A Numerical Experiment of Unsteady Glottal Flow
Based on Two-dimensional Rigid Model

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Abstract
Voice is one of the most fundamental and important tools for human communications. The purpose of this study is to analyse physical phenomena, in particular turbulent flows as nonlinear dynamics, of speech production process. As the first step in our study, this paper shows numerical simulations of an unsteady glottal flow that is assumed to be a compressible viscous fluid, based on a two-dimensional rigid body model. The obtained glottal flow had several vortices and was a complicated pattern which was changed with time, i.e., the flow was turbulence. Moreover, pressure in the turbulent glottal flow began to oscillate with time, and the oscillating amplitude of the pressure was larger as increasing the lungs pressure.

1. Introduction
Understanding of mechanisms in the phonation is important, since that may become a breakthrough in improvement of qualities of synthesized voices, and is also expected to contribute to developments of medical examination techniques against voice disorders.

Some equivalent electric circuit models have been proposed for vocal cords vibrations and flow dynamics [1], [2]. Their models were simple structures and principal mechanisms of the phonation could be understood using them. However, they could not describe complicated and nonlinear phenomena in a high Reynolds number flow. In general, the glottal flow has a jet-like structure near the glottis and it is known that the flow is generated with turbulence. However, little is known about such nonlinear dynamics in the speech production process.

The purpose of this study is to analyse effects of vortices caused by a fluid viscosity and a nonlinear dynamics of motion on the speech production process. As the first step of our study, this paper describes numerical simulations of an unsteady glottal flow that is assumed to be a compressible viscous fluid, based on a two-dimensional rigid body model. Moreover, we consider an effect of lungs pressure on the turbulent glottal flow.

2. Model and numerical scheme
2.1. Rigid glottal model
We consider now the glottis model as a rigid body and numerically analyse an unsteady glottal flow in the model. The rigid glottal model appears in Fig. 1. It is assumed that a lungs pressure can be approximated by an air reservoir at the boundary \( \Gamma_1 \) where a pressure is set to \( P^* \).

Figure 1: Rigid glottal model.
meters or less, and a jet like flow with a comparable velocity to the sound velocity has been observed [5]. In addition, since a voice is a sound wave; i.e., elastic wave in a fluid, compressibility will be important in the phenomena from the stand points of physics. Therefore, in this paper, we assume the glottal flow to be compressible viscous fluid which is described as nonlinear partial differential equations [6].

2.2. Initial and boundary condition
We suppose that the air in the larynx is uniform and at rest for \( t < 0 \), where \( t = c_0 t^*/D \) is dimensionless time in terms of actual time \( t^* \), the sound velocity \( c_0 \), and a characteristic length \( D = D_0 \). Initial conditions are readily given in all the space of the larynx and the vocal tract

\[
|\mathbf{u}| = 0, \quad \rho = 1, \quad P = 1/\gamma \quad (t = 0),
\]

where, dimensionless variables are introduced: \( \mathbf{u} = \mathbf{u}^*/c_0, \rho = \rho^*/\rho_0, \ P = P^*/(\rho_0 c_0^2), \) and \( \gamma \) is the specific heat ratio. The subscript 0 in the variables designates a given in all the space of the larynx and the vocal tract

\[
P_L(t) = \left\{ \begin{array}{ll}
P_{L0}/2 & (0 < t \leq t_1), \\
P_{L0} & (t > t_1),
\end{array} \right.
\]

where, \( P_{L0} \) and \( t_1 \) are a steady value of \( p_L(t) \) and a rise time while \( p_L(t) \) attains \( P_{L0} \) from zero.

2.3. Numerical scheme
Solving nonlinear hydrodynamic equations analytically subject to initial and boundary conditions is extremely involved. Instead, we employ a numerical computation method, the MacCormack finite-difference scheme that has a fourth-order accuracy in space and a second-order accuracy in time [7].

3. Results and discussion
3.1. Analysis condition
We examined a time sequence of glottal flow distribution in the two-dimensional rigid model and effects of the lungs pressure in the flow. Table 1 indicates the larynx size parameters. These parameters are based on the data measured by Schere et al. [8].

In reality, voice production involves the excitation of many acoustic modes within the vocal tract, i.e., for-

Table 1: Size parameters of the glottis (unit in mm).

<table>
<thead>
<tr>
<th>( L_{fivc} )</th>
<th>( D_a )</th>
<th>( D_g )</th>
<th>( D_s )</th>
<th>( D_f )</th>
<th>( D_t )</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.8</td>
<td>16.4</td>
<td>1.0</td>
<td>10.3</td>
<td>5.1</td>
<td>19.0</td>
</tr>
</tbody>
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![Figure 2: Glottal flow distributions. (a) Pressure and (b) flow velocity distributions on the x axis. (c) Vorticity and flow vector distributions in the larynx. In Fig. (c), line segments present the glottal flow vectors and the contours denote the z component of vorticity. \( P_{L0} = 800 \) Pa, \( t^* = 10 \) ms.](image)

ments. We assumed that the vocal tract configuration approximated by a uniform duct in order to highlight acoustic phenomena within the larynx. Effects of such acoustic loading were ignored here.

The integration region was divided into 380 grids, which was refined near the vocal cords, in the x direction and 60 regular grids in the y direction. Here, the minimum grid sizes became \( \Delta x^* \approx 0.07 \) mm and \( \Delta y^* \approx 0.02 \) mm. In this experiment, the rise time was set to a constant value of \( t_1 = 10 \) ms.

3.2. Flow pattern in glottis
The flow patterns in the glottis at \( t^* = 10 \) ms appear in Fig. 2. The lungs pressure is set to \( P_{L0} = 800 \) Pa. One-dimensional pressure and velocity distributions on the x axis are shown in Figs. (a) and (b), respectively. In figures, \( x = x^*/D \) and \( y = y^*/D \) are both dimensionless spatial variables. \( p = P - 1/\gamma \) indicates a dimensionless pressure difference between the total pressure and the atmospheric that, and \( u \) and \( v \) are the \( x \) and \( y \) components of the velocity vector \( \mathbf{u} \), respectively. Each values are normalized by \( M_a = P_{L0}/(\rho_0 c_0^2) \). In Figs. 2 (a) and (b), maximum values of the pressure and the velocity were
800 Pa and 33 m/s, respectively. A sudden pressure drop occurred at the glottal entrance, $x \simeq -0.2$, due to a flow acceleration in Fig. (a). In the velocity distributions Fig. (b), a main flow on the $x$ direction occurred for $x$ between 0 and 2.5.

The two-dimensional glottal flow distribution is shown in Fig. (c). Line segments present glottal flow vectors and contour denotes a $z$ component of vorticity, $\omega = \nabla \times \mathbf{u}$, which measures an angular velocity of a fluid particle. In Fig. (c), the flow was almost symmetric about the $x$ axis, and the flow had two vortices at $x \simeq 2.5$. That location was consistent with a location at which the main flow $u$ decreased in Fig. (b). Moreover, the vector distribution indicated that the jet-like flow was concentrated on the $x$ axis excluding the flow front with vortices.

Time sequences of the two-dimensional glottal flow are shown in Fig. 3. The lungs pressure $P_{L0}^*$ is set to 80 Pa in Fig. (a) and 800 Pa in Fig. (b). When $P_{L0}^* = 80$ Pa, the flow structure was a jet-like pattern, which had two vortices and was a symmetric pattern about the $x$ axis, for $t^* = 0 \sim 30$ ms. On the other hand, when $P_{L0}^* = 800$ Pa, although the flow was a symmetric jet for $t^* \leq 10$ ms, a vortex structure became asymmetric at $t^* \simeq 15$ ms. These vortex patterns changed as time passes and the vortex grew in size, in finally, the size of vortex was comparable with the width of the vocal tract. In addition, large vortices were generated within $0 < x < 2$, i.e., downstream of the glottis. Although, the results at $P_{L0}^* = 80$ Pa showed symmetric and simple jet patterns for $t^* \leq 30$ ms, the jet for $t^* > 50$ ms translated into an asymmetric flow similar to that at 800 Pa. The numerical experiment in a lungs pressure range of 8 to 2000 Pa showed that transitions occurred for $P_{L0}^* \geq 20$ Pa, and the translation to a complicated flow took about 90 ms at $P_{L0}^* = 20$ Pa.

The result clearly showed that the initial flow was a simple jet, after that, the flow pattern changed with time and translated into a complicated flow, i.e., the glottal flow was turbulence.

3.3. Pressure waveform

Pressure waveforms at $P_{L0}^* = 80$ and 800 Pa at $x = 2$ and $y = 0$ are shown in Figs. 4 (a) and (b), respectively. Both results tended to increase by $t^* = 10$ ms, and to decrease after that. In addition, high frequency fluctuations occurred in the pressure after $t^* \simeq 40$ and 10 ms in conditions $P_{L0}^* = 80$ and 800 Pa, respectively. Transition times at which the pressure began to fluctuate were almost consistent with the times translated from a simple jet into turbulence in Fig. 3. Therefore, the transition to the turbulence causes the pressure fluctuation.

Relation between a normalized RMS (root mean squared) value of the pressure $P_{RMS}/M_a$ and the lungs pressure $P_{L0}^*$ was examined for an effect of the lungs pressure on the fluctuations in the flow. The results are shown in Fig. 5. Open and closed circles are measured data, and a dashed line indicates a fitting curve for the
data at $x = 2$ for $P_{L0}^* > 100$ Pa. Here, RMS values are obtained by data for $t^* = 60 \sim 100$ ms. Overall, the result showed that the RMS value increased with the lungs pressure except for $x > 3$ and $P_{L0}^* < 100$ Pa. Since the transition time was relatively larger for $P_{L0}^* < 100$ Pa, a transient response of the transition to the turbulence would affected a calculation of the RMS value. Given that the RMS value of the flow pressure indicated a turbulent intensity in the flow, increasing the lungs pressure caused more intense turbulent glottal flow.

In addition, the data could be classified into two categories, $x \leq 2$ and $x \geq 3$, according to levels of the RMS value. One interpretation of this fact was that a sound source caused by a vortex was generated in the area for $0 < x < 2$. There was considerable validity in that suggestion, because the large vortices have been obtained within $x < 2$ in Fig. 3.

It was found from the result in the high frequency pressure oscillation that the glottal flow translated into the turbulence as time passes. This fact is same that obtained from the result in the flow patterns in the glottis.

4. Conclusions

We numerically examined the glottal flow based on the two-dimensional rigid vocal cords model. The nonlinear hydrodynamics equations in the compressible viscous fluid were integrated using the MacCormack finite-difference scheme. The following results were obtained: (1) the initial flow was a simple jet with two vortices and a symmetric pattern about the $x$ axis; (2) after that, the flow pattern changed with time and translated into the complicated flow, i.e., the glottal flow became turbulence; (3) the pressure in the turbulent glottal flow began to oscillate with time, and the oscillating amplitude was promoted as increasing the lungs pressure. In summary, the glottal flow in the two-dimensional rigid model is the turbulent flow with vortices rather than the laminar that, and the lungs pressure affects the intensity of turbulence.

5. References


