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REVIEW ARTICLE

Measuring Vibrations in Large Structures with Laser-Doppler Vibrometry and Unmanned Aerial Systems: A Review and Outlook

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Vibrations in large structures such as buildings, dams, cranes, plants, drilling platforms, bridges, and wind turbines are often difficult to measure because, among other reasons, it is challenging or even impossible to attach suitable vibration sensors to all the positions/locations of interest. Optical, noncontact measurements from the ground, conversely, are only possible for the visibly accessible parts and often require long measurement distances or unfavorable viewing angles from the ground due to the vertical extent of the location of interest on the large structure. Employing noncontact vibration measurement methods from or via an unmanned aerial vehicle (UAV) is preferable for many applications and is, therefore, becoming an increasingly interesting research topic around the world. This paper reviews the current state of the art for measuring and analyzing vibration in large structures with laser-Doppler vibrometry (LDVy) supported by unmanned aerial systems (UASs)—which employ one or more UAVs and associated ground-based control equipment—and related topics, including excitation as well as data collection, transfer, processing, and interpretation. The review includes a brief overview of vibration-determined damage detection in large mechanical and civil structures, associated nondestructive testing (NDT) sensor technologies including in particular LDVy, UAV technology, and other NDT measurements supported by UASs with a focus on LDVy as the preferred vibration sensor technology. Ultimately, following the presentation of the state of the art, we discuss some of the currently foreseen challenges for implementing LDVy with UASs for operational stability analysis of large structures and the currently addressed and possible future research topics required to maximize the benefit of this exciting system integration opportunity.

Introduction

The collapse of the Morandi traffic bridge in Genoa (Italy) in 2018 caused by corrosion in Pillar 9 [1] (see Fig. 1), resulting in the death of 3 people, was a particularly dramatic demonstration of the impact and severity of material fatigue in civil structures, which can include numerous other technical facilities and infrastructure such as cranes [2], wind turbines, and oil and gas platforms to name but a few examples. It is reported that such structural damage has recently increased due to climate change and associated accelerated aging [3–5]. Since the number of structures with a critical age is ever-increasing, the requirement for structural health monitoring (SHM) and associated techniques becomes more important every day in every industrialized, urbanized country around the world.

Minimization of damage risks to structures and outdoor engineering facilities is possible by increasing the level and quality of knowledge about their structural properties and their aging behavior by regularly analyzing their vibrational or dynamic characteristics. So-called forced and ambient vibration testing (AVT) methods [4,6–8] can be implemented, with the choice over which to implement being a function of numerous factors, as will be described subsequently. Whichever approach is taken, structural response measurements are typically achieved by installing dozens to hundreds of transducers—accelerometers, strain gauges, or fiber-optic sensors are most commonplace—at critical points on the structure under test [9,10]. Figure 2 shows 2 examples of the kinds of large infrastructure that can be dynamically characterized using such an approach.

In Fig. 2A, very large cable-stayed bridge has been instrumented with a range of transducers including accelerometers, strain gauges, etc. as can be seen in the annotation. While some of the slower acquisition rate installed devices (i.e., wind speed/direction sensors, corrosion gauges, and tiltmeters) may be
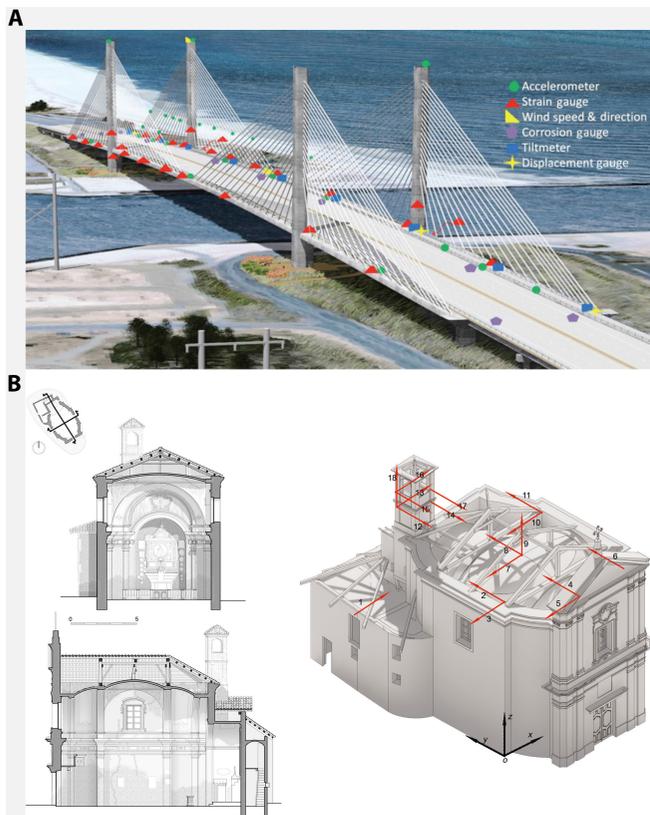
Fig. 1. The collapse of the Morandi traffic bridge in Genoa (Italy) 2018 caused by corrosion in Pillar 9 [1], image from [173].

Fig. 2. Examples of structural damage assessment campaigns for large infrastructure: (A) SHM of a cable-stayed bridge [174] and (B) SHM of a historic church [175], showing in particular the complexity of the task due to the scale and inaccessible nature of the surfaces of interest on the structures.

orthogonal directions. While effective instrumentation of such a scenario is still not trivial, here the further challenge identified is in the complexity of the geometry and the necessary measurement locations. Such historical buildings are more problematic in terms of accessing the locations of interest and mounting, often inevitably at least somewhat invasively, the transducers themselves and their cabling. In both scenarios, it is suggested, based on the above observations, that alternative, noncontact vibration measurement approaches would overcome at least some of the associated challenges and be more applicable in some cases.

Determining the optimal sensor placement or measurement location is a common problem in many engineering applications and, for the reasons described, is a critical issue in implementing effective SHM campaigns [10–12], especially for large structures with many inaccessible areas. In addition to the complexity of the measurement hardware installation, complications in measured data transfer and processing—as well as in visualization and evaluation of results to determine the state of health of the structure—further adds to the challenge. Damage assessment based on vibration-pattern measurements involves the extraction of modal parameters, i.e., natural frequencies and mode shapes, using an operational modal analysis technique. There are 2 discrete methods for analyzing modal parameters for damage assessment: data-based and model-based methods [10]. The data-based method is based on the changes in modal parameters over time, which can be correlated with structural changes or damage [13]. The model-based method, conversely, is based on the creation of an initial finite element (FE) model. This model contains assumptions about the mechanical properties of the structure with a high degree of uncertainty [10,13]. The modal parameters from the measurements are used to refine the FE model. This step is called FE model updating and aims to minimize the uncertainty of the model to best represent the actual properties of the structure. The updated FE model can be used to subsequently study the response of the structure in the future, it having been subjected for example to various earthquakes and other environmental conditions.

Vibration measurements, together with the comparison of simulation outputs, is a powerful tool set for damage detection in large structures. Optical, noncontact response measurements can overcome the problems that occur when one would have to place sensors—each generally requiring cabling to provide power and to retrieve the signal—all over the structure that can be huge like a skyscraper, a bridge, or a wind turbine. However, not all measurement positions can be measured from a ground-based optical sensor—for example, a camera-based system or a laser scanner—because not all positions of interest are visible from the ground or an oblique incidence of the laser light may falsify the measurement. Unmanned aerial vehicles (UAVs), also often referred to as drones, can play, therefore, an important role in damage detection and failure analysis since they can reach locations on such a structure, which are inaccessible otherwise. UAVs—the key component in an unmanned aerial system (UAS), which also includes the necessary ground-based control equipment including the pilot operator—have gained increasing attention for such tasks because they can carry sensors to any location and can thereby compensate for these highlighted disadvantages.

Preferable for the vibration measurements are noncontact sensors such as microwave vibrometers [14] or laser-Doppler

possible to be battery/solar powered and remotely/wirelessly communicated with, this is unlikely to be readily possible with the vibration transducers, which will require power for signal conditioning and will produce information at much higher data rates, typically transmitted over either copper or optical fiber cables. It does not take much imagination to anticipate the challenges associated with installing and maintaining such power and signal transmission cables in such a scenario. Figure 2B, on the other hand, shows a scenario where the number of transducers (18) is smaller with multiple channels colocated in

vibrometers (LDVs) [15,16]. Microwave vibrometers use electromagnetic radiation at frequencies ranging from 100 MHz up to several gigahertz and, thus, employ wavelengths within the millimeter to meter scale. Such relatively long wavelengths allow for robust measurements and, thus, recent developments show that microwave vibrometry is a powerful tool for vibration measurements from large structures [17–19]. However, also due to the long wavelength, microwave techniques do not yield spatial resolutions as fine as their light-based counterparts and thus cannot resolve picometer vibration amplitudes. Recent developments in LDVy have allowed us to overcome some of the primary former obstacles of the approach, which arguably previously limited the technology to higher frequencies measurements and well-controlled measurement scenarios. As we will discuss in this paper, techniques like signal diversity, differential measurements, and compensation of sensor head vibration now theoretically enable very robust measurements with LDVs, even in challenging, field-based campaigns and at such low frequencies as are common for large infrastructure. Since high spatial and vibration amplitude resolution is key to the detection of small-scale structural damage at an early stage, we will concentrate in this paper on vibration measurements using laser-based solutions.

Such a laser-based optical sensor, which is particularly suited to the measurement of vibration in large structures, is the LDV. We believe that LDVs, in combination with UAVs, provide the means to collect all the necessary data to dynamically characterize and determine the failure risks of large mechanical structures. This paper, therefore, gives a review of the current state of the art on this topic. As we will demonstrate, the current state of the art does not resolve all of the requirements in order to obtain accurate and complete datasets from this unique and contemporary UAS. Therefore, we herein identify some important, currently foreseen future research tasks in this field and invite the readership to contribute to this new and exciting area of scientific and engineering investigation.

Dynamic Characterization of Large Structures

Dynamic characterization fundamentals

The effective characterization of the dynamics of components and assemblies is of fundamental importance in the mechanical engineering discipline through which, in combination with other appropriate engineering disciplines, the built, human environment is realized. Modern-day vibration engineering incorporates the several processes of designing systems and structures to have predetermined, predictable, and safe dynamic behavior in the presence of given, expected loading conditions. The combination of analytical, computational numerical, and experimental approaches will take into account aspects to include geometries, material properties, assembly or construction techniques, load cases, and so on. Historically, linearization and other simplifications of the complex scenarios—often synonymous with frequency-domain-based techniques—have been necessary to enable computationally efficient models for ease of implementation processing, storage of (sparse) data and results, etc. More recently, however, the increasingly cost-effective availability of (cloud-based) computational effort and storage, in tandem with lower-cost, ubiquitous Internet of Things like sensing and Big Data, has led to time-domain-based capabilities becoming a more viable alternative. Indeed, statistics-based approaches, integral to artificial intelligence (AI) and machine learning, potentially informed by some physics, are a paradigm-shift away from the application of validated, linearized models toward data-based equivalent capabilities for the effective design, operation, and condition assessment of dynamic mechanical systems.

Whatever the specific nature of the design and production approach, at installation or commissioning of such systems, forced vibration testing (FVT) is often implemented as a dynamic characterization method appropriate to relatively quickly characterize the initial, undamaged nature of the structure. Subsequently, equivalent information can be collected and compared back to that of the system in its known healthy state. FVT involves the use of some form of excitation system, such as an impact hammer or a shaker/impactor. FVT normally therefore realizes strong structural vibration responses, achieving high signal-to-noise ratio (SNR) and a higher sensitivity to changes in the vibration behavior, required for better fatigue or other damage assessment. FVT might often be described as NDT. AVT, on the other hand, is a method appropriate for structures that are excited by environmental loads, such as wind forces or nearby traffic activities. AVT has the advantage that, unlike for FVT, external excitation is not required and many large structures (e.g., historically important structures) prohibit the use of such directly applied external excitation. However, AVT generally relies on having permanently installed response measurement transducers that record vibration data at lower sample rates but over longer durations than FVT. Processing of these response only datasets differs, given the lack of a known excitation or forcing function, with results to be compared with those from reference measurements when the structure was in its initial, undamaged state. FVT is generally more expensive and resource intensive to implement than AVT, which tends to use lower-cost, embedded sensors, some of which may not need to survive the lifetime of the parent structure. AVT, in general, comes under the SHM umbrella.

Nondestructive testing vs. SHM

Characterizing the dynamics of structures and systems is important for confirming optimal performance. Performance can come in many forms and includes, for example: accuracy, precision, repeatability (in the case of a structure that performs a process), efficiency, comfort, etc.. Non-destructive testing (NDT) techniques can be implemented for a detailed, typically one-off—often at the time of installation or commissioning and infrequently periodically thereafter—assessment of a structure's dynamic characteristics. A wide range of approaches exist making use of traditional contacting through to more contemporary noncontacting exciters and sensors, all with the common attribute that material, component, subassembly, or system-level insights can be obtained without the cause of any damage or impact on functionality. NDT can include the collection of physical parameters in addition to those directly associated with structural dynamic characteristics, for example, electromagnetic, temperature, humidity, and chemical composition; however, in the context of dynamic characterization, NDT is an FVT approach. NDT measurement campaigns are typically time-consuming and resource-/cost-intensive to undertake, hence their relative infrequency. Expensive, research-grade sensors and associated measurement chain elements (signal conditioners, cabling, data acquisition systems, data processing, and storage systems) with high sensitivities, low noise floors, wide dynamic, and, perhaps, frequency ranges are often used

in order that high SNR and accurate and reliable measurements are collected. When implemented at commissioning/installation, processed datasets constitute the reference data against which all future such or alternative measurements are compared to determine the state of health of the structure and, perhaps, predict its remaining useful life/service interval requirements. For the sake of also obtaining high-quality datasets, large vibration responses are typically elicited in the structure using vibration exciters such as steady-state, electro-/hydro-dynamic shakers or transient, impact-/thumper-based approaches. For this reason, such FVT approaches generally require the structure to be taken out of service for the duration of the test, further adding to the cost of the campaign.

SHM, alternatively, is an AVT technique in which generally lower-cost sensors—for example, strain gauges or telecommunication grade fiber optics-based equivalents—are installed throughout and within the structure at the time of production or commissioning [12,20]. SHM approaches allow for the detection of dynamic characteristics in engineering structures at significantly lower costs and, due to their more frequent, periodic implementation during continual operation, at an earlier stage. Since SHM aims to detect defects, damage, and failure in structures that can potentially lead to their collapse, effective SHM may ultimately save human lives. Defect detection of civil, mechanical, and aerospace engineering infrastructure through changes in its vibration response by monitoring a specimen frequently or continually over an extended period of time is the typical SHM approach. The aim of SHM is to, periodically and frequently during the product or structure life cycle, obtain information on structural integrity which will also, more typically than for NDT, include measurements of parameters beyond those directly associated only with dynamics including, e.g., operating temperature, lubrication analysis, and so on. Comparison of this information to equivalents that were obtained at the commissioning of the system—i.e., when the health/structural integrity was known to be optimal—allows for the status of the structure and, for example, the remaining useful life to be determined. Since, however, the locations and severity of defects that occur in service are usually unknown and initially small, effective SHM requires the means to monitor a specimen with a fine resolution and over its entirety. However, these 2 requirements—fine resolution and whole-field—are often in direct conflict due to limited resources, channel count, acquisition, and storage capacity.

Dynamic characterization challenges in large structures

The attachment of sensors on large structures is often a challenge, for the reasons previously described, and, due to this, the generally limited number of sensors is often insufficient to obtain data for a sophisticated vibration analysis. Sensors are usually permanently installed, in advance at the time of manufacture in discrete locations, generating measurement data continuously from then. Therefore, in SHM, the temporal frequency with which data are generated is usually quite high, whereas the spatial frequency is low due to the limited number of sensors sparsely spread across the specimen [21]. However, small defects—which all are at initiation—typically generate quite localized changes in the operational deflection shapes. Effective SHM systems should, therefore, cover the surface completely in order to detect and localize defects. Meanwhile, cross-sensitivities of the measured quantity to environmental influences can cause false-negative or false-positive defect detection, undermining the robustness and effectiveness of the SHM system. Only if these cross-sensitivities can be suppressed sufficiently, without adversely impacting sensitivity to the defect-originating measured parameters, is the measurement technique suitable for effective SHM [22].

Numerous different measurement methods are currently deployed in SHM. The most commonly used SHM techniques that have been studied for several decades are vibration-based methods, where the modal properties (natural frequencies—or eigenvalues, mode shapes—or eigenvectors, and damping ratios) of the specimen are investigated [23]. Alternative techniques, for example, the potential drop method, evaluate the changes in impedance in metal structures with age/fatigue and have also been proven to be promising techniques to detect cracks early [24]. However, such techniques require a permanent installation that is difficult to realize for existing structures. Thus, sensor networks should be installed in the first place during the construction. In addition, integral methods give just the information that fatigue is present but they do not give sufficient information to locate or specify defects. Sometimes, it is not practically possible to retrofit sensors to existing civil structures. It is often also the case that such integrated sensors measure acceleration and, for the relatively low frequency vibration experienced in large structures, acceleration levels are typically very low. In this case, a regular damage inspection with a contactless measurement means may be the better choice to ensure the integrity of structures.

The simplest form of noncontact inspection method is visual inspection by the naked eye, which can be supported by optical aids such as magnifying glasses, telescopes, or binoculars. Capturing and storing or processing such visual information can be achieved with the use of cameras and, with the help of digital image analysis, the method can be extended with modern methods, for example, optical flow or digital image correlation (DIC) [12,25,26]. Digital image data enable automated comparison with old, reference image data and can even be used with AI for enhanced interpretation and classification of the differences [12]. Microwave vibrometry is another alternative to measure displacements of several millimeters with high robustness [14,17,18]. Both this and DIC will be discussed further subsequently in the context of damage detection measurements from UAVs. Displacement or strain is generally the parameter collected with such approaches and this is good for low-frequency motions where displacement levels are relatively high. This is appropriate in the context of the dynamic assessment of large infrastructure, where vibration frequencies can be expected to be in the scale of Hz as opposed to kHz. However, for mid- to higher frequencies, displacement levels are much lower and velocity may be the preferred vibration parameter.

Differentiation of displacement-based and integration of acceleration-based measurement data are both options to derive velocity, but at the risk of the introduction of noise with the former and the need to detrend due to unknown initial conditions with the latter. Alternatively, direct velocity measurement with LDVy to determine dynamics and thereby damage has gained a lot of attention during the last decades [15]. LDVy has the additional benefits of being inherently noncontact/noninvasive, industrially robust/reliable, and highly accurate with high dynamic and frequency ranges. In respect of the latter specifically, this genuinely extends from several GHz in the upper limit (imposed only by the demodulating electronics

and not the light itself) all the way to DC in the lower limit, thus making LDVy also a viable solution for large infrastructure measurements. Recent research papers show that an LDV together with UAS technology constitutes a particularly powerful tool set for vibration measurements of large engineering structures. LDVy integrated within UASs has the potential to offer a flexible, contactless, automated solution that can be used to find locations of defects with high frequency and dynamic ranges and fine spatial resolution in a particular location of interest or a wider survey over the entire structure. The following chapters will, therefore, offer a more detailed review of each of these 2 primary technology topic areas: LDVy and UAS. Subsequently, the current state of the art on their ongoing integration and the important research and engineering tasks yet to be completed will be reviewed.

Laser-Doppler Vibrometry

LDVy origins

Laser-Doppler techniques were explored shortly after the first demonstration of the LASER in 1960 by Maiman [27]. Yeh and Cummins [28] investigated flow fields and introduced the laser-Doppler technique in 1964 to measure velocities of moving microscopic monodispersed polystyrene spheres by the frequency shift of scattered laser light. These frequency shifts are generally called Doppler shifts, named after the Austrian physicist who first considered the phenomenon in 1842 [29]. In 1965, Foreman [30] demonstrated the detection of smoke in a gas flow. The flow measurement with Doppler technique, laser-Doppler anemometry, was the most popular application of the laser-Doppler technique in the 1960s. Also in 1965, Kroeger [31] was the first researcher who measured a Doppler shift of light scattered at a solid moving surface. Deferrari and Andrews [32] demonstrated in 1966 the application of a laser-Doppler technique with a homodyne interferometer to measure vibrations by evaluating the sidebands at small vibration amplitudes. A year later, the same group measured with the same homodyne interferometer the first mode shape by measuring the vibration at different positions on a structure with respect to a phase reference [33]. G.A. Massey introduced the first heterodyne laser Doppler vibrometer in 1968 and already integrated mode shape measurements by scanning the beam over a structure [34].

The homodyne interferometer simply detects the interference of the Doppler-shifted measurement light and the reference beam. The direction of the movement cannot be determined. Therefore, the first simple configurations were just used to measure flow in one direction or the speed of turbine blades also always moving in one direction [35,36]. Later, improved solutions were introduced. A predefined frequency shift to the reference beam enables determination of the direction of the motion. Approaches to this include the use of a rotating diffraction grating [37,38] and rotating scattering disc [39]. The setup in Fig. 3A, for example, has a stabilization on the quadrature point, which is the most sensitive point of the fringe pattern in the center between the dark and the bright fringe. Thus, within a certain bandwidth defined by the low-pass (LP) filter in the figure, the phase between the reference and measurement beam is fixed. The high-pass (HP) signal, on the other hand, can unambiguously measure displacements at high frequencies with amplitudes smaller than a quarter of the laser wavelength. A piezo-transducer (PZT) at the reference mirror (M) is used to keep the average optical path lengths between the reference and measurement beams constant with the control signal obtained from the LP output. Such solutions are still used to measure high-frequency vibrations in the GHz range.

The most sophisticated, commercially available homodyne LDV was developed by the company Ometron Ltd. in the late 1980s. Since the company did not patent and hardly published, there are only a few direct publications on their technology available [40,41]. Other customers or competitors gave a short description when using their technology [42,43]. In this solution, an in-phase-quadrature (IQ) signal is generated optically by generating 2 interference signals where there is a 90° phase difference in the delays between the measurement and reference beams. This novel arrangement enabled direction determination without frequency shifting of the reference beam and was optically efficient, yielding relatively (for the time) excellent performance in situations where back-scattered light from the target was low, for example, due to optically noncooperative surfaces.

However, the homodyne technique had some fundamental disadvantages when compared to the heterodyne alternative. Minor optical imperfections in the elements generating the delay can lead to strong signal distortions. In addition, small velocities were difficult to demodulate and also nonlinearities in the photo detector resulted in signal distortions. Due to these issues, the homodyne technique disappeared from commercial
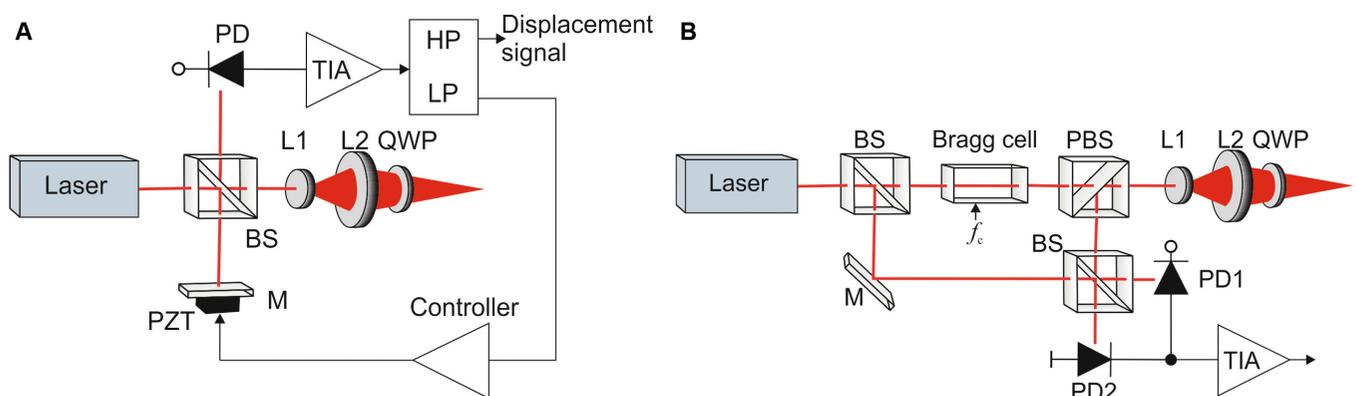
Fig. 3. Schematics of (A) a homodyne interferometer with quadrature stabilization and (B) a heterodyne interferometer with Bragg cell as acousto-optic frequency shifter. PZT is a piezoelectric actuator also known as a piezo-transducer, BS is a beam splitter, PBS is a polarization beam splitter, M is a mirror, L is a lens, QWP is a quarter wave plate, PD is a photo diode, and TIA is a transimpedance amplifier.

systems but were rediscovered for integrated IQ interferometers for LDVy [44]. A detailed description of this type of LDV can be found in these book chapters [16]. Nowadays, heterodyne LDVy—as shown in Fig. 3B—is the dominant technology for noncontact vibration measurement and all commercial systems employ this technology [15,16]. The heterodyne interferometer introduces a frequency shift between measurement and reference beam of the interferometer. Therefore, a carrier signal is generated by the photodetector at the frequency of the frequency shift between the 2 interferometer beams. The movement of the specimen leads to a frequency modulation of that nonzero carrier, enabling discrimination of the direction of motion. The frequency modulation is the Doppler frequency shift detected by the LDV, which is given by [16]:

$$\Delta f_{\mathrm{D}}(t) = 2v(t)/\lambda \qquad (1)$$

which explicitly and importantly shows that, for a given laser wavelength, the Doppler shift is directly proportional to the target surface vibration velocity.

The inherent frequency shift is usually introduced by an acousto-optical modulator in a specific arrangement called Bragg cell since it makes use of Bragg diffraction on an ultrasound wave. Frequency demodulation of the AC component of the detector signal reveals the velocity signal of the surface movement in the direction of the measurement laser beam while a phase demodulation results in the displacement signal.

LDV evolutions

Inventions and innovations continued at pace during the 1980s with important developments like the scanning LDV (SLDV) for modal testing [45] or making LDVs portable [39,46]. The fiber-based vibrometer [47,48] was developed in order to access vibrating surfaces in a narrow environment with a small probe head. The dual parallel beam torsional vibration measuring vibrometer [49,50] or the dual cross-beam in-plane vibrometer [51] enabled measurement of other vibration components, specifically angular and in particular torsional vibration from rotors. In the 1990s, LDVy became more widely commercially available and, especially, the SLDV was established as a gold standard tool for the experimental investigation of vibration behavior of technical systems [15,16,52,53]. Here, the measurement beam is scanned point-wise over the surface—typically with an orthogonal pair of galvanometer-driven mirrors—and the LDV captures the vibration with a phase relation to the other measurements of the scan. Usually a reference signal is required to establish the phase relation—often this is taken from the signal used to excite the structure in a repetitive way for each of the multiple averages taken for each point on the structure. Displaying phase and amplitude at a certain frequency reveals the operational deflection shape (ODS), which is an important output to determine vibration modes. If a force transducer was used to determine the input excitation force, then these ODSs are known as mode shapes with such frequency response functions or transfer functions (input-independent) being highly powerful for the effective dynamic characterization of vibrating structures and systems.

Fundamental to the proper interpretation of scanning LDVy (SLDVy) datasets is the integrated high-resolution video camera and geometry scanning capability—and associated computer-aided engineering software environment—which enables mapping of the vibration shapes onto images of the structure under test. Delivering a step change over equivalent

measurement capabilities based on traditional, contacting transducer technologies—especially due to the fine spatial resolution, elimination of mass-loading, and increased dynamic and frequency ranges—SLDVy data became critical for the correlation of numerical/computational models such as those from FE analysis. As a direct result of the the advent and rapid evolution of SLDVy, the automotive and aerospace sectors in particular saw a huge uptake in SLDVy at this time, with significant improvements in noise, vibration, and harshness, including body panel vibration, brake squeal, and, through the adoption of an evolution of SLDVy to continuously scan or track a point of interest, windscreen wiper growl [54,55]. Other important new applications for SLDVy that arose in the 1980s and 1990s were hard disks [56], micro electro-mechanical systems (MEMS) [57], medicine [58], and ultrasonics [59,60]. The combination of LDVs with microscopes for MEMS and medicine in particular became important in order to measure with a much tighter probe laser beam focus [61,62].

Physical influences by the laser speckle phenomenon [63], refractive-index fluctuations [64–66] that lead to refracto laser vibrometry [67,68], or parasitic reflections within the internal interferometric arrangement [69] were all studied intensively and ultimately better understood. New instrument developments aimed to mitigate or, indeed, overcome some of these influences, with laser speckle—arguably a "necessary evil" but also often "the nemesis" in LDV measurements—in particular receiving much attention [70–72]. When a monochromatic, coherent light source—i.e., a laser—is reflected by a surface that is rough on the scale of the optical wavelength—i.e., most surfaces of interest in engineering—the scattered, dephased wavelets interfere constructively and destructively in the far field forming an apparently chaotic distribution of intensity (and phase) known as a speckle pattern [63]. Off-beam-axis movement of the surface leads to motion of the speckle pattern over the collecting optics with the result being amplitude and phase modulations additional to the measured signal and known therefore as "pseudo-vibration" [71]. While it might initially be tempting to suppose that a mirror-like (i.e., specular) reflection would be preferable, so as to eliminate this speckle noise, the diffuse nature of scattering from rough surfaces allows for at least some light to be collected in the instrument, even in the presence of inevitable misalignment between the optical axis and target surface normal. Measurements from mirror-like surfaces—the likes of which are often confined, from an LDVy standpoint, to very important, but largely out-of-scope here, microsystems—are, on the other hand, much more difficult to align. The challenges with laser speckle persist to the current era, driving recent developments such as signal diversity [73,74] which will be addressed in more detail subsequently. Meanwhile, accurate measurements became more and more important and dedicated standards were explored for LDV calibration [75], LDVy having already become established as the traceable reference against which contacting vibration transducers are evaluated [76]. It was also first shown in the 1990s that LDVs can be miniaturized with planar waveguides [77–79].

An SLDV is not applicable to the measurement of an ODS for transient vibration phenomena, as are present in self-excited vibrations, for example, in buildings or bridges by wind, in biological structures, or in the human body. Means to overcome this limitation have been explored in the period since 2000. Here, parallel measurements with a multidetector array [80,81] or a multipoint LDV [82–84] need to be applied, since multiple

repeated vibration events to allow the surveying of a structure are precluded. The first practical, industrially applicable multipoint LDV was, however, introduced quite recently [85] and can measure at up to 48 points in one dimension or at up to 16 points in three dimensions, simultaneously. Another approach to overcome some of the limitations of point-wise scanning is continuous scanning [86,87]. Here, the SLDV beam scans the surface continuously with externally generated analogue functions necessary to prescribe the required beam path introduced directly to the scanning mirror galvanometer controller pair. However, surface structure and laser speckle also have a strong influence and ultimately limit the practical application of this approach. Synchronizing the galvanometer drive signals with, for example, the rotation frequency of a shaft such as a turbine or other bladed disc led to synchronized scanning or tracking LDVy, which has received some attention [88,89]. Subsequently, an alternative, now fully commercialized technique, incorporating a half-of-shaft-speed rotating dove prism to optically de-rotate the object under test, was realized [90]. LDVy was also first used for the detection of (underwater) acoustic fields [91]—now known as refracto-vibrometry [68]—and the detection of mines [92]—an ever-important, humane application of LDVy—during this period.

An alternative approach to miniaturizing an LDV is the use of laser diodes and coupling the light from the specimen back into the laser diode. The light field is measured by the monitoring photo diode of the laser diode. Since light is injected back into the laser diode, the technique is called self-injection or self-mixing laser diode LDV. The processes in the laser resonator are nonlinear and, therefore, the signal from the photo diode in the laser diode is dependent on many influences. The signal is also affected by aging effects of the laser diode. It is possible to realize a dynamic range of approximately 40 to 50 dB with careful design and sophisticated signal processing [93].

Another hugely important development was the 3-dimensional (3D) SLDV. Here, the vibration is measured simultaneously from 3 directions with 3 discrete but interconnected SLDVs [94] and a dedicated additional 3D controller to merge and resolve the measurements into 3 independent components. Now fully commercialized into a robust solution, the highly powerful technique

has been developed to be the workhorse for modal analysis verification including, for example, in combination with an industrial robot [95] with further improvements to address simplifications of the scanning means also more recently realized [96–98].

LDVy was further advanced, for example, by developing heterodyne interferometers with high carrier frequencies in order to measure vibrations in the GHz range [99] or by using components from the telecommunication to realize complex sensors in a compact form [100,101]. From 2010, it became more and more obvious that the telecommunication near-infrared (NIR) wavelength of 1550 nm offers a significant advantage over the previously common visible wavelengths 568 (green) and 633 (red) nm. Firstly, a NIR source can emit 10 mW laser power at the laser-safety Class 1 compared with only 1 mW for a visible range source and be laser-safety Class 2 LDV due to the greater absorption of the former in the eye, which largely consists of water. In addition, the same light power has 5 times more photons compared to green visible light. Therefore, the shot-noise limit [102] can be achieved more easily for the photo detector and the resolution is much better due to better noise conditions, although the sensitivity drops due to the longer wavelength [102,103]. The long work on calibration procedures was finalized after 2010 [104,105], resulting in a specific ISO standard for LDVs [106].

LDVy current state of the art

A very important development in the second decade was that known as signal diversity [73,74] that made LDVs (almost) insensitive to speckle noise. Here, light from different polarization states and/or light received from different angles is evaluated in order to obtain different signals that can be combined to a signal with much better quality. Dräbenstedt [73] demonstrated the combination of the single demodulated velocity signals by a weighted sum. This technique was already well-established in radio communication but was new for LDVy. Schewe and Rembe [107] showed an improvement in noise of the velocity signal if the raw detector signals were combined. In 2022, Wang et al. published a combination algorithm based on maximum ratio combining to minimize the noise level. Figure 4 shows the improvement of this technique
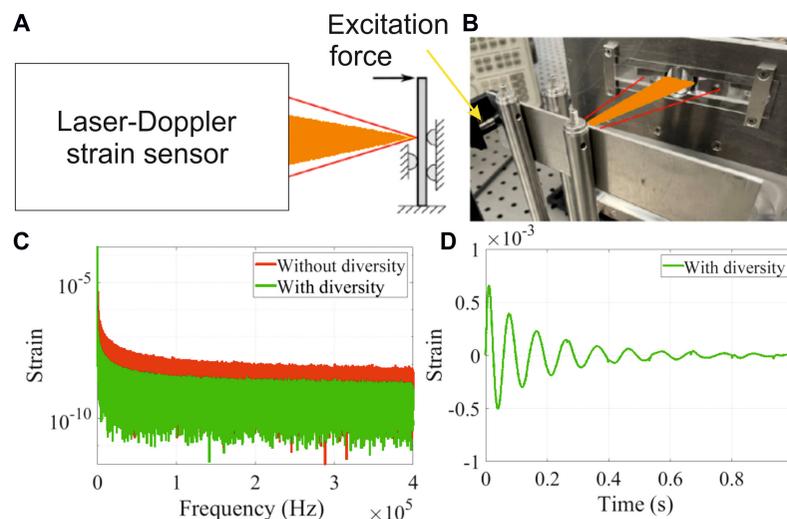
Fig. 4. Schematic (A) and photograph (B) of the laser-Doppler strain sensor measurement setup. The noise reduction of the measurement of the transient motion is shown as spectrum (C) and the time signal of the measurement with signal diversity is demonstrated in (D). The result was first published in Ref. [176].

for a laser-Doppler strain sensor. Improving the signal for this kind of sensor is even more critical than for conventional LDVs because both the reference and measurement beams interact with the surface and thereby suffer as a result of the laser speckle effect. In addition, at least 2 measurement spots are required, which makes it challenging to find a measurement location on the target with a good back-scattered optical signal for both beams. Signal diversity largely resolves these issues and can make LDVy almost completely insensitive to the detrimental effects of laser speckle.

A better understanding of the nature of the evaluated Doppler effect [99] and its 3D properties [108] led to a further important advancement: the development of 3D vibration measurement with just one impinging laser beam. Here, the scattered light is detected from different angles. The numerical aperture of the impinging light defines the spot size with a high numerical aperture, while other objectives detecting the light from an angle can have smaller numerical apertures. With this technique, 3D vibrations can be obtained with picometer amplitude resolution from a spot with a diameter slightly above 3 μm [108]. Besides laser speckle effects, LDV measurements are affected strongly by parasitic movements of the LDV itself and by atmospheric fluctuations of the refractive index called optical turbulence. Both effects can be treated by a differential LDV (DLDV) measurement. In DLDV, the reference beam of the interferometer also impinges on the specimen and a measurement of the relative displacement of the point of the measurement beam with respect to the reference point [111] is made. A suitable, nonvibrating reference point close to the point of interest needs to be available in order to make this technique feasible. The main idea is to pick up the same optical disturbances with both beams and to have the measurement information only in the measurement beam. This works particularly well if both beams can be guided close to each other. Figure 5 shows a displacement measurement in a 600 °C furnace and compares the measured spectrum with that from a single-beam LDV measurement. At least an order of magnitude improvement in the noise floor in the frequency range of interest below 10 mHz is observed for the DLDV vs. the single beam LDV in the presence of such (thermal) optical turbulence [109].

Putting the DLDV to one side for the moment, an LDV, in general, measures the relative motion or vibration between the sensor head and the specimen under examination. LDVs are commonly, therefore, tripod- or otherwise anti-vibration mounted to eliminate sensitivity to and "ambient vibration" from the measurement. In the absence of such devices or, indeed, when measuring from "vibrating platforms", any

motion of the LDV itself is an additional, "self-noise" source for the intended measurement of the target vibration. Halkon and Rothberg [110] were the first to investigate the compensation of LDV movements to the velocity signal by making measurements with a vibration sensor (typically an accelerometer, for ease of application) attached to the LDV at a location along the laser beam path, as indicated in Fig. 6. Application of a totally general geometrical, vector-based approach [111] allows for determination of the optimal location(s) of the compensation sensors and evaluation of the performance of the practically applicable measurement correction approaches. Subtraction of the integrated accelerometer signal—taking into account signal conditioning and processing aspects—renders the LDV measurement significantly more robust to perturbations due its own vibration, to which it is 100% sensitive.

The same researchers also proposed a complementary solution for the equivalent phenomenon that occurs when a vibrating steering optical element (a mirror, for example) is used to direct the probe laser beam to/from the location of interest on the target [112]. Here, as shown in Fig. 7, a measurement of the mirror vibration in the mirror normal at the laser beam incident location is required to fully correct the LDV measurement, which is subject to an additional velocity contribution as a result of the mirror vibration twice—once to and once from the point of interest on the target. As can be observed in Figs. 6D and 7B, significant reductions in the measurement error—on the order of 20 to 40 dB for typical vibration levels of practical "real-world" relevance—are realized. The corrected signal is only limited by the noise of the correction accelerometer (and associated processing for velocity) as well as the synchronization (equivalent to the phase adaption) between the 2 sensors and not by the vibration of the LDV. In both cases and in general, the measured signal, significantly perturbed by the instrument or steering optic vibration, differs hugely from the measurement of the true target vibration. True target vibration is, of course, not available in practice, but only in the lab-based scenarios that have been conceived for capability research and development purposes; otherwise, there would be no need for the measurement technique! After correction, however, the LDV signal is almost impossible to differentiate from that of the intended measurement. In the case of the case of the vibrating sensor head, the result is an absolute measurement of the target vibration, equivalent to that which might be achieved with a contacting transducer but benefiting from the inherent remote, noninvasive nature of LDVy.

More recently, the same authors have extended the capability to SLDVs, taking into account the alternative combination of correction measurement components that need to be
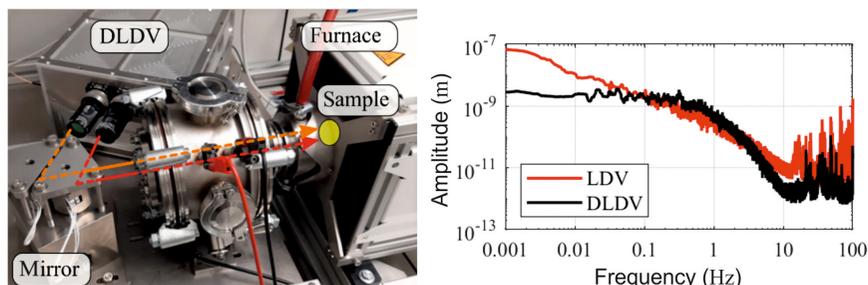
Fig. 5. Measurement setup for measuring the slow displacement of a chemically driven actuator in a 600 °C hot furnace with a DLDV on the left side. The right side shows the measurement results and compares it with a single-beam LDV measurement. Results were accomplished at TU Clausthal [109].
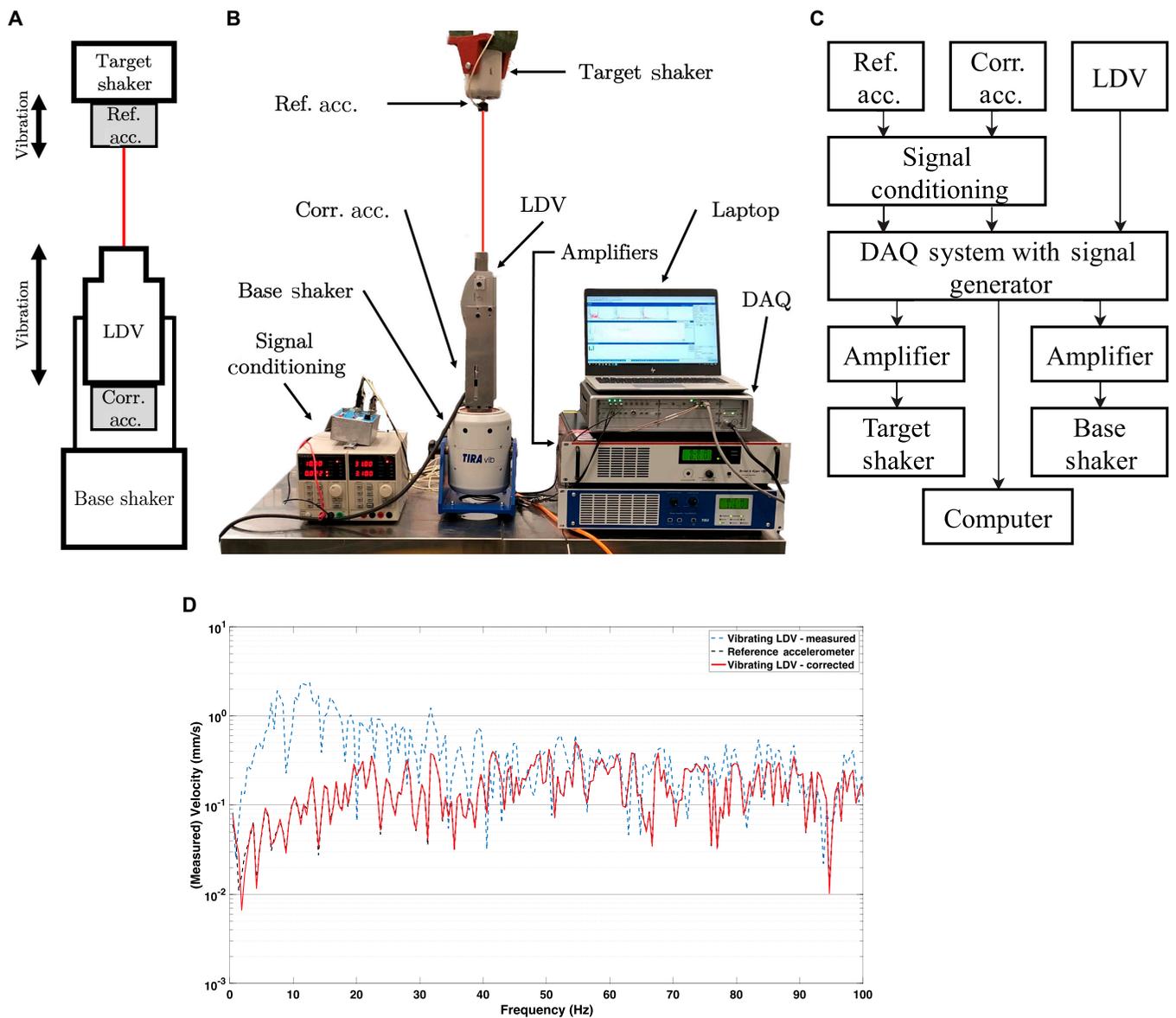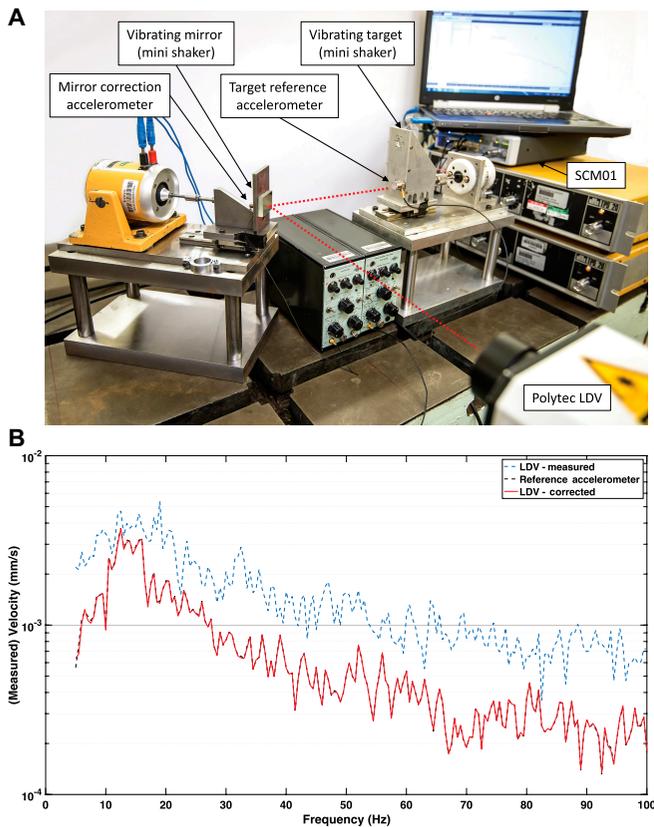
Fig. 6. An LDV measurement in the presence of base motion vibration: (A) schematic of the scenario, (B) annotated photograph of the physical setup (laser beam path highlighted for clarity), (C) block diagram showing the instrumentation connections, and (D) comparison between original and corrected LDV measurements with respect to the true target vibration (adapted from Ref. [171]).

applied as a function of scan angle in the presence of arbitrary, 6 degree-of-freedom "base motion" [113]. Figure 8 shows a simplified experimental setup—with a single correction accelerometer only—for the correction of on-axis SLDV vibration. Again, the researchers rigorously explored mathematically, and validated experimentally, the extent of the correction possible for a practical, fixed accelerometer location as a pragmatic compromise to the ideal location, which is at the laser beam incidence on the second mirror, in the direction of the outbound laser beam. It should be noted that (a) it is not possible to attach a transducer to the mirror without significantly affecting the mirror galvanometer dynamics; (b) even if it was possible to attach a transducer to the mirror, it would measure the vibration in the mirror normal, not outbound laser beam direction; and (c) the laser beam incidence on the second mirror changes as a result of the first mirror angle—this is how scanning in 2 directions is achieved with an orthogonal mirror pair.

Lastly, for field-based as opposed to lab-based (or benchtop) vibration measurement campaigns, it can be expected that the nature of the vibrations of interest, both of the target and of the LDV itself, is more likely to be time-varying or transient in nature, as opposed to statistically stationary. Here, correction algorithms that implement the necessary inertial sensor integration in the time, rather than frequency, domain are of importance and the implementation and relative performance of such techniques have been recently rigorously explored [114]. Another possibility for suppression of such noise by UAV vibrations and movements is the DLDV measurement that compensates for atmospheric influences as well [107]. Also, the combination of both capabilities—including the possibility of building in redundancy for additional robustness—might be a more appropriate approach.

Some of the very latest advancements address the improvement of the frequency range [115], the lateral resolution
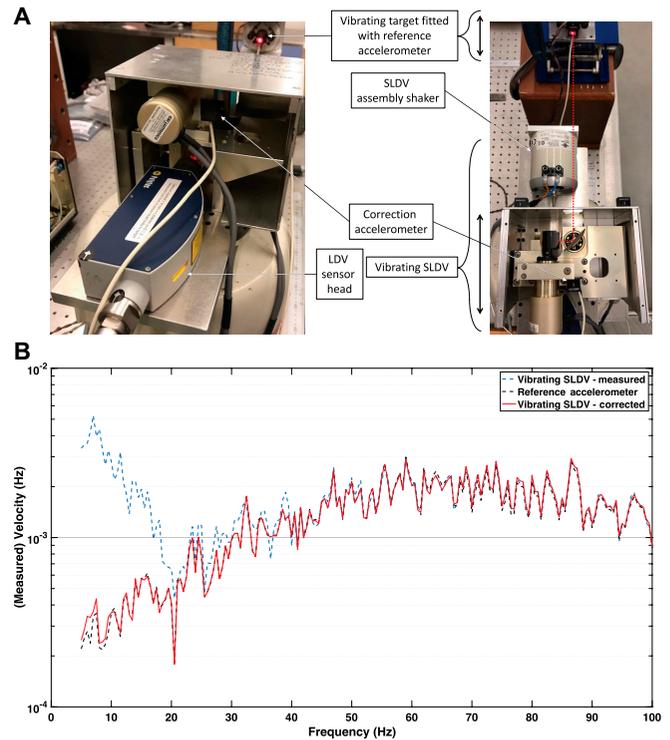
Fig. 7. An LDV measurement in the presence of laser beam steering mirror vibration: (A) annotated photograph of the experimental setup (laser beam highlighted for clarity) and (B) comparison between original and corrected LDV measurements with respect to the true target vibration [112].

Fig. 8. Correction of SLDV measurements in the presence of single-degree-of-freedom on-axis base motion vibration [113]: (A) annotated experimental setup (laser beam path highlighted) and (B) comparison between original and corrected SLDV measurements with respect to the "true" target vibration (adapted from Ref. [113]).

[116,117], and the improvement of the amplitude resolution [118,119] at and below the shot noise limit. In particular, the application of entangled quantum mechanics states of the photons can reduce the shot noise substantially below the shot-noise limit and enables the new field of attometer LDVy [120,121]. The combination of LDVy and drones requires a sophisticated suppression of all such disturbances as have been the focus of the recent state-of-the-art research efforts described herein.

LDV application to structural dynamic characterization

As previously noted, the very fine spatial resolution of SLDVy measurements lends the technique well to the updating of FE models where numbers of nodes and elements is increasingly large due to access to ever-growing computational performance. Indeed, SLDV experimental campaigns can be further enhanced with the integration of sophisticated commercially available structural excitation solutions such as automatic modal impact hammers or mini inertial shakers, which truly yield excellent experimental data with high SNR that are ideal for the correlation and validation of such computational numerical models. An LDV measures vibration with picometer displacement resolution and, therefore, is well-suited to the measurement of operational deflection or mode shapes that are sensitive to damage and material fatigue, particularly as vibrational energy levels in the structure are varied [122]. Structural vibration needs to be excited at higher frequencies because smaller cracks have greater influences on higher- than on

lower-frequency modes. Piezo actuators (PZTs) can generate vibrations of several 10 kHz [123]. Cao and Rembe [124] showed that the best sensitivity is achieved if vibrations are excited in the range above 50 kHz and that picosecond laser pulses are well suited to excite a frequency comb with the frequency distance of the pulse repetition rate. Frequencies are excited up to several MHz due to the short pulse width. Siringoringo and Fujino [125] showed that ambient vibrations can excite some modes sufficiently to detect larger defects or areas of damage. Uehan [126] created an LDV for the diagnosis of railway structures with integrated compensation for sensor head ambient vibration; such a solution is clearly relevant in the context of making LDV measurements from vibrating systems such as UASs. Since 2012, SLDVy became more and more commonly deployed for crack detection in mechanical structures [127] and, especially, Lamb waves were used in combination with 3D SLDVs to detect damage in composite panels [128,129] or propeller blades [130].

Algorithms to process the data were also further improved, for example, by using wavelet transform techniques [131]. Multipoint LDVy can, of course, detect damage in real time during the operation of mechanical systems where vibration signatures are time-varying and transient in nature, rather than being steady state and statistically stationary [124]. Similarly, continuous SLDVy allows for a faster detection compared to SLDVy since vibration shapes can be extracted from the data much more rapidly [132]. LDVs became more and more important for bridge damage detection in the recent decade [73,133] with, for example, the Deutsche Bahn and Japan Rail both heavily relying LDVy on a regular basis to inspect and determine the health of railway bridges.

LDVy is a promising sensing technology for conducting the fast and efficient AVT of many types of large structures [134–138] with high bandwidth and high vibration amplitude resolution in the picometer range. The technical feasibility of LDVy in monitoring civil and historical structures was intensively reviewed in the lab and in situ in many research projects [127,139]. It was shown that structural damages and cracks are practically detectable by signal features from LDVy data under ambient excitation conditions. Recently, there have been several successful case studies using an LDV to measure the dynamic response of large structures [127,134–139] that may replace wireless sensors attached to the structures [140].

Hu et al. [134] utilized a long-range LDV for monitoring the lateral displacement feature of a skyscraper at a distance of 245 m. This feature showed an effective performance criterion to avoid damage to the brittle building elements of the skyscraper. Göhler at al. [135] presented the intensive research efforts of the Fraunhofer Institute of Optronics, System Technologies and Image Exploitation for using a long-range LDV to monitor the dynamic response of wind turbines and blades. The LDV was mounted on a motorized pan-tilt stage to monitor the rotating blades. The stage was controlled by a vision-based tracking system to create a rotating LDV spot that was synchronized with the blade rotations. While the measurement results are quite promising, the LDV testing conditions for monitoring the blades cannot be generalized for other large structures because of 3 key aspects. First, the rotating blades are subjected to a significant excitation by high wind forces at a special wind farm area. Second, the blades are manufactured using a relatively elastic material with a large strain. Lastly, the LDV was located on the ground at a large distance (approximately equal to the wind turbine height) to keep a large incident laser-beam angle (up to 45°) on the blade. With this distance, the sensitivity of the LDV is significantly reduced by the air density fluctuations and the reflective index of the blade surface. Nevertheless, tracking LDV is a powerful tool and has been used to successfully measure the mode shapes of wind turbine blades [141], the dynamics of windscreen wiper blades [55,142], or even fast rotors with a derotator [143]. These studies demonstrate that

it is practically feasible to track a specific measurement point on a moving target. Therefore, the means already exist to further research and develop the effective tracking of measurement points on a static structure measured from a moving platform, such as a UAV.

UAS Technology and Infrastructure Inspection Challenges

Aerial vehicle type

UAVs, sometimes referred to as drones, are aircraft that are operated remotely without a pilot on board. Often UAVs are smaller aircraft—enabled not only due to the removal of human passengers but also due to the increasing miniaturization of the various hardware subcomponents, i.e., batteries, actuators, and control/communication electronics. Drones are simultaneously becoming increasingly low cost and accessible to the mass market and there is, therefore, an increasing trend to use drones for inspecting and monitoring the health of large structures [144,145]. These UAVs may carry various noncontact inspection devices, such as cameras, to access otherwise hard-to-reach locations. The term "hard-to-reach" refers to locations that are difficult to access due to high costs, long installation times, and safety hazards. For instance, inspecting a tall building for damage requires an expensive scaffolding setup and a long installation time for integrating inspection kits. However, UAVs can easily convey these kits to the entire building with compact and more rapid arrangements. Drones can be categorized into 2 types: fixed-wing and multicopter, as illustrated in Fig. 9.

Most of the research in this field is focused on multicopter UAVs, which are preferred for their excellent maneuverability and stability in flight and their ability to take off and land vertically [146]. Such multicopter systems have wing spans generally no more than 1 m with multiple rotors with propeller blade lengths on the order of hundreds of millimeters. Fixed-wing drones, on the other hand, have longer endurance and produce less on-board vibration, noise, and disturbance emission than multicopter UAVs. However, due to their ability to operate at relatively high altitudes and speeds, they are better suited for

A fixed wing drone

Multicopter drone

Fig. 9. Different UAV types for remote inspection and monitoring applications. (A) is from [177] and (B) was taken by M.A.A.I.

large area surveillance applications with long-range inspection devices. Fixed-wing drones have, in general, wing spans over 1 m. This study concentrates on multicopter UAVs and is focused on their use for vibration-based dynamic characterization of large structures where the vibration and noise of the UAV itself therefore plays a key role in the quality of the data that can be obtained. An LDV is a very sensitive measurement instrument and its noise level is affected easily by external disturbances. An LDV on a UAV is exposed to particular interference. These disturbances lead to challenges that are described in the following and are summarized in the Table.

UAV noise and vibration sources

According to the literature and our recent flight tests, there are 2 main challenges for using multicopters for vibration measurement: onboard vibration noise and UAV hovering stability.

Onboard vibration noise

Onboard vibration noise is commonly experienced in UAVs due to the propulsion system, which includes electric motors and propellers. Indeed, the unique signatures of UAVs can be used to detect and classify them [147,148]—useful counter-drone capability. A vibration measurement on a quadcopter UAV with an LDV is shown in Fig. 10, indicating the motor

Table. Summary of key challenges for developing an airborne LDVs measurement system

Challenge	Root causes and effects	Mitigation
Onboard vibration noise	1. Motor and propeller vibration noises [178]. 2. Vibration excitation transferred to the drone body and its payload at the motor spinning frequency (about 50–100 Hz for small drones) and fundamental BPFs (100–200 Hz for small drones) and their higher harmonics [152].	1. Passive vibration dampers between the drone and its payload [149,150]. 2. Custom propeller airfoils or higher number of blades per propeller [151]. 3. Active vibration isolation and damping mechanisms [152].
Hovering stability	1. The drone controller cannot maintain a stable and fixed position and orientation using onboard IMU. 2. The drone is continuously moving and rotating around the hovering position [149,154,155]. 3. LDV laser beam is not correctly aligned to the target. The laser beam is subjected to micromovements that induce speckle noise [150].	Using advanced positioning sensors in addition to onboard IMU such as the following: 1. Onboard LiDAR [155] 2. Ground LiDAR [154] 3. RTK-GPS [150]
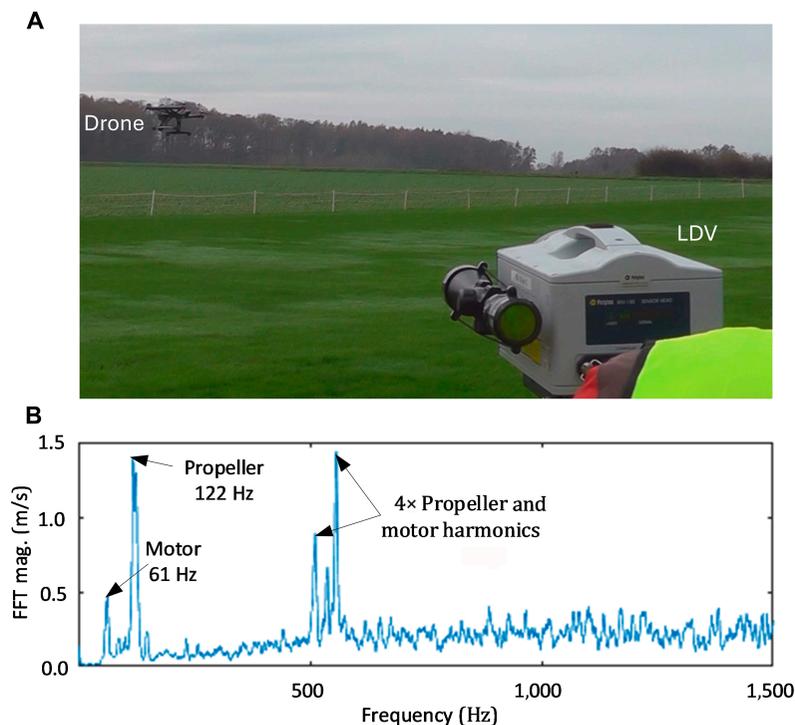
Fig. 10. Measurement of onboard vibration of a hovering quadcopter in the frequency domain using a long range LDV (results first shown in Ref. [178]): (A) the experimental setup and (B) the measurement of the onboard vibration that would become self-noise in an LDV measurement if the LDV is attached to the UAV.

speed of 61 Hz or 3660 RPM, the blade pass frequency (BPF) of the propellers of 122 Hz, and higher structural and BPF harmonics near 500 Hz. These vibrations in a UAV result in noise in an LDV measurement signal if the LDV is attached to the UAV in order to measure vibrations in a construction. When the propellers are rotated at their individual speed, which is equal to the motor speed multiplied by the number of blades per propeller (here, 2), it results in BPF. In a hovering quadcopter, with all 4 propellers rotating at similar speeds, there is only one average BPF for all propellers. However, if the UAV is moving or rotating, each propeller pair will have at least 2 different BPFs with a series of interfered, beating harmonics. All these sources of vibration are transmitted to and influence the UAV sensor payload—such as an LDV. It is important to note that onboard UAV vibration is not deterministic even when the UAV is hovering because the UAV controller continuously changes the propeller speeds to overcome transient wind gusts and UAV positioning errors.

The challenge of onboard vibration noise is not significant for low-rate inspection devices such as standard UAV cameras, which operate below 30 frames per second. However, it becomes a challenge for higher-bandwidth devices such as LDVs. To minimize the onboard vibration, the most common practice is to use efficient vibration dampers between the UAV body and the payload [149,150]. Additionally, advanced techniques such as special types of propeller airfoils [151] and active vibration cancellation techniques [152] are available to reduce onboard vibration noise. The shape of the propeller blades can affect the noise level by a few decibels [152]. A common technique to reduce drone vibration noise is to use a smaller propeller diameter with more blades to generate the same amount of thrust. Having more blades reduces the tip speed and therefore yields a reduction of the noise level by 4 dB [152]. However, more blades decrease the propeller's energy efficiency. A detailed comparison of active and passive vibration isolation for UAV payloads can be found in Ref. [153]. It is noted that employing dual passive and active isolation stages can cancel out 90% of the vibration noise for the UAV payload. These techniques can be utilized in applications where minimizing vibration noise is essential.

UAV hovering stability

A multicopter UAV can perform various flight phases, such as hovering, translational movement, or rotation around its axes. During the hovering phase, the UAV is intended to remain in a fixed position and orientation while in the air. However, it is challenging to achieve perfect hovering due to positioning and orientation errors. These errors can occur due to the UAV controller's efficiency and the UAV's positioning sensors. Wind disturbances can also play a significant role in causing and exacerbating these errors. Large hovering errors can pose a significant problem when using an LDV to carry an optical sensor payload. These errors can make it difficult to focus the laser beam on a remote location and mitigate speckle noise. As previously described, speckle noise occurs when the laser beam moves continuously over a remote rough surface, distorting the vibration signal and limiting the LDV performance. To minimize hovering errors, we need to explore different UAV positioning technologies. These technologies can be grouped into 2 levels: basic and advanced. The first basic level utilizes the Inertial Measurement Unit (IMU), which is a must for any UAV control system to ensure flight stability. The IMU provides

acceleration and gyro data to the UAV controller to keep the UAV stable. During the hovering phase, IMU data support the UAV controller to maintain the UAV in a fixed position and orientation. However, IMU has accumulative drift errors that increase over time. A popular commercial UAV can experience a large hovering error of up to 500 mm for both vertical and horizontal axes due to these errors as shown in Fig. 11. These positioning errors are challenging for LDVs as a payload.

Conventional Global Positioning System (GPS) technology is inadequate for addressing hovering errors due to its low position resolution of ± 2 m. For an advanced positioning solution, optical positioning systems, such as those described in Refs. [154,155], are recommended. In Ref. [154], a reflector prism, functioning as an optical marking tag, is fitted to the drone to achieve a positioning accuracy of up to 10 mm with a ground light detection and ranging (LiDAR) scanner. It involves the attachment of a reflector prism to the drone, which acts as an optical marking tag. The drone is then flown in such a way that the prism makes contact with the bottom side of a bridge. During flight, a ground laser scanner continuously monitors the drone-prism, which is in contact with the bridge, with a spatial resolution ranging from 10 down to 0.1 mm. This setup compensates for the micro-movements of the drone by maintaining full contact with the bridge. However, this approach is not practical for the majority of large structures due to geometric and safety constraints.

Another example in Ref. [155] showcases a custom-built quadcopter with an onboard LiDAR sensor. During the flight phase, the average drone position errors are 40 and 200 mm in horizontal and vertical directions, respectively. The current state-of-the-art drone positioning solution is Real-Time Kinematic (RTK)-GPS technology. In this technology, GPS data are deeply processed using a GPS receiver attached to the drone and a second GPS receiver fixed at a ground station to increase the position accuracy to around ± 20 mm, instead of $\pm 2,000$ mm for conventional GPS receivers [156,157]. The RTK data are fed to the drone controller to maintain hovering errors within ± 20 mm.

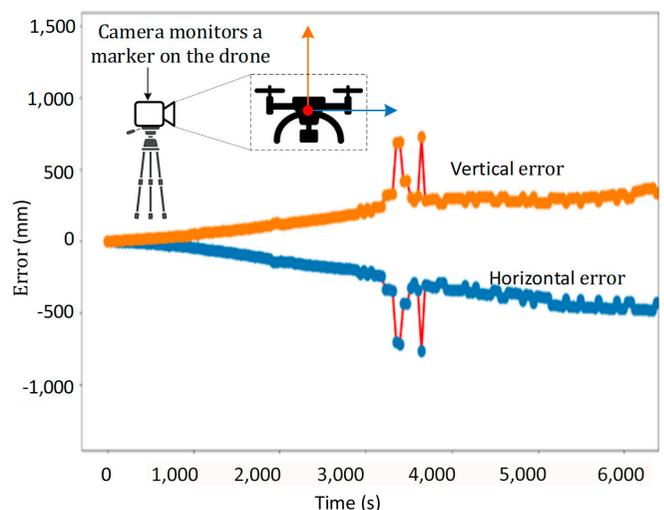The project "flying mirror" [156], based on DJI M300 RTK, represents the first practical use of RTK technology with an

Fig. 11. Example for measuring positioning stability for DJI Phantom 1 in hovering phase [179].

LDV. The hovering errors are bound to ±15 mm thanks to the DJI RTK station and 3 onboard RTK-GPS receivers on the drone. Multiple RTK antennas on the same drone are also used to measure the drone's yaw angle with higher precision than the onboard magnetic compass.

UAV-based inspection of large structures

There are currently 3 categories of drone-based inspection of large structures. These include (a) visual/camera-based inspection, (b) LiDAR, and (c) special drone measuring setups. Drone-based visual inspection involves the use of visible or infrared cameras to capture images of a remote structure [145,158,159]. The captured images are then analyzed manually or, more commonly, using image processing—including photogrammetry—and AI techniques to detect the presence of any visual abnormalities, which might indicate external damage to the surface of the structure. A further inspection approach is to use LiDAR technology attached to a drone, which scans the outer surfaces of a structure and creates a 3D reconstruction profile. Many higher-end drones are already equipped with LiDAR for navigation and path-planning/object avoidance purposes; thus, also utilizing this sensor for structural inspection is readily achievable. The technique may detect geometric abnormalities such as material deformation and disintegration [145,149]. An example of drone-based LiDAR is discussed in Ref. [145], in which a LiDAR—model DJI Zenmuse L1—is attached to a DJI Matrice 300 drone for bridge inspection.

The third category pertains to specialized drone configurations such as those described in Refs. [149,154]. Herrmann et al. [149] have devised a drone-based measurement system for monitoring modal shapes of a wind turbine tower. The system employs a laser triangulation sensor that is attached to a drone, model DJI Matrice 100, to measure the tower deflection shapes. The primary challenge of this approach was the micro-movements of the drone, even when at a fixed hovering position. These micro-movements are, however, of several orders of magnitude larger than the vibration amplitude of interest for the tower. Nevertheless, a signal compensation method to mitigate the drone's micro-movements, utilizing measurements from onboard accelerometers and gyro-sensors, was implemented. Experimental work demonstrated a deflection spectrum for the wind tower below 1 Hz, including a dominant peak for the drone micro-movement at 0.13 Hz (1 cm amplitude) and a single eigenfrequency of 0.345 Hz for the structure.

Noncontact damage detection using drone-based vibration measurements

In 2021, Ghaedi et al. [160] presented a review of remote sensing in damage detection of civil structures. They listed the different techniques for a static displacement between measurements on a larger time scale. They focused on the methodology rather than on the detailed measurement properties and discussed displacements in the meter range. Later, in 2023, Aminzadeh et al. [161] discussed noncontact inspection methods for wind turbine blade maintenance. The highlighted methods are thermography, radiographic techniques, machine vision, laser-shearographic testing, and microwave testing. The authors describe the approaches qualitatively, however, and do not discuss their integration with UAV. Sabato et al. [162] provided a review on noncontact sensing techniques for AI-aided SHM. They focused on the application of AI in different sensing techniques to
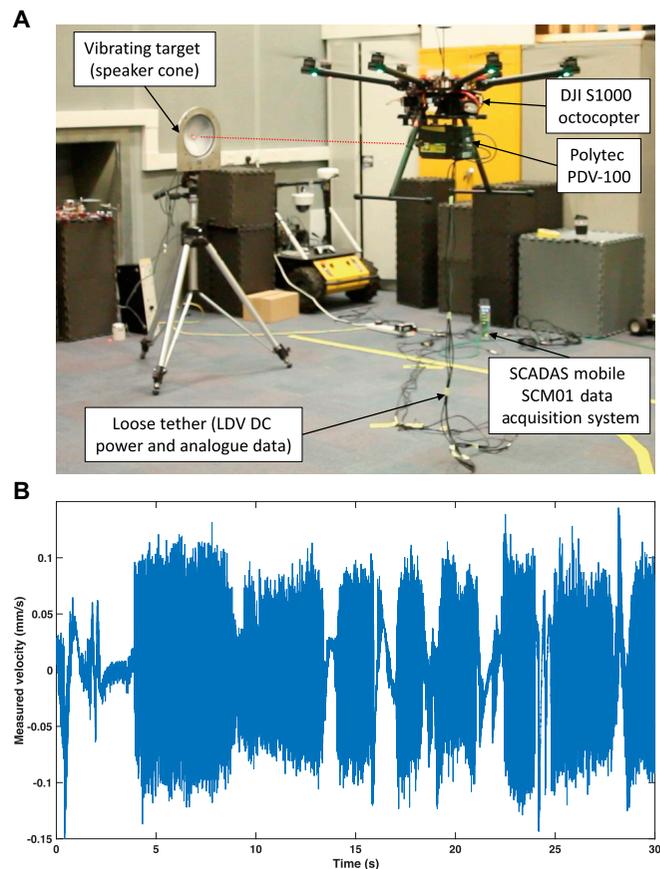
Fig. 12. First documented indoor UAV-mounted LDV measurement setup for remote vibration measurement applications: (A) annotated experimental setup (laser beam path highlighted) and (B) example data showing intermittent and noisy characteristics [169].

identify damages. In 2020, Abu Dabous and Feroz [163] gave a comprehensive overview of noncontact measurement techniques for condition monitoring of bridges. Most of the techniques discussed in this paper are suitable for combination with drones; at least, there are no fundamental reasons why a combination should not be possible. Bagheri and Kafashan [164] gave a review on UAV-based remote sensing in an orcha-forest environment. Here, noncontact techniques in combination with drones are discussed. The paper demonstrates how diverse the research is on the analysis of environments from flying platforms. However, just a few examples for noncontact measurements for damage detection with drones have been published so far.

Radio detection and ranging (RADAR) is an established technique called microwave vibrometry [14,17–19] for noncontact distance ranging measurement. Since powerful RADAR sensors can be miniaturized [165], such sensors are potentially well-suited for noncontact motion measurements from UAV. However, damage detection has not yet been demonstrated from drones with RADAR, although motion measurements from UAV were applied for the detection of vital signs from buried persons [166,167]. Microwave vibrometry is a robust technique but its resolution is limited by the long wavelength. It is possible to achieve a good vertical displacement resolution by phase evaluation but the lateral resolution is strongly limited by diffraction. This makes the technique not the preferred

choice for damage detection because damage often starts as small cracks close to the surface , requiring high resolution for effective detection.

In 2021, Ribeiro et al. [168] showed a noncontact structural displacement measurement using UAV and video-based systems. They focused on data fusion of the lateral displacement computed from the image data and transformations considering the drone position obtained by GPS. The resolution of the shown measurements is rather a millimeter range. Obviously, the pixel resolution for the cameras and the optics limit the performance even more than the vibrations of the drone. Khadka et al. [26] demonstrated vibration measurement with DIC from a drone. One camera can measure strain in a plane, and a setup with at least 2 cameras can measure strain on a complex curved surface. The low framing rate of the camera allows only measuring low frequencies or requires stroboscopic techniques, which lead to aliasing problems and, thus, add noise. DIC is a triangulation technique if more than one camera is used. Since the vibration amplitude resolution relies on the camera pixel resolution and, for stereo vision, the angle between the cameras, the achieved resolution is rather in the higher micrometer regime. The resolution and bandwidth of this technique are not sufficient for the detection of small cracks and fatigue in the early stage of the structural impairment.

UAV-Based Inspection of Large Structures Using LDVs

Examples for using UAVs with an LDV are cited in Refs. [146,159,169]. While there are earlier references to the integration of LDVy with UAVs [170], Halkon is the first to have presented the combined approach in a peer-reviewed article [169]. Here, application of the unique capability, previously described in the "LDVy current state of the art" section, for compensation of the vibration of the sensor head to the challenge of removing sensitivity to the drone vibration is addressed for the first time. As shown in Fig. 12A, commercially available octocopter (DJI S1000) was equipped with a Polytec PDV-100 Portable Digital Vibrometer (with DC power and analogue data cables loosely connected to ground) and used to take measurements from a ground-based vibrating speaker cone during indoor flight. Without the benefit of GPS/GNSS for UAV stabilization, maintaining the probe laser beam on the location of interest was challenging.

As shown in Fig. 12B, captured vibration signals were observed to be intermittently lost (when the laser beam strayed from the target) and subject to laser speckle-induced noise (when the laser beam was on the target but "wandering" in sympathy with the drone motion). Recently, therefore, a solution to the wandering laser beam issue—namely, an "LDV Gimbal"—has been proposed [171]. Residual speckle noise contributions may be addressed by instead using an LDV incorporating the recently developed signal diversity capability as previously described.

More recently, Garg et al. [159] utilized a Polytec Compact LDV attached to a tethered (with data and power cables) commercial hexacopter (DJI Matrice 600) for measuring transverse displacements of a railroad bridge. The drone hovering status involves drone micro-movements concentrated below 0.5 Hz. Garg therefore decided to filter out all frequencies below 0.5 Hz—thereby cutting off the lower-frequency performance of the system—for the LDV data to maintain the dynamic

displacement deflection of the bridge. An average peak difference of 10% was observed between the actual displacement, determined by linear variable differential transformers, and the displacement captured by the UAV–LDV setup.

As an innovative alternative to flying the LDV itself, the UAV flying mirror concept was first introduced in Ref. [156], comprising a mirror attached to a quadcopter and a ground-based LDV, as shown conceptually in Fig. 13. The main principle is to use low-mass UAVs with a minimum level of vibration noise to carry a mirror, rather than the complete LDV equipment. The flying mirror project is still under development and recent flight tests described in Ref. [156] show promising results as shown in Fig. 14. A reference vibration excitation from an eccentric shaker was remotely measured by the flying mirror setup and an accelerometer attached directly to the shaker table. Spectra from both flying mirror setup and the accelerometer are in reasonable agreement as shown in Fig. 14C. It is worth mentioning that the experiment shown in Fig. 14 is for manual drone control and better results are expected for the fully controlled drone with better dynamic stability. It is also worth noting that the LDV will also be sensitive to mirror vibrations and, as indicated by air density fluctuations in Fig. 13, path length changes due to refractive index fluctuations along the length of the laser beam path. In both cases, these additional Doppler shift contributions will occur both to and from the target.

Movements of and vibrations at the UAV introduce measurement disturbances, as do refractive index fluctuations in the atmosphere through which the laser beam passes to and from the target. LDV measurements with UAVs require, therefore, the means to suppress such disturbances. While, as previously described, Halkon's group at the University of Technology Sydney measures the vibration of the UAV with inertial sensors and uses the signals to compensate movements of the
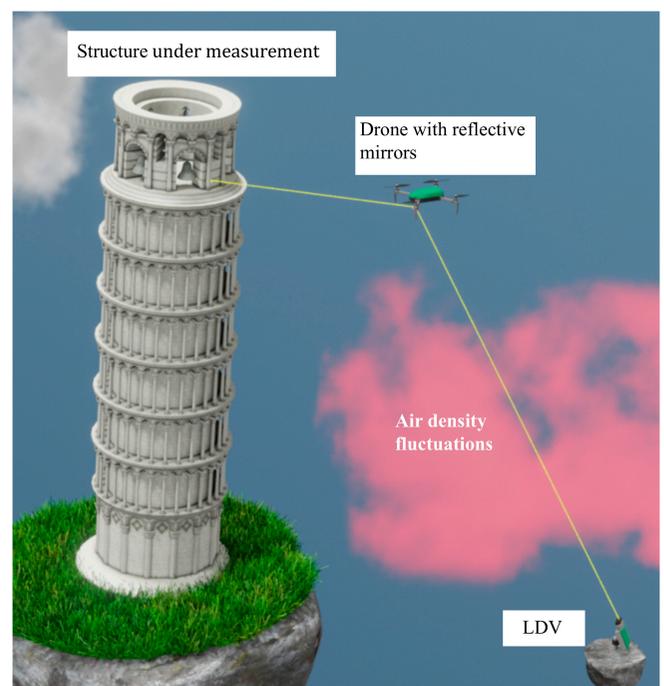
Fig. 13. A conceptual drawing for the flying mirror concept for LDV measurements from large structures with inaccessible measurement locations of interest [156]; image courtesy of M. Schewe.
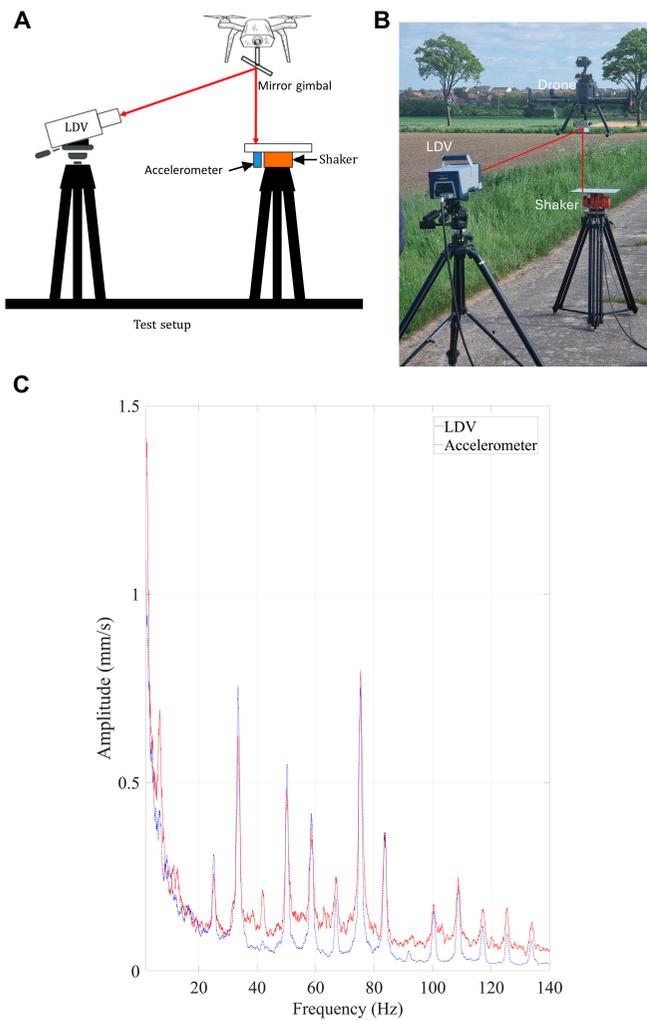
Fig. 14. Test setup schematic (A), photograph (B), and (C) vibration measurement (frequency resolution = 0.9 Hz) with an LDV and an accelerometer acquired from the same target (eccentric shaker) [150].

UAV, the collaborating group from TU Clausthal and the DLR in Braunschweig proposed a DLDV technique to suppress movements and vibrations of the UAV as well as the atmospheric disturbances, as shown in Fig. 15. As described previously, Rembe's TU Clausthal group developed the DLDV technique to perform highly resolved displacement measurements in the mHz regime in a 600 °C hot furnace with subnanometer vibration amplitude resolution [109]. However, the system can also be applied successfully to measurements with UAVs, as shown schematically in Fig. 15A. By inserting a stationary retro-reflector in front of the objective, the DLDV performs a single-point LDV measurement and thus captures the noise of an LDV measurement as a reference. The atmospheric disturbances between the UAV and DLDV and the movements of the UAV relative to the LDV are suppressed by this differential measurement setup, as are demonstrated by the reduced noise level observed in the measured data in Fig. 15B [150].

It is expected that combinations of existing and emerging capabilities can address both of these challenges. Halkon and Rothberg [112] have previously shown that a measurement of the vibration of the mirror normal at the laser beam incidence is required to fully remove the additional velocity due to the

drone-induced mirror vibration. Meanwhile Rembe's group's DLDV capability has been shown to address the issue of path length fluctuations [109] where one beam is only sensitive to those while the other measures both the target vibration and the environmental perturbations; (optoelectronic) subtraction of the former from the latter leaves only the desired measurement. The progression of these and other remaining research questions and challenges in order to fully realize the great potential of integrating LDVs into UASs for the remote measurement of vibration from large infrastructure is the topic of the next section.

Open UAV–LDV Research Tasks

LDVy is such a sensitive method for vibration measurement that it can detect picometer and even subpicometer modulations of the optical path length between sensor and specimen. Unfortunately, the optical path length is altered not only by displacements of the target surface but also by parasitic movements of the sensor and vibrations at the sensor or at a beam steering mirror (or optical component such as a retro-reflector) on the UAV. The sensor or a deflecting mirror at the UAV is, therefore, strongly affected by parasitic optical path length modulations. All motions and vibrations of the UAV affect the intended measurement performance. Optimizing the position stability and accuracy has, therefore, a great influence on the measurement uncertainty. Vibrations generated by the UAV also increase the background noise level and, therefore, decrease the measurement accuracy.

The TU Clausthal group together with the DLR group in Braunschweig performed the outdoor measurements, as summarized in this paper, in reasonable weather conditions at low wind speeds [150,156]. Meanwhile, Zheng et al. [172] have recently demonstrated that a UAV can compensate a constant wind load in an experimental indoor setup. Whether in the presence of wind or not, the multirotor UAV itself needs to pitch or roll in order to maneuver forwards/backwards or to the left/right. Therefore, it is challenging to hold an UAV–LDV steady in a windy environment if the system has no means for automatically controlling the measurement point by steering the laser beam(s). Thus far, experiments were accomplished indoors or in good weather when this problem could be addressed by careful adjustment of the UAV to a proper spot with a fixed mirror or with a fixed LDV directly mounted on the UAV. The effective tracking of the selected measurement spot on the specimen surface remains an open challenge that needs to be addressed in the future. Existing means for tracking LDV measurements on moving targets by maintaining the laser spot on a moving part using a camera image, e.g., Refs. [98,141,142], can be developed further to solve this challenge.

Ambient light and particles in the air do not significantly adversely affect an LDV measurement because the focused 10-mW laser beam substantially exceeds the power spectral density of the sunlight collected in a small aperture on the photodetector. Additionally, the incoherent sunlight does not contribute to the signal; only the mutually coherent, monochromatic laser light in the back-scattered measurement beam interferes with the (internal) reference beam. However, measurements via UAVs from large structures may suffer from optical path length modulations due to optical turbulence in the atmosphere, although initial research results demonstrate
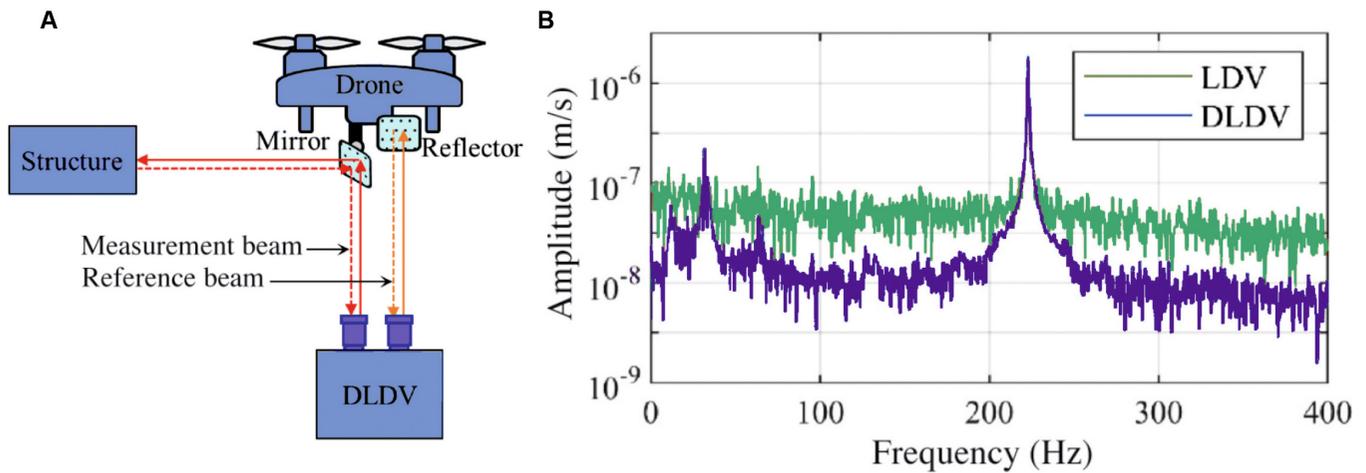
Fig. 15. Early measurement from a remote structure by a differential LDV via a "flyable mirror"; (A) schematic showing the measurement with a DLDV when the reference beam impinges on a reflector at the UAV while the measurement beam is deflected with a scanning mirror at the UAV toward the measurement object and (B) example measurement data for comparison [150].

that such influences can be suppressed by DLDV measurements, where the reference beam is also exposed to the same parasitic modulations. Similarly, this inherent differential measurement compensation applies to UAV or laser beam steering mirror vibrations. Alternatively or additionally, these "self-noise" vibrations can be compensated by an additional measurement signals obtained at the UAV with inertial sensors, as described by the work of Halkon and Rothberg [110,112]. In any case, the current state-of-the-art science leaves plenty of room for future research. We are still orders of magnitude away from the shot-noise limited resolution limit for an LDV when it is combined with an UAV.

The concept to use a mirror at the UAV to deflect the measurement beam from an LDV for measurements with optimal inline angles on hard-to-reach positions prevents the requirements to attach a complete LDV (complete with data collection and processing) to the drone. As discussed in the review part of this paper, it has already been demonstrated that it is an effective method for LDV measurements with UAV. However, it is not the proper approach to achieve a shot-noise limited resolution, since the measurement distance between the target and the LDV can be quite high, even if the UAV is positioned in close proximity to the measurement location. Therefore, it is preferable—from the standpoint of minimization of the disturbances to the LDV measurements—to attach the LDV directly to the UAV. Measurement hardware miniaturization and energy efficiency need to be advanced to achieve that goal. In order to minimize energy consumption, energy-efficient components and energy harvesting seems to provide the means to attach an LDV directly to a UAV. Therefore, all aspects of miniaturization of the LDV and reduction of power consumption are of great interest for LDV measurements with UAVs. Power generation through energy harvesting is an important topic to provide the electrical energy required by the LDV.

In addition, only single-point measurements were demonstrated so far although a complete 3D geometry and 3D vibration pattern contains more meaningful data for assessing the state of damage for a mechanic structure. An SLDV measurement with the aid of a UAV would be an excellent first step. Detailed information of the UAV position in respect to the structure under test, as well as the information of the measurement

beam orientation, both outbound from the UAV and when impinging the measurement spot, are required. Additional surveillance cameras (2D and 3D), GPS information, trim/tilt measurement of the UAV with respect to the known test object, accurate control of scanning angles, and many further tasks have to be addressed in future research projects. As pointed out in the review part of this paper, local cracks and other types of damage change vibration patterns more significantly locally than globally. Therefore, a complete spatially resolved measurement of operational deflection shape is of great interest for crack detection and evaluation. However, obtaining 3 vibration patterns with the aid of UAVs is quite a challenge since every measurement point has to be measured from 3 different directions and the signal acquisition has to be synchronized in order to achieve phase matching for the 3 measurements from the 3 directions. Finding UAV paths, scanning sequences and routines for scanning measurements or parallel measurements with one or more UAVs with LDVs, or deflecting mirrors for LDV measurement beams is also a major research and engineering task for optimal vibration pattern determination. An important goal of this research is a minimization of measurement time and an optimization of data quality. It is conceivable that AI can be used to optimize the complete measurement process and to extract relevant information from the measurement data and this requires research.

Attaching the LDV to the UAV requires requires the transmission of measurement data from the UAV to the ground or storage of the data until the UAV has landed. Otherwise, a cable connection would be necessary, which would mean that the advantage of contactless measurement with the UAV–LDV would be largely lost. Therefore, data transfer and data storage are also research topics of great interest for LDV measurements with UAVs. In order to reduce the amount of data for storage and transfer, it is necessary to implement effective data reduction capabilities in the sensor acquisition system on the UAV. It may be helpful to define data structures with propagation meta data optimized to the specific applications discussed in this paper. Metrology with UAV offers many research challenges. The priority program 2433 Messtechnik auf fliegenden Plattformen (https://www.uni-bremen.de/en/spp-2433) funded by the National Science Foundation of Germany (DFG) started

in November 2024 with 19 research projects and addresses many general challenges for accurate measurements with an UAV. The research discussed in this paper is also part of this program with 19 partners.

Ultimately, however, even after an effective reduction of disturbances and sources for measurement uncertainty, some sources of uncertainty will inevitably remain. Thus, the uncertainties of LDV measurements with UAVs need to be quantified. This requires sophisticated knowledge about the sources of uncertainty in order to consider them properly in the uncertainty computation. Therefore, research on the uncertainty contributions is a further open research field with many opportunities for research groups around the world.

Conclusions, Perspectives, and Outlook

Field-based LDV measurement campaigns from UASs is an interesting, promising, challenging, and emerging research field, especially in the context of determination of the vibration behavior of large mechanical and civil structures. These kinds of measurements are relevant and important for ensuring the safety of structural infrastructure in the built environment. Such measurements suffer, however, from strong disturbances by parasitic optical path length modulations of a large frequency band that does influence the measurement of large constructions. Natural frequencies of large structures are typically below 100 Hz. A customized version of a DLDV for measuring very low frequency vibration even down to 1 mHz is discussed in Ref. [109]. Therefore, the DLDV has a greater potential for monitoring low-frequency vibrations of large structures than the traditional LDV. However, the DLDV requires more sophisticated technology. As explained in this paper, early results demonstrate the potential of the method and show promising directions for suppression of the strong disturbances. The future goal of this research topic is to achieve vibration amplitude resolutions in the picometer or even sub-picometer range that are common nowadays for more conventional LDV measurements. Some early promising results were achieved by compensating movements of the LDV sensor head with synchronized signals obtained from inertial sensors but further research remains. Another approach employs DLDV measurements by pointing the reference beam of the DLDV onto a location with minimal vibration such that the additional disturbances experienced are as similar as possible to those experienced by the measurement beam. The parasitic influences are thereby canceled out while the intended measurement signal of the remote target of interest remains.

The current state of the art of the UAV–LDV system is far away from reaching the possible shot-noise limited resolution of LDVy. Thus, a lot of future research work is required to overcome the current limits and to achieve shot-noise limited measurements. Miniaturization of LDV and supplying the LDV with energy harvested from the environment may allow to measure for longer and to place the LDV in closer proximity to the specimen than is currently possible with flyable mirrors on a UAV. Designing weight- and size-reduced sensor solutions that do not need additional power supplies is another challenging topic for the future research on this topic. So far, early research addressed just accurate, single-point measurements with manual adjustments and alignments. The analysis of the vibration behavior of large structures requires sophisticated procedures for the UAV positioning and scanning schemes.

These procedures still need to be developed. Analyzing the data onboard the UAV also requires the means to process and transmit the data to the ground or to store it until the UAV has landed. In addition, synchronization between positioning the laser beam or beams and the data acquisition and the transfer of the measured signal into displacements in a global coordinate system are unsolved challenges. The "base motion" vibration disturbances present on the UAV lead to additional uncertainty contributions for vibration amplitude measurements. Quantification of the remaining uncertainties after compensation of such effects also remains a future research task.

It is ultimately concluded that LDV measurements made with the aid of UAVs is an important, current research topic with many open remaining and interesting research tasks to be explored and completed. The work in this field has really only just begun and there is a long road ahead until such measurements will be possible in commercially available, industrially robust, and reliable solutions. Finally, we wish to point out explicitly that, while progression of the state of the art in this research area remains the interest for but a few researchers at this time, all are invited and encouraged to contribute to the solution of the open issues by joining the research field and sharing their findings.

Acknowledgments

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Measuring Vibrations in Large Structures with Laser-Doppler Vibrometry and Unmanned Aerial Systems: A Review and Outlook

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Vibrations in large structures such as buildings, dams, cranes, plants, drilling platforms, bridges, and wind turbines are often difficult to measure because, among other reasons, it is challenging or even impossible to attach suitable vibration sensors to all the positions/locations of interest. Optical, noncontact measurements from the ground, conversely, are only possible for the visibly accessible parts and often require long measurement distances or unfavorable viewing angles from the ground due to the vertical extent of the location of interest on the large structure. Employing noncontact vibration measurement methods from or via an unmanned aerial vehicle (UAV) is preferable for many applications and is, therefore, becoming an increasingly interesting research topic around the world. This paper reviews the current state of the art for measuring and analyzing vibration in large structures with laser-Doppler vibrometry (LDVy) supported by unmanned aerial systems (UASs)—which employ one or more UAVs and associated ground-based control equipment —and related topics, including excitation as well as data collection, transfer, processing, and interpretation. The review includes a brief overview of vibration-determined damage detection in large mechanical and civil structures, associated nondestructive testing (NDT) sensor technologies including in particular LDVy, UAV technology, and other NDT measurements supported by UASs with a focus on LDVy as the preferred vibration sensor technology. Ultimately, following the presentation of the state of the art, we discuss some of the currently foreseen challenges for implementing LDVy with UASs for operational stability analysis of large structures and the currently addressed and possible future research topics required to maximize the benefit of this exciting system integration opportunity.
Image

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