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Optimization of a lensless digital holographic otoscope system for transient measurements of the human tympanic membrane

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Abstract

In this paper, we propose a multi-pulsed double exposure (MPDE) acquisition method to quantify in full-field-of-view the transient (i.e., >10 kHz) acoustically induced nanometer scale displacements of the human tympanic membrane (TM or eardrum). The method takes advantage of the geometrical linearity and repeatability of the TM displacements to enable high-speed measurements with a conventional camera (i.e., <20 fps).

The MPDE is implemented on a previously developed digital holographic system (DHS) to enhance its measurement capabilities, at a minimum cost, while avoiding constraints imposed by the spatial resolutions and dimensions of high-speed (i.e., >50 kfps) cameras. To our knowledge, there is currently no existing system to provide such capabilities for the study of the human TM.

The combination of high temporal (i.e., >50 kHz) and spatial (i.e., >500k data points) resolutions enables measurements of the temporal and frequency response of all points across the surface of the TM simultaneously. The repeatability and accuracy of the MPDE method are verified against a Laser Doppler Vibrometer (LDV) on both artificial membranes and ex-vivo human TMs that are acoustically excited with a sharp (i.e., <100 μ s duration) click.

The measuring capabilities of the DHS, enhanced by the MPDE acquisition method, allow for quantification of spatially dependent motion parameters of the TM, such as modal frequencies, time constants, as well as inferring local material properties.

Keywords

Acoustic-solid interaction; High-speed digital holography; Miniaturization engineering; Otology; Transient response; Tympanic membrane

1 INTRODUCTION

Acoustically induced vibrations of the human tympanic membrane (TM) are the initial mechanical response of the ear to airborne sound. Ongoing hearing research efforts [1-8] are focused on studying displacements resulted from tone stimuli, however, transient response of the TM, e.g., the behavior of the eardrum excited by a short pulse (as opposed to tone), needs further investigations.

Quantification of the transient response of the TM could help understand the processes by which acoustical energy is transformed and transmitted to the ossicular chain [6, 7]. Measurements of such parameters as rate and efficiency of energy transformation as well as delays in the energy transmission are crucial for the investigation of the modes of operation of the TM [5], which may involve traveling waves [5], modal standing waves [6], or a combination of both [8]. Quantification of wave speeds, standing wave ratios [5, 6], damping [4, 9], stiffness [4], and modal frequencies could give limits to the mechanical properties of the TM and quantify the absorbance and immittance [8] of acoustical energy within the TM and the ossicular chain.

Current state-of-the-art methods to measure the transient response of the TM include measurements of averaged acoustic responses that describe the acoustic input impedance or reflectance at the TM [10], Scanning laser Doppler vibrometer for single [11] or multiple point [12] velocity measurements, and capacitive probes [13] for local displacement measurements. However, the spatially averaged acoustic measurements or sparsely sampled points are not sufficient for the full description of the complex patterns unfolding across the full surface of the TM. Existing full-field-of-view acquisition methods for transient nanometer displacements in engineering [14-16] require complicated timing electronics, costly high-speed (i.e., >10 kfps) or double-exposure cameras [17]. To our knowledge, currently there are a limited number of methodologies to provide full-field-of-view displacement measurements of the transient response of the human TM [18, 19].

We have designed a multi-pulsed double exposure (MPDE) acquisition method that allows the quantification of nanometer transient response of the entire surface of the human TM without the need for costly hardware and custom timing electronics. The MPDE method has been implemented within an existing digital holographic system (DHS) that was originally developed for the recording of steady state response of the TM of various species including human [1, 2]. The implementation of the MPDE method requires minimum hardware modification and utilizes a conventional camera (i.e., <20 fps) while allowing for high speed (i.e., >50 kHz) acquisition. The MPDE method utilizes the geometric linearity and repeatability [20, 21] of the acoustically induced nanometer deformations [1, 2] of the human TM. The transient displacement measurement capabilities of the DHS are verified against a laser Doppler vibrometer (LDV), on both artificial (latex membrane) and ex-vivo human TM samples, and we found samples a temporal repeatability > 96%, a time waveform correlation > 95%, and temporal and displacement difference of <10 μ s and <15nm, respectively.

2 EXISTING DHS CAPABILITIES

A digital holographic system (DHS), shown in Fig. 1, has already been deployed in medical research conditions and allows for time-averaged [6] and stroboscopic measurements [1,2,4] of the steady state response of the TM.

In the stroboscopic mode of operation, the operator adjusts the acquisition parameters via a unified control software [22], which in turn automatically synchronizes the operation of four hardware modules: I/O control, sound presentation [23], laser delivery and camera, as

schematized in Fig. 2. The camera and sound presentation modules are physically incorporated within a compact otoscope head (OH) package [are physically incorporated within a compact otoscope head (OH) package [24]. During a measurement, the control software utilizes the stimulus generator to control the stimulus generator component of the I/O module to automatically execute the acoustic excitation, illumination, and frame acquisition processes of the stroboscopic acquisition [22].

3 OBJECTIVES AND CONSTRAINTS FOR TRANSIENT ACQUISITION

3.1 Assumptions

A major design goal is incorporation of transient measuring capabilities to an existing DHS [14-16], while making minimum hardware modifications. To fulfill this goal, we assume that the acoustically induced transient displacement response of the TM is sufficiently repetitive. This means that the response of the human TM can be represented by several individual pulsed displacement measurements at different time instances by applying the same transient acoustic excitation. We also assume that we can reproduce the particular transient acoustic excitation with sufficient repeatability.

The assumption for repetitive transient response of the TM is supported by previous measurements of nanometer scale displacements induced by steady state acoustic excitation [1-8]. Such measurements indicate that, even at high (i.e., >100 dB) sound pressure levels (SPL), the displacements of the surface of the TM are more than 3 orders of magnitude smaller than typical TM characteristic dimensions [20]. This suggests that the strains within the TM are in the linear regime and have negligible hysteresis [21]. We validate these assumptions as part of the development of the MPDE method.

3.2 Constraints

In order to add transient measurement capabilities to the existing DHS, we first need to establish criteria and corresponding design parameters defining the temporal and spatial resolution requirements that the acquisition system needs to meet. Previous research [1, 2, 24] indicates that the existing DHS has sufficient spatial (i.e., >7 lp/mm) and displacement (i.e., <15 nm) resolution and accuracy for the quantification of acoustically induced displacements of the human TM. Based on the physiology of the human ear, a set of design criteria were developed in order to set bounds to the image acquisition parameters to enable transient measurement capabilities to the DHS. The major parameters, defining the temporal and frequency resolutions needed, are summarized in Table 1.

The sampling rates (temporal resolution) are defined by the frequency range to which the ear is most sensitive: typically 0.2-8 kHz [25, 26]. To allow sufficient temporal resolution for the measurement of the instantaneous magnitude and phase [1,2] of the acoustically induced motion of the TM as well as its total harmonic distortion [27], the acquisition system needs to sample at rates of at least 5-10 samples per cycle [1,2]. Thus, a sampling rate of up to 40 kHz is required.

The temporal precision of the DHS is defined by its exposure time relative to the period of oscillation of the TM, analogous to stroboscopic holographic acquisition methods [1,2],

where the illumination duty cycle defines the effective exposure time per cycle. Using an upper frequency limit of interest of 8 kHz, a typical stroboscopic duty cycle [1,2] of 5-10% corresponds to an equivalent single frame exposure time of $\sim 6\text{-}12\ \mu\text{s}$.

Assuming the acoustical energy propagates across the surface of the TM [5], acousto-mechanical energy transmission rate and direction will depend on the surface wave speed and direction. Existing steady state measurement methods [8, 27, 28] estimate surface wave speed in the range of 5-70m/s, corresponding to acoustic delays across the 8 mm [20] diameter membrane of 110-1600 μs . In order to reliably quantify the rate and direction of acoustic energy transfer across the surface of the TM, an acquisition method should allow the capture of at least 3 instances [29] of the spatio-temporal evolution of the surface waves within the duration of the acoustical delay. This results in a maximum acquisition period (inter-frame time) of $<36\ \mu\text{s}$ (for $\sim 110\ \mu\text{s}$ acoustic delay) corresponding to a minimum sampling rate of $\sim 30\ \text{kHz}$.

The number of samples and frequency resolution of the DHS measurements depend on the duration of the transient repose of the human TM, which is $\sim 5\ \text{ms}$ for an acoustic click [30]. At a minimal sampling rate of 30 kHz, the full duration of the transient event will be represented within ~ 150 frames, resulting in a minimal frequency resolution of $> 200\ \text{Hz}$ for a single measurement. The frequency resolution of the acquisition method could be further improved by averaging several click responses of the TM.

4 METHODS

4.1 Transient acquisition method with a conventional camera

Based on the specified design assumptions and constraints, we propose a multi-pulsed double exposure (MPDE) acquisition method [18, 19] for the acquisition of the full-field acoustically induced transient displacement response of the human TM.

The MPDE operates by repeatedly applying a pulsed acoustic excitation while sequentially capturing holograms at consecutive time increments throughout the duration of the transient response of the TM. The MPDE was implemented with minimal modifications to the existing hardware of the DHS including a conventional ($<20\text{fps}$) camera capable of global shutter, instantaneous readout and capture, as well as sufficient light sensitivity with low readout noise.

The principle of the MPDE, shown in Fig. 3, is based on the synchronization of the camera exposure, illumination time, and acoustic excitation in a double exposure mode of acquisition. For the acquisition of a single pair of double exposure holograms, a reference hologram is captured at an initial state of deformation, an acoustic excitation is applied, and a deformed hologram is captured after a controlled time delay, as shown in Fig. 3a. The temporal resolution of the double exposure pair is constrained by the minimum time between exposures (MTBE) allowed by the camera.

By utilizing the simultaneous readout and capture capability of the camera, the MBTE is minimized by setting the exposure time to the minimum inter-frame time, as shown in Fig.

3b [31]. Under these conditions the laser illumination is strobed (P_{REF}) once before the end of the first exposure and once (P_{DEF}) at the beginning of the next exposure. The minimum gap between P_{REF} and P_{DEF} achievable with commercially available cameras is in the range of 20 – 200 μ [31], without any hardware or firmware modifications. The temporal resolution of the method is defined by the strobe length of the illumination pulse of each hologram. For cadaveric human TM samples tested with the DHS, the typical strobe length is less than 15 μ s.

Assuming sufficient repeatability of the acoustical response of the TM, we execute the double exposure acquisition multiple times by reapplying the same excitation while recording a new deformed state with a controlled time delay that allows for the capture of a slightly different (i.e., < 20 μ s) instance of the transient response of the TM in every successive acquisition. A timing diagram of all controlled events of the acquisition and control algorithm of the MPDE are shown in Fig. 4.

The acquisition method allows for reconstruction of the transient response of the TM by temporal “scanning” through multiple sequential transient pulses and combining the individual full-field-of-view temporal data points into a 3D structure of data representing the time into a 3D structure of data representing the time-waveform of every recorded point on the surface of the TM. The maximum practical sampling rate of the MPDE is dependent only on the geometrical repeatability of the transient displacement of the TM and the acoustic excitation and the acoustic excitation. It should be noted that the temporal resolution of the proposed method is independent of the MBTE of the camera, making it independent of type of camera used.

4.2 Double exposure phase sampling methods

The double exposure deformation of the object between a reference-deformed pair of frames is quantified by a lensless digital holographic reconstruction [24] and spatial phase sampling methods [19, 24]. The digital holographic reconstruction method implemented in the DHS is based on an approximation of the wave front propagation described by the Fresnel-Kirchhoff integral [32]:

$$\Gamma(\xi, \eta) = \frac{i}{\lambda} \int \int_{-\infty}^{\infty} h(x, y) R(x, y) \frac{\exp(-i \frac{2\pi}{\lambda} \rho)}{\rho} \times \left(\frac{1}{2} + \frac{1}{2} \cos \theta \right) dx dy, \quad (1)$$

with

$$\rho = \sqrt{(x - \xi)^2 + (y - \eta)^2 + d^2}, \quad (2)$$

where $h(x, y)$, is the hologram function in the camera sensor coordinate system, $R(x, y)$, is the reference wave used for reconstruction, ρ is the distance between a point on the hologram plane (camera sensor) and a point in the reconstruction plane (ξ, η), and d , is the reconstruction distance. Accounting for the discretization parameters of the DHS's camera sensor and the Fresnel approximation, Eq. 1 can be expressed in terms of the computationally optimized Fast Fourier Transform (FFT) in the following form [24]:

$$\Gamma(m, n) = z(m, n) FFT^{-1} [h(k, l) R(k, l) w(k, l)], \quad (3)$$

where k and l are the pixels on the CCD plane (hologram plane), m and n are the pixels on the object plane (reconstruction plane), $h(k, l)$ is the hologram function digitized by the CCD, $R(k, l)$ is a discrete model of the reconstruction reference wave, and $w(k, l)$ is a discrete chirp function used for reconstruction of the complex wave front. The chirp function $w(k, l)$ can be expressed as:

$$w(k, l) = \exp \left[-i \frac{\pi}{\lambda d} (k^2 \Delta x^2 + l^2 \Delta y^2) \right], \quad (4)$$

where Δx and Δy are the pixels size in the CCD plane, λ is the laser wave length, and d is the reconstruction distance. The coefficient $z(m, n)$ in Eq. 3 adds a constant phase change to the reconstructed hologram $\Gamma(m, n)$ and is often omitted from computation of the phase change due to deformation of the object. We utilize an off-axis holographic optical setup within a compact microscope head [24] that allows for single frame phase sampling of the object information through a spatial phase shifting of the reconstructed hologram, $\Gamma(m, n)$.

The deformation of the object is quantified by double exposure of holograms recorded at the reference, Γ_{ref} , and deformed, Γ_{def} , states. The holograms are individually reconstructed using Eq. 3 and their double exposure phase difference, Φ , in space, (m, n) corresponding to the deformation of the object at a specific time instance, t can be expressed as [29]:

$$\Delta\phi(m, n, t) = \text{angle}(\Gamma_{def} \cdot \Gamma_{ref}^*) = \tan^{-1} \left[\frac{\text{Re}(\Gamma_{ref}) \text{Im}(\Gamma_{def}) - \text{Im}(\Gamma_{ref}) \text{Re}(\Gamma_{def})}{\text{Im}(\Gamma_{ref}) \text{Im}(\Gamma_{def}) + \text{Re}(\Gamma_{ref}) \text{Re}(\Gamma_{def})} \right], \quad (5)$$

where $\text{Re}(\Gamma)$ and $\text{Im}(\Gamma)$ specify the real and imaginary parts of the complex field of a hologram, Γ , at the specified state of the object. The expanded expression of Eq. 5 allows for improved computational time by requiring only one arctangent calculation per pixel.

4.3 Implementation of the control system

The hardware implementation of the MPDE acquisition, as shown in Fig. 5, allows for the synchronization of procedures for acoustic excitation of the sample, pulsed illumination, and frame acquisition. The existing control architecture of the DHS has been optimized to allow for the MPDE acquisition with minimal hardware modifications. The optimization relies on the use of the I/O module's digital output component to trigger the execution of all procedures of the MPDE acquisition. The corresponding hardware modification required rewiring only three of the control signal lines and no modification or customization of any components or modules of the control architecture.

To perform MPDE transient measurements of a TM sample, the user is required to specify the following parameters:

- *Frame acquisition* - starting time, resolution, and exposure time of the camera.

- *Multi-pulsed illumination* - starting time of reference frame pulse, starting time of the initial deformed frame pulse, temporal range of deformed pulses (i.e., 0-3 ms after the initial pulse), temporal increment of deformed pulses, and pulse duration.
- *Acoustic excitation* - starting time, transient excitation type (i.e., click, chirp, sine), duration, and signal input level.

During a measurement, the control software utilizes the digital output component of the I/O module to automatically trigger the execution of all procedures of the MPDE acquisition through correlated timing signals with a temporal accuracy better than 1 μ s. The applied sound pressure level (SPL) of the acoustic excitation at each measurement is automatically quantified by a calibrated microphone in the sound presentation module read by an analog input component of the IO module [1,2].

The implementation of the control software [22] of the DHS offers customization of the timing signals of all digital outputs. It offers customization of the timing signal output channels (up to 32 for our particular model), which allows for a modular and expandable control system architecture without major hardware modifications or custom timing electronics.

5 VALIDATION OF THE ACQUISITION METHODS

The principle of operation of the MPDE method is based on the assumption that the acoustically induced transient response of the samples is repetitive. This assumption was experimentally validated for both the samples and the DHS, by:

- *Transient response repeatability of the samples*—comparison between multiple LDV measurements of the acoustically induced transient response of each sample.
- Validation of the DHS with MPDE for transient measurements
 - *Temporal repeatability*—comparison between multiple DHS measurements of the response of each sample
 - *Displacement accuracy*—comparison of DHS and LDV measurements of the transient displacement and velocity time-waveforms of both samples.

5.1 Experimental setup and sample preparation

The experimental setup of the DHS includes an otoscope head (OH) and a sound presentation module, as shown in Fig. 6. The sound presentation module consists of a calibrated microphone (Etymotic Research ER-7C.) and a speaker (SB Acoustics SB29RDCC000C000-4) [23]. The otoscope head, shown in Fig. 6a, includes a camera (AVT Pike F505B) and an object illumination component providing 532 nm laser light with 19 intensity at the object plane. For validation of the transient measurement capabilities of the DHS, a LDV is incorporated within the DHS experimental setup.

The samples used for the DHS measurements presented in this paper include an 8mm diameter human cadaveric TM sample, shown in Fig. 6b, and a 10mm diameter latex circular membrane, shown in Fig. 6c. The human TM sample is part of a temporal bone from a 90-year-old female donor. The sample was prepared in accordance with previously

established procedures [8]. The surface of the TM was coated with a solution of ZnO to improve the surface reflectivity and reduce required camera exposure times resulting in better temporal resolutions.

Concomitantly to each DHS measurement, we conducted LDV measurements at several predefined points on the surface of each sample. In order to improve the signal quality of the LDV measurements, retro-reflective markers were applied at the predefined points of both samples. In the case of the human TM sample, shown in Fig. 6b, markers were placed at the approximate centers of the umbo (point 1: the most inferior point on the manubrium of the malleus which is rigidly connected to the TM [4]) as well as the interior, inferior and posterior halves (points 2-4) of the surface of the TM. Additionally, in order to monitor the rigid body motion of the temporal bone, a LDV marker was placed on the temporal bone close to the edge of the TM (point 1). The markers on the latex membrane's surface were distributed equidistantly (points 1-5), as shown in Fig. 6c.

5.2 Validation of the samples repeatability

In order to investigate the validity of assumption behind the principle of operation of the MPDE method, we measured the transient response of all marked points on both samples multiple times with an LDV at a sampling rate of 125 kHz and 16-bit digitization resolution. Representative results of the time waveforms and frequency domain transfer functions (TF) of the maximum and minimum response among all measurement points, as described in Section 5.1, on each sample are shown in Fig. 7.

The TF is calculated based on calibrated microphone readings of the sound pressure level at the surface of the samples [8]. The two measurements shown in Fig. 7 are temporally separated by ~1 min, which is representative of the full recording time for one set of measurements with the MPDE method. The repeatability of the time waveforms of the response of all points on the surfaces of both samples is >99 %. The deviation of the values of the local maxima and minima of the time waveforms of individual measurements is <5 % of the global maximum.

There is no significant temporal deviation in the locations of the local maxima and minima of the time waveforms of individual measurements within the temporal resolution of the LDV sampling (i.e., < 10 μs). The frequency domain transfer function (velocity normalized by sound pressure) varies within <3 dB between all measurements. Response of the bony structure (point 5 as indicated at Fig. 6b) of the human TM is <0.5 % relative to displacement of the surface of the TM, indicating insignificant rigid-body motion.

5.3 Validation of the DHS with MPDE for transient measurements

To assess the repeatability of the MPDE method, we compared multiple sets of repeated DHS measurements for both a latex membrane and a human TM. We quantified the accuracy of the transient displacement measurements of the DHS by comparison with LDV.

To ensure adequate sampling of the full-field transient response of the both samples, we adjusted the MPDE acquisition method's sampling rate, exposure time, and recording duration in accordance with acquisition design constraints, specified in Table 1 (Section

3.2), as well as with the preliminary LDV measurements indicated in Fig. 7. The LDV was sampled as described in section 5.2. The acoustic excitation was a 100 μ s click at 124 and 108 dB maximum SPL for the human TM and the latex membrane respectively. Due to the relative distance of the speaker to the sample (i.e., $\sim$ 5 cm) the delay between the beginning of the acoustical excitation and the response of the sample was $\sim$ 150 μ s.

The LDV measurements of the acoustically induced response of the TM (Fig. 7), indicate total duration of the transient event of <3 ms and significant frequency content of up to 8 kHz. Based on that, as well as accounting for the acquisition constraints in Table 1, the human TM transient response was recorded by the DHS with 50 kHz sampling rate and 5ms sampling duration, allowing for a Nyquist frequency of up to 25 kHz and frequency resolution of 200 Hz. The sampling rate and duration was achieved by 20 μ s sampling step with 250 samples. Smaller sampling steps are constrained by the minimum available exposure time (temporal accuracy) of 15 μ s (corresponding to camera shutter speed of 67 kHz), which is mainly dictated by the available laser light power at the object and the sensitivity of the camera. The minimum exposure time is 25 % higher than the recommended maximum in Table 1 (Section 3.2); however, resulting displacement and temporal accuracy as well as repeatability, as shown in this Section, were deemed sufficient for our preliminary results.

Every transient DHS measurements of the TM constituted a set of 260 frames representing a period from -0.1 ms to 5 ms relative to the beginning of the acoustic excitation. Recordings (10 frames) from -0.1 ms until the beginning of the excitation were used for monitoring potential environmental disturbances during the measurements. Every deformed frame, corresponding to the transient response of the human TM, was related to a new reference frame recaptured at same moment (i.e., 0.5 ms) before the application of every acoustic excitation, as described in Section 4.1. Accounting for the reduced range of the frequency response (i.e., <7 kHz) and the longer (i.e., >10 ms) click response of the latex membrane, sampling rate was reduced to 20 kHz (50 μ s inter-frame time) in order to reduce the measurement time to similar durations as with the human TM ($\sim$ 1 min). Minimization of the total measurement time while maintaining sufficient temporal resolution (exposure time) and sampling rate (sampling period) for the response of each sample will be part of our future work.

The temporal accuracy of the timing signals (Section 4.3) is an order of magnitude smaller than the typical (i.e., 20 μ s) sampling period, thus any temporal jitter affecting the timing precision is assumed to be negligible.

5.3.1 Temporal repeatability of the DHS—To validate the repeatability of the DHS measurements, we compared three consecutive measurements of the transient time waveforms and frequency domain transfer function (TF). Figure 8 shows representative results of the maximum and minimum response of both samples. The repeatability is estimated based on the correlation of the time waveforms of every individual measurement relative to the average of all measurements at each point. The temporal variation of the location of the maximum displacement positions of the time waveforms is <20 μ s for both samples. The variation of the magnitudes of the maximum displacements of the time

waveforms is <15 nm. Measured time waveforms show >99 % correlation, and frequency domain transfer function show <5 dB variation. The total measurement time for all three consecutive measurements is ~ 10 min. This indicates that there is not a significant variation in the repeatability of the DHS measurements within the typical duration of the experiments.

5.3.2 Displacement accuracy of DHS versus LDV—To validate the accuracy of the DHS we compared its measurements versus LDV. We compared the time waveforms of both velocity and displacement by integrating or differentiating the LDV and DHS correspondingly. Correlation between the time waveforms of the two methods is >96 %. Accuracy of the temporal location of the local maxima and minima in the time waveform in the time waveforms measured by the DHS relative to LDV is $<20\mu\text{s}$. The velocity and displacement error of the DHS measurements relative to the LDV is <5 % normalized to the maximum response of each sample.

6 APPLICATIONS

The DHS provides high temporal (>50 kHz) and spatial ($>500\text{k}$ data points) resolutions that enable the simultaneous measurements of the spatial distribution and the temporal and frequency domain of the displacement of transient response of the human TM. We present our preliminary results on the quantification of the transient acoustically induced displacement as well as corresponding temporal acousto-mechanical properties of the human TM and their spatial dependence. Acquisition parameters are the same as described in Section 5.3: sampling rate was 50 kHz ($20\mu\text{s}$ sampling step), exposure time was $15\mu\text{s}$, and sampling duration was 5ms resulting in 250 frames.

Figure 10 shows representative full-field-of-view displacement measurements at several temporal instances of the acoustically induced transient response of a human TM. The acoustic excitation was a $100\mu\text{s}$ click with a 124 dB maximum SPL. The acoustic source was $\sim 5\text{cm}$ away from the surface of the human TM resulting in ~ 0.15 ms in ~ 0 . transmission delay.

By analyzing time waveforms of the full-field-of-view transient response of the human TM, the spatial distributions of various temporal acousto-mechanical properties are extracted, including dominant modal frequencies and time constants, as shown in Fig. 11.

The time constant of the transient decay response at a particular point of the TM is important as it is related to the damping of the TM and the local material properties [4, 9, 21]. The time constant of the decaying time waveform at a particular point can be automatically estimated by fitting an exponential function to the envelope of the waveform, as shown in Fig. 11a. Automatically applying this analysis to all measured time waveforms across the full surface of the TM allows for quantification of the spatial dependence of the time constants, as shown in Fig. 11b. The range of measured time constants is 0.3–1.5 ms with a mean of 0.71 ms, which is in agreement with previous research [30, 33].

Based on the local maxima of the power spectrum of the frequency domain transfer function (TF) at any point on the TM we can automatically determine the dominant modal

frequencies. The detected modal frequencies at the umbo, shown in Fig. 11c, based on the DHS and LDV differ by <5 %. By automatically estimating the global maxima of the TF at every point across the TM, spatial dependence of the dominant modal frequency is quantified, as shown in Fig. 11d. The dominant frequency map indicates noticeable differences (2-3 fold) between the regions of the TM near the manubrium and the central region midway between the manubrium and the TM boundary. Assuming that the spatial distribution of the dominant frequency is representative of the local variations of stiffness and thickness of the TM, our observations can be related to previous studies [20] indicating analogous magnitude variation and spatial distribution in the thickness of the TM.

7 CONCLUSIONS AND FUTURE WORK

In this paper we reported the development and implementation of a new method to quantify the full-field transient dynamics of the TM using a custom digital holographic system (DHS) and an optimized multi-pulsed double-exposure (MPDE) acquisition method that exploits the geometrical linearity and repeatability of the acoustically induced displacements of the human TM. The MPDE method is aided by the development and implementation of a modular and expandable control architecture that requires minimal modifications to the existing hardware within previously implemented digital holographic system (DHS). The DHS allows for simultaneous high-speed (i.e., >50 kHz) measurement of the time waveform of >500 k data points on the surface of the TM using a conventional speed (i.e., <20 Hz) camera. The total measurement time is decreased >10³ fold compared to existing stroboscopic holographic measurement methods [1,2], thus reducing the effects of the environmental disturbances and allowing *in-vivo* applications [24].

Simultaneous measurement of the frequency and time domain of the transient response across the full surface of the TM, allows for observations of spatially dependent motion parameters such as modal frequencies and time constants. Such capabilities could be used to infer local material properties across the surface of the TM as well as further the understanding of the sound-receiving function of the TM in the process of acousto-mechanical energy coupling into to the ossicular chain and inner ear. The DHS could provide a new tool for the investigation of the auditory system with applications in research, medical diagnosis and hearing aid design.

Future work is focused on the extraction of medically relevant information on TM's health condition through analysis and interpretation of the measured transient displacement response. Further research is also needed to explain the transient dynamics of the TM and its relationship to the energy transfer into the middle-ear, as well as its connection to previous steady-state dynamics research. Improvements of the DHS should include optimization of the acquisition parameters, improvements of the optical design, as well as optimizations for *in-vivo* applications.

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Fig. 1.

Overview of the existing digital holographic system (DHS)[1, 2]. The DHS is composed of: (1) laser delivery system with temporal phase stepping, stroboscopic illumination and fiber coupled output capabilities; (2) otoscope head (OH) for lensless digital holography and sound presentation capabilities; (3) a mechatronic otoscope positioner (MOP) that provides support for the OH during measurements; (4) and (5) control software and a I/O modules for user control of the excitation, illumination, and frame acquisition parameters

Fig. 2.

Schematic showing the major modules of the stroboscopic acquisition hardware and software of the original DHS, shown in Fig. 1. The components within the I/O control module communicate with the sound presentation, laser delivery, and camera modules that are synchronized by the stimulus generator component serving as the master.

Fig. 3.

Timing diagrams of the acquisition of a set of double exposure holograms with the MPDE method: (a) synchronization between the reference hologram, acoustic excitation, and deformed hologram; (b) the minimum time between exposures is achieved by setting the exposure time of the camera to the minimum inter-frame time. Pulsed illumination for the reference state, P_{REF} , is applied at the end of the first camera exposure while a pulsed illumination for the deformed state, P_{DEF} , is applied at the beginning of the second exposure.

Fig. 4.

Timing diagrams of the acquisition of a set of multiple double exposure holograms with the MPDE method. The same procedure as the one depicted in Fig. 3 is applied multiple times. This allows for a sampling rate Representative values of major parameters are indicated independent of the camera frame rate. Representative values of major parameters are indicated

Fig. 5.

Schematic showing the major modules of the MPDE acquisition hardware and software. The components within the I/O control module communicate with the sound presentation, laser delivery and, and camera modules that are synchronized by the digital output component serving as the master clock. Changes in the new control architecture of the MPDE relative to the original, Fig. 2, include the addition of a digital output component connected as a master clock to the camera interface, signal generator, analog input, and laser delivery module.

Fig. 6.

Experimental setup and samples utilized for validation of the MPDE: (a) schematic of the DHS setup that includes otoscope head (OH) and sound presentation module; (b) cadaveric human TM sample; (c) circular latex membrane. The manubrium of the TM in (b) is outlined with solid line also indicating the separation between pars tensa and pars flaccida

Fig. 7.

Representative LDV measurements, in the time and frequency domains, demonstrating the repeatability of the acoustically induced transient response of the latex membrane and the human TM. The graphs indicate the time waveform and frequency domain transfer function with the maximum and minimum response across the surface of each sample at two consecutive measurements (solid and dotted line). Measured time waveforms show >99 % correlation, and frequency domain transfer functions show <3 dB variation. Maximum instantaneous sound pressure was 124 dB SPL for the human TM and 108 dB SPL for latex sample. The microphone response (Mic.) is marked with a dashed line.

Fig. 8.

Representative transient measurements, in the time and frequency domains, demonstrating the repeatability of the MPDE acquisition in the DHS. The graphs indicate the time waveform and frequency domain transfer function (TF) with the maximum and minimum response across the surface of each sample for three consecutive measurements (dotted lines) and their average (solid line). Measured time waveforms show >99% correlation, and frequency domain transfer functions show <5 dB variation. Maximum instantaneous sound pressure was 124 dB SPL for the human TM and 108 dB SPL for latex sample.

Fig. 9.

Representative transient measurements demonstrating the accuracy of MPDE acquisition in the DHS versus LDV. Correlation of the velocity and displacement time waveforms between DHS (solid line) and LDV (dotted line) is $>96\%$. Maximum instantaneous sound pressure level (SPL) was 124 dB SPL for the human TM and 108 dB SPL for latex sample. The microphone response (Mic.) is marked with a dashed line.

Fig. 10.

Representative displacement maps of the response of the human TM due to a 100 μ s click at 124 dB SPL, recorded with the MPDE at 0.3-1.26ms (a-ad) after the beginning of the acoustic excitation. The outlines of the membrane and the manubrium are indicated with solid black line also indicating the separation between pars tensa and pars flaccida of the TM. The data indicate a 0.62 μ m p-p maximum displacement across the surface throughout the full duration of the transient response

Fig. 11.

Spatial dependence of the motion parameters across the surface of the TM: (a) quantification of the time constant based on automatic decay envelope estimation and exponential fitting of the time waveform of the transient response at the umbo; (b) map of the time constant at each point on the surface of the TM indicating a mean of 0.71ms; (c) power spectrum of the displacement transfer function (TF) at the umbo measured with DH (blue line) and LDV (red line); and (d) map of the dominant frequency at each point on the surface of the TM. Outline of the manubrium in (b) and (d) is indicated with a dashed line. Dashed lines in (c) refer to automatically determined modal frequencies indicating <5% difference between DHS and LDV

Tab. 1

Major acquisition parameters to perform transient measurements of the human TM with a DHS

Human hearing parameters	Value	Acquisition design constraints	Value
Frequency range	0.2-8 kHz[25]	Sampling rate	1-40 kHz[1,2] ^a
		Exposure time	<6-12 μ s[1,2] ^a
TM's acoustical delay	40 μ s[5] - 1.3 ms[8]	Minimum sampling rate	>30 kHz[29]
Impulse response duration	<5 ms settling time[30]	Number of samples	~150 frames @ 30 kHz
		Frequency resolution	200 Hz

^aWith 5 samples per cycle and 5-10% duty cycle.