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MODAL ANALYSIS OF THE HUMAN TYMPANIC MEMBRANE OF MIDDLE EAR USING THE FINITE-ELEMENT METHOD

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This paper provides a theoretical vibrations model of tympanic membrane constructed and solved using the finite-element method. This method is an appropriate tool to analyze the middle-ear vibrations because it enables modeling in details the complicated shape of the middle-ear and, moreover, and allows to calculate the distribution of vibrations stimulated by sinusoidal signals. The number of the 3-dimensional tetrahedral elements was assumed to be 591 and material properties used were based on data available in the literature. This model has a uniform density of $1.2 \cdot 10^3$ kg/m^3, an area of $70 \cdot 10^{-6}$ m^2, a depth of $1.54 \cdot 10^{-3}$ m at the umbo, a mean thickness of $1.32 \cdot 10^{-4}$ m, and a Poisson's ratio 0.3. Constrains were accomplished by two different springs, linear and torsional. The results obtained are compared with their counterparts scattered in the literature.

Key words: finite-element model, modal analysis.

1. Introduction

Encountered in the literature models of the tympanic membrane (TM) may by divided into three main groups: lumped parameter models based mainly on electro-mechanical analogies [8, 15–16], analytical models [10] and models based of the Finite-Element Method [3–6, 14]. Detailed survey of tympanic membrane models can be found in [11]. The most important recent FEM-models of tympanic membranes (for human and animals) are those of Funnell and co-workers (for a cat) [3–5] and Wada and co-workers (for human TM) [6, 14]. It is emphasized by many investigators that the Finite-Element Method (FEM) is a powerful tool for analysing middle-ear vibrations because its important parts can be modelled in detail and direct measurements are often not necessary. Moreover, the method enables prediction the effects of various kinds of middle-ear pathologies on the vibrational behaviour.

Our aim was to build a simplified three-dimensional model of the human TM in the physiological state. The TM was modelled as an isotropic structure, with geometry and physical parameters, i.e. volume density, Young's modulus of elasticity and constrains chosen to be as close as possible to parameters of the human TM. The aim of modelling was to achieve results which would be comparable to results obtained from TM mechanical behaviour measurements [13]. The model was tested by calculation of: modes of vibration and typical curves known from measurements, i.e. input-output functions and velocities of the selected points on the TM.

2. Model parameters and assumptions

The Finite-Element Method was applied to modelling of the modal behaviour of the tympanic membrane [1, 7]. The NE/NASTRAN v.8.3K solver for FEM [7] together with FEMAP v.8.3.0.1 pre- and post processor [2] was used, and both programs were run on PC Pentium IV, 2.4 GHz.

The human TM is modelled as a circular, three-dimensional structure and its dimensions as well as isotropic material constants are listed in Table 1. Geometry of the model is shown in Fig. 1. Radial and circumferential fibers were not taken into account, similarly to [6, 14]. Geometry and material constants were chosen to be as close as possible to those of humans and reported in literature [6, 14]. Five hundred and ninety one 3-dimensional tetrahedral elements were used to mesh model geometry.

Table 1. Geometry and isotropic constants of the tympanic membrane FEM model.

Geometry		
Tympanic membrane		
Total area (m²) [14]		$70 \cdot 10^{-6}$
Depth at the umbo (m) [14]		$1.54 \cdot 10^{-3}$
Radius (m)		$4.58 \cdot 10^{-3}$
Physical constants		
Young's modulus (N/m²)		
Tympanic membrane (pars tensa) [6]		$3.34 \cdot 10^{7}$
Tympanic membrane (pars flaccida) [6]		$1.11 \cdot 10^{7}$
Maleus [6]		$1.2 \cdot 10^{10}$
Spring constant at the tympanic ring		
Linear spring (N/mm)		
Superior portion [6]		$3.0 \cdot 10^{3}$
Inferior portion [6]		$1.5 \cdot 10^{5}$
Torsional spring, Nm/m		
Superior portion [6]		$3.0 \cdot 10^{-5}$
Inferior portion [6]		$1.0 \cdot 10^{-4}$
Density (kg/m³)		
Tympanic membrane [6, 14]		$1.2 \cdot 10^{3}$
Maleus [12]		$3.70 \cdot 10^{3}$
Poisson's ratio		0.3
Damping parameters	α (s^{-1})	β (s)
Tympanic membrane [6]	260	$3.7 \cdot 10^{-5}$
Cochlea [6]	$D_c = 8.91 \cdot 10^{-1}$ Ns/m	

The damping was expressed by the Rayleigh damping, [1]. The loading of the cochlea on the stapes was expressed by the constant damping, and its value was assumed to be $8.91 \cdot 10^{-1}$ Ns/m, similarly to [6]. The boundary conditions at the tympanic ring were represented by linear and torsional springs. The stiffness of the springs differed in the superior portion and the inferior portion (Table 1).

In Fig. 1 geometry and mesh of the tympanic membrane model is shown. Black dots with numbers indicate nodes for which input-output functions and velocity were calculated. In Fig. 1a the model view from the outer ear is shown; shaded area is the pars flaccida. In Fig. 1b the model view from the middle ear is shown; shaded area is the maleus.

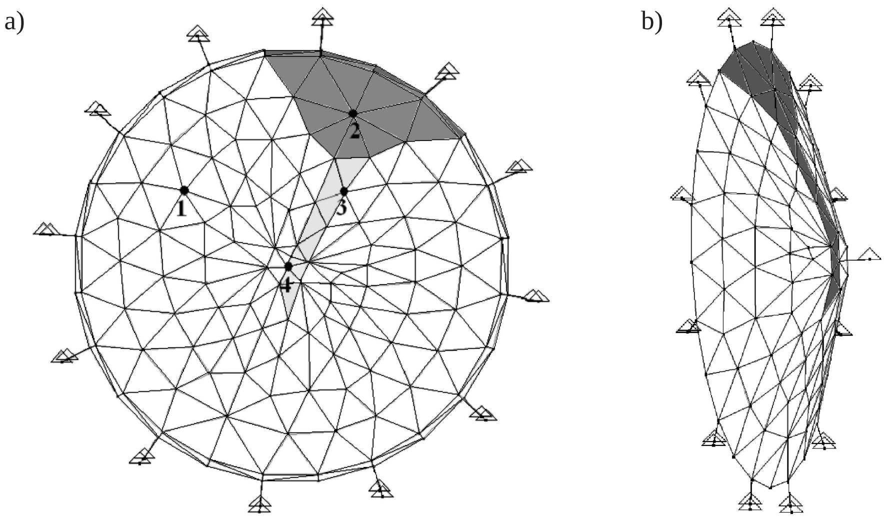


Fig. 1. Geometry and mesh of the tympanic membrane model.

3. Numerical results and discussion

In Table 2 results of modal analysis are presented. In general, modes of a continuous structure form an infinitive set. However, in this paper only the first 4 most distinctive and the best pronounced modes of the tympanic membrane are presented. The first mode of vibration, at a frequency of $f_1 = 519$ Hz, is characterized by two maximal displacement amplitudes, one each in the anterior and posterior portions of the TM. Subsequent modes appear at frequencies above 3 kHz and their shapes are more complex. The highest modal frequency shown in Table 1 is 7218 Hz. These results are in a good agreement with experimental observations performed by TONNDORF and KHANNA [13] and FEM calculations performed by KOIKE *et al.* [6].

The TM model was tested by calculations of the dynamic characteristics (input-output functions) and velocity in points (model nodes) shown in Fig. 1a. Point no. 1 was chosen on the pars tensa portion, point no. 4 – on the manubrium; the damper imitating loading of the cochlea was mounted in this point, too. Point no. 2 was chosen on the pars flaccida portion and point no. 3 – in the middle of on the maleus. The model was loaded by sinusoidal pressure of frequency 0.5, 0.8. 1, 1.5, 2, 3, 4, 5, 6 and 7 kHz. The pressure load was applied perpendicular to model surface. Applied sound pressure levels along the main axis of symmetry were 20–110 dB SPL, with 10 dB step.

Examples of calculated input-output functions are presented in Fig. 2. All presented curves show linear behaviour, as it is expected for the TM and the linear model.

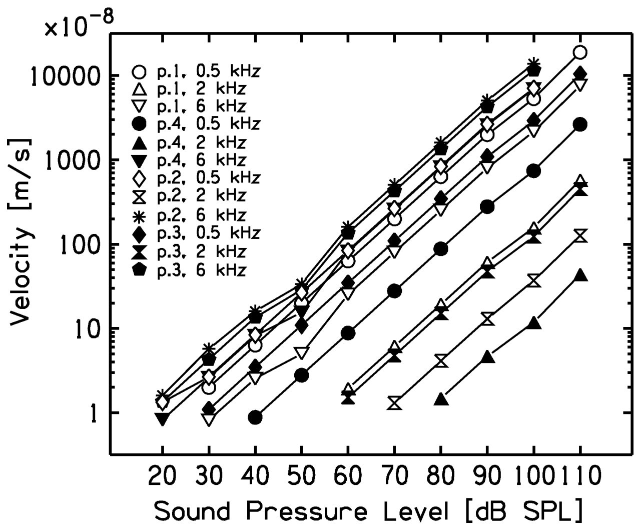


Fig. 2. Input-output functions from the physiological model of the tympanic membrane.

In Fig. 3 calculated velocity of the selected points vs. load frequency is shown. For the first glance the course of all curves is somewhat strange: maximum of velocity occurs at 5 kHz and in 1.5 kHz the minimum is visible while for the middle ear at 1.5–2.0 kHz the maximum is expected [9]. However, this effect is not surprising because in our model the external auditory meatus as well as the middle-ear cavities were not included. These cavities have a great effect on the TM vibrations at low frequencies [6].

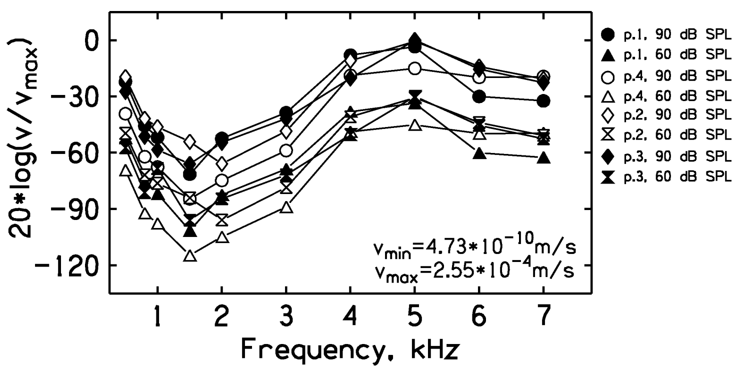
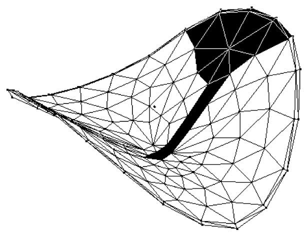
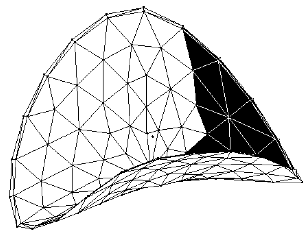
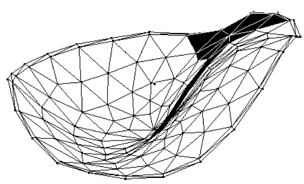
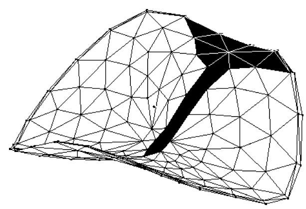
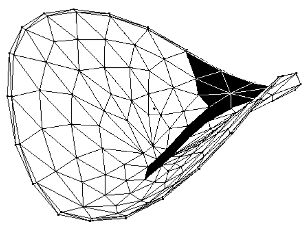
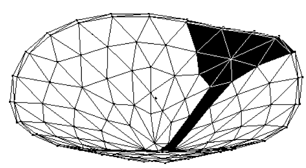


Fig. 3. Velocity values from the physiological model of the tympanic membrane.

Moreover, the assumed damping is Rayleigh damping – proportional to stiffness at high frequencies [1]. If both those factors were included to the model, they would probably damp vibration at higher frequencies and enhance vibrations at lower frequencies. Velocities calculated from the model (for selected points) are qualitatively and quantitatively similar to those reported in literature [6, 13]. Due to vast range of velocities the ordinate in Fig. 3 is expressed as $20\log(v/v_{\max})$. For a given sound pressure level the smallest velocity values were generally observed at the umbo. Relatively highest velocity values were observed for different parts of the model, depending on frequency: pars flaccida (0.5–1.5 kHz and 6–7 kHz), pars tensa (2–4 kHz), maleus (5 kHz).

Table 2. Modal analysis results from the physiological model of the tympanic membrane

Mode No.	Modal frequency, Hz	Mode shape	Mode No.	Modal frequency, Hz	Mode shape
1.	519		4.	4760	
2.	3678		5.	5203	
3.	4448		6.	7218	

The main simplifications of the presented model is neglecting of fibrous structure of the TM and simplified geometry (radial instead of elliptic) as well as the effect of the external auditory meatus and middle-ear cavities. Assumed point load of the cochlea is simplification too. These factors influence model accuracy for sure. However, the model of the human TM predicts at least qualitatively expected dynamical behaviour for the physiological TM, i.e. reasonable modal frequencies, mode shapes, TM velocities and input-output functions.

4. Conclusions

The simplified FEM model of the human tympanic membrane was built and tested. For chosen geometry, physical parameters, constraints and loads, and in spite of simplifications the TM model predicted mode shapes, modal frequencies, the input-output functions, and TM velocities in the form expected for the TM in the good physiological state. Thus, the TM model may be used in further investigation of the TM dynamic behaviour, e.g. it may be used for predictions of its malfunctions caused by physical changes or damages on the TM [12].

It is planned to improve the model of the TM including material and geometrical nonlinearities to accommodate large displacements and large strain, which is typical for biological structures. Fibrous structure of the TM and the middle-ear cavities and the external auditory meatus will be also included to model the TM anisotropy.

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