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Phase Modulated Frequency Shifted Digital Holographic Vibrometry with Enhanced Robustness

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Abstract. We report experimental results of a frequency shifted digital holography setup for spatially resolved vibrometry. A spatially homogeneous artificial phase modulation is used as a reference to correct for speckle noise. Furthermore, when superimposed upon the object vibration with slightly different frequency, the resulting beat can be evaluated. The beat frequency is invariant under relative motion between the object and interferometer, providing robustness in presence of parasitic low-frequency vibrations. In addition, the 'working point' is raised out of the noise floor, providing the opportunity to enhance the sensitivity at small vibration displacements. The method is demonstrated by measurements on a vibrating clarinet reed.

1 Introduction

Contactless optical surface vibration measurements are widely used in industrial development and manufacturing processes [1]. The measurement of vibrations with small displacements in the range of nanometres usually employs interferometric techniques such as Laser Doppler Vibrometry (LDV), Electronic Speckle Pattern Interferometry (ESPI), Time Averaging Holography (TAH) or Frequency Shifted Time Averaging Holography (FSTAH) [2]. The latter offers better sensitivity at very small displacements ($\ll \lambda$) compared to ESPI and TAH. The frame rate of the detector limits the application of FSTAH to object vibrations with narrow temporal bandwidth. However, unlike LDV, it does not require sequential point-by-point scanning of the surface to provide a spatially resolved vibration image, drastically reducing measurement times.

Introducing an additional artificial harmonic phase modulation (PM) which is superimposed upon the object vibration adds further possibilities to capture and evaluate data [3]. Building upon [4], where PM was used to enhance the detection limit of ESPI, we applied it to FSTAH in a similar fashion ('PMFSTAH').

2 Measurement Principle

A sinusoidal object vibration with frequency ω_{obj} and out of plane displacement $\hat{z}$ as well as monochromatic laser light with frequency $\omega_L = c/\lambda$ and perpendicular incidence to the object are assumed. According to the Jacobi-Anger-Expansion (Eq. 1), the spectrum of the reflected, phase-modulated beam exhibits sidebands at integer multiples of the object frequency to the left and right of the laser frequency.

$$e^{i\omega_L t} e^{i\frac{4\pi\hat{z}}{\lambda}\sin(\omega_{\text{obj}}\, t)} = \sum_n J_n\left(4\pi\frac{\hat{z}}{\lambda}\right) e^{i(\omega_L + n\,\omega_{\text{obj}})} \qquad (1)$$

The respective sideband amplitudes are connected to the displacement via Bessel functions of the first kind, as illustrated in Fig. 1.

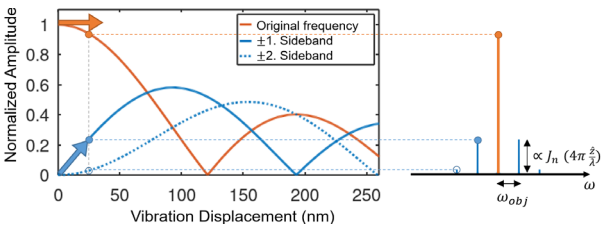

Fig. 1. Normalized amplitudes of the original frequency and first/second sidebands depending on $\hat{z}$ for λ = 632.8 nm.

In TAH and ESPI, the light in the reference arm of the interferometer produces static interference only with the remaining fraction of light at the laser frequency in the object arm, such that the decline and following quasi-periodic modulation of J_0 for increasing $\hat{z}$ are evaluated. The behaviour of J_0 leads to vanishing sensitivity at small displacements, while J_1 exhibits a more favourable, linear trend. Shifting the laser frequency in the reference arm by (roughly) ω_{obj} enables static interference (or a low-frequency beat) with and therefore access to the first sideband in FSTAH. This allows to measure vibrations down to displacements in the range of few nanometres (depending on the experimental conditions).

The introduction of an artificial reference vibration (phase modulation) adds several possibilities. If the displacement of the reference is much larger and its frequency differs from the one of the object, it can easily be identified in the frequency spectrum on the detector

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and act as a reference image to compensate speckle effects lateron. If there is relative motion between the object and the interferometer, the frequencies on the detector associated to the reference and object vibration are doppler-shifted accordingly. However, the frequency difference and the resulting beat frequency is unchanged, which allows to measure in presence of parasitic low-frequency vibrations which are ubiquitous in real world applications.

3 Setup and Methods

3.1 Experimental Setup

The experimental setup is illustrated in Fig. 3. The beam with λ = 632.8 nm from a Helium Neon Laser (633-10p, Spindler & Hoyer, Germany) passes an optical isolator (DLI-2, Gsänger, Germany), and is coupled into a SM fiber (SM600, Thorlabs, United States). A beam splitter generates the reference- and object arms of the interferometer, where the first diffraction orders of acousto-optic modulators (AOMs) are used to shift the respective laser frequencies (ref: IMD 80-H; obj: IMD 80, ISOMET, United States). In the object arm, a cylindrical lens forms a laser line which illuminates a clarinet reed on which a bending vibration is excited by a loudspeaker. In the reference arm, the beam is expanded, attenuated with a ND 2.3 filter and reflected from a mirror on which piston-like vibrations are excited with a piezo actuator. The respective signals are generated by an arbitrary waveform generator (33522B, Keysight, United States). A beam combiner superimposes the reference beam and the light scattered from the clarinet reed at an off-axis angle on the camera (MV1-D2048x1088-160-CL-10, Photonfocus, Switzerland).

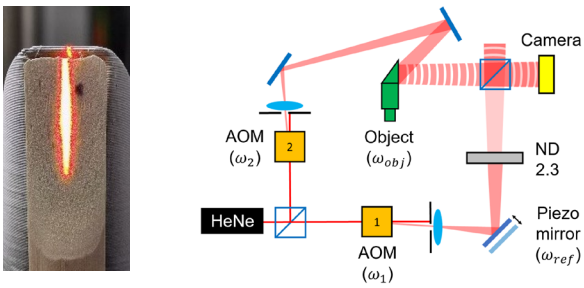

Fig. 3. Photograph of the illuminated object (left) and schematic of the experimental PMFSTAH setup (right).

The AOMs operate at fixed frequencies of ≈ 80 MHz, but show a small frequency difference of ω_1-ω_2 = 1340Hz due to manufacturing tolerances. The clarinet reed is excited with 1410 Hz and the reference mirror with 1420 Hz, producing beat frequencies of 50 Hz and 60 Hz between the respective first sideband and the light from the reference arm. Both can be captured by the camera with 335 fps (limited by the exposure time of 2.985 ms = 4/1340 Hz) at a resolution of 512x512 pixels. In each measurement, a series of 1000 images is acquired. The reference mirror is excited (at its maximum displacement of 28.5 nm) simultaneously to the object.

3.2 Evaluation Algorithm

Hann windows are applied to the stack of images in the spatial and temporal domain to minimize spectral leakage. The holograms are reconstructed by multiplication of a focusing spherical phase term and a following spatial 2D-FFT. A temporal 1D-FFT is applied to the reconstructed holograms to obtain the frequency spectrum.

The images of the reference and object vibrations form at frequencies of 60 Hz and 50 Hz, respectively. If there is an unknown frequency shift (due to parasitic motion), it is convenient to evaluate the unaffected beat-frequency between the object and reference which is accessible by taking the absolute value of the signals in the time-domain. Finally, the object image is normalized to the reference image to correct for speckle effects.

4 Results and Conclusion

The result of the proposed PMFSTAH method is presented in Fig. 4, demonstrating a detection limit in the sub-nm range. The method can also be implemented without additional hardware by phase modulating the AOM signal. Optimizing the parameters of the reference vibration is expected to further improve its performance. The robustness in presence of parasitic vibrations is yet to be demonstrated experimentally.

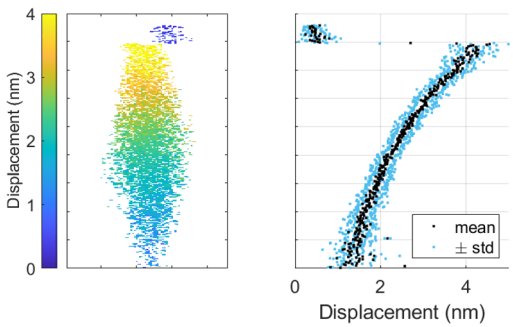

Fig. 4. Measured displacement distribution (left) and the corresponding vertical profile (right)

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