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EFFECT OF VIBRATION ON SEMICIRCULAR CANAL DURING WHOLE BODY VIBRATION

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RESEARCH ARTICLE

ABSTRACT: Chronic exposure to whole body vibration can affect the lumbar spine, the gastrointestinal system, the peripheral veins and the vestibular system. The semicircular canals (SSC), 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 paper, the influence of random vibration on the body of the subject at an excitation of 1.0 m/s^2 and 1.5 m/s^2 was investigated. The 3D geometry of the SSC canal was obtained using DICOM CT images. Simulation of endolymph flow is carried out. Numerical analysis provides the pressure generated on SSC. Response of cupula is obtained for various rotational velocities of head. Variation of pressure generated on cupula and response of cupula is studied and reported.

KEY WORDS: *numerical analysis, random vibration, semicircular canals, whole body vibration*

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UTICAJ VIBRACIJA CELOG TELA NA POLUKRUŽNI KANAL UHA

REZIME: Hronična izloženost vibracijama celog tela može uticati na lumbalni deo kičme, gastrointestinalni sistem, periferne vene i vestibularni sistem. Polukružni kanali (eng. semicircular canals - SSC), kao deo vestibularnog sistema, odgovorni su za detekciju ugaonog kretanja glave u trodimenzionalnom prostoru i za obezbeđivanje neuronskih ulaza u centralni nervni sistem. U ovom radu je ispitivan uticaj nasumičnih vibracija na telo ispitanika pri pobudama od 1.0 m/s^2 i 1.5 m/s^2. 3D geometrija SSC kanala dobijena je korišćenjem DICOM CT slika. Sprovedena je simulacija endolimfnog toka. Numerička analiza pokazuje pritisak koji se stvara u SSC kanalima. Odziv kupule se dobija za različite brzine rotacije glave. Proučavaju se i prikazuju promene pritiska generisanog na kupuli, kao i odziv kupule.

KLJUČNE REČI: *numerička analiza, slučajna vibraija, polukružni kanali, vibracije celog tela*

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INTRODUCTION

The oscillatory comfort of a vehicle is a complex problem that is influenced by several factors, of which the road characteristics, the mechanical characteristics of the vehicle as well as the speed of the vehicle should be mentioned. In the thirties of the last century, with the rapid development of industrial machines and motor vehicles, the negative effects of the effects of vibrations on the human body were noticed. Much research in recent decades has been devoted to investigating the effects of vibrations and the effects they cause [1], [2], [3]. The reaction of the human body to the action of vertical vibrations can be divided into five different effects, which include: perception of low vibration, nausea while driving, reduced comfort, impaired health and disruption of activity. These effects depend on the manner and degree of vibration transmission through the human body (biomechanical response of the human body). In order to reduce the negative impact of vibrations on humans, the European Union adopted the Vibration Directive (2002/44 / EC) in 2002, which defines the permissible levels of exposure to whole human body vibrations in working conditions and appropriate safety measures to protect health. When describing vibrations, it is important to fully describe what vibration characteristics are involved. To expose the body to vertical vibrations, these are: frequency content, amplitude, direction and length of vibration exposure. A vibration wave may consist of a single frequency wave or it may be as complex as a broadband wave consisting of multiple frequencies. The frequency of vibration waves describes how fast the vibrations move [4], [5]. 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) [6] was adopted today. ISO 2631-5 (2004) [7] is used to assess exposure to high levels of vibration and shock. ISO 2631-4 (2001) [8] 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 eyeballs.

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 centres 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.

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 [9].

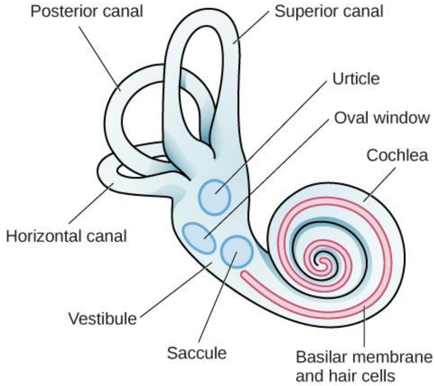

Figure 1 The major sensory organs of the vestibular system - the utricle, saccule, and the three semicircular canals (posterior, superior/anterior, and horizontal) [9]

1. MATERIALS AND METHODS

A healthy human right membranous labyrinth based on the morphologically descriptive model were reconstructed using the CT scans. The high resolution CT data were read into Mimics 17.0 (Materialise Inc., Leuven, Belgium) visualization software, where the images were segmented by thresholding to obtain 3D model (Figure 2).

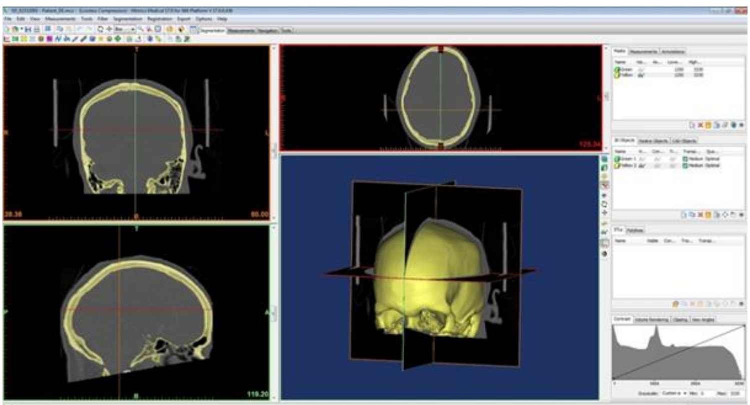

Figure 2 Automatic segmentation of CT scans

The computational model consists of the utricular cavity, the horizontal canal (HC), the anterior canal (AC), the posterior canal (PC), and their ampullae (Figure 3) [10].

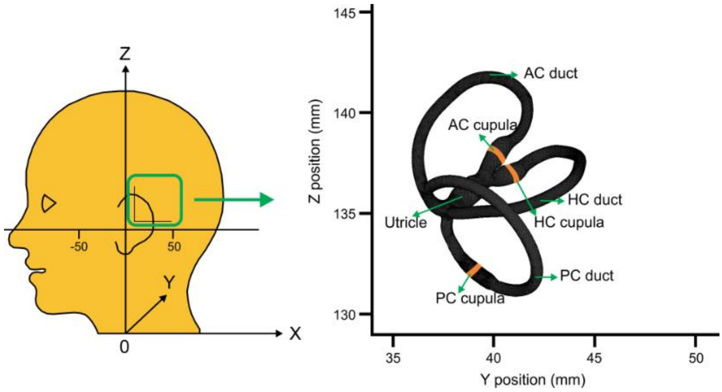

Figure 3 The reconstructed model of a healthy human membranous (the semicircular canals) labyrinth and position in head

The endolymph flow were described by the conservation equations of mass, momentum, and energy. An Arbitrary Lagrangian Eulerian (ALE) approach is adopted, and the endolymph is assumed to be a slightly compressible Newtonian fluid with constant properties. All the governing equations are listed below.
The continuity equation is approximated as [11]:

$$v_{i,i} + \frac{p}{\lambda} = 0 \tag{1}$$

where λ is a selected large number, the penalty parameter. Substituting the pressure p from Eq. 1 into the Navier-Stokes equations it can be obtained

$$p\left(\frac{\partial v_i}{\partial t} + \partial v_{i,k} v_k\right) - \lambda v_{j,ij} - \mu v_{i,kk} - f_i^V = 0 \tag{2}$$

Then the FE equation of balance becomes

$$M\dot{V} + \left(K_{vv} + K_{vv}^{\lambda}\right)V = F_v + F_\lambda \tag{3}$$

where

$$\left[K_{KJ}^{\lambda}\right]_{ik} = \lambda\int_V N_{K,i} N_{J,k} dV, \qquad \left(F_\lambda\right)_{Ki} = \lambda\int_S N_K v_{j,j} n_i dS \tag{4}$$

Fluid-structure interaction for cupula deformation and endolymph flow is implemented. Cupula was modeled as elastic 3D membrane with brick finite element and endolymph domain as 3D 8–node finite elements. The values for the endolymph conductivity, reference density, and viscosity are taken from measured data provided by [12]. The physical and structural properties of the endolymph and cupula are shown in Table 1.

Table 1 *The* physical *and structural properties of the endolymph and cupula [12]*

Property	Value
Cupula density (kg/m3)	1000
Cupula Young's modulus (Pa)	5
Cupula Poisson ratio	0.45
Endolymph density (kg/m3)	1000
Endolymph dynamic viscosity (Pa·s)	0.000852

In this paper, the HP-2007 electro-hydraulic pulsator were used to induce excitation of different amplitudes and frequencies, which includes a car seat on which the subject were exposed to vibrations. This device has the ability to cause random vibrations in both the vertical and horizontal axes simultaneously. The excitation frequency were in range 0.1-35Hz. Test subject were man of 95 kg and 188 m height. Measuring equipment 01dB-Metravib NetdB PRO-132 was used for signal acquisition. There was an accelerator on the subject's head to determine the head displacements, which are the input values of the acceleration given to the numerical model.

2. RESULTS

Numerical simulation was performed using PAKFS solver. Two cases of acceleration were investigated – 1 m/s^2 and 1.5 m/s^2. The results of velocities and pressures changes in the channels of the vestibular system are shown in the following figures.

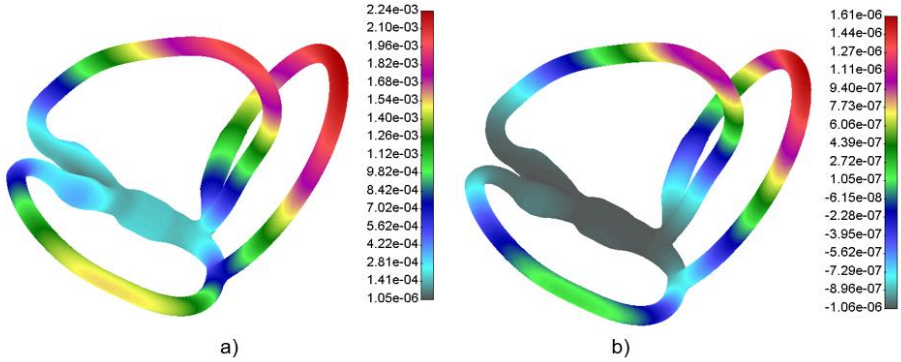

Figure 4 The numerical result the velocity (a) and pressure (b) distribution along the human membranous labyrinth during 1 m/s2 acceleration

The figure 4a shows that the highest velocity occurs in the PC duct, 2.24e-03 mm/s, while in the PC cupula measured velocity of 1.12e-03 mm/s. The HC duct has a velocity value of 2.05 m/s^2. The highest pressure of 1.61e-06 Pa, also for the first case of 1 m/s^2, was observed in the PC duct. A slightly lower pressure value was recorded in the HC duct, 9.55e-07 Pa. The second case (Figure 5) showed higher maximum values of both velocity and pressure.

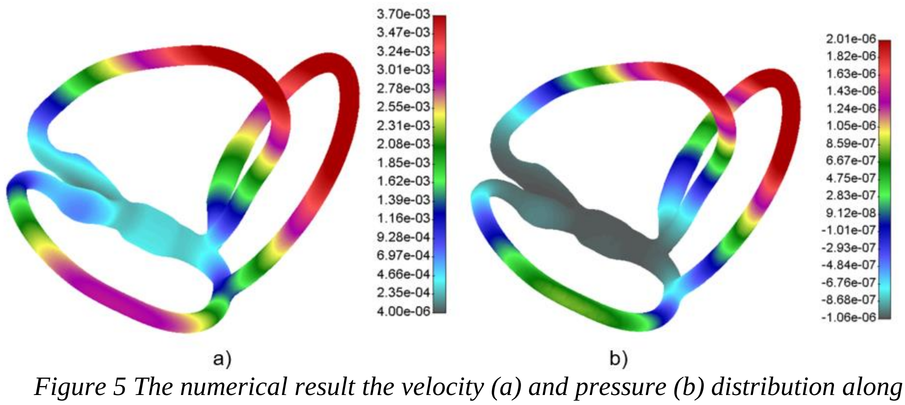

Figure 5 The numerical result the velocity (a) and pressure (b) distribution along

the human membranous labyrinth during 1.5 m/s2 acceleration

From the Figure 5, it can be concluded that the maximum value of the velocity and pressure is always in the PC duct, while the slightly lower values were recorded again in the HC duct. The highest pressure values of the 2.01e-06 Pa and 1.96e-06 Pa were recorded in the posterior and horizontal duct, respectively. It can be concluded that the acceleration change to which the human body was exposed, greatly affects the endolymph flow and pressure in membranous labyrinth. All of this has impact on small calcium carbonate crystals placed inside the semicircular canals, who are responsible for maintaining balance.

3. CONCLUSIONS

This paper showed the specific effect of whole body vibrations, to which the driver is exposed in the vehicle, on the vestibular system. A full 3D mathematical model of the semicircular canals with a full fluid-solid interaction of endolymph fluid flow and cupula deformation is investigated. Laboratory testing on a hydraulic pulsator determined the acceleration of the head via the accelerator, and then these values represented the input for the numerical model of the semicircular canals. On the example of two input accelerations, of 1 m/s^2 and 1.5 m/s^2, it is shown how the increase of acceleration affects the endolymph flow in these canals. An increase in the endolymph flow in the three semicircular canals leads to an increase in pressure which leads to an imbalance. For the first case the highest pressure of 1.61e-06 Pa was observed in posterior duct, while for the second case maximum value of pressure was 2.01e-06 Pa. This type of simulation may help medical doctors for better diagnostic procedures and therapy of balance disorder disease when high accelerations violates human health.

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