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Digital holographic interferometry applied to the study of tympanic membrane displacements

María del Socorro Hernández-Montes [a,*], Fernando Mendoza Santoyo [a], Carlos Pérez López [a], Silvino Muñoz Solís [a], Jesús Esquivel [b]

[a] Centro de Investigaciones en Optica, A.C., Loma del Bosque 115, 37150 León, Guanajuato, Mexico
[b] Hospital Aranda de la Parra, Hidalgo 333, 37000 León, Guanajuato, Mexico

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ABSTRACT

Quantitative studies of the mechanical properties of tympanic membrane (TM) are needed for better understanding of its role in detailed clinical evaluation, its research being of extreme importance because it is one of the most important structures of the middle ear. By finding the membrane's vibration patterns and quantifying the induced displacement it is possible to characterize and determine its physiological status. Digital holographic interferometry (DHI) has proved to be a reliable optical non-invasive and full-field-of-view technique for the investigation of different mechanical parameters of biological tissues, i.e., DHI has demonstrated an ability to detect displacement changes in quasi-real time and without the need to contact the sample's surface under study providing relevant information, such as clinical and mechanical sample properties. In this research fresh tympanic membrane specimens taken from post-mortem cats are subjected to acoustic stimuli in the audible frequency range producing resonant vibration patterns on the membrane, a feature that results in an ideal application for DHI. An important feature of this approach over other techniques previously used to study the tympanic membrane vibrations is that it only requires two images and less hardware to carry out the measurements, making of DHI a simpler and faster technique as compared to other proposed approaches. The results found show a very good agreement between the present and past measurements from previous research work, showing that DHI is a technique that no doubt will help to improve the understanding of the tympanic membrane's working mechanisms.

1. Introduction

Optical non-invasive techniques are extremely attractive and very well received in biomedicine due to their non-destructive and non-contact nature, capable of rendering full-field-of-view measurements. Optical techniques such as electronic speckle pattern interferometry (ESPI) and digital holographic interferometry (DHI) have shown to be a prominent assessment tool in a wide range of applications due to their demonstrated capacity to characterize the behavior of an ample variety of samples subjected to different types of stimuli [1–4]. While these techniques are very similar in their optical setups, DHI obtains phase maps in quasi-real time and ESPI displays amplitude fringe patterns in real time. Because of their ability to measure surface displacements they play an important role in the non-invasive detection of anomalies in diverse samples. Both techniques have the advantage that while collecting the measurement data from the sample's surface, the mechanical and biological properties of the latter are not modified.

DHI has been successfully applied in many fields, including the displacement measurement of biological tissues like the fragile tympanic membrane. The data gives qualitative and quantitative information, in the order of micrometers, precisely the amount of displacement that the TM surface suffers when it is subjected to pressure from acoustic waves.

One important biological structure in the human body is the middle ear whose main function is the sound signal amplification. The structure has two components, the tympanic membrane or eardrum and the bony chain. The TM, extremely thin and delicate, is a major structure between the outer and inner ear, and it is responsible for a large number of important functions in the auditory process due to it being the first structure within the ear that vibrates in accordance to the sound pressure waves it receives. The TM has two distinct zones. The larger of the two zones is the pars tensa. The smaller zone is the pars flaccida, which lies superior to the suspensory ligaments of the malleus [5]. The mechanics of hearing commences with sound pressure waves striking the TM, causing it to vibrate. Vibration is then transmitted through the bony chain, from the

* Corresponding author. Tel.: +52 477 4 41 42 00.
E-mail address: mhernandez@cio.mx (M.del S. Hernández-Montes).

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malleus to the incus and to the stapes. At present, the TM's clinical evaluation often relies on methods that depend on examining the medical doctor's experience through visual assessment. Other evaluation methods and typical tools also commonly used include tympanometry, audiometry, and the like, which, although of great use and value in certain examinations also comprise several deficiencies [6–10]. These current medical methodologies used to evaluate the middle ear, and in particular the TM motion quantification, are usually subjective, in that they depend on the physician's judgment based on experience, and thus the diagnosis is often unsatisfactory or over diagnosed. Furthermore, due to this eye inspection and to the fact that the qualitative observation is made pointwise, the whole TM surface mobility characterization is not done. Furthermore sometimes the evaluation is uncomfortable to patients, e.g., in tympanometry it is necessary for an airtight canal to connect the instrument and the external auditory canal which requires a great deal of cooperation from the patient.

The study of the tympanic membrane by means of optical techniques has been of great interest among the biomedical optics community since 1970. The first series of experiments used time-averaged interferometry in animal and human cadaver samples [11,12], which were later followed by several studies using alternative optical techniques, like Laser Doppler Velocimetry and phase-shift moiré [13–18]. Several further studies had objectives to improve the understanding of the function of the tympanic membrane and the middle ear by means of different procedures and techniques, like the evaluation of the middle ear function via acoustic power assessment, static pressures, and using the finite-element method [19–21]. However, if the sound heard is interpreted in terms of the tympanic membrane motion, a way to characterize it is by measuring displacements on the TM's surface using non-invasive optical techniques, which provide reliable quantitative data of the effect of the acoustic pressure that reaches the eardrum. By finding the membrane's vibration patterns and from these quantifying the induced displacement, it is possible to characterize and determine the TM's physiological status. The key objective of this paper is to contribute to the understanding of the working mechanisms of the tympanic membrane that are associated with the displacements measured on its surface. An important feature of employing DHI over the other techniques previously used to study the vibrations of the tympanic membrane is that it only requires two images and less hardware (optoelectronics, pzt devices for phase acquisition, etc.) to carry out measurements, with one key advantage: phase acquisition without the need for phase shifting methods. The resonant vibration modes found for a specific range of frequencies and their corresponding displacement amplitudes, induced by the acoustic stimuli, show the outstanding potential that DHI has to help improve understanding of the tympanic membrane's working mechanisms. Good agreement was found between the present and past measurements from previous research work [12–17]. Results show the usefulness of the optical technique in the medical field in providing relevant data about key mechanical characteristics of biological samples.

2. Experimental study with digital holographic interferometry

Digital holographic interferometry is a well-known optical technique that uses two holograms registered at two different states (positions) of the sample under study. As mentioned before, its optical setup is similar to that of ESPI, one main difference being the fact that the latter uses a CCD camera working in real time (25–30 fps, for European PAL and USA NSTC standards, respectively), with a smaller pixel matrix and dynamic range. For the purpose of this research the optical configuration used is that of DHI where the CCD camera has a larger pixel matrix and a significantly larger dynamic range, hence it does not display images in real time; the typical CCD cameras used have less than 15 fps, quasi-real time. Each hologram is created by the object and the reference beam interference, and is digitally stored in the computer. Subtracting the holograms yields interferometric fringes, observed in quasi-real time, thus allowing a rapid qualitative evaluation of the TM's performance. A Fourier transform procedure is followed in the computer in order to calculate the phase of the TM's surface displacement.

Fig. 1 shows the compact layout of the experimental setup for the study and measurement of out-of-plane TM displacements, when it is exposed to acoustic waves. A continuous wave Nd:YAG laser beam with $\lambda = 532$ nm at 40 mW output power, was split in two beams, object and reference beams. The object beam is conveyed through a single-mode optical fiber which illuminates the TM surface observed in-full-field-of-view. The light scattered by the object and collected by the imaging lens contains information due to the TM displacements. The CCD camera used to capture the out-of-plane image holograms has a high resolution sensor comprised by a 1392×1024 pixel matrix with a sensitive area of 8.97×6.6 mm^2, and 12-bit dynamic range. The CCD sensor receives an image of the TM surface and is combined with the reference beam, forming a so-called image hologram. The smooth reference beam is conveyed to the CCD sensor via a single-mode optical fiber whose length is used to match the optical path lengths of both reference and object beams in order to be within the laser coherence length. A low price off-the-shelf tweeter speaker driven by a low amplitude frequency generator through an amplifier is used to stimulate the TM surface.

The digital holographic interferometer optical arrangement is set to be sensitive to out-of-plane displacements, i.e. along the z direction. The intensity at each point of the CCD camera sensor can be described as

$$I(x,y) = a(x,y) + b(x,y)\cos[\varphi_o(x,y) - \varphi_r(x,y) + w(x,y)] \quad (1)$$

where x and y are the coordinates in the sensor, where $a(x,y)$ and $b(x,y)$ indicate unwanted irradiance variations arising from the non-uniform light reflection or transmission by the test object, φ_o and φ_r are the phase distribution of the object beam and the reference beam respectively, and w is a spatial carrier term introduced as a reference beam tilt at the beam combiner.

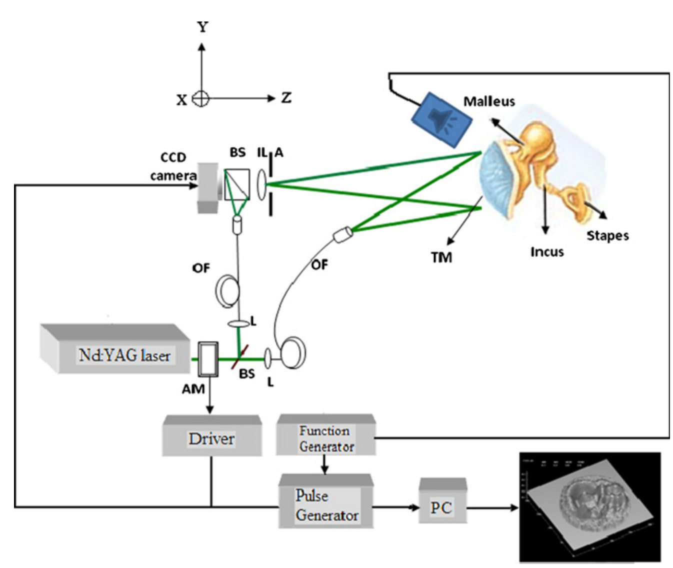

Fig. 1. DHI Experimental Setup: Bs, beam splitter; Bc, beam combiner; L, lens; IL, Imaging lens; A, aperture; OF, single-mode optical fiber; TM, tympanic membrane; AM, acousto-optic modulator.