Developments in Opto-Electronic Holography (OEH) for measurement of sound-induced eardrum motion

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Abstract

Prior to 2009 the data available to characterize the function of the mammalian eardrum was rather limited and consisted of time-averaged holograms gathered 30 to 40 years previously or laser-vibrometer measurements usually made with low spatial density or over small regions of the eardrum. These few measurements could be compared to the plethora of Finite-Element models of eardrum and middle ear function. More recently, a collaboration between an optics group at the Center for Holographic Studies and Laser micro-mechaTronics at the Worcester Polytechnic Institute in Worcester MA and physiologists and acousticians at the Eaton-Peabody Laboratory at the Massachusetts Eye and Ear Infirmary in Boston MA have applied new computer controlled holographic methods to greatly increase the data describing eardrum function. The techniques and their results include: (1) One-dimensional Stroboscopic Opto-Electronic Holography (OEH) to describe the magnitude (with nanometer resolution) and phase of over 200,000 points on the surface of the eardrum to a broad range of sinusoidal stimuli that led to descriptions of combinations of stationary-wave and traveling-wave like motions on the eardrum surface. (2) Dual-wavelength OEH that produced rapid micron-level measurements of the 3D-shape of the eardrum that allowed estimations of the effect of shape on our 1D measurements. (3) Three-dimensional OEH that produced high resolution measurements in time and space of the 3D motion of the eardrum surface. The combination of the 3D shape and motion measurements led to assessment of the contribution of in-plane motions to eardrum function, where these motions have been found to be small compared to out-of-plane motions. (4) High-speed OEH (HS-OEH) that allows measurements of the response of the eardrum to acoustic or mechanical transients, where these impulse responses enable continued investigations of the role of stationary and traveling surface waves on eardrum function. Each of these methods will be reviewed and available results summarized.
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Introduction

The mammalian eardrum serves as an acoustic-mechanical transducer to conduct sound energy from the environment to vibrations within the middle ear and greatly increases the ear’s sensitivity to sound. However, prior to 2009 our knowledge of sound-induced eardrum vibrations was rather limited. Although many measurements of eardrum motion had been done in the past using laser Doppler Vibrometry [1-3], these measurements were made at only a few locations on the eardrum surface, such as the umbo (where the ossicles connect to the eardrum), and the results did not describe the vibration of the eardrum in any spatial detail. Earlier time-averaged holographic measurements of sound-induced eardrum vibration described motion patterns highly dependent on frequency, which became very complicated in space above a few kHz [4-5]. These early measurements did not provide information on the motion phase, which is needed to describe relative motion between different portions of the eardrum.

Beginning in 2007, two groups, optics experts from Worcester Polytechnic Institute and hearing researchers from the Massachusetts Eye and Ear Infirmary, have worked together to develop new computer-controlled fiber-optic-based opto-electronic holographic (OEH) interferometry systems [6-7] that rapidly record both the magnitude (with nanometer resolution) and the phase of eardrum vibration at more than 200,000 points on the eardrum surface over a broad frequency range (<0.2 to 20 kHz) of sound stimuli. Novel holographic techniques were also developed to study other aspects of the sound-induced motion of the eardrum, including stroboscopic holography, dual-wavelength holography to measure eardrum shape, multi-illumination 3D
holography to measured motion in three dimensions simultaneously, and high-speed holography to measure transient responses [8-12] in real time. The results have led us, for the first time, to describe a combination of stationary-wave and traveling-wave like motions on the eardrum surface due to tonal stimuli; separate out-of-plane motion of the eardrum (the motion perpendicular to the local eardrum surface) from in-plane motion and point out the dominance of the out-of-plane component, and describe the transient response of the eardrum with high spatial and temporal resolution by incorporating a high-speed camera into the holography system.

Methods

1D and 3D Motion Measurements

Digital holography uses changes in the optical path length between an object and the recording camera plane to quantify the shape or motion of the object [8, 9]. As shown in Figure 1a, an object’s displacement \( d \) induces a change in the optical path length of the laser light (OPD). Based on the geometry of the system (i.e., the illumination and observation vectors), OPD is related to the z-axis displacement \( d_z \) by

\[
OPD = d_z \cos(\theta_1),
\]

where \( \theta_1 \) is the angle between illumination and observation directions. Using the wavenumber equation, \( k = \frac{2\pi}{\lambda} \), OPD is converted to the phase \( \Omega \) by \( \Omega = \frac{2\pi}{\lambda} OPD \), and consequently, the 1D object’s displacement along the \( z \) axis \( d_z \) is calculated as

\[
d_z = \frac{\lambda \Omega}{2\pi(1+\cos(\theta_1))}.
\]

In order to measure all three components of the displacement vector, \( d \), shown in Figure 1a, at least three independent measurements with different sensitivity vectors are required. This can be achieved by varying the illumination direction \( (IPi) \) to form different sensitivity vectors \( (Ki) \) as shown in Fig. 1b. In our approach, optical phase maps are obtained with four sensitivity vectors to form an overdetermined system of equations that is solved iteratively in Matlab with the least-squares error minimization method with

\[
\{d\} = \left[[S]^T[S]\right]^{-1} \times \left[[S]^T\{\Omega\}\right],
\]

where \([S]\) is the sensitivity matrix containing all the sensitivity vectors \( K_i \), and \{\Omega\} is the fringe-locus function that defines the unwrapped optical phase difference.
Figure 1: Principles of 1D and 3D displacement measurements in holographic interferometry: (a) as the object deforms, the optical pathlength (OPD) of the laser light changes and the change is used to quantify the displacement; and (b) the surface of the eardrum is illuminated from at least three different directions for 3D displacement measurements.

3D Shape Measurements
A two-wavelength holographic contouring technique was developed to generate depth contours to define the 3D shape of the eardrum surface. The technique is based on the utilization of a coherent polarized light source with wavelength tuning capabilities [10]. The technique requires acquisition of a set of optical amplitude and phase information at wavelength $\lambda_1$, the reference state, as well as a second set of amplitude and phase information at wavelength $\lambda_2$. Interferometric depth contours, related to the 3D geometry of the object under investigation, are generated by speckle phase correlation of two sets of phase-stepped speckle intensity patterns. The phase difference of the two corresponding sets of data $\Delta \phi$ is given by,

$$\Delta \phi = \phi_2 - \phi_1 = \frac{2\pi}{\Lambda} OPL,$$

where $\phi_1$ is the phase of the optical path length recorded at the first wavelength $\lambda_1$, $\phi_2$ is the phase of the optical path length recorded at the second wavelength $\lambda_2$, $OPL$ is the optical path length defined as the distance in wavelengths between the illumination point, the object point and the observation point, and $\Lambda$ is the synthetic wavelength given by

$$\Lambda = \frac{\lambda_1 \lambda_2}{|\lambda_1 - \lambda_2|}.$$

The fringe-locus function $\Omega(m,n)$ defined by the optical phase difference $\Delta \phi(m,n)$ is used to calculate the relative height of each point on the surface of the object $Z(m,n)$, where

$$Z(m,n) = \frac{\Omega(m,n) \Lambda}{4\pi}.$$

High-speed Motion Measurements
Quantification of the spatio-temporal response of the human TM to transient acoustic or mechanical stimuli has been enabled through the development and implementation of a novel High-Speed Opto-Electronic Holographic (HS-OEH) system capable of full-field very rapid (>85
kHz) nanometer-scale displacement measurements. The HS-OEH operation is based on a novel hybrid spatio-temporal local correlation (LC) phase sampling approach [11], where a reference frame \( I_{\text{ref}} \), a second reference frame \( I_{\text{ref}+\pi/2} \), phase shifted from \( I_{\text{ref}} \) by \( \pi/2 \), and a deformed frame, \( I_{\text{def}} \), are spatially correlated to quantify the motion-induced optical phase change, \( \phi(m, n, t) \), proportional to the object deformation at time \( t \) as

\[
\phi(m, n, t) = \tan^{-1} \left[ \frac{\rho(I_{\text{ref}}(m, n), I_{\text{def}}(m, n, t))}{\rho(I_{\text{ref}+\pi/2}(m, n), I_{\text{def}}(m, n, t))} \right],
\]

where \( \rho \) is the Pearson’s correlation coefficient for finite discrete sets having the measured intensities as arguments and computed based on a spatial kernel (with dimensions of 3x3 or 5x5 pixels) centered around each measurement point \((m, n)\) of a pair of reference and deformed frames. The LC phase sampling approach is implemented through a novel high-speed \( 2+N \) frame acquisition method [11], with a timing diagram shown in Figure 2.

**Figure 2:** A timing diagram demonstrating the principle of operation of the high-speed \( 2+N \) frame acquisition method based on a hybrid spatio-temporal local correlation (LC) phase sampling approach. The magenta rectangles describe the times when the camera is recording an image.

As shown in Fig. 2, the \( 2+N \) frame acquisition method starts by recording two reference frames, \( I_{\text{ref}} \) and \( I_{\text{ref}+\pi/2} \), temporally separated to allow the piezo-transducer (PZT) phase shifter to settle after the introduction of a \( \pi/2 \) phase shift [11]. While keeping the PZT at its final phase shift position, a set of \( N \) (i.e., >1k) consecutive frames, \( (I_{\text{def}})_i, i \in 1,2,N \), are recorded, at a rapid sampling rate (85 kHz or faster), before and throughout the evolution of an transient event. The spatio-temporal phase sampling and acquisition methods of the HS-OEH system fully utilizes the temporal resolution of a high-speed camera (i.e., Photron SA-5 or SA-X) without imposing constraints on the spatial resolution or requiring specialized optical setups. Additionally, since the LC algorithm is applied independently at every measurement point \((m, n)\) the evaluation of all measurement points across each measurement frame is executed in parallel through custom multi-threaded-GPU-accelerated software.

**Results**

**3D sound-induced Motions of Human TM**

We show stroboscopic holographic measurements of 3D motion of the eardrum surface elicited by two tones (Figure 3). At each stroboscopic phase, sound-induced motions of the TM along each of the three orthogonal (Cartesian) axes \( x, y \) and \( z \) are calculated from the unwrapped optical
phases measured with the four sensitivity vectors. FFT algorithms are used to compute the magnitude and phase of motions along all three axes [8]. The displacement patterns are simple at lower frequencies and increase in complexity as the excitation frequency increases. At 1.56 kHz, one or two regions of large displacement along all three Cartesian axes can be seen, while the phase plots suggest that a majority of the eardrum surface moves in phase. Also the displacement magnitude along the z axis is ~5 times higher than the x and y axis. At 10.7 kHz the TM motion has many local maxima and minima along all three axes, and we observe systematic variations in phase. The displacement along the z axis is generally twice the magnitude along the other two axes.

Figure 3: 3D magnitudes and phases of sound-induced motion of human TM at two different tonal stimuli 1.56 and 10.7 kHz. x, y, and z axes are defined by the global axes of the measuring system. One colorbar is used for x and y-axes motions; the z-axis motion has its own colorbar. The units of the magnitude plots are micrometer and the units of phase plots are radian.
In-plane and out-of-plane motion components

Data obtained from the shape measurement of the same eardrum are mathematically combined with the 3D motion measurements (Fig.3) to perform the first computation of the displacement components locally normal (out-of-plane) and tangent (in-plane) to the eardrum at each point (Figure 4). As described in detail in [9], a numerical rotation matrix was developed and implemented to compute the out-of-plane ($d_\eta$) and in-plane ($d_\alpha$, $d_\beta$) components. A general conclusion is that the displacement components normal to the eardrum plane are larger than those tangent to the drum. These results are consistent with the thin-plate theory in which nearly all motion is normal to the plate surface and tangential components are negligible.

![Figure 4: 3D magnitudes and phases of sound-induced motion of human TM at two different tonal stimuli 1.56 and 10.7 kHz. The in-plane and out-of-plane motions correspond to sound-induced motion tangent and normal to the local plane of the TM, respectively. The unit of magnitude plots are micrometer and the unit of phase plots are radian.](image)

Response of the human eardrum to local mechanical transients

A set of experiments were conducted utilizing the HS-OEH system to quantify the transient displacement of the human TM when excited by a localized (i.e., <1\text{mm}^2) mechanical input via a PZT stimulator. Providing local (point or small area) rather than global (full surface) excitation
allows us to separate the initial stages of energy transfer to the eardrum independently of phenomena such as reflections and interference of the surface waves.

**Figure 5:** Response of the human TM excited at position 1 by a 50µs mechanical click: (a) spatial distribution of displacements during the first 20-80µs after the application of the mechanical pulse; (b) time waveform of the first 150 µs of the displacement at points 1 and 2 as well as the acceleration of the stimulator; (c) spatial dependence of the first local maxima (FLM) of the time waveform at all measurement points. Black regions in (c) indicate data below the noise floor (<8.5nm) of the HS-OEH. The manubrium is outlined with a solid black line.

In preparation for the experiments, the lateral surface of an eardrum from a human cadaver supported by its normal bony ring was placed in front of the HS-OEH while the mechanical stimulator drove a point, indicated as point 1 in Figure 5a, on the medial surface of the eardrum. The high speed camera (Photron SA-5) of the HS-OEH system was set at 256×256 pixels² and 87,500 frames/s sampling rate, resulting in 40µm spatial and 11.4 µs temporal resolutions, respectively.
Figure 5a shows the spatial distribution of the displacement of the eardrum at 6 instants in time between 20 and 80 µs after the application of a local mechanical pulse at point 1. All timing labels are referenced to the application of the control signal to the stimulator. The initial (23-46 µs) region of maximal outward (+) displacement corresponds to the location of the stimulator (point 1) while a region of inward (−) displacement develops at the connection between the eardrum and the ossicles (point 3). The outward motion gradually (within 57-80 µs) evolves into surface traveling waves that emanate from the contact point of the stimulator and move circularly around the umbo. Focusing on the 69-80 µs images in Figure 5a, it can be seen that the superior-posterior area of the eardrum moves with a magnitude of about 0.05 µm before the arrival of the surface wave. This suggests a mechanical coupling between the anterior and posterior halves of the eardrum, possibly through the manubrium and the internal fiber structure of the TM. In order to quantify the speed of propagation of the surface traveling waves, the time waveforms at points 1 and 2, marked in Figure 5a, were plotted together with the measured acceleration from the stimulator, shown in Figure 5b. The two points are located 1.65mm away from each other. Each displacement waveform in Figure 5b shows the average of three measurements together with a confidence interval of ±1σ standard deviation for each time instance. The temporal separation between first local maxima (FLM) of the time waveforms at point 1 and 2 is 57 µs, which corresponds to an average surface wave speed of 29 m/s, which is in agreement with previously reported estimates [12]. Analysis of the timewaveforms of all measurement points relative to point 1 results in the FLM map shown in Figure 5c, indicating the spatio-temporal distribution of the surface waves traveling across the eardrum.

Conclusions
We developed Opto-Electronic Holography systems for investigations of the function of the eardrums and humans and other animals. These techniques measure the 3D shape (with µm resolution) and 3D sound-induced motion (with nm resolution) of cadaveric mammalian eardrums at spatial densities of near 2000 points per mm². The results suggest that the in-plane motions of the eardrum are small compared to the out-of-plane motions, consistent with thin-plate like behavior of the eardrum. Our High-Speed Opto-Electronic Holographic (HS-OEH) system enables full-field nanometer transient displacement measurement of the eardrum with similar spatial resolution but with extremely fast temporal (i.e., > 80 kHz) resolutions that enable the study of the acoustical and mechanical characteristics of the middle-ear at a level of detail that have never been reached before. Using this system to measure the effect of localized mechanical stimulation demonstrated the spread of excitation across the surface of the TM. The data greatly expand our knowledge of sound-induce eardrum motion and the function of the eardrum in transducing sound to mechanical vibration.

Acknowledgements
This work was supported by the National Institute on Deafness and other Communication Disorders (NIDCD), Massachusetts Eye and Ear Infirmary (MEEI), the Swiss National Science Foundation (SNSF), and the Mechanical Engineering Department at Worcester Polytechnic Institute. We also acknowledge the support of all of the members of the CHSLT labs at WPI and Eaton-Peabody labs at MEEI.
References


