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Enhanced optical coherence vibration tomography for subnanoscale-displacement-resolution calibration of piezoelectric actuators

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ABSTRACT

We report a subnanoscale-displacement-resolution optical coherence vibration tomography (SOCVT) system for real-time calibration of piezoelectric actuators. The calibrations of the actuators at nanoscale or microscale displacement ranges were performed by varying the input voltage over the entire range in the ascending and descending directions. The computational and experimental results demonstrated that the developed SOCVT could be used to characterize the dynamic hysteretic behavior, nonlinear effect, and impulsive behavior of piezoelectric actuators. The SOCVT technique is non-contact and non-invasive in nature, making it ideal for real-time and in situ ultra-precision calibration of piezoelectric actuators, which are widely used in active vibration control and nanopositioning.

1. Introduction

Optical coherence tomography (OCT) is a non-invasive and cross-sectional imaging technique that permits, for example, three-dimensional images of micrometer resolution to be obtained from within the retina [1,2]. Historically, OCT systems were developed and optimized for medical applications. However, due to their excellent sensitivity and spatial resolution, OCT systems have been increasingly used for non-medical applications, including detection and characterization of subsurface Hertzian cracks in ceramic materials [3], in vivo thickness measurement of the sweat film layer [4], and non-destructive and quantitative characterization of pharmaceutical tablet coatings [5,6]. OCT is also used in deformation characterizations [7–10]. Targowski et al. [10] used OCT to track deformations in paintings on canvas caused by periodic humidity changes. Recently, an optical coherence vibration tomography (OCVT) system was reported, by which structural vibration monitoring and inner structure characterization can be characterized simultaneously [11]. Both the vibration amplitude and frequency were demonstrated to be quantified with an axial resolution of 1 μm; therefore, this system cannot be used for nanoscale dynamic characterization of PZT actuators. For nanoscale characterization, laser Doppler vibrometry [12,13], holographic interferometry [14–16], and Speckle interferometry [17] exhibit high reliability and enable wideband, phase-resolved, single-point vibration measurements. For these interferometry techniques, the displacement is obtained from the phase change of the interferometric patterns, providing extremely high depth resolution (down to10^{-12} m). However, the detection range is usually limited to half the wavelength of the laser source due to the 2π *p*-phase ambiguity [13]. The detection range can be extended beyond the half wavelength limit by using phase-shift modulation (or phase unwrapping) techniques at the cost of increased instrument complexity and decreased measurement accuracy (related to the inherent phase-shift error) [17]. In the present work, we report a sub-nanoscale-resolution optical coherence tomography (SOCVT) system for real-time calibration of piezoelectric actuators in which the amplitude of the FFT of the spectral interferogram was used instead of the phase information. Therefore, phase-shift modulation techniques are not required in the SOCVT system. SOCVT

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Nomenclature

$I(\lambda, t)$	The spectral interferogram of the interferometer of an optical coherence tomography system
λ	The wavelength of light in air
$I_0(\lambda)$	The intensity of the incident light
ϵ_0	The vacuum permittivity
μ_0	The vacuum permeability
S_r	The reflection coefficient of a reference
$S_{s0}(\lambda)$	The surface reflection of a sample
$S_{s1}(\lambda)$	The coating/core interface reflection of a sample
d	Thickness of a coating layer
$\Delta l(t)$	The optical path length difference between the reference and sample arms
P	The surface position of the PZT actuators
M	The number of spectral interferograms
p_{ti}	The precise determination of the surface position of the vibrating PZT actuator
t_i	Time
FI_i	The FFT of the spectral interferogram
FI_{Mj}	The peak value of the j-th spectral line of FFT of the spectral interferogram
L_{Mj}	The corresponding number of spectral lines in the discrete spectrum
N	The length of the spectral interferogram
c	The velocity of light in air
n	Refractive index of air
Δf_M	The frequency interval
q	The number of spectral lines used for spectral correction

is an absolute displacement measurement method; as a result, SOCVT does not require phase-shift modulation or the integration of the velocity along the time axis, both of which are required for laser Doppler vibrometers to obtain the displacement information. The non-contact and non-invasive SOCVT system is a tool for subnanoscale-displacement-resolution calibration of actuators at nanoscale or microscale displacement ranges.

2. Enhanced optical coherence vibration tomography

Fig. 1 shows a schematic diagram of the use of spectral-domain optical coherence tomography for piezoelectric actuator calibration. The light from a 50-W halogen lamp (a short-coherence white light source) is delivered into a Michelson interferometer using a biconvex lens. The light is then split into reference and sample beams using a beamsplitter (50/50). Both the “object image” and the “reference image” are formed at the entrance slit of a broadband CCD-based spectrometer (USB2000+, Ocean Optics, USA). Interference occurs when both the “object image” and the “reference image” are spatially matched in size and orientation and their optical path lengths are matched within the coherence length of the light source. Note that the minimum integration time of the spectrometer is limited to 1 ms; i.e., it could conduct 1000 measurements in 1 s. Due to this limitation of the spectrometer, this SOCVT setup can only measure low-frequency vibrations with a frequency of up to 250 Hz. However, the frequency range could be easily increased to tens of kHz if a high-performance spectrometer is used. The sample used here is a PZT stack actuator (AE0203D04F, Thor labs). The vibration amplitude and frequency of the PZT actuator were controlled by the signal generated from a signal generator (Agilent 33220) and amplified by a programmable DC power supply (Chroma 62000P). Our SOCVT setup here (in which a linear CCD is used) is different from the 2DOCVT setup we developed recently [18]. The 2DOCVT requires a high-speed camera with area CCD sensors, which enable measurement of the 2D beam-like structural vibration with a displacement resolution of ~0.1 nm. Due to its high speed, the highest sampling frequency of ~40 kHz for the 2DOCT could be achieved if the lowest resolution of the PCO-TECH high-speed CCD camera was used [18].

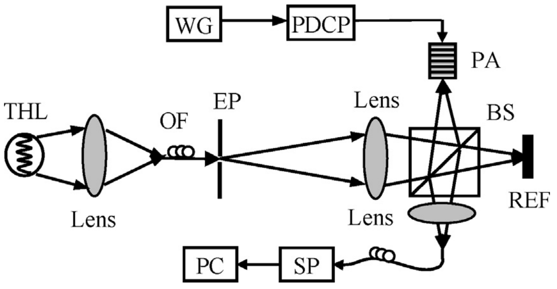

Fig. 1. Experimental configuration of optical coherence vibration tomography: THL, tungsten halogen lamp; OF, optical fibre; EP, entrance pupil; BS, beam-splitter; RM, reference; WG, waveform generator; PDCP, programmable DC power supply; SP, spectrometer; PC, computer; PA, PZT stack actuator.

For a vibrating sample, the spectral interferogram of the interferometer of an optical coherence tomography system can be expressed as [11]

$$\begin{aligned} I(\lambda, t) = {} & I_0(\lambda)S_r{}^2 + I_0(\lambda)(S_{s0}(\lambda)^2 + S_{s1}(\lambda)^2) \\ & + 2I_0(\lambda)S_rS_{s0}(\lambda)\cos\left[\frac{2\pi\Delta l(t)}{\lambda}\right] \\ & + 2I_0(\lambda)S_rS_{s1}(\lambda)\cos[2\pi\Delta l(t)/\lambda + 4\pi d/\lambda] \\ & + 2I_0(\lambda)S_{s0}S_{s1}(\lambda)\cos\left(\frac{4\pi d}{\lambda}\right) \end{aligned} \tag{1}$$

where λ is the wavelength of light in air, $I_0(\lambda) = \sqrt{\frac{\epsilon_0}{\mu_0}}|E_i(\lambda)|^2$ is the intensity of the incident light, ϵ_0 and μ_0 are the vacuum permittivity and the vacuum permeability, S_r is the reflection coefficient of a reference and is wavelength-independent, and $S_{s0}(\lambda)$ and $S_{s1}(\lambda)$ correspond to the surface reflection and the coating/core interface reflection of the sample, respectively, which are usually wavelength dependent for a layered sample. For simplicity, here, we assume that the sample has a single coating layer of thickness d and that the contribution from the multiple reflections within the coating is negligible. $\Delta l(t)$ is the optical path length difference between the reference and sample arms, which is a function of t for a vibrating sample. For a static sample, that is, when time t in Eq. (1) is a constant, the system operates as a traditional optical coherence tomography system [2–6]. The fast Fourier transform (FFT) of the measured spectral interferogram provides both the surface position (i.e., $\Delta l(t)$) and the depth profile of the sample [11]. We previously reported an OCVT system by which the layer thickness of the vibrating structures can be characterized. Furthermore, the vibration frequency and amplitude (with an axial resolution of 1 μm) could be measured simultaneously. The vibration amplitude was simply based on the FFT results of the measured spectral interferogram.

However, due to signal leakage effects [19–21], the calculation of amplitude, phase and frequency from the FFT of the measured finite-length spectral interferogram is normally different from the real one. Therefore, the vibration amplitude measured by the previously reported OCVT system [11] is not a perfect result. Generally, applying windowing functions to the measured spectral interferogram is a common method to minimize the effect of leakage. However, theoretically, the maximum relative error of the amplitude estimation will be 36.4% and 15.3% when Rectangle and Hanning windows, respectively, are used to minimize leakage [20];