NUMERICAL SIMULATION OF THE GLOTTAL FLOW AND GLOTTAL EXCITATION

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ABSTRACT

Up to now, little is known about the glottal flow while phonated speech is produced. We derive a model of the glottal flow which includes nonlinear flow, the dynamic generation of sound waves by the vibrating vocal cords and the interaction of those two phenomena. Results of a numerical simulation based on this model and the compressible Navier-Stokes equations are given and compared with theoretical values.

1. INTRODUCTION

Up to now, most models for speech production represent the vocal tract by a linear filter with the glottal excitation as source. Nonlinear phenomena like energy dissipation and noise creation by vortices are not taken into account. A crucial point of speech production is the sound generation at the glottis. So far only very crude glottal models are used showing great deviations from reality, as these models do not include nonlinear time-dependent flow and its interaction with the glottal excitation [1]. For investigating the behaviour of the elastic vocal folds, Ishizaka and Flanagan introduced a basic mass-spring model [2], whose driving force is the estimated pressure of the flow. Another approach is, to get insight into the nonlinear flow connected with speech generation. Since measurements of the flow are difficult and have to be based upon simplified mechanical models [3], numerical simulation is needed. As a first effort, T. Thomas simulated the flow in a two-dimensional model of the supraglottal vocal tract with a coarse grid and steady equations [4]. Recently, Iijima et al. computed the two-dimensional flow at the glottis in different but time-invariant stages of glottal opening [5]. They have shown that complicated vortical flow develops causing pressure variations which may acoustically affect the glottal flow. As sound waves result from the compressibility of air, phonation can not be represented by their incompressible approach. Connecting both approaches, our model of the glottal flow and glottal excitation for the first time includes the dynamic generation of sound waves and their interaction with two-dimensional vortical flow. It is based on the Navier-Stokes equations for compressible viscous gases in a domain with moving boundaries. Due to the high computational effort, we presently restrict our simulation to two space dimensions.

2. A MODEL OF THE GLOTTAL FLOW

The glottal excitation is generated by the unstationary flow of moist air bounded by the moving vocal cords.

This flow is governed by the compressible Navier-Stokes-equations, which are based on the *balance of mass*

$$\frac{\partial\rho}{\partial t} + \nabla\cdot(\rho\mathbf{V}) = 0, \qquad (1)$$

and the *balance of momentum* [6]:

$$\frac{\partial}{\partial t}(\rho\mathbf{V}) + \nabla\cdot(\rho\mathbf{VV} + p\mathbf{I} - \boldsymbol{\tau}) = 0. \qquad (2)$$

(t: time, ∇: gradient in space, ρ: density, V: velocity vector, p: pressure, τ: viscous tensor for air [6], I: unit matrix; bold letters: vector-valued functions). The equations describe that no mass can be lost (1) and how mass flow, density fluctuations, pressure and viscosity interact (2). An adiabatic relation between pressure and density is used:

$$p / \rho^{\gamma} = const. \qquad (3)$$

Although the flow at the glottis is slow compared to the velocity of sound, we cannot neglect compressibility (by assuming constant pressure in (1)), since the generation of sound waves is basically connected with density fluctuations.

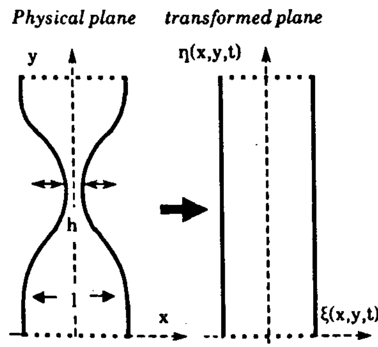

Fig. 1: *Time-dependent transform*

The geometry of the simulation is a simplified model of the glottal region. To treat the moving boundaries, we use a time-dependent coordinate transform from the physical domain to a rectangular geometry (see [7]). The transform should not distort the grid too much, otherwise the transformed equations and the numerical method get unstable. Thus a simplified geometry neglecting the false vocal folds (fig. 1) is presently used. Our computational domain contains *solid wall boundaries* (fat lines in Fig. 1, here the air moves with the walls of the vocal tract) and *artificial boundaries* (dotted lines in fig. 1), where absorbing boundary conditions are used. Table 1 gives the values of constants used in our computation.

The glottal excitation is induced by the pressure of the flow. A model comparable to Ishizaka's model with one mass and one spring characterizing the movement of the elastic vocal cords [2] can simulate this effect. It leads to a differential equation based on the balance of inertia, friction, the nonlinear elasticity of the vocal cords and the pressure of the flow. Presently, a sinusoidal movement of the vocal cords is imposed from outside, the model for flow-induced excitation is being developed.

Table 1: Values of some constants used in the computation

initial density of air	ρ = 0.15 kg/m³
dyn. viscosity of air:	μ = 0.19 10⁻⁴ kg/(m sec)
ratio of specific heat capacities :	γ = 1.4
volume flow:	V_{Vel} = 50 to 500 cm³/sec.
lenght of the constrictions:	l = 1,2 cm
depht of the glottis:	l_d = 1.2 cm
glottal opening:	h = 4.0 to 6.7 mm (realistic: 0 to 3 mm)

3. NUMERICAL SOLUTION

The compressible Navier-Stokes equations are very delicate numerically. We have adapted the ASWR (Asymetric Separated Weighted Residuals) -method for solving the transformed equations gained from (1), (2) [8]. Although we use an efficient implicit method for time-integration, the computational expense is immense, in the current implementation a Tera-FLOP-computer would be necessary for a realtime calculation. The results have been verified by simplified fluid dynamic considerations and by comparing the calculated pressure loss for a steady geometry with an approximative theoretical value [2].

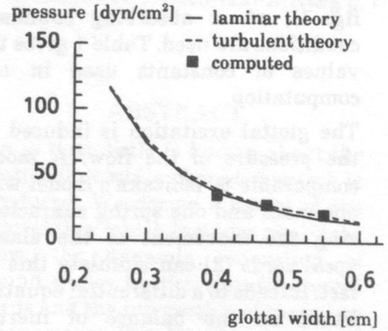

Fig. 2: *Translaryngeal pressure loss in the glottis compared to the approximate theoretical value [3].*

4. RESULTS

By the vibrating glottal model, the generation of sound waves can be modeled. The constriction moves with a frequency of 100 Hz from a slightly to a maximally constricted tube. The pressure in space and time and the velocity have been watched during several oscillation periods. Results are shown in Figures 3 to 5. After the initial value of zero flow, the flow increases, causing the initial pressure rise in fig. 3. The pressure in time shows a steeper rise and a softer decline than the sine, which governs the movement of the constriction. This is an effect of the finite speed of sound, it agrees with experimental results also using a sinusoidal excitation [4]. The deformation of a sound wave by the flow pressure can be watched in fig. 4. In fig. 5, the vortical flow caused by the moving constriction is depicted. The strongest nonlinear effects develop while the glottis opens (right).

5. CONCLUSIONS

This simulation is only the first step towards a nonlinear dynamic glottal model, but it already includes substantial effects. A fully nonlinear dynamic vocal tract model is beyond the reach of today's computers, but by coupling a usual linear model of the vocal tract with the nonlinear model at the glottis, simulation of the generation of voiced speech including nonlinear effects can be accomplished.

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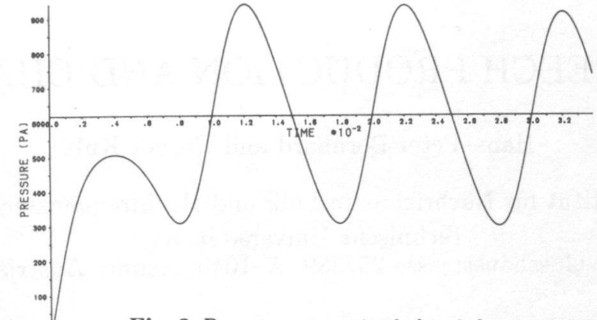

Fig. 3: *Pressure at a point behind the glottis during time.*

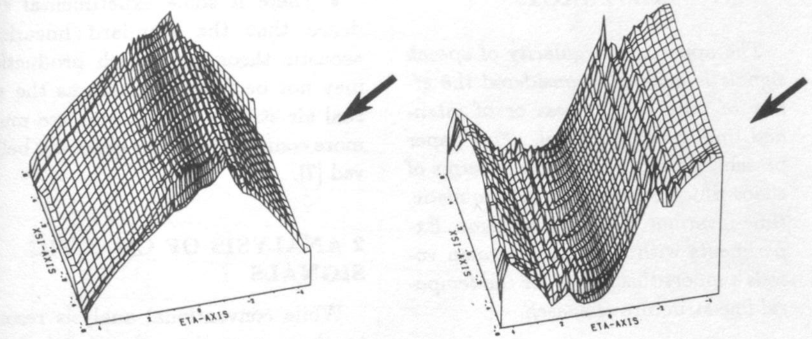

Fig. 4: *Spatial pressure distribution in the transformed plane at the slightly constricted (left) and the the fully constricted area (right). Arrow: direction of the flow). Maximal pressure difference: 289 dyn/ cm²(left) to 330 dyn/ cm²(right)*

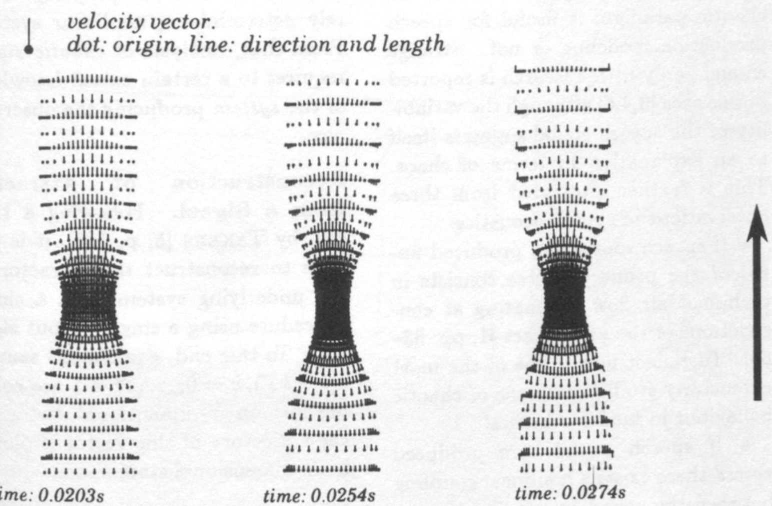

Fig. 5: *Velocity vectors in a central section of the geometry drawn in the physical plane. Max. velocity: 5.7 m/sec. (Scaled to 3.5m/sec)*