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Two-dimensional optical coherence vibration tomography for low-frequency vibration measurement and response-only modal analysis

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ABSTRACT

A high-speed camera-based two-dimensional optical coherence vibration tomography (2DOCVT) system with a subnanometre displacement resolution was developed and employed for low-frequency vibration measurement and modal analysis. Experimental results demonstrated the ability of low-frequency absolute displacement measurement of structural line vibrations without scanning. Three-dimensional (3D) surface displacement of a vibrating structure could also be obtained using the developed 2DOCVT by scanning the structure. The scanning 2DOCVT system acted like a 3D optical coherence vibration tomography system. The developed 2DOCVT system could capture structural modal parameters without vibration excitation input information, and therefore, it is a response-only method. The 2DOCVT could be recommended in the application of low-frequency vibration measurement and modal analysis of beam and plate structures, especially when the vibration amplitude is at nanometre or micrometre scale.

1. Introduction

Mechanical vibrations are often measured by using Laser Doppler Vibrometry (LDV) [1–4]. The LDV method exhibits high reliability and enables wideband, phase-resolved, single-point measurements. A single-point spectral-domain optical coherence vibration tomography (OCVT) system [5] to quantify both vibration and the inner structure (layer thickness) of a vibrating sample was reported. However, these single-point methods require time-consuming point scanning of the tested sample [6]. Recently, Fu et al. [7] have employed single photodetector or high-speed imaging for multi-point laser Doppler vibrometry that allows for 20-point measurement. MacPherson et al. [8] reported a multi-point laser vibrometry that is capable of resolving 256 measurement points. Speckle interferometry [9], holographic interferometry [10], heterodyne interferometry [6] and Self-mixing interference [11] enable reliable measurements of mechanical vibrations. Generally, these interferometer techniques are non-contact and whole-field techniques, providing different physical information in the form of fringe patterns. For example, the displacement is obtained from the phase change of the interferometric patterns [12,13], providing extremely high depth resolution down to 10^{-12} m [10]. However, the detection range is usually limited to

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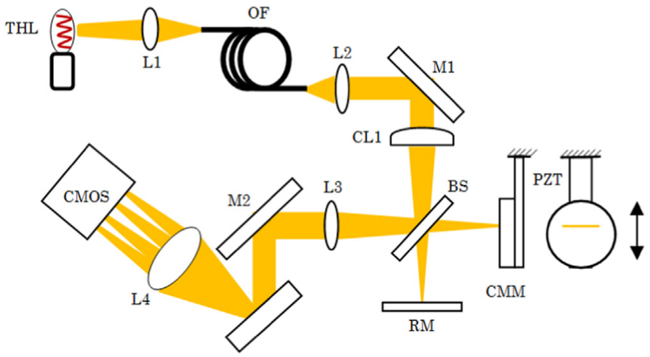

Fig. 1. The schematic diagram of a developed 2DOCVT system. The vibrating structure was excited by a PZT plate. The spectral interferograms were recorded using a high-speed CMOS camera. THL: 50-W tungsten halogen lamp; L: lens; OF: optical fibre; M: mirror; CL: cylindrical lens; BS: 50/50 beam-splitter; RM: reference mirror; PZT: PZT plate; CMM: circular metal mirror; RG: reflection grating; CMOS: 1280 × 1024 pixels CMOS camera (PCO-TECH, Germany).

half the wavelength of the laser source due to the 2π phase ambiguity [2]. The measurement 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) [8]. Recently, a two-dimensional Fourier-domain optical coherence vibration tomography (2DOCVT) [14] was reported. 2DOCVT could measure a series number of points in the vibrating structure simultaneously without scanning. This simultaneous data acquisition ability is the major difference of 2DOCVT from the traditional OCVT system [5] in which point-by-point scanning is required to obtain a line vibration. The other one-point measurement techniques [1,2,5] require the reconstruction of the line vibration or modal shape from single-point measurements in which a scanning device is usually used to perform two-dimensional measurement. Here, we employed the developed 2DOCVT system in a demonstration of low-frequency vibration measurement and modal analysis without scanning. Three-dimensional (3D) surface displacement of a vibrating structure could also be achieved by scanning the structure using the developed 2DOCVT. For such a case, the scanning 2DOCVT system acted as a 3D optical coherence vibration tomography system which is the novelty of the present work.

2. Two-dimensional optical coherence vibration tomography (2DOCVT)

Fig. 1 shows a schematic diagram of the 2DOCVT system. Light from a 50-W tungsten halogen lamp was focused and then delivered by an optical fibre onto a biconvex lens to produce a parallel light beam. A line focus was created using a cylindrical lens and was then imaged at a ratio of 1:1 onto the surface of a reference and the vibrating structure using a beam-splitter (50:50). The line light that reflected or scattered back from both the reference and the structure was collimated using a biconvex lens and then directed to a reflection grating. A holographic reflective grating (1800 lines/mm) was placed in the Fourier plane of the imaging system. The interference fringe of each point from different positions of line focus was imaged onto the corresponding row pixels of a CMOS camera, and spectral interferogram was recorded for all points of the line focus simultaneously by the high-speed camera. In the developed 2DOCVT system, the spectral interferogram $I(\lambda, y, t)$ can be expressed as [14]

$$I(\lambda, y, t) = |E_r(\lambda, y, t)|^2 + |E_s(\lambda, y, t)|^2 + 2|E_r(\lambda, y, t)E_s(\lambda, y, t)|\cos(\Delta ?(\lambda, y, t)) \tag{1}$$

where E_r is the reference electric field and E_s is the sample electric field, λ is the wavelength of the source light, y is the coordinate of the line focus on the vibrating structure, t is time, and $\Delta ?(\lambda, y, t)$ is a phase term resulting from the optical path length difference $\Delta Z(y, t)$ between the reference and the structure surface as

$$\Delta ?(\lambda, y, t) = ?_r(\lambda, y, t) - ?_s(\lambda, y, t) = \frac{4\pi n \Delta Z(y, t)}{\lambda} \tag{2}$$

where n is the refractive index of air. The Fast Fourier Transform (FFT) process was applied to each measured spectral interferogram; the FFT result can provide the surface position (i.e., $\Delta Z(y, t)$) that is a function of t in y coordinates in line. The system has the same function as a traditional optical coherence tomography system for a static sample, that is, time t in Eq. (1) is a constant, and the system could be operated as a traditional optical coherence tomography system [15]. If the coordinate of the line focus y in Eq. (1) is a constant, then the system functions as a single-point vibration measurement system, such as an OCVT system [5]. For this 2DOCVT system, the line vibrations are obtained in one single measurement, i.e., all of the point vibrations of the line are acquired simultaneously [14]. A 3D surface displacement of the vibrating structure is obtained when the developed 2DOCVT is used while scanning the structure. In the present work, the scanning 2DOCVT functions as a 3DOCVT system.