MODELLING OF COCHLEAR MECHANICS

Karel PELLANT[1], Daniel DUŠEK[2]

Rezumat. *Articolul de faţă descrie crearea unui model tridimensional cu elemente finite (EF) ale cohleei, adică al organului auditiv periferic al urechii interne. Forma reală şi proprietăţile mecanice reale ale cohleei umane au fost folosite pentru construirea unui model cu EF. Acest model conţine:* (1) *Capsulă osoasă ce are* 2½ *spire;* (2) *Utriculul sculei, fereastra ovală şi cea rotundă de la intrarea în ductul (canalul) cohlear;* (3) *Spaţiul spiralat cu fluid al ductului cohlear, umplut cu endolimfă;* (4) *Spaţiul spiralat cu fluid al scalei vestibulului şi al scalei timpanului, umplut cu perilimfă;* (5) *spiralele membranei bazilare şi membranei Reissler. Analiza armonică a fost aplicată pe acest model pentru a simula funcţia cohleei ca analizor de sunet. Sistemul de programe ANSYS a fost utilizat pentru crearea unui model cu EF şi pentru studiul vibraţiilor membranei bazilare. Analiza armonică a acestui model a fost evaluată pentru frecvenţe de stimulare de ordinul a* 250 Hz *până la* 10 kHz. *Stimularea a fost asigurată prin deplasarea oscioarelor scăriţei de la intrarea în scala medie, adică în fereastra ovală. Răspunsul a fost o undă progresivă în ductul cohlear, aceasta excitând vibraţiile membranei bazilare. În cazul stimulării la frecvenţe înalte, deplasarea maximă a membranei bazilare a fost localizată la capătul ei bazal şi, totuşi, în cazul unei stimulări la frecvenţe joase, deplasarea maximă a membranei bazilare a fost localizată la capătul său apical.*

Abstract. *The paper describes the creation three-dimensional finite element (FE) model of cochlea i.e. of the peripheral auditory organ of the inner ear. The real shape and real mechanical properties of human cochlea were used for the construction of FE model. The model contains:* (1) *The bony capsule showing the* 2½ *coils;* (2) *the utricle of saccule, oval and round window in the entrance of cochlear duct;* (3) *the coiling fluid space of cochlear duct filled by endolymph;* (4) *the coiling fluid spaces of the scala vestibuli and scala tympani filled by perilymph;* (5) *the spirals of basilar and Reissner´s membrane. Harmonic analysis was applied on the model to simulate the function of the cochlea as sound analyzer. The program system ANSYS was used for the creation of FE model and also for the studies of basilar membrane vibrations. Harmonic analysis of this model was evaluated for stimulating frequencies in the range of* 250 Hz *to* 10 kHz. *Stimulation was ensured via displacements of the stapes in the entrance of scala media i.e. in the oval window. The response was a traveling wave in cochlear duct, this wave excited the vibrations of basilar membrane. In the case of high frequency stimulation the maximal displacement of basilar membrane was located at its basal end, however, in the case of low frequency stimulation the maximal displacement of basilar membrane was located at its apical end.*

Keywords: modeling, human cochlea, basilar membrane, Reissner's membrane, harmonic analysis, ANSYS.

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[1] Prof., Institute of Solid Mechanics, Mechatronics and Biomechanics, Faculty of Mechanical Engineering, Brno University of Technology, Czech Republic.
[2] Eng., Institute of Solid Mechanics, Mechatronics and Biomechanics, Faculty of Mechanical Engineering, Brno University of Technology, Czech Republic.

1. Introduction

Mathematical modeling is a fertile approach to investigating the transmission characteristics of the mechanisms of hearing. Sound pressure waves are funneled through the acoustic meatus of the external ear to the tympanic membrane and mechanically transduced through the middle ear into the inner ear fluid-filled chamber (vestibulus) where the individual organs of the inner ear branch off. The anatomy of inner ear is shown in Fig. 1. The most important part of the inner ear is cochlea with membrane labyrinth. The sound-induced vibrations of basilar membrane (where sensory cells are situated) are transformed in electrical signals that are further transmitted by nerve fibers to brain. Cochlea has the shape resembling snail shell and is divided longitudinally by the basilar membrane and Reissner's membrane in three spiral ducts (scala vestibuli, scala media and scala tympani) that are full of fluid.

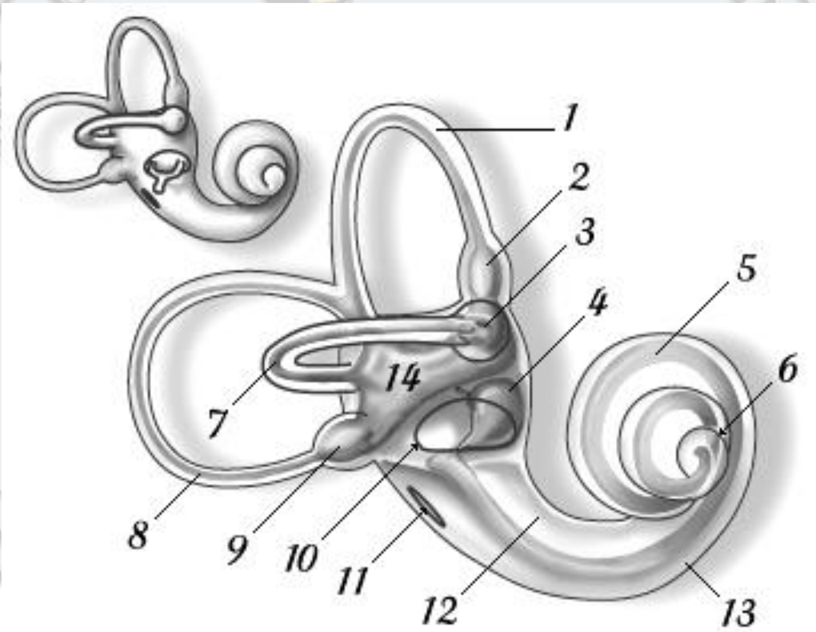


Fig. 1. Anatomy of the inner ear: 1. Anerior semicircular canal, 2. Ampulla (superior canal), 3. Ampulla (lateral canal), 4. Sacculus, 5. Cochlear duct, 6. Helicotrema, 7. Lateral (horizontal) canal, 8. Posterior canal, 9. Ampulla (posterior canal), 10. Oval window, 11. Round window, 12. Vestibular duct (scala vestibuli), 13. Tympanic duct (scala tympani), 14. Utricule.

The most important is scala media (cochlear duct), which has on cut triangular form. The scala vestibuli and the scala tympani are interconnected in the apex of the snail by a small orifice called helicotrema and they are filled with a clear fluid - perilymph. The volume of scala media is filled by endolymph and it is connected via thin duct to the utricle of sacculus. Mechanical properties of perilymph and endolymph are similar to those of water. When the stapes is pushed in the space of scala vestibuli, pressure waves start propagate in perilymph from the base of scala vestibuli to its apex. These traveling pressure waves cause bending waves of the basilar membrane and the stimulation of the sensory cells. This phenomenon was described for the first time by von Békésy [1]. According to his experimental measurements on cadaverous samples the position of the maximal amplitude of bending waves of basilar membrane should depend on frequency. Low frequency stimulation causes vibrations of the membrane close to its apical end and as the frequency increases the point of maximal amplitudes continuously transfers to its basal end. So the different nerves sensors are excited for different frequencies and the decomposition of acoustic signals into harmonic components in the inner ear is possible. Passive and active models of the cochlea are distinguished nowadays. The passive model is supposed to have the linear response with respect to the stimulation and the markedly broad region of distinct vibration amplitudes. Generally, the values of basilar membrane vibration amplitudes are supposed significantly smaller compared to the active model. On the contrary, for active models non-linear response of basilar membrane vibrations with respect to the magnitude of stimulating force is supposed and the origin of strong secondary acoustic emission is possible [2], [3]. The region of distinct amplitudes on the basilar membrane is narrow for these models.

2. Aim of work

This work aimed at creating 3D mathematical model of the human cochlea, the linear response of basilar membrane in the region of audible frequencies was supposed. Simultaneously drive for the frequency dependent position of maximal amplitudes according to Bécésy experimental results was putted on. The reasons to create the model of cochlea were following:

(1) The study of frequency characteristics of basilar membrane response;
(2) The study of possible interactions between cochlea and ossicular chain movement;
(3) The discussion of the possible relationship between mechanical defects of basilar membrane and internal auditory sensation (e.g. tinnitus-[4]);
(4) To contribute to the interpretation of audiological observations [5];
(5) The simulation of otoacoustic emission [6];
(6) Assembling of the complete mechanical model of the human ear (the model of external auditory canal, tympanic membrane, inner ear cavity and ossicle chain was yet finished).

In the present study, the movements of basilar membrane in cochlea for exciting frequencies from 250 to 10000 Hz were determined, the stimuli by the movements of stapes footplate in oval window were applied.

The finite element computational system (ANSYS 7.1) was used to solve this problem.

3. Development of model

The external sight on the finite element model of cochlea created in this work is presented in Fig. 2a. The network of three-dimensional fluid elements in the form of helix creates the fluid spaces of the saccule, scala vestibuli, scala tympani and scala media (Fig. 2b). The semicircular canals (hosting the sensors of head acceleration) were not considered are not relevant from the point of view of the auditory function. The walls representing boundary of the fluid medium were modeled as rigid ones by introducing the condition of zero displacement. The structures of basilar membrane and Reissner´s membrane were modeled as soft tissues inside of the fluid medium (Fig. 3.). The model of stapes (Fig. 4) was placed in the entry of the scala vestibuli i.e. in the oval window. The geometry of the model and the volumes of the scala vestibuli, the scala media and the scala tympani were adopted from the results of measurements of real human cochlea [7]. According to this source, the volume of fluid medium in the scala vestibuli, the scala media and the scala tympani is $5{,}1\cdot 10^{-8}$ m^3. The volume of the complete finite element model presented in this work is $5{,}638\cdot 10^{-8}$ m^3. Overall height of the cochlea was considered to be v=3,67 mm. This height was achieved by turning upward two and half threads of helix, the changing cochlea cross section was considered. From the point of view of basilar membrane design we assumed according to the literature data [7] the dependency of the diameter of helix on the angle θ of the thread turn according to the relation

$$R\ (\theta)=c_I\ exp\ (c_{II}\ \theta\ ). \tag{1a}$$

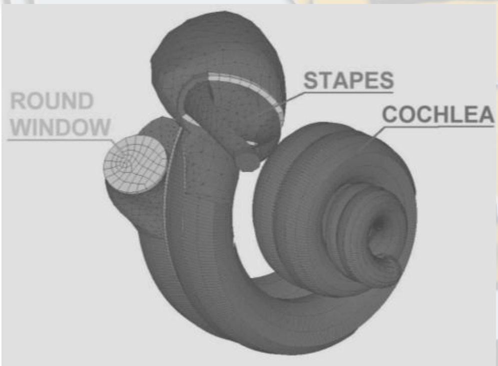


Fig. 2a. Cochlea model-external sight

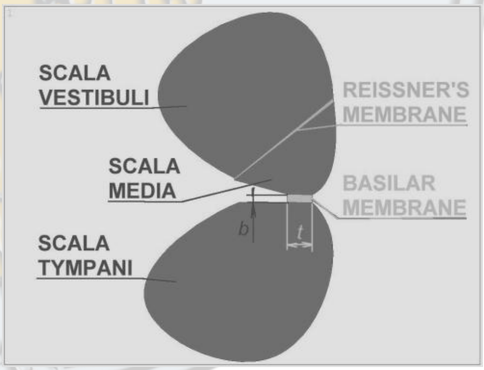


Fig. 2b. Cochlea model-crossection

Similarly the height of the thread changed with θ according to the equation

$$z(\theta)=c_{III}\ \theta. \tag{1b}$$

The angle θ is in the interval (0–4,75 rad), the constants c_I , c_{II} and c_{III} have values: c_I =4,5.10^{-}4m, c_{II} =0,3 rad^{-1} and c_{III} =4,3.10^{-6} m/rad. Logarithmic course of the rigidity is usually mentioned in literature (e.g. [8]), the minimum respectively the maximum of rigidity is supposed on its apical respectively basal end.

There were not founded the informations about mechanical properties of the basilar membrane in literature that would correspond to the above mentioned logarithmic course of rigidity. As the progressive enhancement of the membrane material stiffness seems to be not probable, we assumed that the membrane has constant material property, however, we had considered variable thickness and variable width of the membrane. Some numerical experiments were necessary to find suitable type function and right values of function parameters. Finally the thickness t of the basilar membrane was considered to increase logarithmically from its apical end to its basal end according to the formula

$$t(\theta)=c_{IV}\exp(c_V z(\theta)), \qquad (2)$$

where c_{IV} and c_V are the constants: $c_{IV}=1{,}2\cdot10^{-5}$ m, $c_V=581{,}39$ m^{-1}.

The height of the thread $z(\theta)$ changed according to the equation (1b). According to this Equation (2), the thickness of the basilar membrane on its apical end was $t_{APEX}=1{,}2\cdot10^{-5}$ m and the thickness on its basal end was $t_{BASE}=1{,}02\cdot10^{-4}$ m.

The width b of the membrane was considered to increase linearly with θ according to the formula

$$b(\theta)= c_{VI}-(c_{VII}\,\theta), \qquad (3)$$

where the values of constants c_{VI} and c_{VII} are: $c_{VI}=5{,}0.\ 10^{-4}$ m and $c_{VII}=4{,}651$m/rad. Therefore the width of the apical and basilar end of the membrane passed the values from the value $b_{APEX}= 5{,}0.\ 10^{-4}$ m to the value $b_{BASE}=1{,}0.10^{-4}$ m.

The material characteristics of the basilar and Reissner´s membranes were supposed linearly elastic and isotropic, their values are presented in Table 1.

The coefficient of damping c of the structural part was set constant c=0,1. For the fluid medium of the scala vestibuli, scala media and scala tympani was considered constant density ρ=1100 kg/m^3 and the sound velocity v=1550 m/s.

From the point of view of the absorption on the inner bony walls of the cochlea, the coefficient of the absorption MU=0,5 was considered.

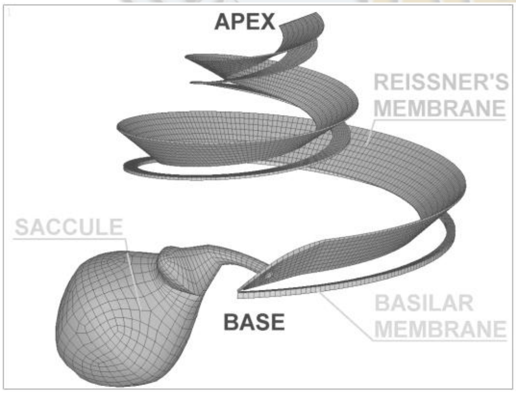


Fig. 3. Elastic parts of cochlea model.

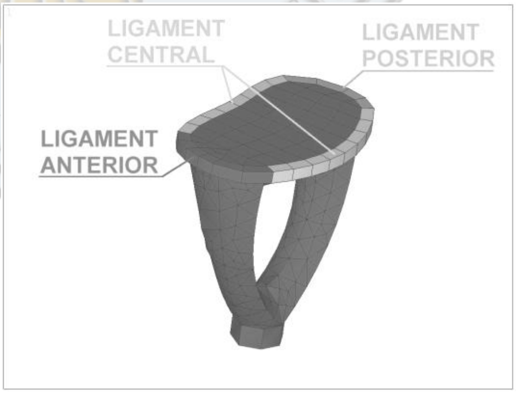
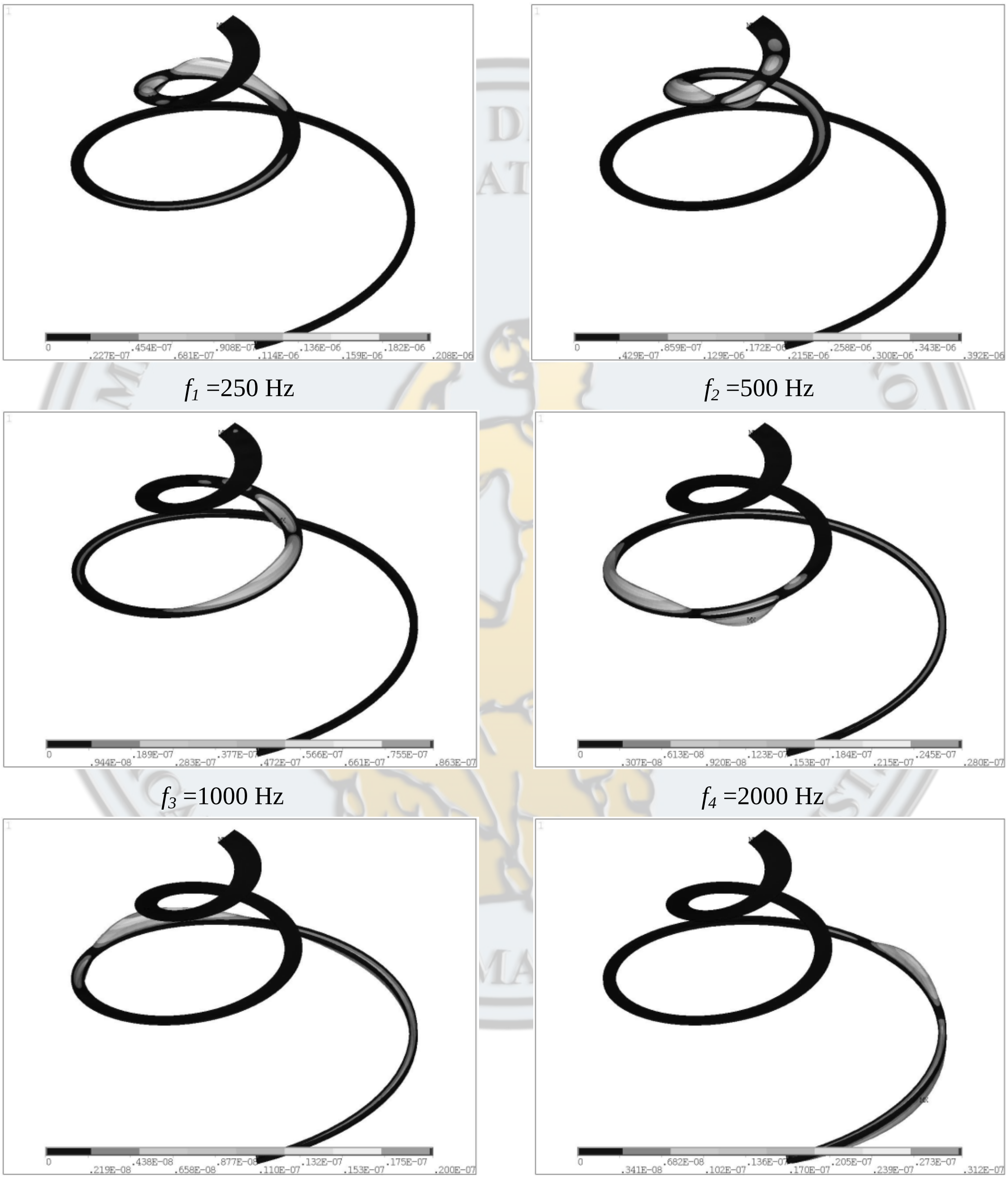


Fig. 4. Model of stapes.

To solve the problem in ANSYS, the elements SOLID45 were used for structural part of the model (i.e. for the membranes, for the stapes with ligaments and for the walls of saccule). These elements create 8 node hexahedrons with linear basal functions in their non-degenerated form and they have, three degrees of freedom are in every node (three displacements along axes *x*,*y*,*z*).



f_1 =250 Hz f_2 =500 Hz

f_3 =1000 Hz f_4 =2000 Hz

f_5 =4000 Hz f_6 =8000 Hz

Fig. 5. Amplitudes of travelling wave on basilar membrane.

Elements FLUID30 were used for the fluid medium of the scala vestibuli, scala media and scala tympani. Each element FLUID30 had on the boundary with the structure four degrees of freedom (pressure and three displacements along the axes *x,y,z*). Only one degree of freedom (pressure) was considered for the junctions of the elements FLUID30 located inside of the fluid medium. To solve the problem, 8714 elements of SOLID45, 35487 elements of Fluid 30 with four degrees of freedom and 18135 elements FLUID30 with one degree of freedom was used. Altogether, the task had 128766 degrees of freedom.

4. Results

Harmonic analysis in the range of frequencies 250 Hz to 10 kHz was applied on the described cochlea model. The movement of the stapes in the entrance of the scala vestibuli i.e. the displacement boundary condition (in the perpendicular direction to the oval window) was considered for the stimulation, the amplitude value of the displacement was taken $1{,}0.10^{-8}$ m. First of all the response of basilar membrane was studied.

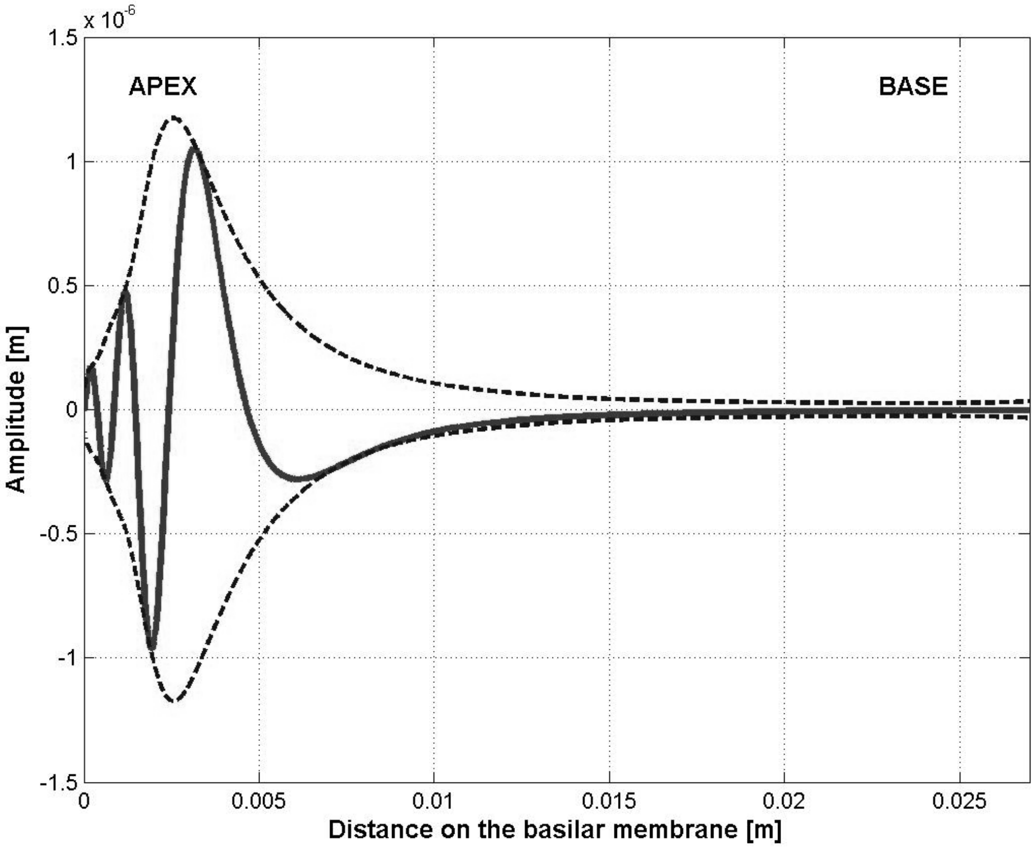


Fig. 6. The snapshot of basilar mebrane vibrations (full line) and the envelope of these vibrations (dashed line) for stimulation frequency f_1 =250 Hz.

The shapes of the traveling bending waves on the basilar membrane for the frequency f_1=250 Hz, f_2 =500 Hz, f_3 =1000 Hz, f_4 =2000 Hz, f_5 =4000 Hz and f_6 =8000 Hz are shown in Fig. 5, the frequency dependent shift of the maximal amplitude position is obvious. It is clearly seen that for low frequency f_1 =250 Hz the maximal displacements occur close to apical end and that it is the continuous shift of the maximal amplitude position from the apical to basal end with increasing frequency, the position of maximal amplitude for the high stimulating frequency f_6 =8000 Hz occurs already very close to the basal end. It is also easy to see that if stimulating frequency increases, the position of the maximal amplitude increases continuously from the apical to the basal end. The envelopes of the time impulses were calculated using Hilbert transformation of the time array to determine the position of the maximal amplitude more precise (program system Matlab was applied). The result of such processing for the frequency f_1 =250 Hz is in the Fig. 6 . The envelopes of individual time impulses arising for individual harmonic stimulating frequencies are shown in Fig. 7.

The dependence of the pressure on frequency was determined in the entrance of scala vestibuli, at the apical end of scala tympani and at the basal end of the scala tympani - Fig. 8.

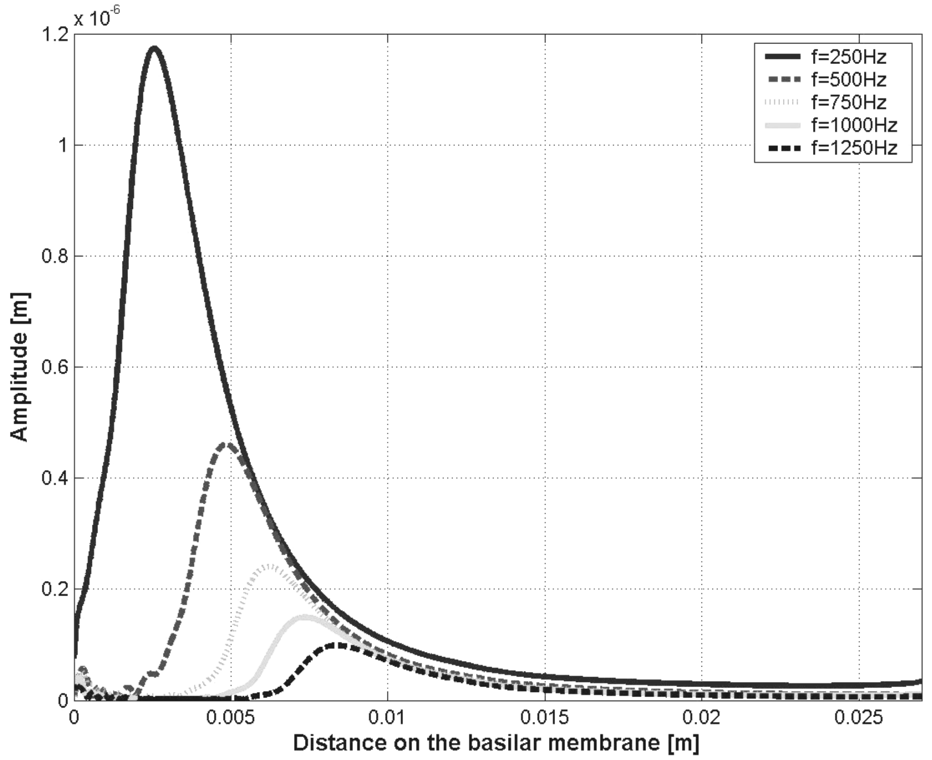


Fig. 7. The envelopes of basilar membrane vibrations for different stimulation frequencies.

It is obvious from this picture, that for the same frequency of stapes movements, an increase of acoustic pressure with frequency occurs in the close proximity of the stapes due to increase of acoustic velocity. The value of the acoustic pressure at 10 kHz is about 100 Pa, while at 250 Hz it is only about 5 Pa. However, in due of the influence of the absorption on the cochlear duct walls, such pronounced changes of the pressure with frequency do not occur for the positions more outlying from the entrance of scala vestibuli. Simultaneously the pressure gradient compensation on basilar membrane via helicotrema probably also occurs.

Therefore the pressure decreases with increasing frequency from the value round 3 Pa to the value 1 Pa close to helicotrema. At the basal end of the scala tympani a tiny pressure increase with frequency (from 1 Pa to 5 Pa) can be seen. This phenomenon is probably the result of interaction of the fluid medium in scala tympani with basilar membrane, when - just on high frequencies - the flexure of basilar membrane achieves its maximal amplitude at the basal end.

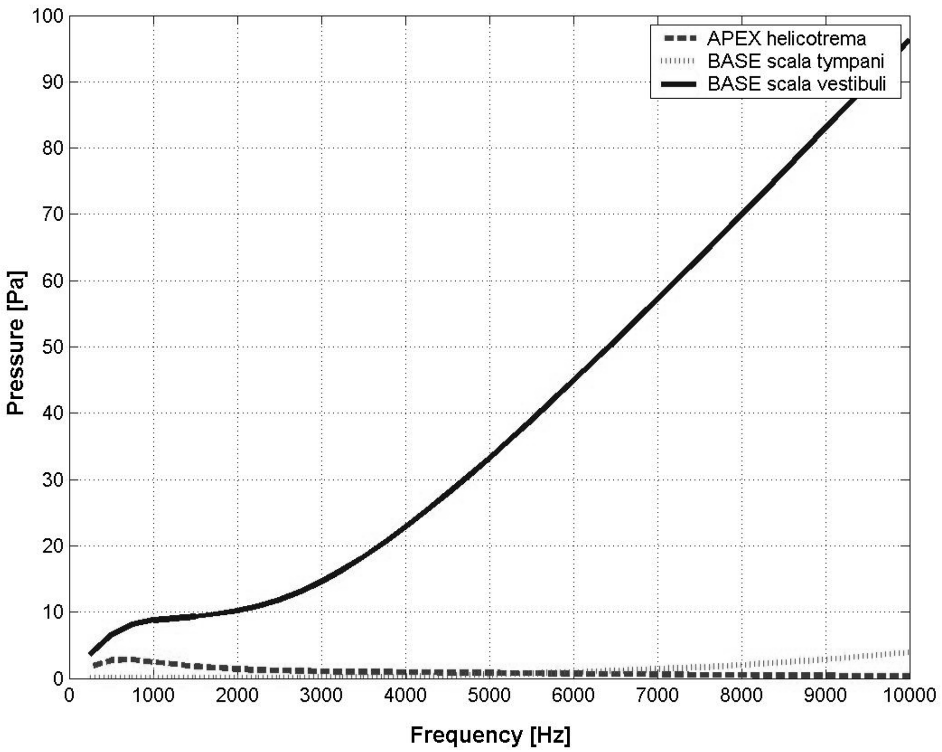


Fig. 8. The pressure response for different positions of the receiver:
basal end of scala vestibuli-continuous line; the apical end of scala vestibuli - dashed line;
basal end of the scala tympani-dotted line.

That way the fluid medium in scala tympani on the basal end is on high frequencies compressed by basilar membrane and the increase of pressure occurs compared to lower frequencies.

The analysis of acoustic pressure distribution inside of cochlea exhibited that the values of pressure in scala tympani up to 5 kHz are lower than those in helicotrema and that above this frequency.
Simutaneously the video observations detected the impact of basilar membrane vibrations on pressure distribution in cochlea and minimal pressure transmission from scala vestibuli into scala tympani.

Conclusions

As a result of our mathematical modeling the functioning of human cochlea as frequency analyzer was confirmed pursuant to the mechanical response from the stapes movements. The conformity with the results of Békésy experiments was achieved i.e. the position of maximal amplitude vibrations of basilar membrane was depending on frequency. The maximal amplitude of basilar membrane vibrations was located close to the apical end of the cochlea in the case of low frequencies and the continuous shift of the maximal amplitude to the basal end with increasing frequency was achieved. Furthermore, the pressure distribution in the cochlea for the stimulation by movements of the stapes in the oval window was determined.

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