

Document Version

Final published version

Licence

CC BY

Citation (APA)

Zeng, Y., Núñez, A., Rembe, C., & Li, Z. (2026). Laser Doppler vibrometers on moving platforms: advancements, challenges, and future opportunities. *Mechanical Systems and Signal Processing*, 253, Article 114312. <https://doi.org/10.1016/j.ymssp.2026.114312>

Important note

To cite this publication, please use the final published version (if applicable). Please check the document version above.

Copyright

In case the licence states “Dutch Copyright Act (Article 25fa)”, this publication was made available Green Open Access via the TU Delft Institutional Repository pursuant to Dutch Copyright Act (Article 25fa, the Taverne amendment). This provision does not affect copyright ownership.

Unless copyright is transferred by contract or statute, it remains with the copyright holder.

Sharing and reuse

Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

Takedown policy

Please contact us and provide details if you believe this document breaches copyrights. We will remove access to the work immediately and investigate your claim.



ELSEVIER

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

Review

Laser Doppler vibrometers on moving platforms: advancements, challenges, and future opportunities

Yuanchen Zeng^a , Alfredo Núñez^a , Christian Rembe^b, Zili Li^{a,*} 

^a Section of Railway Engineering, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Stevinweg 1, 2628 CN Delft, The Netherlands

^b Institute of Electrical Information Technology, Clausthal University of Technology, Leibnizstrasse 28, 38678 Clausthal-Zellerfeld, Germany

ARTICLE INFO

Communicated by Xingjian Jing

Keywords:

Laser Doppler vibrometer
Vibration measurement
Vehicle
Drone
Mobility
Structural health monitoring
Remote sensing

ABSTRACT

Laser Doppler Vibrometer (LDV) is a non-contact sensing technology widely used for vibration, acoustic, and wave measurements. In recent years, the deployment of LDV on moving platforms (LDVom), such as ground vehicles, robots, and drones, has enabled new solutions for remote sensing and condition monitoring of (infra)structures. LDVom leverages the mobility of manned and unmanned platforms, which offer distinct advantages in flexibility, coverage, and efficiency, but also face challenges arising from laser speckle, platform motion and vibration, and optical turbulence. This review synthesizes the technological enablers, diverse applications, unresolved challenges, and future opportunities of LDVom. The key technological enablers include tailored de-noising, signal diversity, laser head vibration compensation, and multi-point sensing. Current implementations of LDVom are predominantly vehicle-based, achieving real-world monitoring of road and railway infrastructure at near-traffic speeds, while emerging airborne implementations extend LDVom to drones and aircraft. Despite these advances, unresolved issues related to platform dynamics, target surface properties, environmental disturbances, and operational complexity continue to limit measurement quality, resolution, and reliability. Future advances in miniaturization, advanced signal diversity, multi-dimensional, multi-quantity LDV, and digital twins hold the potential to expand the capability and performance of LDVom. This review positions LDVom as an evolving and versatile technology with strong application potential across diverse domains.

Glossary

AI	artificial intelligence
CCD	charge-coupled device
CMOS	complementary metal oxide semiconductor
DIC	digital image correlation
ESPI	electronic speckle pattern interferometry
IMU	inertial measurement unit
MEMS	microelectromechanical systems
NDT	non-destructive testing

(continued on next page)

* Corresponding author.

E-mail addresses: Y.Zeng-2@tudelft.nl (Y. Zeng), A.A.NunezVicencio@tudelft.nl (A. Núñez), rembe@iei.tu-clausthal.de (C. Rembe), Z.Li@tudelft.nl (Z. Li).

<https://doi.org/10.1016/j.ymssp.2026.114312>

Received 28 January 2026; Received in revised form 2 April 2026; Accepted 18 April 2026

Available online 26 April 2026

0888-3270/© 2026 The Author(s). Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

Glossary (continued)

LDV	laser Doppler vibrometer
LDVom	laser Doppler vibrometer on moving platform
LiDAR	light detection and ranging
PIC	photonic integrated circuit
RSSI	received signal strength indication
SHM	structural health monitoring
SNR	signal-to-noise ratio
TSD	traffic-speed deflectometer

1. Introduction and motivation

Laser Doppler Vibrometer (LDV) has become a key instrument for non-contact vibration, acoustic, and wave measurement. LDVs measure based on the Doppler frequency shift between an emitted light and the light backscattered from a vibrating target [1–3]. Unlike contact-based sensors, LDV eliminates the need for mounting sensors on targets, thereby avoiding mass-loading effects and enabling measurements on remote or difficult-to-access targets. Table 1 further compares common non-contact vibration measurement techniques, based on recent reviews [4–6]. The indicated performance levels are approximate and represent those under general-use conditions. Compared to other techniques, LDV has superior frequency bandwidth, resolution, working distance, and robustness to surface conditions.

Since its commercialization in the 1990s, LDV technologies have advanced significantly. Table 2 summarizes the best performance metrics of current commercial LDV systems (not all achieved simultaneously by a single system) as of 2025, according to publicly available specifications on the Internet. These capabilities have enabled precise, broadband, and reliable vibration measurements across a wide range of applications, including modal testing, material testing, structural health monitoring (SHM), quality control, biomedical diagnostics, acoustic analysis, non-destructive testing (NDT), and microelectromechanical systems (MEMS) testing [3,7–13]. Fig. 1 shows the number of publications on LDV in the Scopus database over the past decades, indicating a long-term growth trend.

Depending on the relative position between the laser and target, LDV setups can be generally categorized as follows:

- **Fixed-point LDV:** measures at a single target position, functioning as a massless uniaxial accelerometer [14,15].
- **Discrete-scanning LDV:** steers the laser spot to measure multiple target positions sequentially [1,2,7,16]. This setup is widely used in modal testing and generally requires the vibration response to be stationary or repeatable.
- **Continuous-scanning LDV:** steers the laser spot to scan continuously along a target path, where short scans aim to measure local rotational and translational vibrations, and long scans aim at modal testing [16–18]. This setup also requires a stationary or repeatable vibration response, and the scanning path is confined to a certain area and, in many applications, repeated.
- **Tracking LDV:** steers the laser spot to follow moving targets, thus extending the above setups to translating or rotating structures, such as tires and wind turbines [1,9,19].
- **LDV on moving platforms (LDVom):** While terminology varies across the literature, LDVom generally refers to setups in which an LDV is mounted on a platform that moves relative to an absolute reference frame while measuring the vibration of a target structure relative to the same absolute reference frame. The key distinction of LDVom compared to other setups is that platform motion enables spatial coverage over a larger, less confined area, where the scanning path is usually non-repeatable, and it does not strictly require stationary or repeatable vibration.

This paper focuses on LDVom, the diverse applications of which are illustrated in Fig. 2 (a). By leveraging the mobility of various moving platforms, LDVom enables flexible, high-coverage, and efficient vibration measurements with minimal or no disruption to the normal operation of target structures. Such capabilities are particularly valuable for measuring large-scale structures, such as

Table 1
Comparison of non-contact vibration measurement techniques.

Technique	Primary quantity	Frequency bandwidth	Resolution	Working distance	Surface preparation
Laser Doppler vibrometer (LDV)	Velocity (point-wise)	High	High	Long	Usually unnecessary
Laser displacement or distance sensor	Displacement (point-wise)	Medium	High	Medium	Usually unnecessary
Digital holography, electronic speckle pattern interferometry (ESPI)	Displacement (full-field)	Medium	High	Medium	Required
High-speed camera, digital image correlation (DIC)	Displacement (full-field)	Low	Medium	Medium	Usually required
Millimeter wave radar	Velocity (area-average)	Medium	Low	Long	Unnecessary

Table 2
Performance metrics of commercial LDV systems.

Metric	Performance	Metric	Performance
Bandwidth	Up to 50 MHz (8 GHz for microscope-integrated systems)	Velocity measurement resolution	Down to $\sim (\text{nm/s})/\sqrt{\text{Hz}}$
Velocity measurement range	Down to 10 $\mu\text{m/s}$ Up to 50 m/s	Stand-off distance	Exceeding 500 m
Ingress protection level	Up to IP 63 (against dust and spraying water)		

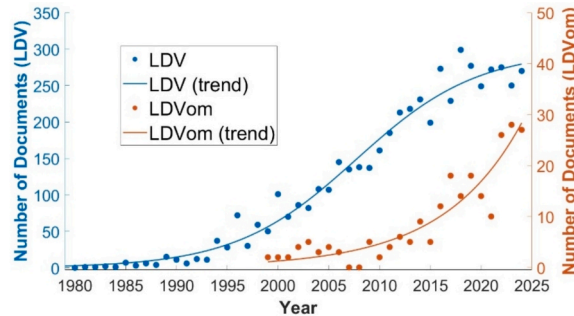


Fig. 1. Research trend of LDV and LDV on moving platforms (LDVom). The data for LDV is from the Scopus database, and the data for LDVom is based on the literature survey conducted in this review.

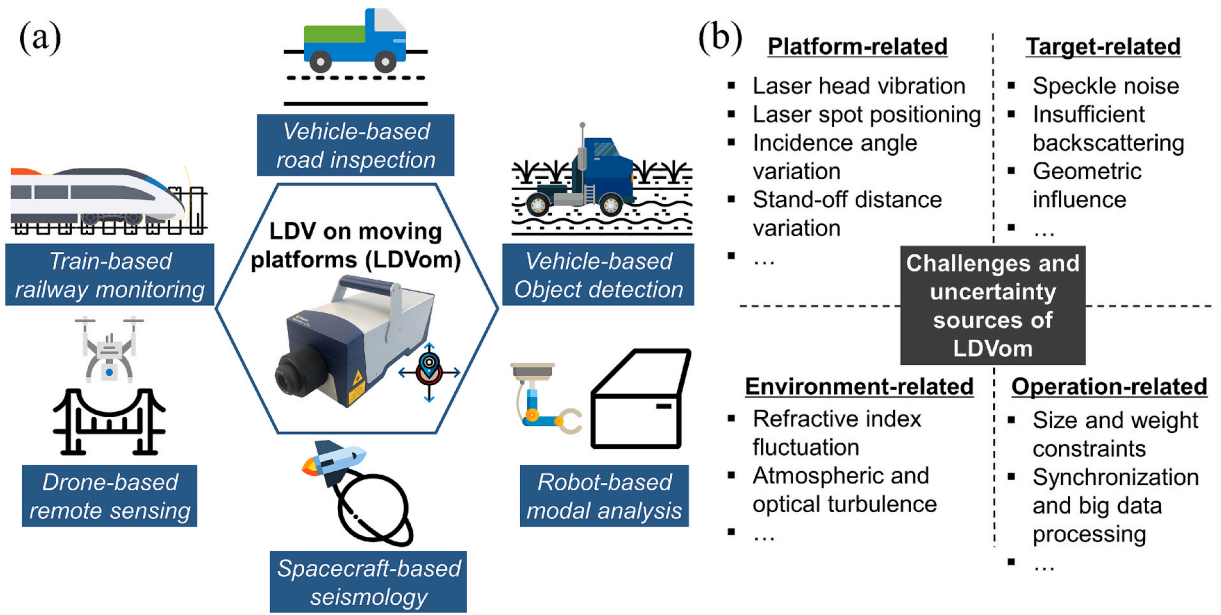


Fig. 2. (a) Existing concepts and applications of LDVom (all icons are from SVG Repo under CC0 license). (b) Key challenges and uncertainty sources of LDVom.

transportation infrastructure networks.

Integrating non-contact sensors on moving platforms is not new. Common examples include the use of cameras and radars on cars, drones, and trains [20–22], which are primarily designed for measuring the geometry and/or distance of remote objects. In contrast, LDVom targets vibrations and wave propagation that are generally too small in amplitude and/or too high in frequency to be captured by these cameras and radars. The high resolution and wide bandwidth of LDV make it well-suited for measuring such dynamic behaviors.

At the same time, the use of LDV on moving platforms introduces many challenges that are less critical in conventional setups, which must be addressed to ensure measurement effectiveness. These factors contribute to large volumes of spatio-temporal data affected by diverse uncertainties, such as those listed in Fig. 2 (b). Early studies of LDVom appeared in the late 1990s, and research efforts and applications have been increasing since then. As shown in Fig. 1, the number of publications on LDVom has increased

notably in recent years, with a growth rate surpassing that of overall LDV research. This reflects the timeliness of a dedicated review on LDVom.

To date, only a few review papers have examined general LDV applications [3,7–11] or continuous-scanning LDV setups [17,18]. More recently, a focused review has explored LDVom on drones [23]. However, a comprehensive review of LDVom across different moving platforms and applications is still lacking. Such a cross-domain review is necessary as it can facilitate the transfer of innovations and solutions between applications, enable more effective mitigation of shared challenges, and inspire new research directions and emerging application scenarios. This paper addresses this gap by providing a systematic overview of LDVom technologies, covering five key aspects presented in the following sections: definition and uniqueness, technological enablers, diverse applications, unresolved challenges, and future opportunities.

2. Definition and uniqueness of LDVom

This section defines the key features and challenges of LDVom. While some of these challenges, such as speckle noise when measuring moving targets (discussed in Section 4), can also occur in other LDV setups, it is the simultaneous occurrence of multiple factors that makes LDVom uniquely challenging.

Fig. 3 (a) presents a simplified schematic of an LDV [1,2,16]. Fig. 3 (b) further shows an LDVom measurement in two dimensions, where the target specimen exhibits vibrations at the laser spot position in both the in-plane and out-of-plane directions, denoted as $x_s(t)$ and $z_s(t)$, respectively. Due to the use of a moving platform, the laser head also undergoes motions $x_h(t)$ and $z_h(t)$, as well as time-varying incidence angle $\alpha(t)$ and stand-off distance $l(t)$. The surface roughness is considered to enable backscattering while also introducing speckle noise.

According to the standard working principle of an LDV, the backscattered light from the target interferes with a reference beam on a photodetector, and the AC component of the resulting photodetector signal $i(t)$ contains the vibration information as follows [1,2],

$$i(t) \propto a(t) \cos(2\pi f_c t + \phi(t) + \phi_n(t) + \phi_0) \tag{1}$$

where $a(t)$ is the signal amplitude, f_c is the artificial frequency shift between the measurement beam and the internal reference beam (in heterodyne systems), $\phi(t)$ is the phase shift induced by the target and laser head vibrations, $\phi_n(t)$ is the phase noise, and ϕ_0 is a constant phase offset.

Vibration displacement and velocity can be extracted from $i(t)$ through phase and frequency demodulation, respectively. Effective demodulation requires sufficiently strong signal amplitude $a(t)$, which depends on factors such as laser power, laser spot size, surface properties, incidence angle, stand-off distance, and light collection efficiency. Inadequate signal amplitude may lead to errors or signal drop-outs. Taking the frequency demodulation as an example, the demodulation output $u(t)$ in velocity is expressed as follows,

$$u(t) = K \left(\frac{\dot{\phi}(t)}{2\pi} + \frac{\dot{\phi}_n(t)}{2\pi} \right) \tag{2}$$

where the derivative of $\phi(t)$ and $\phi_n(t)$ with respect to time corresponds to the vibration velocity and frequency noise, respectively, and K is a sensitivity constant. In the configuration of Fig. 3 (b), $\phi(t)$ can be expressed as follows,

$$\phi(t) = \frac{4\pi}{\lambda} [(z_s(t) - z_h(t)) \cos(\alpha(t)) + (x_s(t) - x_h(t)) \sin(\alpha(t))] \tag{3}$$

where λ is the laser wavelength. Clearly, the laser head vibration and the incidence angle influence the measurement of target vibrations.

A major source of the phase noise $\phi_n(t)$ in LDVom is speckle noise, caused by coherent light scattering from rough surfaces. While amplitude and phase are assumed to remain constant within a single speckle, they vary across speckles. While dark speckles can cause signal drop-outs, changes in speckle patterns, especially those caused by the relative in-plane motion of the laser spot, introduce phase noise. The characteristics of speckle noise depend on both the speckle size and the rate of speckle pattern change. The average speckle

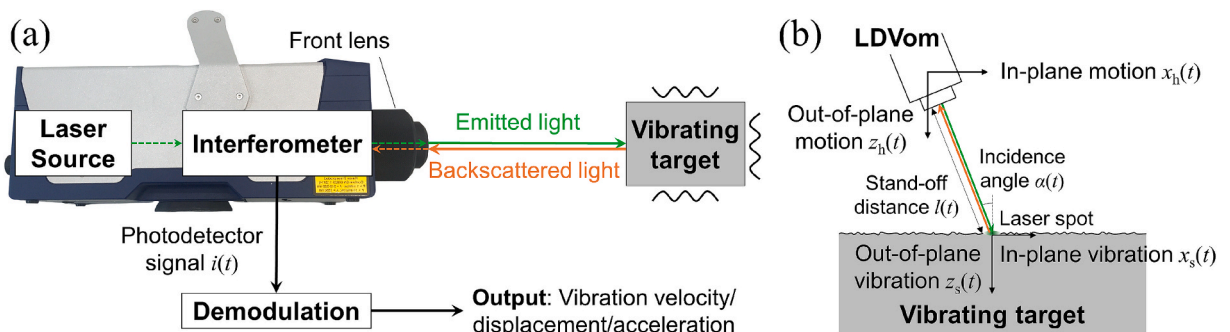


Fig. 3. (a) Core components of an LDV system. (b) An LDVom measurement in two dimensions.

size d is [24,25],

$$d \approx \frac{\lambda l(t)}{w} \quad (4)$$

where w is the laser spot diameter on the target surface. The rate of speckle pattern change is proportional to the in-plane speed of the laser spot across the target surface [24,25]. Overall, speckle noise is affected by surface properties, laser spot size, stand-off distance, and the in-plane motion speed of the laser spot.

Additionally, when a laser beam propagates through inhomogeneous media, such as an atmosphere with temperature and pressure variations, the variation in refractive index can introduce additional phase noise, known as optical turbulence [26].

Based on the above characterization, the following challenges can be identified in LDVom measurements:

- LDV measures the relative vibration between the target and the laser head; thus, laser head vibration due to the platform vibration contaminates LDVom signals.
- In-plane movement of a laser spot on a rough surface causes speckle pattern changes, generating speckle noise.
- Variations in laser spot position, incidence angle, and stand-off distance affect signal strength and may result in signal drop-outs and changes in noise properties.
- Variations in laser spot position and beam orientation introduce misalignment with the target position and coordinate, leading to measurement errors.
- Outdoor operation exposes LDVom to environmental disturbances.

The combined effect of these factors distinguishes LDVom from conventional LDV setups, making it uniquely challenging and necessitating tailored solutions.

3. Technological enablers of LDVom

The challenges of LDVom, together with increasingly complex LDV measurement scenarios, have driven a series of technological advancements that enable and enhance LDVom measurements.

3.1. Optics and demodulation

Modern LDV systems typically employ He-Ne (633 nm wavelength) or infrared (1550 nm) laser. He-Ne lasers offer cost advantages but exhibit periodic variations in signal strength with varying stand-off distances due to multi-mode beating [2,11]. Infrared lasers, in contrast, provide superior stand-off distance robustness, higher eye-safe power, and improved carrier-to-noise ratios [2,27], making them preferable for long distances [27] and on rough target surfaces [28]. While infrared lasers have high absorption in water, which may affect performance in very humid or foggy conditions, the advantage of operating at higher eye-safe power usually compensates for this drawback.

The front lens of an LDV serves to focus the emitting laser beam on a target position and collect the backscattered light [1]. Although diffuse reflections from most engineering surfaces relax the need for perpendicular beam alignment, the intensity of backscattered light still decreases at larger incidence angles [1]. Maintaining focus within the depth of focus is essential to ensure high signal strengths [16], achievable in most commercial LDVs through manual or automated lens control, with auto focusing being more accurate and faster [11]. Many LDV systems also allow the front lens to be changed to vary the stand-off distance range [11], and larger-aperture lenses are often used to enhance light collection for scenarios involving long distances [27] or large in-plane motions [29,30].

The signal strength and quality of an LDV are also affected by the laser beam and spot diameters. Large beam diameters can improve backscattered light intensity [27] and reduce noise when the laser spot traverses a surface [30,31]. A practical alternative is to slightly defocus the beam to enlarge the spot size, which can provide an averaging effect on speckle patterns and better signal quality [10]. Commercial LDV systems often provide received signal strength indications (RSSI) to assist in setup optimization and focusing [1,2,32,33].

Most commercial LDVs utilize Mach-Zehnder heterodyne interferometers, which have the advantages of eliminating directional ambiguity and canceling common-mode noise [1,2]. The demodulation process, which converts optical interference signals into vibration data, has evolved from analog to digital techniques [2,34]. Analog demodulation suffers from noise sensitivity, drift, and limited linearity, whereas digital demodulation offers higher resolution, adaptivity, and traceability [1,2,34,35]. Digital demodulation typically requires a small time delay, which is bandwidth-dependent but constant [1,35]. Digital demodulation also enables additional signal processing algorithms to be embedded for real-time signal quality improvement, such as drop-out detection and mitigation [1], as well as digital tracking filter and signal diversity techniques, which are discussed in the next subsections.

3.2. Filtering and denoising

The resolution of LDV systems is fundamentally limited by noise from multiple sources, including shot noise due to the quantum nature of light, thermal noise from detectors and amplifiers, and signal processing noise [35]. Among these, shot noise is the ultimate

physical limit, and advanced LDV designs are often optimized to approach this shot-noise-limited regime, thereby providing the best theoretically possible signal-to-noise ratio (SNR) [2,27,35].

However, even with optimized system design, non-ideal operating conditions introduce additional noise sources and degrade the performance. As mentioned in Section 2, a significant one is speckle noise that arises from laser speckle patterns [17,36–39]. In fixed-point and discrete-scanning setups, speckle patterns remain relatively stationary for each target position. However, dark speckles can dominate the photodetector, causing signal drop-outs due to insufficient signal strength, so small adjustments of the laser spot position are necessary to redistribute the speckle patterns and recover signal strengths [17,33,37]. In continuous-scanning and LDVom setups, the continuous in-plane movement of a laser spot on a target surface induces rapid variations in speckle patterns, producing transient drop-outs and phase noise, elevating the noise floor of LDV measurement. Interestingly, such speckle variations also help destroy the stationarity of dark speckles, mitigating persistent signal loss [1,2,9].

A detailed understanding of speckle noise is essential for effective mitigation. Insights have been gained about its dependence on surface roughness, spot size, stand-off distance, and the in-plane scanning speed through numerical simulations [24,25,36,40,41] and experiments under translational [38,39,42,43] and rotational [25,31,37,44] motions. Fig. 4 (a) presents an experimental characterization of speckle noise using an LDVom setup, and Fig. 4 (b) presents the measurements along the same target segment at two speeds. As expected, speckle noise appears as random, transient spikes, which become more frequent and increase in amplitude at higher speeds. The spectra in Fig. 4 (c) show that the speckle noise is broadband, with a flat spectral region (overlapping vibration components) followed by a fall-off at higher frequencies. Using similar setups, it is further found in [45] that the root-mean-square of the speckle noise increases proportionally with scanning speed. These findings are consistent with the study in [41] for rough surfaces and high in-plane velocities typical of LDVom setups.

Numerous approaches exist to mitigate speckle and related noise. While surface treatment can improve light backscattering [1,2,36], it cannot fully eliminate drop-outs and speckle noise [31,37] and can be costly or infeasible in some applications. Adjusting stand-off distances can alter the spatial and time correlation of speckle patterns and possibly reduce speckle noise [25], but such adjustments are often constrained by spatial and operational limitations.

Signal processing techniques are a more generic alternative for noise mitigation. Commercial LDV systems typically include built-in filters. Analog and/or digital low/high/band-pass filters allow isolation of specific frequency bands of interest [28]. However, these filters risk discarding useful components and cannot suppress the noise level within the passing bands. Tracking filters, available in some commercial LDV systems with adjustable intensities (slow, medium, fast), operate on photodetector or demodulated signals to preserve signal trends while suppressing high-frequency and impulsive noise [1,2,46]. However, their effectiveness is not significant for continuous-scanning and LDVom setups, and they may attenuate transient vibration components [16,36].

In addition, specialized post-processing denoising algorithms have been developed. Unlike real-time filters that process streaming data, post-processing algorithms analyze complete signal segments, allowing for more sophisticated and potentially more effective processing. In continuous-scanning LDV setups, repeated scanning along closed paths produces quasi-periodic speckle noise components that appear as distinct spectral features corresponding to the known scanning frequencies. These periodic artifacts are usually separated in the frequency domain, and the remaining non-periodic noise is further mitigated in the modal analysis process by averaging across multiple scans [17,18,39]. For other LDV setups, conventional filters often fail to adequately suppress transient and broadband speckle noise [42,47], which has motivated the development of specialized denoising algorithms, including for fixed-point LDV setups [15,48,49], LDVom setups [42,43,47,50–53], and LDV measurements on rotating objects [54]. These algorithms generally involve a detection-reconstruction process: drop-outs and spikes in LDV signals are first detected based on their impulsive signatures and subsequently reconstructed based on vibration trend analysis and predictions. These methods were tested under various scanning speeds, from 0 to a few cm/s to over 10 m/s. Reported SNR improvements include approximately 12 dB [50] and > 20 dB [51]; however, these values are not directly comparable due to differences in experimental conditions. More detailed discussions on these algorithms can be found in [42,52]. While effective, these algorithms often require parameter tuning to suit specific applications, scanning speeds, or surfaces. Table 3 summarizes and compares the filtering and denoising methods discussed in this section.

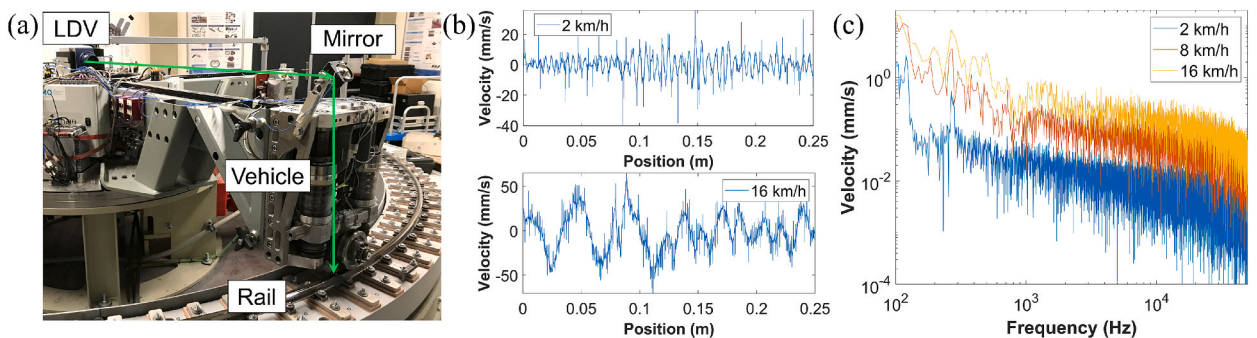


Fig. 4. (a) An LDVom setup for characterizing speckle noise on a vehicle-track test rig. (b) LDVom signals measured on the same rail segment at two different vehicle speeds, including speckle noise in the signals. (c) Spectra of the LDVom signals at three different speeds.

Table 3
Comparison of the filtering and denoising methods.

Methods	Typical use case	Advantages	Disadvantages	Computational cost and real-time capability	Requirements (hardware, algorithm, etc.)
Low/high/band-pass filters	Known, narrow-band target vibration	Simple, built-in	Cannot suppress noise within passing bands	Low, real-time	Minimal
Tracking filters	Occasional impulsive noise	Built-in	May attenuate transient vibration response, not fully transparent	Low, real-time	Commercial LDV with such filters available
Specialized denoising methods	Fixed-point LDV and LDVom	Detailed, data-point-level processing	Computationally intensive	High, post-processing	Development, parameter tuning, and validation

3.3. Signal diversity

Using larger photodetectors to capture more speckles can potentially reduce phase noise in the case of in-plane speckle translation [25]. However, large photodetectors are expensive and typically have limited frequency bandwidth [25]. This has motivated alternative approaches that achieve similar benefits of capturing more speckles. Early implementations employ active beam control strategies. For fixed-point and discrete-scanning setups, this involves taking multiple measurements around each target location, whereas for continuous-scanning setups, multiple, slightly offset scan paths are utilized [11,16,33]. These approaches reduce noise through weighted averaging of multiple measurements, but they increase measurement time and require extra control systems. They are difficult to implement in LDVom scenarios. A more integrated solution is the scanning average technique proposed in [55], where a high-speed optical scanner rapidly oscillates the laser beam within a small area around the target, and a low-pass filter removes the high-frequency scanning components from the signal.

A more general and flexible approach is signal diversity, which combines signals from multiple independent channels measuring the same target position. It leverages the statistical independence of speckle patterns across channels, where the likelihood of simultaneous signal drop-outs decreases as more channels are added [2,44]. Signal diversity can be implemented through the following approaches:

- **Aperture diversity:** utilizes multiple sub-apertures of a lens to collect multiple receiving paths (with still a single emitting beam and laser spot) and generate multiple interference patterns [32].
- **Polarization diversity:** utilizes different polarization components of a single laser beam to generate multiple interference patterns [9,32,56].
- **Wavelength diversity:** utilizes different wavelengths of a single laser beam to generate multiple interference patterns [57].
- **Spot diversity:** utilizes a multi-point LDV or multiple LDVs with separate laser beams and spots to generate multiple interference patterns [58]. Inter-channel crosstalk must be avoided, for instance, by configuring some channels to act as receivers only [58,59].

Signals from multiple channels can be combined using various methods. In [32], demodulated velocity signals from different channels are averaged with weights determined by their RSSI. This method is further improved in [58] by directly combining raw signals prior to demodulation and in [44] by optimizing the weighting strategy. Signal diversity has been demonstrated to significantly reduce drop-outs and speckle noise. An example from [58] is shown in Fig. 5, where the noise level is reduced by around 17 dB when

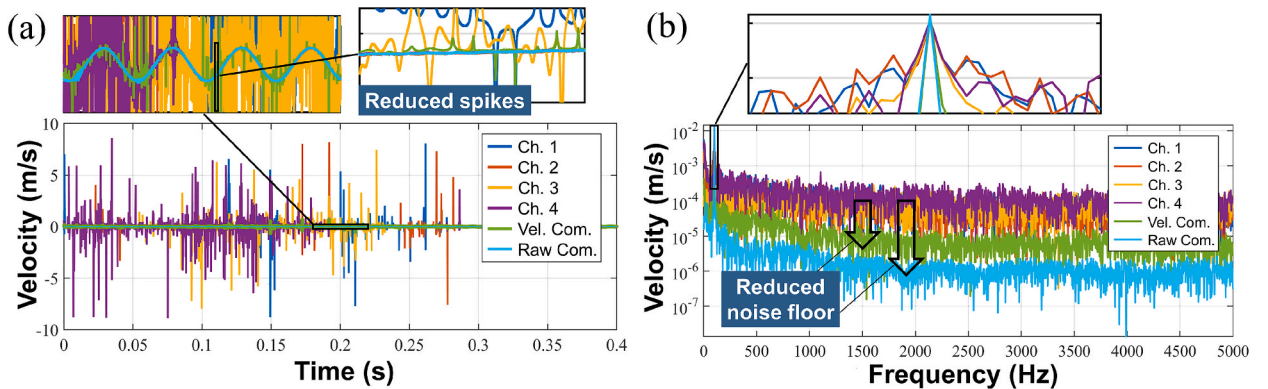


Fig. 5. Example of combining demodulated velocity signals (Vel. Com.) and raw signals (Raw Com.) from four diversity channels (Ch. 1, Ch. 2, Ch. 3, Ch. 4) (figure adapted from [58] under CC BY 4.0 license). (a) Speckle noise reduction in the time domain. (b) Speckle noise reduction in the spectra.

combining the demodulated signals and by an additional 15 dB when combining the raw signals. Signal diversity techniques are well-suited to modern digital demodulation architectures, although they usually require a small processing delay [2,32,59], and research has been conducted on improving their real-time capability [59]. Signal diversity with real-time capability has been successfully integrated into the latest commercial LDV systems, such as the Polytec QTEC series, with reported noise reduction of 10–20 dB on its product website.

It should be noted that many signal diversity techniques, such as aperture diversity and polarization diversity, do not significantly increase the sensor weight or size, although they add optical and signal-processing complexity. The number of diversity channels is generally limited by the number of subapertures or polarization states realizable physically or practically. For example, polarization diversity with two orthogonal polarization states can already provide substantial improvements in many applications. Only when using spot diversity based on multiple standalone LDVs, the weight and size increase significantly with the number of diversity channels, requiring an application-specific balance between the performance improvement and cost.

3.4. Multi-point LDV

Multi-point LDV is a key technological advancement, enabling simultaneous vibration measurements at multiple locations. This capability is particularly valuable for capturing complex vibration modes or wave propagation that would otherwise require multiple single-point LDVs. A common approach involves splitting a single laser beam into multiple pairs of measurement and reference beams, with each pair measuring a target location and forming an interference signal on a photodetector. Based on this approach, Ometron developed a homodyne system featuring an array of 16 laser points [60]. MetroLaser also developed a heterodyne system with customizable laser point arrays (ranging from 9 to 31 points) and adjustable beam spread angles [61]. MetroLaser further developed a system using optical fibers to emit a 16×16 matrix of laser points [62]. A comparative study showed that the 2-point and 4-point heterodyne LDVs can achieve resolutions comparable to single-point commercial LDVs [63]. Since each point uses separate photodetectors and demodulation channels, these systems have greater complexity and require precise synchronization among channels.

Compact alternatives of multi-point LDV using a single photodetector have also been developed. In [64], a laser beam is split into multiple beams (2×5 points), each with a different frequency shift, and the backscattered beams interfere with a reference beam on a single high-speed photodetector. This technology is later expanded to a system with 4×5 points [65]. This approach relies on careful carrier frequency design to separate multiple channels and mitigate inter-channel crosstalk. However, the performance is sensitive to photodetector nonlinearities, and the number of measurement points is limited.

Another approach to increasing the number of measurement points involves replacing conventional analog photodetectors with high-speed cameras capable of simultaneously capturing interference patterns from multiple channels. In [66], an LDV system with an array of 256 points is developed using a Charge-Coupled Device (CCD) array, with demodulation performed on consecutive image frames. In [67], a heterodyne system with an array of 99 beams is developed using a digital line-scan Complementary Metal Oxide Semiconductor (CMOS) camera, in which pixels within each interference pattern are used for demodulation. Although these camera-based systems offer higher channel density, their bandwidth and amplitude are fundamentally constrained by the camera frame rate and dynamic range.

3.5. Compensation of laser head vibration

As mentioned in Section 2, any vibration of the laser head and steering optics along the laser beam leads to additional components in an LDV signal. A vectorial framework for theoretically characterizing such influences has been developed in [68]. Conventionally, laser head vibrations can be measured using accelerometers or inertial measurement unit (IMU) and then removed from LDV signals during post-processing. Refined accelerometer configurations have been developed, including dual accelerometers placed symmetrically about the laser beam [69] and a single accelerometer behind the laser head or steering optics, aligned with the laser beam [70]. Based on these configurations, both frequency-domain and time-domain compensation algorithms have been developed [71]. However, these methods are limited to compensating for rigid-body, low-frequency laser head vibrations; they are sensitive to sensor installation, numerical integration of the accelerometer signal, and mismatches in time and frequency response between the LDV and accelerometers.

An optical solution for laser head vibration compensation is offered by differential LDV techniques. Unlike traditional LDVs that emit a measurement beam and maintain an internal reference beam, a differential LDV emits both beams toward two target positions, and the interference of their backscattered light can cancel their common-mode components and preserve the relative vibration between the two target positions [2,72]. Speckle effects are particularly severe in this configuration due to the two backscattered beams;

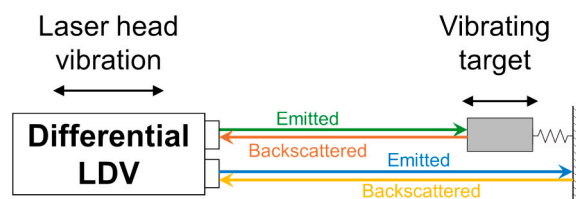


Fig. 6. Differential LDV for laser head vibration compensation.

therefore, a search for bright speckles is often needed in fixed-point measurement, whereas for LDVom measurement, signal diversity is needed to handle time-varying speckles. The differential LDV technique has been extended to a multi-point system [73], where paired interference of adjacent laser beams enables spatial profiling of relative vibrations along an array of target positions. An alternative implementation involves using multiple single-point LDVs to measure different positions, with signal subtraction yielding relative vibrations [74]. Successful compensation of laser head vibrations relies on parallelism between differential laser beams. When absolute vibrations are targeted, the reference beam must be directed at a stationary object, as shown in Fig. 6.

4. Applications of LDVom

Building upon the technological enablers introduced above, this section presents a variety of LDVom applications.

4.1. LDVom on vehicles

1) Deflection measurement under quasi-static loads

One of the earliest applications of LDV on road vehicles is the Traffic-Speed Deflectometer (TSD), also known as the High-Speed Deflectograph, aiming to assess road structural capacity and identify weak sections at normal traffic speeds. The first prototype was developed at the end of the 1990s by the Danish Road Institute and Greenwood Engineering [75], in which two LDVs are mounted on a heavy truck trailer to measure road deflection velocity as the truck moves. Initial tests were conducted in Denmark and France at speeds up to 95 km/h [75,76]. In 2005, an improved version was introduced, featuring four Polytec OFV-503 LDVs—three positioned within the deflection basin and one outside [77], which also improved the robustness against temperature and weather conditions. This improved version was tested in the UK [77,78], followed by many other countries, with some systems incorporating up to seven LDVs [79–83]. An illustration of the TSD system is shown in Fig. 7, and it has been successfully commercialized by Greenwood Engineering. Long-term, large-scale tests and applications have demonstrated that the TSDs provide good repeatability and also good correlation with traditional Falling Weight Deflectometers, which measure at discrete locations.

To address inherent challenges in TSD systems, several key solutions have been developed and applied [75–77,82,84,85]:

- All LDVs are mounted on a stiff beam, and the LDV positioned outside the deflection basin serves as a reference to eliminate common-mode disturbances; an IMU is also mounted on the beam to aid in compensating for the laser head vibrations.
- All LDVs are tilted by a small angle (around 2°) relative to the vertical axis to introduce forward-speed components into the LDV signals for stable data acquisition; actual tilt angles are determined through a calibration procedure and then combined with speed measurement with an odometer to remove the forward-speed components.
- A servo control system adjusts the height of the mounting beam to maintain laser focus on road surfaces.
- Strain gauges are installed on wheel axles to indicate dynamic loads, which should be kept low; meanwhile, the vehicle speed should be relatively constant during operation.

TSD systems target the quasi-static deflection component, so a low sampling frequency of 1 kHz and a 10-m spatial moving average are widely used [75,76,78,81–83]. While effective at reducing noise, such averaging may also smooth out important localized features [78,84]. To address this limitation, more advanced processing techniques have been developed, such as spline smoothing [86], wavelet denoising [87], and enhanced basis pursuit [88].

TSD data can be analyzed in both spatial and temporal domains [83]. The most basic approach involves direct analysis of deflection velocity (in mm/s), where abrupt changes along a road indicate potential structural anomalies [75]. To eliminate speed dependence, deflection velocity is normalized by vehicle speed to obtain deflection slope (mm/m) [76–78]. When multiple LDVs are used within the deflection basin, their measurements can be integrated to reconstruct deflection basin profiles [81,89] or temporal deflection evolution [80]. A benchmark comparison of these reconstruction algorithms is provided in [90]. These features can support structural capacity assessment through deflection-based indicators [84,87,89] and modulus identification [89,91], providing valuable insights for

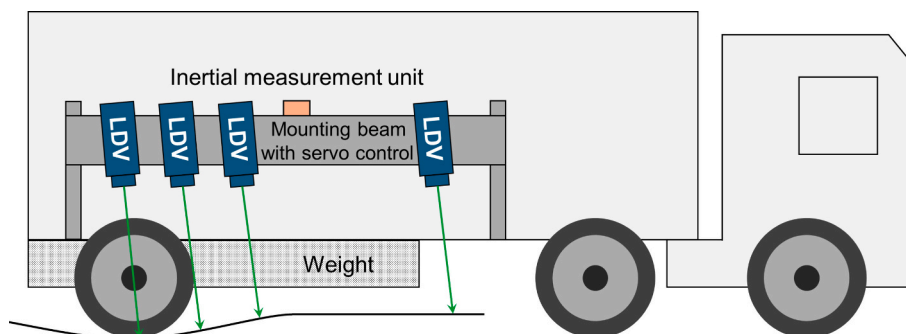


Fig. 7. Illustration of a TSD system for measuring road deflection.

infrastructure management and maintenance planning. A detailed review of the data analysis method is available in [83].

TSD principles have also been explored for bridge monitoring. Numerical studies indicate promising damage detection capabilities [92,93], with methods developed to mitigate disturbances from road profiles and noise. However, no field test results have been reported to demonstrate its effectiveness in real-world conditions. Moreover, the applicability of TSD principles to railway monitoring has also been explored [94,95]. In a recent study [96], homodyne LDVs are mounted on a moving train to measure lateral and vertical rail movements at a sampling frequency of 33 Hz; the laser heads are tilted to introduce offset velocities, and speckle noise is mitigated using a detection-reconstruction algorithm; in a field test in the USA at speeds up to 32 km/h, the system effectively detects an artificially weakened track segment.

2) Vibration measurement under dynamic loads

Beyond measuring quasi-static deflections, vehicle-mounted LDVs have emerged as a promising tool for capturing broadband vibrations excited by dynamic vehicle loads, as illustrated in Fig. 8 (a). Delft University of Technology (TU Delft) has pioneered this research since the early 2010s [97], with substantial efforts in developing denoising algorithms to mitigate speckle noise [42,47,51,53]. The vehicle-mounted LDV setup has been implemented on a vehicle-track test rig, which consists of a rotating platform with vehicles running along a circular track, as shown in Fig. 4 (a). The measurement system integrates a Polytec RSV-150 LDV with a steering mirror. During operation, the LDV measures track vibrations excited by the moving vehicle, and accelerometers are mounted on the laser head and mirror for vibration compensation. Previous studies have successfully measured vibrations of the rail [51,53], sleepers, and track slabs [42,98] at speeds up to 20 km/h; the denoising and compensation algorithms have been validated by comparing the processed LDV signals with synchronized accelerometer measurements on the corresponding track components.

Field implementation of train-mounted LDV emerged in the early 2020s through parallel efforts by the University of Texas at Austin (UT Austin) and TU Delft:

- UT Austin conducted field tests first on a test line in the USA. In [100], a Polytec OFV-505 LDV is mounted on the bogie of a wagon to measure rail vibrations, and an accelerometer is mounted on the laser head for vibration compensation and sleeper passage

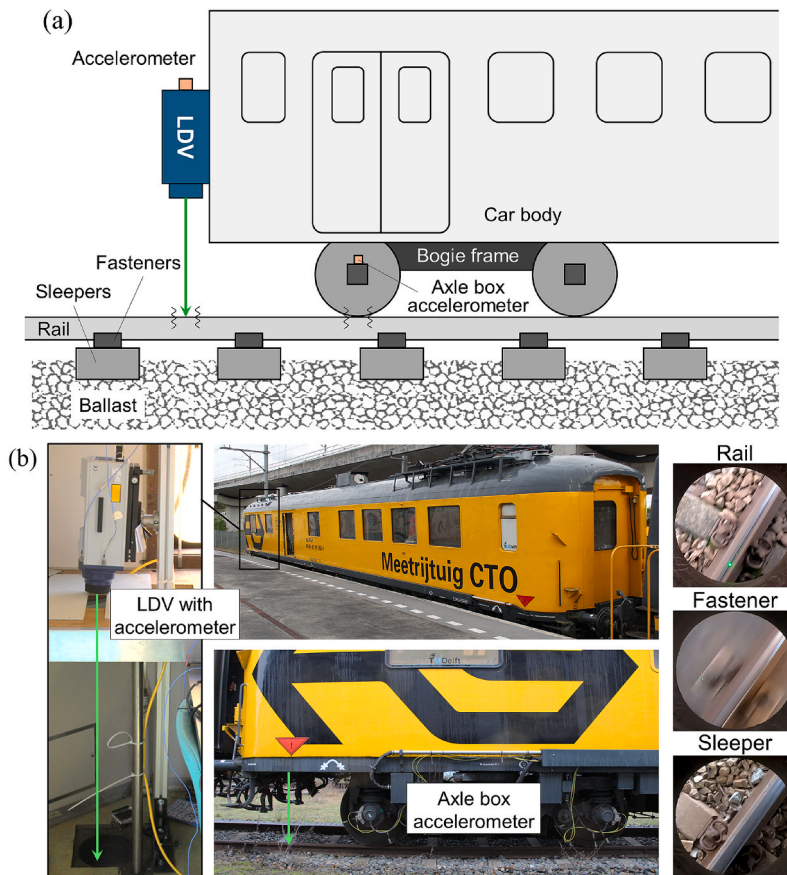


Fig. 8. (a) Illustration of a train-mounted LDV system for measuring railway track vibrations. (b) The system developed by TU Delft based on a measurement wagon [45,99].

identification; with speckle noise mitigated by a tracking filter, the frequencies of the first three rail bending modes are identified at speeds of 8–45 km/h. Subsequent tests in [101] employ two LDVs (Polytec VibroFlex Xtra and MLV100 Xtra) on one end of a wagon with a separation of 40 cm; vibration isolators are used to mitigate the laser head vibrations, and an impulsive noise filter is developed to mitigate speckle noise; the system effectively detects a rail weld at 16–48 km/h. The same setup was later shown to be effective for detecting missing rail fasteners through analysis of measured rail vibrations [102] and has more recently been adapted for field tests on an operational track at speeds up to 32 km/h to detect anomalies in rails, such as welds [103].

- TU Delft conducted field tests on operational railway lines in the Netherlands [45]. As shown in Fig. 8 (b), the setup incorporates a Polytec RSV-150, accelerometers on the laser head, and a video camera recording the laser spot trajectory. With the denoising and compensation algorithms applied, this setup measures sleeper vibrations at speeds up to 60 km/h and rail fastener vibrations at speeds up to 75 km/h [45,99,104]. Considering the nonstationary nature of dynamic vehicle loads and track vibrations, TU Delft has further integrated accelerometers on vehicle components with the train-borne LDV to achieve synchronized measurements of train-track vibrations. A signal fusion method was developed to detect surface and support anomalies in railway tracks [99]. Furthermore, a method for estimating transfer functions of track structures was proposed to characterize the dynamic load-response relationship by normalizing track responses measured by the LDV with the dynamic vehicle load estimated from vehicle accelerations. This method enables traditional impact modal testing, which can only be conducted locally, to be conducted continuously along railway tracks under operational conditions [98,105].

The use of vehicle-mounted LDV for bridge monitoring under dynamic vehicle loads has also been explored [106]. This simulation study employs accelerometers for LDV vibration compensation and differential analysis of multiple LDV signals to suppress the geometric influence of road profiles; the fundamental frequency and mode shape of the bridge are estimated from simulated signals at speeds up to 8 m/s and further used for damage detection and localization.

Beyond infrastructure monitoring, vehicle-mounted LDV has also received interest for measuring road vibrations induced by nearby, visually obscured vehicles, which is potentially useful for autonomous driving. In a preliminary field test [107], a Polytec VibroFlex QTec is mounted on a stationary car to measure the road vibration induced by passing traffic; this LDV is selected for measuring rough road surfaces due to its signal diversity technique.

3) Vibration measurement with additional excitations

In contrast to the above applications of vehicle-mounted LDVs, which measure structural responses to vehicle-induced loads, another line of research focuses on measuring structural vibrations excited by additional sources. This approach enables controlled excitation amplitude and frequency, potentially improving signal quality and simplifying data interpretation.

Research into vehicle-mounted LDV systems for ground vibration measurement and buried object detection dates back to the 1980s [108]. These systems typically employ loudspeakers or mechanical shakers to excite ground vibrations with random noise or single-frequency tones; buried objects, such as landmines, are detected and localized based on features of ground surface vibrations. Early implementations utilized fixed-point and discrete-scanning LDV setups on stationary vehicles, with mechanical isolation between the LDV and excitation source [108,109]. Another work introduced a continuous-scanning LDV setup, along with time–frequency coherence analysis to mitigate speckle noise [110]. In 2002, MetroLaser developed a 16-point LDV for landmine detection, tested in both discrete and continuous scanning modes, and speckle noise limited the continuous scanning speed to 100 cm/s [50,111]. Subsequent developments led to the 31-point system [61] and the 16×16 -point system [62] mentioned in Section 3.4. However, all these

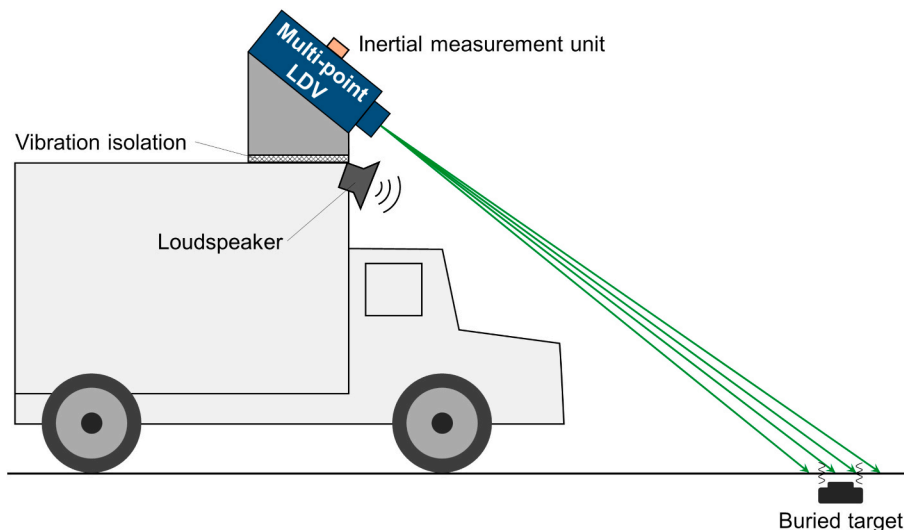


Fig. 9. Illustration of a multi-point LDV system for buried object detection.

systems require vehicles to remain stationary during data acquisition, thereby limiting survey efficiency.

As research progressed toward moving vehicles, a prototype using two Polytec PDV100 LDVs was developed in the USA in 2002, achieving speeds up to 11.25 cm/s in laboratory tests [112]; this prototype combines time- and frequency-domain filters to mitigate speckle noise and laser head vibrations. Follow-up testing at higher speeds (~100 cm/s) confirmed speckle noise as the primary limitation on further speed increases [113]. In the same year, a prototype with 5 MetroLaser 300 LDVs was tested outdoors at speeds up to 8 cm/s, featuring mechanical laser head vibration isolation [114]. This system was later upgraded to include 16 LDVs with reduced beam spacing and a higher excitation frequency [115].

Fig. 9 illustrates such a vehicle-mounted LDV system for buried object detection. Further developments have achieved higher operating speeds:

- In 2010, an LDV system optimized for moving vehicles was developed by MIT [29], which incorporates a 5-point array with large (7 mm) spot diameters to reduce speckle noise; one beam serves as a reference for common-mode disturbance cancellation, and accelerometers are used for laser head vibration compensation; a real-time tracking technique enables large incidence angles and stand-off distances (e.g., 10 m ahead of the vehicle); the system was tested on a dirt road at speeds up to 200 cm/s.
- In 2012, MetroLaser adapted its stationary multi-point LDV system for use on a moving vehicle at 110 cm/s [116]; the 16 laser beams are aligned along the travel direction, sequentially measuring a region to ensure adequate signal lengths; a denoising algorithm from [50] is used to mitigate speckle noise, and low-frequency components, including the LDV vibrations, are filtered out.
- In 2019, an applied landmine detection system was reported in [117]; this system employs 60 photodetectors, each resolving backscattered light from 16 different positions with wavelength multiplexing, so vibrations at 960 positions can be measured simultaneously; this system employs an IMU for laser head vibration compensation and supports stand-off distances up to 35 m; during operation at speeds of 100–150 cm/s, the laser points scan ground surfaces in 0.5 m × 1 m grids, with a dwell time of 200 ms per grid.

Differential LDVs have also been employed in such applications, leveraging their capability to cancel common-mode vibrations and disturbances. In 2018, the multi-point differential LDV described in [73] was tested for measuring relative vibration profiles across a 30-point array, achieving a 10 m stand-off distance and vehicle speeds up to 380 cm/s; to mitigate speckle noise on sandy surfaces, the laser beams were defocused to enlarge the spot size. This system was upgraded in 2022 by integrating a line-scan CMOS camera as a multichannel photodetector [118] and further expanded in 2023 to a matrix of 34 × 23 beams [119].

Beyond military applications, vehicle-mounted LDVs with external excitations have also been explored for civil and geotechnical purposes. In [120], a Polytec RSV-150 is mounted on a minivan to measure seismic waves on road surfaces generated by a thumper truck, with the goal of analyzing subsurface composition; the laser head is stabilized with an electrodynamic isolation table, with a geophone measuring the laser head vibration, and the steering mirror is damped with foam; the system measures multiple positions sequentially under rainy and windy weather conditions, with validation performed against traditional geophone measurements. In [121], a Polytec MLV-I-120 is mounted on a moving cart to measure acoustic waves on a concrete specimen excited by a loudspeaker for defect detection; at the scanning speed of 26 cm/s, speckle noise is mitigated using a median filter, and the stationary laser head vibration is removed by subtracting the LDV signal measured on undamaged parts of the specimen.

4.2. LDVom on robots

The combination of LDV with robots is a natural extension of its use on stationary frames, such as tripods. A 3D discrete-scanning LDV system mounted on a robotic arm has been applied in industry, especially for vibration and modal testing of automotive body structures [122]. Similarly, a discrete-scanning LDV mounted on an industrial lifter has been reported for measuring a building [123], and a robotic arm-mounted LDV has been integrated into a mobile platform for automated diagnostics of household appliances during large-scale life testing [124]. In [125–128], an LDV is mounted on a robotic arm to perform 1D or 3D modal testing, similar to discrete-scanning or continuous-scanning LDV but without optical scanners.

In addition to structural vibration measurements, LDV has also been explored on robots for measuring ultrasonic waves in non-destructive testing and inspection. In [129], an LDV is mounted on a robotic arm to measure the torsional guided waves in a pipe at multiple locations for defect detection; the guided wave is generated using a magnetostrictive sensor operating at 70 kHz; the focal point and beam direction are controlled by the robotic arm. In [130], a Polytec OFV-505 is mounted on a translating robot to measure discrete positions on a concrete slab and capture surface waves generated by a piezoelectric source at the central frequency of 110 kHz; the recorded signals are used to derive dispersion curves for estimating modulus and moisture content. In [131], an LDV is mounted on a robotic arm to scan a grid of points on a non-planar composite structure and measure bulk waves excited by a Q-switched laser; the robotic arm controls the stand-off distance and incidence angle, and the result shows effective detection of subsurface defects. A similar inspection system was developed in [132], where an LDV remained stationary while the specimen is manipulated by a robotic arm. In [133], a Polytec OFV-505 is mounted on a translational stage to measure discrete positions on an aluminum plate excited by a piezo shaker; the measurement is used to reconstruct the Lamb wavefield, further supporting damage detection.

In general, these systems leverage the mobility of robots to achieve efficient and flexible measurements on structures with large dimensions or complex geometries. Since measurements are typically conducted with precise and stable robotic control, disturbances from laser head vibration and speckle noise are usually insignificant. A more challenging scenario arises when an LDV is handheld rather than using a robotic arm, where laser head vibration, position errors, and speckle noise become significantly more pronounced [134].

4.3. LDVom on drones

The rapid advancement of drone technologies has enabled new LDVom applications. Existing research on drone-mounted LDV has revealed both its potential and its limitations. In 2018, an indoor test of a hovering drone carrying a Polytec PDV-100 LDV identified the control and stability of laser spot position as major challenges [135]. Utilizing also a hovering drone, another study conducted indoor and outdoor tests with a Polytec OFV-534, incorporating drone motion compensation using accelerometers and low-pass filtering [136,137]. The objective of this research is to measure transverse bridge vibrations under train passage, as illustrated in Fig. 10 (a). While successful in measuring dynamic displacements, the study also identified challenges related to target tracking, cabling, and payload constraints. In 2024, a lightweight LDV of OmniSensing MV-H100 is utilized on a drone to measure glass curtain wall responses during impact modal testing [138]; the laboratory test investigated the influence of stand-off distance, ambient noise, and wind conditions, revealing that strong wind and long distances degrade measurement quality.

To address cabling and payload constraints, an innovative concept, known as the flyable mirror, was proposed by German Aerospace Center [139]. In this configuration, only a steering mirror is carried by a drone while an LDV system remains on the ground, as shown in Fig. 10 (b); the laser beam is directed onto target positions through synergistic control of the LDV and the drone. An outdoor test using a Polytec VibroFlex Qtec confirmed its feasibility but also revealed challenges, including the drone vibration, atmospheric disturbance, target tracking stability, and incidence angle variations [140]. Fig. 10 (c) presents an outdoor test of such a flyable mirror system at Technical University of Clausthal (TU Clausthal).

To better compensate for the drone vibration and atmospheric disturbance, differential LDV has been incorporated into the flyable mirror system. In [141], the measurement beam of a differential LDV is directed onto the target position through a flyable mirror, while the reference beam is directed onto a retro-reflector on the drone; the interference of the two beams inherently cancels common-mode disturbances, including the drone vibration and atmospheric disturbance between the LDV and the flyable mirror. In this project, real-time kinematic (RTK) GPS technology is employed to enhance the hovering stability and measure the yaw angle of the drone [23]. Another setup involving a differential LDV is introduced in [142], where the reference beam targets a non-vibrating retro-reflector near the target, improving the compensation of disturbances between the mirror and target; indoor and outdoor tests demonstrate the superiority of the differential LDV over conventional accelerometer-based compensation; however, access to a non-vibrating object near the vibrating target may not be feasible in practical scenarios.

Along with drone vibrations, hovering stability has been identified as a critical challenge by a recent review of drone-mounted LDV systems [23]. Positioning errors directly affect measurement accuracy and spatial consistency. Wind disturbances are particularly critical for flyable mirror systems, as they may disrupt the optical path if the mirror deviates from the laser beam [143]. Modern drones

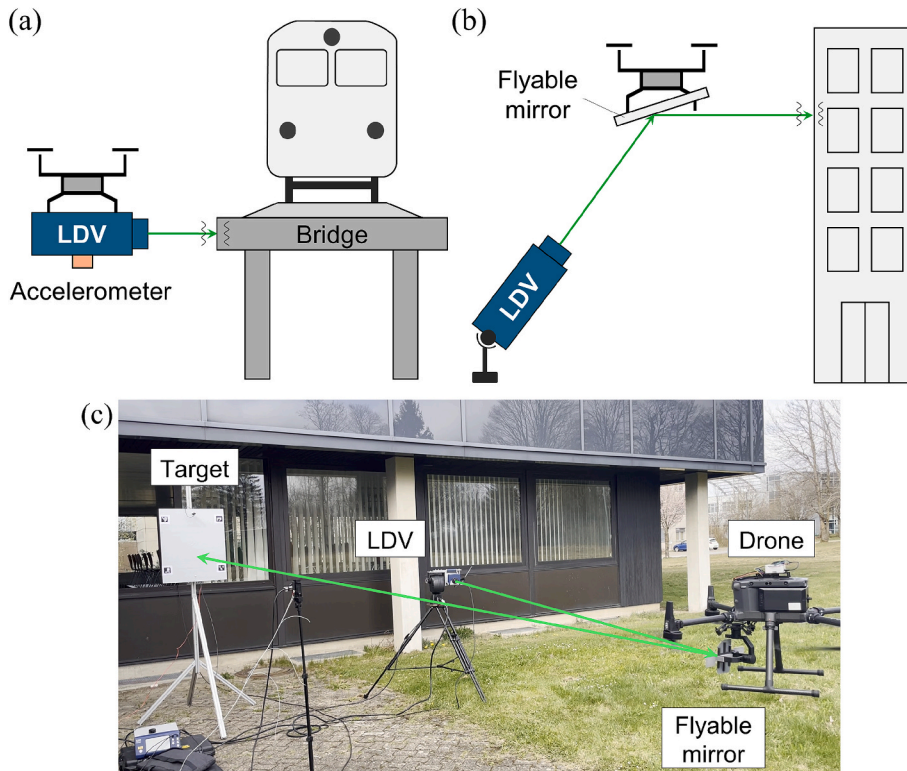


Fig. 10. (a) Illustration of a drone-mounted LDV system for measuring bridge vibration. (b) Illustration of a flyable mirror system for measuring building vibration. (c) The flyable mirror system developed and tested at TU Clausthal.

can maintain position automatically using onboard control systems. IMUs are widely used for drone motion stabilization, but may result in positioning errors on the order of hundred millimeters due to drift accumulation [23]. Advanced positioning technologies such as RTK GPS can significantly improve stability, reducing hovering errors to the order of tens of millimeters [23,143].

4.4. LDVom on aircraft or spacecraft

The use of LDVs on aircraft or spacecraft is an emerging area with relatively limited reported implementations. In the project AeroQGrav (Absolute Aero Quantum Gravimetry) in Germany, a six-channel laser Doppler sensor is being developed for deployment on an aircraft to measure the vertical motion of the aircraft relative to the ground; this serves to compensate for kinematic disturbances in a quantum flight gravimeter, enabling large-scale gravity field measurements from the aircraft. The design of an airborne scanning system for landmine detection is discussed in [144]; a high-power pulsed laser mounted on an aircraft excites ground seismic waves, and an LDV mounted on a towed pod measures the resulting surface waves; the system also integrates LiDAR (Light Detection and Ranging) for terrain profiling and employs adaptive optics with fast scanning mirrors for laser head vibration compensation.

In 2019, the concept of orbital LDV seismology was studied through theoretical analysis and simulations [145], which envisions three LDVs mounted on separate spacecraft in polar orbits around a spinning asteroid or comet; 3D surface vibrations are measured and reconstructed at multiple locations across the target object, enabling remote imaging of the mechanical interior of small celestial bodies. The vacuum space environment offers distinct advantages for LDV operation, including the absence of spacecraft vibration and optical turbulence and the possibility of using high-power lasers. Nevertheless, speckle noise is still a major challenge [145,146]. In [146], simulations are performed to examine noise properties assuming a stand-off distance of 2 km, a laser diameter of 2.5 cm, and an orbital speed of 5 cm/s; this study evaluates the signal diversity technique with different numbers of detector channels for noise reduction, and also discusses an alternative approach that involves controlling the spacecraft to track a fixed point during measurement.

Although no experimental demonstration of aircraft- or spacecraft-mounted LDV has been reported, primarily due to its technical complexity and high costs, the concepts nevertheless remain of interest for the aforementioned and emerging applications.

4.5. LDV for moving targets

Instead of moving an LDV instrument relative to a target structure, there are also applications in which a stationary LDV is used to measure moving target structures. Although these applications do not directly fall under the definition of LDVom in terms of the LDV setup, they do share several fundamental challenges, since the underlying physics of the Doppler shift and speckle effect depend on the relative motion between the sensor and the target, regardless of which is moving (under the non-relativistic assumption). For this reason, they are included in this paper to provide a comprehensive discussion of related measurement scenarios and their shared challenges. In [147,148], discrete- and continuous-scanning LDV measurements are performed on translating belts for condition

Table 4
Key features of existing LDVom applications.

Application	Moving platform	Excitation	Target variable	Analysis bandwidth	Max. speed	Stand-off distance	Key challenges	Development stage
Road inspection (Section 4.1)	Road vehicle	Quasi-static vehicle load	Deflection slope	Up to 20 Hz	70–90 km/h	~1 m	Dynamic loading, non-ideal road surface	Commercialized
Railway monitoring (Section 4.1)	Rail vehicle	Dynamic vehicle load	Broadband vibration	Up to several kHz	60–75 km/h	~2 m	Speckle noise, non-stationary and unknown excitation	Field tests
Buried object detection (Section 4.1)	Specialized road vehicle	Loudspeaker	Narrowband vibration	<1 kHz	~380 cm/s	Up to 35 m	Speckle noise, large stand-off distance	Commercialized
Modal testing (Section 4.2)	Robotic system	Shaker	Broadband vibration	Up to a few kHz	0 (stationary)	<1 m	None	Commercialized
Wave analysis (Section 4.2)	Robotic system	Piezoelectric actuator or laser ultrasonics	Ultrasonic waves	Tens to hundreds of kHz	0 (stationary)	<1 m	Small vibration amplitude	Laboratory tests
Remote sensing (Section 4.3)	Drone	Operational or ambient loads	Low-frequency vibration	<200 Hz	~0 (hovering)	Several meters	Drone stability and motion	Laboratory outdoor tests
Seismology of asteroid/comet (Section 4.4)	Spacecraft	Natural or artificial sources	Seismic waves	<200 Hz	5 cm/s	~2 km	Ultra-long stand-off, speckle noise, high test cost	Simulations

monitoring, in which the belt translation introduces additional velocity components and speckle noise in the LDV signals.

Over the past decade, LDV has been employed for remote target recognition and classification. In vehicle identification studies [149,150], an LDV is used to measure a slowly moving vehicle at ~ 1.2 m/s, where the use of reflective tape is necessary to achieve acceptable signal quality; these studies also identify challenges from short measurement durations and the need for rapid focusing. In 2018, an LDV was used to measure hovering drones for identification and payload estimation [151], which identifies challenges in target tracking at long distances. A recent study used an LDV to measure the vibration of hovering drones for offboard propeller fault detection; an indoor experiment with artificial faults and minimal wind influence was conducted [152].

The use of stationary LDVs to measure vibrations of rotating structures represents one of the earliest explorations involving moving targets, with measurements on rotating turbine blades dating back more than 50 years [153–156]. These studies typically employed two configurations: 1) aligning the laser beam parallel to the rotation axis to capture blade vibrations orthogonal to rotational speed, and 2) aligning the laser beam perpendicular to the rotation axis to capture blade vibrations along the rotational speed direction. While characteristic frequencies of blade vibrations have been identified through experiments, key challenges, including noise and limited measurement duration per blade, have been reported. More recently, tracking LDV systems have been developed to overcome these limitations by continuously following the rotating targets, such as in [19].

LDVs have also been used to measure rotating surfaces continuously. In [157,158], a rotating milling spindle is measured by an LDV with the laser beam aligned with the radial direction, simultaneously assessing roundness and vibration characteristics; the surface is polished to a high optical smoothness to avoid speckle noise and the unwanted velocity components associated with rotation; surface contamination and laser beam alignment are identified as challenges in real-field applications during milling processes. In [159,160], a rotating hard disk is measured by an LDV with a small spot size, with the laser beam perpendicular to the disk surface; the setups enable surface morphology assessment, disk oscillation measurement, and local defect detection, supporting product design and quality control. In the above applications, the quasi-periodic and speed-dependent nature of geometric features and speckle noise can assist in feature separation. Furthermore, LDVs have also been used for measuring radial and rotational vibrations of rotating structures [54,161,162], further expanding their usability.

4.6. Summary and comparison

Table 4 summarizes and compares the key features of representative LDVom applications introduced above. The robot-based systems typically perform measurements while remaining stationary and are therefore less susceptible to disturbances compared to other moving platforms. Among the truly moving platforms, vehicle-based systems exhibit the highest level of technological maturity. The TSD system for road inspection can operate at traffic speeds, but is limited to quasi-static deflection measurements. The buried object detection system operates at much lower speeds but has to deal with large stand-off distances and incidence angles. The train-borne LDV systems target broadband vibrations under operational conditions, making them particularly susceptible to speckle noise. Although the drone-based systems perform measurements in hovering conditions, they already encounter challenges related to drone vibrations and stability. The aircraft- and spacecraft-mounted LDV systems remain in early stages of development, constrained by system complexity and costs.

5. Challenges and uncertainty sources of LDVom

This section summarizes the major challenges, uncertainty sources, and limitations encountered in LDVom measurements and applications reported in the literature.

5.1. Platform-related challenges and uncertainty sources

Moving platforms enable LDVom applications but also introduce challenges that significantly affect measurement performance. First, laser head vibrations are a primary source of disturbance. While various compensation techniques based on additional accelerometer measurements have been developed (introduced in Section 3.5), residual noise often persists, particularly problematic when attempting to measure small-amplitude vibrations near laser head vibration frequencies [23,107,120,141]. For example, in vehicle-mounted systems where both the LDV and the excitation source are onboard, the target and laser head vibration can be excited at the same frequencies, further complicating signal analysis [114]. A compensation process involving direct subtraction can also introduce contamination, as signals from reference channels can have different noise and frequency responses [120]. The use of differential LDV for this task (introduced in Section 3.5) requires careful alignment and positioning of the reference beam [142], which can be difficult in some applications.

Additionally, platform motions introduce several other challenges for LDVom measurements:

- **Laser spot positioning:** Most vehicle-mounted systems typically pre-determine laser spot positions and passively scan target structures following the moving vehicle, while exceptions exist, such as the real-time tracking configuration in a landmine detection vehicle [117]. While passive scanning simplifies implementation, it risks missing target objects, particularly small ones like rail fasteners [104]. Drone-mounted systems typically require real-time control of laser spot positions in the presence of drone motion and turbulence [23,136,137,139]. Multi-point LDVs (introduced in Section 3.4) can increase the chances of capturing desired positions, though their performance per channel is generally lower than using a single-point LDV and simultaneous handling of multiple beams adds complexity [112].

- **Incidence angle variation:** Most LDVom applications focus on out-of-plane vibrations, but a non-zero incidence angle between the laser beam and surface normal is often unavoidable. Such deviations not only lead to amplitude errors in measuring out-of-plane vibrations [11,139,141] but also introduce additional components from the in-plane motions, potentially leading to range overloading. Therefore, it is sometimes necessary to measure and control the incidence angle as well as to compensate for the resulting speed component. A typical example is the calibration of incidence angles in TSD systems, but calibration processes can be inefficient and largely manual [85].
- **Stand-off distance variation:** As the platform moves, the stand-off distance between the front lens and the laser spot may change, which is more problematic for LDV systems with limited depth of focus or with He-Ne lasers [2,10,11,27]. To address this issue, some systems employ stand-off distance control, such as the servo control system in TSD, which dynamically adjusts the laser head height and maintains laser focus [75,76,84], or employ auto-focus (introduced in Section 3.1).

Another challenge arises when a moving platform also serves as the excitation source, such as the quasi-static vehicle loading in TSD systems and the dynamic vehicle loading in train-borne LDV systems. In the former case, unwanted dynamic loads can disturb quasi-static measurements, necessitating careful speed control and instrumentation to measure dynamic loads [85,163]. In the latter case, the dynamic vehicle loads are typically unknown and nonstationary. Accurately estimating or measuring these loads remains a major challenge for properly normalizing measured vibration responses [98,105]. In addition, the variation of the platform moving speed can affect the level of speckle noise and laser head vibration, as well as the dynamic load that generates the structural response. A typical example is the speed dependency of a train-borne LDV revealed in [45]. In these cases, measuring or estimating the platform speed, for example, using GPS or tachometers, is therefore necessary [99].

5.2. Target-related challenges and uncertainty sources

Target surface characteristics strongly influence the quality and reliability of LDVom measurements. For optically smooth surfaces, specular reflection necessitates near-orthogonal LDV alignment to capture reflected light [79,84]. Rough surfaces allow for greater alignment flexibility, though backscattering is typically strongest near orthogonal incidence [1,145]. Therefore, applications requiring large incidence angles, such as landmine detection [29,117], have to contend with reduced signal strengths due to large incidence angles.

Measurements on rough surfaces also introduce speckle noise and signal drop-outs, especially when measuring very rough or low-reflectivity surfaces, such as gravel, dark, and rusted surfaces [17,28,79,83,107,137,145] or at high in-plane scanning speeds [42,45,52]. An LDV mounted on a train traveling at 20 m/s can experience a full speckle translation approximately every 2 μ s, generating highly transient noise components. In these scenarios, post-processing denoising is typically required, but existing specialized algorithms (introduced in Section 3.2) were developed for specific applications, lacking a benchmark development and analysis. Though these algorithms are adaptable, their performance may vary for different cases, and they remain computationally demanding and require careful parameter tuning. Signal diversity (introduced in Section 3.3) is an effective tool for mitigating speckle noise, though LDV systems with signal diversity are more complex and expensive. Their performance depends on the specific design and implementation of the diversity technique. Commercial systems are often designed for real-time operation, which may compromise signal quality improvement, and their performance in challenging LDVom scenarios remains to be evaluated.

Additionally, scanning curved structures or surfaces with spatially varying geometry can introduce additional components into LDV signals [30,106,154,164]. Most LDVom applications target surfaces that are relatively flat or exhibit geometric wavelengths longer than the structural behaviors of interest, so geometric influences are usually insignificant. However, for structures with more complex geometries, these influences can become significant and must be accounted for to isolate structural vibrations. One such solution is included in the vehicle-mounted LDV system for bridge monitoring, where the influence of road profiles is removed through differential analysis of signals from multiple LDVs [106].

5.3. Environment-related challenges and uncertainty sources

Environmental factors can attenuate signal strengths and elevate noise levels of LDVom measurements, particularly at long stand-off distances and under harsh operating conditions. A major contributor is refractive index fluctuation caused by temperature and pressure variations along the beam path, which leads to optical turbulence and phase noise [72]. Other atmospheric disturbances, including light absorption, refraction, and scattering caused by gas, dust, and liquid particles, may also occur [11,165], although their influence is usually insignificant except in extreme scenarios [23]. These effects accumulate with increasing stand-off distances, further exacerbating signal degradation [26]. Meanwhile, rain, fog, smoke, and airborne particulates can also distort the laser beam. For instance, dust generated by passing trains has been reported to possibly disrupt LDV signals [136], while wet road surfaces have caused unsuccessful TSD measurements [84]. In addition, backscattering from unwanted objects, such as birds, insects, and vegetation [165], can generate spurious signals in LDVom measurements.

5.4. Operation-related challenges and uncertainty sources

Challenges also arise in the practical deployment and operation of LDVom systems:

- Integrating LDV systems on a moving platform may face critical constraints concerning the size, weight, power supply, cabling, and ingress protection of both the LDV and auxiliary instruments, such as reference sensors and data acquisition and storage units. Most commercial LDV systems employ heterodyne configurations with bulk optics, resulting in relatively large size and weight, which can limit deployment flexibility, particularly for drone-mounted applications [137].
- Achieving optimal LDV performance usually requires careful parameter setting by experienced operators [11], with adjustments often needed for different measurement conditions. Long-term operation may also introduce slow performance variations due to thermal expansion and electronic drift [33,120]. Many existing LDVom systems lack automated mechanisms to maintain consistent performance during continuous operation, leading to data quality issues. For example, in TSD applications, data segments that do not meet quality thresholds are discarded [79], resulting in gaps in continuous inspection.
- Synchronization between LDVom signals and auxiliary data, such as the laser spot position and laser head vibration, is essential for signal processing and data analysis [99]. When signals are acquired using a single data acquisition system at the same sampling rate, synchronization is generally reliable, aside from minor time delays between channels. However, synchronization becomes more challenging when combining data from different acquisition systems with different sampling rates and time bases, such as synchronizing an LDV signal sampled at tens of kHz with GPS data sampled at a few Hz [99].
- LDVom systems often generate large volumes of high-frequency data (from tens of kHz to several MHz), especially in long-duration or large-scale measurements. This leads to high storage and computational demands. In addition, the data are often affected by noise, spatiotemporal variability, nonstationarity, and sometimes unknown excitations. These challenges become more pronounced at higher scanning speeds, where shorter signal durations reduce achievable resolution [98,104]. Some applications require real-time or near-real-time processing capabilities. As a result, conventional analysis methods may become inefficient or unreliable in practical applications.
- Laser safety considerations, particularly regarding eye and skin exposure, may limit the permissible laser power, thus constraining achievable signal strength or necessitating additional safety measures [1,2,137]. While infrared lasers (introduced in Section 3.1) can often operate within Class 1 limits while maintaining good performance, auxiliary visible lasers are sometimes required for beam alignment or targeting.

These operational challenges further compound the platform-, target-, and environment-related factors discussed above, jointly causing a variety of disturbances and uncertainties in LDVom measurements [2,163]. These disturbances manifest as measurement noise and errors that deteriorate the traceability of LDV, compared to being used as a metrology tool [166]. These uncertainties propagate through the data analysis pipeline, leading to uncertainties in the final assessment and identification results. In this process, different uncertainties can accumulate and interact, sometimes amplifying errors, particularly in inverse analyses.

Quantifying and mitigating these uncertainties is therefore essential to ensure the reliability and practical utility of LDVom systems. While general uncertainty quantification methods are well established [167–169], their application to LDVom requires models tailored to the dominant sources and propagation mechanisms specific to each application case. A practical implementation pathway for uncertainty budgeting in LDVom applications includes: 1) identifying and probabilistically characterizing dominant uncertainty sources, including residual errors after mitigation or compensation; 2) integrating and propagating these uncertainties through the application-specific pipeline, such as forward and/or inverse analysis, using techniques such as Monte Carlo simulation or Bayesian inference; 3) interpreting the results to support decision-making. Depending on the application, this process can be conducted offline to assess the reliability of a given measurement and analysis, or embedded directly into the data analysis pipeline to enable uncertainty-aware detection and identification.

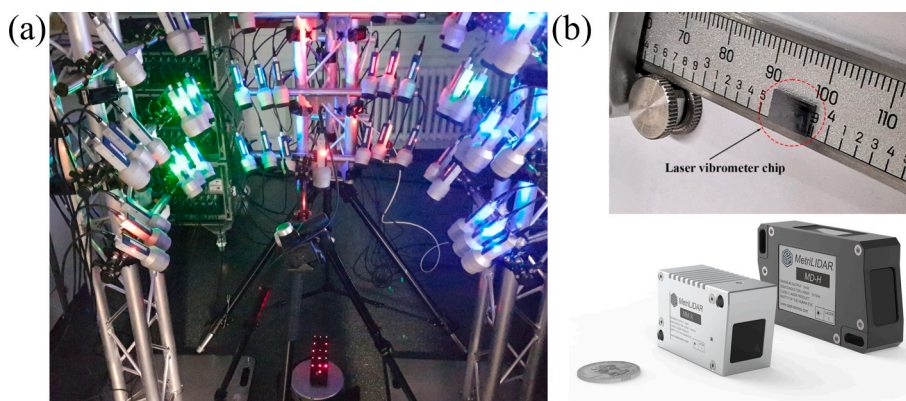


Fig. 11. Miniaturization of LDV. (a) The Polytec multi-point LDV with fiber probes. (b) The on-chip LDV of OmniSensing (figure from [171] under CC BY 4.0 license).

6. Future opportunities of LDVom

Based on the challenges discussed above, this section further introduces and discusses advancements in LDV and relevant technologies that can potentially enhance the capability, performance, and robustness of LDVom systems.

6.1. Miniaturized LDV

A variety of research and development efforts have been made to miniaturize LDV systems.

1) Fiber Optics-based LDV

Fiber optics has advanced LDV design and miniaturization through various implementations. The most commercially mature approach utilizes an optical fiber connection to decouple a front lens from the main laser head, forming a compact and flexible measurement probe. This design improves accessibility in confined spaces and enhances robustness by allowing the laser head to remain protected in a controlled environment [1,170]. However, movement of the fiber cables can alter the optical path length and introduce disturbances into the LDV signals, which must be carefully managed in practical applications. Representative products include the VibroFlex Fiber single-point/differential LDV and MPV-800 multi-point LDV of Polytec, as well as the multi-point LDV of Optomet. The MPV system, shown in Fig. 11 (a), also offers configurable fiber probes capable of operating in either active (transmit/receive) or passive (receive-only) modes [7,58].

More integrated LDV designs incorporate fiber optics directly into their interferometers, leveraging their compactness and flexibility. Examples include several multi-point LDVs introduced in Section 3.4 [62,64,65], among which the system in [65] was later modified to include 4 fiber probes [172] and subsequently expanded to 16 fiber probes [173], which was later commercialized by HoloBright. Earlier developments include fiber-based homodyne LDVs (single- and two-point) demonstrated up to 800 Hz [174], as well as heterodyne configurations based on wavelength division multiplexing [175]. Moreover, fully fiber-based single-point LDVs have been developed, as reported in [9,176].

A key distinction exists between traditional multi-point LDVs and fiber-probe systems. The multi-point LDVs introduced in Section 3.4 typically generate a fixed array or matrix of laser beams with predefined spatial or angular separations. In contrast, fiber-probe systems allow independent positioning of each laser point, offering greater flexibility.

2) On-chip LDV

Waveguide-based photonic integrated circuit (PIC) technology has opened new frontiers in LDV miniaturization. While heterodyne configurations have been explored for on-chip implementations [177,178], homodyne configurations have become more favorable due to their simplicity [179]. However, this comes with trade-offs in performance, as homodyne configurations are more susceptible to nonlinearity and electrical noise [2,179]. In 2013, Ghent University developed an on-chip homodyne LDV with a footprint of less than 1 mm², which was tested with a vibration of 30 Hz [180]. In 2016, an on-chip interferometer was developed and tested with a mirror vibrating at 15 Hz [181]. In 2024, OmniSensing introduced an LDV featuring a 7 mm × 5 mm chip within a compact system measuring 58 mm × 34 mm × 22 mm, as shown in Fig. 11 (b); this LDV achieves stand-off distances up to 100 m and velocity range up to 20 m/s; experimental validation was performed on various surfaces using sinusoidal vibrations at frequencies ranging from 0.1 Hz to 1 MHz [171].

Beyond single-point implementations, on-chip multi-point LDV systems have been developed to overcome the size, complexity, and robustness limitations of conventional bulk-optical designs. In [182], two single-point on-chip homodyne LDVs from [180] are integrated into an arterial pulse wave velocity measurement system. In 2018, a six-beam homodyne LDV with a footprint of 2.5 mm × 5 mm was developed, successfully measuring elastic waves in an aluminum plate at 61.5 kHz [183]. In 2024, an on-chip multi-beam frequency shifter was introduced to further reduce electrical connections in multi-point LDV systems [184].

3) Self-mixing LDV

Self-mixing LDV represents one of the more compact LDV configurations, which directly mixes the emitted and the backscattered light within a laser diode cavity, eliminating the need for a reference beam [1]. This inherent simplicity offers several advantages, including self-alignment, low cost, high sensitivity, and broad frequency bandwidth [1]. A wide range of developments has been reported over the past few decades. For example, in [185], a self-mixing LDV prototype capable of measuring vibrations on rough surfaces at 70 kHz was reported. In 2006, two such self-mixing LDVs were integrated to create a differential LDV system [186]. In 2016, a digital control loop was integrated in a self-mixing LDV to reduce interferometric signal distortion and improve accuracy [187]. More recent advances include a balanced detection configuration to enhance SNR [188], a prototype for long stand-off measurements (tested at up to 12 m) [189], a prototype for sub-micron displacement sensing with the aid of retro-reflective targets [190], a multi-point system capable of measuring an array of 8 points [191], among others. However, the limited dynamic intensity range for the received light, the lack of a defined reference arm, and the inherent nonlinearity and complexity of the self-mixing effect introduce significant challenges for self-mixing LDV to achieve high accuracy and robustness [179]. Self-mixing LDVs are also susceptible to speckle effect, and various mitigation techniques have been explored, including the adjustment of laser spot position [185], signal tracking [192], adaptive optics [193], and spot diversity [193]. Laser head vibration compensation has also been investigated using

the differential configuration [186] and an embedded accelerometer [194,195].

A more detailed review of on-chip and self-mixing LDV can be found in [179,192,196]. In general, the performance of current on-chip and self-mixing LDVs is still not as good as that of conventional bulk-optical systems, partly due to limitations imposed by laser source phase noise [179]. Users have to balance the benefits of miniaturization against potential compromises in measurement accuracy. Although conventional heterodyne LDV with signal diversity is generally better suited for challenging LDVom scenarios, the reduced size and weight of miniaturized LDVs also offer distinct advantages in less demanding applications. Continued advancements are expected to further enhance their performance and broaden their range of applications in the future.

6.2. Holographic LDV

Traditional LDVs require mechanical elements, such as adjustable mounting platforms and steering mirrors, to direct laser beams to desired measurement positions. Alternative solutions have been explored through the incorporation of holographic technologies to enable non-mechanical beam steering and full-field vibration sensing.

In 2010, a novel discrete-scanning LDV was introduced, in which the laser beam is steered and focused using a spatial light modulator driven by computer-generated holograms [197]. In 2012, this technology was extended into a multi-point system capable of simultaneously measuring vibrations at 14 arbitrary positions using programmable holograms [198]. While these systems offer greater flexibility in selecting measurement positions, they face challenges such as unwanted diffraction orders, hologram crosstalk, and reduced light efficiency.

In 2008, a full-field LDV system was developed utilizing holographic optical elements to illuminate an entire target area [199]; a CMOS camera captured heterodyne interference patterns, from which the vibration at any arbitrary position could be demodulated using the corresponding pixel; this system successfully measured vibrations up to 100 Hz. In 2015, a digital heterodyne holography was developed to achieve full-field vibration measurements with high sensitivity [200], with experimental validation for periodic vibrations.

Despite the promising advancements of holographic LDV systems, their low frequency bandwidths and the need for calibration still limit their use for measuring high-frequency and transient vibrations, particularly in LDVom scenarios. Nevertheless, technological advancements in holographic optics and high-speed imaging are expected to broaden their practical applicability in the future.

6.3. Adaptive optics

Adaptive optics refers to optical elements capable of adaptively altering their optical properties to improve system performance. In LDV systems, they have been explored as a means of mitigating signal drop-outs caused by laser speckle. For example, spatial light modulators are integrated into LDV systems in [197,201], enabling the laser beam wavefront to be modified and held onto bright speckles, thereby increasing signal strength and reducing drop-outs. Similarly, a voltage programmable liquid lens is employed in a self-mixing LDV system in [193] to adjust the focal position and spot size, enhancing signal strength. However, due to the limited time response, the effectiveness of these approaches is better suited to slowly varying speckle patterns. An alternative was developed in [202], where adaptive photodetectors are utilized within a homodyne LDV to mitigate wavefront distortions and suppress noise.

As discussed in Section 5, optical turbulence remains a significant challenge for LDVom measurements in harsh environments, particularly in airborne or long stand-off applications. Adaptive optics has the potential to overcome these difficulties. In [203], adaptive optics, consisting of a deformable mirror, a fast steering mirror, and a wavefront sensor, is incorporated into an LDV system to estimate and compensate for wavefront distortions caused by the air–water interface when measuring underwater acoustic signals. In [204], a similar technique is applied to an airborne laser weapon system to compensate for atmospheric turbulence. Looking forward, advances in adaptive optics will potentially enhance LDVom performance under rapidly varying conditions.

6.4. Advanced signal diversity

Signal diversity is one of the most effective solutions to treat speckle noise. Though existing commercial LDV systems with signal diversity have achieved significant noise reduction, the pursuit of real-time processing may impose a trade-off that limits performance in handling rapidly varying speckle patterns due to fast in-plane motion in LDVom scenarios. Further performance improvements can be achieved through more advanced strategies. An example of such an advancement is presented in [205], which enables in-plane velocity and strain to be measured on a specimen accelerated to speeds up to 30 m/s during tensile tests. At such high in-plane motion, a full speckle translation occurs in less than 2 μ s—comparable to the speckle translation duration encountered in a train-borne LDVom. In this case, the combination of multiple diversity channels must be fast enough, so a sampling rate of 150 MHz is used, yielding 150 samples within half of a full speckle translation. This allows effective computation of optimal weights for each diversity channel using a sufficient number of samples. While such high sampling rates across multiple channels introduce challenges for real-time implementation and may lead to processing delays, they offer substantial benefits in applications where the primary objective is signal quality improvement rather than strict real-time processing.

In addition to signal processing complexity, increasing the number of diversity channels also raises optical implementation complexity. For conventional bulk optics, the number of diversity channels is limited by the number of realizable subapertures or polarization states. PIC technologies, discussed in Section 6.1 for miniaturizing LDV systems, offer a promising route to implement even more complex optical architectures within compact spaces.

6.5. In-plane, 3D, and rotational LDV

Most of the LDV systems discussed above are designed to measure out-of-plane vibrations. For applications requiring measurements of in-plane motion or tangential vibration, in-plane LDV has been developed. As shown in Fig. 12 (a), an in-plane LDV has a configuration similar to a laser Doppler velocimeter, directing two beams at a common target spot from opposing oblique angles [1,2]; the resulting interference fringes are captured by a photodetector, from which the in-plane velocity component is extracted. A single in-plane LDV can measure the tangential vibration at one target position along the plane defined by the two laser beams [206]. Using two in-plane LDVs for two nearby target positions further enables surface strain analysis. In [207], a laser Doppler strain sensor was developed, capable of directly measuring differential displacement between two points with a single sensor head. Accurate in-plane LDV measurements require careful alignment of the two laser beams to maintain their intersection on the target surface, with their centerline ideally perpendicular to the surface [1,2]. Large out-of-plane movements or vibrations can degrade signal quality. Additionally, speckle noise is a major noise source, especially under large in-plane motions, which has been effectively mitigated through polarization diversity in [56].

Most of the aforementioned LDV systems measure 1D vibration. To obtain the full velocity vector, 3D LDV systems have been developed. As shown in Fig. 12 (b), a typical 3D LDV system consists of three single-point LDVs targeting the same position from different directions, and the velocity vector is reconstructed from the LDV signals using the known beam orientations [2,8,46]. 3D scanning LDV systems, primarily implemented in discrete-scanning setups, with recent advances in continuous-scanning implementations [164], have become one of the most prominent applications of commercial LDV systems, such as the Polytec PSV series. However, such systems are associated with high cost, large size, and the complexity of alignment and calibration [11]. More compact solutions have emerged, such as the SMART 3D Fiber system of Optomet, which integrates three lenses into a single fiber head but requires a fixed stand-off distance. In [59], a 3D system using four LDVs was proposed to reduce the sensitivity to alignment errors, and the use of signal diversity is suggested to further enhance signal quality. In [208], a novel configuration was developed, in which a single laser beam is emitted and 3D vibration is captured by collecting scattered light in three directions, as shown in Fig. 12 (c); this design is well-suited for measuring small structures or scenarios where precise alignment of multiple beams is challenging.

LDV, especially 1D and 3D discrete-scanning LDV, has also become an effective tool for ultrasonic (especially Lamb wave) wavefield reconstruction on plate or shell structures, supporting NDT of metals or composites in aerospace, wind turbine, pipeline, and additive manufacturing engineering [209–212]. In these measurements, LDV is typically used to capture stationary surface wavefields at frequencies ranging from tens of kHz to a few MHz, usually excited by external sources, such as piezoelectric transducers or laser ultrasonics. The high frequencies and small amplitudes of such waves require sufficient SNR, which is usually achieved through careful setup, surface preparation, and averaging over repeated measurements [213]. A variety of wavefield imaging and analysis techniques have been developed in the time, frequency, and wavenumber domains [213,214], including recent methods based on deep learning [215,216].

In addition to translational vibrations, LDV can also measure rotational or torsional vibrations, such as those occurring in rotating shafts. A common configuration of a rotational LDV employs two interferometers measuring at two positions on a rotating or torsional surface [1,2,161], as shown in Fig. 12 (d). Such a design requires the plane defined by the two laser beams to be orthogonal to the rotational axis and the two laser beams to be symmetrical with respect to the rotational axis. In addition, factors such as backscattering intensity and speckle noise can also significantly affect signal quality [1].

These specialized LDV systems are mainly used in stationary setups, while they have the potential for deployment on moving platforms to complement LDVom systems that primarily measure 1D out-of-plane vibrations. However, they typically impose stricter requirements on the positioning and alignment of multiple laser beams and on the level of measurement noise, which remain key challenges for reliable implementation in LDVom applications.

6.6. Multi-modal sensing

Integrating LDV with other non-contact sensing technologies can potentially provide complementary information and yield more comprehensive insights into structural conditions and behaviors. Several major options are discussed in this subsection.

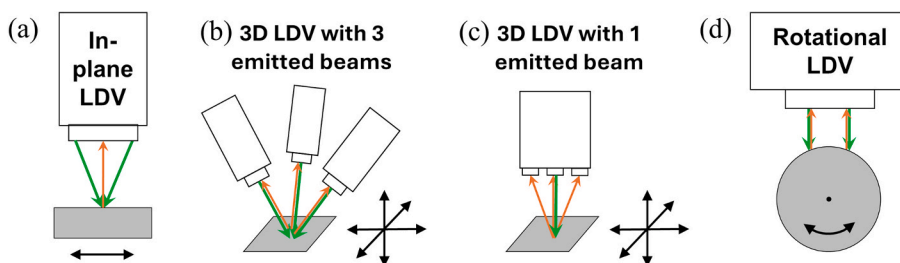


Fig. 12. Illustration of specialized LDV systems. (a) In-plane LDV. (b) 3D LDV with three emitted beams. (c) 3D LDV with a single emitted beam. (d) Rotational LDV.

1) Camera

Cameras have already been used alongside LDVs to assist with data acquisition and analysis. In many applications [19,45,121], cameras are employed to track the laser spot position, supporting data processing or enabling active steering of the laser position. Some commercial LDV systems now incorporate embedded cameras for such purposes. In [217], an infrared camera and a pan-tilt-zoom camera are combined with an LDV to support target selection and localization. In [218], dual pan-tilt-zoom cameras are used to identify reflective surfaces and to measure stand-off distances. In [131,219], 3D cameras are used to generate 3D models of target structures to guide LDV measurements across multiple target positions. In [134], a 2D camera is utilized to estimate the position and orientation of a hand-held LDV, supporting vibration field reconstruction. In [137], using cameras on a drone for the motion compensation of the drone-mounted LDV system is discussed.

Beyond visual guidance, cameras can also measure full-field vibrations. A comprehensive review of optical techniques for vibration measurement in [4] compared interferometric and imaging-based techniques and concluded that fusing LDV with cameras can potentially offer both high temporal and spatial resolutions. For example, LDVs have been used to aid Fourier Transform Profilometry and DIC, improving their precision and extending their frequency ranges [220,221]. However, integrating cameras with LDVom remains challenging, as platform motion and vibration can degrade image quality and vibration detection.

2) LiDAR

LiDAR is another promising sensing technology that can complement LDV. While conventional LiDAR is primarily used for distance measurement, it has also been explored for vibration measurement. In [222,223], ground-based (terrestrial) LiDAR systems are employed to measure bridge vibrations, where a single laser beam is controlled to scan across multiple positions in a repeating sequence; spatio-temporal processing of the dynamic point cloud data is implemented to extract the displacement time history at each position. The use of multi-beam LiDAR systems for vibration measurements has also been explored [224]. However, scanning and sampling rate limitations confine such applications to low-frequency vibrations.

LiDAR systems based on coherent detection are better suited for vibration measurements. In [225], a single-point coherent LiDAR vibrometer was developed and tested for measuring building vibrations at a stand-off distance of 150 m with a laser spot size of 12.2 cm. This system was subsequently extended to a three-point system for measuring mode shapes [226]. While these coherent LiDAR vibrometers share interferometric principles with LDV, they are designed for long-distance applications, at the cost of lower frequency bandwidth, reduced sensitivity, and higher noise levels compared to LDV [225–227].

Recent advancements in Frequency-Modulated Continuous-Wave LiDAR have opened up new possibilities for simultaneous distance and vibration measurements. For example, a solid-state single-point LiDAR system was developed in [228], which uses a crystal beam scanner to steer the laser beam across different positions and a triangular frequency sweep for extracting vibrations; however, the resolution of the system remains limited to 15 mm in distance and 19 mm/s in velocity. Another approach, presented in [229], involves a single-point LiDAR based on an external cavity diode laser, but its reliability degrades significantly at stand-off distances beyond 10 m. A notable commercial example is the on-chip multi-point LiDAR systems of Ommatidia, which offer an array of 65–128 measurement points for parallel sensing [230].

The fusion of LDV and LiDAR can be achieved in different ways. For instance, the combined use of an LDV and a LiDAR system can improve vibration measurement accuracy at a single target point, as demonstrated in [231]. Given the widespread use of LiDAR on mobile platforms, such as vehicles and drones [232,233], it can complement LDVom measurements by providing critical auxiliary data, including stand-off distances and target geometry along a scanning path. Moreover, recent developments in motion compensation for LiDAR systems on moving platforms, such as [234,235], may inform the development of similar compensation techniques in LDVom applications.

3) Microphone

As sound and vibration are inherently linked, LDVs have been used as optical microphones for remote acoustic sensing and sound recording [10]. Compared to conventional microphones, LDV has the advantages of long-distance capability, directionality, and resilience to ambient noise. A few studies have also explored the combination of LDV with conventional microphones, leveraging their complementary characteristics. In [236], an LDV is used to provide a reliable estimator of speech presence probability, thereby enhancing the accuracy of microphone-based speech recognition. In [237], an LDV is combined with a microphone to extend the bandwidth of speech acquisition. In [124], an LDV and a spiral-shaped array of microphones are combined in a mobile diagnostic system for household appliances. Such hybrid sensing systems hold significant promise for more comprehensive and informative sensing of structural dynamics, potentially unlocking new application areas.

6.7. Big data and digital twins

Advances in big data analytics and artificial intelligence (AI) provide powerful tools to process and analyze the large volumes of measurement data generated by LDVom systems. They can be applied across the data analysis pipeline, from signal processing and feature extraction to anomaly detection and decision-making.

At the signal processing and feature extraction stage, data-driven approaches have been widely explored. In [42,52], spike detection and signal reconstruction methods are built to reduce speckle noise in the LDVom signals, with a variety of other data-driven

alternatives discussed in [42]. In [104], statistical analysis and clustering are combined to process LDVom measurements on rail fasteners, and the extracted features further support the assessment of group behaviors and the detection of abnormal individuals. In [238], an unsupervised representation learning method combines empirical mode decomposition with a convolutional autoencoder to automatically extract features from LDVom signals on rail fasteners.

Data-driven approaches have also been adopted at the anomaly detection stage. In [96], an unsupervised learning algorithm analyzes low-frequency rail movement captured by the LDVom to detect artificially weakened track segments. In [150], various neural computing methods are used to identify vehicles by their engine types using remote LDV measurements over short durations. In [152], a deep extreme learning-based neural network is developed to classify the type and severity of propeller faults from vibration measurements of a hovering drone with a stationary LDV. In [103], a long short-term memory autoencoder is developed to detect anomalies on rails from LDVom measurements, including the integration of transfer learning to address speed and measurement condition variations.

As LDVom applications and AI technologies advance, the use of data-driven methods is expected to increase, enabling more intelligent and automated analysis. However, these data-driven approaches may have low interpretability and higher computational demand. An effective approach to address this is to incorporate the physics of moving platforms and/or structures, known as physics-informed methods. In [91], a theoretical model of the TSD measurement is established using the spectral element method and combined with minimization algorithms to identify the layer moduli of pavements. In [98], a multi-body vehicle dynamics model is updated using the measured vibration responses, enabling the transfer functions of the track structures to be estimated using the onboard LDVom measurement. Physics-informed neural networks have been applied for wavefield reconstruction from LDV measurements using a translational stage in [133].

Building upon these developments, the integration of measurement data with physics-based models can further evolve into an interactive framework, known as a digital twin [239–241]. LDVom measurements can provide broadband, full-field response data that enable digital twin models to be continuously updated. These updated models can track structural changes and predict structural behaviors, supporting intelligent decision-making and predictive maintenance. For example, location-specific, digital representations of transportation infrastructure can be established and updated using regular vehicle-based LDVom measurements, which can be used to assess safety, predict degradation, regulate operations, and optimize maintenance decisions. Uncertainty quantification (discussed in Section 5) can be further integrated into this framework to enable probabilistic analysis and uncertainty-aware decision-making. In the meantime, to reduce data transmission and storage costs or to meet real-time requirements in some applications, data, model, or feature reduction [242–244] and edge or fog computing [245,246] can be potentially employed, enhancing the practicality of LDVom-based digital twins.

7. Conclusions

This paper reviews LDVom technologies, leading to the following main conclusions:

- **Technological enablers:** Advances in LDV technologies, such as infrared lasers, signal diversity techniques combined with digital demodulation, specialized denoising algorithms, and laser head vibration compensation, have made LDVom measurements feasible and improved their performance. Developments in multi-point and differential LDVs have further expanded measurement capabilities.
- **Diverse applications:** Most current LDVom implementations are vehicle-mounted systems under various excitation modes, including quasi-static vehicle loading (e.g., TSD for road inspection), dynamic vehicle loading (e.g., train-borne LDV for railway monitoring), and additional excitations (e.g., landmine detection). Real-world operation at or near traffic speeds has been achieved for transportation infrastructure monitoring, highlighting substantial advantages of LDVom in coverage efficiency. Some airborne concepts and implementations based on drones, aircraft, and spacecraft are emerging but remain in early stages of development.
- **Unresolved challenges:** While many gaps have been filled to reach current implementation and application levels, many challenges still have not been fully addressed, limiting the signal quality, resolution, and reliability of LDV measurements. These challenges stem from diverse sources, including platform dynamics, target surface properties, environmental disturbances, and operational complexity, and their influence varies across different application scenarios.
- **Future opportunities:** The continued advancements in relevant technologies, particularly miniaturization, multi-dimensional and multi-quantity sensing, and digital twins, can enhance the adaptability, capability, and performance of LDVom systems. The integration of LDVom systems with complementary sensors, such as cameras and LiDAR, can further expand their application potential.

Overall, LDVom stands as a promising and evolving direction for remote, flexible, and efficient vibration sensing. With ongoing technological innovations and interdisciplinary collaboration, LDVom is expected to play a broader and more effective role in remote sensing and structural health monitoring across diverse application domains.

CRediT authorship contribution statement

Yuanchen Zeng: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Alfredo Núñez:** Writing – review & editing, Visualization, Methodology, Conceptualization. **Christian Rembe:** Writing – review & editing, Visualization, Investigation, Formal analysis, Conceptualization. **Zili Li:** Writing – review & editing,

Resources, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

Funding: This work was partly supported by the project 3D-LDV Scan from Moving Platforms, funded by ProRail and De Ministerij van Economische Zaken en Klimaat of the Netherlands [project number PPS23-3-03604895] and the project Reliable Embankments for Safe Expansion in Rail Traffic (RESET), funded by ProRail.

The authors thank the Editorial Board and the Reviewers for their valuable comments and suggestions.

Data availability

Data will be made available from the corresponding author upon reasonable request.

References

- [1] E.P. Tomasini, P. Castellini, eds., *Laser Doppler Vibrometry A Multimedia Guide to Its Features and Usage*, Springer, 2020. <https://doi.org/10.1007/978-3-662-61318-4>.
- [2] P. Chiariotti, C. Rembe, P. Castellini, M. Allen, Laser Doppler vibrometry measurements in structural dynamics, in: *Handbook of Experimental Structural Dynamics*, Springer, 2022. https://doi.org/10.1007/978-1-4614-4547-0_4.
- [3] C. Rembe, I. Bucher, B. Halkon, Y. Li, V. Mazzoni, L. Scalise, M. Schewe, Y. Zeng, *Laser-Doppler Vibrometry*, *Nat. Rev. Methods Primers* (2026) accepted.
- [4] Y. Fu, Y. Shang, W. Hu, B. Li, Q. Yu, Non-contact optical dynamic measurements at different ranges: a review, *Acta Mech. Sin.* 37 (2021) 537–553, <https://doi.org/10.1007/s10409-021-01102-1>.
- [5] J. Baqersad, P. Poozesh, C. Niezrecki, P. Avitabile, Photogrammetry and optical methods in structural dynamics – a review, *Mech. Syst. Signal Process.* 86 (2017) 17–34, <https://doi.org/10.1016/j.ymsp.2016.02.011>.
- [6] H. Kong, C. Huang, J. Yu, X. Shen, A survey of mmWave radar-based sensing in autonomous vehicles, smart homes and industry, *IEEE Commun. Surv.* Tutorials 27 (2025), <https://doi.org/10.1109/COMST.2024.3409556>.
- [7] S.J. Rothberg, M.S. Allen, P. Castellini, D. Di Maio, J.J.J. Dirckx, D.J. Ewins, B.J. Halkon, P. Muyschondt, N. Paone, T. Ryan, H. Steger, E.P. Tomasini, S. Vanlanduit, J.F. Vignola, An international review of laser Doppler vibrometry: making light work of vibration measurement, *Opt. Lasers Eng.* 99 (2017) 11–12, <https://doi.org/10.1016/j.optlaseng.2016.10.023>.
- [8] W.J. Staszewski, R. Bin Jenal, A. Klepka, M. Szewdo, T. Uhl, A review of laser Doppler vibrometry for structural health monitoring applications, *Key Eng. Mater.* 518 (2012), <https://doi.org/10.4028/www.scientific.net/KEM.518.1>.
- [9] P. Lutzmann, B. Göhler, C.A. Hill, F. van Putten, Laser vibration sensing at Fraunhofer IOSB: review and applications, *Opt. Eng.* 56 (2016), <https://doi.org/10.1117/1.oe.56.3.031215>.
- [10] R. Buchanan-Dunlop, M.J. Newton, M. Parker, Perspectives on immersion through laser Doppler vibrometry, in: *Proceedings of the Sound and Music Computing Conference, 2024, 2024.*, pp. 403–410.
- [11] P. Castellini, M. Martarelli, E.P. Tomasini, Laser Doppler Vibrometry: Development of advanced solutions answering to technology's needs, *Mech. Syst. Signal Process.* 20 (2006) 1265–1285, <https://doi.org/10.1016/j.ymsp.2005.11.015>.
- [12] Z. Qiu, T. Qu, Y. Pan, Y. Jia, Z. Fan, K. Yang, J. Yuan, H. Luo, Optical and electrical method characterizing the dynamic behavior of the fused silica cylindrical resonator, *Sensors (Switzerland)* 19 (2019), <https://doi.org/10.3390/s19132928>.
- [13] C. Rembe, G. Siegmund, H. Steger, M. Wörtge, Measuring MEMS in motion by laser doppler vibrometry, *Optical Inspection of Microsystems* (2016), <https://doi.org/10.1201/9780429186738-11>.
- [14] T. Yu, Q. Tang, S. Vinayaka, Identifying structural properties of a steel railway bridge for structural health monitoring using laser Doppler vibrometry, *Autom. Constr.* 160 (2024), <https://doi.org/10.1016/j.autcon.2024.105320>.
- [15] J. Vass, R. Šmíd, R.B. Randall, P. Sovka, C. Cristalli, B. Torcianti, Avoidance of speckle noise in laser vibrometry by the use of kurtosis ratio: Application to mechanical fault diagnostics, *Mech. Syst. Signal Process.* 22 (2008) 647–671, <https://doi.org/10.1016/j.ymsp.2007.08.008>.
- [16] M. Martarelli, *Exploiting the Laser Scanning Facility for Vibration Measurements*, University of London, 2001. Doctoral dissertation.
- [17] D. Di Maio, P. Castellini, M. Martarelli, S. Rothberg, M.S. Allen, W.D. Zhu, D.J. Ewins, Continuous Scanning Laser Vibrometry: a raison d'être and applications to vibration measurements, *Mech. Syst. Signal Process.* 156 (2021), <https://doi.org/10.1016/j.ymsp.2020.107573>.
- [18] S. Yang, D. Ehrhardt, M.S. Allen, A review of signal processing techniques for continuous-scan laser Doppler vibrometry, *Proceedings of the ASME Design Engineering Technical Conference* (2015), <https://doi.org/10.1115/DETC2014-34972>.
- [19] Y. Hu, W. Zhu, K. Yu, Y. Yang, Y. Kang, Operational modal analysis of outdoor slanted rotational blades under natural excitation using a long-range tracking continuously scanning laser Doppler vibrometer, *Opt. Laser Technol.* 181 (2025), <https://doi.org/10.1016/j.optlastec.2024.111516>.
- [20] B. Olivier, F. Guo, Y. Qian, D.P. Connolly, A review of computer vision for railways, *IEEE Trans. Intell. Transp. Syst.* 26 (2025), <https://doi.org/10.1109/TITS.2025.3552011>.
- [21] S. Yao, R. Guan, X. Huang, Z. Li, X. Sha, Y. Yue, E.G. Lim, H. Seo, K.L. Man, X. Zhu, Y. Yue, Radar-camera fusion for object detection and semantic segmentation in autonomous driving: a comprehensive review, *IEEE Trans. Intell. Veh.* 9 (2024), <https://doi.org/10.1109/TIV.2023.3307157>.
- [22] J. Besenyő, A. Ősz, Sensing from the skies: a comprehensive analysis of the latest sensors on drones, *J. Robot.* 2025 (2025), <https://doi.org/10.1155/joro/3896195>.
- [23] C. Rembe, B.J. Halkon, M.A.A. Ismail, Measuring vibrations in large structures with LDV and UAS: a review and outlook, *Adv. Devices Instrum.* 6 (2025), <https://doi.org/10.34133/adi.0103>.
- [24] S. Rothberg, Numerical simulation of speckle noise in laser vibrometry, *Appl. Opt.* 45 (2006) 4523–4533, <https://doi.org/10.1364/AO.45.004523>.
- [25] M. Denman, N.A. Halliwell, S. Rothberg, Speckle noise reduction in laser vibrometry: experimental and numerical optimisation, *Second International Conference on Vibration Measurements by Laser Techniques: Advances and Applications* (1996), <https://doi.org/10.1117/12.248633>.
- [26] K. Tolchkova, C. Rembe, Evaluation of turbulence parameters with a multipoint Laser Doppler Vibrometer, *Tech. Mess.* 90 (2023) 120–125, <https://doi.org/10.1515/teme-2023-0076>.
- [27] A. Dräbenstedt, J. Sauer, C. Rembe, Remote-sensing vibrometry at 1550 nm wavelength, in: *10th International Conference on Vibration Measurements by Laser and Noncontact Techniques AIVELA 2012, 2012*: pp. 113–121. <https://doi.org/10.1063/1.4730549>.

- [28] N. Hasheminejad, C. Vuye, W. van Den Bergh, J. Dirckx, S. Vanlanduit, A comparative study of laser Doppler vibrometers for vibration measurements on pavement materials, *Infrastructures* (Basel) 3 (2018), <https://doi.org/10.3390/infrastructures3040047>.
- [29] L.A. Jiang, M.A. Albota, R.W. Haupt, J.G. Chen, R.M. Marino, Laser vibrometry from a moving ground vehicle, *Appl. Opt.* 50 (2011) 2263–2273, <https://doi.org/10.1364/AO.50.002263>.
- [30] P. Martin, S. Rothberg, Laser vibrometry and the secret life of speckle patterns, Eighth International Conference on Vibration Measurements by Laser Techniques: Advances and Applications (2008), <https://doi.org/10.1117/12.803156>.
- [31] P. Martin, S.J. Rothberg, Pseudo-vibration sensitivities for commercial laser vibrometers, *Mech. Syst. Signal Process.* 25 (2011) 2753–2765, <https://doi.org/10.1016/j.ymssp.2011.02.009>.
- [32] A. Dräbenstedt, Diversity combining in laser Doppler vibrometry for improved signal reliability, in: 11th International Conference on Vibration Measurements by Laser and Noncontact Techniques - AIVELA 2014: Advances and Applications, 2014: pp. 263–273. <https://doi.org/10.1063/1.4879592>.
- [33] S. Serafini, N. Paone, P. Castellini, Agent-based station for on-line diagnostics by self-adaptive laser Doppler vibrometry, *Rev. Sci. Instrum.* 84 (2013), <https://doi.org/10.1063/1.4845475>.
- [34] M. Bauer, F. Ritter, G. Siegmund, High-precision laser vibrometers based on digital Doppler signal processing, Fifth International Conference on Vibration Measurements by Laser Techniques: Advances and Applications (2002), <https://doi.org/10.1117/12.468166>.
- [35] M. Johansmann, G. Siegmund, M. Pineda, Targeting the limits of laser Doppler vibrometry, in: Proc. IDEMA, 2005.
- [36] S.J. Rothberg, B.J. Halkon, Laser vibrometry meets laser speckle, Sixth International Conference on Vibration Measurements by Laser Techniques: Advances and Applications (2004), <https://doi.org/10.1117/12.579760>.
- [37] P. Martin, S.J. Rothberg, Methods for the quantification of pseudo-vibration sensitivities in laser vibrometry, *Meas. Sci. Technol.* 22 (2011), <https://doi.org/10.1088/0957-0233/22/3/035302>.
- [38] S. Rahimi, Z. Li, R. Dollevoet, Measuring with laser Doppler vibrometer on moving frame (LDVMF), in: 11th International Conference on Vibration Measurements by Laser and Noncontact Techniques - AIVELA 2014: Advances and Applications, 2014, <https://doi.org/10.1063/1.4879593>.
- [39] M.W. Sracic, M.S. Allen, Experimental investigation of the effect of speckle noise on Continuous Scan Laser Doppler Vibrometer measurements. 27th International Modal Analysis Conference (IMAC XXVII), 2009.
- [40] Y. Jin, R. Dollevoet, Z. Li, Numerical simulation and characterization of speckle noise for laser Doppler vibrometer on moving platforms (LDVom), *Opt. Lasers Eng.* 158 (2022), <https://doi.org/10.1016/j.optlaseng.2022.107135>.
- [41] A. Dräbenstedt, Quantification of displacement and velocity noise in vibrometer measurements on transversely moving or rotating surfaces, *Optical Measurement Systems for Industrial Inspection V* (2007), <https://doi.org/10.1117/12.726115>.
- [42] Y. Zeng, A. Núñez, Z. Li, Speckle noise reduction for structural vibration measurement with laser Doppler vibrometer on moving platform, *Mech. Syst. Signal Process.* 178 (2022), <https://doi.org/10.1016/j.ymssp.2022.109196>.
- [43] T. Lv, X. Han, S. Wu, Y. Li, The effect of speckles noise on the Laser Doppler Vibrometry for remote speech detection, *Opt. Commun.* 440 (2019) 117–125, <https://doi.org/10.1016/j.optcom.2019.02.014>.
- [44] F. Wang, C. Rembe, Statistical behaviour of laser Doppler vibrometer detector signals and application of statistics for signal diversity, in: 15th International AIVELA Conference on Vibration Measurements by Laser and Noncontact Techniques, 2024, <https://doi.org/10.1088/1742-6596/2698/1/012020>.
- [45] Y. Zeng, A. Núñez, Z. Li, Railway sleeper vibration measurement by train-borne laser Doppler vibrometer and its speed-dependent characteristics, *Comput. Aided Civ. Inf. Eng.* 39 (2024) 2408–2426, <https://doi.org/10.1111/mice.13150>.
- [46] D.E. Oliver, V. Palan, G. Bissinger, D. Rowe, 3-dimensional laser Doppler vibration analysis of Stradivarius violins. *Proceedings of the 25th International Modal Analysis Conference*, 2007.
- [47] Y. Jin, Z. Li, Eliminating speckle noises for laser doppler vibrometer based on empirical wavelet transform, *Proceedings of the 13th International Conference on Measurement*, 2021, <https://doi.org/10.23919/Measurement52780.2021.9446777>.
- [48] Y. Wang, W. Zhang, Z. Wu, X. Kong, H. Zhang, Speckle noise detection and removal for laser speech measurement systems, *Appl. Sci.* 11 (2021), <https://doi.org/10.3390/app11219870>.
- [49] Y. Avargel, I. Cohen, Speech measurements using a laser Doppler vibrometer sensor: Application to speech enhancement, in: 2011 Joint Workshop on Hands-Free Speech Communication and Microphone Arrays, 2011. <https://doi.org/10.1109/HSCMA.2011.5942375>.
- [50] V. Aranchuk, A.K. Lal, C.F. Hess, J.M. Sabatier, R.D. Burgett, I. Aranchuk, W.T. Mayo Jr., Speckle noise in a continuously scanning multibeam laser Doppler vibrometer for acoustic landmine detection, *Detection and Remediation Technologies for Mines and Minelike Targets XI* (2006), <https://doi.org/10.1117/12.668783>.
- [51] Y. Jin, R. Dollevoet, Z. Li, Removing speckle noise from the signals of a laser Doppler vibrometer on moving platforms (LDVom) by ensemble empirical mode decomposition, *Meas. Sci. Technol.* 33 (2022), <https://doi.org/10.1088/1361-6501/ac8daf>.
- [52] K. Kaynardag, C. Yang, S. Salamone, An impulsive noise filter for rail vibration measurements using a laser Doppler vibrometer on a moving platform, *Mech. Syst. Signal Process.* 223 (2025), <https://doi.org/10.1016/j.ymssp.2024.111918>.
- [53] Y. Zeng, A. Núñez, Z. Li, Mitigating speckle noise while preserving impact response in vibration measurements with laser Doppler vibrometer on a moving platform. *Proceedings of the IMAC-XLIII Conference*, 2025.
- [54] H. Liu, D. Ji, J. Lin, Z. Liu, H. Li, Residual angular speed analysis based on laser Doppler vibrometer and its application in planetary gearbox diagnosis, *Measurement* (Lond.) 250 (2025), <https://doi.org/10.1016/j.measurement.2025.116987>.
- [55] J. Zhu, Y. Li, R. Baets, Mitigation of speckle noise in laser Doppler vibrometry by using a scanning average method, *Opt. Lett.* 44 (2019) 1860–1863, <https://doi.org/10.1364/ol.44.001860>.
- [56] F. Wang, S. Krause, C. Rembe, Signal diversity for the reduction of signal dropouts and speckle noise in a laser-Doppler extensometer, *Meas.: Sens.* 22 (2022), <https://doi.org/10.1016/j.measen.2022.100377>.
- [57] C. Lu, Z. Xu, J. Liu, B. Lu, Z. Yu, L. Zou, G. Liu, Reducing decoherence introduced by a rough target in laser Doppler vibrometry using a dual-wavelength structure, *Measurement* (Lond.) 247 (2025), <https://doi.org/10.1016/j.measurement.2025.116743>.
- [58] M. Schewe, C. Rembe, Signal diversity for laser-doppler vibrometers with raw-signal combination, *Sensors* 21 (2021), <https://doi.org/10.3390/s21030998>.
- [59] M. Schewe, C. Rembe, Analyzing real-time capability of raw laser-Doppler vibrometer signal combination for signal diversity, *Optical Measurement Systems for Industrial Inspection XII* (2021), <https://doi.org/10.1117/12.2592048>.
- [60] E. Cupido, S. Morel, D. Smith, Multipoint laser Doppler vibrometer for transient analysis, *Proceedings of IMAC XXI* (2003).
- [61] A.K. Lal, C. Hess, Array and Matrix based laser Doppler vibrometers for measuring noise and vibration, in: INTER-NOISE and NOISE-CON Congress and Conference Proceedings, 2006.
- [62] J.M. Kilpatrick, V. Markov, Matrix laser vibrometer for transient modal imaging and rapid nondestructive testing, Eighth International Conference on Vibration Measurements by Laser Techniques: Advances and Applications (2008), <https://doi.org/10.1117/12.802929>.
- [63] J.J.J. Dirckx, H.J. van Elburg, W.F. Decraemer, J.A.N. Buytaert, J.A. Melkebeek, Performance and testing of a four channel high-resolution heterodyne interferometer, *Opt. Lasers Eng.* 47 (2009) 488–494, <https://doi.org/10.1016/j.optlaseng.2008.05.011>.
- [64] Y. Fu, M. Guo, P.B. Phua, Spatially encoded multibeam laser Doppler vibrometry using a single photodetector, *Opt. Lett.* 35 (2010) 1356–1358, <https://doi.org/10.1364/ol.35.001356>.
- [65] Y. Fu, M. Guo, P.B. Phua, Multipoint laser Doppler vibrometry with single detector: Principles, implementations, and signal analyses, *Appl. Opt.* 50 (2011) 1280–1288, <https://doi.org/10.1364/AO.50.001280>.
- [66] W.N. MacPherson, M. Reeves, D.P. Towers, A.J. Moore, J.D.C. Jones, M. Dale, C. Edwards, Multipoint laser vibrometer for modal analysis, *Appl. Opt.* 46 (2007) 3126–3132, <https://doi.org/10.1364/AO.46.003126>.
- [67] V. Aranchuk, R. Kasu, J. Li, I. Aranchuk, C. Hickey, Multi-beam heterodyne laser Doppler vibrometer based on a line-scan CMOS digital camera, *Appl. Opt.* 61 (2022) 5876–5883, <https://doi.org/10.1364/ao.461368>.

- [68] S.J. Rothberg, M. Tirabassi, A universal framework for modelling measured velocity in laser vibrometry with applications, *Mech. Syst. Signal Process.* 26 (2012) 141–166, <https://doi.org/10.1016/j.ymssp.2011.06.022>.
- [69] B.J. Halkon, S.J. Rothberg, Taking laser Doppler vibrometry off the tripod: correction of measurements affected by instrument vibration, *Opt. Lasers Eng.* 91 (2017) 16–23, <https://doi.org/10.1016/j.optlaseng.2016.11.006>.
- [70] B.J. Halkon, S.J. Rothberg, Restoring high accuracy to laser Doppler vibrometry measurements affected by vibration of beam steering optics, *J. Sound Vib.* 405 (2017) 144–157, <https://doi.org/10.1016/j.jsv.2017.05.014>.
- [71] A. Darwish, B. Halkon, S. Rothberg, S. Oberst, R. Fitch, A comparison of time and frequency domain-based approaches to laser Doppler vibrometer instrument vibration correction, *J. Sound Vib.* 520 (2022), <https://doi.org/10.1016/j.jsv.2021.116607>.
- [72] M. Schewe, D. Kohlmann, H. Wulfmeier, H. Fritze, C. Rembe, Differential laser Doppler vibrometry for displacement measurements down to 1 mHz with 1 nm amplitude resolution in harsh environments, *Measurement (Lond)*. 210 (2023), <https://doi.org/10.1016/j.measurement.2023.112576>.
- [73] V. Aranchuk, I. Aranchuk, B. Carpenter, C. Hickey, D. Kleinert, H. Buchanan, J. Heffington, Laser multi-beam differential interferometric sensor for acoustic detection of buried objects, in: *Detection and Sensing of Mines, Explosive Objects, and Obscured Targets XXIII*, 2018. <https://doi.org/10.1117/12.2304663>.
- [74] Y. Fu, H. Liu, Q. Hu, J. Xie, Photo-vibrational sensing of trace chemicals and explosives by long-distance differential laser Doppler vibrometer, in: *Chemical, Biological, Radiological, Nuclear, and Explosives (CBRNE) Sensing XVIII*, 2017. <https://doi.org/10.1117/12.2261783>.
- [75] G. Hildebrand, S. Rasmussen, *Development of a High Speed Deflectograph, The Directorate (2002)*.
- [76] J.-M. Simonin, D. Lièvre, S. Rasmussen, G. Hildebrand, Assessment of the Danish High Speed Deflectograph in France, in: *Proceedings Seventh International Conference on the Bearing Capacity of Roads, Railways and Airfields*, 2005.
- [77] B.W. Ferne, P. Langdale, N. Round, R. Fairclough, Development of a calibration procedure for the U.K. highways agency traffic-speed deflectometer, *Transp. Res. Rec: J. Transp. Res. Board* 2093 (2009) 111–117, <https://doi.org/10.3141/2093-13>.
- [78] G.W. Flintsch, B. Ferne, B. Diefenderfer, S. Katicha, J. Bryce, S. Nell, Evaluation of traffic-speed deflectometers, *Transp. Res. Rec: J. Transp. Res. Board* 2304 (2012) 37–46, <https://doi.org/10.3141/2304-05>.
- [79] S. Baltzer, D. Pratt, J. Weligamage, J. Adamsen, G. Hildebrand, Continuous bearing capacity profile of 18,000 km Australian road network in 5 months. *Proceedings of the 24th ARRB Conference*, 2010.
- [80] A. Zofka, J. Sudyka, M. Maliszewski, P. Harasim, D. Sybilski, Alternative approach for interpreting traffic speed deflectometer results, *Transp. Res. Rec: J. Transp. Res. Board* 2457 (2014) 12–18, <https://doi.org/10.3141/2457-02>.
- [81] W.B. Muller, J. Roberts, Revised approach to assessing traffic speed deflectometer data and field validation of deflection bowl predictions, *Int. J. Pavement Eng.* 14 (2013) 388–402, <https://doi.org/10.1080/10298436.2012.715646>.
- [82] R. Wix, C. Murnane, M. Moffatt, Experience gained investigating, acquiring and operating the first traffic speed deflectometer in Australia, in: *Transportation Research Procedia* 14: 6th Transport Research Arena, 2016: pp. 3060–3069. <https://doi.org/10.1016/j.trpro.2016.05.450>.
- [83] D. Jiang, D. Wang, Z. Pei, Z. Sun, J. Yi, A comprehensive survey of the new generation pavement structural condition assessment in pavement management system: traffic speed deflection device, *IEEE Trans. Intell. Transp. Syst.* (2025), <https://doi.org/10.1109/ITITS.2025.3560418>.
- [84] G. Flintsch, B. Ferne, B. Diefenderfer, S. Katicha, J. Bryce, S. Nell, T. Clark, *Assessment of Continuous Pavement Deflection Measuring Technologies*, 2013. <https://doi.org/10.17226/22766>.
- [85] J. Liao, H. Lin, Q. Li, D. Zhang, A correction model for the continuous deflection measurement of pavements under dynamic loads, *IEEE Access* 7 (2019) 154770–154785, <https://doi.org/10.1109/ACCESS.2019.2947196>.
- [86] S.W. Katicha, G.W. Flintsch, B. Ferne, Optimal averaging and localized weak spot identification of traffic speed deflectometer measurements, *Transp. Res. Rec.* (2013), <https://doi.org/10.3141/2367-05>.
- [87] S.W. Katicha, G. Flintsch, J. Bryce, B. Ferne, Wavelet denoising of TSD deflection slope measurements for improved pavement structural evaluation, *Comput. Aided Civ. Inf. Eng.* 29 (2014) 399–415, <https://doi.org/10.1111/mice.12052>.
- [88] M. Scavone, S.W. Katicha, G.W. Flintsch, B.K. Diefenderfer, Reweighted L1 minimization for networkwide weak spot detection from traffic speed deflectometer measurements, *J. Comput. Civ. Eng.* 37 (2023), <https://doi.org/10.1061/jccee5.cpeng-4946>.
- [89] F. Xiao, Q. Xiang, X. Hou, S.N. Amirhanian, Utilization of traffic speed deflectometer for pavement structural evaluations, *Measurement* 178 (2021), <https://doi.org/10.1016/j.measurement.2021.109326>.
- [90] M. Nasimifar, S. Thyagarajan, N. Sivaneshwaran, Computation of pavement vertical surface deflections from traffic speed deflectometer data: evaluation of current methods, *J. Transp. Eng. Part B: Pavements* 144 (2018), <https://doi.org/10.1061/jpeodx.0000025>.
- [91] Z. Sun, C. Kasbergen, K.N. van Dalen, K. Anupam, A. Skarpas, S.M.J.G. Erkens, A parameter identification technique for traffic speed deflectometer tests of pavements, *Road Mater. Pavement Des.* 24 (2023) 1065–1087, <https://doi.org/10.1080/14680629.2022.2060125>.
- [92] E.J. O'Brien, J. Keenahan, Drive-by damage detection in bridges using the apparent profile, *Struct. Control Health Monit.* 22 (2015) 813–825, <https://doi.org/10.1002/stc.1721>.
- [93] A. Malekjafarian, D. Martinez, E.J. O'Brien, The feasibility of using laser doppler vibrometer measurements from a passing vehicle for bridge damage detection, *Shock Vib.* 2018 (2018), <https://doi.org/10.1155/2018/9385171>.
- [94] A.P. de Man, S. Rasmussen, The high speed deflectograph and the hammer excitation test: two measurement techniques for determining track performance, *Rail Eng. Int.* 29 (2000).
- [95] P. Wang, L. Wang, R. Chen, J. Xu, J. Xu, M. Gao, Overview and outlook on railway track stiffness measurement, *J. Modern Transp.* 24 (2016) 89–102, <https://doi.org/10.1007/s40534-016-0104-8>.
- [96] A. Radmehr, S.M.H. Mirzaei, I. Larson, C. Holton, M. Ahmadian, Railroad track gage widening assessment using on-board Doppler LiDAR velocity measurements and unsupervised machine learning techniques, in: *Advances in Dynamics of Vehicles on Roads and Tracks III (IAVSD 2023)*, 2024: pp. 97–106. https://doi.org/10.1007/978-3-031-66971-2_11.
- [97] Z. Li, Rixen Daniel, Method for detection of a flaw or flaws in a railway track, and a rail vehicle to be used in such a method, US 9731734B2, 2017.
- [98] Y. Zeng, A. Núñez, Z. Li, Measuring transfer functions of track structures in a test rig with laser Doppler vibrometer and accelerometers on a moving vehicle, *Mech. Syst. Signal Process.* 214 (2024) 111392, <https://doi.org/10.1016/j.ymssp.2024.111392>.
- [99] Y. Zeng, A. Núñez, R. Dollevoet, A. Zoeteman, Z. Li, A train-borne laser vibrometer solution based on multisignal fusion for self-contained railway track monitoring, *IEEE Trans. Industr. Inform.* 21 (2025) 1585–1594, <https://doi.org/10.1109/TII.2024.3485764>.
- [100] K. Kaynardag, G. Battaglia, A. Ebrahimkhanlou, A. Pirrotta, S. Salamone, Identification of bending modes of vibration in rails by a laser Doppler vibrometer on a moving platform, *Exp. Tech.* 45 (2021) 13–24, <https://doi.org/10.1007/s40799-020-00401-9>.
- [101] K. Kaynardag, C. Yang, S. Salamone, A rail defect detection system based on laser Doppler vibrometer measurements, *NDT & E International* 137 (2023), <https://doi.org/10.1016/j.ndteint.2023.102858>.
- [102] C. Yang, K. Kaynardag, S. Salamone, Missing rail fastener detection based on laser Doppler vibrometer measurements, *J. Nondestr. Eval.* 42 (2023), <https://doi.org/10.1007/s10921-023-00981-7>.
- [103] C. Yang, K. Kaynardag, J. Sohn, S. Salamone, Transfer learning in LSTM autoencoders for rail anomaly detection across diverse operational conditions, *J. Intell. Mater. Syst. Struct.* (2025), <https://doi.org/10.1177/1045389X251386605>.
- [104] Y. Zeng, A. Núñez, A. Zoeteman, R. Dollevoet, Z. Li, Direct monitoring of in-situ rail fastener vibrations from a moving train with laser Doppler vibrometer, in: *27th IEEE International Conference on Intelligent Transportation Systems*, 2025, <https://doi.org/10.1109/ITSC58415.2024.10919662>.
- [105] Y. Zeng, A. Nunze, Z. Li, Onboard approximation of dynamic load-response relationship of track structure using laser Doppler vibrometer and axle box accelerometer, *IEEE International Instrumentation and Measurement Technology Conference*, 2025, <https://doi.org/10.1109/I2MTC62753.2025.11079168>.
- [106] E.J. O'Brien, A. Malekjafarian, A mode shape-based damage detection approach using laser measurement from a vehicle crossing a simply supported bridge, *Struct. Control Health Monit.* 23 (2016) 1273–1286, <https://doi.org/10.1002/stc.1841>.
- [107] M.A.A. Ismail, M. Schewe, C. Rembe, M. Mahmood, M. Kiehn, Traffic-Induced Vibration monitoring using laser vibrometry: preliminary experiments, *Remote Sens. (Basel)* 14 (2022), <https://doi.org/10.3390/rs14236034>.

- [108] N. Xiang, J.M. Sabatier, Land mine detection measurements using acoustic-to-seismic coupling, *Detection and Remediation Technologies for Mines and Minelike Targets V* (2000), <https://doi.org/10.1117/12.396292>.
- [109] R.D. Costley, J.M. Sabatier, N. Xiang, Forward-looking acoustic mine detection system, *Detection and Remediation Technologies for Mines and Minelike Targets VI* (2001), <https://doi.org/10.1117/12.445514>.
- [110] V. Valeau, J. Sabatier, R.D. Costley, N. Xiang, Development of a time-frequency representation for acoustic detection of buried objects, *J. Acoust. Soc. Am.* 116 (2004) 2984–2995, <https://doi.org/10.1121/1.1806824>.
- [111] V. Aranchuk, A. Lal, H. Cecil, J. Sabatier, Multi-beam laser Doppler vibrometer for landmine detection, *Opt. Eng.* 45 (2006), <https://doi.org/10.1117/1.2358975>.
- [112] T. Writer, J.M. Sabatier, M.A. Miller, K.D. Sherbondy, Mine detection with a forward-moving portable laser Doppler vibrometer, *Detection and Remediation Technologies for Mines and Minelike Targets VII* (2002), <https://doi.org/10.1117/12.479136>.
- [113] T.V. Writer, Determination of speed limitations in acoustic-to-seismic mine detection using a laser Doppler vibrometer, *Detection and Remediation Technologies for Mines and Minelike Targets VIII* (2003), <https://doi.org/10.1117/12.487188>.
- [114] R.D. Burgett, M.R. Bradley, M. Duncan, J. Melton, A.K. Lal, V. Aranchuk, C.F. Hess, J.M. Sabatier, N. Xiang, Mobile mounted laser Doppler vibrometer array for acoustic landmine detection, *Detection and Remediation Technologies for Mines and Minelike Targets VIII* (2003), <https://doi.org/10.1117/12.487186>.
- [115] J.M. Sabatier, R.D. Burgett, V. Aranchuk, High-frequency A/S coupling for AP buried-landmine detection using laser Doppler vibrometers, *Detection and Remediation Technologies for Mines and Minelike Targets IX* (2004), <https://doi.org/10.1117/12.540511>.
- [116] R. Burgett, V. Aranchuk, I. Aranchuk, Experimental investigation of buried landmine detection using time division multiplexing of multibeam laser Doppler vibrometer channels, in: *Detection and Sensing of Mines, Explosive Objects, and Obscured Targets XVII*, 2012, <https://doi.org/10.1117/12.919481>.
- [117] B. Libbey, J. Perea, Doppler-vibrometer landmine-detection system operated from a moving vehicle, in: *Detection and Sensing of Mines, Explosive Objects, and Obscured Targets XXIV*, 2019, <https://doi.org/10.1117/12.2519299>.
- [118] V. Aranchuk, S. Johnson, I. Aranchuk, C. Hickey, Laser Doppler multi-beam differential vibration sensor based on a line-scan CMOS camera for real-time buried objects detection, *Opt. Express* 31 (2023) 235–247, <https://doi.org/10.1364/OE.477115>.
- [119] V. Aranchuk, B. Zhang, S. Johnson, I. Aranchuk, C. Hickey, Laser Doppler multi-beam differential vibrometers for detection of buried objects, *Electro-Optical and Infrared Systems: Technology and Applications XX* (2023), <https://doi.org/10.1117/12.2684137>.
- [120] A. Dräbenstedt, X. Cao, U. Polom, F. Pätzold, T. Zeller, P. Hecker, V. Seyfried, C. Rembe, Mobile seismic exploration, in: *Proceedings of the 12th International A.I.V.E.L.A. Conference on Vibration Measurements by Laser and Noncontact Techniques: Advances and Applications*, 2016, <https://doi.org/10.1063/1.4952659>.
- [121] Y. Nakagawa, T. Sugimoto, K. Sugimoto, I. Uechi, C. Kuroda, N. Utagawa, Y. Nihei, Research on improving defect detection performance using noise reduction processing during movement measurement with noncontact acoustic inspection method, *Jpn. J. Appl. Phys.* 64 (2025), <https://doi.org/10.35848/1347-4065/adc466>.
- [122] D.E. Oliver, M. Schuessler, Automated robot-based 3d vibration measurement system, *Sound and Vibration* (2009).
- [123] E. Esposito, S. Copparoni, B. Naticchia, Recent progress in diagnostics of civil structures by laser vibrometry, 2004, <https://www.ndt.net/?id=2166>.
- [124] A. Cesetti, C.P. Scotti, G. Di Buò, G. Angione, L. Lattanzi, C. Cristalli, S. Longhi, Development of a flexible test platform for household appliance testing based on mobile agents, in: *2010 IEEE International Conference on Automation Science and Engineering 2010*, 2010, <https://doi.org/10.1109/COASE.2010.5584512>.
- [125] O. Devigne, S. Hoffait, O. Brüls, Development of a robot-aided modal analysis measurement method using laser Doppler vibrometry, *Proceedings of ISMA 2020 - International Conference on Noise and Vibration Engineering and USD 2020 - International Conference on Uncertainty in Structural Dynamics*, 2020.
- [126] P. Margerit, T. Gobin, A. Lebé, J.F. Caron, The robotized laser doppler vibrometer: on the use of an industrial robot arm to perform 3D full-field velocity measurements, *Opt. Lasers Eng.* 137 (2021), <https://doi.org/10.1016/j.optlaseng.2020.106363>.
- [127] L. Bertini, P. Neri, C. Santus, A. Guglielmo, Automated experimental modal analysis of bladed wheels with an anthropomorphic robotic station, *Exp. Mech.* 57 (2017), <https://doi.org/10.1007/s11340-016-0223-5>.
- [128] K. Yuan, W. Zhu, Vibration measurement and modal identification of a beam using a novel robotic continuously scanning laser Doppler vibrometer system, *Opt. Laser Technol.* 192 (2025), <https://doi.org/10.1016/j.optlastec.2025.114060>.
- [129] T. Hayashi, Y. Kojika, K. Kataoka, M. Takikawa, Visualization of guided wave propagation with laser doppler vibrometer scanning on curved surfaces, *AIP Conf. Proc.* (2008), <https://doi.org/10.1063/1.2902654>.
- [130] O. Abraham, G. Villain, L. Lu, L.-M. Cottineau, O. Durand, A laser interferometer robot for the study of surface wave sensitivity to various concrete mixes, *Symposium International Sur Les Essais Non Destructifs Pour Le Génie Civil*, 2009.
- [131] H. Ahmed, A. Mohsin, S.C. Hong, J.R. Lee, J.B. Ihn, Robotic laser sensing and laser mirror excitation for pulse-echo scanning inspection of fixed composite structures with non-planar geometries, *Measurement* (Lond). 176 (2021), <https://doi.org/10.1016/j.measurement.2021.109109>.
- [132] K.J. Lee, J.R. Lee, Path planning and inspection of complex-shaped 3D-printed composites based on robotic pulse-echo laser ultrasonic testing, *Adv. Compos. Mater.* 34 (2025), <https://doi.org/10.1080/09243046.2024.2372902>.
- [133] S.A. Zargar, F.G. Yuan, Physics-informed deep learning for scattered full wavefield reconstruction from a sparse set of sensor data for impact diagnosis in structural health monitoring, *Struct. Health Monit.* 23 (2024), <https://doi.org/10.1177/14759217231202547>.
- [134] S. Sels, S. Vanlanduit, B. Bogaerts, R. Penne, Three-dimensional full-field vibration measurements using a handheld single-point laser Doppler vibrometer, *Mech. Syst. Signal Process.* 126 (2019) 427–438, <https://doi.org/10.1016/j.ymssp.2019.02.024>.
- [135] B. Halkon, S. Rothberg, Taking laser Doppler vibrometry off the tripod, *25th International Congress on Sound and Vibration 2018*, 2018.
- [136] P. Garg, F. Moreu, A. Ozdagli, M.R. Taha, D. Mascareñas, Noncontact dynamic displacement measurement of structures using a moving laser Doppler vibrometer, *J. Bridg. Eng.* 24 (2019), [https://doi.org/10.1061/\(asce\)be.1943-5592.0001472](https://doi.org/10.1061/(asce)be.1943-5592.0001472).
- [137] F. Moreu, M.R. Taha, Railroad Bridge Inspections for Maintenance and Replacement Prioritization Using Unmanned Aerial Vehicles with Laser Scanning Capabilities, 2018.
- [138] H. Zheng, T. Guo, G. Zhi, Z. Hu, A novel debonding damage identification approach of hidden frame-supported glass curtain walls based on UAV-LDV system, *Applied Sciences* (Switzerland) 14 (2024), <https://doi.org/10.3390/app14135412>.
- [139] M.A.A. Ismail, A. Bierig, S.R. Hassan, R. Kumme, Flyable mirrors: Laser scanning vibrometry method for monitoring large engineering structures using drones, *Optical Technology and Measurement for Industrial Applications Conference*, 2019.
- [140] M. Schewe, M.A.A. Ismail, R. Zimmermann, U. Durak, C. Rembe, Flyable Mirror: Airborne laser Doppler vibrometer for large engineering structures, in: *15th International AIVELA Conference on Vibration Measurements by Laser and Noncontact Techniques*, 2024, <https://doi.org/10.1088/1742-6596/2698/1/012007>.
- [141] M. Schewe, M.A.A. Ismail, C. Rembe, Towards airborne laser Doppler vibrometry for structural health monitoring of large and curved structures, *Insight: Non-Destructive Testing and Condition Monitoring* 63 (2021) 280–283, <https://doi.org/10.1784/insi.2021.63.5.280>.
- [142] B. Halkon, C. Gao, R. Zimmermann, C. Rembe, Differential laser Doppler vibrometer measurements using “flyable mirrors” for the vibration assessment of remote structures, 2025, <https://doi.org/10.2139/ssrn.5189527>.
- [143] R. Zimmermann, U. Durak, M.A.A. Ismail, Towards laser-doppler-vibrometry with UAVs - the effect of wind disturbances on the position of a mirror attached to a drone, *CEAS Aeronaut. J.* (2026), <https://doi.org/10.1007/s13272-026-00955-1>.
- [144] A.D. McAulay, Airborne laser vibrometer for seismic subsurface inspection, *Laser Radar Technology and Applications XVI* (2011), <https://doi.org/10.1117/12.884352>.
- [145] P. Sava, E. Asphaug, Seismology on small planetary bodies by orbital laser Doppler vibrometry, *Adv. Space Res.* 64 (2019) 527–544, <https://doi.org/10.1016/j.asr.2019.04.017>.
- [146] S.W. Courville, P.C. Sava, Speckle noise attenuation in orbital laser vibrometer seismology, *Acta Astronaut.* 172 (2020) 16–32, <https://doi.org/10.1016/j.actaastro.2020.03.016>.

- [147] P. Chiariotti, M. Martarelli, P. Castellini, Exploiting continuous scanning laser doppler vibrometry in timing belt dynamic characterisation, *Mech. Syst. Signal Process.* 86 (2017) 66–81, <https://doi.org/10.1016/j.ymssp.2016.01.001>.
- [148] A. Agnani, M. Martarelli, E.P. Tomasini, V-belt transverse vibration measurement by means of laser Doppler vibrometry, Eighth International Conference on Vibration Measurements by Laser Techniques: Advances and Applications (2008), <https://doi.org/10.1117/12.803167>.
- [149] J. Wei, C.-H. Liu, Z. Zhu, O. Mendoza-Schrock, K. Vongsy, Classification of uncooperative vehicles with sparse laser Doppler vibrometry measurements, in: *Ground/Air Multisensor Interoperability, Integration, and Networking for Persistent ISR VI*, 2015. <https://doi.org/10.1117/12.2179277>.
- [150] J. Wei, C.H. Liu, Z. Zhu, L.R. Cain, V.J. Velten, Vehicle engine classification using normalized tone-pitch indexing and neural computing on short remote vibration sensing data, *Expert Syst. Appl.* 115 (2019) 276–286, <https://doi.org/10.1016/j.eswa.2018.07.073>.
- [151] M.A.A. Ismail, A. Bierig, Identifying drone-related security risks by a laser vibrometer-based payload identification system, *Laser Radar Technology and Applications XXIII* (2018), <https://doi.org/10.1117/12.2314441>.
- [152] M.A.A. Ismail, S.T. Kurdi, M.S. Albaraj, C. Rembe, Offboard fault diagnosis for large UAV Fleets using laser doppler vibrometer and deep extreme learning, *Automation 7* (2025), <https://doi.org/10.3390/automation7010006>.
- [153] R.A. Cookson, P. Bandyopadhyay, A fiber-optic laser-doppler probe for vibration analysis of rotating machines, *J. Eng. Gas Turbine. Power* 102 (1980) 607–612, <https://doi.org/10.1115/1.3230310>.
- [154] A.J. Oberholster, P.S. Heyns, Online condition monitoring of axial-flow turbomachinery blades using rotor-axial Eulerian laser Doppler vibrometry, *Mech. Syst. Signal Process.* 23 (2009) 1634–1643, <https://doi.org/10.1016/j.ymssp.2009.01.001>.
- [155] A.J. Oberholster, P.S. Heyns, A study of radial-flow turbomachinery blade vibration measurements using Eulerian laser Doppler vibrometry, in: 11th International Conference on Vibration Measurements by Laser and Noncontact Techniques AIVELA 2014: Advances and Applications, 2014, <https://doi.org/10.1063/1.4879565>.
- [156] Q.V. Davis, W.K. Kulczyk, Vibrations of turbine blades measured by means of a laser, *Nature* 222 (1969) 475–476, <https://doi.org/10.1038/222475a0>.
- [157] K. Tatar, M. Rantatalo, P. Gren, Laser vibrometry measurements of an optically smooth rotating spindle, *Mech. Syst. Signal Process.* 21 (2007) 1739–1745, <https://doi.org/10.1016/j.ymssp.2006.08.006>.
- [158] K. Tatar, P. Gren, Measurement of milling tool vibrations during cutting using laser vibrometry, *Int. J. Mach. Tools Manuf* 48 (2008) 380–387, <https://doi.org/10.1016/j.ijmactools.2007.09.009>.
- [159] K.M. Lee, A.A. Polycarpou, Dynamic microwaviness measurements of super smooth disk media used in magnetic hard disk drives, *Mech. Syst. Signal Process.* 20 (2006) 1322–1337, <https://doi.org/10.1016/j.ymssp.2005.11.010>.
- [160] S. Zhu, W. Zhou, Y. Song, Detecting oscillation amplitude and defects of hard disk rotating in high speed by laser Doppler technique, *Measurement* 45 (2012) 74–78, <https://doi.org/10.1016/j.measurement.2011.09.021>.
- [161] S. Rothberg, J. Bell, On the application of laser vibrometry to translational and rotational vibration measurements on rotating shafts, *Measurement* 35 (2004) 201–210, <https://doi.org/10.1016/j.measurement.2003.04.001>.
- [162] B.J. Halkon, S.J. Rothberg, A practical guide to laser Doppler vibrometry measurements directly from rotating surfaces, in: *IMEChE Vibrations in Rotating Machinery (VIRM11)*, 2016.
- [163] A. Zofka, M. Graczyk, J. Rafa, Qualitative evaluation of stochastic factors affecting the traffic speed deflectometer results, *Transportation Research Board 94th Annual Meeting* (2014).
- [164] K. Yuan, W.D. Zhu, A novel general-purpose three-dimensional continuously scanning laser Doppler vibrometer system for full-field vibration measurement of a structure with a curved surface, *J. Sound Vib.* 540 (2022), <https://doi.org/10.1016/j.jsv.2022.117274>.
- [165] A. Olsson, *Target Recognition by Vibrometry with a Coherent Laser Radar*, Linköping University, 2003.
- [166] H.J. Von Martens, Invited article: expanded and improved traceability of vibration measurements by laser interferometry, *Rev. Sci. Instrum.* (2013), <https://doi.org/10.1063/1.4845916>.
- [167] E. Simoen, G. De Roeck, G. Lombaert, Dealing with uncertainty in model updating for damage assessment: a review, *Mech. Syst. Signal Process.* 56 (2015), <https://doi.org/10.1016/j.ymssp.2014.11.001>.
- [168] C. Fu, H. Zhao, W. Zhu, Z. Zheng, K. Lu, A review of uncertainty quantification techniques for frequency responses of mechanical systems, *Arch. Comput. Meth. Eng.* (2025), <https://doi.org/10.1007/s11831-025-10332-6>.
- [169] K. Zhou, Z. Wang, Q. Gao, S. Yuan, J. Tang, Recent advances in uncertainty quantification in structural response characterization and system identification, *Probab. Eng. Mech.* 74 (2023), <https://doi.org/10.1016/j.probengmech.2023.103507>.
- [170] T. Haist, C. Lingel, W. Osten, K. Bendel, M. Giesen, M. Gartner, C. Rembe, Characterization and demonstration of a 12-channel Laser-Doppler vibrometer, *Optical Measurement Systems for Industrial Inspection VIII* (2013), <https://doi.org/10.1117/12.2020475>.
- [171] K. Yuan, Z. Zhu, W. Chen, W. Zhu, Development and validation of a new type of displacement-based miniaturized laser vibrometers, *Sensors* 24 (2024), <https://doi.org/10.3390/s24165230>.
- [172] C. Yang, M. Guo, H. Liu, K. Yan, Y.J. Xu, H. Miao, Y. Fu, A multi-point laser Doppler vibrometer with fiber-based configuration, *Rev. Sci. Instrum.* 84 (2013), <https://doi.org/10.1063/1.4845335>.
- [173] Y. Fu, C. Yang, Y.J. Xu, H. Liu, K. Yan, M. Guo, Multi-point laser coherent detection system and its application on vibration measurement, *Optical Measurement Systems for Industrial Inspection IX* (2015), <https://doi.org/10.1117/12.2185264>.
- [174] R. Di Sante, L. Scalise, A novel fiber optic sensor for multiple and simultaneous measurement of vibration velocity, *Rev. Sci. Instrum.* 75 (2004) 1952–1958, <https://doi.org/10.1063/1.1753091>.
- [175] A.T. Waz, P.R. Kaczmarek, K.M. Abramski, Laser-fibre vibrometry at 1550 nm, *Meas. Sci. Technol.* 20 (2009), <https://doi.org/10.1088/0957-0233/20/10/105301>.
- [176] J. Shang, Y. He, Q. Wang, Y. Li, L. Ren, Development of a high-resolution all-fiber homodyne laser doppler vibrometer, *Sensors* 20 (2020), <https://doi.org/10.3390/s20205801>.
- [177] Y. Li, S. Verstuft, G. Yurtsever, S. Keyvaninia, G. Roelkens, D. Van Thourhout, R. Baets, Heterodyne laser Doppler vibrometers integrated on silicon-on-insulator based on serrodyne thermo-optic frequency shifters, *Appl. Opt.* 52 (2013) 2145–2152, <https://doi.org/10.1364/AO.52.002145>.
- [178] D.B. Cole, C. Sorace-Agaskar, M. Moresco, G. Leake, D. Coolbaugh, M.R. Watts, Integrated heterodyne interferometer with on-chip modulators and detectors, *Opt. Lett.* 40 (2015) 3097–3100, <https://doi.org/10.1364/ol.40.003097>.
- [179] Y. Li, E. Dieussaert, R. Baets, Miniaturization of laser doppler vibrometers—a review, *Sensors* 22 (2022), <https://doi.org/10.3390/s22134735>.
- [180] Y. Li, R. Baets, Homodyne laser Doppler vibrometer on silicon-on-insulator with integrated 90 degree optical hybrids, *Opt. Express* 21 (2013) 13342–13350, <https://doi.org/10.1364/oe.21.013342>.
- [181] W.A. Merzouk, B. Cagneau, F. Gardillou, K. Hilouane, L. Chassagne, Highly compact and easy-to-use optical chip interferometer with picometric performances, *Rev. Sci. Instrum.* 87 (2016), <https://doi.org/10.1063/1.4963899>.
- [182] Y. Li, P. Segers, J. Dirckx, R. Baets, On-chip laser Doppler vibrometer for arterial pulse wave velocity measurement, *Biomed. Opt. Express* 4 (2013) 1229–1235, <https://doi.org/10.1364/boe.4.001229>.
- [183] Y. Li, J. Zhu, M. Duperron, P. O'Brien, R. Schüler, S. Aasmul, M. de Melis, M. Kersemans, R. Baets, Six-beam homodyne laser Doppler vibrometry based on silicon photonics technology, *Opt. Express* 26 (2018) 3638–3645, <https://doi.org/10.1364/oe.26.003638>.
- [184] E. Dieussaert, R. Baets, Y. Li, Scaling silicon photonics-based laser Doppler vibrometry with multi-beam frequency shifters, in: 2024 IEEE Silicon Photonics Conference, 2024. <https://doi.org/10.1109/SiPhotonics60897.2024.10543570>.
- [185] G. Giuliani, S. Bozzi-Pietra, S. Donati, Self-mixing laser diode vibrometer, *Meas. Sci. Technol.* 14 (2003), <https://doi.org/10.1088/0957-0233/14/1/304>.
- [186] S. Donati, M. Norgia, G. Giuliani, Self-mixing differential vibrometer based on electronic channel subtraction, *Appl. Opt.* 45 (2006) 7264–7268, <https://doi.org/10.1364/AO.45.007264>.
- [187] A. Magnani, D. Melchionni, A. Pesatori, M. Norgia, Self-mixing digital closed-loop vibrometer for high accuracy vibration measurements, *Opt. Commun.* 365 (2016), <https://doi.org/10.1016/j.optcom.2015.12.002>.

- [188] P. Esmaili, M. Norgia, S. Donati, Noise decrease in a balanced self-mixing interferometer: theory and experiments, *IEEE Trans. Instrum. Meas.* 72 (2023), <https://doi.org/10.1109/TIM.2023.3287259>.
- [189] A. Albert, S. Donati, S.L. Lee, Self-mixing interferometry on long distance: theory and experimental validation, *IEEE Trans. Instrum. Meas.* 73 (2024), <https://doi.org/10.1109/TIM.2024.3485399>.
- [190] Y. Tan, M. Ali, Z. Su, F. Lin, W.H. Liao, H. Wong, Innovative prototype design and benchmarking for vibration displacement measurement ranging from sub-micron to micron via laser self-mixing interference, *Measurement (Lond)*. 253 (2025), <https://doi.org/10.1016/j.measurement.2025.117528>.
- [191] W. Xia, J. Yu, S. Shao, Z. Qian, H. Hao, M. Wang, D. Guo, Multi-channel vibration measurements based on a self-mixing vertical-cavity surface-emitting laser array, *Photonics* 12 (2025), <https://doi.org/10.3390/photonics12030178>.
- [192] S. Donati, Vibration measurements by self-mixing interferometry: an overview of configurations and benchmark performances, *Vibration* 6 (2023) 625–644, <https://doi.org/10.3390/vibration6030039>.
- [193] R. Atashkhouei, S. Royo, F.J. Azcona, Dealing with speckle effects in self-mixing interferometry measurements, *IEEE Sens. J.* 13 (2013) 1641–1647, <https://doi.org/10.1109/JSEN.2013.2240156>.
- [194] U. Zabit, O.D. Bernal, T. Bosch, Design and analysis of an embedded accelerometer coupled self-mixing laser displacement sensor, *IEEE Sens. J.* (2013), <https://doi.org/10.1109/JSEN.2013.2251626>.
- [195] Z.A. Khan, U. Zabit, O.D. Bernal, M.O. Ullah, T. Bosch, Adaptive cancellation of parasitic vibrations affecting a self-mixing interferometric laser sensor, *IEEE Trans. Instrum. Meas.* 66 (2017), <https://doi.org/10.1109/TIM.2016.2626018>.
- [196] S. Donati, Displacement and vibration measurements with interferometers: benchmark configurations, performance, and R&D opportunities, *Adv. Photonics Res.* 6 (2025), <https://doi.org/10.1002/adpr.202500193>.
- [197] S. Zwick, M. Warber, T. Haist, F. Schaal, W. Osten, S. Boedecker, C. Rembe, Advanced scanning laser-doppler vibrometer with computer generated holograms, in: 9th International Conference on Vibration Measurements by Laser and Non-Contact Techniques and Short Course, 2010, pp. 279–290, <https://doi.org/10.1063/1.3455467>.
- [198] T. Haist, C. Lingel, W. Osten, M. Winter, M. Giesen, F. Ritter, C. Rembe, Advanced multipoint vibrometry using spatial light modulators, in: 10th International Conference on Vibration Measurements by Laser and Noncontact Techniques - AIVELA 2012, 2012: pp. 234–241. <https://doi.org/10.1063/1.4730562>.
- [199] M.J. Connelly, P.M. Szczówka, R. Jallapuram, S. Martin, V. Toal, M.P. Whelan, Multipoint laser Doppler vibrometry using holographic optical elements and a CMOS digital camera, *Opt. Lett.* 33 (2008) 330–332, <https://doi.org/10.1364/ol.33.000330>.
- [200] N. Verrier, M. Atlan, M. Gross, Full field holographic vibrometry at ultimate limits, in: P. Picart (Ed.), *New Techniques in Digital Holography*, 2015: pp. 255–293. <https://doi.org/10.1002/9781119091745.ch7>.
- [201] C. Rembe, A. Dräbenstedt, Speckle-insensitive laser-Doppler vibrometry with adaptive optics and signal diversity, *Proceedings SENSOR 2015* (2015) 505–510, <https://doi.org/10.5162/sensor2015/d1.1>.
- [202] I.A. Sokolov, Adaptive photodetectors: Novel approach for vibration measurements, *Measurement* 27 (2000) 13–19, [https://doi.org/10.1016/S0263-2241\(99\)00042-1](https://doi.org/10.1016/S0263-2241(99)00042-1).
- [203] P. Land, D. Robinson, J. Roeder, D. Cook, A.K. Majumdar, Integration of a laser doppler vibrometer and adaptive optics system for acoustic-optical detection in the presence of random water wave distortions, *Ocean Sensing and Monitoring VIII* (2016), <https://doi.org/10.1117/12.2229300>.
- [204] A.D. McAulay, Military laser technology for defense: technology for revolutionizing 21st century warfare, John Wiley & Sons (2011), <https://doi.org/10.1002/9781118019559>.
- [205] F. Wang, M. Hess, J. Wölck, C. Rembe, Using laser Doppler extensometry with polarization diversity to measure strain in high-speed tensile testing, *Tech. Mess.* 92 (2025) 179–189, <https://doi.org/10.1515/teme-2025-0014>.
- [206] P. Castellini, P. Chiariotti, M. Martarelli, E.P. Tomasini, Valvetrain motion measurements in firing conditions by Laser Doppler Vibrometer, in: *Conference Proceedings of the Society for Experimental Mechanics Series*, 2013, pp. 395–400, https://doi.org/10.1007/978-1-4614-6546-1_43.
- [207] F. Wang, S. Krause, J. Hug, C. Rembe, A contactless laser doppler strain sensor for fatigue testing with resonance-testing machine, *Sensors* 21 (2021), <https://doi.org/10.3390/s21010319>.
- [208] C. Rembe, R. Kowarsch, W. Ochs, A. Dräbenstedt, M. Giesen, M. Winter, Optical three-dimensional vibrometer microscope with picometer-resolution in x, y, and z, *Opt. Eng.* 53 (2014), <https://doi.org/10.1117/1.oe.53.3.034108>.
- [209] A. Zabihi, F. Aghdasi, C. Ellouzi, N.K. Singh, R. Jha, C. Shen, Non-contact wind turbine blade crack detection using laser Doppler vibrometers, *Energies (Basel)* 17 (2024), <https://doi.org/10.3390/en17092165>.
- [210] P. Kudela, T. Wandowski, P. Malinowski, W. Ostachowicz, Application of scanning laser Doppler vibrometry for delamination detection in composite structures, *Opt. Lasers Eng.* 99 (2017), <https://doi.org/10.1016/j.optlaseng.2016.10.022>.
- [211] M. Philibert, K. Yao, M. Gresil, C. Soutis, Lamb waves-based technologies for structural health monitoring of composite structures for aircraft applications, *European Journal of Materials* 2 (2022), <https://doi.org/10.1080/26889277.2022.2094839>.
- [212] L. Xie, Y. Lian, F. Du, Y. Wang, Z. Lu, Optical methods of laser ultrasonic testing technology in the industrial and engineering applications: a review, *Opt. Laser Technol.* 176 (2024), <https://doi.org/10.1016/j.optlastec.2024.110876>.
- [213] C.C. Chia, S.Y. Lee, M.Y. Harmin, Y. Choi, J.R. Lee, Guided ultrasonic waves propagation imaging: a review, *Meas. Sci. Technol.* 34 (2023), <https://doi.org/10.1088/1361-6501/acae27>.
- [214] S. Zheng, Y. Luo, C. Xu, G. Xu, A review of laser ultrasonic lamb wave damage detection methods for thin-walled structures, *Sensors* 23 (2023), <https://doi.org/10.3390/s23063183>.
- [215] A. Ijeh, S. Ullah, M. Radziński, P. Kudela, Deep learning super-resolution for the reconstruction of full wavefield of Lamb waves, *Mech. Syst. Signal Process.* 186 (2023), <https://doi.org/10.1016/j.ymssp.2022.109878>.
- [216] D. Ji, J. Lin, F. Gao, J. Hua, W. Li, A deep learning-based spatial gradient reconstruction method for efficient damage identification in composite with high-sparsity Lamb wavefield, *Mech. Syst. Signal Process.* 224 (2025), <https://doi.org/10.1016/j.ymssp.2024.112018>.
- [217] Z. Zhu, W. Li, G. Wolberg, Integrating LDV audio and IR video for remote multimodal surveillance, in: 2005 IEEE Computer Society Conference on Computer Vision and Pattern Recognition, 2005, <https://doi.org/10.1109/CVPR.2005.478>.
- [218] T. Wang, Z. Zhu, C.N. Taylor, A multimodal temporal panorama approach for moving vehicle detection, reconstruction and classification, *Comput. Vis. Image Underst.* 117 (2013) 1724–1735, <https://doi.org/10.1016/j.cviu.2013.02.011>.
- [219] S. Sels, B. Ribbens, B. Bogaerts, J. Peeters, S. Vanlanduit, 3D model assisted fully automated scanning laser Doppler vibrometer measurements, *Opt. Lasers Eng.* 99 (2017) 23–30, <https://doi.org/10.1016/j.optlaseng.2016.09.007>.
- [220] P. Wang, B. Chen, Z. Gao, Y. Fu, S. Chen, X. Zhu, High precision full-field vibration measurement by LDV-induced stroboscopic fringe projection, *Opt. Lasers Eng.* 183 (2024), <https://doi.org/10.1016/j.optlaseng.2024.108481>.
- [221] Y. Wei, J. Weng, B. Chen, Z. Gao, H. Miao, Q. Yu, Y. Fu, Interferometric-scale full-field vibration measurement by a combination of digital image correlation and laser vibrometer, *Opt. Express* 32 (2024) 20742–20761, <https://doi.org/10.1364/oe.521211>.
- [222] A. Trias-Blanco, J. Gong, F.L. Moon, Characterization of operational vibrations of steel-girder highway bridges via LiDAR, *Remote Sens. (Basel)* 15 (2023), <https://doi.org/10.3390/rs15041003>.
- [223] N. Meyer, L. Schmid, A. Wieser, T. Medic, Vibration monitoring of a bridge using 2D profile laser scanning: lessons learned from the comparison of two spatio-temporal processing strategies, in: 5th Joint International Symposium on Deformation Monitoring, 2023, pp. 177–184, <https://doi.org/10.4995/jisdms2022.2022.13813>.
- [224] J. Lee, R.E. Kim, Noncontact dynamic displacements measurements for structural identification using a multi-channel Lidar, *Struct. Control Health Monit.* 29 (2022), <https://doi.org/10.1002/stc.3100>.
- [225] P. Gueguen, V. Jolivet, C. Michel, A.S. Schweitzer, Comparison of velocimeter and coherent lidar measurements for building frequency assessment, *Bull. Earthq. Eng.* 8 (2010) 327–338, <https://doi.org/10.1007/s10518-009-9137-2>.

- [226] M. Valla, P. Gueguen, B. Augère, D. Goular, M. Perrault, Remote modal study of reinforced concrete buildings using a multipath lidar vibrometer, *J. Struct. Eng.* 141 (2015), [https://doi.org/10.1061/\(asce\)st.1943-541x.0001087](https://doi.org/10.1061/(asce)st.1943-541x.0001087).
- [227] D. Han, Y. Li, M. Li, K. Jin, Performance analysis of vibration signals detected by coherent LiDAR, Sixth Conference on Frontiers in Optical Imaging and Technology: Imaging Detection and Target Recognition (2024), <https://doi.org/10.1117/12.3018560>.
- [228] S. Suyama, H. Ito, R. Kurahashi, H. Abe, T. Baba, Doppler velocimeter and vibrometer FMCW LiDAR with Si photonic crystal beam scanner, *Opt. Express* 29 (2021) 30727–30734, <https://doi.org/10.1364/oe.438453>.
- [229] H. Jang, J.W. Kim, G.H. Kim, C.H. Park, S.W. Jun, M. Jo, H. Lee, C.S. Kim, Simultaneous distance and vibration mapping of FMCW-LiDAR with a kinematic external cavity diode laser, *Opt. Lasers Eng.* 160 (2023), <https://doi.org/10.1016/j.optlaseng.2022.107283>.
- [230] W. Zhou, O. Enriquez, G. Pandraud, E. Margallo, J.L. Rubio, F. Beekman, Multi channel Laser Radar for acousto-seimics, *IMAC 2026* (2026).
- [231] K. Kim, H. Sohn, Dynamic displacement estimation by fusing LDV and LiDAR measurements via smoothing based Kalman filtering, *Mech. Syst. Signal Process.* 82 (2017) 339–355, <https://doi.org/10.1016/j.ymssp.2016.05.027>.
- [232] H. Liu, L. Yao, Z. Xu, X. Fan, X. Jiao, P. Sun, A railway lidar point cloud reconstruction based on target detection and trajectory filtering, *Remote Sens. (Basel)* 14 (2022), <https://doi.org/10.3390/rs14194965>.
- [233] X. Li, C. Liu, Z. Wang, X. Xie, D. Li, L. Xu, Airborne LiDAR: State-of-the-art of system design, technology and application, *Meas. Sci. Technol.* 32 (2020), <https://doi.org/10.1088/1361-6501/abc867>.
- [234] P. Qin, C. Zhang, X. Ma, Z. Shi, High-precision motion compensation for LiDAR based on LiDAR odometry, *Wirel. Commun. Mob. Comput.* 2022 (2022), <https://doi.org/10.1155/2022/5866868>.
- [235] J. Wang, L. Xu, Y. Fan, X. Liu, Z. Tian, X. Wang, Y. Cheng, A method for compensating platform attitude fluctuation for helicopter-borne LiDAR: Performance and effectiveness, *Measurement* 125 (2018) 37–47, <https://doi.org/10.1016/j.measurement.2018.04.049>.
- [236] Y. Avargel, T. Bakish, A. Dekel, G. Horovitz, Y. Kurtz, A. Moyal, Robust speech recognition using an auxiliary laser-doppler vibrometer sensor, *Proceedings of Speech Processing Conference* (2011).
- [237] R. Peng, C. Zheng, X. Li, Bandwidth extension for speech acquired by laser Doppler vibrometer with an auxiliary microphone, in: 2015 10th International Conference on Information, Communications and Signal Processing, 2016, <https://doi.org/10.1109/ICICS.2015.7459894>.
- [238] W. Phusakulkajorn, Y. Zeng, Z. Li, A. Nunez, Unsupervised representation learning for monitoring rail infrastructures with high-frequency moving vibration sensors, *IEEE Trans. Intell. Transp. Syst.* 26 (2025) 12746–12760, <https://doi.org/10.1109/ITTS.2025.3557712>.
- [239] T.G. Ritto, F.A. Rochinha, Digital twin, physics-based model, and machine learning applied to damage detection in structures, *Mech. Syst. Signal Process.* 155 (2021), <https://doi.org/10.1016/j.ymssp.2021.107614>.
- [240] H. Liu, M. Xia, D. Williams, J. Sun, H. Yan, Digital twin-driven machine condition monitoring: a literature review, *J. Sens.* 2022 (2022), <https://doi.org/10.1155/2022/6129995>.
- [241] A. Ferrari, K. Willcox, Digital twins in mechanical and aerospace engineering, *Nat. Comput. Sci.* 4 (2024), <https://doi.org/10.1038/s43588-024-00613-8>.
- [242] T.T. Khoei, A. Singh, Data reduction in big data: a survey of methods, challenges and future directions, *Int. J. Data Sci. Anal.* 20 (2025), <https://doi.org/10.1007/s41060-024-00603-z>.
- [243] K. Lu, K. Zhang, H. Zhang, X. Gu, Y. Jin, S. Zhao, C. Fu, Y. Yang, A review of model order reduction methods for large-scale structure systems, *Shock Vib.* 2021 (2021), <https://doi.org/10.1155/2021/6631180>.
- [244] W. Jia, M. Sun, J. Lian, S. Hou, Feature dimensionality reduction: a review, *Complex Intelligent Systems* 8 (2022), <https://doi.org/10.1007/s40747-021-00637-x>.
- [245] M. Sharma, A. Tomar, A. Hazra, Edge computing for industry 5.0: fundamental, applications, and research challenges, *IEEE Internet Things J.* 11 (2024), <https://doi.org/10.1109/JIOT.2024.3359297>.
- [246] R. Das, M.M. Inuwa, A review on fog computing: issues, characteristics, challenges, and potential applications, *Telematics and Informatics Reports* 10 (2023), <https://doi.org/10.1016/j.teler.2023.100049>.