



Heterodyne laser speckle imaging enabling kHz mechanical vibration mapping using a lower frame rate camera

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Abstract: Laser speckle-based vibrometry offers simplicity and ease of alignment for spatial vibration measurement; however, its detection range is limited by the camera speed. We propose a simple optical method for detecting high-frequency vibrations by illuminating the vibrating surface with periodically modulated laser light tuned close to the vibration frequency. The resulting heterodyned speckle signal is captured by a camera, which records slowly varying signal components that encode vibration information. This information is then extracted and visualized using a vibration mapping algorithm. Theoretical and experimental analyses demonstrate vibration-mapping capabilities in the kilohertz range, even with a 200 Hz camera.

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1. Introduction

Mechanical (or structural) vibrations are critical faults in machinery and construction structure [1], which can cause structural problems such as fatigue (wear, tear, and weakening), resonance (leading to larger amplitude vibrations), and noise (which adversely affects human beings) [2–4]. Failure to detect these faults can lead to the premature failure of machine and constructions, or even more catastrophic consequences. Thus, the early diagnosis and prediction of abnormal vibrations are essential to prevent failure and ensure reliable operation, necessitating effective vibration measurement techniques [5].

Considerable research and development has been conducted on vibration measurement techniques [6–8]. Among these, laser-based optical sensors significantly extend the measurement capabilities compared to traditional vibration sensors (such as accelerometers and strain gauges) as they allow non-contact, non-intrusive, remote sensing of the vibrating structure [8–10]. Laser Doppler vibrometry (LDV) is a laser interferometric vibrometry technique that investigates the laser Doppler effect of a probe beam reflected on a vibrating surface [11,12]. LDV exhibits remarkable sensing performance, achieving a detectable frequency of 1 GHz and vibration velocity of up to 1 mm/s [13]. With the evolution of measurement methods from single-point to continuous scanning, LDV has become the most widely used method for the vibration analysis of various engineering and composite structures [14–16].

However, speckle noise is a significant problem in LDV [17]. When a laser beam is projected onto the rough surface of an object, the interference of scattered light generates a speckle pattern that appears as randomized bright and dark spots. The speckle pattern can vary in phasor as the target structure vibrates or the laser scans over the structure, inducing stochastic fluctuation in the LDV output signal, observed as either random spikes in time or a broadband noise floor in the spectra, namely speckle noise [18]. This dominant pseudo-vibration noise may distort the actual vibration and significantly reduce the detection sensitivity of LDV [17,18].

While in LDV, this speckle generates undesired noise, prior knowledge of some speckle pattern properties can be used to measure the translation or rotation of a target object [19]. Speckles

are random self-interference patterns, and each individual speckle serves as a reference point, from which changes in the intensity of the light scattered from the target surface in motion may be tracked. Because speckle dynamics encode information about the target's vibrations, speckle pattern-based interferometry has been recently proposed as an effective non-contact, remote technique to measure vibrational motion and employed for surface displacement analysis (amplitudes, slopes and modes of vibration) and characterization of deformations [19–23]. Speckle interferometry techniques typically employ a single-pixel detector (e.g., a photodiode) or a one-dimensional (1D) array detector (e.g., a line-scan CCD) to collect the speckle pattern from a small portion of the laser-illuminated surface [19–23]. This approach offers a high detection range at audio frequencies ($>$ few kilohertz (kHz)) with good sensitivity. However, the single-point detection method has a limited ability to measure multiple vibrations that occur at different locations on the surface.

Laser speckle imaging using a two-dimensional (2D) array detector (e.g., digital camera) has been developed to address this limitation [24–33]. Electronic (or digital) speckle pattern interferometry (ESPI) is a conventional optical method for non-contact, full-field vibration measurement using a digital camera, which has been widely utilized in various fields that require the measurement of surface displacement [24–31]. ESPI is classified into time-averaged ESPI [24–27] and stroboscopic ESPI [28–31]. Both types of ESPI commonly employ a laser interferometer similar to the Mach Zehnder or Michelson interferometer, in which the speckle interference images are acquired by a conventional CCD camera. For time-averaged ESPI, the speckle interferograms (specklegrams) modulated by the vibration are accumulated during the camera integration time period and then subtracted from a vibration-free reference image to yield a distinct Bessel fringe pattern representing characteristic vibrational modes [24]. On the other hand, stroboscopic ESPI employs a time-triggered scheme with phase-shifting interferometry. The pulsed laser generates strobe illumination that allows for stroboscopic specklegrams during loading. The specklegrams are quadrature phase-shifted using a phase-stepping device (e.g., piezoelectric actuator) in the reference arm and then sequentially captured by a camera. With these snapshots of phase-shifted interference images, vibration amplitude and displacement can be reconstructed [28]. Despite successful applications as a high-frequency vibrometry, both ESPI techniques may be vulnerable to environmental vibrations due to the use of a double-arm interferometer. Surrounding vibrations may easily be involved during measurement, which can generate unwanted phase modulation in the specklegram, leading to errors in vibration analysis. The techniques also may require synchronization between the vibration period and the camera exposure time or the strobe lights, which complicates their control [24]. For stroboscopic techniques, especially, the camera can receive just a very small portion of the laser power, and therefore, it may not be widely accepted for the measurement of relatively large objects.

However, vibration imaging methods utilizing classical laser speckle imaging system have been reported [32,33]. These methods allow simultaneous multipoint detection of speckle intensity signals at different locations within the speckle region. Vibrations and deformations on the surface can be visualized by analyzing the correlation statistics of the consecutively captured speckle pattern images [32,33]. This scheme simultaneously analyzes multiple inspection points, which is essential for monitoring structural health and detecting failures over large surface areas. Since the techniques are based on a conventional laser speckle imaging setup, they are compact and simple to operate. However, the detection range of this approach is inherently constrained by camera frame rates, which are typically a few hundred hertz at full resolution. This limits monitoring mechanical vibrations in the kHz range using slower-speed detectors.

In this study, we demonstrated a laser speckle imaging system designed to measure high-frequency mechanical vibrations. A key feature of the proposed technique is the utilization of light modulation to probe the laser speckle signals. When a periodic laser beam illuminates a vibrating surface, the probed speckle signal is modulated with a beating frequency if the modulation beam

frequency is slightly offset from the vibration frequency. The beat speckle signal is demodulated using the slow sampling rate of the camera, from which the envelope of the beat speckle signal is extracted. This beam modulation-based “optical heterodyne detection” effectively refines original high-frequency speckle signals into a demodulated slow-motion speckle pattern, whose intensity variation can be contrasted via statistical analysis to estimate the time-varying motion, generating a vibration contrast map. The proposed approach was numerically simulated and experimentally validated by visualizing kHz vibrations using a conventional laser speckle imaging system.

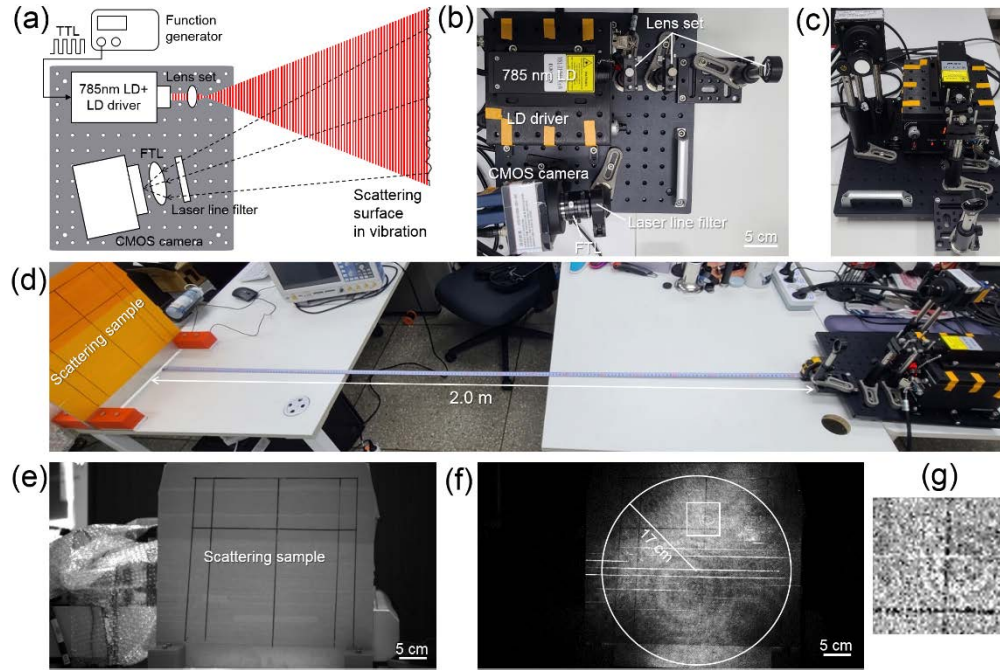


Fig. 1. (a) Schematic of the 785 nm heterodyne laser speckle imaging setup. Photographs of the implemented system, showing the top view (b) and front view (c). (d) Remote measurement of laser speckle on a scattering sample (a taped aluminum plate) using the system. (e) Image of the sample under ambient light. (f) Laser speckle image of the same sample with the laser and filter on. The magnified image (g) taken from a box in (f) highlights the typical features of the speckle pattern.

2. Materials and methods

2.1. Description of a heterodyne laser speckle imaging system

Figure 1(a) shows a schematic of the proposed heterodyne laser speckle imaging system. The system comprised a laser source and a 2D array detector. A 785 nm single-mode laser diode (LD) (MSL-III-785 L, 50 mW, CNI) with a spectral linewidth of 0.1 nm was used as a highly coherent light source, providing a coherence length exceeding 2 m. The output beam from the laser was expanded using a series of near infrared (NIR) lenses and used to illuminate the sample. The light scattered from the laser-illuminated sample was filtered through a 90° flip-mounted 785 nm laser line filter (LL01-785-12.5, Semrock) to eliminate ambient scattered light and subsequently imaged onto the pixel plane of a CMOS camera (VC-2MC-M/C 340, 2048 × 1088 pixels, 200 fps, Viewworks), forming a laser speckle pattern across the pixel plane. The focus of the speckle pattern was adjusted by tuning the imaging distance with a focus-tuning lens (FTL, MV3519, Ex

Technology) assembled on the camera. The NIR light, which was invisible to the user, effectively minimized the discomfort glare caused by strong diffuse reflection at the scattering surface.

The transistor–transistor logic (TTL) signals generated by the function generator were directed to the trigger input of the LD driver, which modulated the continuous laser beam into a square wave. The beam illumination of the vibrating sample generated an optical heterodyne effect on the probed speckle signals. Figures 1(b) and 1(c) show photographs of the implemented laser speckle imaging setup (Fig. 1(a): top view; Fig. 1(b): front view) with dimensions of 29 cm (length) $\times$ 29 cm (width) $\times$ 20 cm (height) and a weight of less than 5 kg, making it lightweight and portable for on-site inspections. Figure 1(d) shows the measurement of laser speckle on a scattering sample (a taped aluminum plate), which is positioned more than 2 m from the system. Figure 1(e) shows a bright-field image of the sample illuminated by the LD after filtering. When the LD and filter were on, a laser speckle image of the same sample was captured by excluding the ambient light (Fig. 1(f)), where the speckle pattern was generated across a surface area of at least 900 cm². In the enlarged view (Fig. 1(g)) of the boxed region in Fig. 1(f), the speckle pattern exhibited a granular structure with randomized bright and dark dots, which is typical of an optical speckle.

2.2. Principle of heterodyne laser speckle imaging

To modulate the speckle signal at a high vibration frequency with a slow camera, the speckle signal can be probed by modulating the LD with a frequency that is slightly different from the vibration frequency. This probing induces optical heterodyning (or beating) in the speckle signal, which is demodulated by the camera, extracting its slowly varying envelope for vibration measurement.

Assuming an ideal case of perfectly coherent (monochromatic) light with a single frequency that has undergone multiple propagation paths for a stationary scattering sample, the speckle signal intensity $I(x, y)$ at a given point on the camera pixel plane is the sum of the contributions of several complex amplitudes.

$$I(x, y) \propto \left| \sum_{\text{Path } l} A_l(\mathbf{r}) e^{i\phi_l(\mathbf{r})} \right|^2. \quad (1)$$

where A_l and ϕ_l are the amplitude and phase of the electric field for different propagation paths l , respectively. Considering the fully-developed speckle, where the phases are uniformly distributed over the interval $(0, 2\pi)$, the speckle intensity $I(x, y)$ on the detector plane exhibits well-defined statistical properties and can be described as an exponentially distributed random variable [34]. For the stationary speckle, the speckle intensity is therefore considered as an arbitrary value. However, the speckle intensity changes as the target surface deforms under the surface vibration. Assuming that the vibration amplitude $a(t)$ is sufficiently small, the detected speckle intensity $I(x, y, t)$ can be expressed as a truncated Taylor expansion [19]

$$I(x, y, t) \cong I_0 + I_1 a(t) + \frac{1}{2} I_2 a(t)^2 + \dots + \xi(t), \quad (2)$$

where $I_n = \partial^n I / \partial a^n$ and ξ is a noise term. The simple case is considered in which the system geometry remains the same during the measurement and the high-order terms and noise term in Eq. (2) are marginal enough to be ignored [19]. Then, we can simply model the time-varying speckle intensity induced by the sinusoidal surface vibration as

$$I(x, y, t) = I_0 + I_1 \cos(2\pi f_v t). \quad (3)$$

where f_v is the vibration frequency of the sample. The camera output signal is obtained by integrating the signal in Eq. (3) during the camera accumulation time period T as

$$I_{camera}(x, y, t) = \int_t^{t+T} \{I_0 + I_1 \cos(2\pi f_v t)\} dt = I_0 T + I_1 \int_t^{t+T} \cos(2\pi f_v t) dt. \quad (4)$$

Here, the second term vanishes when the accumulation period T is significantly longer than the oscillation period of the vibration or $T \gg 1/f_v$. This implies that the camera captures only the average of the high-frequency speckle signal, thereby losing most of the vibration information encoded by the time-varying speckle.

When continuous laser light is modulated by the TTL pulse train designed to have a 50% duty cycle and a frequency similar to that of the surface vibration, the laser output becomes a rectangular wave that can be presented with a Fourier series and normalized sinc function as

$$m(t) = \frac{1}{2} + \sum_{n=1}^{\infty} \text{sinc}\left(\frac{n}{2}\right) \cos(2n\pi(f_v + \Delta f)t + \theta_m). \quad (5)$$

Here, Δf is the offset frequency, which is marginal compared to f_v and θ_m is the initial phase between the probing beam and sample vibration, which ranges from $-\pi$ to π . Unlike Eq. (4), for the beam modulation on a vibrating surface, the camera output signal is obtained by integrating Eq. (3), after multiplying it by Eq. (5) as

$$\begin{aligned} I_{camera}(x, y, t) &= \int_t^{t+T} (I_0 + I_1 \cos(2\pi f_v t)) m(t) dt \\ &= \frac{1}{2} I_0 T + I_0 \sum_{n=1}^{\infty} \text{sinc}\left(\frac{n}{2}\right) \int_t^{t+T} \cos(2n\pi(f_v + \Delta f)t + \theta_m) dt + \frac{1}{2} I_1 \int_t^{t+T} \cos(2\pi f_v t) dt \\ &\quad + I_1 \sum_{n=1}^{\infty} \text{sinc}\left(\frac{n}{2}\right) \int_t^{t+T} \cos(2\pi f_v t) \cos(2n\pi(f_v + \Delta f)t + \theta_m) dt, \end{aligned} \quad (6)$$

where the second and third terms on the right-hand side vanish because of $T \gg 1/f_v$. However, the product of the two cosines in the integral at fourth term is rewritten using the product to sum formula of trigonometric identities as

$$\cos(2\pi f_v t) \cos(2n\pi(f_v + \Delta f)t + \theta_m) = \frac{1}{2} \left\{ \begin{aligned} &\cos(2\pi((n+1)f_v + \Delta f)t + \theta_m) \\ &+ \cos(2\pi((n-1)f_v + \Delta f)t + \theta_m) \end{aligned} \right\}. \quad (7)$$

As evident from Eq. (7), multiplying two signals at frequencies f_v and $n(f_v + \Delta f)$ creates two new signals at the sum of the two frequencies $((n+1)f_v + \Delta f)$ and at the difference between them $((n-1)f_v + \Delta f)$. This mixing product is referred as “heterodyning,” a signal processing technique that extracts information encoded as modulation of the phase, frequency or both of electromagnetic radiation [35]. Here, the surface vibration and the modulation beam are regarded as an input signal and a local oscillator for the heterodyning, respectively. Furthermore, the heterodyne signal is related to a “beat,” that is, a superposition of coherent signals with different frequencies.

Equation (7) can be substituted into Eq. (6), and the summation of the last term in Eq. (6) is expanded for the first few terms as

$$\begin{aligned}
 & I_1 \sum_{n=1}^{\infty} \text{sinc}\left(\frac{n}{2}\right) \int_t^{t+T} \cos(2\pi f_v t) \cos(2n\pi(f_v + \Delta f)t + \theta_m) dt \\
 &= I_1 \frac{1}{2\pi} \int_t^{t+T} \{\cos(2\pi(2f_v + \Delta f)t + \theta_m) + \cos(2\pi\Delta f t + \theta_m)\} dt \\
 &- I_1 \frac{1}{6\pi} \int_t^{t+T} \{\cos(2\pi(4f_v + \Delta f)t + \theta_m) + \cos(2\pi(2f_v + \Delta f)t + \theta_m)\} dt \\
 &+ \dots,
 \end{aligned} \tag{8}$$

where the even terms regarding the summation index n vanished due to the normalized sinc function. For the camera integration time T , all terms of Eq. (8) become negligible except the term: $I_1 \frac{1}{2\pi} \int_t^{t+T} \cos(2\pi\Delta f t + \theta_m) dt$, and the resulting Eq. (6) is given as

$$I_{\text{camera}}(x, y, t) = \frac{1}{2} I_0 T + \frac{1}{2\pi} I_1 \int_t^{t+T} \cos(2\pi\Delta f t + \theta_m) dt. \tag{9}$$

Equation (9) expresses the camera output signal resulting from optical heterodyne detection during the camera acquisition period T . The second term in Eq. (9) includes I_1 , the magnitude of the speckle signal contributed by the surface vibration, which implies that the integral value in the second term should be nonzero to extract the vibration information from the camera output signal. This is possible when the camera sampling rate (camera frame rate) is sufficiently high to resolve the cosine signal in the integral (*i.e.*, $1/T \geq 2\Delta f$) according to the Nyquist theorem. At this camera speed, we can obtain a time series of camera output signals involving the sampled envelope of the cosine waveform, and the obtained camera images can be utilized to measure the surface vibration. It is noted that heterodyne detection would be also possible for a sinusoidally modulated beam, specifically, the first order harmonic with the fundamental frequency ($n = 1$) in Eq. (5). Since the rectangular wave is composed of multiple harmonics, mixing the sinusoidal vibration with them, followed by camera integration, leaves only the component with the offset frequency, ultimately resulting in the same formation as Eq. (9).

Based on the working principle, a numerical simulation of the heterodyne laser speckle imaging was performed; the results are presented in Fig. 2. Figure 2(a) shows the waveforms of the 1 kHz speckle signal (black line) and 1.015 kHz modulation signal (red line) with an offset frequency of 15 Hz relative to the speckle signal frequency, where the magnitude of the speckle signal is set to be equal to that of the modulation signal, and the initial phase θ_m between the signals is arbitrarily given as $\pi/3$. The product of the two signals (heterodyning) creates the beat signal shown as a blue line in Fig. 2(b), in which the spectrum amplitudes are observed at four heterodynes: 15 Hz, 1 kHz, 1.015 kHz, and 2.015 kHz (Fig. 2(c)). As the beat signal is projected onto the camera operating at a frame rate of 200 Hz, the camera filters out the fast oscillating high frequency (≥ 1 kHz) signal components while extracting the low frequency signal component, which forms an envelope function of the beat signal as shown in Fig. 2(d). The spectral frequency of the slowly varying camera output signal was identified as 15 Hz (Fig. 2(e)), which was the same as the offset frequency. The simulation results indicate that the proposed method enables conventional Hz cameras to measure kHz vibrations by downscaling the high-frequency speckle signal to a lower, more measurable frequency using optical heterodyne detection, regardless of phase mismatch.

2.3. Vibration mapping algorithm

The time-varying speckle signals generated by the vibrating sample allow the vibration to be visualized as a speckle contrast, which can be investigated by applying a conventional motion-contrast imaging algorithm to the optical speckle data. We adopted the eigen-decomposition

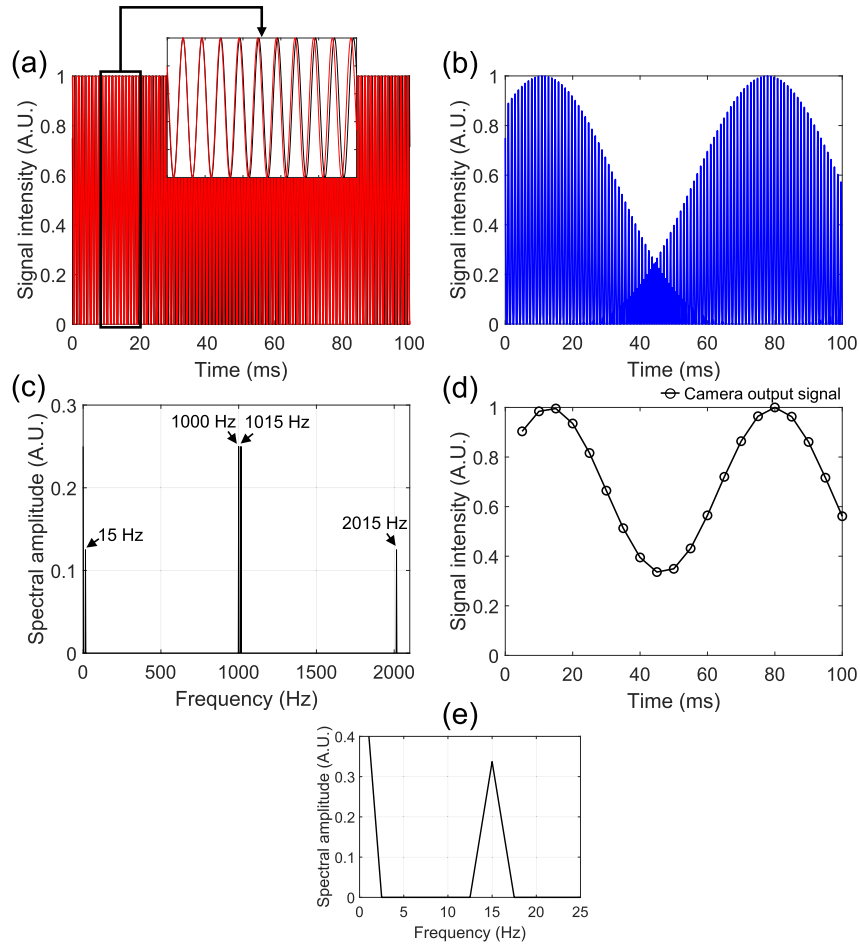


Fig. 2. Simulation results of heterodyne laser speckle imaging. (a) Waveforms of oscillating speckle signal at 1 kHz (black line) and modulation beam signal at 1.015 kHz (red line) with an initial phase of $\pi/3$. (b) Product of the speckle signal and modulation signal, generating signal beating (blue line). (c) Spectrum of the beat signal, exhibiting four heterodynes (15 Hz, 1 kHz, 1.015 kHz, and 2.015 kHz). (d) Camera output signal of the beat signal, obtained by 200 Hz (integration time period: 5 ms) camera. The heterodyne detection of the beat signal extracts the slow-varying envelope of the beat signal, involving the surface vibration information. (e) Spectral frequency (15 Hz) of the Camera output signal.

(ED) analysis method [36], a popular high-sensitivity motion-contrast imaging technique in optical coherence tomography angiography (OCTA), often used to image functional blood vessels within the scattering tissues [36–38]. In this study, the ED approach was used to delineate the mechanical vibrations on the scattering surface. The working principle of the algorithm is detailed in the previous papers [36,37]. In brief, assuming there are N repeated camera captures at the same area, the acquired speckle images can be then collectively expressed as a 2D vector form

$$X = [X(1), X(2), \dots, X(N)]. \quad (10)$$

where N is the ensemble size ($N=4$ for this work) and $X(i)$ represents the i -th captured speckle image. Since the raw speckle signal is the summation of the static component X_s , vibration-induced dynamic component X_d , and additive noise X_n , the signal of each 2D vector can be given

as

$$X = X_s + X_d + X_n. \quad (11)$$

However, the dynamic component X_d in Eq. (11) can be obtained through the eigenvector decomposition of the signal correlation matrix R_X , defined as

$$R_X = \frac{1}{N} X X^H, \quad (12)$$

where H is the Hermitian transpose operation. The correlation matrix can be thus written with eigenvalues and eigenvectors in the following form:

$$R_X = E \Lambda E^T = \sum_{i=1}^N \lambda_B(i) e_B(i) e_B(i)^H. \quad (13)$$

where $E = [e_B(1), e_B(2), \dots, e_B(N)]$ is the $N \times N$ unitary matrix of eigenvectors and $\Lambda = [\lambda_B(1), \lambda_B(2), \dots, \lambda_B(N)]$ is the $N \times N$ diagonal matrix of eigenvalues. Because the static components are dominant to X , they only contribute to the first few eigenvalues. Hence, the dynamic components X_d can be isolated from the speckle signals by designing eigen regression filter to remove the static component as

$$X_d = \left[I - \sum_{i=1}^K e_B(i) e_B(i)^H \right] X. \quad (14)$$

where I is the identity matrix and K is an integer between 1 and N , empirically chosen to 2 in this study.

3. Experimental results

3.1. Vibration mapping with no laser modulation

Vibration mapping was performed using the implemented laser speckle imaging system. To mimic the scattering surface vibrating at high frequencies of the order of kHz, a piezoelectric actuator (PZT) with a reflective sheet was prepared as shown in Fig. 3(a), where the PZT (PK4GA7P2, resonant frequency of 14 kHz, Thorlabs) comprised multiple piezoelectric chips and generated a free stroke displacement up to 10 μm at 15 V. A 5-cm-diameter circular high-reflective fabric sheet (Scotchlight, 3 M) was mounted on the PZT to diffuse the laser light incident on the sheet surface. When feeding a continuous sine wave in voltage from a function generator to the PZT, the sheet oscillates at a given displacement and frequency and serves as a scattering surface in vibration (inset in Fig. 3(a)). For laser speckle imaging, the vibration phantom was affixed to the aluminum plate with a pair of magnetic disks.

In CW laser mode (no laser modulation), the captured image of the vibration phantom with no PZT motion, exhibited a laser speckle pattern generated on the reflective fabric sheet (Fig. 3(b)). As a sinusoidal voltage (13 V sine wave) was applied to the PZT, the speckle pattern was time-variant by the PZT displacement of 9 μm . Figures 3(c-f) show the resulting speckle contrast images obtained using the ED analysis method with an ensemble of four raw speckle images consecutively captured by a 200 Hz camera under PZT motions at 80 Hz, 120 Hz, 150 Hz, and 200 Hz, respectively. Interestingly, the speckle contrast gradually decreases with increasing PZT motion frequency, almost dropping to the background signal level at 600 Hz (see Fig. 3(g)). This decrease in contrast may be attributed to the relatively low camera frame rate (200 Hz), which was insufficient for resolving fast-oscillating speckles over 200 Hz. A rebound in contrast was observed at 200-300 Hz, which may be attributed to the undersampling-induced aliasing, resulting in slow-varying signals. However, the signal amplitude decrease again at the higher frequencies, where the speckle signals become nearly constant over time. This temporal aliasing effect is a technical constraint in mapping mechanical vibrations using conventional cameras.

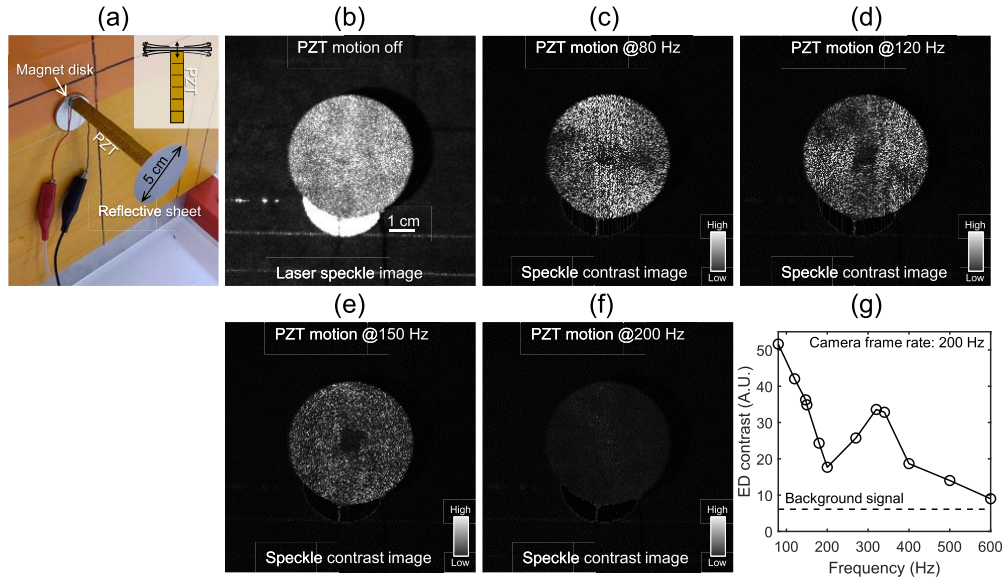


Fig. 3. Vibration mapping with no laser modulation. (a) Photograph showing a reflective sheet mounted on a piezoelectric actuator (PZT) as a vibration phantom, in which the sheet is oscillated by the PZT motion (inset). (b) Laser speckle image of the vibration phantom with no PZT motion. (c-f) Speckle contrast images of the vibration phantom with PZT motion at different frequencies: 80 Hz (c), 120 Hz (d), 150 Hz (e), and 200 Hz (f). (g) Graph showing change in speckle contrast with PZT motion frequency. The speckle contrast was calculated as the mean value of speckle magnitudes on the sheet.

3.2. High frequency vibration mapping with laser modulation

The feasibility of high-frequency vibration mapping was tested using the same system, but in the laser modulation. A 5 V TTL wave was applied to the LD driver to modulate the LD output beam. Heterodyne detection was adjusted by achieving the modulation frequency to an offset frequency of a few Hz from the given PZT motion frequency. For beam modulation, laser speckle imaging was conducted at a camera frame rate of 200 Hz while the PZT motion frequencies were increased from 600 Hz to 2 kHz. Figure 4(a) shows the time-course change in the speckle intensity obtained from an arbitrary pixel of raw speckle images captured during beam on/off. In Fig. 4(a), no significant variation in the speckle intensity of the PZT motion is observed at 1 kHz owing to the time averaging of the oscillating speckle signals. As the modulation starts at 1.018 kHz, the variation manifests; however, the drop in speckle intensity is because of the decreased laser output power. An enlarged view of the box in Fig. 4(a) shows that the time variation is sinusoidal, and its FFT spectrum (Fig. 4(b)) exhibits a main spectral peak at approximately 18 Hz, which is the same as the offset frequency of the modulation beam. The slowly varying signal results from the optical heterodyne detection achieved by the beam modulation and low-frequency camera, which experimentally validates the principle and simulation results in Section 2.2.

Figures 4(c) and 4(d) are the speckle contrast images of the vibrating phantom at 600 Hz with and without modulation at 604 Hz, respectively. The vibration is visualized as speckle contrast at beam modulation mode (Fig. 4(d)), while no contrast appears without modulation (Fig. 4(c)) (Visualization 1). The vibration mapping could be also achieved for the vibrations at the higher frequencies up to few kHz, as shown in Figs. 4(e-h) (Visualization 2 and Visualization 3). We evaluated SNRs of the speckle contrast images (Figs. 4(d-h)), calculated using the averaged values from the speckle contrast region (15×15 pixels) and the background region (15×15

pixels), respectively. The measured SNR values were 9.97, 8.59, 8.08, 7.13, and 5.69 at the vibration frequencies of 0.6 kHz, 0.8 kHz, 1.0 kHz, 1.2 kHz, and 2.0 kHz, respectively. The result indicate that the SNR remains above 5 at several kHz vibrations, which is the minimum required to distinguish image features with certainty [39]. Moreover, the speckle contrasts were measured with different PZT displacements proportional to the applied voltage. As shown in Fig. 4(i), the speckle contrasts increased with the PZT displacement for 1 kHz and 2 kHz PZT motions; the contrast was observed at the small displacements below $0.8\ \mu\text{m}$, representing the measurable vibration sensitivity of the proposed system. However, the contrast slope is relatively gradual for 2 kHz compared to that for 1 kHz. This may be attributed to the phase lag of the sheet motion relative to the PZT motion, which reduces the amplitude of speckle oscillation

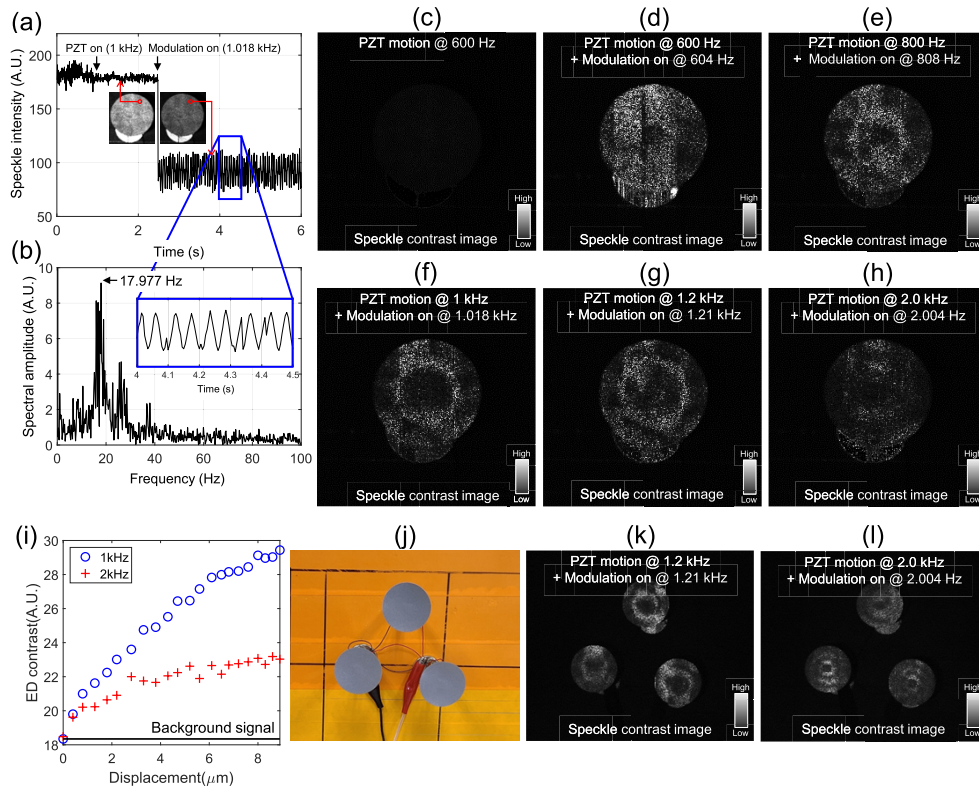


Fig. 4. Vibration mapping with laser modulation. (a) A plot showing a time course of laser speckle intensities on the sheet under PZT motion at 1 kHz and followed by 1.018 kHz laser light modulation. As PZT is on, the resulting speckle oscillation is not seen because of the signal washout due to the long integration time (5 ms) of camera. As the modulation starts, however, the speckle oscillation appears thanks to optical heterodyne detection. (b) A FFT spectrum of the oscillating speckle signal (a magnified view of a box in (a)), exhibiting a main spectral peak at nearby the offset frequency of the modulation (18 Hz). (c) Speckle contrast image of the vibration phantom with PZT motion at 600 Hz. As soon as the CW lasing mode is switched to modulation mode (604 Hz), the surface vibration is disclosed as speckle contrast (d). (e-h) Speckle contrast images with laser modulation under higher frequency PZT motions up to 2 kHz. (i) Speckle contrasts with PZT displacements for kHz PZT motions. (j) A photograph of three separate vibration phantoms and corresponding speckle contrast images (k) and (l), demonstrating the feasibility of concurrently monitoring the kHz local vibrations.

and is more prominent for higher frequencies. For the multiple ($n = 3$) vibrators (Fig. 4(i)), furthermore, the local vibrations were imaged and located (Figs. 4(k) and 4(l)) (Visualization 4). These experimental results demonstrate that the proposed method can simultaneously monitor high frequency mechanical vibrations occurring within the laser-illuminated surface area.

4. Discussion and conclusion

This study developed a heterodyne laser speckle imaging method for high-frequency vibration measurements and experimentally validated its ability to visualize locally vibrating surfaces using a portable laser speckle imaging system and simple mechanical vibrators. In addition to the unique capability of probing kHz vibrations in real-time with a low-frame rate (Hz) camera, the proposed method is beneficial for measuring unknown mechanical vibrations onsite. Because the frequency of the modulation beam can be freely tuned using a function generator for heterodyning, an optimal speckle contrast image can be obtained when the modulation frequency is close to the vibration on the illuminated surface.

The stroboscopic illumination method used in this study is similar to the method described in the previous our paper [40]. Commonly, two methods are used to extract the envelope of a modulation signal. However, the main difference between them is that the previous method is based on optical homodyne detection, whereas our method is based on optical heterodyne detection. Specifically, the former demodulates the partially coherent interferogram with strobe light, the frequency of which should be precisely matched to the Doppler frequency (2 kHz) of the interferogram. This demodulation extracts a slow varying envelope signal by sampling the peaks of the interferogram fringes. On the other hand, the latter modulates the sinusoidally modulated speckle intensity with strobe light, the frequency of which should be approximately the same as the speckle modulation frequency to generate a beat signal. The envelop of the beat signal can then be extracted by low-pass filtering using a camera.

Table 1 shows a summary of our system's performance, compared to previous laser speckle-based vibration mapping techniques. In comparison with conventional techniques, the current system exhibited comparable or outstanding mapping performance. When compared the laser speckle imaging similar to the present platform, in particular, our system outperformed in the measurable vibration frequency, which has been entirely limited to few tens of Hz in the conventional techniques.

Table 1. Comparison of the laser speckle-based vibration mapping techniques.

	Measurement mechanism	Measurable vibration frequency	Measurement time	Measurement distance	References
Electronic speckle pattern interferometry (ESPI)	Time-averaging ESPI, Stroboscopic ESPI	Few tens of kHz	Up to ten minutes	Few meters	[24–31]
Laser speckle imaging	Image correlation	Few tens of Hz	2 s	Few meters	[32,33]
Our technology	Optical heterodyne detection	> 2 kHz	0.2 s	> 2 m	

The vibration-detection range and sensitivity of the proposed system were measured to be 2 kHz and sub-micrometers, respectively. The vibration detection range may be limited to a used CW laser diode, which is typically modulated to a few kHz. Although optical or mechanical modulation using an acousto-optical modulator (AOM) or an optical chopper may increase the modulation beam frequency up to hundreds of kHz; however, significant loss of output beam power results. Improving the vibration detection sensitivity may be difficult for current speckle intensity-based method. A minor modification of the system to laser speckle holography [41,42]

may be an alternative to achieve nanometer-scale vibration sensitivity by retrieving the optical phase information of the time-varying speckle holograms, including the optical path length difference between the vibrating surface and reference arm.

The surface of the vibration phantom used in this study was highly rough, generating uniform speckle patterns. However, for application to smooth or flat surfaces, an optical diffuser must be placed in front of the lens set at the laser exit to spread light evenly across the surface, minimizing strong specular reflection or high-intensity bright spots from the surface image.

In conclusion, the proposed laser speckle imaging method is applicable to existing camera-based laser speckle vibrometers, enabling them to monitor broadband mechanical vibrations; this facilitates multidimensional diagnosis of machinery health.

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