Fluctuations in pressure wave within the larynx

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1. Introduction

Recently, with the improvements in computing power, numerical simulation has become an efficient tool for clarifying complex phenomena in speech production [1].

In a previous study [2], we numerically simulated glottal flows based on a rigid-wall model of the larynx, and showed unsteady glottal flows. In order to consider the effects of unsteady glottal flow motion in speech production, we proposed a glottal source model, which is constructed from a two-dimensional unsteady flow model and a distributed parameter model for the vocal folds [3]. Simulations of speech production using the proposed model revealed fluctuated pressure waves caused by vortices within the larynx. However, little is known about the fluctuations within the larynx.

The purpose of the present study is to investigate the fluctuations within the larynx by numerical experiments. In order to quantitatively evaluate the fluctuations, we estimate three types of fluctuation measures in speech waves, i.e., the coefficient of variation (CV) of fundamental frequency, the CV of amplitude, and the harmonic-to-noise ratio (HNR) [4].

2. Model and computational method

A two-dimensional larynx model in the coronal (z - x) plane is shown in Fig. 1(a). We assume that the configuration is uniform in the y direction, and that the initial configuration is symmetric about the glottal midline (z -axis). The vocal tract attached to the larynx is approximated by a uniform rigid duct. The detailed description of the larynx shape has been presented in the previous papers [2,3].

2.1. Mechanical vocal folds model

A vocal fold can be divided into two tissue layers with different mechanical properties: a cover layer and a body layer. The cover layer is assumed to be an elastic cover with the effective mass of the vocal fold. In order to take the mechanical properties of the vocal fold into account, the elastic cover is supported by an array of small mechanical elements having nonlinear springs and dampers [5].

Figure 1(b) shows the proposed vocal folds model. In Fig. 1(b), there are only three mechanical elements on each side; in the present simulation, however, a greater number of elements, about 100 elements, are located on each surface of the vocal fold.

In the present study, in order to simplify the analysis, we restrict vocal fold vibrations to the lateral direction x . The vibration of vocal fold is governed by the equation of motion consisting of the fluid force, i.e., the pressure and the viscous stress of the flow, the restoring force of the spring, the viscous drag force of the damper, and the shear force of the elastic cover [3].

2.2. Glottal flow model

The glottal flow is assumed to be an unsteady two-dimensional compressible viscous fluid. The fluid motion is analysed on the basis of boundary fitted coordinates along the surface of the larynx. In order to consider a moving boundary problem arising as a result of the shape change of the vocal folds, we employ a finite difference method based on the arbitrary Lagrangian-Eulerian method [6].

2.3. Numerical simulation of speech production

Speech production is simulated on the basis of a moving boundary problem by alternately solving the flow equations and the motion equations of vocal fold vibrations.

A differential grid system moving with the wall boundary is employed to discretize the fluid domain. In order to determine an instantaneous larynx shape, vibrations of the mechanical elements of the vocal fold are computed by the fourth-order Runge-Kutta method. On the basis of the instantaneous vocal fold displacement, we update the boundary shape of the larynx and the differential grids in the fluid domain at every time step. The details of the computational method have been presented in the previous paper [3].

2.4. Simulation conditions

For the initial conditions, assume that the air in the entire fluid space is uniform and at rest, and the vocal folds have neither strain nor tension. The physical parameters of left and right vocal folds are symmetric about the z axis.

Lung pressure P_{L0} is applied to the inflow boundary Γ_1 in Fig. 1(a). A non-reflecting characteristic boundary condition [7] is imposed at the outflow boundary Γ_2 in order to minimize acoustic reflection. The obtained displacements and velocities of the vocal folds are applied to boundaries Γ_3 and Γ_4 .

3. Numerical experiments

3.1. Pressure wave within the larynx

Figure 2 shows examples of pressure waves p at different distances z from the glottis at $P_{L0} = 800$ Pa, which corresponds to the value for an ordinary conversation level.

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Fig. 1 Analytical models of speech production.

Fig. 2 Pressure wave at $P_{L0} = 800$ Pa.

The time (phase) delay between the pressure waves at 0 and 20 mm is observed, although no time delay is observed between the pressure waves at 20 and 160 mm. This is because supraglottal ($z > 0$ mm) and subglottal ($z < 0$ mm) pressure waves are almost out of phase [3,5], and the phase of the pressure at 0 mm is in the range of both phases.

The normalized average values (DC components) of pressure at 0, 20, and 160 mm are about 0.2, -0.4 and 0, respectively. The positive average pressure at 0 mm is caused by the applied lung pressure P_{L0} , and the zero average

Fig. 3 Segmentation into pitch periods by detecting zero crossing of fundamental wave.

pressure at 160 mm is caused by the static pressure of the atmosphere. The negative average pressure at 20 mm is the result of the pressure drop caused by the flow from the glottis. However, the pressure drop is restricted near the downstream of the glottis.

Pressure waves indicate fluctuations, that is, fundamental frequency (pitch frequency, f_0) fluctuation, amplitude (peak-to-peak, P_{p-p}) fluctuation, and waveform fluctuation, that imply a slight waveform change from pitch period to pitch period [8]. These fluctuations are caused by the passage of vortices [2].

3.2. Estimation of fluctuation

In the present study, we estimate three types of fluctuation measures, i.e., the CV of f_0 , the CV of P_{p-p} , and the HNR, as the fundamental frequency, amplitude and waveform fluctuations, respectively.

The CV is the ratio of the standard deviation of sequence σ to the average value of sequence m , that is, $CV = \sigma/m$. f_0 and P_{p-p} sequences are extracted at each pitch period from a pressure wave as follows (see Fig. 3).

- (1) Extract the fundamental wave from the pressure wave by fundamental wave filtering [9].
- (2) Segment by detecting the zero crossing of the fundamental wave.

Fig. 4 Distributions of fluctuation measures along the z axis at $P_{L0} = 800$ Pa.

- (3) Extract f_0 (reciprocal number of segment duration T) and P_{p-p} from individual segments.

The HNR is a measure of the cycle-to-cycle similarity of a waveform, and is sensitive to waveform aperiodicity [4]. The HNR is defined as the ratio between the energy of the periodic (harmonic) component H to the energy of the aperiodic (noise) component N in a wave, that is, $HNR = H/N$. The energy of the periodic component is consistent with the energy of the average wave that is determined by taking the average of a succession of period sequences. The energy of the aperiodic component is the mean energy of the difference between individual periods and the average wave [4,10].

Figure 4 shows the distributions of fluctuation measures, CV of f_0 , CV of P_{p-p} , and HNR, along the z axis at a lung pressure of 800 Pa. At $z = 20$ mm, the CVs of f_0 and P_{p-p} are the greatest, and the HNR is the smallest, although significant fluctuations are not observed for other locations.

Figure 5 shows the relationship between the fluctuation measures and lung pressure at different distances from the glottis. Solid, dotted, and dashed lines denote the fitted curves obtained using a linear function of the lung pressure. With increasing the lung pressure, the CVs of f_0 and P_{p-p} increase, and HNR decreases. For all fluctuation measures, the magnitude relation between the fluctuation levels at 0, 20, and 160 mm shows no change with lung pressure in the range of 400 to 2,000 Pa.

These results suggest that the effect of unsteady glottal flow, i.e., the fluctuations, is observed only in a limited area downstream of the glottis for nonpathological speech organs with symmetric physical parameters.

4. Conclusion

In the present study, we estimated fluctuations in the

Fig. 5 Relationship between fluctuation measures and lung pressure.

pressure wave within the larynx using numerical simulations based on our proposed glottal source model in order to investigate the effects of unsteady glottal flow motion on phonation. With increasing lung pressure, marked fluctuations were observed within the larynx. The fluctuation measures indicated higher fluctuations downstream of the glottis, although marked fluctuations are not observed for other locations. The results suggest that the fluctuations in pressure waves within the larynx as a result of unsteady glottal flow is observed only in a limited area downstream of the glottis for nonpathological speech organs with symmetric physical parameters.

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