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Imaging acoustic vibrations in an ear model using spectrally encoded interferometry

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ABSTRACT

Imaging vibrational patterns of the tympanic membrane would allow an accurate measurement of its mechanical properties and provide early diagnosis of various hearing disorders. Various optical technologies have been suggested to address this challenge and demonstrated *in vitro* using point scanning and full-field interferometry. Spectrally encoded imaging has been previously demonstrated capable of imaging tissue acoustic vibrations with high spatial resolution, including two-dimensional phase and amplitude mapping. In this work, we demonstrate a compact optical apparatus for imaging acoustic vibrations that could be incorporated into a commercially available digital otoscope. By transmitting harmonic sound waves through the otoscope insufflation port and analyzing the spectral interferograms using custom-built software, we demonstrate high-resolution vibration imaging of a circular rubber membrane within an ear model.

1. Introduction

By transferring air pressure waves to bone vibrations, the tympanic membrane plays a key role in the human hearing process, with unique anatomy that allows it to receive acoustic waves with amplitudes as small as 20 μPa [1]. Partial loss of sensitivity to acoustic stimulation could be the result of tympanic membrane perforations [2], ear infection, fluid accumulation in the middle ear [3], hemangioma of the tympanic membrane [4] and congenital cholesteatoma [5]. In addition, being highly sensitive to its mechanical properties and surroundings, the tympanic membrane dynamics is strongly dependent on physiological changes in its environment. Sensing the full vibrational patterns of the tympanic membrane could thus serve as a direct diagnostic tool for outer and middle ear pathologies, and could also assist surgical intervention procedures including myringoplasty and tympanoplasty that depend on detailed inspection of the tympanic membrane.

Optical interferometry is currently the most sensitive approach for safely and accurately measuring tissue acoustic vibrations. Laser Doppler vibrometry allows high-sensitivity measurements of sub-nanometer axial displacements of a single point on the tympanic membrane [6,7]. Three-dimensional imaging of the acoustic vibrations in an excised (*ex vivo*) tympanic membrane was demonstrated using optical coherence tomography, by scanning the membrane point-by-point [8]. Resolving the relative oscillation phases at all points on a membrane *in vivo*, however, could be challenging with this approach due to the lengthy scanning time and the size and weight of the scanning mechanism. Full-frame *ex vivo* measurement of the motion of a surgically exposed and white-painted tympanic membrane within a fresh temporal bone was demonstrated at discrete phase delays between laser pulses using stroboscopic holography [9]; *in vivo* imaging is yet to be demonstrated with this technique, but could be challenging due to the relative complexity of the holographic imaging apparatus.

Using single-shot imaging of a transverse line with slow single-axis scanning, interferometric spectrally encoded endoscopy [10] captures high-resolution images through a single-fiber imaging probe. Using high-speed line cameras, nanometer-scale axial displacements were imaged across two-dimensional vibrating surfaces [11]. A bench-top system that employs sophisticated processing of the acquired spectral interferograms has recently been demonstrated [12], allowing the recovery of a two-dimensional vibrational motion. In this work, we employ a novel design of our spectrally encoded acoustic imaging system as part of a commercially available digital otoscope, and demonstrate vibrational imaging inside an ear model with approximately 4.5-mm-diameter field of view and up to 0.6 nm axial resolution.

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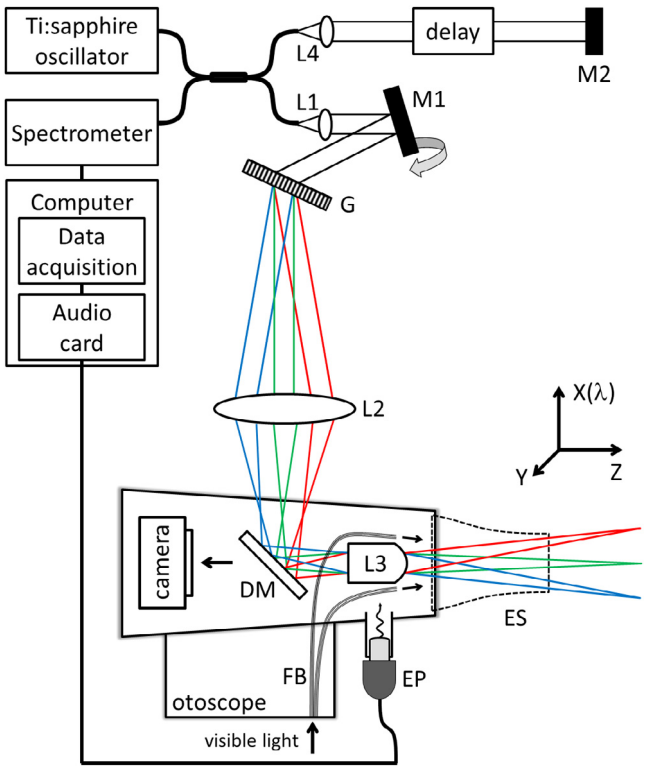

Fig. 1. Spectrally encoded vibration imaging system integrated into a digital otoscope. L1, L2, L4—lenses, L3—otoscope integral lens system, M1, M2—mirrors, G—diffraction grating, DM—dichroic mirror, EP—ear phone, FB—fiber bundle, ES—ear specula.

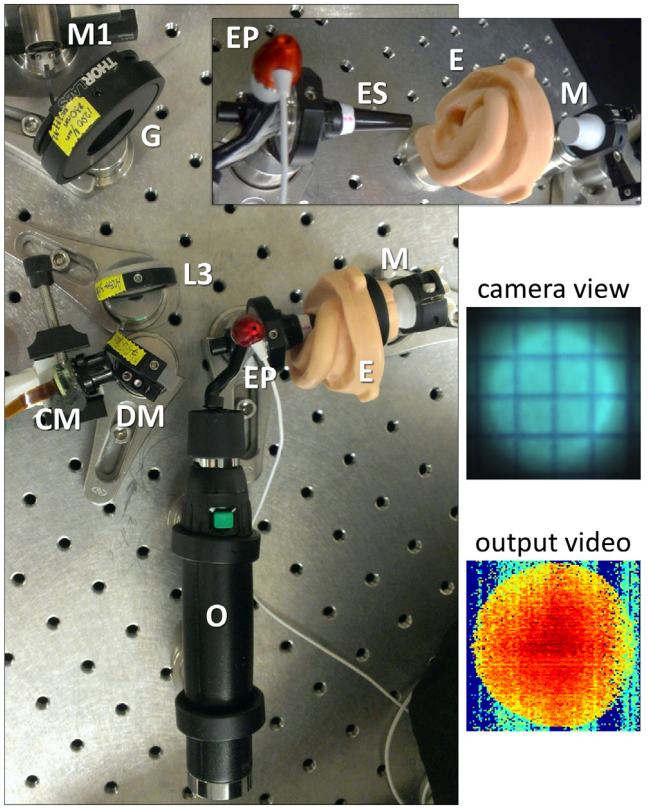

Fig. 2. Photograph of the optical system: O—otoscope handle, M1—scanning mirror, G—grating, L3—achromatic lens, DM—dichroic mirror, CM—otoscope camera, EP—ear phones, E—anatomic ear model, M—membrane, ES—ear specula.

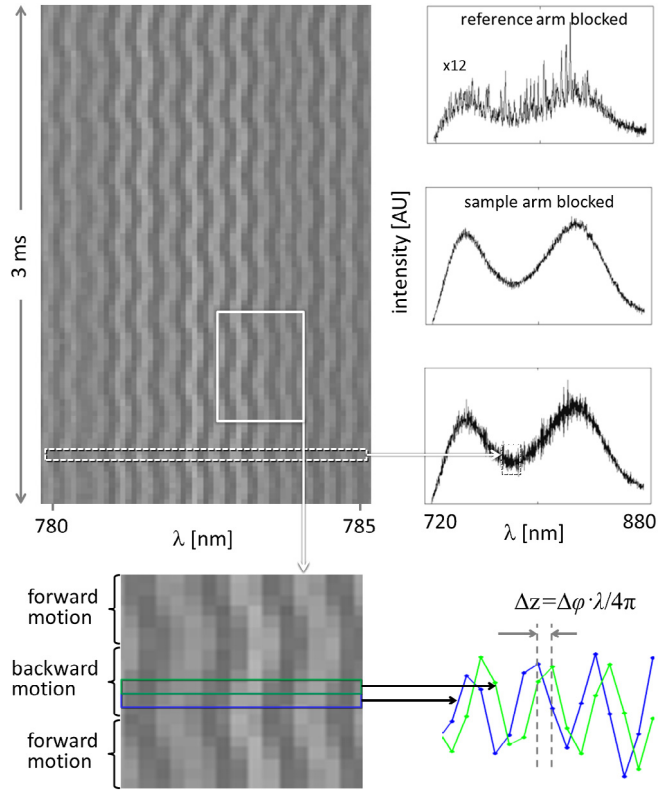

Fig. 3. Interferometric raw data obtained at 20 kHz from a single line on a membrane vibrating at 2.1 kHz. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2. Experimental setup

The experimental setup for imaging acoustic vibrations (Fig. 1) was modified from our previous work [12] to allow integration into the optical path of a commercially available digital otoscope (Digital macroview, Welch Allyn). Broadband (130 nm) light from a titanium sapphire oscillator (Femtolasers Rainbow, 800 nm center wavelength) was coupled into a 50/50 single-mode fiber coupler, collimated by an achromatic 11-mm-focal length lens (L1), deflected by a single-axis galvanometric scanning mirror (Cambridge Technology, M1), diffracted by a 1200 lines/mm transmission grating (Wasatch photonics, G), and imaged onto the back aperture of the otoscope 5-mm-diameter original lens system (L3) using a 30-mm-focal length achromatic lens (L2). A long-pass dichroic mirror (750 nm cutoff wavelength) was placed inside the otoscope optical path after removing its plastic casing for coupling the near-infrared beam into the otoscope optical path. The light was focused by the otoscope lens system to a 4.5-mm-wide transverse spectrally encoded line with a working distance of approximately 25 mm from the front aperture of the otoscope lens. Light reflected from the sample propagated back through the same optical path and coupled back into the fiber coupler. The resulting spectral line (x axis) was slowly scanned by the mirror M1 in the perpendicular y axis, covering a lateral field of view of approximately 4.5 mm × 4.5 mm with 630 × 630 resolvable points [13] and a lateral resolution of approximately 7 μm (FWHM). The reference arm of the Mickelson interferometer comprised of a collimating 11-mm-focal length lens (L4) and a mirror (M2) mounted on a linear translation stage. Spectral interferograms were recorded using a custom-built spectrometer, comprised of a collimating 50-mm-focal length lens, a 1800 lines/mm transmission diffraction grating, a multielement focusing lens (Nikon, 85 mm focal length) and a high-speed line CMOS camera (Sprint spL4096-70k, Basler Vision, 4096 pixels, 70 kHz maximum line rate). Two polarization controllers (not