ICSSM 2021
Proceedings

8th International Congress
of the
Serbian Society of Mechanics

June 28-30, 2021
Kragujevac, Serbia

Hellenic Society
for Theoretical &
Applied Mechanics
(HSTAM)

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СРПСКО ДРУШТВО ЗА РАЧУНСКУ МЕХАНИКУ
SERBIAN SOCIETY FOR COMPUTATIONAL MECHANICS

MINISTRY OF EDUCATION,
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The 8th International Congress of the Serbian Society of Mechanics Kragujevac, Serbia, June 28-30, 2021

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Welcome Message

Dear colleagues,

It is a great pleasure for us to welcome you all at *the* ***8th International Congress of the Serbian Society of Mechanics*** in Kragujevac, Serbia Well-known for its culture, history and industrial heritage, Kragujevac was the first capital of modern Serbia and the place where the first constitution in the Balkans was proclaimed. Today, we are more than proud to say that Kragujevac is also becoming one of the scientific capitals in the region.

In this very difficult time of the COVID-19 pandemic, we decided to make this congress a hybrid event combining physical and online sessions, so that everyone interested can join us despite the obstacles we have all been facing for more than a year now.

8th International Congress of the Serbian Society of Mechanics aims to bring together leading academic scientists, researchers and research scholars to exchange and share experiences and research results on various aspects of *Theoretical and Applied Mechanics*. It will bring an interdisciplinary platform for researchers, practitioners and educators to present and discuss the most recent innovations, theories, algorithms, as well as practical challenges encountered and solutions adopted in the fields of *Classical Mechanics, Solid and Fluid Mechanics, Computational Mechanics, Biomechanics, Applied Mathematics and Physics, Structural Mechanics and Engineering.*

The Congress is organized by the Serbian Society of Mechanics (SSM) in partnership with: Faculty of Engineering, University of Kragujevac, Faculty of Mechanical Engineering, University of Belgrade, Faculty of Technical Science, University of Novi Sad, Faculty of Mechanical Engineering, University of Niš, Hellenic Society of Theoretical and Applied Mechanics, Institute of Information Technology Kragujevac, University of Kragujevac, with the support of the Serbian Ministry of Education, Science and Technological Development, Serbian Academy of Sciences and Arts and Serbian Society for Computational Mechanics.

Six distinguished plenary speakers will deliver lectures:

1. Prof. Georgios E. Stavroulakis – Technical University of Crete, Greece
2. Prof. Themis Exarchos – Ionian University, Corfu, Greece
3. Prof. Mihailo R. Jovanović – University of Southern California, USA
4. Prof. Ricardo Ruiz Baier – Monash University, School of Mathematics, Clayton, Australia
5. Dr Božidar Jovanović – MISANU, Serbia
6. Dr Marko Janev – MISANU, Serbia

The Congress encompasses six main topics: General Mechanics, Fluid Mechanics, Mechanics of Solid Bodies, Biomechanics, Control and Robotics, Interdisciplinary and Multidisciplinary Problems.

Also, there are four Mini-Symposia:

- M1: 5th Serbian-Greek Symposium on Advanced Mechanics
  Chairs: Prof. Georgios Stavroulakis, President of HSTAM, Greece; Prof. Nenad Filipović, President of SSM, Serbia
- M2: Turbulence
  Chair: Prof. Đorđe Čantrak, University of Belgrade, Serbia
- M3: Mathematical Biology and Biomechanics
  Chair: Dr. Anđelka Hedrih, MI SANU, Serbia
- M4: Nonlinear Dynamics
  Prof. Julijana Simonović, University of Niš, Serbia

Within the Congress, we are also very proud to organize the 5th Serbian-Greek Symposium on *Current and Future Trends in Mechanics*. The Symposium is organized by the Serbian Society of Mechanics (SSM) and the Hellenic Society of Theoretical and Applied Mechanics (HSTAM).

This year, *8th International Congress of the Serbian Society of Mechanics* received more than 150 high-quality research papers. Each paper was reviewed and ranked by at least 2 professors and scientists in the program and the scientific review committee. As a result of the strict review process and evaluation, the committee selected 120 research papers.

We must also say that the conference would certainly not have been so successful without the efforts of many people who were actively engaged in organization of such a major nationally and internationally recognized academic event. We give our special gratitude to the members of the program and scientific review committee as well as to all chairs, organizers and committee members for their dedication and support.

On behalf of the Organizing Committee, we wish you all a pleasant stay in Kragujevac and a productive conference.

Chairs:

Prof. Nenad Filipović, ***president of SSM, University of Kragujevac***
Prof. Miloš Kojić, ***Serbian Academy of Sciences and Arts***

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Kragujevac, Serbia, June 28-30, 2021

NUMERICAL MODELING THE MOTION OF OTOCONIA PARTICLES IN THE SEMICIRCULAR CANAL UNDER WHOLE BODY VIBRATION

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Abstract:

Vibrations of the human body are a multisciplined field that includes knowledge and other disciplines, such as: ergonomics, engineering, mathematics, medicine and others. Exposure to whole body vibrations reduces the comfort of passengers in the vehicles, causing stress, fatigue and discomfort. Vibrations can affect the lumbar spine, the gastrointestinal system, the peripheral veins and the vestibular system. The semicircular canals, as a part of vestibular system, are responsible for sensing angular head motion in three-dimensional space and for providing neural inputs to the central nervous system. In this study, one male subject was exposed to root-mean-square WBV acceleration levels of 0.7 m/s^2 and 1.1 m/s^2 at the frequencies of 0.5–20 Hz while seated on an electro hydraulic vibration simulator with multi-axial excitation. The movements recorded on the head of the examinee were transferred to a 3D model as input data. In this research, a numerical model is presented that enables the analysis of motion of multiple otoconia particles within the labyrinth and the change of cupular displacement due to this motion.

Key words: numerical analysis, random vibration, semicircular canals, whole body vibration

1. Introduction

The vestibular system is the sensory apparatus of the inner ear that helps the body maintain its postural equilibrium. The information furnished by the vestibular system is also essential for coordinating the position of the head and the movement of the eyes. There are two sets of end organs in the inner ear, or labyrinth: the semicircular canals, which respond to rotational movements (angular acceleration); and the utricle and saccule within the vestibule, which respond to changes in the position of the head with respect to gravity (Figure 1). The information these organs deliver is proprioceptive in character, dealing with events within the body itself, rather than exteroceptive, dealing with events outside the body, as in the case of the responses of the cochlea to sound. Functionally these organs are closely related to the cerebellum and to the reflex centers of the spinal cord and brainstem that govern the movements of the eyes, neck, and limbs. Because the three semicircular canals - superior, posterior, and horizontal - are positioned at right angles to one another, they are able to detect movements in three-dimensional space. When the head begins to rotate in any direction, the inertia of the endolymph causes it to lag behind, exerting pressure that deflects the cupula in the opposite direction.

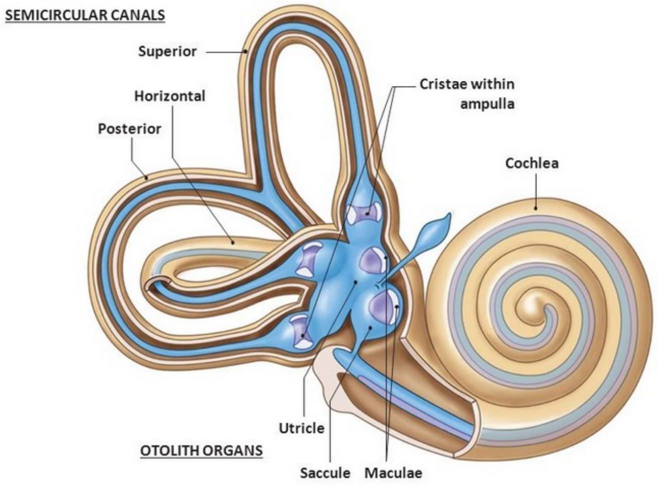

Fig. 1. The major sensory organs of the vestibular system - the utricle, saccule, and the three semicircular canals (posterior, superior/anterior, and horizontal)

Exposure to vibrations affects a person in different ways, starting from ordinary disturbances, to reduced work performance and damage to health. A guideline in defining human tolerance to whole-body vibration as an international standard ISO 2631-1 (1997) [1] was adopted today. ISO 2631-5 (2004) [2] is used to assess expo-sure to high levels of vibration and shock. ISO 2631-4 (2001) [3] is used to define different methods for measuring periodic, random and transient vibrations. The vibrations that are absorbed lead to muscle contractions that can cause muscle fatigue, especially at resonant frequencies. Vertical vibrations in the range of 5–10 Hz cause resonance in the thoracic abdominal system, from 4 – 8 Hz in the spinal part, from 20 – 30 Hz in the area of the head and neck and from 60 – 90 Hz in the area of the eye-balls [4-6].

Whole body vibrations can weaken the senses and lead to balance disorders, movement disorders or visual disturbances. Periodic vibrations of low frequency of 10-20 Hz show a detrimental effect on the vestibular apparatus [7]. The aim of this paper is to show how exposure to vibrations of different amplitudes affects the endolymph flow in the semicircular channels and changes in cupula deformation.

2. Materials and methods

2.1 Laboratory experiments

Laboratory research was performed with an electro hydraulic pulsator HP-2007. The seat for the respondent is placed on the platform of the device. This device has the ability to excite vibrations in two directions. On the head of the subjects via plastic helmet was mounted a system of three-axis accelerators where the accelerator AC102-1A, weight of 90g, sensitivity of 100mV/g, and frequency range of 0.5–15.000 Hz was used. In order to determine head displacements, accelerations was measured on the head using three-axis accelerometers. The 01dB-Metravib NetdB PRO-132 acquisition systems was used. The measurement scheme is shown in Figure 2. The parameters of the experiment were: the block duration 80 ms, the number of averaging 2, and sampling step $\Delta t = 0.0195$ ms. Signal overlap was 75%. The frequency step was $\Delta f = 0.390625$ Hz.

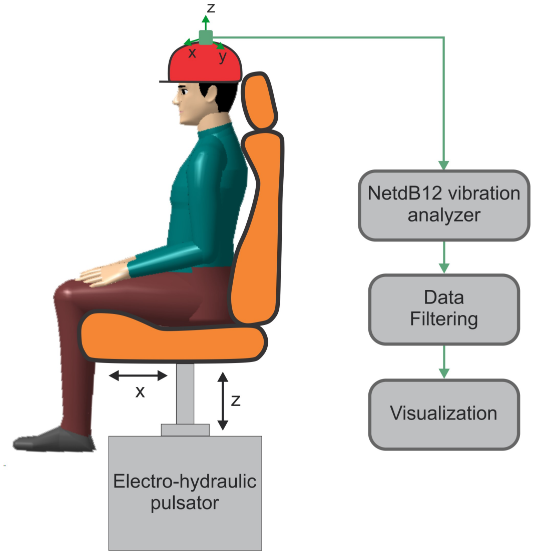

Fig. 2. The subjects position on the electro-hydraulic pulsator

One male healthy subject (aged 37 years, 188cm tall and 95kg mass) was exposed to a random stimulus to both single-axis vibration in vertical and fore and aft. The vibration amplitude were 0.7 m/s^2 and 1.1 m/s^2. The excitation frequency range was 0.5 Hz to 20 Hz. There was one seating angle of 90 degrees of inclination. The subject rested his hands on thighs.

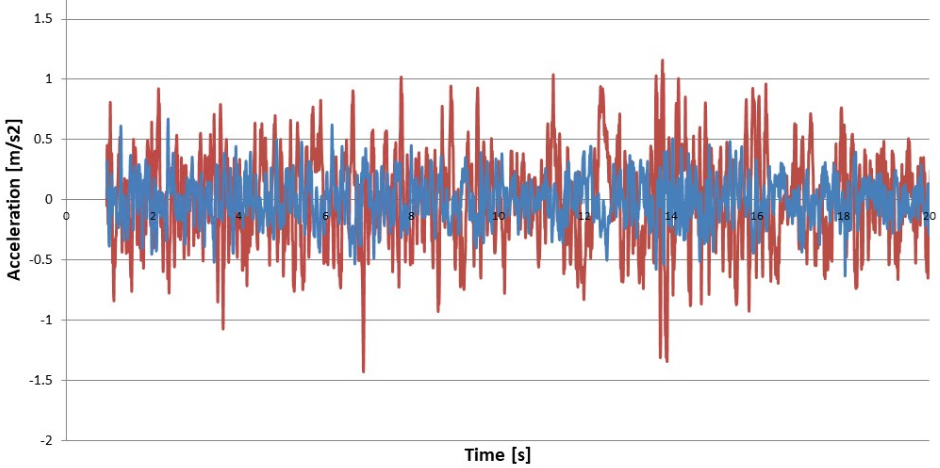

Fig. 3. R.m.s. acceleration measured on subject head (blue line - 0.7 m/s^2, red line – 1.1 m/s^2)

These acceleration values (Figure 3) represents input boundary condition for numerical model. The point of rotation is defined in the center of the 3D model, so the model rotates in relation to it, based on the two given function of changing the acceleration. Gravitation force also was included.

2.2 3D computer model of vestibular labyrinth

A 3D computer model of the geometry of the SCCs and cupular membranes was developed using the CT scans, scanned by a normal CT scanner (SOMATOMDefinition, Siemens Medical, München, Germany) at a slice thickness of 0.5 mm. The geometry used in numerical simulations is shown in Figure 4. The corresponding cupulas for each SCC are colored in red (for the posterior SCC), green (for anterior SCC) and blue (for lateral SCC).

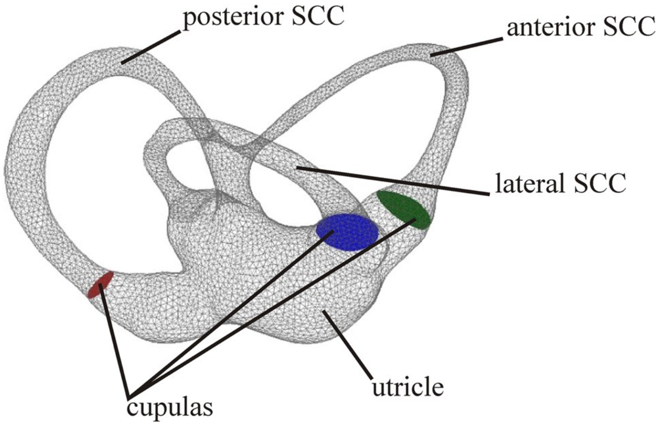

Fig. 4. Geometry of the labyrinth, with denoted cupulas corresponding to each SCC.

2.3 Numerical modeling

The motion of endolymph in the SCCs is modeled using an approach developed by Yu et al. [8], also known as mass-conserved volumetric lattice Boltzmann method (MCVLB). This approach represents adaptation of the standard LB method [9], [10], and enables the boundary points to have predefined velocity.

In this study, the solid boundary, i.e., the walls of the SCCs are not deformable and they move along with the internal fluid in space, so there is no relative motion of the boundary with respect to the defined fluid mesh. During the simulation in the defined domain, each cell in the lattice mesh can be either occupied completely by solid, by fluid or partially by fluid and solid. The collision of the particles in MCVLB method is modeled using the following equation:

$$n_i'(\mathbf{x},t) = n_i(\mathbf{x},t) - \frac{1}{\tau}\left(n_i(\mathbf{x},t) - n_i^{(0)}(\mathbf{x},t)\right) + \left(1 - \frac{1}{2\tau}\right)\mathbf{F}_i\,, \tag{1}$$

where τ represents the relaxation time, F_i represents the external force term and $n_i^{(0)}$ represents the equilibrium particle distribution function.

In this study, the three-dimensional isothermal flow of incompressible fluid is simulated and the lattice structure denoted by D3Q27 is used. The propagation of the particles is modeled using the following equation:

$$\begin{aligned} n_i''(\mathbf{x},t) = {} & [1 - P(\mathbf{x},t)]\, n_i'\left(\mathbf{x} - \boldsymbol{\xi}_i \Delta t, t\right) \\ & + P\left(\mathbf{x} + \boldsymbol{\xi}_{i*}\Delta t, t\right) n_{i*}'(\mathbf{x},t) \end{aligned}\,, \tag{2}$$

where the index $i*$ corresponds to the direction opposite to the i-th direction, ξi represents vectors defining the abscissae of the lattice structure.

In this study, it is considered that the cupula has a thickness of 1mm that it is linearly elastic and and consists of finite elements. The value of cupular stiffness is defined according to the values used in the literature [11].

Otoconia particle is considered as a rigid body, with mass m_p, density ρ_p and radius a_p. The particle can move freely through the endolymph under the influence of several forces:

gravitational force F_g, Stokes drag force F_s (the influence of the surrounding fluid), inertial forces F_c (caused by the angular motion of the entire domain), lubrication force F_L (the influence of the walls) and force that represents the interaction with other particles. The forces F_g, F_s and F_c were calculated as follows:

$$\mathbf{F}_g = -m_p\left(1 - \frac{\rho}{\rho_p}\right)\mathbf{G}, \tag{3}$$

$$\mathbf{F}_S = -6\pi\,\nu\,\rho\,a_p\left(\dot{\mathbf{x}}_p - \mathbf{u}_p\right), \tag{4}$$

$$\mathbf{F}_C = m_p\left(\dot{} \times \dot{} \times \mathbf{x}_R + 2\dot{} \times \dot{\mathbf{x}}_p\right), \tag{5}$$

where ***G*** represents the gravity acceleration, $\dot{}$ is the angular velocity of the entire domain, ρ is fluid density, v is fluid viscosity and $\mathbf{u}_\mathrm{p}$ represents the fluid velocity in the particular point of the domain, i.e., at the current location of the particle $\mathbf{x}_\mathrm{p}$.

The lubrication force is defined according to the model proposed in the literature [12, 13, 14]. The components of the lubrication force are tangential component $\boldsymbol{F}_{LT}$ and normal component $\boldsymbol{F}_{LN}$. These components are given by:

$$\mathbf{F}_{LT} = m_p\frac{\dot{\mathbf{x}}_p}{\log\left(d/a\right)}, \tag{6}$$

$$\mathbf{F}_{LN} = m_p\dot{\mathbf{x}}_p\frac{d}{a}, \tag{7}$$

The interaction of the particles is modeled using an interaction force that is used within the discrete element method (DEM). The force between particles in DEM method is defined using a nonlinear elastic Hertz law [15]. If the distance between two particles is less than the sum of their radii, overlap of particles in contact causes an interaction force that is given by:

$$\mathbf{F}_{\mathrm{DEM}}^{ij} = K^{ij}\varepsilon^{3/2}\mathbf{n}, \tag{8}$$

where K^{ij} is the contact stiffness coefficient and **n** is unit vector.

The interaction of the cupula and the immersed particles with the surrounding endolymph was modeled using the immersed boundary method that was first presented by Peskin [16]. A fixed Cartesian mesh is used to represent the fluid domain, immersed objects are treated as a separated part of the fluid, and a set of Lagrangian points is used to represent the boundary between two domains. The cupula and particles are affecting the surrounding fluid. The influence of these entities is introduced in the fluid flow equations using an external force field. On the other hand, the fluid is opposing this influence and causing the deformation of the cupula through a force that deforms the boundary between these two domains. At the same time, the fluid is opposing the motion of the particles through a drag force. The fluid domain and the cupulas are discretized using different meshes and all the quantities necessary for the modeling of the solid–fluid interaction have to be interpolated over the surrounding points. For each node of the mesh representing the cupula, the influence of several points from the fixed fluid mesh is considered and vice versa. Similarly, for each immersed particle, the influence of all surrounding points from the LB mesh is considered.

The surrounding fluid is causing a deformation of the cupula, more precisely the movement of the nodes that form the cupula. The velocity of these nodes can be calculated using interpolation over the surrounding points in the fluid mesh, using the following equation:

$$\mathbf{u}_B^l\left(\mathbf{X}_B^l, t\right) = \sum_{i,j,k}\mathbf{u}\left(\mathbf{x}_{ijk}, t\right)D_{ijk}\left(\mathbf{x}_{ijk} - \mathbf{X}_B^l\right), \tag{9}$$

The Euler forward method is applied in Eq. (9), to determine the new position of the nodes:

$$^{t+\Delta t}\mathbf{X}_B^l = {}^{t}\mathbf{X}_B^l + \mathbf{u}_B^l \Delta t, \qquad (10)$$

This motion of the nodes of the cupula caused a deformation of the cupula, and this deformation further causes a reaction force that is opposing this deformation. This force is then reintroduced into the fluid flow equations using the already defined external force field. Similarly, the immersed particles affect the fluid flow and cause a change in the velocity field. This change is then included in the equations of motion of the particle when the Stokes drag force is recalculated in the next iteration. And this force is further reintroduced into the fluid flow equations, to simulate the effect of the immersed particles.

3. Results

Results of the numerical simulations are presented in this section. In all simulations, the parameters of the numerical model are defined the same way, using the data published in the literature [11, 12]. In order to validate our model we perform simulation of free fall of a single particle and compare to data from literature (Figure 5).

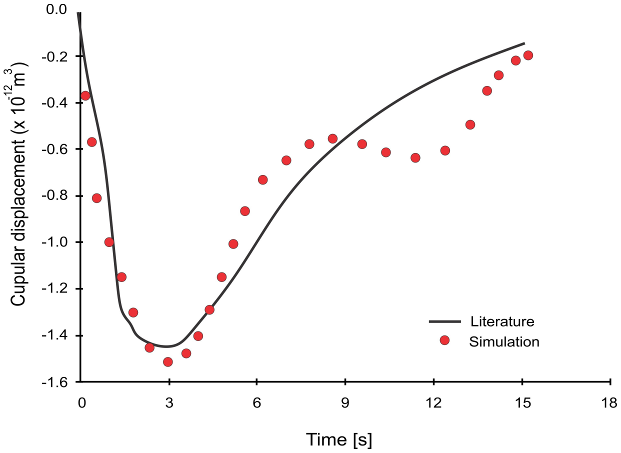

Fig. 5. Comparison of change of cupular displacement over time, during the free fall of a single particle in the posterior SCC, with results from the literature [7]

The disagreement of results after the peak of the cupular displacement is caused by the different way the interaction of the particle with the wall is simulated. In the literature, no lubrication force was considered, while in this study, the lubrication force is included in the equations of motion of the particle.

Figure 6 shows the result of the first numerical analysis. The figure shows the motion of particles under the influence of the first acceleration function of 0.7 m/s^2. It can be observed that the maximum velocity of the particles is in all three SSC channels was 1.7e-1mm/s. The average recorded velocity was 1.57e-1mm/s. Figure 7 shows the cupular displacement for utricle cupula, anterior cupula and posterior cupula. The largest displacement of ultricle cupula was 0.0045 mm, while the other two, the anterior cupula and posterior cupula, have the largest displacements of 0.0033 mm and 0.0014 mm, respectively.

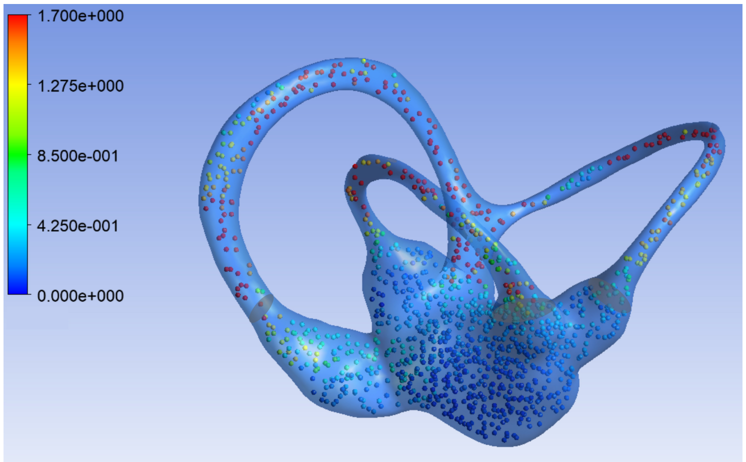

Fig. 6. Particle velocity due to 0.7m/s^2 acceleration [units in 10^{-1} mm/s]

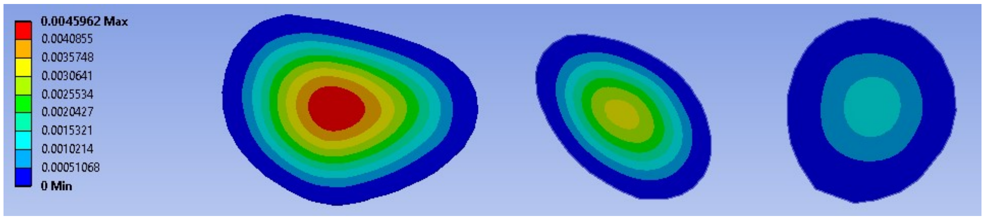

Fig. 7. Numerical results of total displacements of utricle cupula, anterior cupula and posterior cupula [units in mm]

Figure 8 shows the result of the second numerical analysis - the motion of particles under the influence of the second acceleration function of 1.1 m/s^2. In all SCC channels was observed the maximum velocity of the particles of 1.84e-1mm/s. It can be noticed that this acceleration affects the appearance of a larger number of particles with which the velocity of movement increases, as well as the average values of the velocity through the mentioned channels. The average recorded velocity was 1.76e-1mm/s. Figure 9 shows the cupular displacement for three SCC canals. The largest displacement of utricle cupula was 0.0061 mm, while the other two, the anterior cupula and posterior cupula, have the largest displacements of 0.004 5mm and 0.0023 mm, respectively.

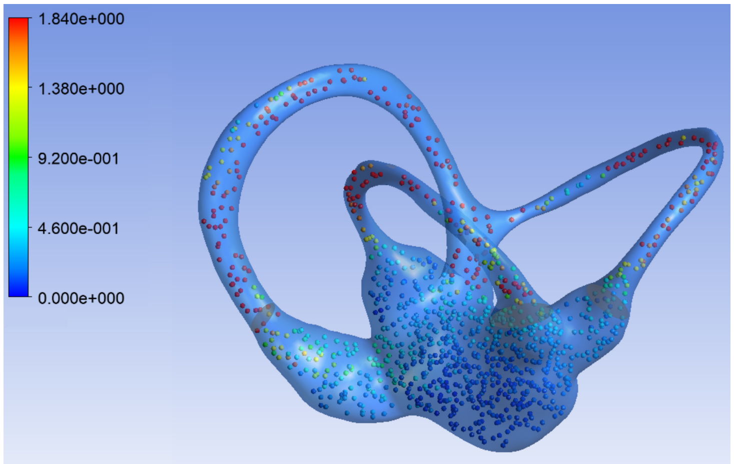

Fig. 8. Particle velocity due to 1.1 m/s^2 acceleration [units in 10^{-1} mm/s]

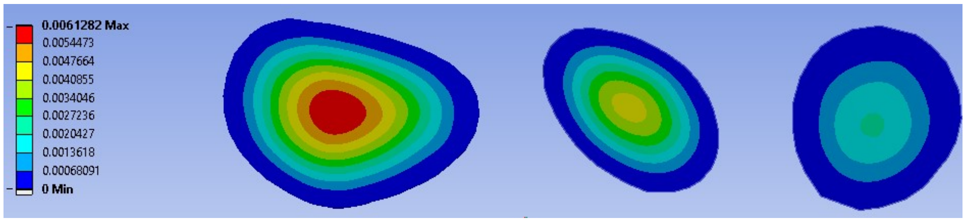

Fig. 9. Numerical results of total displacements of utricle cupula, anterior cupula and posterior cupula [units in mm]

3. Conclusions

Numerical simulations was used to model the motion of otoconia particles in the semicircular canal under whole body vibration. A 3D computer model of the geometry of the SCCs and cupular membranes was developed using the CT scans. The motion of endolymph in the SCCs is modeled using an mass-conserved volumetric lattice Boltzmann method. It is considered that the cupula has a thickness of 1mm that it is linearly elastic and and consists of finite elements, while the walls of the SCCs are not deformable. Otoconia particle was considered as a rigid body. The interaction of the particles was modeled using an interaction force that is used within the discrete element method. Process of validation was performed with simulaton of free fall of a single particle and compare to data from literature. The disagreement of results after the peak of the cupular displacement is caused by the different way the interaction of the particle with the wall is simulated. In the literature, no lubrication force was considered, while in this study, the lubrication force is included in the equations of motion of the particle.

Numerical simulations were used to determine particle velocities in all channels of the vestibular system, as well as deformations of capular membranes. The first acceleration function of 0.7 m/s^2 gave a maximum particles velocity of 1.57e-1 mm/s, while the second simulation of 1.1 m/s^2 gave a maximum particles velocity of 1.84e-1mm/s. The highest recorded values of cupular membrane displacement in both cases were 0.0045 and 0.0061 mm. Results showed that the change of cupular displacement over time, with immersed particles, can be accurately predicted using the presented numerical model. The small discrepancies with results from the literature are mostly due to the different geometries that are used and the differences in the modeling of particle interactions.

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