ANALYSIS OF ACOUSTIC PROPERTIES OF THE NASAL TRACT USING 3-D FEM

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ABSTRACT

In order to examine acoustic effects of complicated morphological construction of the nasal tract, we have analyzed acoustic models constructed according to a measurement by a magnetic resonance imaging (MRI). A prototype model was made to be as similar as possible with the actual nasal tract, which is asymmetrical in the left passage and the right, and has complicated cross sectional shapes. Sound pressure and particle velocity and sound intensity in the model were calculated by finite element method (FEM). Several modifications were applied on the shape of the prototype model in order to learn what acoustical effects are produced by such modifications: (1) models having elliptic shape, (2) models with and without a pair of maxillary sinuses, (3) a left-right symmetry model in which the one passage is modified to be identical with the other passage, (4) models having narrowed or stuffed passages. Result shows that the poles and zeros are produced and shifted by a mutual branching effect caused by left-right asymmetry of the nasal passages and the additional side branch effect of the sinus cavities. Those effects are also produced by complicated cross section shapes of the nasal tract at 3kHz region. The reduced cross section in the narrowed passage models causes the shift of pole and zero frequency and weakens the mutual side branch effect of the left and right when either of two passages are excessively narrowed.

1. INTRODUCTION

Among the phonemic sounds in speech language the nasal sounds are particularly interesting because the sounds of nasal consonants, nasal murmurs, and nasalized vowels highly represent an individual voice property, a dialectal difference, and emotional and physical condition of the talker. The acoustic analysis of them has been performed extensively so far [1]-[7], but the characteristics of nasal sound have not perfectly been understood since the nasal tract has quite complicated morphological structure. Modern technology such as magnetic resonance imaging (MRI) provides us the measurements of morphological structure of the vocal organs in detail [8]-[11], and high speed computer and computational algorithms such as finite element method (FEM) permit us to estimate the three dimensional sound wave in the vocal organs. The authors had measured the morphological structure of the nasal tract by MRI and estimated the acoustic properties using conventional acoustic model [12]. The nasal tract is essentially a non-uniform acoustic tube whose axial direction of the tube is curved and the cross sectional shape is quite complicated. The nasal tract acts as a branch for the vocal tract and has a bifurcation in itself to make the left and right passages, which are not symmetrical one another and have several paranasal cavities called sinuses. Although the nasal tract is relatively static organ whose shape and size do not change as rapidly as those of oral cavity, the cross section area of the nasal tract is changed by so called nasal cycle in which the thickness of the mucous is altered by congestion and uncongestion of a physiological function of the nasal mucous[13]. Thus, it is interesting to estimate an acoustic characteristics of the nasal tract having narrowed or choked nasal passage.

In the present study we introduce some modification on the real shape and analyze the acoustic effects caused by such a modification. We have used finite element method to solve three dimensional Helmholtz wave equation. Thus, we avoided to assume that there is only a plane wave along the axial direction in the nasal tract, and to apply rather uncertain values of open end correction at the bifurcation of the left and right passages and at the conjunctions of the paranasal cavities.

At first, the prototype model (called "real model" or "L100-R100" model, hereafter) was made to be as similar as possible with the actual nasal tract. Then, several modifications were applied on the prototype model in order to learn what acoustical effects are produced by such modifications: (1) models having elliptic cross section shape, (2) models with and without a pair of maxillary sinuses, (3) a left-right symmetry model in which either one passage is modified to be identical with the other passage, (4) models having narrowed or stuffed passages. Discussion in this paper will be focused mainly on the subjects (3) and (4), and will refer the conclusions of preceding works [14] and [15] in which the subjects (1) and (2) were discussed .

2. MODELING AND MODIFICATION OF THE NASAL TRACT FROM MORPHOLOGICAL MEASUREMENT

Using MRI measurements of morphological structure of the nasal tract of one male subject [12], we have constructed a three dimensional FEM model of the nasal and paranasal cavities. The MR images were taken every 3mm space providing 27 coronal sections for the nasal tract from velopharyngeal port to the nostrils. Thousands of voxels of size 0.997mm x 0.997mm x 3.0mm were used to construct the model. The resulting nasal tract model is composed of 27 sections having 3mm length and different cross section shapes depending on location in the nasal tract, and has a bent form as shown in Fig. 1. It has quite realistic shape except for being eliminated the sinus cavities.

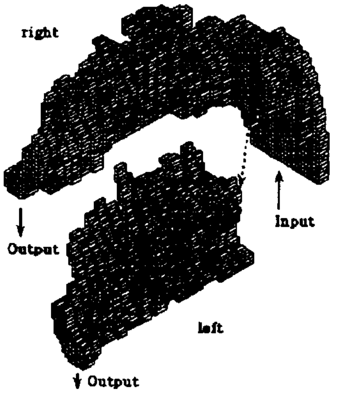

Fig. 1: FEM model of the nasal tract having realistic shape (L100-R100 model).

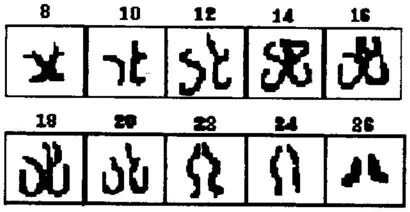

Fig. 2: Coronal cross section shapes of the nasal tract at every second sections from 8-th to 26-th section (from the bifurcation to just behind of nostrils).

Several acoustic tube models were constructed by modifying this prototype model so that each model had different degree of simplification of actual nasal tract. Elliptic cross section models whose cross section area and circumference length are identical with the MRI data were constructed. Two types of elliptic model were made so that the one has the sinus cavity and the other has not. Comparing these models, we can learn how the sinus cavities and the cross section shape give acoustic effects or the transfer function of the nasal tract [14,15].

Cross section shape of the nasal tract shows considerable variation from section to section. Fig. 2 shows the cross sections of every second sections from the bifurcation (8-th section) to just behind of the nostrils (26-th section). The posterior portion of it has a simple shape like a circle, but the middle portion and the anterior portion bifurcate to make two parallel branches whose cross section area and shape are not identical. This produces double effects on acoustic property of the nasal tract: one by the asymmetry and the other by the complicated flow of sound wave in each passage. To investigate these effects, we made modified models in which the left/right passage was reformed to be symmetrical with its counter part (R'-R model/ L-L' model).

The cross section area of the mid portion is often narrowed or choked by thickening the mucous as a physiological response to the moisture and the temperature. To investigate the acoustic effect of the thickening the mucous membrane, we have further introduced several models whose cross section area are reduced to 56%, 25%, and 6% by reducing the size of FEM elements by 75%, 50%, and 25%. Both cases of left-right symmetry and asymmetry in this type of modification were examined.

3. FINITE ELEMENT ANALYSIS

Three dimensional finite element analysis (3-D FEM) was applied to solve the Helmholts equation. A commercial software, SYSNOISE by NIT, was used for solver of FEM. Boundary condition at the nostrils were a radiation impedance of a piston on a infinite plane baffle. Unit amplitude sinusoidal pressure waves of frequencies 20Hz to 8000Hz in 20Hz steps were input at the velopharyngeal port. Loss components such as viscosity, heat conduction and yielding wall were neglected.

Number of elements and nodes in the prototype FEM model were approximately 6,700 and 12,600, respectively. Sound pressure and particle velocity at each node in the models were calculated. The sound intensity was also calculated to observe the energy flow in the nasal tract. Input-admittance at the velopharyngeal portion was calculated as an average of ratios of particle velocity to sound pressure at the elements of the first section.

4. RESULT AND DISCUSSION

Frequency characteristics of transfer function of prototype model (Real model or L100-R100 model) is shown in Fig. 3, where the transfer function is defined as a ratio of sound pressure at the nostrils p_o to that at the velopharyngeal port p_i. The solid line curve represents the response of the right passage and the broken line curve represents that of the left passage. Frequencies of pole and zero below 4kHz are listed in Table 1. The pole frequency is identical in both the left passage and the right passage even though they have different shape. On the contrary, the frequencies of zero are different in each other. The lowest pole frequency is 1200Hz because the sinus cavity is not built in this model. It was shown in references [14] and [15] that if the maxillary sinus was built in the lowest pole frequency is shifted down to 450Hz-500Hz and all other poles and zeros are shifted by some extent to higher frequency.

The input admittance looking into the nasal tract from the velopharyngeal port is shown in Fig.4. The frequencies at which the admittance is infinitely large are exactly same with the pole frequency of transfer function.

Fig. 5 shows transfer function of a modified model R'100-

R100 model. The R'100-R100 model is so modified to make a symmetric shape that the left passage is reformed to be identical with the right passage. A set of poles at 1860Hz (left, right) and zeros at 1840Hz (left) and 1880Hz (right) in Real model is diminished in the R'100-R100 model. We can understand that this pole-zero set is produced by asymmetry in the passages. This pole-zero set causes also the shift of almost all higher frequency poles and zeros in Real model. Although many zeros in Real model are diminished in the symmetric model, there are still zero-pole sets remained at about 3200Hz and very higher frequencies. This is first observed by the authors [15], and is evidenced by inspecting the flow diagram of sound intensity in the passages in which the complicated cross section shape of the nasal tract causes something like cyclic or side branch flow of sound wave inside the nasal passage.

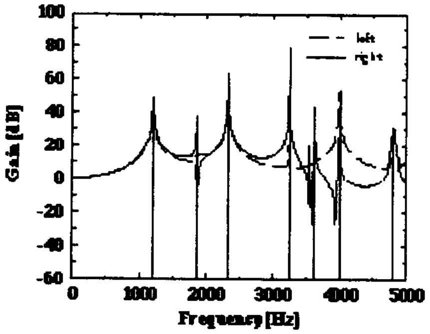

Fig. 3: Frequency characteristics of transfer function (Ratio of output to input sound pressures (dB)) in L100-R100 model.

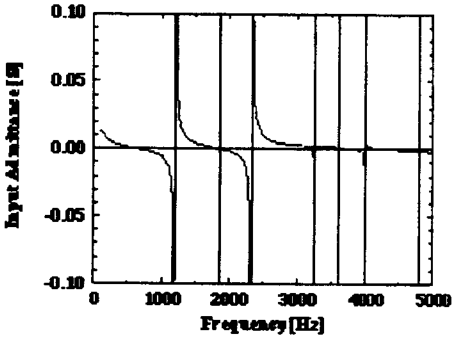

Fig. 4: Input admittance of L100-R100 model.

Table 1: Frequency of pole and zero in transfer function of L100-R100 model.

Frequency [Hz]	Left	Right
1200	x	x
1840	o	-
1860	x	x
1880	-	o
2330	x	x
3236	x	x
3245	o	-
3514	-	o
3516	o	-
3717	x	x
3568	-	o
3611	o	-
3614	x	x
3920	-	o
3980	x	x

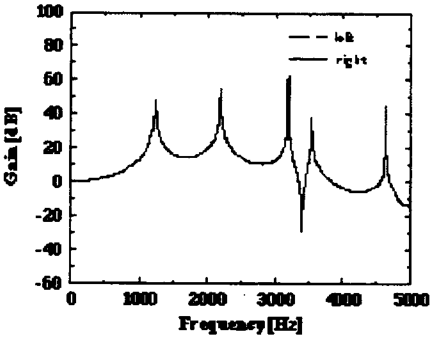

Fig. 5: Transfer function of symmetric model R'100-L100 model.

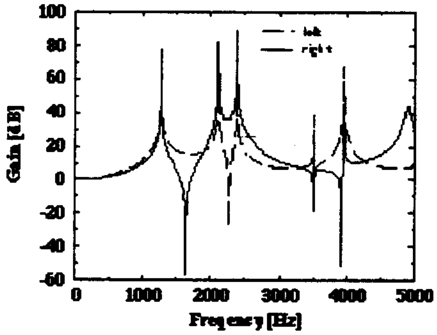

Fig. 6: Transfer function of L100-R50 model (right side reduced by 50%).

As to the acoustic effect of the thickening the mucous membrane, models having reduced cross section area in either or both sides of nasal passages as much as 56%, 25%, and 6% were investigated. Fig. 6 shows, as an example, a transfer function of L100-R50 model in which the cross section area of right passage is reduced to 25% (50% in FEM element size) of the original. The sets of pole and zero in the 1800Hz region are much emphasized in this case. This can be understood by considering that those pole and zeros are inherent property of asymmetry in left and right and the asymmetry is emphasized by reducing the cross section area of one side. As an extreme case of asymmetry we examine a case where the right passage is closed at bifurcation of nasal tract. Fig.7 shows a transfer function of L100-R0 model.

This model corresponds to the case of one side of the nasal passage is choked, and therefore the nasal tract becomes single tube. The poles and zeros caused by asymmetric passages are diminished. However, there still remains at 3500Hz region a pair of pole and zero caused by the complicated cross section shape.

Next, let us consider the cases of symmetrical shape with reduced cross section areas. Fig. 8 is transfer function of R'50-R50 model in which the left passage is reformed to have the same shape with the right passage to make symmetric shape. and the cross section area of both passages are reduced to 25% (50% in FEM element).

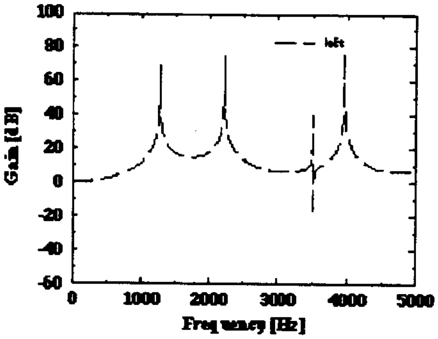

Fig. 7: Transfer function of L100-R0 model (right side choked).

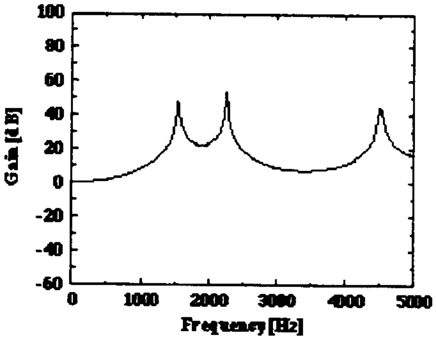

Fig. 8: Transfer function of R'50-R50 model (reformed to be symmetric and both sides reduced by 50%).

Comparing Fig. 8 with Fig. 5 and Fig. 6, we see that zeros produced by the interaction of left and right passages is diminished by the symmetric shape, and the poles and zeros around 3kHz-4kHz are also diminished because the flow of sound intensity becomes simpler in such a narrow passage.

5. CONCLUSIONS

The nasal tract has quite complex morphological structure such as the sinus cavities, the bifurcation, the left-right asymmetry, and the complicated cross sections. This causes complex acoustic character and produces many poles and zeros in transfer function and input impedance/admittance of the nasal tract. Introducing several types of modification on the real shape and analyzing the effects caused by such modifications by FEM, the present study have revealed some detailed acoustic properties of the nasal tract. In conclusion, not only the sinus cavities and the left to right asymmetry in the nasal tract produce the pole-zero pairs in the transfer function of the nasal tract, but the complicated cross section shape also produces remarkable resonance frequency shifts and possibly extra pole-zero pairs at 3kHz region. The present study has also shown how the acoustic transfer functions are changed when the cross sectional area of nasal tract is changed by thickened mucous membrane as in cases of nasal cycle or illness.

This research is supported by the Grant in Aid of Scientific Research of Japanese Government (No.07650423).

REFERENCES

[1] Fant, G., Acoustic Theory of Speech Production (Mouton, The Hague), 1960 (2nd ed,1970).

[2] Fujimura, O., and Lindqvist, J., "The sine wave response of the nasal tract", *Phonetica*, **37**, 55-86 (1964).

[3] Fujimura, O., and Lindqvist, J., "Sweep-tone measurement of vocal tract characteristics," *J.Acoust Soc. Am.*, **49**, 541-557 (1971).

[4] Lindqvist-Gauffine,J.,and Sundberg, J., "Acoustic properties of the nasal tracts", *Phonetica*, **33**, 161-168 (1976).

[5] Takeuchi,S.,Kasuya, H.,and Kido,K.,"A study on the effects of nasal and paranasal cavities on the spectra of nasal sounds"*,J.Acoust.Soc.Jpn.*,**33**,163-172 (in Japanese) (1977).

[6] Fant, G., "The relation between area function and the acoustic signals", *Phonetica*, **37**, 55-86 (1980).

[7] Maeda, S., "Role of the sinus cavities in the production of nasal vowels"*Proc.IEEEInt. Conf. ASSP*,**2**,911-914 (1982).

[8] Baer, T. Gore,J.C., Gracco,L.C., and Nye,P.W. "Analysis of vocal tract shape and dimensions using magnetic resonance imaging:Vowels",. *J.Acoust.Soc.Am.*,**90** (2), 799-828(1991).

[9] Greenwood, A. R., Goodyear, C. C., and Martin, P. A. (1992). "Measurement of vocal tract shapes using magnetic resonance imaging", *IEE Proc. I (Commun.,Speech Vision) (UK)*, **139** (6), 553-560.

[10] Kumada, M., Niimi, S., Hirose, H., and Itai, Y., "A study on the inner structure of the tongue for production of the 5 Japanese vowels by tagging snapshot MRI; a sound report", *Ann. Bull.RILP.*, **27**, 1-12 (1993).

[11] Honda,K.,Hirai,H.,and Kusakawa,N.,"Modeling vocal tract organs based on MRI and EMG observations and its implication on brain function"*Ann Bull.RILP.*,**27**,37-50 (1993).

[12] Dang, J., Honda, K., and Suzuki, H., "Morphological and acoustical analysis of the nasal and the paranasal cavities", *J. Acoust. Soc., Am.*, **96** (4), 2068-2100 (1994).

[13] Williams, H. L., "Nasal Physiology", in Otolalyngology, Vol.1, Basic Science and Related Disciplines, edited by M. M. Paparella and D. A. Shumrick (Saunders, Phyladelphia), pp.329-346 (1973).

[14] Suzuki, H., Dang,J.,Nakai,T., Ishida,A., "3-D FEM analysis of sound propagation in the nasal and paranasal cavities", *Proc., ICSLP'94*, **S06-6.1**, 171-174 (1994).

[15] Suzuki, H., Nakai,T., Sakakibara,H., "3-D FEM analysis of sound propagation in the nasal tract", *Proc., EURO-SPEECH'95*, **WEpm1B.5**, 1301-1304 (1995).