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Michael Atlan, Benjamin Samson

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Benjamin Samson[1] and Michael Atlan[1]

[1] *Institut Langevin. Centre National de la Recherche Scientifique (CNRS) UMR 7587, Institut National de la Santé et de la Recherche Médicale (INSERM) U 979, Université Pierre et Marie Curie (UPMC), Université Paris Diderot. École Supérieure de Physique et de Chimie Industrielles - 10 rue Vauquelin. 75005 Paris. France*

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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 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.

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 about the mm/s. 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 metallic plate's out-of-plane vibration modes around 3.2 kHz are presented.

The optical setup is similar to the one reported in the demonstration of video-rate vibrometry at a single frequency [14], at the 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 LO field $E_{\rm LO}$, in reflective geometry. The main optical radiation field is provided by a 100 mW, single-mode laser (wavelength $\lambda = 532$ nm, optical frequency $\nu_{\rm L} = 5.6 \times 10^{14}\,$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 object studied is a a thin metallic plate with hexagonal holes, shined over $\sim 30\,{\rm mm} \times 30\,{\rm mm}$ with ~ 50 mW of impinging light. It is excited with a piezo-electric actuator (PZT, Thorlabs AE0505D08F), vibrating sinusoidally, driven at 10 V. The structure's vibrations provoke a local phase modulation ϕ (eq.7) of the backscattered optical 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 $\nu_{\rm S} = \omega_{\rm S}/(2\pi) = 250\,{\rm Hz}$, 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 $\mathcal{I}(t) = |E(t) + E_{\rm LO}(t)|^2$ is dumped to a $1024 \times 1024 \times 1\,$byte frame buffer in the GPU RAM of a NVidia GTX 580 graphics card by a CPU thread (fig. 1). The object field of complex amplitude $\mathcal{E}$ is noted

$$E = \mathcal{E} \exp\left(i\omega_{\rm L} t + i\phi(t)\right) \quad (1)$$

where $\omega_{\rm L} = 2\pi\nu_{\rm L}$ 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 $\mathcal{E}_{\rm LO}$ to be detuned by $\Delta\nu = \Delta\omega/(2\pi)$

$$E_{\rm LO} = \mathcal{E}_{\rm LO} \exp\left(i\omega_{\rm L} t + i\Delta\omega t\right) \quad (2)$$

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 $\mathcal{I}$ with a quadratic phase map, depending on the relative curvature of the wavefronts of E and $E_{\rm LO}$ in the sensor plane. This calculation is handled by the GPU (thread #1, Fig. 1), by an algorithm elaborated with Microsoft Visual C++ 2008 and NVIDIA's Compute Unified Device Architecture (CUDA) software development kit 3.2. The practical implementation of free-space propagation with a discrete Fresnel transform [14, 15] yields complex-valued holograms $I = |E|^2 + |E_{\rm LO}|^2 + E^* E_{\rm LO} + E E_{\rm LO}^*$ reconstructed in the object plane. In off-axis configuration [16], the zero-order terms $|E|^2$ and $|E_{\rm LO}|^2$ and the twin-image term $E^* E_{\rm LO}$ can be filtered-out. After filtering, the remaining complex-valued contribution to the off-axis hologram is

$$H(t) = E E_{\rm LO}^* = \mathcal{E}\mathcal{E}_{\rm LO}^* \exp(i\phi(t) - i\Delta\omega t) \qquad (3)$$

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 (fig. 1, thread # 2), 10 times per second. The m-th Fourier component of the DFT,

$$\tilde{H}_m(t) = \sum_{n=1}^{N} H\left(t - n/\nu_{\rm S}\right) \exp\left(-2i\pi mn/N\right) \qquad (4)$$

is a heterodyne measure of the laser fluctuation spectrum at time t, at frequency $\Delta\nu + \nu_m$

$$\tilde{H}_m(t) = \tilde{H}(t, \Delta\nu + \nu_m) \qquad (5)$$

iThe discrete frequencies ν_m of the measured spectra lie wthin the Nyquist limits of the camera bandwidth $\pm\nu_{\rm S}/2$, while the LO detuning frequency $\Delta\nu$ can be set arbitrarily by the acousto-optic modulators (fig. 2).

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 $\nu_{{\rm M}_1}$, and $\nu_{{\rm M}_2}$. In either case, the resulting out-of-plane motion at a given point of the surface of the plate is

$$z(t) = \sum_{p=1}^{P} z_p \sin\left(\omega_{{\rm M}_p} t\right) \qquad (6)$$

where $\omega_{{\rm M}_p} = 2\pi\nu_{{\rm M}_p}$ and z_p are the angular frequency and the local amplitude of each component, respectively. The phase modulation of the backscattered light is

$$\phi(t) = \frac{4\pi}{\lambda} z(t) = \sum_{p=1}^{P} \phi_p \sin\left(\omega_{{\rm M}_p} t\right) \qquad (7)$$

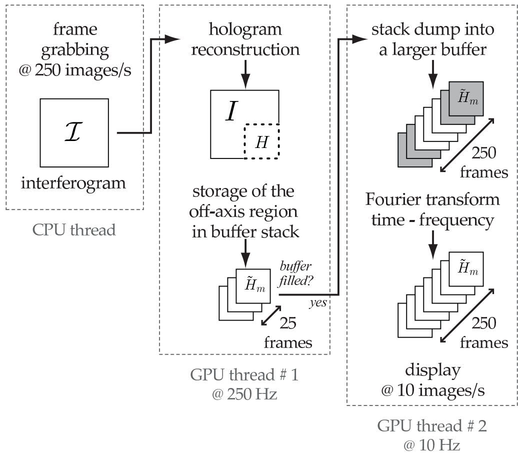

FIG. 1: Algorithmic layout of holographic rendering. Raw interferograms are recorded by the main CPU thread. Spatial Fresnel transforms are performed by a first GPU thread. Short-time temporal Fourier transforms are performed by a second GPU thread.

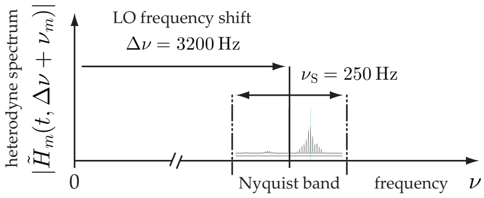

FIG. 2: Sketch of the spectral screening region.

where $\phi_p = 4\pi z_p/\lambda$. The temporal part of the field undergoing sinusoidal phase modulation can be decomposed in a basis of Bessel functions with the Jacobi–Anger identity. If $P = 1$, the object field is

$$E = \mathcal{E} \exp\left(i\omega_{\rm L} t\right) \sum_{n=-\infty}^{\infty} J_n\left(\phi_1\right) \exp\left(in\omega_{{\rm M}_1} t\right) \qquad (8)$$

where J_n is the Bessel function of the first kind of rank n. The only remaining low frequency, camera-filtered term in eq. 3 beating around $\Delta\nu$, within the Nyquist domain (i.e. for $|\nu_{{\rm M}_1} - \Delta\nu| < \nu_{\rm S}/2$) is

$$H_{\rm LF}(t) = \mathcal{E}_{\rm LO}^* \mathcal{E} J_1(\phi_1) \exp\left(i\omega_{{\rm M}_1} t - i\Delta\omega t\right) \qquad (9)$$

This modulated hologram yields a single component in the short-time DFT spectrum $\tilde{H}_m(t)$, at the frequency $\nu_m = \nu_{{\rm M}_1} - \Delta\nu$. In the first part of the movie (media 1, when $P = 1$), the excitation frequency $\nu_{{\rm M}_1}$ was swept from 3210 Hz to 3290 Hz, and the LO was detuned by $\Delta\nu = 3200$ Hz; the measurement frequency ν_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.

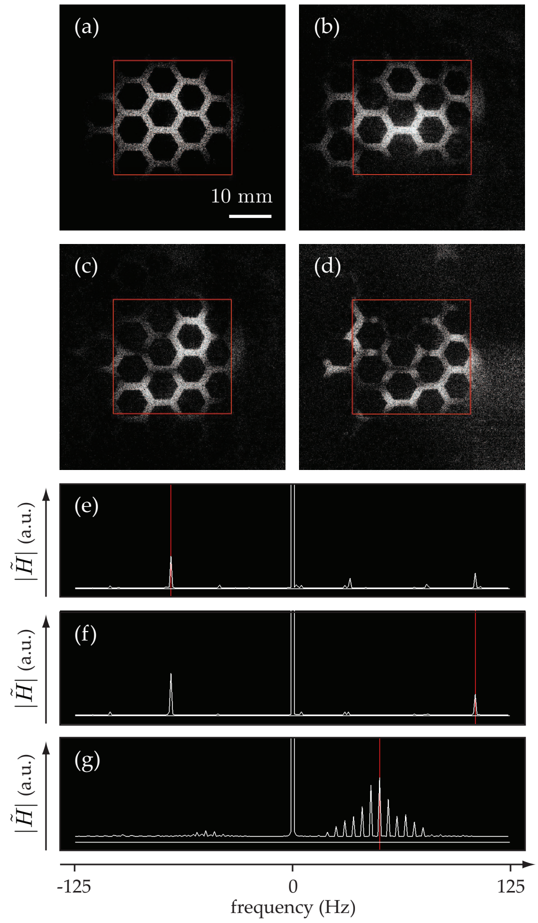

FIG. 3: Short-time Fourier transform vibration maps and spectra of a metallic structure excited sinusoidally. No excitation (a). Excitation at $P = 2$ frequencies : $\nu_{\mathrm{M}_1} = 3200 + 100\,\mathrm{Hz}$ and $\nu_{\mathrm{M}_2} = 3200 - 70\,\mathrm{Hz}$ (b-c,e-f). Excitation at $P = 2$ frequencies : $\nu_{\mathrm{M}_1} = 3200 + 50\,\mathrm{Hz}$ and $\nu_{\mathrm{M}_2} = 3200 + 45\,\mathrm{Hz}$ (d,g). LO detuning : $\Delta\nu = 3200\,\mathrm{Hz}$; The movie of the experiment is reported in media 1.

The metallic structure was then excited sinusoidally at two frequencies : ν_{M_1}, and ν_{M_2}. The object field undergoing phase modulation from a double excitation ($P = 2$ in eq. 7) takes the form

$$E = \mathcal{E} \exp\left(i\omega_{\mathrm{L}} t\right) \prod_{p=1}^{2} \sum_{n=-\infty}^{\infty} J_n\left(\phi_p\right) \exp\left(in\omega_{\mathrm{M}_p} t\right) \quad (10)$$

The terms of eq. 3 modulated at frequencies within the camera bandwidth $\pm\omega_{\mathrm{S}}/2$ are actually measured. The others are filtered-out. The temporal part of the camera-filtered hologram reduces to the low frequency component

$$H_{\mathrm{LF}}(t) = \mathcal{E}_{\mathrm{LO}}^{*} \mathcal{E} \mathrm{e}^{-i\Delta\omega t} \sum_{n\geq 0} c_{n+1,1} c_{-n,2} + c_{-n,1} c_{n+1,2} \quad (11)$$

where

$$c_{n,p} = J_n(\phi_p) \exp\left(in\omega_{\mathrm{M}_p} t\right) \quad (12)$$

Eq.11 yields the frequency comb observed in fig.3(g), whose peaks are separated by $|\nu_{\mathrm{M}_2} - \nu_{\mathrm{M}_1}| = 5\,\mathrm{Hz}$. In the second part of the movie reported in media 1, the first excitation frequency was set to $\nu_{\mathrm{M}_1} = 3290\,\mathrm{Hz}$, the second one was swept from $\nu_{\mathrm{M}_2} = 3290\,\mathrm{Hz}$ to $\nu_{\mathrm{M}_2} = 3250\,\mathrm{Hz}$, in 5 Hz steps. The frequency comb broadened with $|\nu_{\mathrm{M}_2} - \nu_{\mathrm{M}_1}|$ in accordance with equations 11 and 12. For a larger frequency difference $|\nu_{\mathrm{M}_2} - \nu_{\mathrm{M}_1}|$, only two lines of the comb are visible (fig.3(e,f)).

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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