We report a demonstration of laser Doppler holography at a sustained acquisition rate of 250 Hz on a 1 Megapixel complementary metal-oxide-semiconductor (CMOS) sensor array and image display at 10 Hz frame rate. The holograms are optically acquired in off-axis configuration, with a frequency-shifted reference beam. Wide-field imaging of optical fluctuations in a 250 Hz frequency band is achieved by turning time-domain samplings to the dual domain via short-time temporal Fourier transformation. The measurement band can be positioned freely within the low radio-frequency (RF) spectrum by tuning the frequency of the reference beam in real-time. Video-rate image rendering is achieved by streamline image processing with commodity computer graphics hardware. This experimental scheme is validated by a non-contact vibrometry experiment.

Keywords: Laser Doppler, vibrometry, holography, GPU

1 INTRODUCTION

Though effective for single-point analysis [1], laser Doppler measurements are more difficult to perform in wide-field imaging configuration, because of a technological challenge: digital image frames have to be read out at kHz rates and beyond to perform short-time discrete Fourier transforms (DFT) [2]. Recently, image-plane laser Doppler recordings with a high throughput CMOS camera in conjunction with short-time DFT calculations by a field programmable gate array (FPGA) reportedly enabled continuous monitoring of blood perfusion in the mm/s range. Full-field flow maps of 480 × 480 pixels were rendered at a rate of 14 Hz, obtained from image recordings at a frame rate of 14.9 kHz [3]. For transient dynamics imaging of faster phenomena, high throughput laser Doppler schemes were designed by multipoint [4] or time multiplexing [5] approaches. High speed holography enabled offline vibrometry from time-resolved optical phase measurements [6]. Heterodyne holography, as a variant of time-averaged holography [7, 8] with a strobe [9] or a frequency-shifted reference beam [10, 11], is appropriate for steady-state (at the scale of the exposure time) mechanical vibrations mapping. Advances in reconstruction techniques of optically-measured digital holograms with Graphics Processing Units (GPUs) [12, 13] have led to real-time holographic screening of a single vibration frequency, demonstrated in this regime [14].

In this letter, we report an experimental demonstration of video-rate image reconstruction and display of laser fluctuation spectra from high speed holographic measurements. Sustained Fresnel reconstruction of off-axis holograms at 250 Hz and 10 Hz rendering by short-time DFTs is performed. Images and RF spectra of a thin metal plate’s out-of-plane vibration modes around 3.2 kHz are presented.

2 EXPERIMENTAL METHOD AND DETAILS

The optical setup, sketched in Figure 1, is similar to the one reported in the demonstration of video-rate vibrometry at a single frequency [14], at a difference that a high throughput CMOS camera is used to achieve megapixel recordings at 250 frames per second. An off-axis, frequency-shifted Mach-Zehnder interferometer is used to perform a multipixel heterodyne detection of an object field $E$ beating against a separate local oscillator (LO) field $E_{LO}$, in reflective geometry. The main optical radiation field is provided by a 100 mW, single-mode laser (wavelength $\lambda = 532$ nm, optical frequency $\nu_L = \omega_L / (2\pi) = 5.6 \times 10^{14}$ Hz, Oxxius SLIM 532). The optical frequency of the LO beam is shifted by an arbitrary quantity $\Delta \nu$ in the low RF range by two acousto-optic modulators (AA-electronics, MT80-A1.5-VIS). The optical frequency of the LO beam is shifted by an arbitrary quantity $\Delta \nu$ in the low RF range by two acousto-optic modulators (AA-electronics, MT80-A1.5-VIS). The object studied is a thin metal plate with hexagonal holes, shined over $\sim 30 \text{ mm} \times 30 \text{ mm}$ with $\sim 50$ mW of impinging light. It is excited with a piezoelectric actuator (PZT, Thorlabs AE0505D08F), vibrating sinusoidally, driven at 10 V. The structure’s vibrations provoke a local phase modulation $\phi$ (Eq. (7)) of the backscattered opti-
cal field \( E \). Interference patterns are measured with a Basler A504k camera (Micron MV13 progressive scan CMOS sensor array of 1280 × 1024 pixels, quantum efficiency ~ 25% at 532 nm). The camera is run in external trigger mode at \( v_S = \omega_S/2(2\pi) = 250 \text{ Hz} \), at 8 bit/pixel quantization. Images of the central 1024 × 1024 pixels region are recorded. The image acquisition is interfaced with a National Instruments NI PCIe-1433 frame grabber. Each raw interferogram digitally acquired at time \( t \), noted \( I(t) = |E(t) + E_{LO}(t)|^2 \) is dumped to a 1024 × 1024 × 1 byte frame buffer in the GPU RAM of a NVIDIA GTX 580 graphics card by a CPU thread (Figure 2). The object field of complex amplitude \( \mathcal{E} \) is noted

\[
E = \mathcal{E} \exp \left(i\omega_L t + i\phi(t)\right) \tag{1}
\]

where \( \omega_L = 2\pi\nu_L \) and \( \phi(t) \) is the fluctuating phase, as a result of optical path length modulation. The acousto-optic modulators enable the optical LO field of complex amplitude \( \mathcal{E}_{\text{LO}} \) to be detuned by \( \Delta\nu = \omega_L / 2(2\pi) \)

\[
E_{\text{LO}} = \mathcal{E}_{\text{LO}} \exp \left(i\omega_L t + i\Delta\omega t\right). \tag{2}
\]

Holographic image rendering from each recorded interferogram is performed with a numerical Fresnel transform. The hologram \( I \), back-propagated to the object plane, is calculated by forming the Fast Fourier Transform (FFT) \( \mathcal{F} \) of the product of \( I \) with a quadratic phase map, depending on the relative curvature of the wavefronts of \( E \) and \( E_{\text{LO}} \) in the sensor plane [15]. This calculation is handled by the GPU (thread #1, Figure 2), by an algorithm elaborated with Microsoft Visual C++ 2008 and NVIDIA’s Compute Unified Device Architecture (CUDA) software development kit 3.2, on single precision floating point arrays. The practical implementation of free-space propagation with a discrete Fresnel transform [8] yields complex-valued holograms carried by the cross-terms of the interference pattern \( I = |E|^2 + |E_{\text{LO}}|^2 + E^*E_{\text{LO}} + E_{\text{LO}}^*E \) reconstructed in the object plane. In off-axis configuration [16], the zero-order terms \( |E|^2 \) and \( |E_{\text{LO}}|^2 \) and the twin-image term \( E^*E_{\text{LO}} \) can be filtered-out. After filtering, the remaining complex-valued contribution to the off-axis hologram is

\[
H(t) = EE^*_{\text{LO}} = \mathcal{E}^*E_{\text{LO}}^* \exp(i\phi(t) - i\Delta\omega t). \tag{3}
\]

The heterodyne spectrum of the radiation field \( E \) is detected by a short-time discrete Fourier transform (DFT) of \( H(t) \) over \( N = 250 \) consecutive samples (Figure 2, thread #2), 10 times per second. The \( m \)-th Fourier component of the DFT,

\[
\tilde{H}_m(t) = \sum_{n=1}^{N} H(t - n/v_S) \exp(-2i\pi mn/N) \tag{4}
\]

is a heterodyne measurement of the laser fluctuation spectrum at time \( t \), at frequency \( \Delta\nu + v_m \)

\[
\tilde{H}_m(t) = \tilde{H}(t, \Delta\nu + v_m). \tag{5}
\]

The discrete frequencies \( v_m \) of the measured spectra lie within the Nyquist limits of the camera bandwidth \( v_S/2 \), while the LO detuning frequency \( \Delta\nu \) can be set arbitrarily by the acousto-optic modulators (Figure 3).

We assessed the thin metal plate’s out-of-plane vibration modes around 3.2 kHz with the presented holographic approach. The metallic structure was excited sinusoidally at one \( (P = 1) \) or two \( (P = 2) \) frequencies \( \nu_M \) and \( \nu_{2M} \). In either case, the resulting out-of-plane motion at a given point of the surface of the plate, considered as a linear medium for acoustic waves, is

\[
z(t) = \sum_{p=1}^{P} z_p \sin\left(\omega_{Mp} t\right) \tag{6}
\]
This modulated hologram yields a single component in the short-time DFT spectrum \( \tilde{H}_m(t) \), at the frequency \( \nu_m = \nu_{M1} - \Delta \nu \). In the first part of the movie (media 1, see Fig. 4 Movie, when \( P = 1 \)), the excitation frequency \( \nu_{M1} \) was swept from 3210 Hz to 3290 Hz, and the LO was detuned by \( \Delta \nu = 3200 \) Hz; the measurement frequency \( \nu_m \) of the short-time DFT was swept concurrently from 10 Hz to 90 Hz, in 5 Hz steps. The reported spectra result from the magnitude \( |\tilde{H}(t, \Delta \nu + \nu_m)| \) averaged within the red square superimposed on the vibration maps.

The metallic structure was then excited sinusoidally at two frequencies: \( \nu_{M1} \) and \( \nu_{M2} \). The object field undergoing phase modulation from a double excitation (\( P = 2 \) in Eq. 7) takes the form

\[
E = \mathcal{E} \exp (i \omega_1 t) \sum_{n=-\infty}^{\infty} J_n(\phi_p) \exp \left( i n \nu_{M1} t \right). \tag{10}
\]

The terms of Eq. (3) modulated at frequencies within the camera bandwidth \( \pm \omega_b/2 \) are actually measured. The others are filtered out. The temporal part of the camera-filtered hologram reduces to the low frequency component

\[
H_{LF}(t) = \mathcal{E}_{LO}^* \mathcal{E} e^{-i \Delta \omega t} \sum_{n=-\infty}^{\infty} c_{n,1} e^{-n+1} \tag{11}
\]

where

\[
c_{n,p} = J_n(\phi_p) \exp \left( i n \nu_{M1} t \right). \tag{12}
\]

Eq. (11) yields the frequency comb observed in Figure 4(g), whose peaks are separated by \( |\nu_{M2} - \nu_{M1}| = 5 \text{ Hz} \). In the second part of the movie reported in media 1 (see Fig. 4 Movie), the first excitation frequency was set to \( \nu_{M2} = 3290 \) Hz, the second one was swept from \( \nu_{M2} = 3290 \) Hz to \( \nu_{M2} = 3250 \) Hz, in 5 Hz steps. The frequency comb broadened with \( |\nu_{M2} - \nu_{M1}| \) in accordance with equations 11 and 12. For a larger frequency difference \( |\nu_{M2} - \nu_{M1}| \), only two lines of the comb are visible (Figure 4(e),(f)).

3 CONCLUSION

In conclusion, we performed laser Doppler imaging from sustained sampling of 1 Mega pixel interferograms at a throughput of 250 Mega bytes per second, and rendering of 0.25 Mega pixel off-axis heterodyne holograms by short-time discrete Fourier transform with a refreshment rate of 10 Hz. This demonstration was made with commodity computer graphics hardware. We reported video-rate optical monitoring of out-of-plane vibration amplitudes in a frequency band of 250 Hz, shifted by 3.2 kHz from DC. This demonstration opens the way to high bandwidth laser Doppler holography in real time.

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