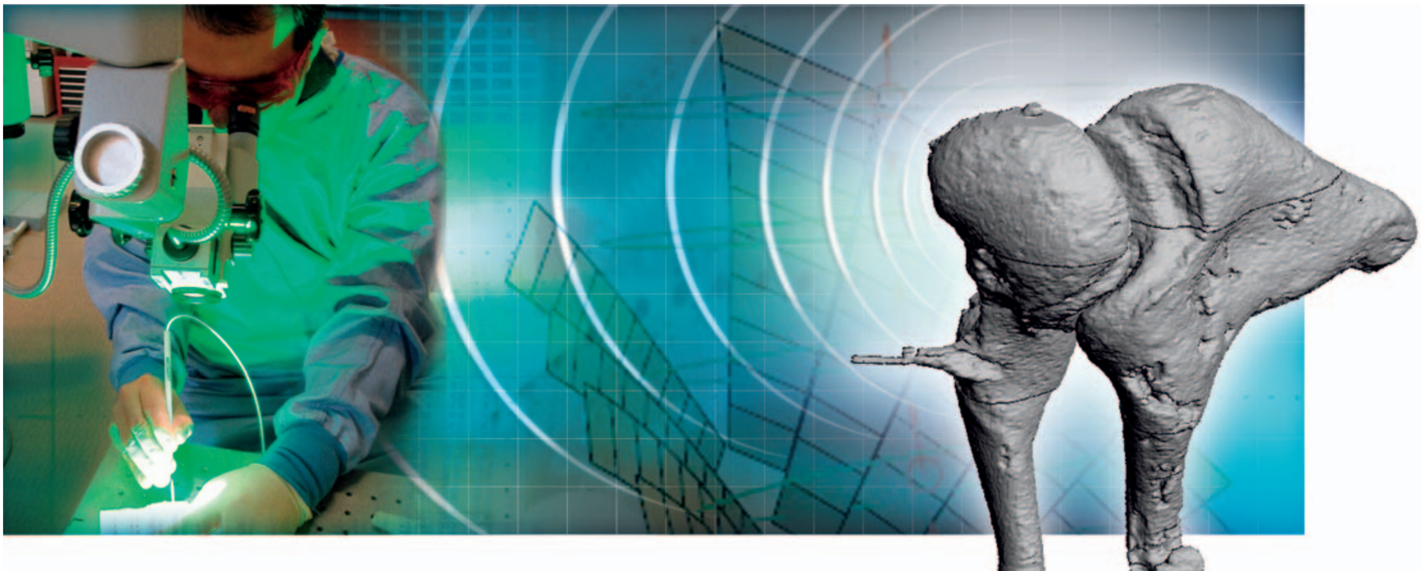
Illuminating *Sound Transmission*



Motion and Biomechanics of the Human Middle Ear

Significant advances are being made in our understanding of the structure and functional relationships of normal and pathological middle ears. One reason for the enhanced understanding has been the use of non-contact laser Doppler vibrometers to measure motions of the middle ear both in-vitro (cadaver in laboratory) and in-vivo (patient in operating room).

Introduction

In the physiological range, motions of the middle ear are typically less than 100 nm. Thus, accurate measurements with good signal-to-noise in the acoustic hearing range of 20 Hz to 20 kHz are necessary to characterize the response of the human ear, and at higher frequencies for similar measurements on animals.

We are now on the verge of understanding the relationship between human middle ear morphometry, tailored to individual ears, and the biomechanical processes that lead to physiological responses in individual subjects.
Yet, despite all of the recent advances, there exists a significant lack of knowledge about the relationship between middle ear structures and sound transmission. The goal of our new study is to make precision measurements that result in a better understanding and model of the middle ear and thus improved middle ear repairs and better clarity in interpreting otoacoustic emissions that travel from the cochlea through the middle ear and are measured in the ear canal.

Experimental Approach

The Stanford OtoBiomechanics group uses the approach of deconstructing middle ears of cadaver temporal bones into sub systems that are each characterized through a combination of physiological and morphological measurements as well as three-dimensional mathematical analyses. The subsystems are mathematically reconstructed for comprehensive analyses representing the intact middle ear of each individual. The sub systems are:

- the tympanic membrane coupled to the ear canal and isolated by removing the incus
- the malleus-incus complex (Figure 1) isolated by dissecting the eardrum and the stapes from the temporal bone
- the isolated stapes footplate

Measurement Setup

Dynamic measurements using a Polytec HLV-1000 Laser Doppler Vibrometer (Figure 2) are made in order to determine the biomechanical parameters of the morphologically based sub models. Without an eardrum or stapes the malleus-incus complex (Figure 3) cannot be driven with sound.

Figure 1: Isolated malleus-incus complex (microCT image) without suspensory ligaments.

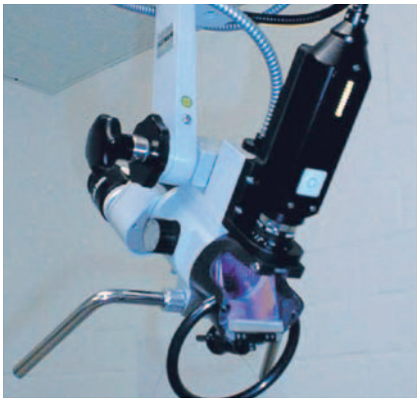


Figure 2: Polytec HLV-1000 Hearing Laser Vibrometer

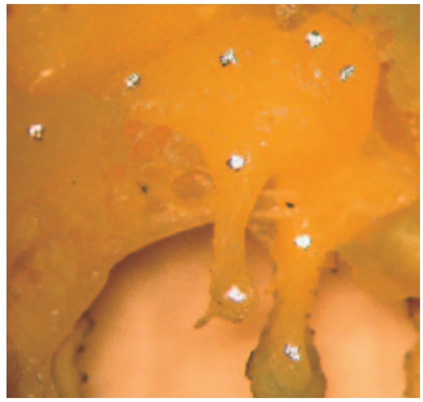


Figure 3: Preparation of the middle ear ossicles, with reflective material

A magnet attached to the tip of the malleus is driven by a coil around the tympanic annulus. The magnitude and phase-angle of the velocity are measured at several points on the malleus and incus. Each point is measured from five or more unique angles to allow decomposition into three vector components: in-plane (X,Y) and out-of-plane (Z)).

Once a cadaver middle ear preparation is mounted with the medial side facing the laser, two stacked goniometers are used to provide two orthogonal axes of rotation around a common fixed rotation point 17.5 mm above the goniometer. Each goniometer has an angular range of ±15 degrees around one-axis, and ± 20 degrees around the other. Angular resolution is 5 arc minutes. Care is taken to choose an xyz coordinate system which is a body-axis system, that is, fixed in the temporal bone and rotated with it. Alignment of the y-axis should be along the incus handle with the x-axis in the plane of eardrum. The z-axis is along the laser measurement direction.

Geometry Model

components of velocity are related as follows:

$$v_i = -\sin(\beta_i)v_x + \sin(\alpha_i)\cos(\beta_i)v_y + \cos(\alpha_i)\cos(\beta_i)v_z$$

The relation between measured velocities and xyz components of velocity can be compactly expressed in matrix form as:

$$\mathbf{v_m} = \mathbf{A} \cdot \mathbf{v}$$

where **v** is a vector with calculated xyz components, $\mathbf{v_m}$ is the measured velocity and **A** is the matrix determined from the measurement angles. The method of least squares is used to calculate **v**. For each sub system and for the intact middle ear, high resolution micro-CT images are used to describe individual temporal bone ears. The micro-CT images are segmented and combined to obtain three-dimensional volume reconstructions of the ear canal, eardrum, ossicles, ligaments and tendons, which are further analyzed to obtain the desired morphometry.

Mathematical Model

A mathematical model is formulated, incorporating anatomical features of the eardrum, including its angular placement in the ear canal, conical shape and its highly organized circumferential and radial fiber layers. The dynamic motion of the ossicular chain is modeled by methods of the multi-body system:

$$\mathbf{M}\ddot{\mathbf{x}}(t) + \mathbf{C}\dot{\mathbf{x}}(t) + \mathbf{K}\mathbf{x}(t) = \mathbf{F}(t),$$

where the vector $\mathbf{x}(t)$ denotes the displacement at time t, and the vectors $\ddot{\mathbf{x}}(t)$ und $\dot{\mathbf{x}}(t)$ are the corresponding velocity and acceleration. The force vector $\mathbf{F}(t)$ is the force generated by the magnet/coil system. The mass matrix **M**, the damping matrix **C** , and the stiffness matrix **K** are obtained from the basic relations from the methods for linear systems. The challenge in the above description is to estimate the viscoelastic parameter values of each ligament and tendon. These estimates are obtained by 3-D velocity measurements using the laser Doppler vibrometer.

Conclusion and Outlook

By combining each of the sub models, these studies result in anatomically-based biocomputational models of the intact middle ear. Furthermore, the studies will provide a solid foundation for the structural basis for middle ear sound transmission and will have applications in many areas of hearing health care including surgical reconstruction of the middle ear, otoacoustic emissions and passive and active prostheses. Laser Doppler vibrometers are a critical component in the battery of tests used to understand structure/function relationships of the ear.

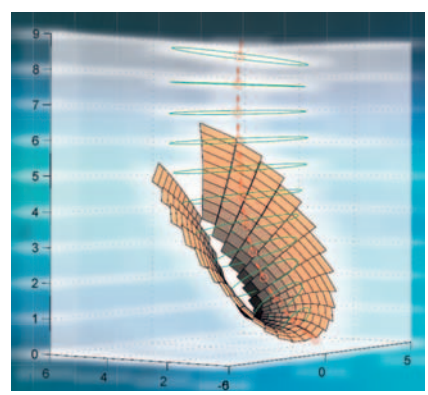


Figure 4: Mathematical model of the eardrum

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