Modelling the Dynamic Behaviour of the Human Middle Ear Using the Finite Element Method

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Introduction

A finite element (FE) model of the whole head including the inner and outer ear is elaborated at our institute [1]. So far the BOchum Head and EAR model (BOHEAR) did not include an FE model of the middle ear but used the results of the three-dimensional circuit model of the middle ear developed by Weistenhöfer [2]. The main focus of this model was the functional analysis of the middle ear. For such an analysis the advantage of a circuit model is that it uses only several selected points on the ossicles, ligaments and muscles to describe the spatial vibrations of the whole structure. The resulting low computing time makes the model particularly well suited to observe the effects of parameter changes. But future applications of BOHEAR shall also include modifications in the middle ear including area related coupling and general excitation. Therefore an FE model of the middle ear was developed that is based on the results of the circuit model but offers a wider field of application.

Development of the model

The development of an FE model can be divided into two parts. One part is the construction of a geometric model and the second is the determination of the material parameters of all concerned structures. To build the actual FE model the geometric model is meshed with finite elements. The relation between the model parts is calculated from the geometry of the elements and the material equations.

Geometric model

An existing computer aided model of the ossicles can be used for the development of the geometric model. This model needs to be combined with the existing geometric models of the tympanic membrane and the middle ear cavities taken over from BOHEAR. As these models are based on different data and represent individual anatomy some geometrical adaptation needs to be carried out. To derive the dimensions and locations of the considered ligaments, joints and muscles tomograms of temporal bones are used.

Acquisition of material parameters

Depending on the different kinds of structures contained in the model different material parameters need to be derived. Solid or membranous structures (ossicles, tympanic membrane and muscles) need mechanical parameters like Young's modulus and Poisson's ratio. Fluid structures (air filled ear canal and tympanic cavity) need values for damping and sound velocity. The parameters of the ossicles, tympanic membrane and the air can be taken over from the existing FE models. The development of the circuit model included several measurements to determine three-dimensional material parameters of the joints and ligaments. These parameters (translational and rotational compliance and frictional resistance) are depending on geometry and cannot be easily transferred into appropriate mechanical parameters for the FE model. Equivalent mechanical parameters with comparable accuracy are not available from literature. So a procedure is developed that transfers the parameters of the circuit model into input parameters for self programmed elements. These elements are developed for the joints, the posterior ligament of the incus and the anterior ligament of the malleus. Each of them is meshed with only one self programmed beam element that describes the behaviour of the joint or ligament between two attachment points located on the ossicles or the wall of the tympanic cavity respectively. As a result the geometry of the joints and ligaments needs not to be modelled in detail and the number of elements used for the model is reduced. Figure 1 shows the completed geometry model without the tympanic cavity.

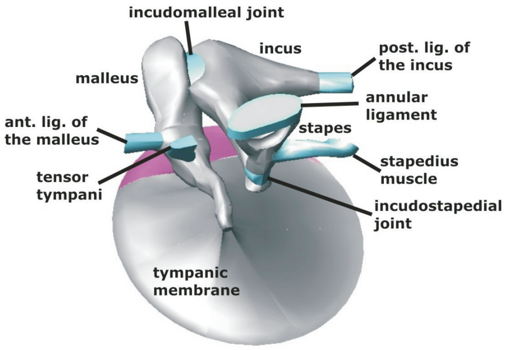

Figure 1: The geometric model of the middle ear without the tympanic cavity.

Self programmed elements

The general equation of motion which has to be solved by the FE method reads

$$M \cdot \ddot{U} + C \cdot \dot{U} + K \cdot U = F \qquad (1)$$

This equation describes the balance between the vector of the applied loads F (forces and moments) and the sum of the inner forces. These inner forces arise from the mass matrix M, the damping matrix C and the stiffness matrix K multiplied by the nodal acceleration vector $\ddot{U}$, the nodal velocity vector $\dot{U}$ and the nodal displacement vector U respectively. With the harmonic approach for the nodal displacement equation 1 can be written as

$$\underbrace{\left(-\omega^2 M + j\omega C + K\right)}_{Z_{FE}\cdot j\omega} \cdot U = F \qquad (2)$$

The point impedance matrix Z_{mech} describes the relation between the generalized force vector F and the generalized displacement vector U for one point of an object:

$$Z_{mech} \cdot j\omega \cdot U = F \qquad (3)$$

Taking into account the same structure of equation 2 and 3 the vibration of a body can be described with an FE model and a circuit model in an analogous manner. This theory can be expanded to develop different kinds of self programmed elements like point elements, beam elements or even elements without a special structure which are also used for other parts of BOHEAR. For the joints and ligaments beam elements are developed that describe the relation between two attachment points called A and B. Therefor equation 3 needs to be extended to:

$$\underbrace{\begin{bmatrix} Z_{mech,AA} & Z_{mech,AB} \\ Z_{mech,BA} & Z_{mech,BB} \end{bmatrix}}_{\tilde{Z}} \cdot j\omega \begin{bmatrix} U_A \\ U_B \end{bmatrix} = \begin{bmatrix} F_A \\ F_B \end{bmatrix} \qquad (4)$$

The system impedance matrix $\tilde{Z}$ can be calculated from the parameters of the circuit model and its contributions are assigned to the mass, stiffness and damping matrices of the self programmed element. The meshed FE model is displayed in figure 2.

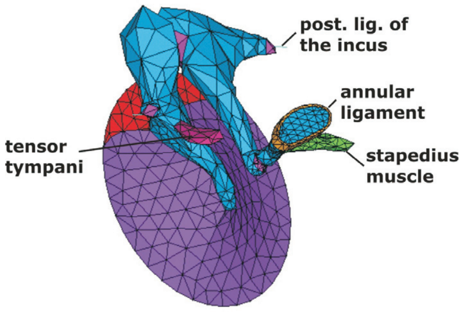

Figure 2: The finite element model of the middle ear without the tympanic cavity. The joints and ligaments are meshed with self programmed beam elements.

Validation of the model

As a basis for the validation of the model measurements of the three-dimensional stapes vibration and the predictions of the circuit model can be used. The transfer function of the displacement of the stapes footplate referred to an excitatory pressure of 1 Pa at the entrance area of the ear canal is determined with both models. In figure 3 this transfer function for the moving direction perpendicular to the plane of the footplate is shown for the models and four measurements. The FE model reproduces the measurements for all frequencies fairly well. The maximum displacement determined with the FE model at approximately 1000 Hz is higher than that of the measurements and the circuit model but this agrees with other measurements results known from literature.

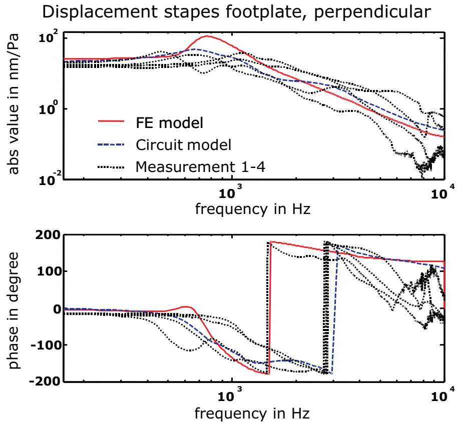

Figure 3: Transfer function of the displacement of the stapes footplate referred to an excitatory pressure of 1 Pa for the moving direction perpendicular to the footplate plane.

Combination with BOHEAR

The completed FE model of the middle ear is combined with the outer and inner ear model of BOHEAR. The resulting model of the peripheral hearing organ is shown in figure 4. A first validation test which simulates the overall transfer function of the displacement at the basilar membrane referred to the pressure in the entrance area of the ear canal shows that the model provides the expected results.

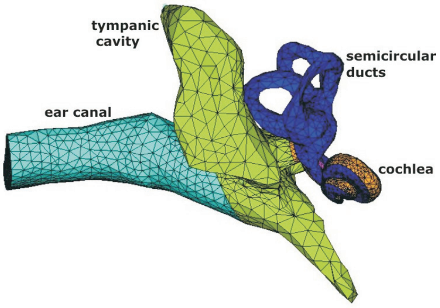

Figure 4: FE model of the whole peripheral hearing organ.

References

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[2] Weistenhöfer, C.: Funktionale Analyse des menschlichen Mittelohres durch dreidimensionale Messung und Modellierung, Dissertation at the Institute of Communication Acoustics, Ruhr University Bochum, 2002