

EFFECTS OF SHAPES OF RADIATIONAL APERTURE ON RADIATION CHARACTERISTICS

Hiroki MATSUZAKI, Kunitoshi MOTOKI* and Nobuhiro MIKI***

*Faculty of Engineering, Hokkai-Gakuen University

**Faculty of Engineering, Hokkaido University

E-mail: *matsu@eli.hokkai-s-u.ac.jp*

ABSTRACT

The acoustic characteristics of acoustic tubes with protrusions at the radiation end are computed by FEM simulation. In the first experiment, two different shapes of the protrusions, a symmetrical and an asymmetrical shape with respect to the vertical, are investigated. Frequency characteristics of the radiation impedance are computed from simulation results. The simulation results show that the results of FEM simulation are in good agreement with our measurement results. The proposed 3-D radiational model is useful for analysis of the acoustic characteristics of human speech. In the 2nd experiment, the protrusion is attached to our 3-D vocal tract model. The vocal tract shape corresponds to the Japanese vowel /a/. The cross sections of the tubes are elliptic in shape. The simulation results show that the vocal tract transfer function of the FEM results is different from our previous FEM results and 1-D analytical solution.

1. INTRODUCTION

The boundary condition at the lips of a vocal tract model is an important factor for determining the characteristics of resonances of the vocal tract. In the traditional model of radiation, studies of 3-D effects of radiation have been superficial for the radiation impedance at the lips, since a plane wave is assumed at the lips. Moreover, when the shape of the radiational aperture is elliptic, little can be known about the characteristics of the radiation impedance and the shape of a wave front after radiation.

We have already measured the sound radiation using acrylic resin tubes with protrusions shaped like the lips[1, 2]. This experiment revealed that the characteristics of the radiation impedance are quite sensitive with respect to small changes in the location at which the radiation impedance is measured.

In this paper, the acoustic characteristics for sound tubes with a 3-D radiational model including protrusions at the radiation end are computed by FEM simulation. The protrusions are set into our 3-D radiational model[3].

In the 1st experiment, two different shapes of the protrusions are investigated. The first one is symmetrical with respect to the vertical, which is the same as our previous experiment model[1, 2]. The second one is similar to the lips, and has asymmetrical shape with respect to the vertical. The cross sections of the tubes are elliptic in shape. Frequency characteristics of the radiation impedance are

computed from simulation results. The computation shows that the results of FEM simulation are in good agreement with our measurement results. The proposed 3-D radiational model is useful for analysis of the acoustic characteristics of human speech.

In the 2nd experiment, the acoustic characteristics in a 3-D vocal tract with the protrusions are simulated by the FEM. The tube is constructed from magnetic resonance imaging data of vocal tract shapes for the Japanese vowel /a/[4]. The cross sections of the tubes are elliptic in shape. Based on the FEM simulation results, the vocal tract transfer functions (VTTFs) are computed and compared with our previous FEM results[5, 6] and 1-D analytical solution[7]. For more detailed explanation of acoustic characteristics, the sound pressure distributions in the proposed 3-D model are shown as well. As to the results of VTTFs, the formant frequencies of the FEM results move to lower frequencies, compared with our previous FEM results[5, 6] and 1-D analytical solution[7].

2. FORMULATION OF THE WAVE EQUATION

It is well known that the acoustic wave equation in steady state is represented using velocity potential ϕ as

$$\nabla^2 \phi = k^2 \phi \quad (1)$$

where $k(\omega(\text{angular frequency})/c(\text{sound velocity}))$ is the wave length constant. Sound pressure p and particle velocity v are represented as

$$p = j\omega\rho\phi \quad (2)$$

$$v = -\nabla\phi \quad (3)$$

where ρ is the air density. Our FEM formulation was based on the above equations.

3. EXPERIMENT FOR TWO TYPE OF PROTRUSIONS

3.1. Simulation Model

The simulation models are uniform sound tubes with a length of 15cm. A rigid wall is assumed. The cross sectional shapes of the tubes are elliptic with major axis length of 40.0mm and a minor axis of 20.5mm. The 3-D radiational model[3] with a radius of 4cm, which is hemispherical in shape, is attached to the aperture surface. As a boundary condition of the volume, the specific acoustic impedance of spherical radiation is assumed on the spherical surface, and a rigid wall baffle is assumed. The driving

surface is driven by sound velocity $v_n = \exp(j\omega t)$. The protrusions are set into this 3-D radiational model. Two different shapes of the protrusions are investigated. The first one is symmetrical with respect to the vertical. This is the same as our previous experiment model[1, 2]. The second one is similar to the lips, having an asymmetrical shape with respect to the vertical. These protrusions are mounted on the baffle with the deepest points of the wedged-shaped cut being located just on the baffle surface. The finite element models and baffle shapes are shown in Fig.1.

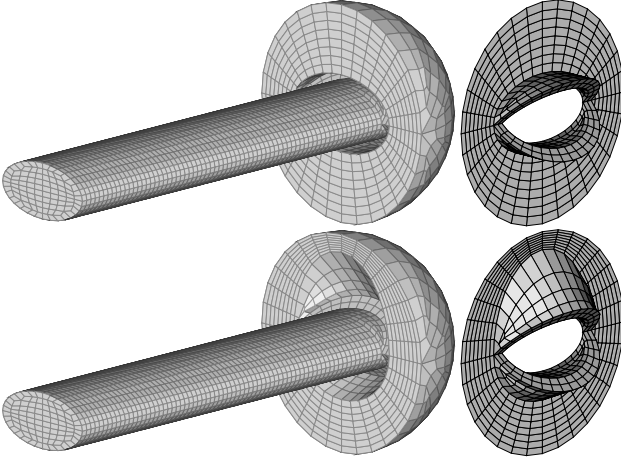


Figure 1: Finite element models and baffle shapes. Top: symmetrical model, bottom: asymmetrical model.

3.2. Radiation Impedance

Radiation impedance $Z(\omega)$ is computed at the aperture surface by

$$Z(\omega) = \frac{p_r(\omega)}{v_r(\omega)} \quad (4)$$

where p_r is sound pressure and v_r is the normal component of particle velocity at the aperture surface.

Frequency characteristics of radiation impedance $Z(\omega)$ along the center line of the radiation area are shown in Fig.2 for the symmetrical model and in Fig.3 for the asymmetrical model. Both the real and imaginary parts of $Z(\omega)$ are normalized by the characteristics of the impedance $Z_0 (= \rho c)$ of air. Symbols p_1 , p_2 , and p_3 are the FEM results on the center line of the radiation area at distances of 1.079, 1.290, and 1.591cm from the radiation end. Symbols P_1 , P_2 and P_3 are the measurement results and are almost in the same positions as p_1 , p_2 and p_3 , respectively. The solid lines are the 1-D analytical solutions[7] using the ideal piston model on an infinite baffle[8]. The area of the circular piston is equivalent to the FEM model. The FEM results, especially p_1 , are in good agreement with measurement results. Therefore, the proposed 3-D radiational model with protrusions is useful for analysis of the acoustic characteristics of human speech.

The results for the asymmetrical model in Fig.3 are a lit-

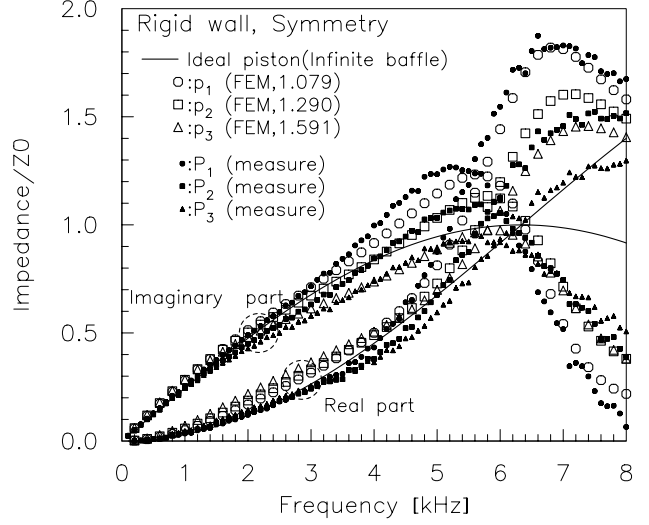


Figure 2: Acoustic impedance density for the symmetrical model.

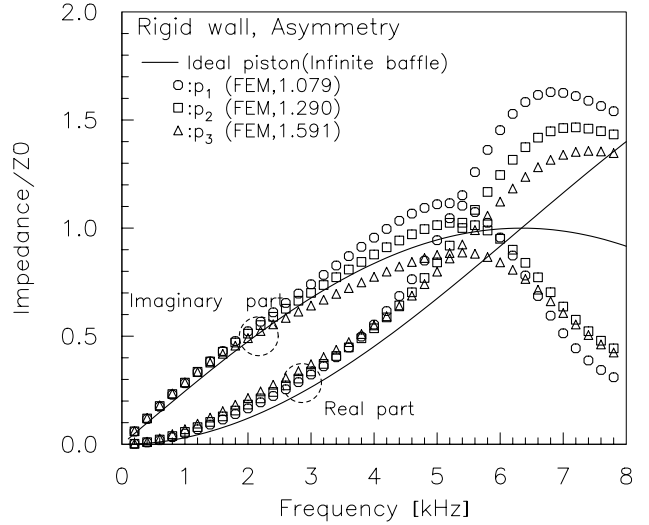


Figure 3: Acoustic impedance density for the asymmetrical model.

tle different from the results for the symmetrical model in Fig.2.

4. EXPERIMENT WITH A VOCAL TRACT MODEL

4.1. Simulation Model

The vocal tract model is based on MRI data of the vocal tract for the Japanese vowel /a/[4], and the shape of the several cross sections is elliptic and determined by the length of the circumference and the area. The tubes

are connected smoothly to each other. The center line is 14.9cm in length. A rigid wall is assumed. The driving surface is driven by sound velocity $v_n = \exp(j\omega t)$. The finite element model is shown in Fig.4. The baffle of the 3-D radiational model with the protrusion is shown in Fig.5.

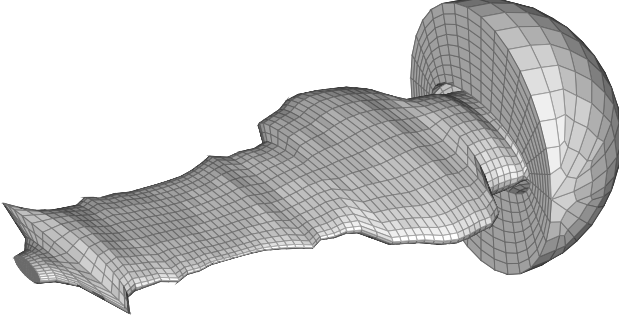


Figure 4: Finite element model.

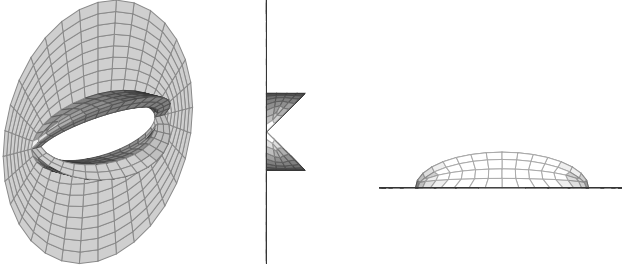


Figure 5: The baffle of the 3-D radiational model. Left to right, oblique view, side view, top view.

4.2. Vocal Tract Transfer Function

From the numerical computation of particle velocities by the FEM simulations, the VTTF $H_v(\omega)$ is computed as

$$H_v(\omega) = 20 \log_{10} \left| \frac{\iint_{\Omega_r} v_r dS}{\iint_{\Omega_g} v_g dS} \right| \quad (5)$$

where $v_g(\omega)$ and $v_r(\omega)$ are the normal components of particle velocity at the driving surface Ω_g and the radiational aperture Ω_r , respectively.

The VTTFs are shown in Fig.6. The solid line is the solution computed from the traditional 1-D analytical model[7]. FEM-1 and FEM-2 are our FEM simulation results. FEM-1 is for the vocal tract model with protrusions. FEM-2 is for our previous FEM model[5, 6] which has no protrusion.

With regard to the FEM results, the two zeros near 4740Hz and 7250Hz are caused by the higher-order modes in the large cavity of the vocal tract model equivalent to the oral cavity. The 1st formant frequency of the FEM-2 has moved approximately 25Hz lower than the 1-D traditional one and

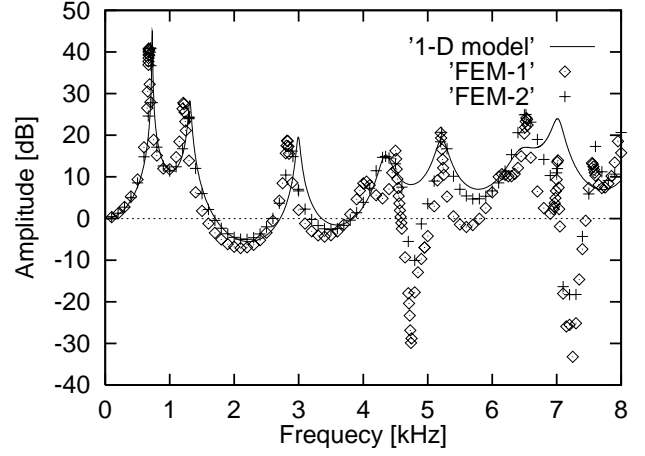


Figure 6: Vocal tract transfer functions.

the 2nd formant frequency approximately 16Hz lower. On the other hand, the 1st formant frequency of the FEM-1 has moved approximately 50Hz lower and the 2nd formant frequency approximately 100Hz lower. Thus we see that the protrusion increases the effect of making the acoustic length of the tube seem longer than the real length, and the FEM-1 results show a zero around 4.3kHz which may also be caused by the protrusion.

4.3. Distribution of sound pressure

The sound pressure distributions on the horizontal plane are shown in Fig.7 for the driving frequency 2.8kHz, and in Fig.8 for the driving frequency 4.3kHz. The driving frequency 2.8kHz is equivalent to the third formant of the VTTF of FEM-1 in Fig.6. The driving frequency 4.3kHz is equivalent to the zero of the VTTF of FEM-1 in Fig.6. In the figures, the dark region indicates high pressure, FEM-1 being for the vocal tract model with protrusions and FEM-2 for our previous FEM model[5, 6] which has no protrusion.

Fig.7 shows that the distribution of FEM-1 is slightly different from the one of FEM-2. Fig.8 shows that the distribution of FEM-1 is absolutely different from and more complex than the one of FEM-2.

5. CONCLUSION

Frequency characteristics of the radiation impedance for uniform sound tubes and vocal tract models with protrusions at the radiation end were computed by FEM simulation.

The simulation results for two types of protrusions showed that the frequency characteristics of radiation impedance of FEM simulation were in good agreement with our measurement results. The results for the asymmetrical model

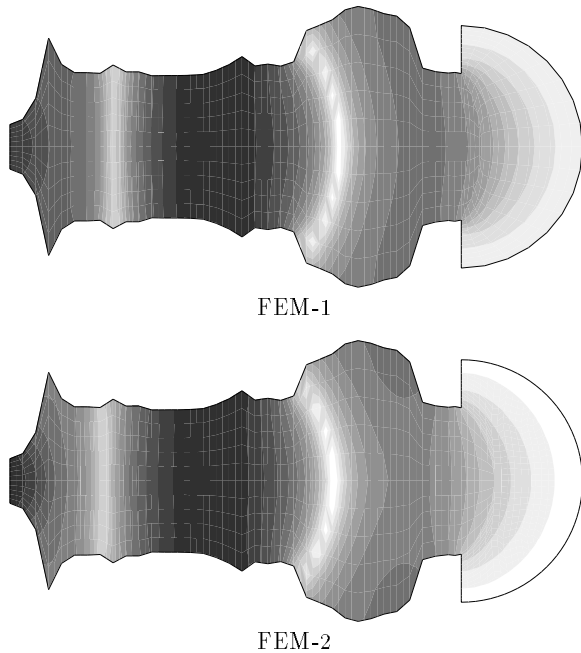


Figure 7: Sound pressure distributions on the horizontal plane. The driving frequency is set at 2.8kHz. Top: FEM-1, bottom: FEM-2.

were only a little different from the results for the symmetrical model. One reason for this small difference may be that the shape of the radiation aperture and wedged-shaped cut are the same.

The simulation results for the vocal tract models with protrusions showed that the formant frequencies of the VTTFs moved to lower frequencies than the ones of the 1-D traditional model and our previous FEM model[5, 6]. Also new zeros were produced.

In these models, the driving surfaces were driven uniformly. If the driving surface is driven non-uniformly, higher-order modes are apt to occur in the low frequency region. In future work we will investigate the acoustic characteristics of a sound tube with protrusions in which the driving surface is driven non-uniformly.

6. ACKNOWLEDGMENT

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7. References

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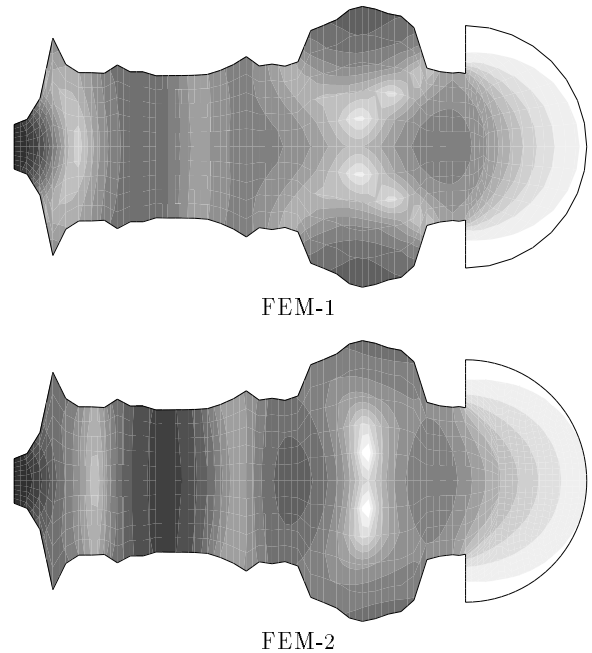


Figure 8: Sound pressure distributions on the horizontal plane. The driving frequency is set at 4.3kHz. Top: FEM-1, bottom: FEM-2.

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