

# Finite Element Analysis of the Human Middle Ear and an Application for Clinics for Tympanoplasty (Static and Harmonic Vibration Analysis)

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## Abstract

We have already proposed a method for estimating the hearing restoration effect of the tympanoplasty operation using the three-dimensional finite element method. In this study, the restoration effect of the operation using the columella instead of the broken incus was estimated for cases in which the incus of auditory ossicles was deficient by the middle ear cholesteatoma. The shape, the mounting position and material of the columella to the malleus were variously changed in the finite element static analysis. It was ascertained that hearing recovery of about 92% could be expected. This result is appropriate from a clinical viewpoint. On the other hand, the harmonic vibration analysis in receiving the sound pressure was carried out in order to obtain the frequency response characteristics of a healthy subject. Then, it was assumed that the incus of the healthy subject was damaged by some causes. The harmonic vibration analysis was carried out for the tympanoplasty model in which the columella was used instead of the damaged incus. It was clarified that hearing recovery of about 98% could be expected. From the viewpoint of the vibration analysis, it was proven that the prediction of a hearing restoration effect was possible by our method, which made the displacement of the stapes basal plane to be a standard.

**Keywords:** geometric model, FEM, human middle ear, tympanic membrane, auditory ossicles, tympanoplasty, sound pressure, hearing ability

## 1 Introduction

The geometric model of the middle ear including the tympanic membrane, tympanic cavity, auditory ossicles, several ligaments, and tensor was constructed using SolidWorks. The method for estimating the hearing restoration effect from the perpendicular displacement to stapes basal plane has been proposed in our research group. In order to verify its validity, the finite element model in which the columella is substituted for the incus of the healthy ear is constructed and the static analysis was performed in

our previous research [1].

In this paper, a geometric model of the middle ear in which the ossicular chain is broken by the middle ear cholesteatoma, is constructed. For this model, the finite element static analysis is carried out by a change of material, shape and the way of mounting the columella. From this, a prediction is made of the degree of hearing ability recovery and the validity of the prediction method is verified with the clinical data.

In actuality, the middle ear transmits the wave of the air vibration received from the tympanic membrane to the inner ear through auditory ossicles. In the internal ear, the stapes vibration is transmitted to the labyrinthine fluid in the cochlea where electrical signals are generated. Finally, it is recognized in the brain as sound. Therefore, harmonic vibration analysis of the middle ear was done in order to examine the frequency response characteristics of the stapes. On the assumption of the case in which the part of the auditory ossicles was deficient, the rectangular part, called the columella, is installed between the malleus and the stapes. In this study, the possibility of clinical application of the prediction method of the hearing restoration effect is investigated from the viewpoint of the vibration analysis, too.

## 2 Middle ear structure and its function

### 2.1 Middle ear structure

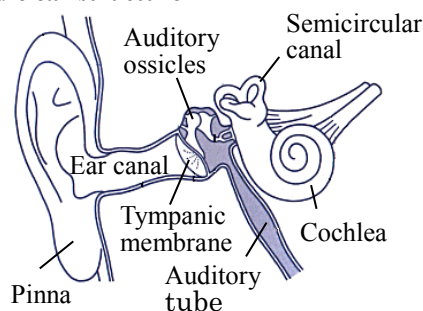
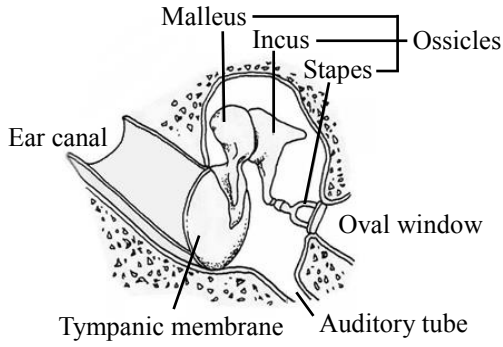


Fig. 1 Ear structure



**Fig. 2 Auditory ossicles**

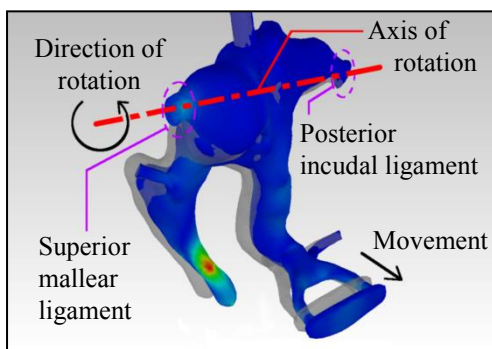
**Figure 1** shows the structure of the ear. The middle ear is composed of the tympanic membrane, tympanic cavity, auditory ossicles and others which are shown in **Fig.2** [2]. Auditory ossicles are behind the tympanic membrane in a small space (tympanic cavity), and they are composed of malleus, incus and stapes. The stapes basal plane connects with the inner ear through an oval window.

### 2.2 Function of tympanic cavity

The tympanic cavity is a space filled with air. The inner wall of the tympanic cavity is covered with a mucous membrane. The air pressure of the tympanic cavity is controlled at the appropriate value by ventilation in order to keep the important function that is “the sense of hearing”. Furthermore, the tympanic cavity has a washing function that absorbs and removes bacterial waste by the secretion and reabsorption of the mucus.

### 2.3 Function of auditory ossicles

Each part of the auditory ossicles is connected with the joints. They are suspended by ligaments and muscles in the tympanic cavity. The vibration amount of the tympanic membrane is amplified about 17 times by the area ratio of the stapes basal plane and the tympanic membrane. In addition, the vibration amount of the tympanic membrane is amplified about 1.3 times by the lever motion of the auditory ossicles.



**Fig. 3 Deformation of auditory ossicles**

### 2.4 Auditory ossicles movement

**Figure 3** shows that the auditory ossicles turn about the axis connecting the superior malleal ligament

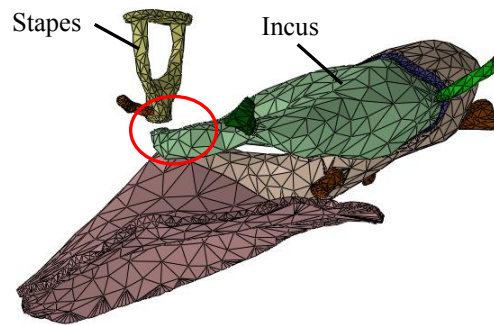
and the posterior incudal ligament. By this rotary motion, the vibration of the tympanic membrane is efficiently converted into Z-direction (perpendicular to the stapes basal plane) movement of the stapes. The stapes vibration is transmitted to the labyrinthine fluid of the internal ear and converted to electrical signals, which are then recognized as sound in the brain. In this study, we consider that there is a certain relationship between hearing ability and the Z-direction displacement of the stapes.

## 3 Static analysis approach

### 3.1 Finite element modeling

#### 3.1.1 Broken ossicular chain model

**Figure 4** shows the geometric model of the middle ear in which the ossicular chain is broken by the middle ear cholesteatoma. The cholesteatoma adhered to the part bounded by the red circle in **Fig.4**. Therefore, a connection between the incus and the stapes is lacking.



**Fig. 4 Broken ossicular chain model**

#### 3.1.2 Tympanoplasty model for broken ossicles

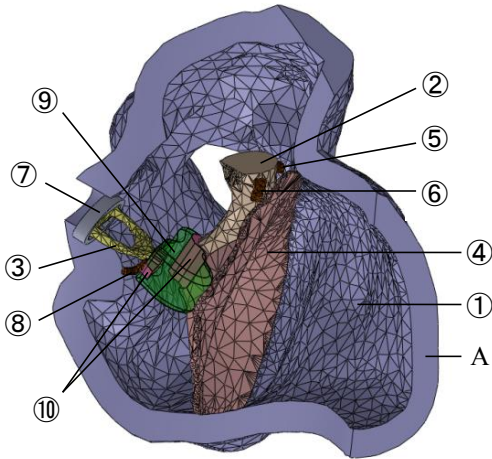
The geometric model for the finite element analysis is shown in **Fig.5**. This model is composed of 10 parts. The CT scanning data of the human head were converted to DICOM data, and subsequently into STL data which were imported into SolidWorks.

The malleus normally does not work, because it is adhered to the neighboring bones by the cholesteatoma. Therefore, the upper part of the malleus was removed from the anterior malleal ligament and superior malleal ligament. In a clinical operation, the columella is installed between the malleus and the stapes instead of the damaged incus. This operation method is called the “Auditory ossicles formation III-i type”. The schematic view of the III-i type formation is shown in **Fig.6** [3]. The material data of the columella are the same as silicon or human bone, and the joint part as cartilage.

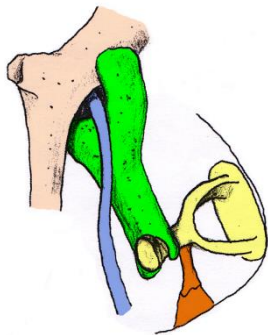
Four kinds of models that change the mounting location of the columella are analyzed in order to investigate the difference of the displacement of the stapes basal plane. These geometric models are shown in **Fig.7**. On the right side of this figure, the columella is connected to the tympanic membrane, too. Material data of each part are shown in **Table 1**. The numbers next to the anatomical names in the table corresponds to the numbers in **Fig. 5**.

**Table 1 Material data**

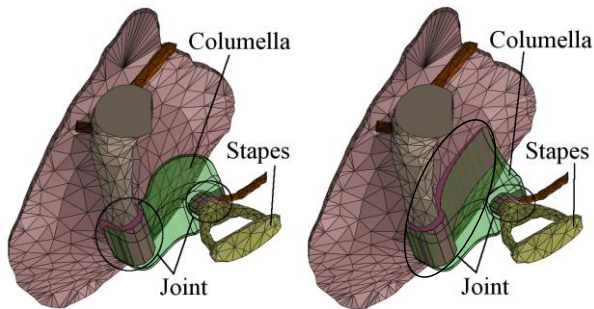
Anatomical name	Young's Modulus [MPa]	Poisson's ratio
1. Tympanic cavity wall	13,436	0.3
2. Malleus		
3. Stapes		
4. Tympanic membrane	64	
5. Anterior malleal ligament	21	
6. Lateral malleal ligament		
7. Stapedial annular ligament	0.65	
8. Stapedial muscle	0.52	
9. Columella	Bone	0.28
	Silicon	
10. Joint	6	0.3



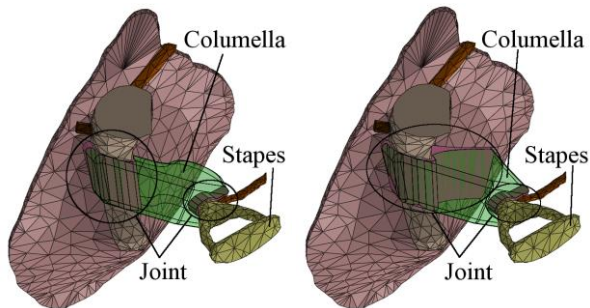
**Fig.5 Geometric model of middle ear**



**Fig.6 Schematic view of III-i type formation**



**(a) Connection to umbilical part of malleus**



**(b) Connection to intermediate part of malleus**

**Fig.7 Geometric model for tympanoplasty**

### 3.1.3 Boundary condition

A total of 3 cross sections (one section is A of Fig.5) of the tympanic cavity were perfectly fixed in constraint conditions. The sound pressure of 120 dB was converted into pressure using the following equation as load conditions.

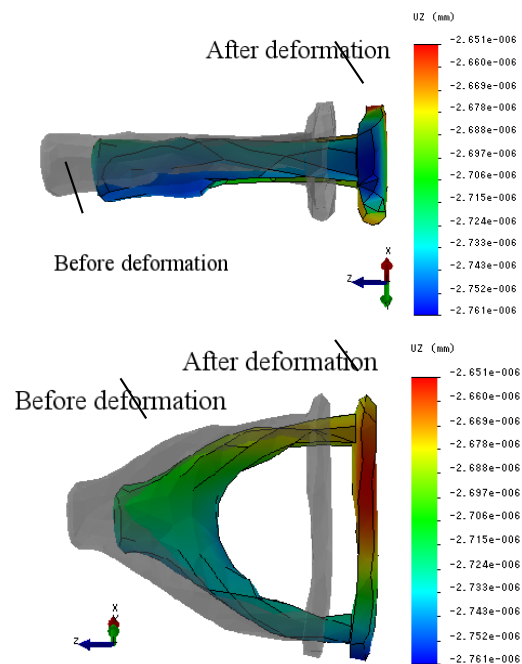
$$L_p = 20 \log_{10}(P/P_0) \quad (1)$$

where,

$L_p = 120 \text{ dB}$ : the limit of the sound pressure which the human auditory sense is able to hear safely.

$P_0 = 20 \times 10^{-6} \text{ Pa}$ : standard value (the lowest value of sound intensity which is audible for humans).

As a result, the pressure of  $P = 20 \text{ Pa}$  was given at the contact surface of the tympanic membrane and malleus.



**Fig.8 Z-direction displacements of stapes (Umbilical connection model)**



### 3.2 Finite element analysis results

Figure 8 shows the displacement of the stapes in the Z-direction, which is perpendicular to the basal plane for the sound pressure of 120dB. In these results, the columella is connected to the umbilical part of the malleus (Fig.7(a)) and its material composition is silicon. Table 2 shows the average displacement of the stapes basal plane in each model.

Table 2 Average displacement of stapes

Connection position of collmela	Displacement [ $10^{-6}$ mm]	
	Silicon	Bone
Umbilical part	2.70	2.67
Umbilical part & Tympanic membrane	2.22	2.22
Intermediate part	2.83	2.78
Intermediate part & Tympanic membrane	2.19	2.12

### 3.3 Considerations

Figure 8 shows that the stapes deform in a perpendicular direction to the basal plane, that is, in the Z-direction. In this study, we consider that there is a certain relationship between hearing ability and Z-direction displacement of the stapes basal plane. For a healthy subject, the average displacement of the stapes for a sound pressure of 120dB is 3.09nm, which becomes a standard value in our study [1].

When the columella made of silicon is attached to the intermediate portion of the incus, a maximum displacement of 2.83nm occurs. This value is about 91.6% of the healthy subject. The tympanoplasty model, in which the middle ear is damaged by the middle ear cholesteatoma, can be sufficiently recovered by the operation of “Auditory ossicles formation III-i type”. This result is appropriate from a clinical viewpoint.

When the columella made of silicon is attached to the umbilical part of the incus, the average displacement is 2.70nm. When the columella made of human bone is attached to the intermediate portion or the umbilical part of the incus is 2.78 nm or 2.67nm, respectively. In these cases, the effect decreases slightly, but a recovery of hearing ability of over 85% can be expected.

Furthermore, when the columella made of silicon is attached to both of the umbilical and the tympanic membrane, the average displacement is 2.19nm (intermediate part of the incus) or 2.22nm (umbilical part of the incus). In these cases, the effect is considerably lowered. The vibration of the tympanic membrane cannot sufficiently transmit to the stapes using the tympanic membrane with its low rigidity. This corresponds with the vibration of the tympanic membrane of III-i tympanoplasty model (the columella is attached to the malleus) is easier to reach the stapes than III-c tympanoplasty model (the columella is attached to the tympanic membrane) [1].

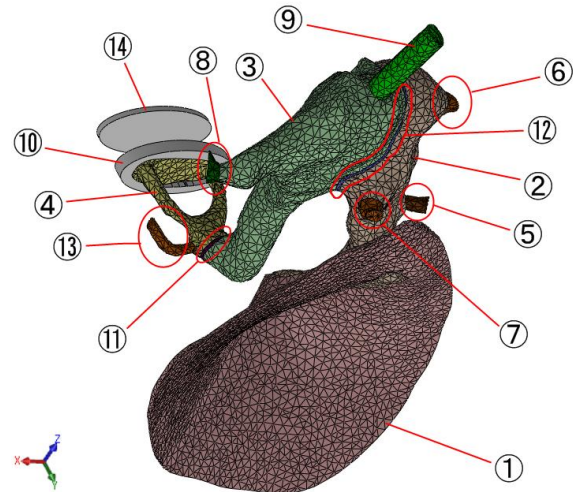
## 4 Dynamic analysis approach

### 4.1 Geometric modeling

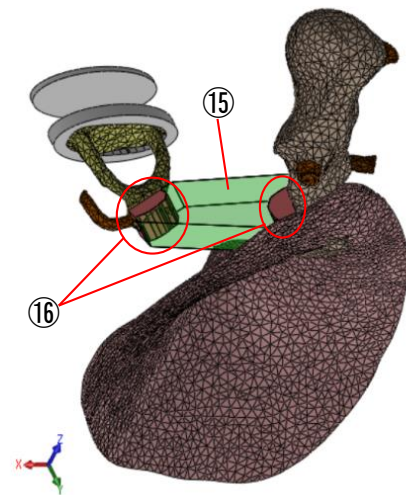
The geometric model of a healthy middle ear for

the finite element analysis is shown in Fig.9(a). This model is composed of 14 parts. The CT scanning data of the human head were converted to DICOM data, and subsequently converted into STL data, which were imported into SolidWorks.

On the other hand, Fig.9(b) shows the operation model called “Auditory ossicles formation III-i type”. In this model, the rectangular part called the columella is installed between the malleus and the stapes instead of the damaged incus.



(a) Healthy type model



(b)III-i type tympanoplasty model

Fig. 9 Geometric model of middle ear

### 4.2 Finite element modeling

#### 4.2.1 Material setting

Material data of each part are shown in Table 3. The anatomical name numbers in the table corresponds to the numbers in Fig.9. These data are determined by referring to the research of Higashimachi *et al.* [1] and Koike *et al.* [4]. The base plate is a virtual part for supporting the spring. Therefore, its Young's modulus can be assumed to be a rigid body. The columella is

composed of the main body and the joint. Silicon was used for the main body, and cartilage for the joint.

**Table 3 Material data**

Anatomical name	Young's Modulus [MPa]	Density [kg/m <sup>3</sup> ]	Poisson's ratio
① Tympanic membrane	33.4	1,200	0.3
② Malleus	13,436	4,350	
③ Incus	13,436	4,350	
④ Stapes	13,436	4,350	
⑤ Lateral malleal ligament	21	2,500	
⑥ Superior malleal ligament	21	2,500	
⑦ Anterior malleal ligament	21	2,500	
⑧ Posterior incudal ligament	0.65	2,500	
⑨ Superior incudal ligament	0.65	2,500	
⑩ Stapedial annular ligament	0.65	2,500	
⑪ Incudostapedial joint	6	1,200	
⑫ Incudomalleal joint	6	1,200	
⑬ Stapedial muscle	0.52	2,500	
⑭ Base plate	$1 \times 10^{10}$	-	
⑮ Columella(Silicon)	112,400	2,330	0.28
⑯ Joint	6	1,200	0.3

#### 4.2.2 Boundary condition

The attachment portion between the tympanic cavity and the tympanic membrane, muscle, and ligament was perfectly fixed in constant conditions. Furthermore, the base plate was perfectly fixed.

The sound pressure of 90dB was converted into pressure using the equation (1) as load conditions.

In equation (1),

$L_p=90\text{dB}$  is the relative noisy sound pressure and  $P_0=20 \times 10^{-6}\text{Pa}$  is standard value.

As a result, a pressure of  $P=3.14\text{Pa}$  was obtained. However, in this analysis,  $P=15.2\text{Pa}$  was given at the contact surface of the tympanic membrane and malleus. The ratio  $15.2/3.14$  equals the ratio of the total area of the tympanic membrane to the contact surface area of the tympanic membrane and malleus.

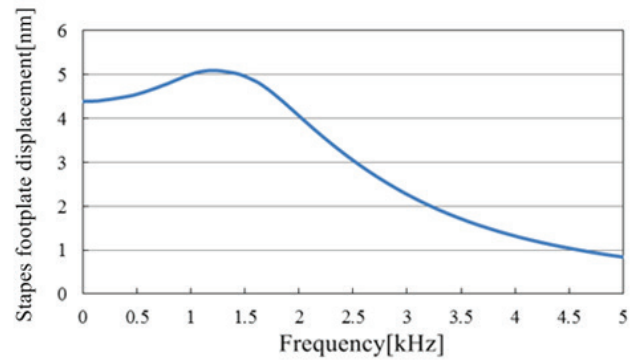
The spring of 40N/m spring constant was installed between the stapes and the base plate referring to the research of Gan *et al.* [5]. Rayleigh damping was assumed and a damping factor  $\alpha=0\text{ s}^{-1}$  and  $\beta=7.5 \times 10^{-5}\text{ s}$ .

#### 4.3 Finite element analysis results

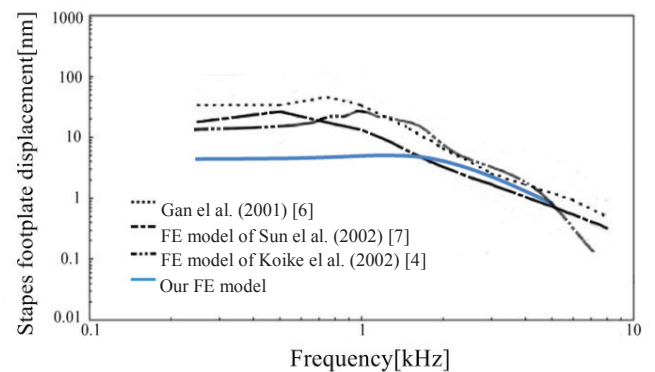
In this research, the harmonic vibration analysis was done as dynamic analysis using the finite element method. **Figure 10** shows the harmonic vibration analysis results of a healthy subject. **Figure 11** shows the comparison of some frequency response graphs. The solid line in **Fig.11** shows the frequency response graph of our harmonic vibration analysis. In **Fig.10**, the longitudinal axis shows the displacement of the stapes bottom in the Z-direction which is perpendicular to the basal plane, and the lateral axis represents the frequency.

The dotted line in **Fig.11** is the measurement result

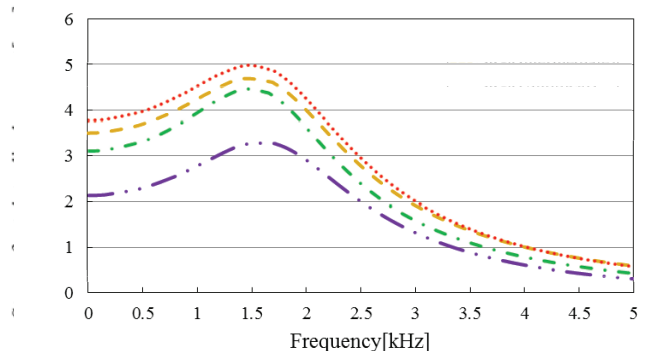
from the research of Gan *et al.* [6]. The dashed and single-dotted line is the finite element analysis result of Sun *et al.* [7]. The dashed and double-dotted line is the finite element analysis result of Koike *et al.* [4]. **Figure 12** shows the frequency response graph of the stapes bottom of our harmonic vibration analysis in auditory ossicles formation III-i type.



**Fig. 10** Frequency response graph of healthy subject



**Fig. 11** Comparison of frequency response graphs



**Fig. 12** Frequency response graph of tympanoplasty III-i model

#### 4.4 Considerations

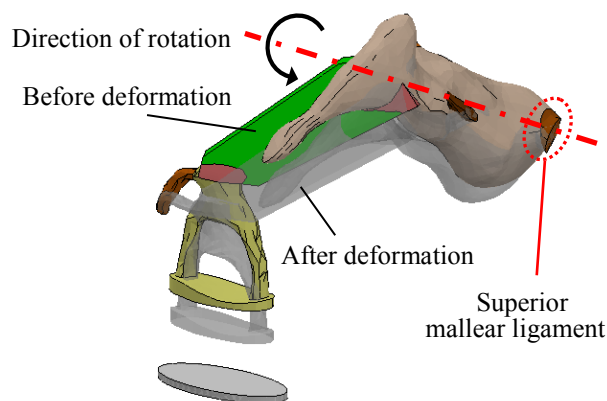
In cases of a healthy subject, it is said that there is a resonance region of the middle ear at 1 to 2 kHz of frequency. Average displacement of the stapes basal plane shows the peak of the resonance to be near 1.3 kHz of frequency in the analytical results of a healthy subject. This displacement decreases gradually with an

increase in frequency over 2 kHz. The measurement result of the research by Gan *et al.* [6] shows the peak of resonance to be near 0.7 kHz in **Fig.11**. This data is a mean value of 17 examinees and the dispersion between individuals is also large. Therefore, it was possible to reproduce the resonance phenomena to some extent by our finite element model. However, the average displacement of the stapes bottom is relatively smaller than the measurement result of Gan *et al.* [6] or the analysis result of Sun *et al.* [7] and Koike *et al.* [4] under 1 kHz in **Fig.11**. Reasons for this could be as follows:

- (a) Some of the material properties such as the ligaments are estimated values.
- (b) The tympanic membrane has been divided into regions, and the material properties differ in each regions. However, in our study, the membrane is treated as one part

**Figure 12** shows that the position of the peak of resonance does not change from about 1.5 kHz, even if the attaching position of the columella is changed in the III-i type tympanoplasty model. However, the average displacement of the stapes has the largest value at the position in which the columella is attached at the umbilical region, that is, the tip of the malleus. The value of the average displacement is 5.0 nm at about 1.5 kHz of frequency. **Figure 13** shows the malleus rotate around the superior malleus ligament. Therefore, the closer the attach point of the columella gets to the umbilical region -that is, the far from the superior malleus ligament-, the larger the stapes displacement becomes.

**Figure 12** shows that the maximum average displacement of the healthy type is 5.1 nm. On the other hand, the maximum average displacement of 5.0 nm of the III-i type model is about 98 % of the healthy type. This means that hearing ability recovers to the normal level. We have proposed that the hearing restoration effect can be estimated by the displacement of stapes basal plane. Its validity has been verified by static finite element analysis. The same statements are true for the harmonic vibration analysis. Therefore, it becomes possible to estimate the restoration ratio by comparing the stapes displacement of the tympanoplasty model with the healthy type in all range of the frequency.



**Fig.13 Vibration mode of III-i model (Frequency  $f=1.7\text{kHz}$ )**

## 5 Conclusions

We have already proposed the method for estimating the hearing restoration rate by comparing the displacement of the stapes basal plane. In this study, the validity of our method was verified by finite element static and dynamic analysis.

On the actual patient whose ossicular chain was broken by the middle ear cholesteatoma, the tympanoplasty operation was simulated and the hearing restoration effect was estimated according to our method. When the columella made of silicon is attached to the intermediate portion of the incus, a maximum displacement of 2.83nm occurs. This value is about 91.6% of a healthy subject. This result is appropriate from a clinical viewpoint.

By harmonic vibration analysis, the frequency response characteristics of a healthy subject were clarified. The displacement of the stapes basal plane shows the peak of the resonance to be near 1.3 kHz of frequency. This displacement decreases gradually with an increase in frequency over 2 kHz.

On the assumption of the case in which the incus of the healthy subject was damaged, harmonic vibration analysis was applied to this broken model. As a result of analysis, hearing ability recovers to the normal level by the III-i type tympanoplasty model.

We have proposed that the hearing restoration effect can be estimated by comparison of the displacement of stapes basal plane. The validity of our proposal was confirmed by the static and dynamic analysis approach. This kind of approach makes it possible to propose a new medical treatment for the recovery of conductive hearing loss.

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