Chapter 15
Towards Differential Laser Doppler Vibrometer Measurements using Flyable Mirrors for the Vibration Assessment of Remote Structures

Benjamin Halkon and Christian Rembe

Abstract This paper will present findings from the use of Differential laser Doppler vibrometer (D-LDV) measurements from remote targets with the use of UAV-mounted "flyable mirrors". A series of measurements – from the laboratory benchtop through to making real measurements of airborne laser beam steering mirrors – have been conducted to demonstrate, for the first time, the inherent insensitivity of D-LDV measurements to self-noise vibration, either due to the vibration of the sensor head itself or, as is the case here, from vibrating laser beam(s) directing optics. Results are compared in the context of those from single-beam LDV measurements with inertial sensor based "vibration compensation", based on earlier work in which the sensitivity of the measurement to the steering mirror vibration was defined theoretically, using a completely general, vector-based mathematical approach, and rigorously experimentally validated. Target vibration scenarios include those which are statistically stationary and those which are transient, time-varying where frequency and time domain approaches to the correction are utilised. While both approaches are shown to be effective for simple, benchtop scenarios, the D-LDV is shown to offer benefits for more complex, real-world campaigns. However, further work is required to better rigorously and systematically determine the full performance envelope and unique challenges which must be solved before high accuracy, low uncertainty measurement outcomes are realised.

Keywords LDV · UAV · vibration · measurement · infrastructure

Introduction

Laser Doppler vibrometers (LDVs) have been rigorously shown to be as sensitive to vibration of the sensor head as to that of the target itself [1, 2]. For the vibrations observed in common-place measurement campaigns, this sensitivity to this so-called "base motion" can be comparable to that of the target vibration, potentially leading to misinterpretation. For increasingly explored *field-based* vibration measurement capabilities – such as measurements from uncrewed aerial vehicles (UAVs) [3–6] – this particular technical hurdle remains one to be surmounted [7]. Solutions – applicable in both the frequency *and* time domains [8] – have been studied in detail for the purpose of correcting such erroneous LDV measurements using sensor-head mounted accelerometers with excellent results observed[1] [1–3,8]. Nevertheless, accelerometer-based corrections cannot achieve the noise floor and dynamic range characteristics for which LDVs are revered. Practical limitations associated with mounting an LDV sensor-head to a UAV (or "drone") – and recovering useful results from it – persist [7].

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[1] with appropriate amplitude and time-alignment approaches implemented for treatment of the correction accelerometer signals

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As shown schematically and generically in Figure 1, a ground-based, dual, parallel beam *Differential* LDV (D-LDV) has, however, recently been proposed [5] as an alternative to the corrected, single-beam LDV equivalent for the purpose of measuring the vibration of large, remote structures. Here, a drone-mounted "flyable mirror" is used to direct the beam(s) – the path for which is shown with a single, yellow line – from the instrument to the target and back. Meanwhile, a simple but effective, image-based, pan-tilt tracking system can be readily realised to track the mirror from the LDV. The laser beam incidence location *and* direction on the target – both important to control, since the LDV measures the target vibration at the point of incidence in the direction of the laser beam – are clearly a function of both the position and orientation of the mirror *and* the LDV optical axis. Insensitivity to (translational) vibration of the flyable mirror and to spurious additional Doppler signal due to path length fluctuations[2] are the specifically inherent D-LDV benefits in such application scenarios [5, 6].

The former property is the principal subject of investigation herein, where the instrument sensitivity to the laser beam interactions at each of the reflections must be determine. Subsequently, a series of investigations are presented to verify the D-LDV performance and compare it with that of a corrected, single-beam LDV alternative. Ultimately, with these aspects defined, the effective application of a D-LDV to measurements of remote structures using flyable mirrors can be established.

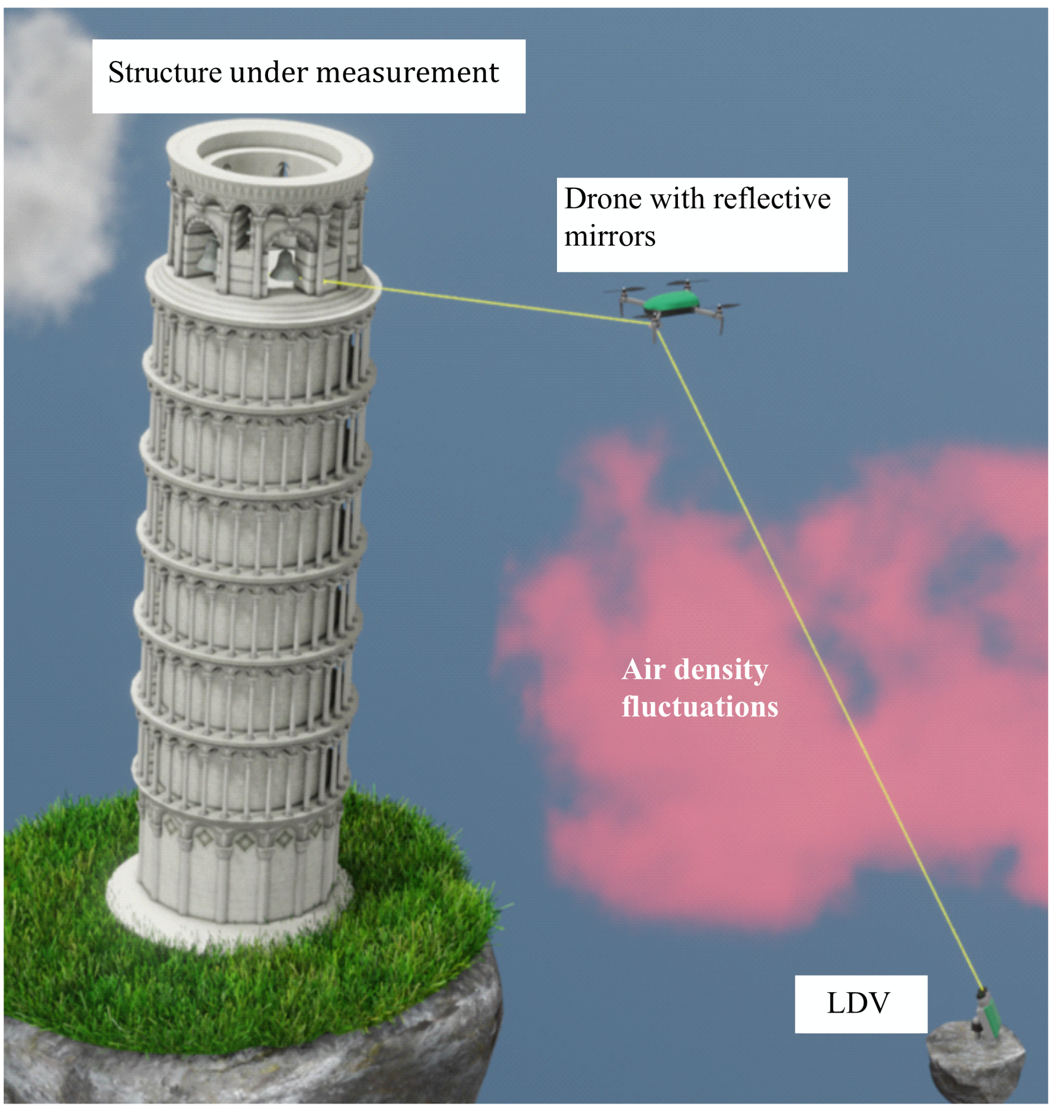

Fig. 1 Schematic LDV measurements from large structures with inaccessible measurement locations of interest [7]

[2] caused by fluid media refractive index between the instrument and the target caused by fluid media refractive index between the instrument and the target

Mathematical Modelling of the Measurement Sensitivity

The total measured velocity in scenarios where vibrating optics are used to steer the laser beam to and from the target of interest is the sum of each of the velocities measured from each vibrating surface at which a change in beam direction occurs. In general, the fundamental relationship between the measured velocity, U_m, and the surface velocity at the point of laser beam incidence, $\overrightarrow{V_P}$, is given by:

$$U_m = \frac{1}{2}\left(\widehat{b}_{n+1} - \widehat{b}_n\right)\vec{V}_{P'} \tag{1}$$

where $\widehat{b}_{n+1}$ and $\widehat{b}_n$ define the directions of the laser beam immediately after and immediately before the laser beam incidence point P', respectively.

For the D-LDV, Figure 2 shows a generalised case where the outbound laser beams are both reflected by a vibrating mirror on their path between the instrument sensor head and the vibrating target. The subscripts $_M$ and $_R$ are used to identify laser beam directions and incidence locations for the Measurement and Reference beams, respectively. In the arrangement shown, the M and R beams are parallel, but this does not have to be the case in general, hence retaining discrete notation for each of the laser beam directions. In alignment with earlier published work [2], further considerations that enable comprehensive modelling of the velocity sensed by each beam are:

a) The points A along the beam path are arbitrarily selected, as is the point B on the mirror surface, which moves to B* following the mirror vibration;

b) While, for simplicity, only one translational and one rotational mirror vibration component are shown, the use of this vector description is completely general, allowing for up to all six degrees-of-freedom of mirror and target vibration;

c) The paths to the target in the absence of mirror vibration (dotted lines) are shown with the beams steered through 90○ which is, again, just an arbitrary choice; and

d) Similarly arbitrarily chosen is the location and orientation of the origin, O, in the plane of the target.

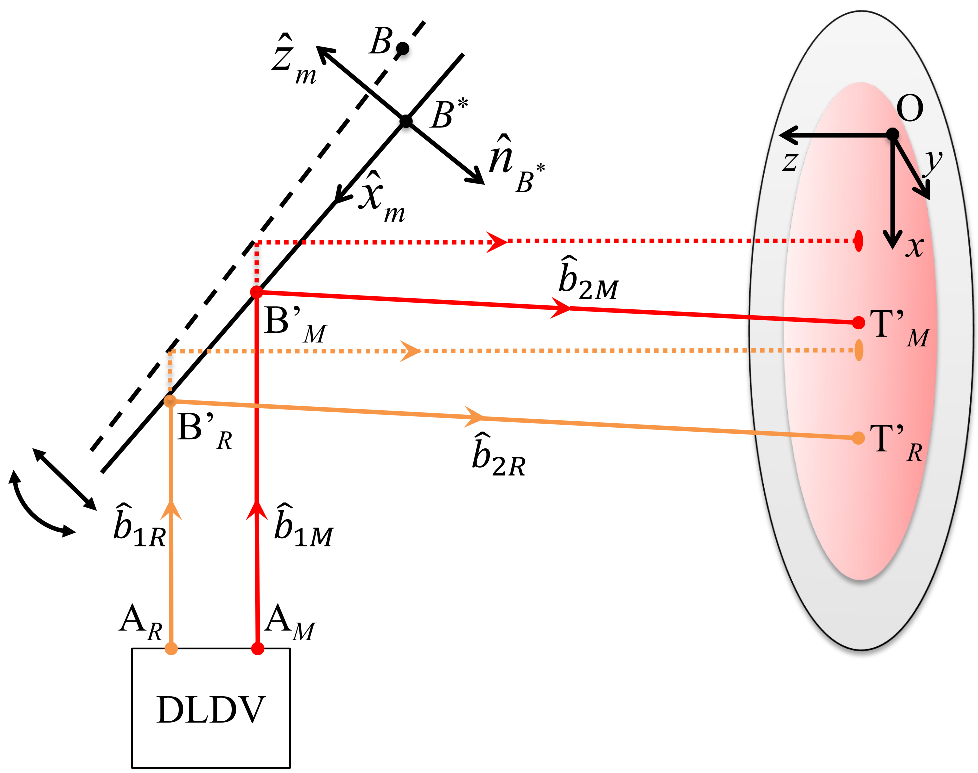

Fig. 2 Schematic showing a generalised D-LDV measurement of target vibration via an angled, vibrating steering mirror [9].

For a conventional parallel beam arrangement - i.e. $\widehat{b}_{1_M} = \widehat{b}_{1_R}$ and $\widehat{b}_{2_M} = \widehat{b}_{2_R}$ - and with the introduction of a nonvibrating retro-reflector in the target plane at the point T′R[3], it can be shown [10] that the measurement is given by:

$$U_m = -\widehat{b}_2 \cdot \overrightarrow{V_{T'_M}} + \left(\widehat{b}_2 - \widehat{b}_1\right) \cdot \left(\overrightarrow{V_{B'_M}} - \overrightarrow{V_{B'_R}}\right) \tag{2}$$

where $\overrightarrow{V_{X'_Y}}$ is the velocity of the point $X(B \text{ or } T)$ for the $Y(M \text{ or } R)$ beam. For scenarios where the mirror vibration is translational only, i.e. where $\overrightarrow{V_{B'_R}} = \overrightarrow{V_{B'_M}}$, this conveniently reduces to:

$$U_m = -\widehat{b}_{2_M} \cdot \overrightarrow{V_{T'_M}} \tag{3}$$

i.e. the intended measurement – the vibration of the target surface at the *Measurement* laser beam incidence in the direction of the incidence beam. This is a very important result since it shows, for the first time in this mathematically rigorous manner without any loss of generality, that the Differential LDV - when configured with a non-vibrating retro-reflector at the target for the *Reference* beam - is inherently insensitive to (translational) mirror vibration.

It should not be a big surprise that such a dual, parallel beam device is insensitive to translational vibration. This is, after all, at the core of the operating principle of the Laser Torsional Vibrometer, first proposed several decades ago [12] and now commercially available and widely deployed for *angular* vibration measurement, especially those associated with rotating shafts and systems. It should be noted that this stationary retro-reflector can be located *anywhere* after the mirror. It is, however, deliberately shown adjacent to the target since the M and R beams takes (almost) the same return path to the target and this delivers the additional benefit that any fluid medium causing path length fluctuations that occur anywhere between the D-LDV and the target are incurred by *both* and are also therefore opto-electronically cancelled [9].

Experimental Investigations

To verify the insensitivity of the D-LDV to steering mirror vibration under controlled conditions, a lab-based, benchtop experimental arrangement as shown in Figure 3 was arranged. The D-LDV and a "check" VibroFlex QTec single beam device are positioned out-of-shot to the lower left of the image field-of-view. A large plane mirror, at nominally 45○ to the laser beams, deflects both M and R beams toward the target plane. The mirror is attached to a large electrodynamic shaker – positioned just out-of-shot to the lower right – with the shaker axis and mirror normal colinear. Vibration of the mirror in the normal direction is realised It is unimportant that the vibrating target – on which the M beam is incident – is a loudspeaker. The signal used to produce the vibration is similarly unimportant, provided that it is analogous in terms of frequencies and amplitude levels to that of a real-world structure. A stationary retro-reflector – on which the R beam is incident – is positioned alongside the target loudspeaker. Reasonable care was taken to align the laser beams, both those from the D-LDV and that from the check LDV, which is directed towards the target via a *stationary* 45○ mirror and approximately incident at/in the same location/direction.

Figure 4 shows an example dataset collected for each of the two LDVs with the shaker-generated mirror vibration also shown for reference. The check LDV captures the true target vibration. While a similar *single-beam* LDV making a measurement of the loudspeaker via the vibrating mirror would be perturbed by the mirror vibration, the D-LDV conversely exhibits no such sensitivity, as can be seen by its very close agreement with the check LDV measurement. The red (D-LDV) curve is almost completely aligned with – and therefore obscured by – the green (check LDV) curve. This is an excellent, expected outcome.

Replacing the mirror/shaker with a mirror attached to a tethered UAV – as shown in Figure 5 – represents an experimental setup with a further level of complication. Here, mirror vibration will certainly be time-varying in nature with a broadband frequency content with peaks associated with the resonances of the vehicle structural and with that of the (inevitably unbalanced) rotors.

Similarly to those data shown and described previously in Figure 4, an example dataset for this experimental scenario is presented in Figure 6. Here, the compact between the D-LDV and the check LDV – in this case targeted directly onto the target loudspeaker from the tripod-mounted instrument (out-of-shot to the bottom right) – is not so evident. While level fluctuations can be seen to occur at similar timeframes, especially from -2.4 to -2.3 s, and underlying signal structures exhibit similar characteristics, differences can surely be attributed to some spurious contribution to the D-LDV measurement as a result of inevitable mirror *rotational* vibration, to which the instrument is *not* insensitive [9]. Future analysis should explore

[3] which may or may not be readily realised yet, for the time being, is a requirement of the proposed approach

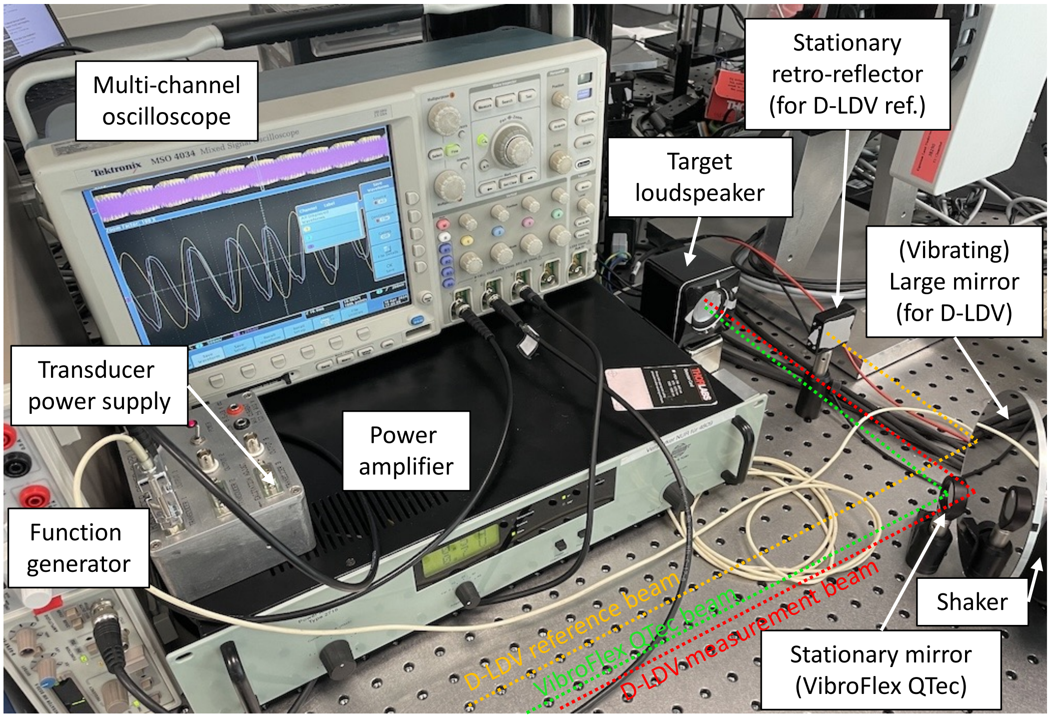

Fig. 3 Experimental setup for a D-LDV measurement from a vibrating target via an instrumented 45○ mirror; laser beam paths for both D-LDV and reference VibroFlex QTec – both out of shot to bottom-left – highlighted for ease of reference [9].

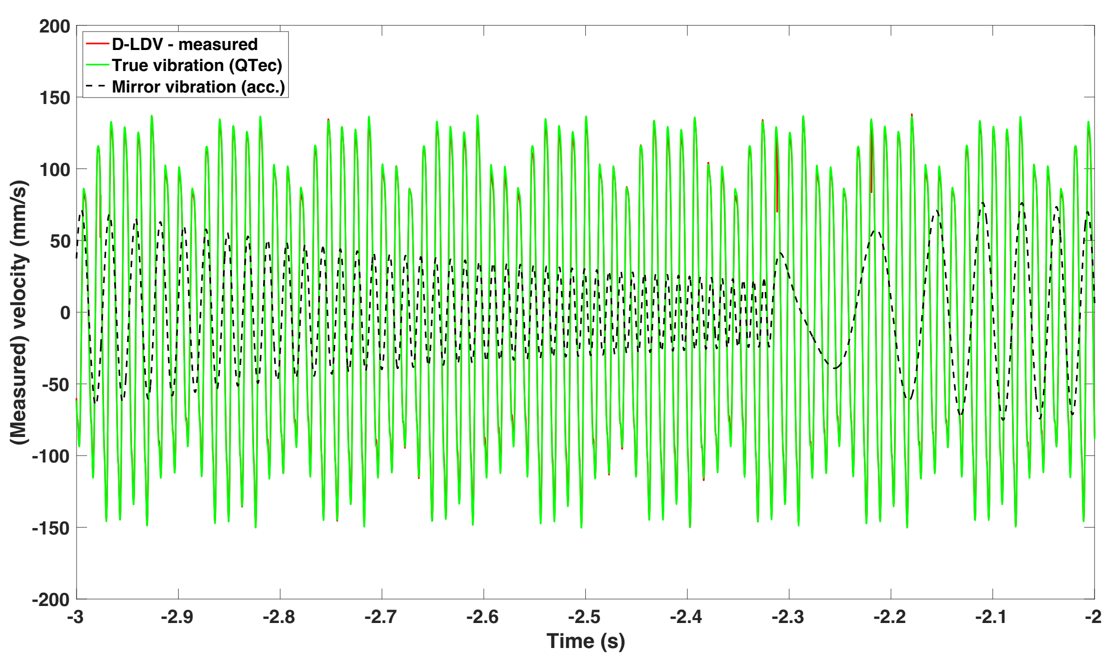

Fig. 4 Example measurement data collected during a D-LDV measurement from a vibrating mirror; 5-100 Hz, 1 s duration chirp – i.e. time-varying – mirror vibration and nominally 75 Hz target vibration [9].

this and the possibility of its correction, for example using an arrangement of transducers on the back-surface of the mirror to extract the required signal.

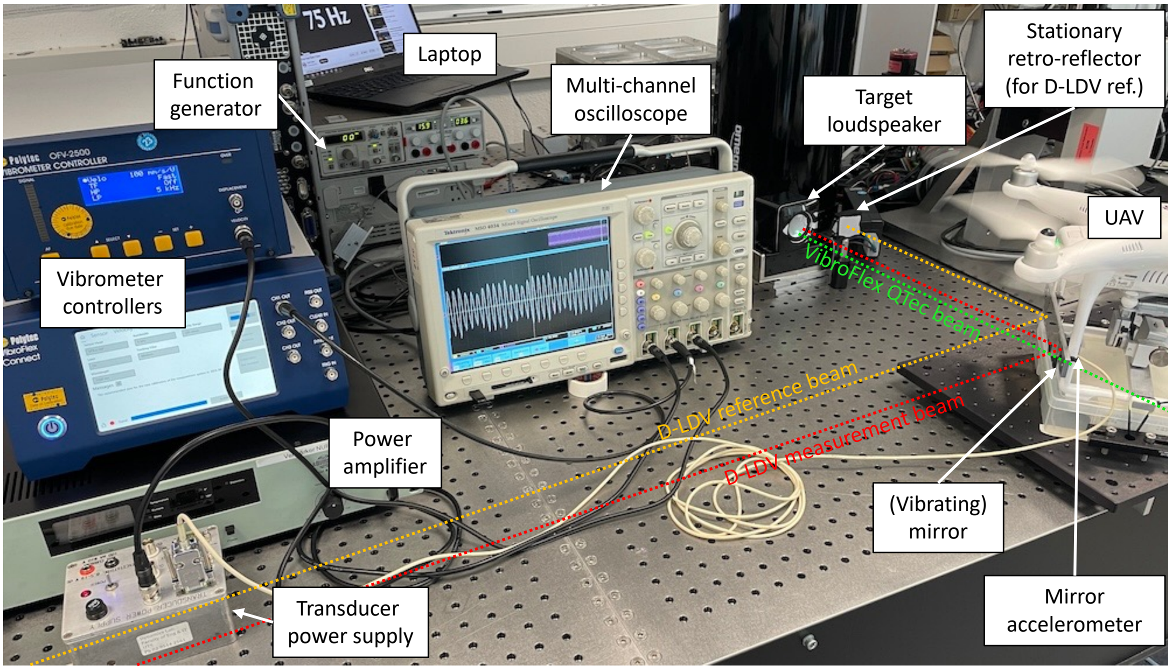

Fig. 5 Experimental setup for a D-LDV measurement from a vibrating target via an instrumented 45○ mirror; laser beam paths for both D-LDV and reference VibroFlex QTec – both out of shot to bottom-left – highlighted for ease of reference [9].

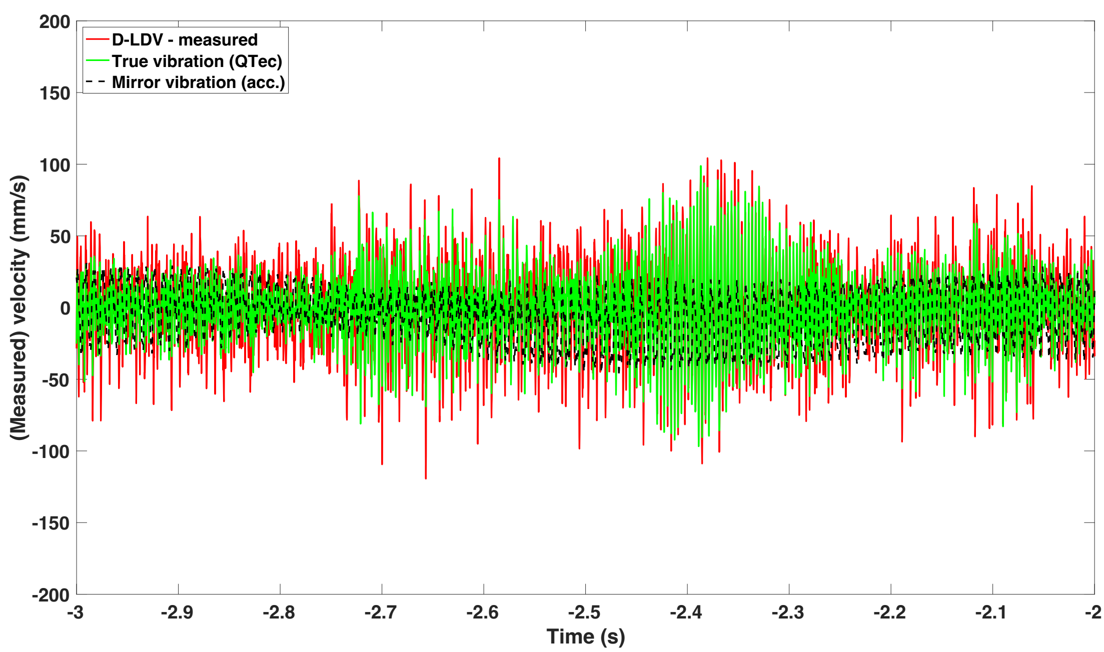

Fig. 6 Example measurement data collected during a D-LDV measurement from a mirror mounted to a tethered UAV; ambient, UAV-generated mirror vibration and transient, time-varying (classical music) target vibration [9].

Lastly, Figure 7 shows a field-based experimental trial where the D-LDV is used to make a remote measurement from a vibrating target via a flyable mirror, as is the ultimate ambition of this emerging capability. While, as before, the target vibration is controlled, here it is realised in the direction of the inbound laser beam using an electrodynamic shaker. The stationary reference beam retro-reflector is adjacent to the target in approximately the same plane. Both surfaces were relatively large to allow for some beam incidence point variation due to inevitable UAV (whole-body) motion during flight. Such are the practical challenges still to be fully overcome with this, as yet proof-of-concept technique. Figure 8 shows

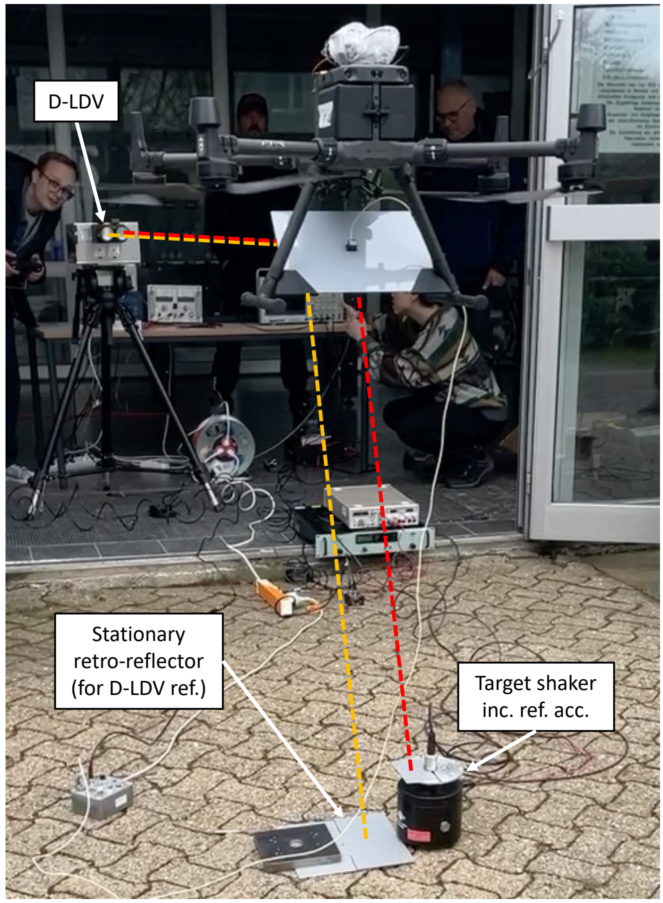

Fig. 7 Experimental setup for a D-LDV measurement from a vibrating target via UAV-mounted flyable mirror [9].

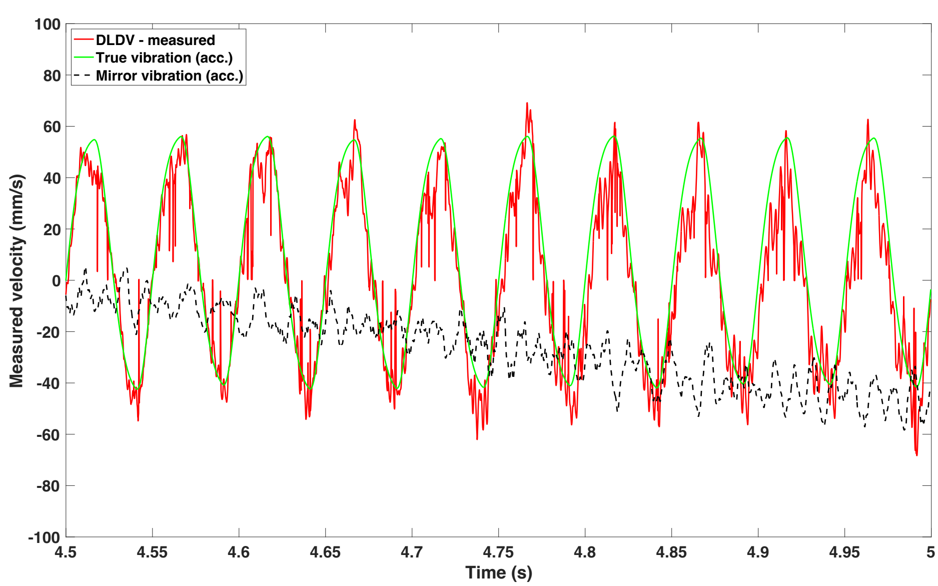

Fig. 8 Example measurement data from an UAV-mounted DLDV for a target vibrating at 20 Hz [9].

an example dataset collected where the 20 Hz (in this case) target shaker vibration is captured quite effectively. Otherwise good agreement between the D-LDV and check measurement – made here with an accelerometer mounted to the target – is impacted by additional signal content with similar characteristics to that of the mirror vibration, surely contributed to by the *rotational* vibration of the mirror.

Conclusions

This paper has presented some of the latest research in the increasingly topical area of LDV measurements of remote structures using UAVs. Rather than directly mounting the LDV to the UAV, combining a ground-based LDV with a "flyable mirror" has the potential to overcome many of the otherwise prohibitive practical challenges. Furthermore, knowing that *conventional* LDVs are as sensitive to sensor head (or beam steering optic) vibration (in the direction of the laser beam) as to that of the target itself, this work focuses on the dual parallel beam *Differential* LDV (D-LDV). Such a device – in which both the Measurement *and* Reference beams take the same path to/from the target of interest – is shown to overcome the self-noise to *translational* vibration as well as offering an inherent means to preclude sensitivity to refractive index fluctuations over the laser beam path length. Increasingly complex experimental set-ups – from lab- to field-based – are used to qualitatively verify a mathematical assessment of the D-LDV sensitivity in the early communication of results offered here. Future investigations will include frequency-domain based representation and quantitative analysis of the D-LDV measured and check signals. Additionally, a means to also mitigate the inevitable sensitivity to mirror *rotational* vibration will be proposed and investigated.

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