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3D Simulation of the Human Middle Ear with Multi-Body Systems

The ear is an essential human sensory organ. In Germany, approximately 10 million people suffer from hearing impairments. Implantable systems can speed recovery from hearing loss, such as the active middle ear implant "Vibrant SoundBridge" produced by MED-El, Innsbruck, Austria. Active middle ear implants are used in cases of sound conduction hearing loss or sensorineural hearing loss.
In recent years, computer-aided 3D simulation has significantly improved the medical world's understanding of the anatomy and function of middle ear structures, thus, promoting the development of middle ear prostheses.

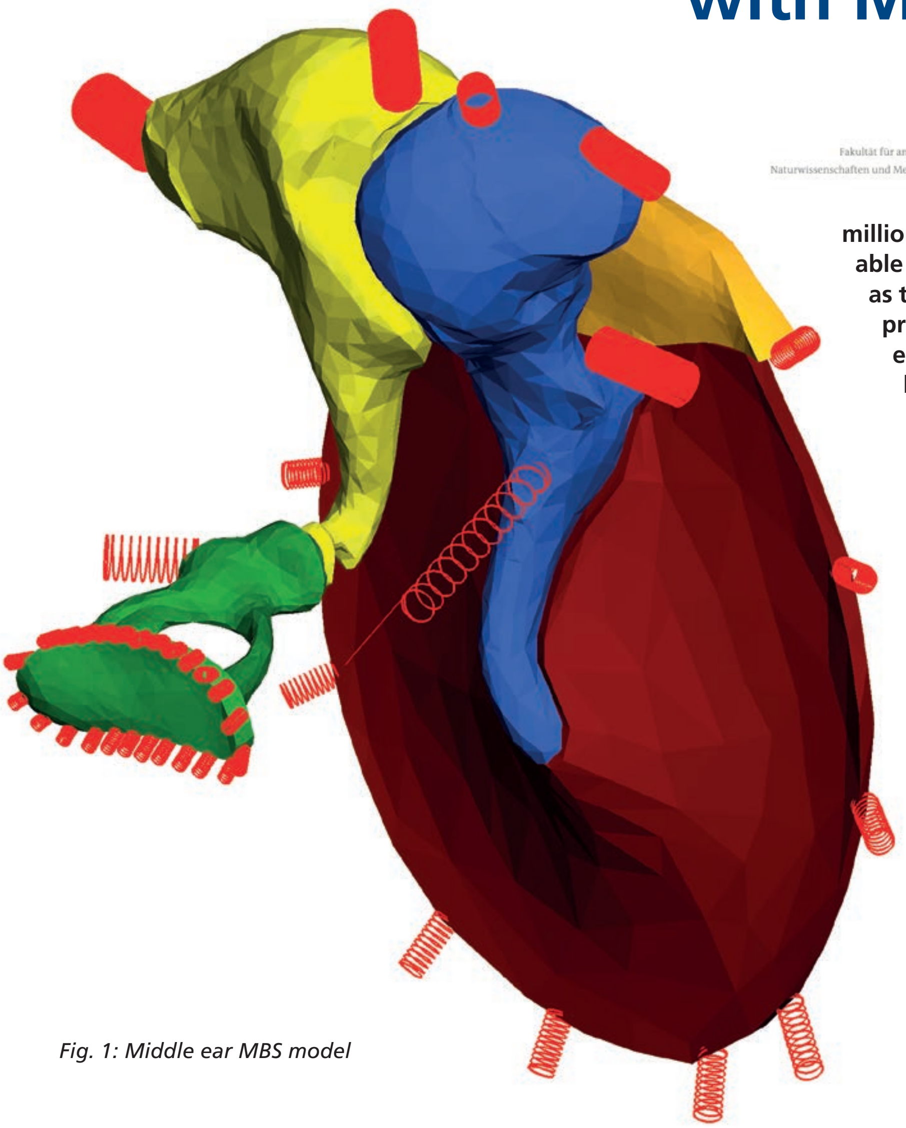

Fig. 1: Middle ear MBS model

INTRODUCTION

A middle ear multi-body model was developed (Fig. 1) to research hearing impairments.
This research focuses on the development and simulation of a 3D multi-body model of the human middle ear. It examines how the middle ear system responds to different types of sound stimulation in both a normal middle ear and a middle ear coupled with an active implant.

MULTI-BODY MODEL

A 3D model of a normal human middle ear and the middle ear coupled with an active implant, as shown in Fig. 2, was developed using the software package SIMPACK.
The MBS model contains the exact geometry of the middle ear structures — the tympanum and the three ossicles (malleus, incus and stapes). This was facilitated by a micro-computer tomographic dataset of the human middle ear.
The physical properties, and the inertia tensor of the aforementioned structures, were calculated together with the active implant using appropriate density values taken from the literature in the CAD software SolidEdge.

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All anatomical structures, their location, and their 3D orientation are included in the model of the middle ear.
The tympanum, the active implant, and the three ossicles are modeled as rigid bodies.
The Kelvin-Voigt model is used for the biomechanical description of linear viscoelastic behavior of the ligaments and muscles of the middle ear.
In the Kelvin-Voigt model, massless springs and dampers are connected in parallel.
The linear elastic material properties of muscles and ligaments have been modeled as massless spring-damper Force Elements in all three axes. To take into account the flexible fiber structure around the tympanum in the model, the annulus fibrocartilagineus is modeled by twelve spring force elements. The ligamentum annulare stapedis is modeled by 25 massless spring-damper elements. The center of gravity of the tympanum is attached to the inertial system with a one-degree of freedom (DOF) Joint. The malleus is rigidly connected with the tympanum. The incudostapedial connection has been modeled as a unilateral contact force element on all three translational axes. Rotational spring damper force elements were used for the rotation. A damping Force Element is used for the coupling of the stapes footplate with the inertial system, which is centrally and vertically arranged on the footplate. The damper represents the cochlea which is filled with incompressible liquid. The system contains 17 elements and has four degrees of freedom. The whole system is considered linear and time-invariant.

SIMULATION

A "click" sound stimulation in the form of a Gaussian pulse with a half-power width of 100 ms and a wobbling signal stimulates all frequencies.

The dynamic behavior of the middle ear in the steady state condition was examined for both the normal model of the middle ear (Fig. 3) and the middle ear model coupled with a active implant with two different types of stimulation on the tympanum: a "click" sound excitation in the form of a Gaussian pulse at various sound pressure levels (SPL) — 60, 80 and 94 dB — and a harmonic acoustic stimulation.
The stapes and umbo deflection in the speech frequency range were studied, and the phase shift between the incus and stapes was analyzed.

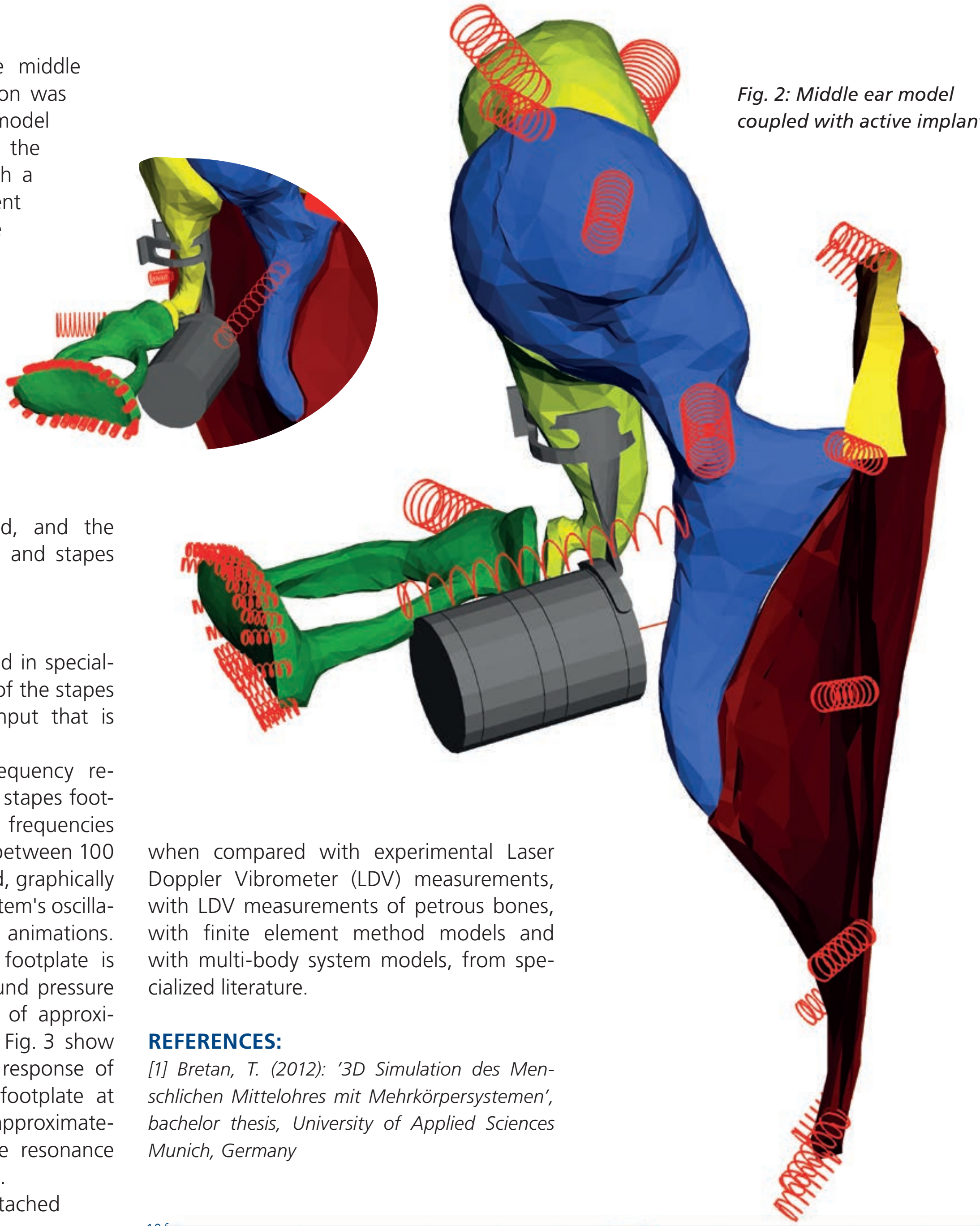

Fig. 2: Middle ear model coupled with active implant

RESULTS

Typically, the result that is noted in specialized literature is the deflection of the stapes footplate. This result is the input that is processed by the inner ear.
The amplitude and phase frequency response of the deflection of the stapes footplate and umbo deflection for frequencies in the speech frequency range between 100 Hz and 10 kHz were determined, graphically displayed and analyzed. The system's oscillation behavior was visualized by animations. The deflection of the stapes footplate is directly proportional to the sound pressure stimulation up to a frequency of approximately 6.5 kHz. The results in Fig. 3 show that the amplitude frequency response of the deflection of the stapes footplate at 60 dB SPL (blue dashed line) is approximately 6.17 nm and reaches at the resonance frequency of 1210 Hz 18.42 nm.
The use of an active implant attached to the incus neck moves the resonance frequency to lower frequencies and amplifies the stapes footplate deflection for both a harmonic and a Gaussian pulse sound excitation at the tympanum.

CONCLUSION

The simulation results have illustrated the complex 3D vibration of the ossicle resulting from the two types of sound stimulation at the tympanum and at different sound pressure levels. The simulation results of an acoustic excitation of the tympanum with a Gaussian pulse coincide with the literature.
The accuracy of the virtual model of the middle ear was always validated when compared with experimental Laser Doppler Vibrometer (LDV) measurements, with LDV measurements of petrous bones, with finite element method models and with multi-body system models, from specialized literature.

REFERENCES:

[1] Bretan, T. (2012): '3D Simulation des Menschlichen Mittelohres mit Mehrkörpersystemen', bachelor thesis, University of Applied Sciences Munich, Germany

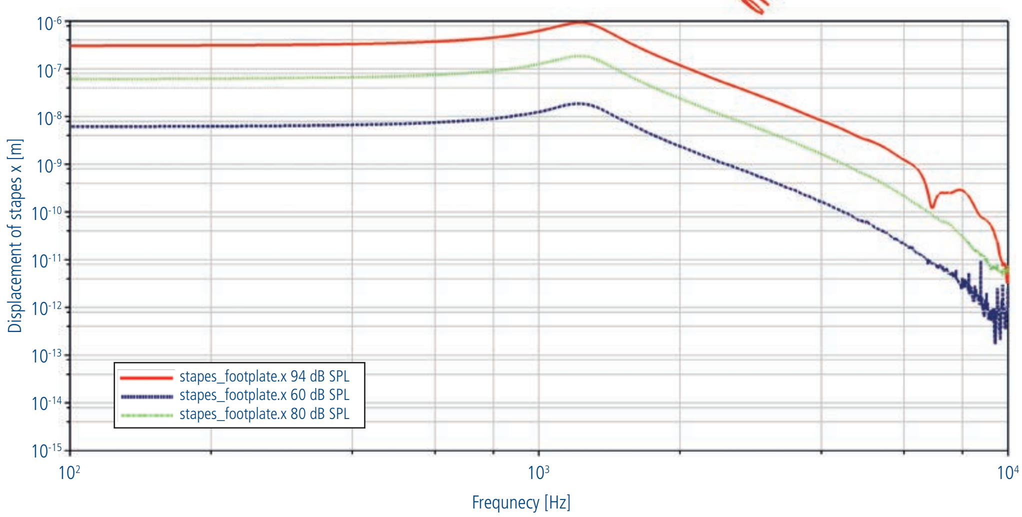

Fig. 3: Amplitude response for a click sound excitation at various sound pressure levels (SPL) — 60, 80 and 94 dB