Modelling of Components of the Human Middle Ear and Simulation of Their Dynamic Behaviour

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Abstract

In order to get a better insight into the function of the human middle ear it is necessary to simulate its dynamic behaviour by means of the finite-element method. Three-dimensional measurements of the surfaces of the tympanic membrane and of the auditory ossicles malleus, incus and stapes are carried out and geometrical models are created. On the basis of these data, finite-element models are constructed and the dynamic behaviour of the combinations tympanic membrane with malleus in its elastic suspensions and stapes with annular ligament is simulated. Natural frequencies and mode shapes are computed by modal analysis. These investigations showed that the ossicles can be treated as rigid bodies only in a restricted frequency range from 0 to 3.5 kHz.

Introduction

Middle ear mechanics has gained a growing interest over the last years because it enables new surgical reconstruction techniques. This progress in therapy requires a better understanding of transfer characteristics of the middle ear where air sound is first transformed into mechanical vibrations of the ossicle chain and then to fluid vibrations in the inner ear. It is a challenging problem to get this better insight which can only be tackled by interdisciplinary co-operation of physicians and engineers and by means of medical experience and modern engineering methods. Objectives of a joint research project at the Dresden University of Technology are mechanical models for all components of the middle ear (tympanic membrane, ossicles and their elastic suspensions) and simulation of their dynamic behaviour by means of the finite-element method.

Parameterized Finite-Element Models

Finite-element models of the various parts are generated separately on the basis of the respective geometrical models and then connected by kinematic and dynamic constraints. The commercial finite-element program

Fig. 1a–c. Geometrical models for the ossicles of the human middle ear.

(ANSYS®) is used for this purpose. Each submodel is individually scalable allowing to generate models with different geometry, thus considering the interindividual variations.

Ossicles

The surfaces of the human auditory ossicles were measured by microscopy, and geometrical models for malleus, incus and stapes were created (fig. 1). By means of these models the mechanical parameters for rigid bodies, i.e. volume, mass, location of the centre of gravity as well as moments and principal axes of inertia were computed (table 1). The values for mass density for these calculations were taken from Kirikae [1960].

The ossicles were meshed with three-dimensional solid elements. We assumed homogeneous isotropic elastic material properties. Young's modulus of bone was taken from the literature with $2 \cdot 10^4 \text{ N mm}^{-2}$ [Fung, 1993].

Submodel of Tympanic Membrane with Malleus and Ligaments

The shape of the surface of a right human tympanic membrane was determined with the help of a scanning laser microscope [Drescher, 1995]. After computing a three-dimensional image, geometrical co-ordinates of points on the surface of the tympanic membrane were available. The geometrical model is defined by about 50 surface points. Following Wada et al. [1992], we distin-

Fig. 2. Geometrical model of the human tympanic membrane with malleus and ligaments.

Table 1. Inertia properties of the ossicles

	Malleus	Incus	Stapes
Centroid location (local coordinate system), mm			
x	4.3	4.77	-0.064
y	1.6	0.48	-0.045
z	1.5	-0.42	1.19
Rotation angle of the principal axes (local coordinate system), Eulerian angle in degrees			
θ_{xy}	8.44	2.62	0.92
θ_{yz}	-39.18	4.15	2.65
θ_{zx}	-34.55	-4.42	-6.47
Principal moments of inertia, mg mm ²			
I_{xx}	10.6	28.8	4.97
I_{yy}	76.3	63.9	6.37
I_{zz}	72.4	79.1	1.87
Weight, mg	25	27.6	3.5
Volume, mm ³	9.5	18.6	1.44
Density ¹ , mg mm ⁻³			
Handle	3.3	1.48	2.43
Neck	4.02		
Head	2.27		

¹ Values were taken from Kirikae [1960] and slightly modified.

guish 10 regions at the eardrum with a thickness ranging from 0.10 to 0.22 mm. The overall area (surface) amounts to 72.3 mm². Using a sophisticated mathematical description for the surface of the eardrum it is possible to adapt the model to measured points of another specimen by varying only 3 basic dimensions: diameter (orientated along the manubrium mallei): 9.7 mm, (orientated perpendicular to the manubrium mallei): 10.0 mm; distance between umbo and plane of the eardrum boundary: 2.1 mm. Based on this information an integrated geometrical model was created which consists of the tympanic membrane and the malleus with its 4 ligaments and musculus tensor tympani (fig. 2). All ligaments and the muscle are illustrated only as symbols, showing their location and direction.

Due to computational advantages the corresponding finite-element model is a combination of the tympanic membrane as elastic shell, the malleus as rigid body and all ligaments and the muscle as generalized massless beams with longitudinal, bending and torsional stiffness [Beer et al., 1997]. The microstructure of the tympanic membrane is taken into consideration by anisotropic elastic material properties and a homogenized one-layer shell

Fig. 3. Finite-element model of the human tympanic membrane with malleus and ligaments. CG = Centre of gravity.

Fig. 4. Finite-element model of stapes and annular ligament.

model. It must be further mentioned that in this model the relation between membrane stiffness and bending stiffness according to Kirchhoff's thesis does not hold. Consequently there is no strict separation between geometrical and material properties. The material parameters were obtained by experimental investigations on temporal bone specimens as described in Bornitz et al. [in press]. As to the boundary conditions, the tympanic membrane is simply supported, that means the boundary cannot transmit

bending moments. The ligaments are clamped at the fictitious bony wall of the tympanic cavity (fig. 3).

Submodel of Stapes with Annular Ligament

Stapes and annular ligament are treated as elastic bodies with ideal isotropic and homogenous elastic material properties which are connected by coupling all degrees of freedom (fig. 4). The annular ligament is modelled with varying dimensions around the circumference and it is

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Fig. 5. Finite-element model of the annular ligament with three-dimensional solid elements (20 nodes); isotropic elastic material.

Fig. 6. First mode of the malleus at 4.6 kHz.

Fig. 7. Characteristic modes of the tympanic membrane; view from tympanic cavity.

Fig. 8. Modal analysis of the integrated system stapes and annular ligament.

fully clamped at the boundary simulating the attachment to the bone. In order to clearly show the elastic properties of the annular ligament we reduced it to a (6 × 6) matrix element at the centre node of the footplate. The vector of displacements $U^T = (u_x, u_y, u_z, \text{rot}_x, \text{rot}_y, \text{rot}_z)$ is defined according to the co-ordinate system of the master node (fig. 5). The stiffness matrix C_{RB} for this element is fully populated due to the geometry of the annular ligament.

$$C_{RB} = c_{ref} \begin{bmatrix} 51.40 & -0.24 & -1.37 & 0.04 \text{ mm} & 9.66 \text{ mm} & 0.35 \text{ mm} \\ & 49.20 & -0.60 & -7.87 \text{ mm} & -1.01 \text{ mm} & -8.40 \text{ mm} \\ & & 27.80 & 0.37 \text{ mm} & 17.10 \text{ mm} & 0.96 \text{ mm} \\ & & & 8.29 \text{ mm}^2 & 0.58 \text{ mm}^2 & 2.60 \text{ mm}^2 \\ & & & & 29.70 \text{ mm}^2 & 1.60 \text{ mm}^2 \\ \text{symmetric} & & & & & 12.90 \text{ mm}^2 \end{bmatrix}$$

In case of a diagonal matrix (i.e. if the extradiagonal matrix elements are negligible, the annular ligament could be substituted by a set of individual springs. According to our experience this ligament must be described mathematically by spatially distributed elastic properties instead of locally concentrated individual springs. The reference stiffness c_{ref} is proportional to Young's modulus of the annular ligament E_{RB} . This value was experimentally determined by static measurements to $c_{ref} = E_{RB} \cdot \text{mm} = (0.035\text{--}0.050) \text{ N mm}^{-1}$.

Results of Dynamic Analyses

The dynamic behaviour of components and submodels can be described either by transfer functions or by natural frequencies and mode shapes. The latter are more suitable for comparison with other models since the modes of vibration characterize the structure independent of external loads. Modes of vibration (i.e. natural frequency and mode shape) were obtained by means of modal analysis. Mode shapes show the vibration at a specific natural frequency at the moment of maximum deflection. The deflection is indicated in the following figures either by its magnitude in a colour scale or by vectors, which show magnitude and direction of the motion.

Considering the ossicles as elastic bodies in free suspension the first natural frequencies occur at 4.6 kHz for the malleus (fig. 6) and 4.8 kHz for the stapes (table 2, column 1). It follows that the ossicles can be treated as rigid bodies only in a restricted frequency range from 0 to 3.5 kHz.

The first 6 natural frequencies of the combination eardrum-malleus range from 200 to 3,500 Hz. The modes 1 and 2 at frequencies $f_1 = 211 \text{ Hz}$ and $f_2 = 319 \text{ Hz}$ are essentially vibrations of the malleus, whereas the eardrum

Table 2. Natural frequencies (kHz) of the integrated system stapes and annular ligament in dependence on the ligament stiffness $c_{ref} = 0\text{--}50 \text{ N mm}^{-1}$

Mode	$c_{ref} = 0$ free – free	$c_{ref} = 0.0005$	$c_{ref} = 0.050$	$c_{ref} = 50.0$
1	0	0.10	1.05	14.7
2	0	0.14	1.4	27.7
3	0	0.32	3.3	(62)
4	0	0.37	3.7	(63)
5	0	0.51	5.1	(89)
6	0	0.72	7.2	(108)
7	4.77	2.30	22.6	(116)
8	5.82	2.33	23.3	(135)
9	5.90	2.40	24.0	(161)

is at rest. Mode 3 at $f_3 = 856 \text{ Hz}$ is the first elastic mode of the membrane (all surface parts are moving in phase) and mode 4 shows at $f_4 = 1,450 \text{ Hz}$ the second elastic mode of the eardrum (anterior and posterior part of the pars tensa vibrate in antiphase; fig. 7). In mode 5 at $f_5 = 1,886 \text{ Hz}$, the pars flaccida participates in the vibrations of the eardrum.

The first 2 mode shapes of the combination stapes-annular ligament are shown in figure 8. The amplitude is represented on the left-hand side by colour and on the right-hand side by arrows. Mode 1 at $f_1 = 1,050 \text{ Hz}$ is essentially a rotation around the transverse axis of the footplate (y-axis), and at $f_2 = 1,370 \text{ Hz}$ we observe mode 2 as a combination of lifting the footplate (z-axis) and rotation around its longitudinal axis (x-axis).

In a parameter study the dependence of the natural frequencies on annular ligament stiffness has been investigated and the results are listed in table 2. The different cases will be individually discussed. $c_{ref} = 0$ corresponds to free suspension of the stapes. This case is only of theoretical interest, for it describes the vibrations of the stapes as an elastic body without any influence of the suspension. Because of the absence of the suspension $f_1\text{--}f_6$ are zero and in the corresponding modes the stapes is not deformed. The first elastic natural frequency occurs at $f_7 = 4.8 \text{ kHz}$. $c_{ref} = 0.0005 \text{ N mm}^{-1}$ corresponds to a soft spring. Here the first 6 modes are motions of the almost non-deformed stapes in an elastic suspension. In the higher modes the stapes deforms substantially. The nominal value $c_{ref} = 0.050 \text{ N mm}^{-1}$ has been used in the modal analysis. Here both stapes and annular ligament are elastically deformed in the lower modes. The case of a very stiff ligament $c_{ref} = 50 \text{ N mm}^{-1}$ is of medical interest. It corre-

sponds to the pathologically ossified annular ligament. The natural frequencies are shifted to substantial higher values, note $f_1 = 14.7$ kHz. In the corresponding modes the footplate is nearly at rest and only the stapes deforms elastically.

Conclusions

Realistic geometrical models have been developed for all parts of the middle ear, the eardrum and the 3 ossicles, which are based on our own measurements. The dynamic behaviour of 2 parts of the middle ear, the tympanic membrane with the elastic suspended malleus and stapes with annular ligament, has been investigated by finite-element simulations. Our investigations showed that the human auditory ossicles are elastic bodies, which can be

regarded as rigid bodies only in a restricted frequency range from 0 to 3.5 kHz. Consequently, our simulations with the submodel of tympanic membrane, malleus (as rigid body) and ligaments were restricted to this frequency range.

Moreover it can be stated that the elastic properties of the annular ligament can also be described by means of a fully populated (6×6) matrix. A further reduction to a set of individual springs is only valid for a diagonal matrix.

Current problems which need further investigations are the restricted knowledge about parameter values, their range of variation and the modelling of appropriate kinematic and dynamic boundary conditions. Satisfying answers to these questions must be found so that the aim of our future activities can be approached, the simulation of the dynamic behaviour for the complete middle ear.

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