequencies of the structure

Figure 4 depicts one oscillation cycle segmented into ten frames for each vocal fold configuration. To display the differences in oscillation, two nodes were chosen in the structural model whose displacements are displayed over time in the diagrams shown in Figure 5. For the node in the upper part of the vocal fold vertical and horizontal displacement is plotted, for the node in the lower part horizontal displacement is plotted. In doing so, the fractions of the three eigenmodes can be seen.

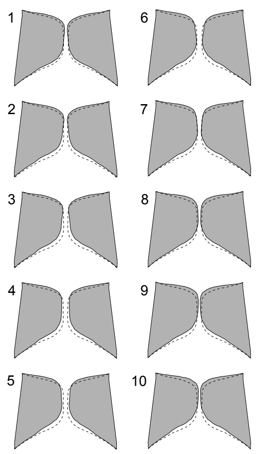

Figure 4: One complete oscillation cycle of 5 ms of the structure divided in ten frames.

With the maximum driving pressure of 800 Pa a stable oscillation could be observed. Two cycles after the onset of oscillation, the horizontal oscillation kept its amplitude while the vertical amplitude still decreased. All of the three first eigenmodes could be recognized. Especially the horizontal and the rotational eigenmode occurred at the same time such that the changing convergent/divergent shape, which is often described in literature, can be observed. Nevertheless, no eigenmode can be considered clearly predominant. The vertical eigenmode superposes both of the other forms but with half the frequency of them. For the whole simulation time

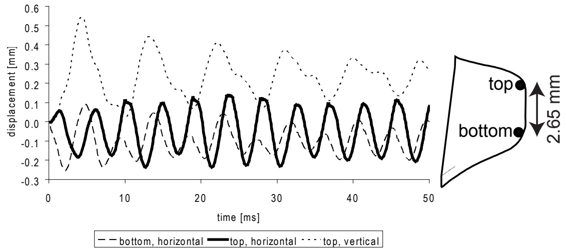

Figure 5: Vertical and horizontal displacements of two nodes and their position.

the oscillation was symmetric in terms of almost the same absolute value of the displacements at the same time step. The maximum absolute displacement was 0.56 mm.

To compare the (self-sustained) oscillation frequencies (OF) with the eigenfrequencies (EF) the absolute displacements over time of the node "top" (Figure 5) was Fast-Fourrier transformed. The obtained frequencies fitted well to the eigenfrequencies. The first OF was 112 Hz (1st EF: 114 Hz), the second OF was 224 Hz (2nd EF: 189 Hz), and the third OF was 337 Hz (3rd EF: 247 Hz).

Air velocity field

The pressure drop leads to a flow from sub- to supraglottal. After the constriction built by the vocal folds a jet is formed, which is modulated by the vocal fold movements. This jet is deflected to one side of the supraglottal channel, commonly referred to as "Coanda effect". The velocities of each simulation are exemplary sampled over time at three nodes in the middle between the vocal folds. These nodes are referred to as "top", "middle", and "bottom" in the following sections. The node positions are illustrated in Figure 2. Figure 6 shows the air velocity over time. The air is accelerated from sub- to supraglottal. The maximum velocity is obtained in the middle of the channel and releases further on supraglottal.

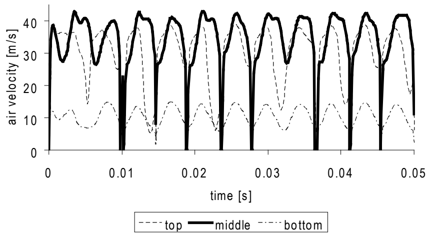

Figure 6: Air velocity over time at three nodes according to Fig. 2.

Air pressure field

Pressure distribution is crucial for the laryngeal fluid-structure interaction. The driving force that opens the glottal gap is subglottal overpressure. For closing the glottal gap, two possibilities exist: The elastic restoring forces of the structure or Bernoulli like effects such as negative pressures in regions of high velocities, which occur between the vocal folds. Combination of both of the forces is also possible.

The air velocities were high in the channel between the vocal folds. This behavior caused pressure to be low at any time. It could be observed that shortly before the vocal folds form a converging channel, pressure was lowest at the top end of the vocal folds. Afterwards, the zone of lowest pressure moved downward and caused the formation of a diverging channel. Generally pressure slightly preceded the motion of the vocal folds so that structure was pulled (and pushed, respectively) by negative (and positive) pressures which occurred a short time before at the interaction boundary.

Conclusion

A coupled FE/FV model of self-sustained vocal fold oscillation was presented. The driving pressure differences for the self-sustained oscillation were set up in a natural range. Other material properties were obtained from literature.

The form of the oscillating vocal folds could be interpreted as combination of the first three eigenmodes. The second (horizontal) eigenmode eigenmode is of major importance since it is directly affects air jet modulation. The periodically changing convergent and divergent intraglottal shape, that has been reported before, is a combination of eigenmode two and three. To obtain a considerable excitement of these eigenmodes a pulling force (negative pressure) is required which varies its vertical position over time. This force turns out to be dependent of a certain channel length.

The supraglottal fluid mesh may not be fine enough to allow detailed insight into all of the fluid effects. Future developments should include small and fast vortices which are supposed to be of great importance for the acoustical pressure and noise generation.

Acknowledgments

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