EAI Endorsed Transactions
on Pervasive Health and Technology

Research Article **EAI.EU**

Numerical simulation of human hearing system

V.M. Isailovic[1,2,]*, M.M. Nikolic[1,2], T. Bibas[3], A. Sakellarios[4], N. Tachos[4], M. S. Milosevic[1] and N.D. Filipovic[1,2]

[1]Bioengineering research and development center – BioIRC,
Prvoslava Stojanovic 6, Kragujevac, Serbia
[2]Faculty of engineering, University of Kragujevac,
Sestre Janjic 6, Kragujevac, Serbia
[3]University of Athens,
Athens 157 72, Greece
[4]University of Ioannina,
Ioannina 455 00, Greece

Abstract

Hearing impairment is a problem faced by many people, mostly the elderly population but occurs even in newborns. Experimental tests performed on patients give information of the level of hearing impairment and the place where the problem is located. In order to understand process of hearing and hearing impairments it would be very useful to have a look inside, but it is not possible with any experimental equipment. However, it is possible to make a virtual look inside human auditory system by development of numerical model. Using data obtained by experimental research it is possible to make sufficiently detailed model and use it to gain new knowledge that can help in understanding of hearing process and problems with hearing. In this paper one such model will be presented. The model contains mechanical and fluid elements of the middle and inner ear.

Keywords: middle ear, inner ear, cochlea, hearing impairments, modeling.

Received on 06 June 2017, accepted on 14 November 2017, published on 28 February 2018

doi: 10.4108/eai.28-2-2018.154144

1. Introduction

There are several parts in human hearing system. The first part is ear with external auditory canal. By this canal sounds from environment can come into hearing system. At the end of external auditory canal, tympanic membrane is placed. That membrane vibrates under acoustic excitation. After that, there is middle ear in which are placed three small bones: malleus, incus and stapes. Those three bones transmit vibrations from tympanic membrane into inner ear. Next to the middle ear is the inner ear with cochlea – bony structure with shape like snail shell. Inside cochlea there are three fluid chambers: scala tympani, scala media and scala vestibuli. Scala tympani and scala vestibuli are coupled at the apex of the cochlea. Between these two chambers, scala media is placed. In scala media there are also several parts: basilar membrane, Reissner's membrane, organ of Corti with outer and inner hair cells. Vibrations which come from tympanic membrane and which are transmited by inner ear ossicles produce oscillations of the basilar membrane. These oscillations organ of Corti, outer and inner hair cells transform into electrical impulse and send them to the brain [1].

As can be seen from the previous, in terms of physical behaviour, the most important processes are movements of elastic structures in the middle and the inner ear and fluid motion inside cochlear chambers. Those two

*Corresponding author. Email:velibor@kg.ac.rs

processes should be modeled in order to simulate physical behavior of human hearing system.

2. Methods

The numerical model for the analysis of physical behavior of the middle and inner ear includes acoustic wave equation for fluid in the cochlear chambers and Newtonian dynamic equation for the solid parts of the middle and inner ear [**Error! Reference source not found.**].

Acoustic wave equation is defined as:

$$\frac{\partial^2 p}{\partial x_i^2} - \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} = 0 \tag{1}$$

where p stands for fluid pressure inside the chambers, x_i are spatial coordinates in Cartesian coordinate system, c is the speed of sound, and t is time.

Matrix form of the acoustic wave equation, obtained by using Galerkin method [**Error! Reference source not found.**], can be presented in the following formulation:

$$Q\ddot{p} + Hp = 0 \tag{2}$$

where Q is the acoustic inertia matrix, and H represents the acoustic ”stiffness” matrix.

The motion of the solid part of the cochlea was described by Newtonian dynamics equation [**Error! Reference source not found.**], [**Error! Reference source not found.**]:

$$M\ddot{U} + B\dot{U} + KU = F^{ext} \tag{3}$$

In equation (3), M, B and K stands for mass, damping and stiffness matrix, respectively.

The real material properties of the basilar membrane (BM) are nonlinear and anisotropic. Also, dimensions of the cross-sections of the BM along the cochlea are not constant. It is known from experiments that different sounds produce different responses of the BM. Sounds with low frequency produce resonant peak near the apex and sounds with high frequency near stapes. Distance from base to the peak is proportional to the logarithm of excitation frequency (**Error! Reference source not found.**) [**Error! Reference source not found.**]. This feature is used for fitting of material or geometrical properties [**Error! Reference source not found.**], [**Error! Reference source not found.**].

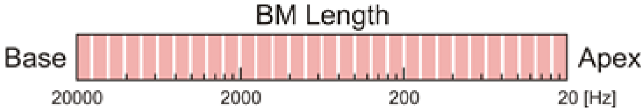

Figure 1. Logarithmic distribution of frequencies along basilar membrane. High frequencies are at the beginning (Base) and low frequencies are at the end (Apex) of the basilar membrane.

Material properties of BM are approximately orthotropic. The Young’s modulus in longitudinal direction of BM is much less then in transversal direction. That fact can be used in modeling in two different ways (Figure 1):

(i) We can approximate BM as a set of independent strips. Each strip has its own value of Young’s modulus calculated according to the logarithmic function obtained from literature [**Error! Reference source not found.**]. That function is fitted by natural frequencies, because each strip should have its own natural frequency value according to the experimentally obtained frequency map.

(ii) Another way to approximate BM is to make tapered model with variable cross section of BM [**Error! Reference source not found.**]. In that case we can use orthotropic material properties so the Young’s modulus in longitudinal direction should be negligible according to modulus in transversal direction.

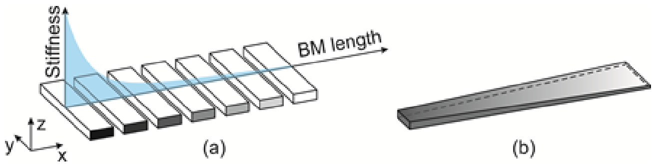

Figure 1. Variable stiffness of basilar membrane: (a) variable Young’s modulus along membrane; (b) variable cross section dimensions (thickness and width).

In first case the value of Young’s modulus is defined as a function of distance from the beginning of the basilar membrane [**Error! Reference source not found.**]:

$$E(x) = \frac{4\pi^2 f_B^2(x) A\rho\left(1-\nu^2\right)}{\beta^4 I} \tag{4}$$

where we have: $f_B(x)$- frequency distribution along the cochlear length which has exponentially decaying character [**Error! Reference source not found.**], A - cross-sectional area of the basilar membrane, ρ - density, ν - Poisson’s ratio, β - coefficient depends on the boundary conditions and I - second moment of inertia.

In second case material properties are constant along basilar membrane. Orthotropic material properties used in this case are given in table 1.

Table 1. Material properties

Symbol	Quantity	Value	Unit
E_X	Young's modulus in X direction	10^4	Pa
E_Y	Young's modulus in Y direction	10^7	Pa
E_Z	Young's modulus in Z direction	10^7	Pa
G_{XY}	Shear modulus in XY plane	$2{\cdot}10^4$	Pa
G_{YZ}	Shear modulus in YZ plane	10^6	Pa
G_{ZX}	Shear modulus in ZX plane	1	Pa
v_{XY}	Poisson's ratio in XY plane	0.005	-
v_{YZ}	Poisson's ratio in YZ plane	0.3	-
v_{ZX}	Poisson's ratio in ZX plane	0.005	-
ρ	Density of fluid	1000	kgm^{-3}

Table 1
Material properties

In the frequency analysis damping could be included using modal damping [**Error! Reference source not found.**]. In that case, inside the stiffness matrix there is an imaginary part, so equation (3) could be written in the following form:

$$M\ddot{U} + K(1+i\eta)U = F^{ext} \tag{5}$$

where η is the hysteretic damping ratio. This value is set by using exponentially increasing function as explained in [**Error! Reference source not found.**], [**Error! Reference source not found.**].

The fluid-structure interaction with strong coupling was used for solving these equations. Strong coupling means that the solution of solid element in the contact with fluid has impact on the solution of fluid element and vice versa. The coupling was achieved by the equalization of normal fluid pressure gradient with normal acceleration of solid element in the contact, as shown in equation (6).

$$n \cdot \nabla p = \rho n \cdot \ddot{u} \tag{6}$$

For the mechanical model of the cochlea we defined a system of coupled equations:

$$\begin{bmatrix} M & 0 \\ -\rho_f R & \end{bmatrix} \begin{Bmatrix} \ddot{U} \\ \ddot{p} \end{Bmatrix} + \begin{bmatrix} K(1+i\eta) & S \\ 0 & H \end{bmatrix} \begin{Bmatrix} U \\ p \end{Bmatrix} \quad \begin{bmatrix} F \\ q \end{bmatrix} \tag{7}$$

where R and S are coupling matrices [**Error! Reference source not found.**].

The solutions for displacement of the basilar membrane and pressure of fluid in the chambers were assumed in the following form:

$$U = A_U \sin(\omega t \quad \alpha)$$
$$p = A_p \sin(\omega t \quad \beta) \tag{8}$$

In equation (8), A_U and A_p represent amplitudes of displacement and pressure, respectively. The circular frequency is ω, t is time, α and β are phase shift factors.

When displacement and pressure solution (8) were substituted in the equation (7) we obtain a system of linear equations that can be solved:

$$\begin{bmatrix} K(1+i\eta) - \omega^2 M & -S \\ -\rho_f R & H \quad \omega^2 Q \end{bmatrix} \begin{Bmatrix} A_U \\ A_p \end{Bmatrix} = \begin{bmatrix} 0 \\ q \end{bmatrix} \tag{9}$$

For solving the system of equations (9), in-house numerical program was developed. The program is part of PAK software package [**Error! Reference source not found.**], [**Error! Reference source not found.**].

3 Finite element model

Finite element model developed for modeling of hearing process is presented in **Error! Reference source not found.**. The model contains several significant parts: ear drum – simply supported round structure with prescribed sound pressure level (SPL) of 90 dB; three small bones: incus, malleus and stapes, supported by several ligaments whose free ends are fixed; cochlea with outer bony structure, two elastic membranes – oval and round window, two fluid chambers and basilar membrane that separates fluid chambers. The frequency of external excitation is 1 kHz.

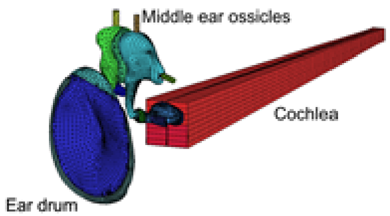

Figure 3. Finite element model of the middle ear and inner ear.

4 Results

The results obtained by using developed finite element model are presented in Fig. Here are given response of basilar membrane under excitation which comes from ear drum and pressure field distribution inside cochlear chambers. Frequency of excitation was 1 kHz.

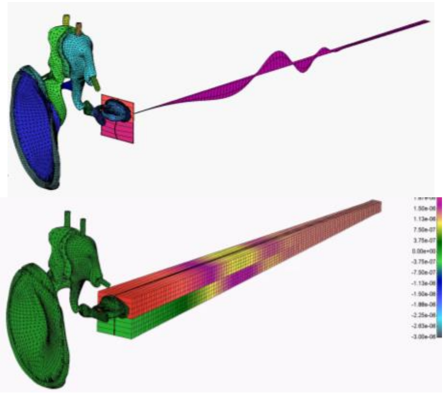

Figure 4. Vibrations of basilar membrane due to pressure excitation at ear (on the top) and pressure field distribution inside cochlear chambers (on the bottom).

In the **Error! Reference source not found.** the basilar membrane centerline displacement and their upper and lower envelopes are presented at a fixed time *t* using a simulation frequency of 1 kHz. Response of basilar membrane is normalized by the highest peak in response. Position of the resonant peak is in good agreement with experimental and literature data.

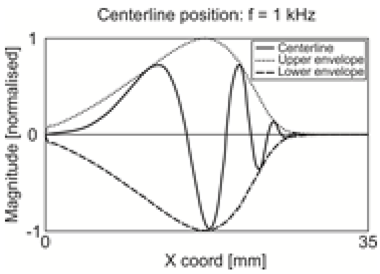

Figure 5. Position of BM centerline at some moment and upper and lower envelope of BM displacement.

5 Conclusion

Presented model was developed in order to simulate physical response of middle ear bones and inner ear fluids and structures. Using this model medical doctors can have virtual view inside physics of hearing process. It can help them in investigations regarding specific hearing problems, because some disorders and physical damages can be included in the model.

Acknowledgements.
Authors would like to acknowledge the support of the Ministry of Education, Science and Technological Development of the Republic of Serbia – projects III41007 and OI174028. This work is partly supported by EU FP7 project SIFEM, project ID 600933.

References

[1] J.O. Pickles (1988), "*An Introduction to the Physiology of Hearing*", 2nd ed. Academic Press, London.

[2] C.R. Steele (1987), "Cochlear Mechanics". In *Handbook of Bioengineering*, R. Skalak and S. Chien, Eds., pp. 30.11–30.22, McGraw-Hill, New York.

[3] David Howard, Jamie Angus (2009), "*Acoustics and Psychoacoustics*", Focal Press, Linacre House, Jordan Hill, Oxford OX2 8DP, UK Elsevier, ISBN: 978-0-240-52175-6

[4] Zienkievicz, O., C., (1983), *The finite element method*, third edition, Published by McGraw-Hill Book Co., New York, 1983, ISBN 10:0070840725 / ISBN 13:9780070840720.

[5] N. Filipovic, M. Kojic, R. Slavkovic, N. Grujovic, M. Zivkovic (2009), *PAK, Finite element software*, BioIRC Kragujevac, University of Kragujevac, 34000 Kragujevac, Serbia.

[6] M. Kojic, N. Filipovic, B. Stojanovic, & N. Kojic (2008), "*Computer Modeling in Bioengineering – Theoretical Background, Examples and Software*". John Wiley and Sons, 978-0-470-06035-3, England.

[7] Guangjian Ni (2012), "*Fluid coupling and waves in the cochlea*" – PhD thesis, University of Southampton.

[8] S.J. Elliott, Ni G, Mace BR, Lineton B., (2013) "A wave finite element analysis of the passive cochlea". *The Journal of the Acoustical Society of America*, 133(3):1535-45.

[9] Namkeun Kim, Kenji Homma, and Sunil Puria (2011), "Inertial Bone Conduction: Symmetric and Anti-Symmetric Components", *Journal of the Association for Research in Otolaryngology*, 12(3):261-79, Springer.

[10] Dallos, P. (1992). The active cochlea, *The Journal of Neuroscience*, 12(12), 4575-4585.