Wave propagation in a 3D-Fluid-Structure System with Cochlear Implant Electrode

Frank Böhnke, Hubert Schwingshandl, Katharina Braun, Thomas Stark
HNO-Klinik, Klinikum rechts der Isar der TU München, 81675 München, E-Mail: frank.boehnke@lrz.tum.de

Introduction

The stimulation of the hearing nerve of deaf people with electric signals applied by Cochlea Implants (CI) makes the perception of acoustical speech signals possible to a large extend. A still remaining problem is their communication in noisy environments. Therefore electro-acoustic stimulation was proposed for patients with remaining low frequency hearing abilities to advance their speech understanding abilities by additional acoustic stimulation [1]. Obviously the implanted electrode will have an influence on the acoustic signal processing in the cochlea. Therefore we scanned temporal bones with implanted electrodes to calculate the influence of the electrode numerically. Because of the challenging demand in implementing the fluid-structure coupled system merely references to future simulations can be given here.

Theory

To calculate the displacement of the basilar membrane (with or without CI-electrode) numerically the problem of fluid-structure coupling must be solved. While former approaches often used the monolithic approach, where a simultaneous solution is achieved by solving only one matrix system at a time, a portioned approach is presented here (Fig. 1).

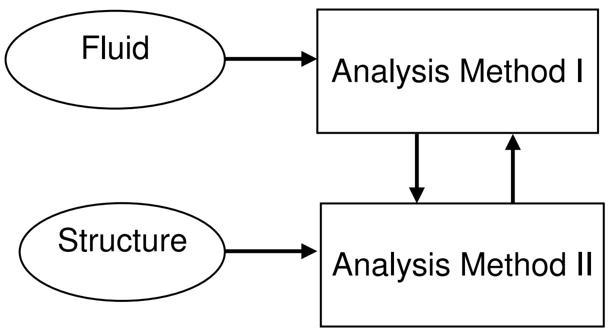

Fig. 1: Weak Coupling Analysis Method by a partitioned approach

Because sound propagates in fluids by density fluctuations $\partial\rho$ three field variables pressure p, displacement u and density ρ must be considered. The structural part is limited to linear stress-strain functions, small deformations and it must include the orthotropic property of the basilar membrane. The fluid part of the solver is limited to Newtonian compressible fluids. The linearized barotropic function ρ (p) is approximately :

$$\rho \approx \rho_0 \, [1 + (p - p_0) / K] \qquad (1)$$

K is the bulk modulus. The fluid field is solved by a Semi-Implicit Method for Pressure-Linked-Equations (SIMPLE) with corrector loops specified by Pressure-Implicit Splitting-Operator (PISO) parameters [2].

The coupling is achieved through boundary condition update (Fig.2). Since a Finite Volume (FV) discretization in OpenFOAM is cell-based, while the boundary is usually defined at the vertices and edges this poses a problem for correct calculation of the mesh movement. Therefore a vertex-based method implementing finite element classes is implemented [2]. Variables are transferred between the fluid and solid surface using a patch-to-patch interpolation. Pressure and viscous force increments (δp_I and $\delta \mathbf{t}_I$) at the fluid side of the interface is transferred to the solid side of the interface. Displacement increment $\delta \mathbf{u}_I$ and velocity $\mathbf{v}_I$ at the solid side of the interface is transferred to the fluid side.

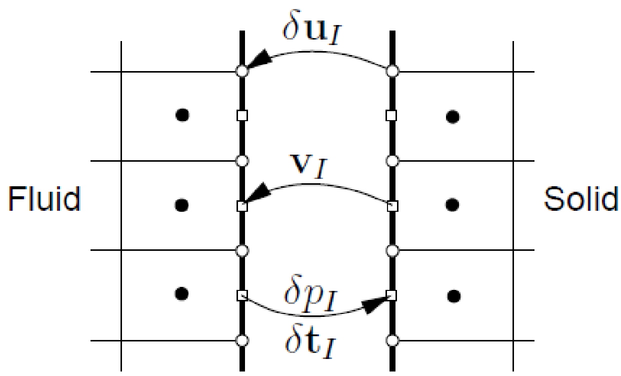

Fig. 2: Transfer of coupling data

Figure 3 shows the preliminary tapered box model of the cochlea including the trapezoidal basilar membrane (BM) which widens from 80 µm at the base to 500 µm at the apex. Usual orthotropic mechanical parameters are used. At the base the width of the box is 3 mm to apply the pressure at the oval window which will have an area of 1.5 mm x 3 mm. The round window below will work in “push-pull” at least for low frequencies.

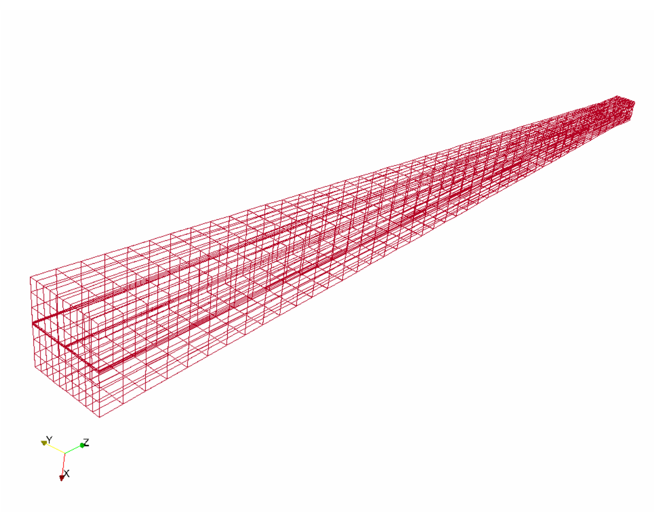

Fig. 3: Tapered box model of the cochlea (length 32 mm, width at the base 3 mm). Done with *blockMesh* utility of OpenFOAM

Anatomical preparation and data representation of structures

To yield geometric data for the simulation of the highly circumflexed structures of the cochlea and the CI electrode cut temporal bones of humans were implanted with special prepared electrodes without metal to prevent artefacts [4]. These were analyzed using a µCT (Scanco, Switzerland) tomography instrument with a resolution in space of down to 5 µm. The manual segmentation of images and 3D-reconstruction by AMIRA® produced mass data of about 30 GByte for each case. Fig. 4 shows one representative image of a slice through the cochlea with the silicon body of special prepared CI electrode. It can be seen that the electrode launched through the round window traverses the BM and takes its way into the scala vestibuli. Of course this should be prevented *in vivo* to maintain patients hearing abilities in the low frequency range. In spite of the high resolution (5 µm) the BM could not be reconstructed und must be integrated afterwards.

Five different materials were distinguished in this reconstruction. These are : 1 lymph of scala tympani and scala vestibule, 2 surrounding bone and stapes footplate, 3 CI-electrode, 4 annular ligament and 5 round window membrane. The reconstructed volumes were stored as .stl (standard lithography) files and imported to the OpenFOAM software package for simulating continuum mechanics.

A delightful feature of this package is its ability to import .stl files of complex structures and mesh it to grids. The utilities *snappyHexMesh* and *splitMeshRegions* are able to detect an imported .stl file and mesh it if a number of capture parameters were chosen correctly. These utilities require a parallel processing scheme and are available for the Linux and not the Windows operating system at this time.

Because the BM could not be included up to now, examples of the complete reconstructed system are not shown. The propagation of pressure impulses along a tube (Fig. 3) with a CI-electrode were be calculated and animations will be given at the conference.

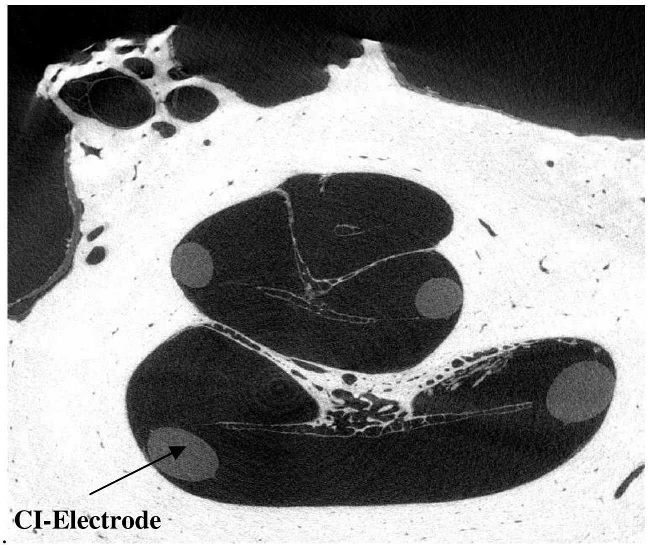

Fig. 4: Slice of a human cochlea with implanted electrode

Conclusions and Discussion

To study the influence of the CI-electrode on the acoustic field inside the cochlea preparations in form of anatomical data acquisition and processing were implemented. The continuum mechanical evaluation by the software package OpenFOAM allows a numerical implementation of the fluid-structure problem in complex geometries. The 3D field will produce a representation of sound waves in a weak compressible and viscous fluid (lymph) and its interaction with a solid (BM), surrounding bone and the CI-electrode. The (orthotropic) BM will be covered by shell theory or as an elastic solid and discretized by Finite Elements or Finite Volumes. Even though the Finite Element Method is able to represent the complex geometry of loaded structures the method only satisfies equilibrium in an average global sense and stress continuity across element boundaries and equilibrium within individual elements are not guaranteed. Therefore alternative methods, which secondary avoid the locking phenomenon in which plate elements respond in an excessively stiff manner were developed [5, 6].

Though numerical results of the influence of a CI-electrode on the sound field in the cochlea and the displacement of the BM could not be given at this time the way for those solutions was presented.

Literature

[1] von Ilberg C., Kiefer J., Tillein J., Pfennigdorff T., Hartmann R., Stürzebecher E., Klinke R. (1999). Electric-acoustic stimulation of the auditory system. *ORL* 61:334-340

[2] Maus K.J. (2009). icoFsiFoam and interFsiFoam Constructing solvers for weakly coupled problems using OpenFOAM-1.5-dev, UMB Norwegian University of Life Sciences

[3] Kiefer J., Böhnke F., Adunka O., Arnold W. (2006). Representation of acoustic signals in the human cochlea in presence of a cochlear implant electrode. Hearing Research, 221, 36-43

[4] Böhnke F., Braun K., Stark T. (2010). 3D-Rekonstruktion der Cochlea mit implantierter CI-Elektrode, 81. Jahrestagung der Deutschen Gesellschaft für HNO-Heilkunde Kopf- und Hals-Chirurgie, Wiesbaden

[5] Demirdzic I., Muzaferija S. (1994). Finite Volume Method for Stress Analysis in Complex Domains, International Journal for Numerical Methods in Engineering, vol. 37, 3751-3766

[6] Wheel M.A. (1997). A Finite Volume Method for analysing the bending deformation of thick and thin plates, Computer methods in applied mechanics and engineering, 147, 199-208

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