ECCOMAS Congress 2016
VII European Congress on Computational Methods in Applied Sciences and Engineering
M. Papadrakakis, V. Papadopoulos, G. Stefanou, V. Plevris (eds.)
Crete Island, Greece, 5–10 June 2016

PRELIMINARY STUDY TO INVESTIGATE THE EFFECT OF PISTON-LIKE AND ROCKING MOTIONS OF THE STAPES FOOTPLATE ON THE BASILAR MEMBRANE VIBRATION

Philipp Wahl, Sebastian Ihrle, Pascal Ziegler, and Peter Eberhard

Institute of Engineering and Computational Mechanics, University of Stuttgart,
Pfaffenwaldring 9, 70569 Stuttgart, Germany
{philipp.wahl, pascal.ziegler, peter.eberhard}@itm.uni-stuttgart.de

Keywords: Biomechanics, Cochlea, Basilar Membrane Vibration, Stapes Footplate, Piston-like Motion, Rocking Motion.

Abstract. *The inner ear or cochlea is a bone structure of spiral shape and is composed of mainly two conical chambers which are filled with fluid and separated by a soft membrane, the basilar membrane. In case of a healthy ear, the closed hydraulic system is excited through the vibration of the stapes. According to present hearing theory, this leads to pressure waves in the cochlear fluid which in turn results in the characteristic vibration behavior of the basilar membrane. Related to the sound frequency, hair cells in certain areas of the basilar membrane are stimulated and cause hearing nerve stimulation.*

As reported in literature, the stapedial motion is mainly piston-like for low frequencies, whereas for higher frequencies rocking motions increasingly occur. Since purely rocking motions of the stapes footplate generate no net fluid displacement, several researches doubt that these motion components can lead to basilar membrane vibration and thus to hearing impression. Therefore, in this study a Finite Element model with simplified geometry of the human cochlea is developed using Eulerian-based acoustic elements to model the inner ear fluid. First the vibrations of the basilar membrane are calculated for a purely piston-like excitation mode. Then, these results are compared with the basilar membrane vibration pattern evoked by purely rocking motion around the short axis of the stapes footplate.

1 INTRODUCTION

The inner ear or cochlea is the sensory organ where mechanical vibrations are transferred to nerve stimuli. It is a bone structure of spiral shape and is composed of conical chambers which are filled with fluid and separated by a soft membrane, the basilar membrane. At the apical end, the upper chamber, scala vestibuli, is connected to the lower chamber, scala tympani, through the helicotrema. At the basal end, the scala tympani is closed by the soft round window membrane, whereas the scala vestibuli is linked to the fluid-filled vestibulum. This in turn is connected to the middle ear through the stapes located at the top of the vestibulum. The cochlea can, therefore, be considered as a closed hydraulic system with fluid properties similar to water.

For a healthy ear, sound is received by the eardrum, transmitted through the middle ear ossicular chain and finally excites the hydraulic system through the vibration of the stapes footplate. The stapedial vibration leads to the propagation of pressure waves in the cochlear fluid which in turn results in the characteristic vibration of the basilar membrane. According to present hearing theory, the oscillation of the basilar membrane reaches a maximum amplitude at a characteristic location along the cochlear partition, which depends on the excitation frequency. This behavior is also called tonotopy. Particularly at this frequency-depending location, hair cells on the basilar membrane are stimulated and cause hearing nerve stimulation.

Experiments on temporal bones indicate, that the physiological motion of the stapes footplate is mainly piston-like for acoustic stimulation frequencies below $1\,\mathrm{kHz}$. For higher frequencies, the rocking motions along the long and short axis of the stapes footplate become increasingly dominant and the stapes footplate motion becomes complex [1, 2]. However, it is not clarified whether and to what extend these rocking motions are capable to evoke the characteristic basilar membrane vibration, because these rotational components lead to no net fluid displacement in the scala vestibuli [3]. Since the cochlea with its complex geometry represents a closed hydraulic system, the small vibrations of the basilar membrane and fluid pressure distributions are almost impossible to measure. Therefore, in this study a Finite Element (FE) model of the inner ear with simplified geometry is developed. First the basilar membrane vibration due to purely piston-like stapes footplate motion is investigated. Then, these results are compared with the basilar membrane vibration resulting from purely rocking motions of the stapes.

2 FE MODEL

In the following section, the geometry, material properties, and applied boundary conditions for the simplified FE model of the human cochlea are presented. Since the cochlear fluid is slightly compressible and represents an enclosed fluid volume with no mean flow, acoustic elements are used to describe the behavior of the inner ear fluid. The discretized equation for the pressure-formulated, linear acoustic elements as well as the formulation between acoustic and structural elements to describe the cochlear fluid-structure interactions are introduced.

2.1 Geometry, material properties, and boundary conditions

The FE model with its simplified geometry is shown in Figure 1. For preliminary investigations, the chambers are modeled cube-shaped and uncoiled. The fluid-filled scala vestibuli and scala tympani are divided through the basilar membrane, which is embedded in the rigid bony wall. At the apex, the chambers are connected through the helicotrema. At the base, the scala vestibuli is linked to the fluid-filled vestibulum, which interacts with the middle ear through the stapes footplate. The scala tympani, however, is closed by the round window membrane which is embedded in the lateral basal wall.

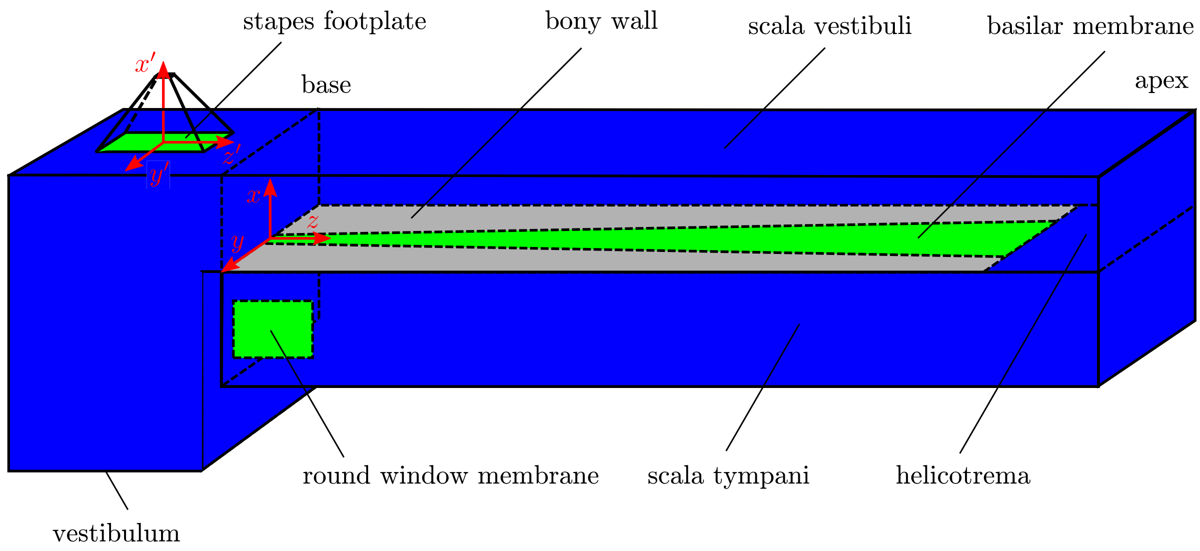

Figure 1: Model of the human cochlea with simplified geometry.

The dimensions of the cochlear fluid spaces and structural components are summarized in Table 1 and are gathered from anatomical data published in literature, from the evaluation of additional CT-data or from other cochlea FE models. The fluid chambers have a width of $1.37\,\mathrm{mm}$ and are slightly different in height, thus the fluid volume of the scala vestibuli is slightly lower compared to that of the scala tympani. The entire cochlea model has a length of $35.9\,\mathrm{mm}$. It should be noted, that the width of the basilar membrane increases from base towards the apex, in contrast its thickness decreases along the cochlear partition. Taking into account the area of the stapes footplate and round window membrane reported in literature, their shapes are assumed to be rectangular.

The material properties used for the FE model are listed in Table 2. The density, viscosity, and sound velocity of the inner ear fluid are in the same range as water [19]. As reported in literature, the basilar membrane comprises transversally orientated fibers which are embedded in an elastic ground substance. Therefore, the orthotropic material formulation described in [20] for a guinea pig is used fitting the Young's modulus to that of a human basilar membrane [13]. Further, a structural damping for the basilar membrane is applied with a modal damping of $\xi = 0.1$. For the round window membrane linear elastic material properties are assumed. The rims of the basilar and round window membrane have fixed translations. The stapes footplate and bony wall are represented as rigid bodies, the latter one is additionally fixed in space.

2.2 Coupling acoustic with structural elements for fluid-structure interaction

The FE model is created using ANSYS Mechanical APDL 15.0. The structural components are meshed with standard shell elements. For the fluid domain the pressure-formulated or Eulerian-based acoustic elements are used, referred to as FLUID30 in ANSYS. The acoustic wave equation for a fluid with viscosity η_f, sound velocity c_f, and density ρ_f is defined by

$$\nabla^2 p - \frac{1}{c_\mathrm{f}^2}\frac{\partial^2 p}{\partial t^2} + \frac{4\eta_\mathrm{f}}{3\rho_\mathrm{f} c_\mathrm{f}^2}\nabla^2\frac{\partial p}{\partial t} = 0. \tag{1}$$

The equation describes the spatial propagation of pressure waves in a fluid with no net flow rate and no source, neglecting effects of thermal conductivity. Further, a compressible fluid

Table 1: Dimensions of the cochlea model.

fluid spaces			
vestibulum	volume	$50\,\mathrm{mm}^3$	[4, 5]
scala vestibuli	volume	$35.3\,\mathrm{mm}^3$	[6, 7, 8, 9, 10]
scala tympani	volume	$44.2\,\mathrm{mm}^3$	[6, 7, 8, 9, 10]
helicotrema	area (y x z)	$0.64\,\mathrm{mm}^2(1.37\,\mathrm{x}\,0.46\,\mathrm{mm})$	[7]
structural components			
basilar membrane	length	$30.4\,\mathrm{mm}$	[11]
	width basal	$0.1\,\mathrm{mm}$	[12, 13, 5]
	width apical	$0.5\,\mathrm{mm}$	[12, 13, 5]
	thickness basal	$7.5\,\mu\mathrm{m}$	[12, 13, 14]
	thickness apical	$2.5\,\mu\mathrm{m}$	[12, 13, 14]
bony wall	length	$30.4\,\mathrm{mm}$	
	width	$1.37\,\mathrm{mm}$	
	thickness basal	$7.5\,\mu\mathrm{m}$	
	thickness apical	$2.5\,\mu\mathrm{m}$	
round window membrane	area (x x z)	$2.1\,\mathrm{mm}^2(1.04\,\mathrm{x}\,2\,\mathrm{mm})$	[15]
	thickness	$65\,\mu\mathrm{m}$	[16, 17]
stapes footplate	area (y' x z')	$3\,\mathrm{mm}^2(1.18\,\mathrm{x}\,2.5\,\mathrm{mm})$	[18]

where density changes are due to pressure variations is assumed and the equation is limited to relatively small pressures p, such that the changes in density are small compared to the mean density. By discretizing Eq. 1, the finite element equation for the pressure-formulated, linear acoustic element is

$$\mathbf{M}_\mathrm{f}\,\ddot{\mathbf{p}} + \mathbf{C}_\mathrm{f}\,\dot{\mathbf{p}} + \mathbf{K}_\mathrm{f}\,\mathbf{p} = \mathbf{F}_\mathrm{f}, \tag{2}$$

where $\mathbf{M}_\mathrm{f}$, $\mathbf{C}_\mathrm{f}$ and $\mathbf{K}_\mathrm{f}$ are the equivalent fluid mass, damping and stiffness matrices. Further, $\mathbf{F}_\mathrm{f}$ represents the vector of applied fluid loads and $\mathbf{p}$ the vector of the unknown nodal acoustic pressures.

To describe the interaction between the inner ear fluid and the stapes footplate, basilar membrane and round window membrane, the acoustic pressure is related to the resulting normal displacement of the structure, using a coupling matrix $\mathbf{R}$ that accounts for the effective surface area associated with each node on the interface. This leads to the equations of the two-way coupled fluid-structure interaction problem

$$\begin{aligned}\mathbf{M}_\mathrm{f}\,\ddot{\mathbf{p}} + \mathbf{C}_\mathrm{f}\,\dot{\mathbf{p}} + \mathbf{K}_\mathrm{f}\,\mathbf{p} &= \mathbf{F}_\mathrm{f} - \rho_\mathrm{f}\mathbf{R}^T\ddot{\mathbf{u}}, \\ \mathbf{M}_\mathrm{s}\,\ddot{\mathbf{u}} + \mathbf{C}_\mathrm{s}\,\dot{\mathbf{u}} + \mathbf{K}_\mathrm{s}\,\mathbf{u} &= \mathbf{F}_\mathrm{s} + \mathbf{R}\mathbf{p}.\end{aligned} \tag{3}$$

There, $\mathbf{M}_\mathrm{s}$, $\mathbf{C}_\mathrm{s}$ and $\mathbf{K}_\mathrm{s}$ are the structural fluid mass, damping and stiffness matrices, $\mathbf{F}_\mathrm{s}$ is the vector of applied structural loads and $\mathbf{u}$ is the vector of unknown nodal displacements. These equations can be formed into a matrix equation, where the assembled mass and stiffness matrices are unsymmetric. Using the linear pressure-formulated acoustic elements to model the fluid domain, the FLUID30-element in ANSYS has one pressure DOF and three additional displacement DOFs at the fluid-structure interface. However, elements inside the fluid domain have only pressure DOFs. For the FLUID30-elements located on the exterior surfaces of the scala vestibuli, scala tympani and vestibulum, the absorption coefficient is set to zero representing a rigid wall boundary condition.

Table 2: Material properties for the cochlea model.

cochlear fluid			
density	ρ_f	$1000\,\mathrm{kg/m^3}$	[19]
viscosity	η_f	$0.001\,\mathrm{Pa\,s}$	[19]
sound velocity	c_f	$1500\,\mathrm{m/s}$	[19]
basilar membrane			
Young's modulus	basal $E_{y,\mathrm{b}}$	$50\,\mathrm{MPa}$	[13]
	apical $E_{y,\mathrm{a}}$	$3\,\mathrm{MPa}$	[13]
	$E_x = E_z$	$E_{y,\mathrm{a}}$	[20]
shear modulus	$G_{xy} = G_{xz} = G_{yz}$	$E_{y,\mathrm{a}}/2.99$	[20]
Poisson ratio	$\nu_{xy} = \nu_{zy}$	$0.49E_{y,\mathrm{a}}/E_y$	[20]
	ν_{xz}	$1-(0.49E_{y,\mathrm{a}}/E_y)$	[20]
modal damping	ξ	0.1	
round window membrane			
density	ρ_rw	$1200\,\mathrm{kg/m^3}$	[13]
Young's modulus	E_rw	$0.35\,\mathrm{MPa}$	[13]
Poisson ratio	ν_rw	0.3	[13]

3 RESULTS

The cochlea model is excited by the motion of the stapes footplate. In this study, first the vibration of the basilar membrane due to purely piston-like motion of the stapes footplate along the x' axis for $0.5, 1, 2$ and $4\,\mathrm{kHz}$ is investigated. Then, these results are compared at $1\,\mathrm{kHz}$ with the basilar membrane vibration pattern for purely rocking motion around the short axis y' of the footplate. For both excitation modes, physiological amplitudes are used and applied to the rigid stapes footplate as kinematic boundary conditions, Table 3. For the following results, the transversal deflections in x-direction of the steady basilar membrane vibration are evaluated in the xz-plane.

Table 3: Displacement amplitude x' (piston-like) and rotational amplitude $\beta_{y'}$ (rocking) applied to the stapes footplate to excite the cochlea model. The amplitudes are gained from physiological data [2] for an ear canal pressure of $1\,\mathrm{Pa}$.

frequency	$0.5\,\mathrm{kHz}$	$1\,\mathrm{kHz}$	$2\,\mathrm{kHz}$	$4\,\mathrm{kHz}$
piston motion x' $[\mathrm{nm}]$	1.80	38.20	7.96	1.99
rocking motion $\beta_{y'}$ $[\mu\mathrm{rad}]$		7.96		

For an excitation frequency of $1\,\mathrm{kHz}$, the transversal deflections of the basilar membrane for three discrete time points of a cycle as well as the envelope of the membrane pattern is shown in Figure 2.

The piston-like motion of the stapes footplate leads to a vibration of the basilar membrane. Due to the fluid viscosity and the structural damping, adjacent partitions of the basilar membrane vibrate with an increasing delay in phase from base towards the apex. The spatially moving oscillation nodes result in a travelling wave of the basilar membrane. Thereby, the amplitude increases from the base towards the apex reaching a maximum amplitude at a char-

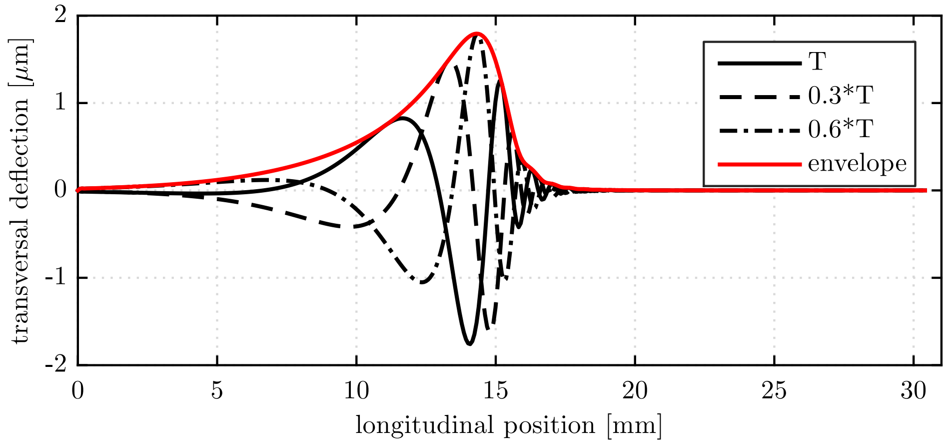

Figure 2: Vibration of the basilar membrane due to piston-like excitation for $x' = 38.2\,\mathrm{nm}$ at $1\,\mathrm{kHz}$.

acteristic point along the cochlea indicated by the envelope in Figure 2. Beyond this point, the amplitude decreases rapidly and the adjacent apical domain of the basilar membrane remains at rest. Further, the basilar membrane vibrations for the piston-like stapedial amplitudes according to Table 3 are calculated. The basilar membrane amplitudes for excitation frequencies of $0.5, 1, 2$ and $4\,\mathrm{kHz}$ are shown in Figure 3.

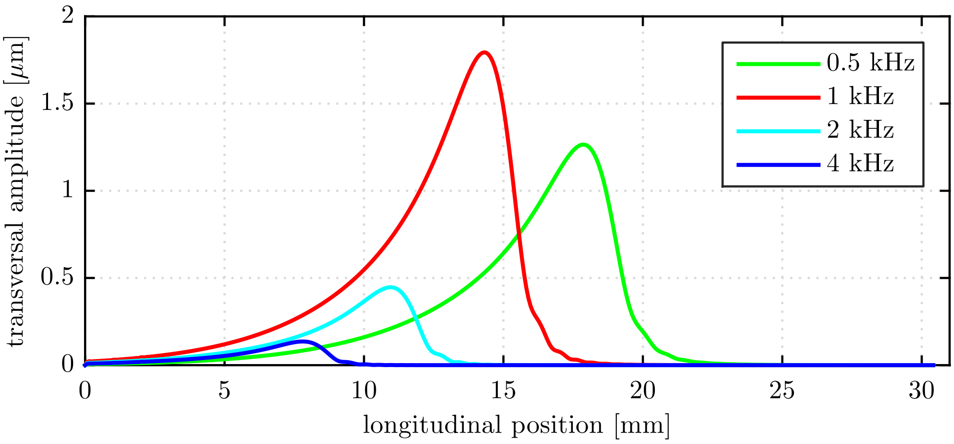

Figure 3: Envelopes of the basilar membrane vibration due to piston-like stapes footplate motion for different excitation frequencies.

By increasing the excitation frequency, the maximum amplitude is shifted towards the base of the cochlear partition. This behavior leads to a unique mapping of each excitation frequency to a distinct location along the basilar membrane. This tonotopic behavior as well as the vibration pattern of the basilar membrane are in agreement with the present hearing theory, described in Section 1. Comparing the maximum basilar membrane amplitudes for the different excitation frequencies, the global maximum amplitude occurs for an excitation frequency of $1\,\mathrm{kHz}$. Assuming, that the amplitude at the characteristic place is a measure for the perceived sound intensity, this result is consistent with the lowest hearing threshold level for human ears at around $1\,\mathrm{kHz}$ [21].

Finally, the cochlea model is excited by rocking motion around the short axis of the stapes footplate with an amplitude of $\beta_{y'} = 7.96\,\mu\mathrm{rad}$. The normalized envelope and the transversal deflections of the basilar membrane for one point of time of a cycle are shown in Figure 4.

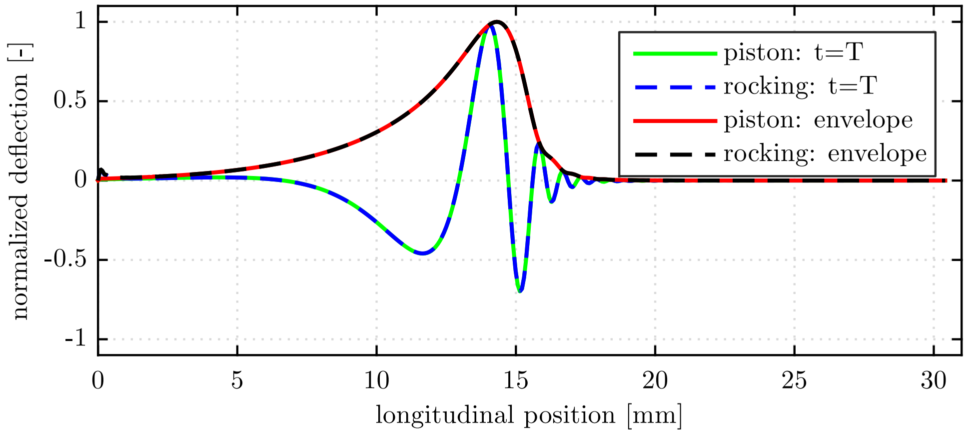

Figure 4: Vibrations of the basilar membrane at $1\,\mathrm{kHz}$ for purely piston-like and rocking motions of the stapes footplate.

For an excitation frequency of $1\,\mathrm{kHz}$, the rocking motion of the stapes footplate leads to a vibration of the basilar membrane. The comparison with the normalized membrane deflections of Figure 2 shows, that the evoked basilar membrane pattern is the same as for the piston-like excitation mode. Obviously, the vibration pattern of the basilar membrane depends primarily on the excitation frequency, not on the mode of excitation. Except in the basal domain, slight differences in the vibration pattern are visible resulting from differences between the basal fluid pressure distributions, Figure 5.

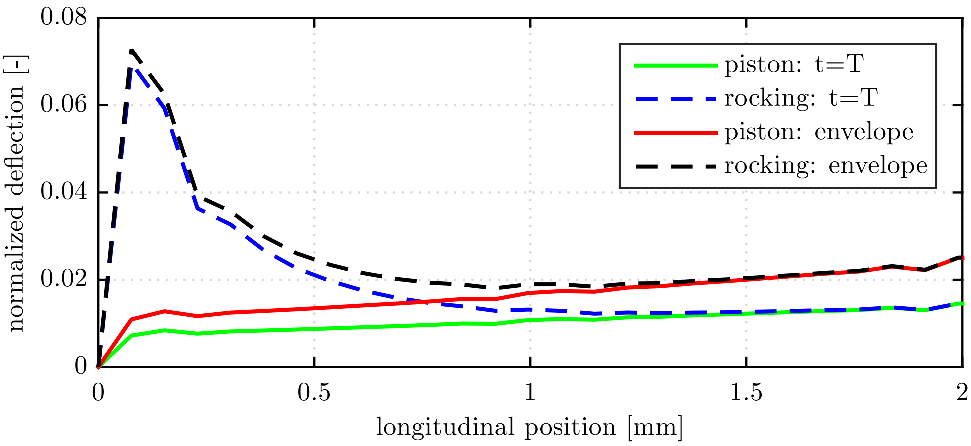

Figure 5: Vibrations of the basilar membrane in the basal domain for 1 kHz.

For the excitation frequency of $1\,\mathrm{kHz}$, the maximum amplitude of the basilar membrane due to stapedial rocking motion is around $43\,\mathrm{dB}$ lower compared with that for the piston-like motion. Thus, for this excitation frequency the contribution of stapedial rocking motion to hearing impression is assumed to be low. However, at this frequency the amplitude of the piston-like motion of the stapes footplate is maximum and decreases considerably for higher frequencies, Table 3. Therefore, further investigations are intended to study the vibration of the basilar membrane over the entire auditory frequency range for both modes of excitation.

4 CONCLUSION

In this study, an FE model of the human cochlea with a simplified geometry is developed. Using Eulerian-based acoustic elements to describe the inner ear fluid, the related equations for the two-way coupled fluid-structure interaction are described. For the piston-like motion of the stapes footplate, the FE model represents the characteristic basilar membrane vibration with a distinct maximum amplitude along the cochlear partition and the results are in agreement with the tonotopic hearing theory. It is further found that also purely rocking motion around the short axis of the stapes footplate is capable to evoke the characteristic basilar membrane vibration. Apart from slight differences in the basal domain, the resulting patterns of the basilar membrane for both excitation modes are identical. For an excitation frequency of $1\,\mathrm{kHz}$, the maximum basilar membrane amplitude due to rocking motion of the stapes footplate is around $43\,\mathrm{dB}$ lower than for the piston-like motion. However, according to physiological data the stapedial amplitude for the piston-like motion decreases for higher frequencies. Therefore, in a next step the basilar membrane vibrations for both excitation modes need to be studied for the entire auditory frequency range.

REFERENCES

[1] Asai, M.; Roberson, J.B.; Goode, R.L.: Acoustic Effect of Malleus Head Removal and Tensor Tympani Muscle Section on Middle Ear Reconstruction. Laryngoscope, Vol. 107, pp. 1217–1222, 1997.

[2] Sim, J.H.; Chatzimichalis, M.; Lauxmann, M.; Röösli, C.; Eiber, A.; Huber, A.: Complex Stapes Motion in Human Ears. Journal of the Association for Research in Otolaryngology, Vol. 11, No. 3, pp. 329–341, 2010.

[3] Hato, N.; Stenfelt, S.; Goode, R.L.: Three-Dimensional Stapes Footplate Motion in Human Temporal Bones. Audiology & Neuro-Otology, Vol. 8, pp. 140–152, 2003.

[4] Tinz, L.: Drei-dimensionale Rekonstruktion des menschlichen Mittel- und Innenohres. Doctoral thesis, Technische Universität München, 2005.

[5] Koike, T.; Sakamoto, C.; Sakashita, T.; Hayashi, K.; Kanzaki, S.; Ogawa, K.: Effects of a Perilymphatic Fistula on the Passive Vibration Response of the Basilar Membrane. Hearing Research, Vol. 283, pp. 117–125, 2012.

[6] Braun, K.; Böhnke, F.; Stark, T.: Three-Dimensional Representation of the Human Cochlea Using Micro-Computed Tomography Data: Presenting an Anatomical Model for Further Numerical Calculations. Acta Otolaryngologica, Vol. 132, pp. 603–613, 2012.

[7] Penteado, C.: Geometric Reconstruction of a Human Cochlea With Basis on Micro-CT Images. Tech. rep., Institute of Engineering and Computational Mechanics, 2011.

[8] Wysocki, J.: Dimensions of the Human Vestibular and Tympanic Scalae. Hearing Research, Vol. 135, pp. 39–46, 1999.

[9] Thorne, M.; Salt, A.N.; DeMott, J.E.; Henson, M.M.; Henson, O.W.; Gewalt, S.L.: Cochlear Fluid Space Dimensions for Six Species Derived From Reconstructions of Resonance Images. Laryngoscope, Vol. 109, pp. 1661–1668, 1999.

[10] Igarashi, M.; Ohashi, K.; Ishii, M.: Morphometric Comparison of Endolymphatic and Perilymphatic Spaces in Human Temporal Bones. Acta Otolaryngologica, Vol. 101, pp. 161–164, 1986.

[11] Poznyakovskiy, A.A.; Zahnert, T.; Kalaidzidis, Y.; Lazurashvili, N.; Schmidt, R.; Hardtke, H.J.; Fischer, B.; Yarin, Y.M.: A Segmentation Method to Obtain a Complete Geometry Model of the Hearing Organ. Hearing Research, Vol. 282, pp. 25–34, 2011.

[12] Kwacz, M.; Marek, P.; Borkowski, P.; Mròwka, M.: A Three-Dimensional Finite Element Model of Round Window Membrane Vibration Before and After Stapedotomy Surgery. Biomechanics and Modeling in Mechanobiology, Vol. 12, pp. 1243–1261, 2013.

[13] Gan, R.Z.; Reeves, B.P.; Wang, X.: Modeling of Sound Transmission From Ear Canal to Cochlea. Annals of Biomedical Engineering, Vol. 35, pp. 2180–2195, 2007.

[14] Böhnke, F.; Arnold, W.: 3D-Finite Element Model of the Human Cochlea Including Fluid-Structure Couplings. Journal for Oto-Rhino-Laryngology, Vol. 61, pp. 305–310, 1999.

[15] Atturo, F.; Barbara, M.; Rask-Andersen, H.: Is the Human Round Window Really Round? An Anatomic Study With Surgical Implications. Otology & Neurotology, Vol. 35, pp. 1354–1360, 2014.

[16] Carpenter, A.M.; Muchow, D.; Goycoolea, M.V.: Ultrastructural Studies of the Human Round Window Membrane. Archives of Otolaryngology- Head and Neck Surgery, Vol. 115, pp. 585–590, 1989.

[17] Becvarovski, Z.: Absorption of Intratympanic Topical Antibiotics. Ear Nose Throat Journal, Vol. 83, pp. 18–19, 2004.

[18] Sim, J.H.; Röösli, C.; Chatzimichalis, M.; Eiber, A.; Huber, A.: Characterization of Stapes Anatomy: Investigation of Human and Guinea Pig. Journal of the Association for Research in Otolaryngology, Vol. 14, pp. 159–173, 2013.

[19] Baumgart, J.: The Hair Bundle: Fluid-Structure Interaction in the Inner Ear. Doctoral thesis, Technische Universität Dresden, 2010.

[20] Fleischer, M.; Schmidt, R.; Gummer, A.W.: Compliance Profiles Derived From a Three-Dimensional Finite-Element Model of the Basilar Membrane. The Journal of the Acoustical Society of America, Vol. 127, pp. 2973–2991, 2010.

[21] Lenarz, T.; Boenninghaus, H.G.: Hals-Nasen-Ohren-Heilkunde. Berlin Heidelberg: Springer, 2012.