Software-hardware system for vertigo disorders

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Abstract—**The (benign paroxysmal positional vertigo) BPPV is the most common type of vertigo, influencing the quality of life to considerable percentage of population after the age of forty (25 out of 100 people are facing this problem after 40). The semicircular canals which are filled with fluid normally act to detect rotation via deflections of the sensory membraneous cupula. We are modeling human semicircular canals (SSC) which considers the morphology of the organs and the composition of the biological tissues and their viscoelastic and mechanical properties. For fluid-structure interaction problem we use loose coupling methodology with ALE (Arbitrary Lagrangian Eulerian) formulation. The tissue of SSC has nonlinear constitutive laws, leading to materially-nonlinear finite element formulation. Our numerical results are compared with nystagmus from real clinical patient. The initial results of 3D Tool software user interface and fluid motion simulation and measurement of the video head impulse test (vHIT) with the Oculus system are presented.**

I. INTRODUCTION

Benign paroxysmal positional vertigo (BPPV) is the most commonly diagnosed vertigo syndrome that affects 10% of older persons. BPPV is characterized by sudden attacks of dizziness and nausea triggered by changes in head orientation, and primarily afflicts the posterior canal [1]. The semi-circular canals are interconnected with the main sacs in the human ear: the utricle and the saccule which make up the otolith organs. These organs are responsible for detecting linear movement, such as the sensation when someone goes up or down with an elevator.

We are focused on the semi-circular canals, fluid-filled inner-ear structures designed to detect circular or angular motion. In situations such as rolling at high speed in an airplane, performing ballet spins, or spinning in a circle, our body detects circular motion with these canals. Sometimes this sense of moving in a circle may lead to dizziness or, in extreme cases, even nausea. People who have something wrong with this motion-sensing system often suffer from a condition known as vertigo and feel as if they are spinning even when they are not [2]. Each ear contains three semi-circular canals. Each set of canals is oriented in a different plane that corresponds to a major rotation axis of the head in space.

Firstly, we described numerical procedures fluid flow and fluid-structure interaction with cupula deformation. Some results for fluid velocity and particle tracking are presented. Finally, numerical results which are correlated with experimental measurement with Oculus Rift and conclusions are given

II. METHODS

A. Fluid domain

For fluid domain we solved full 3D Navier-Stokes equation and continuity equation. We are using Penalty method to eliminate the pressure calculation in the velocity-pressure formulation. The procedure is as follows. The continuity equation is approximated as

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

where λ is a selected large number, the penalty parameter. Substituting the pressure p from Equation 1 into the Navier-Stokes equations we obtain

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

then the FE equation of balance becomes

$$\mathbf{M}\dot{\mathbf{V}}+\left(\mathbf{K}_{vv}+\mathbf{K}_{vv}^{\lambda}\right)\mathbf{V}=\mathbf{F}_v+\mathbf{F}_{\lambda} \tag{3}$$

where

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

In examples above we showed a selection of the range of the penalty parameter λ and its effect on the solution.

B. Solid-fluid interaction

There are many conditions in science, engineering and bioengineering where fluid is acting on a solid producing surface loads and deformation of the solid material. The opposite also occurs, i.e. deformation of a solid affects the fluid flow. There are, in principle, two approaches for the FE modeling of solid-fluid interaction problems: a) strong coupling method, and b) loose coupling method. In the first method, the solid and fluid domains are modeled as one mechanical system. In the second approach, the solid and fluid are modeled separately and the solutions are obtained with different FE solvers, but the parameters from one solution which affect the solution for the other medium are transferred successively.

If the loose coupling method is employed, the systems of balance equations for the two domains are formed separately and there are no such computational difficulties. Hence, the loose coupling method is advantageous from the practical point of view and we further describe this method.

As stated above, the loose coupling approach consists of the successive solutions for the solid and fluid domains.

A graphical interpretation of the algorithm for the solid-fluid interaction problem is shown in Fig. 2 [3].

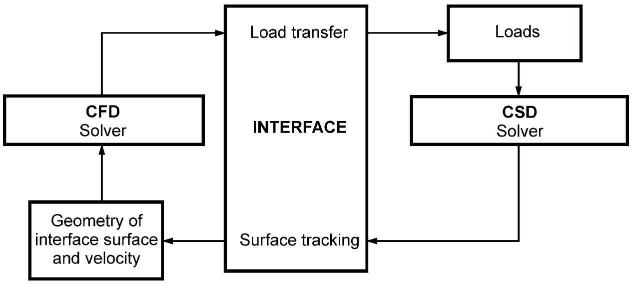

Figure 1. Block-diagram of the solid-fluid interaction algorithm Information and transfer of parameters between the CSD (computational solid dynamics) and CFD (computational fluid dynamics) solvers through the interface block.

Iteration scheme for the solid-fluid interaction, loose coupling approach is presented in Table 1 [3].

Table 1. Iteration scheme for the solid-fluid interaction, loose coupling approach.

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1. **Initial conditions for the time step** '*n*'
   Iteration counter I=0:
   configuration of solid $^{n+1}\mathcal{B}^{(0)} = {}^{n}\mathcal{B}$; common velocities $^{n+1}\mathbf{V}^{(0)} = {}^{n}\mathbf{V}$.
2. **Iterations for both domains**: I=I+1
   a) Calculate fluid flow velocities and pressures $^{n+1}\mathbf{V}_f^{(I)}$ and pressures $^{n+1}\mathbf{P}^{(I)}$
   by an iterative scheme.
   b) Calculate interaction nodal forces from the fluid acting on the solid as

$$^{n+1}\mathbf{F}_S^{(I)} = -\int_S \mathbf{N}^T \; {}^{n+1}\boldsymbol{\sigma}_{Sf}^{(I)} dS$$

c) Transfer the load from the fluid to solid. Find a new deformed configuration of the solid $^{n+1}\mathcal{B}^{(I)}$. Calculate velocities of the common nodes with the fluid $^{n+1}\mathbf{V}^{(I)}$ to be used for the fluid domain.

3. **Convergence check**. Check for the convergence on the solid displacement and fluid velocity increments for the loop on I:

$$\left\|\Delta\mathbf{U}_{solid}^{(I)}\right\| \le \varepsilon_{disp}, \quad \left\|\Delta\mathbf{V}_{fluid}^{(I)}\right\| \le \varepsilon_{velocity}$$

If the convergence criteria are not satisfied, go to the next iteration, step 2. Otherwise, use the solutions from the last iteration as the initial solutions for the next time step and go to step 1.

III. RESULTS

Real patient specific geometry of three SCC is presented in Figure 2. A 3D reconstruction was done from original DICOM images from clinical partners.

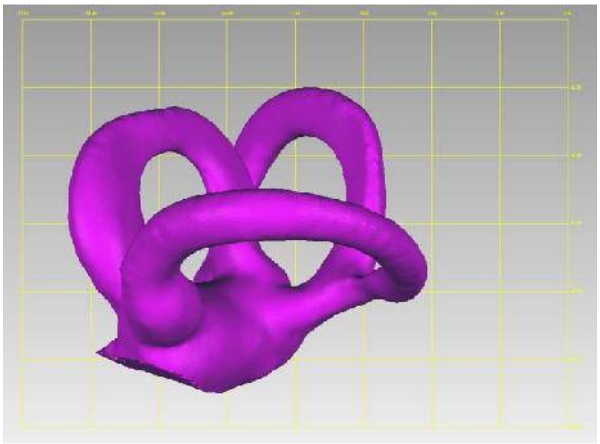

Figure 2. Geometry for three SCC generated from original DICOM images

The video head impulse test (vHIT), which measures the eye movement response to head impulse (brief, unpredictable, passive head rotations), has been used as a simple valid clinical tool for testing the function of the horizontal semicircular canals [4-5].

At the same time, it is possible to use vHIT to identify vertical canal function by measuring vertical eye movement responses to pitch head movements.

The vertical canals lie in planes approximately 45 deg to the sagittal plane of the head and each vertical canal is approximately parallel to the antagonistic canal on the other side of the head [6, 7]. It is possible to test vertical canal function by moving the head of the patient in a diagonal plane, but this turns out to be difficult for the operator and uncomfortable for the patient. A better way of delivering head impulses in the planes of the vertical canals is to use a simple head turned position: the patient is seated with the head and the body facing the target on the wall at a distance of about 1 meter. The clinician then turns the patient’s head on the body about 35 degrees to the left or to the right while the patient’s gaze remains on the target and aligned with the patient’s sagittal plane (Figure 3). The clinician then pitches the patient’s head up or down in the sagittal plane of the body and in this way maximally stimulates the vertical semicircular canals. The angular extent of the head rotations is small (about 10-20 degrees), so the risk of neck injury is very small [8]. We implemented the vHIT method together with the Oculus system (Figure 4).

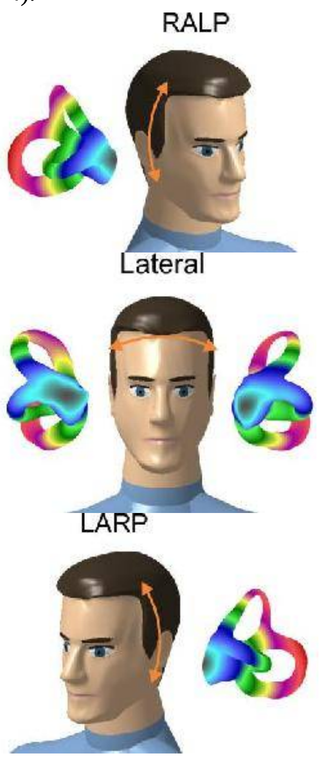

Figure 3. Head rotation during vHIT

Figure 4. Oculus system during vHIT

The Oculus Rift that we are using is a new virtual reality headset that enables us to step into the virtual worlds (Figure 5). This device can provide a custom tracking technology for 360° head tracking with an ultra-low latency.

Each movement of the head is tracked in real time using 4 different sensors: Gyroscope (refresh rate of 1000 Hz), Accelerometer (refresh rate of 1000 Hz), Magnetometer (refresh rate of 1000 Hz), and a Near Infrared CMOS Sensor (refresh rate of 60 Hz), for positional tracking Maps of head movements.

With these sensors we can easily track the head orientation, velocity and acceleration, as well as the eye movement, with respect to a head reference system.

This device creates a stereoscopic 3D view with excellent depth, scale and parallax. Using these features we can easily test the vHIT in the virtual interactive testing room. Applying graphical animations in such virtual interactive testing room, the Oculus device can force the user to move the head or the eyes in the desired position at a certain speed.

In order to test eye movements, we installed a small camera with the IR filter to read the shape and location of a user’s eye to determine the direction in which the user is looking. We investigated the correlation with a nystagmus measurement and a fully 3D fluid with particle tracking simulation inside SCC which can be used for self-patient diagnosis as well as therapy.

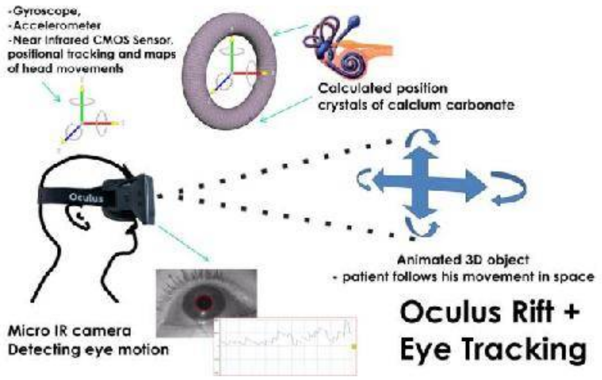

Figure 5. Oculus measurement and computer simulation.

The vHIT test was first described in 1988 by Curthoys and Halmagyi. It is used for the daily work in the set up practice and the clinical application. In many studies, the head impulse test is a standard test in vestibular diagnosis. Our 3D Tool can work separately from standard equipment for vHIT or can be integrated with some existing hardware solutions. We tested our 3D tool system on Oculus. User friendly interface for different head rotations around Z axis is presented in Figure 6 for anti-clock wise direction. For clock wise direction, with head rotation around Z axis, velocity solution for SCC is presented in Figure 7.

Comparison of eye movement, head motion, obtained from measurement, and fluid motion, obtained from computer simulation, has been shown in Figure 8. As it can be seen, there is a small delay in fluid motion response. We think that the reason lies in inertial forces which are incorporated in fluid motion solver based on full 3D Navier-Stokes equation with continuity equation.

User can prescribe boundary conditions through user friendly interface: the axis of rotation, X, Y or Z. Different angles of viewing for velocity, shear stress, pressure and forces on the wall can be defined. The motion of the head is directly connected to the prescribed wall motion of the SCC. We introduce the assumption that axes of the SCC are the main axes X, Y and Z, which is not totally accurate due to patient specific anatomy. The next software 3D Tool version will incorporate different rotation axis other than main axis X, Y and Z. The current software version is using two kinds of approach for mathematical model. The finite element approach gives very accurate calculation of the fluid motion parameters such as velocity profile, pressure, shear stress etc. Also, boundary condition for head motion can be prescribed very precisely. The only drawback is speed of calculation which cannot be in real time. Another approach for solving fluid motion inside SCC is using LB method and implementation GPU with parallel computing algorithm. We are still testing and incorporating both approaches in the current version of 3D Tool software.

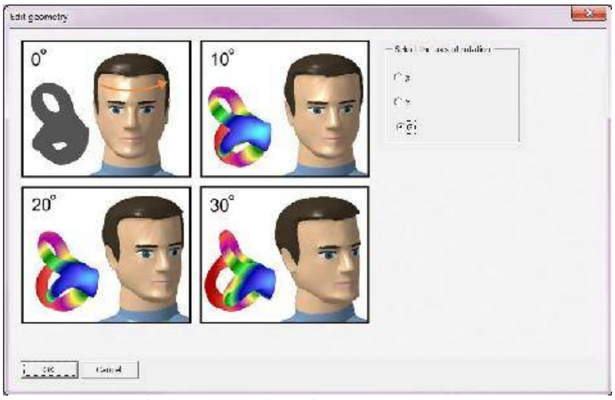

Figure 6. User friendly interface for 3D Tool, results for 10, 20, 30 degrees, head rotation around Z axis, direction anti clock wise.

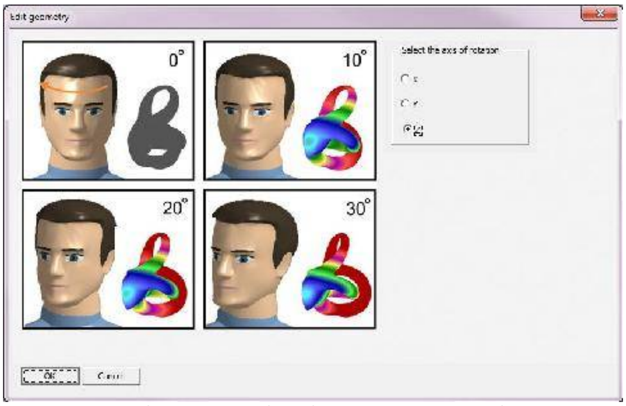

Figure 7. User friendly interface for 3D Tool, results for 10, 20, 30 degrees, head rotation around Z axis, direction clock wise

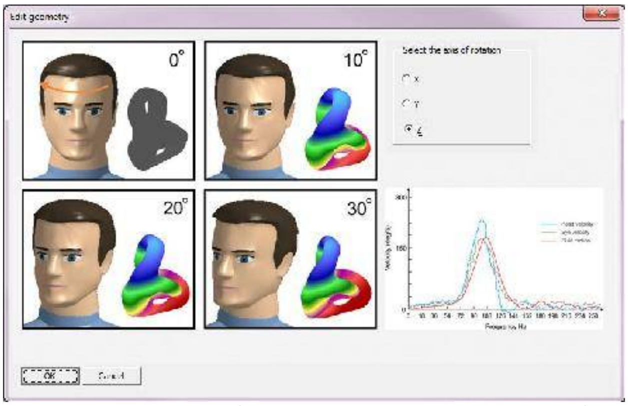

Figure 8. Comparison of eye movement, head motion and fluid motion (computer simulation)

IV. CONCLUSIONS

BPPV is the most common type of vertigo, influencing the quality of life to considerable percentage of population after the age of forty. We have developed 3D software tool for specific measuring dimension of the SCC in the axial, coronal, and sagittal planes. Using viscous fluid flow fluid-structure interaction and dynamics finite element analysis for solid domain we can determine velocity distribution, shear stress, forces, deformation of the cupula. We presented the initial results 3D Tool software user interface and fluid motion simulation and measurement of the video head impulse test (vHIT) with the Oculus system. Different methodologies for 3D visualization tool have been developed using C++, OpenGL, and VTK tools.

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