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3D FEM ANALYSIS OF VOCAL TRACT MODEL OF ELLIPTIC TUBE WITH INHOMOGENEOUS-WALL IMPEDANCE

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ABSTRACT

Acoustic characteristics of sound tubes as a simplified model of vocal tracts are simulated by a three dimensional Finite Element Method(3D FEM). The results suggest some new facts as follows; if the area of the wall impedance distribution is spread or the cross section is flattened more, then the formant band widths are increase more, and the amplitude of sound pressure is decreased near formant frequencies. The sound wave propagates as a non-plane wave along the soft wall, and the inhomogeneous distribution causes distortion of surface wavefront. The pressure ampletude in the bent tube is reduced along the direction from the driving surface to the radiational surface. Moreover, as the effect of radiation, the sound wave is a non-plane wave at the radiational part.

1 INTRODUCTION

In the vocal tract analog model, the vocal tract is approximated by some cylindrical tubes, but cross section of the vocal tract resembles elliptic rather than circle, therefore the traditional modeling is a problem in the approximation by the cylindrical tubes. And since the hard palate should be regarded as a rigid wall and the tongue as a soft, it is hard to regard that both of them are the same wall impedance. We have not had much knowledge of the vocal tract acoustics in the wall effect with inhomogeneous distribution of three dimensional shapes. Moreover recently the bend effect or radiation effect have been investigated for the vocal tract acoustics theoretically or experimentally[1],[2],[3],[4]. Since bend, elliptic shape, radiation and inhomogeneous distribution are important factor on speech production systems, it is necessary to evaluate the effect for modeling.

In this paper, sound pressure and particle velocity in the sound tubes are simulated by 3D FEM for some different boundary conditions. The cross section of the tube is assumed as circle or ellipse, and the distribution conditions of the wall impedance are assumed as three types in the oral cavity: (1) a rigid wall only, (2) a soft wall (corresponded to the tongue, and (3) a rigid and soft wall combination (the upper side wall is regarded as the hard palate, and the lower wall as the tongue). In the next numerical experiment, the tube is assumed to be bent at a right angle at the middle, and the radiational space of a hemisphere is attached at the tube end. As a boundary condition of the radiational space, the specific acoustic impedance of spherical radiation is assumed on the spherical surface.

The acoustic wave equation in steady state is adapted to our FEM formulation, and sound pressure and particle velocity are computed for the above conditions.

2 ADAPTING WAVE EQUATION TO FEM

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

$$\nabla^2\phi = k^2\phi \tag{1}$$

where $k(=\omega$ (angular frequency)$/c$ (sound velocity)) is wave length constant, and that sound pressure p and particle velocity $\boldsymbol{v}$ are represented as

$$p = j\omega\rho\phi \tag{2}$$

$$\boldsymbol{v} = -\nabla\phi \tag{3}$$

where ρ is the atmospheric pressure density. Our FEM formulation is based on the above equations for the following simulation.

3 FEM SIMULATIONS USING ELLIPTIC TUBE MODEL

3.1 Experiment for effect of elliptic cross section and wall impedance

In ordre to evaluate the effect of elliptic cross section and wall impedance in the vocal tracts, we compute about acoustic characteristics in the straight sound tube with the lip radiation. We use a simulation model of the circular sound tube with the cross sectional area of πcm^2, and length of $10cm$. Its driving surface is driven by sound velocity $v_n = 1e^{j\omega t}$. At the radiational surface, the radiational impedance is assumed as one of a circular piston in a rigid sphere[5]. Boundary condition of the wall is defined as the acoustic impedance (called the wall impedance), and we use the Kamiyama's model of the soft wall[6]. The shape of cross section of the tube is determined by a parameter E_f(Elongation Factor)[7], and circle($E_f = 1$) and ellipse($E_f = 2$) are chosen. The distribution conditions of the wall impedance are assumed as three types in the oral cavity:

1. the rigid wall only
2. the soft wall (corresponded to the tongue)
3. the rigid and soft wall combination (the upper side wall is regarded as the hard palate, and the lower wall as the tongue) ; here after the mixed wall

3.1.1 Distribution of Sound Pressure

In Fig.1, we show amplitude of sound pressure from the driving surface to the radiational surface under the condition of $E_f = 1$ and 2 in which the above three types of wall impedance are shown. In this figure, an example of the simulations is shown as the result for a driving frequency of $800Hz$ which is nearly equivalent to formant frequency. The solid line is an analytical solution for E_f=1. The results

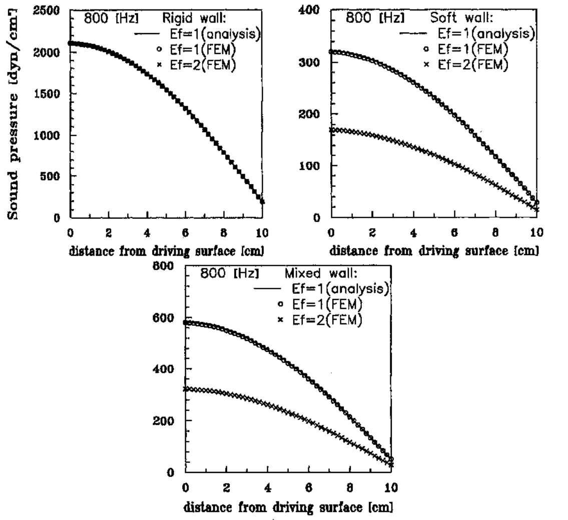
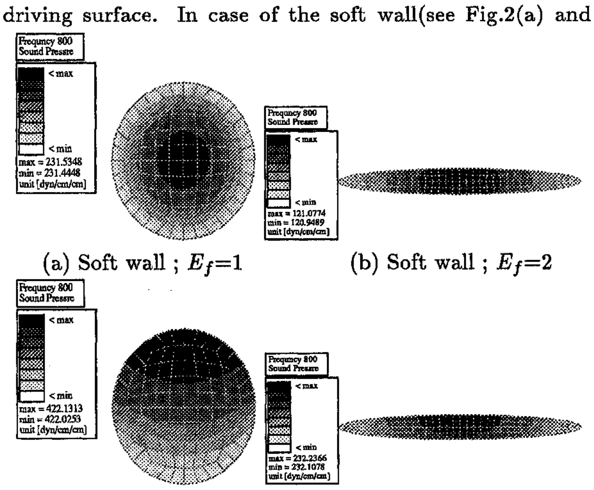


Figure 1: *Distribution of Sound Pressure*

of our FEM analysis are good agreement with analytical solutions very well. The amplitude for the rigid wall is the highest, and the amplitude for the soft wall is the lowest. We see that the pressure distribution is decreased for the flattened tube except for the case of the rigid wall only. If the driving frequency is not chosen as the formant frequency, this effect of the radiation appears very small.

Fig.2(a),(b),(c) and (d) show distribution of sound pressure on the cross section at the location of $5cm$ from the driving surface. In case of the soft wall(see Fig.2(a) and



(a) Soft wall ; E_f=1 (b) Soft wall ; E_f=2

(c) Mixed wall ; E_f=1 (d) Mixed wall ; E_f=2

Figure 2: *Distribution of Sound Pressure on Cross Section*

(b)), the sound pressure is decreased along the direction from the center to the wall gradationally. In case of the mixed wall(see Fig.2(c) and (d)), the sound pressure is decreased from the rigid wall to the soft wall. Fig.2(b) and (d) indicate that the distortion of surface wavefront depends on the cross sectional shape.

3.1.2 Change of formant band width

From the particle velocity simulated by our FEM analysis, a vocal tract transfer function $H_v(\omega)$ is computed as

$$H_v(\omega) = 20\log_{10}\left|\frac{v_l(\omega)}{v_g(\omega)}\right| \tag{4}$$

where v_g (v_l) are the vertical component of particle velocity at the driving (the radiational) surface. Increasing rate of formant bandwidth is shown in Fig.3 As the area of distri-

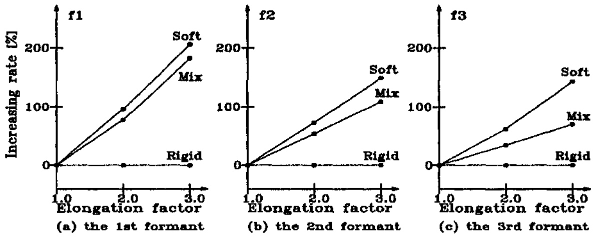


Figure 3: *Increasing rate of formant bandwidth*

bution of the wall impedance is spread or E_f increases, the each formant band width increases except for the case of the rigid wall only. The effect of the wall impedance appears at the first formant the most. The effect of distribution of the wall impedance appears at the third formant the most.

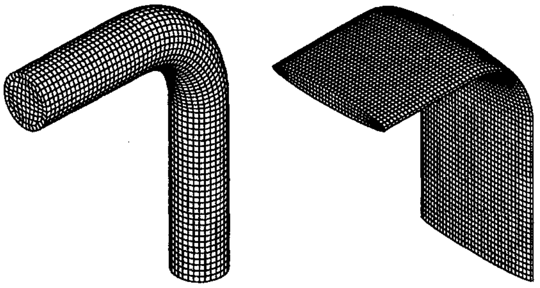
We see that the amplitude of sound pressure is decreased at near formant frequencies, and the inhomogeneous distribution of the wall impedance causes variance of the surface wavefront. Since there is only $10^{-2}dyn/cm^2$ pressure differences, the sound wave can be approximation as the plane wave in the flattened tube. As the area of the wall impedance distribution is spread or the cross section is flattened more, the formant band widths are increase. Moreover the effect of inhomogeneous-wall impedance appears in higher formants.

3.2 Experiment for bent tube

The FEM computation is performed for the sound tube model for the vocal tract which is bend at a right angle at the middle. Evaluating the effect of bend, we simulate the sound wave propagation in the tube with length of $16cm$ on the center line. Other conditions are the same as ones of section 3.1. In Fig.4, we show a finite element model with a circular cross section($E_f = 1$) in (a), and show a model with an elliptic cross section($E_f = 2$) in (b).

3.2.1 Distribution of Sound Pressure

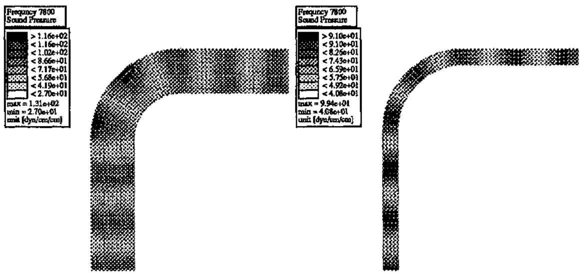
In Fig.5(a), (b), (c) and (d), we show distribution of sound pressure on the sagittal plane. In this figure, an example of the simulations is shown as the result for a driving frequency of $7800Hz$ which is nearly equivalent to formant frequency. When the cross section of circle($E_f = 1$) changes to ellipse(E_f=2), the pressure amplitude is not only decreased in case of the soft wall but also the rigid wall only. In



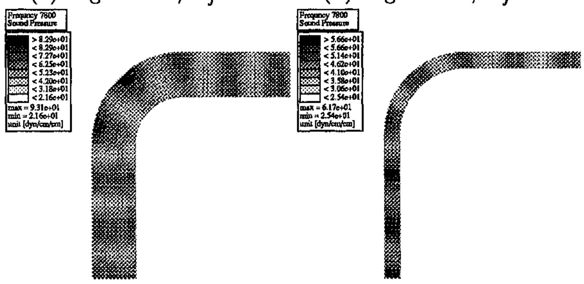
node : 8829, element : 7360 node : 14013, element : 10880
(a) E_f=1 (circle) (b) E_f=2 (ellipse)

Figure 4: *Finite element model*

Fig.5(d), the amplitude is reduced along the direction from the driving surface to the radiational surface gradationally.



(a) Rigid wall ; $E_f = 1$ (b) Rigid wall ; $E_f = 2$



(c) Soft wall ; $E_f = 1$ (d) Soft wall ; $E_f = 2$

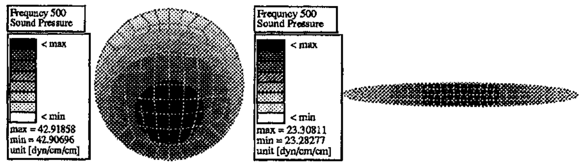
Figure 5: *Distribution of Sound Pressure*

In Fig.6(a), (b), (c) and (d), we show distribution of sound pressure on the cross section at the location of $14cm$ from the driving surface. In this figure, an example of the simulation is shown as the result for a driving frequency of $500Hz$ which is nearly equivalent to formant frequency. Comparing Fig.6(a) with Fig.2(a) and Fig.6(c) with Fig.2(c), we see difference from each other on the surface wavefront. Comparing Fig.6(b) with Fig.2(b) and Fig.6(d) with Fig.2(d), we see no difference.

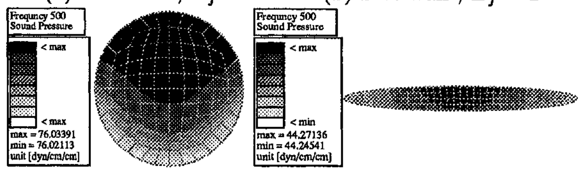
These results suggest that the sound pressure amplitude in the bent tube is reduced along the direction from inlet to outlet gradationally if the cross section is elliptic, and this phenomenon does not appear in the straight cylindrical tube. The bend causes distortion of surface wavefront.

3.3 Experiment for radiational effect

If the radiation influences on the pressure distribution in the tube, in validity of the previous simulation results the



(a) Soft wall ; $E_f = 1$ (b) Soft wall ; $E_f = 2$



(c) Mixed wall ; $E_f = 1$ (d) Mixed wall ; $E_f = 2$

Figure 6: *Distribution of Sound Pressure on Cross Section*

problem would be occurred. Therefore it is necessary to investigate how much the influence is exist. Moreover it is necessary to evaluate the 3D effect which dose not appear in one dimensional model of radiation. As first step for our experiment, our proposed radiational space is modeled as in Fig.7, and we compare the FEM result with analytic solution of the one dimensional model of the equivalent circuit[8]. This model is a rigid cylindric tube with length of $5cm$, and

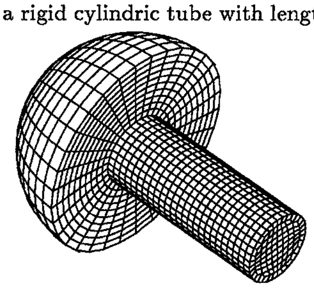


Figure 7: *Finite element model*

a hemispheric-radiational space of $3cm$ radius. As a boundary condition of the radiational space, the specific acoustic impedance of spherical radiation is assumed on the spherical surface, and a rigid wall baffle is assumed. Other conditions are the same as ones of section 3.1.

3.3.1 Radiational Impedance

Radiational impedance $Z(\omega)$ is computed at the radiational surface as

$$Z(\omega) = \frac{p_r(\omega)}{v_r(\omega)} \quad (5)$$

where $p_r(v_r)$ are sound pressure(vertical component of the particle velocity). In Fig.8, we show frequency characteristics of radiational impedance $Z(\omega)$ computed from the FEM and analytic solutions. The computational results of the FEM are indicated the value of "center"(means a center point of the radiational surface), "edge"(means a edge of the radiational surface) and "average" (means the value averaged from the particle velocities). In this figure, the analytic solution of the ideal piston model is plotted as the solid line for the infinite baffle, and as the dotted line for the spherical baffle. The "average" data is almost agreement with the analytic solution for the infinite baffle up to about $4kHz$. and in high frequency more than $4kHz$, the

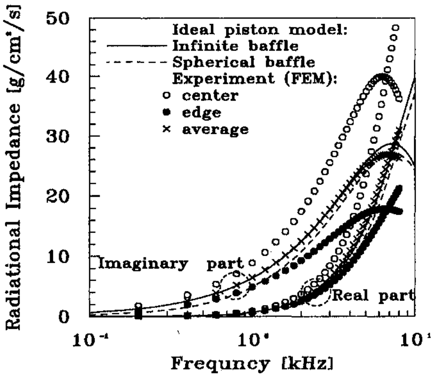


Figure 8: *Frequency characteristics of radiational impedance*

imaginary part of the "average" data shifts to the solution of the spherical baffle. The difference between the "center" and the "edge" suggests that the sound wave is non-plane wave at the radiational part. From the above computational data, we conclude that the model of radiational space in Fig.7 can be used to evaluate the pressure not only at the point in the space but also the "average" data for the plane wave model.

3.3.2 Transfer function with radiational model

In Fig.9, we show the vocal tract transfer function $H_v(\omega)$ computed from the FEM and the analytic solution for the Fig.7. and the analytic solution is plotted as the solid line. There are a few dB differences between the "center" and

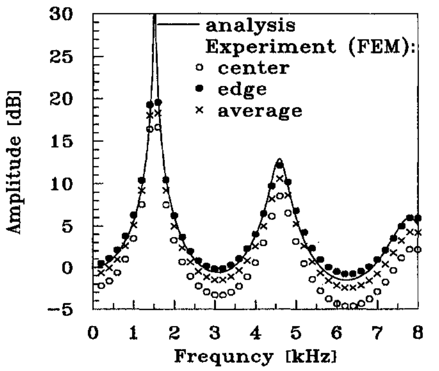


Figure 9: *Transfer function*

the "edge", but formant bandwidths are no difference. The "average" is not good agreement with the solid line. We guess as a reason that the transfer function is computed from only vertical component of particle velocities.

4 CONCLUSION

The pressure amplitude of sound pressure is decreased near formant frequencies in the inhomogeneous distribution of the wall impedance, and the distribution and the bent tube cause variance of the surface wavefront. Since this is very small variation, the sound wave can be approximation as the plane wave. As the area of the wall impedance distribution is spread or the cross section is flattened, the formant band widths are increase. Moreover the effect of inhomogeneous-wall impedance appears at higher formant. From the experimental result for radiational effect, we conclude that the model of radiational space can be used to evaluate the pressure not only at the point in the space but also the average data for the plane wave model.

The results indicated that bend, elliptic shape, radiation and inhomogeneous distribution of wall impedance can be important factor of acoustic characteristics on speech production system.

Acknowledgment

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