Optics and Lasers in Engineering 71 (2015) 42–50

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

journal homepage: www.elsevier.com/locate/optlaseng

Surface strain-field determination of tympanic membrane using 3D-digital holographic interferometry

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ARTICLE INFO

Article history:
Received 16 October 2014
Received in revised form
6 March 2015
Accepted 9 March 2015
Available online 29 March 2015

Keywords:
Digital holographic interferometry
Nondestructive testing
Tissue characterization
Strain
Tympanic membrane

ABSTRACT

In order to increase the understanding of soft tissues mechanical properties, 3D Digital Holographic Interferometry (3D-DHI) was used to quantify the strain-field on a cat tympanic membrane (TM) surface. The experiments were carried out applying a constant sound-stimuli pressure of 90 dB SPL (0.632 Pa) on the TM at 1.2 kHz. The technique allows the accurate acquisition of the micro-displacement data along the x, y and z directions, which is a must for a full characterization of the tissue mechanical behavior under load, and for the calculation of the strain-field in situ. The displacements repeatability in z direction shows a standard deviation of 0.062 μm at 95% confidence level. In order to realize the full 3D characterization correctly the contour of the TM surface was measured employing the optically non-contact two-illumination positions contouring method. The x, y and z displacements combined with the TM contour data allow the evaluation its strain-field by spatially differentiating the $u(m,n)$, $v(m,n)$, and $w(m,n)$ deformation components. The accurate and correct determination of the TM strain-field leads to describing its elasticity, which is an important parameter needed to improve ear biomechanics studies, audition processes and TM mobility in both experimental measurements and theoretical analysis of ear functionality and its modeling.

1. Introduction

The eardrum also known as the tympanic membrane (TM) is a very thin, delicate tissue which separates the outer ear where the sound wave is conducted, and the middle ear. It is most important to understand in depth the eardrum mechanical properties because it is a crucial hearing structure that transforms the sound waves energy into mechanical energy [1,2]. If the TM is too rigid or elastic, the sound waves will not travel into the middle or inner ear properly, mainly because the sound waves cause the TM to vibrate at the same frequency of the sound wave. The behavior of the TM surface motion under different sound vibration frequencies is a major area of investigation relevant to a wide range of medical diagnoses, such as physiological condition, and to experimental applications that go along with the development of finite element (FE) predictions-modeling. It is also relevant to the theoretical investigation of the middle ear transmission role through ear models, which is critical to making progress in diagnostics, treatment and care of patients. In spite of the many publications dealing on the TM structure, to date there are still various issues that need to be investigated to furthering its knowledge, particularly with regards to its mechanical properties such as; strain and elasticity; motion and functionality, among many others. These studies have been conducted with one dimensional optical, and mechanical techniques in combination with various image-processing methods, or using the finite element method (FEM) [3–10]. An important point to notice is that most of the investigations about mechanical properties report mainly on the Young´s modulus, presenting too many discrepancies in their measured values [11–17]. The methods applied to date in those research works do touch (invade) the sample and do not consider the TM shape, and also show a feature that with no doubt will introduce measurement errors: the deformation data contains the contribution from the x, y and z directions, i.e., the deformation components are not separated. For these reasons, it is important to develop an experimental procedure that allows the accurate and reliable investigation of the TM strain behavior under a load which makes itself present when sound pressure is received. Quantifying mechanical properties like strain is a significant part of the TM characterization because its evaluation allows an accurate and more reliable elasticity measurement in the quasi-static and dynamic tissue analysis.

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http://dx.doi.org/10.1016/j.optlaseng.2015.03.008
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There are other techniques such as OCT, Single-point laser vibrometry, Elastography and others [18–21], to analyze soft or hard tissues; however most of them require reposition or scanning of the sample. It represents difficulty to carrying out the measurement and requires more time.

Having considered the aforementioned, more accurate full-field measurements of the surface micro-displacements employing a non-contact procedure are key features to improve strain calculations. Digital Holographic Interferometry (DHI) is an optical non-destructive technique that offers a full-field of view inspection and has been successfully used in a wide variety of applications [22–25]. It has a key advantage to obtain displacement measurements (1D, 2D or 3D) of an object's surface in response to an applied stress without modifying its mechanical properties. From a single digital hologram or from the comparison of two digital holograms, the displacement and strain information is produced. The use of the three-dimensional (3D) digital holographic interferometry [26–29] concept to measure displacements in tissues is necessary for a complete and accurate characterization of their mechanical functionalities. Full-field x, y, and z displacement data are independently obtained when the TM is illuminated from three different directions. For the case study reported here and using one illumination arm of the same optical 3D setup, the TM surface shape was measured with the two source positions contour method [30–32] previous to the application of the load. The shape data were combined with the individually found x, y, and z displacement components, a feature that renders more reliable information concerning the TM actual mechanical performance. This paper's principal contribution resides in the presentation of a reliable and repeatable procedure to obtain surface strain data in very delicate tissues, such as the TM, which is directly related to the elasticity properties, a contribution that will doubtlessly serve to further the understanding of this crucial inner ear component. Increasing the knowledge on the TM mechanical properties provides more data about the mechanism of sound transmission, functioning condition, enabling researchers and design engineers to better develop the ear finite element modeling. The results will present a precise surface strain-field that allows the quantification of the TM elastic properties based on its vibration mode as a response to a sound-stimuli frequency of 90 dB SPL (0.632 Pa) at 1.2 kHz.

2. 3D-DHI and experimental methodology

2.1. 3D-Digital holographic interferometry

Some non-contact and whole field optical techniques, such as DHI, are based on the speckle phenomena an effect resulting from light scattered by an optically rough surface: a process where due to the object surface irregularities, as seen by the wavelength of the light used, the incident light is randomly scattered with different phases and amplitudes. In 3D-DHI the x, y, and z displacement components are obtained as a result of illuminating the object in three different directions. Each illumination direction and reference beam pair may be thought of as an out-of-plane digital holography interferometer, viz., Fig. 1. The result is an interferometer setup that renders three independent out-of-plane equations with three variables, a system that can be mathematically resolved. The procedure consists in acquiring a first hologram in a so called base state by overlapping on an electronic (CCD) sensor the object and reference beams from any of the three illumination directions. This first hologram is digitally correlated, typically via subtraction, with a second hologram taken after the object has been subjected to any type of disturbance in such a way that its state is different from the base state. In this manner, the optical phase difference introduced in the resulting interference pattern is related to the object deformation.

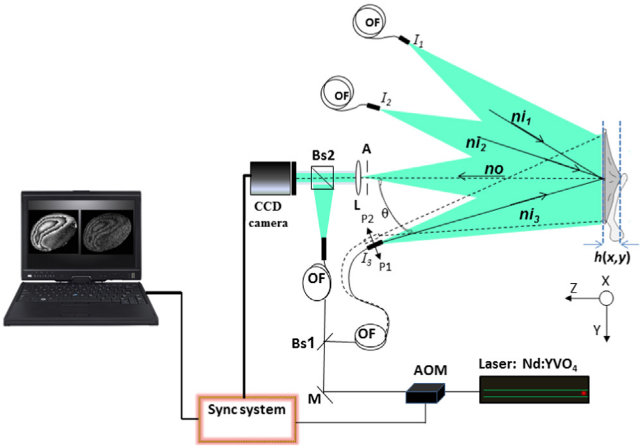

Fig. 1. 3D-DHI optical setup for recording out of plane digital holograms from three object illumination directions, I1, I2, and I3, and for TM shape measurement.

The intensity for the un-deformed, base, Iu and deformed Id states at each pixel (m,n) of the CCD camera sensor may be described as

$$\mathrm{Iu}_j(m,n)=a(m,n)+b(m,n)\cos[\phi(m,n)] \quad \text{and} \quad \mathrm{Id}_j(m,n)$$
$$=a(m,n)+b(m,n)\cos[\phi(m,n)+\psi(m,n)] \quad j=1,2,3, \tag{1}$$

where the terms $a(m,n)=I_{ref}(m,n)+I_{obj}(m,n)$ and $b(m,n)=2\sqrt{I_{ref}(m,n)+I_{obj}(m,n)}$, represent the background intensity, which contains all additive wave field intensity contributions, while the latter relates to the multiplicative wave field intensity contributions. $\phi(m,n)$ is a random phase produced by the reference and object beam, and $\psi(m,n)$ is the optical phase change of the light scattered from the object with respect to the reference beam along each illumination direction of the object, j=1,2,3, and is thus directly proportional to the object beam optical path change.

The procedure used for phase retrieval in DHI requires the introduction of a spatial carrier frequency, and using the relationship $\cos\,\theta=(e^{i\theta}+e^{-i\theta})/2$ in Eq. (1) that hence can be re-written as

$$\mathrm{Iu}_j(m,n)=a(m,n)+b(m,n)\{e^{i(2\pi f_m+2\pi f_n)}e^{i\phi(m,n)}+e^{-i(2\pi f_m+2\pi f_n)}e^{-i\phi(m,n)}\}/2$$

$$\mathrm{Id}_j(m,n)=a(m,n)+b(m,n)\left\{\begin{matrix} e^{i(2\pi f_m+2\pi f_n)}e^{i(\phi(m,n)+\psi(m,n))}+ \\ e^{-i(2\pi f_m+2\pi f_n)}e^{-i(\phi(m,n)+\psi(m,n))}\end{matrix}\right\}\Big/2, \tag{2}$$

(f_m,f_n) are the spatial frequencies that are experimentally introduced via the reference beam by slightly tilting it off-axis at the beam combiner with respect to the object-lens-sensor optical axis.

Then, it follows that upon performing a 2-D Fourier transform to Eq. (2), a trimodal complex function is obtained

$$\mathrm{FT}[\mathrm{Iu}(m,n)]=A(f_m,f_n)+C_u(f_m,f_n)+C_u{}^*(f_m,f_n) \quad \text{and}$$

$$\mathrm{FT}[\mathrm{Id}(m,n)]=A(f_m,f_n)+C_d(f_m,f_n)+C_d{}^*(f_m,f_n), \tag{3}$$

where $C_u(f_m,f_n)$ and $C_d(f_m,f_n)$ are the Fourier transform expressions of $c_u(m,n)=(1/2)b(m,n)e^{i\phi(m,n)}$ and $c_d(m,n)=(1/2)b(m,n)e^{i(\psi(m,n)+\phi(m,n))}$ respectively, and $*$ means the complex conjugate. At the Fourier plane a process of filtering is done by letting through any term $C(f_m,f_n)$ or $C^*(f_m,f_n)$, for the two states of the object. Its inverse Fourier transform is calculated to yield the complex functions $c_u(m,n)$ and $c_d(m,n)$. From the real and imaginary parts of these functions, the optical phase change $\Delta\psi(m,n)$ is the variable of interest to be recovered from the interference patterns, which may contain diverse object information, e.g., surface contour and displacements;