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TAKING LASER DOPPLER VIBROMETRY OFF THE TRIPOD

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Laser Doppler vibrometers are now well-established as an effective non-contact alternative to traditional contacting transducers. Despite over 30 years of successful applications, however, very little attention has been given to sensitivity to vibration of the instrument itself. In this paper, sensitivity to instrument vibration and steering optics vibration is confirmed before development theoretically and experimentally of practical schemes to enable correction of measurements. In the case of instrument vibration, the correction scheme requires a pair of sensors with appropriate orientation and relative location. In the case of a beam steering mirror vibration, the correction scheme requires a single measurement from an appropriate location on the back-surface of the mirror in line with the laser beam incidence point. In both cases, frequency domain processing conveniently accommodates inter-channel time delay and signal integrations. Error reductions in excess of 30 dB are delivered in laboratory tests with simultaneous instrument / steering optic and target vibration over a broad frequency range. The practical nature of the correction techniques is demonstrated by successful applications of each. Finally, a previously unreported challenging real-world measurement scenario is described.

Keywords: laser Doppler vibrometry, base motion

1. Introduction

Laser Doppler vibrometers (LDVs) measure vibration velocity and are technically well-suited to general application with benefits over traditional contacting transducers in a range of challenging measurement scenarios [1]. Until recently, however, very little attention has been given to a quite fundamental aspect of operation which is that the measurement is of velocity relative to the instrument itself. Measurements are directly affected by instrument vibration in the direction of the laser beam and this cannot be distinguished from the intended measurement [2]. Mounting on a tripod with compliant feet is typically used to minimise ambient vibration transmitted to the instrument but application in a moving vehicle, handheld measurements and even UAV mounting are all examples of where compensation for instrument vibration would be required.

Similarly, where laser beam steering optics are used to direct the probe laser beam to the point of interest, for example to measure from a point on a structure that is difficult to access, the measurement will be sensitive to any vibration of those optics [3]. Often it will necessary to mount the optic(s) close to, rather than remote from, the point of interest and, accordingly, the optic vibration is likely to be similar in nature to that under investigation. It cannot, therefore, be differentiated from the genuine vibration on a frequency basis. Again, anti-vibration mounting of the optic(s) may help but can never resolve the problem across the entire frequency range. Either affect may be sufficient to result in serious data misinterpretation unless measurements are corrected completely as set out theoretically and confirmed experimentally herein. The correction configuration schemes presented lend themselves readily to incorporation to most measurement campaigns and an example of each will be described. Ultimately a more recent experimental investigation in which a portable digital LDV was mounted to a UAV will be described.

2. Laboratory-based controlled investigations

2.1 Instrument vibration

Sensitivity to instrument vibration (in the direction of the laser beam) was simply confirmed by a straightforward experiment, as set out in Fig 1a. Here, two LDV measurements were made of a stationary target. The Vibrating LDV sensor head was mounted on a shaker and excited with a broadband signal – level 160x10^{-3} g RMS – while the nominally stationary Fixed LDV was tripod mounted and used to provide the 'true' vibration measurement. As shown in Fig 1b, the true measurement is at a very low level, as expected. The vibrating instrument measurement, however, is not in agreement since it is sensitive to the instrument vibration. This clearly demonstrates that, the LDV makes a relative velocity measurement.

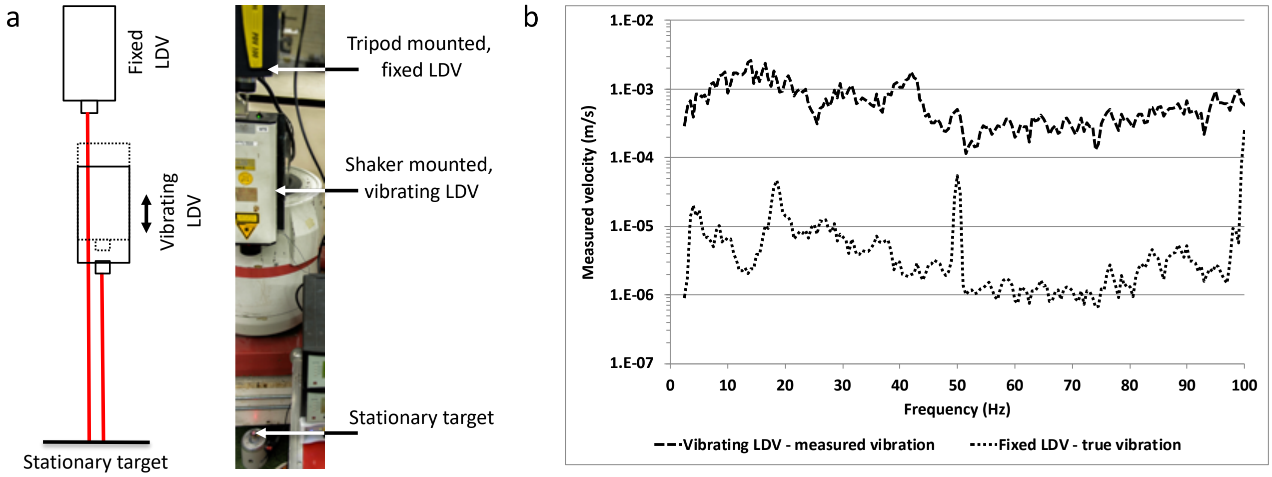

Figure 1: Instrument vibration sensitivity confirmation (a) arrangement and (b) measured data.

To correct the erroneous measurement, an independent measurement of the instrument velocity in the direction the laser beam is required. It might reasonably be expected that such a measurement can be readily obtained by a single traditional contacting transducer (e.g. an accelerometer) mounted somewhere on the instrument sensor head with its sensitive axis parallel with the laser beam direction. Indeed, certain commercially available systems come complete with a mounting location for such a "compensation sensor" [4]. Where instrument motion is only in the direction of the laser beam this would be a satisfactory solution. It has, however, been shown [2] that, for anything other than this ideal and practically unrealistic real-world case, such a solution leads to a sub-optimal correction.

A previously unreported example of such a sub-optimal correction of the measured signal is shown in Fig 2a (*shorter* dash black curve). For the sake of clarity, the measured, U_{meas}, and true, U_{true}, vibration signals, already presented in Fig 1b, are included again (grey curves). While reasonable practical care was taken here to arrange (translational) vibration in the direction of the laser beam only, other components of whole body instrument vibration, particularly *pitch* (angular) motion, due to the instrument rocking slightly in its shaker mounting, were also present. As a result, the 'corrected' vibration signal, U_{corr}, while a significant improvement over that measured, remains significantly different to the true vibration. Fig 2b, shows only the difference between the corrected and measured signals in the form of a dB reduction, calculated as follows:

$$dB\ reduction = 10\log_{10}\left[\frac{U_{corr}-U_{true}}{U_{meas}-U_{true}}\right]^2 \tag{1}$$

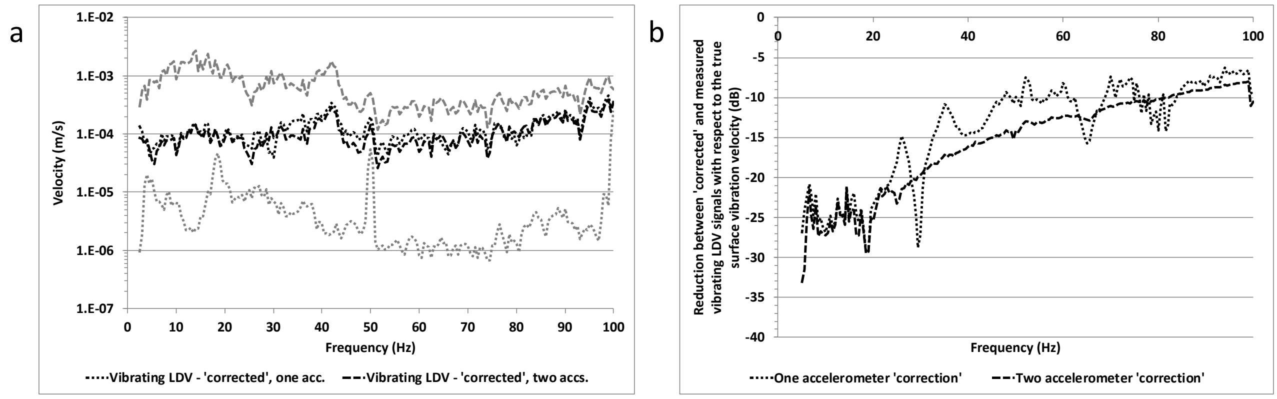

Figure 2: Sub-optimal correction with one and two accelerometers; (a) amplitude and (b) dB reduction.

In most practical, real-world measurement campaigns, arbitrary instrument vibration can be expected, hence there is a motivation for developing a more elegant solution that works for six degree-of-freedom vibration and results in a more effective correction than that achieved with a single correcting transducer. Making use of a totally general, vector-based approach, it can readily be shown [2] that the single compensation accelerometer must be paired with a second. This second transducer must have the same orientation and equal but opposite location coordinates in the two perpendicular axes orthogonal to the beam axis. The two accelerometers need not necessarily be mounted in the same plane, but such arrangement seems likely to be convenient. On or aligned with the front face of the sensor head while equidistant and either side of the laser beam, as shown in Fig 3, is readily achieved.

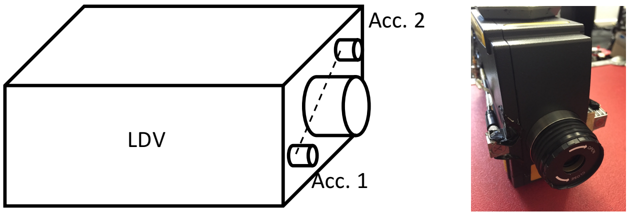

Figure 3: Example positioning of accelerometer pair for effective measurement correction.

With the two accelerometer mounting locations as shown, the required correction signal is theoretically simply the mean of the two measurements. The improvement in the correction of the vibrating LDV measurement is also shown in Fig 2 (*longer* dash black curve). While a further improvement over the one accelerometer correction, there remains a significant difference to the true vibration. Inspection of the dB reduction data in Fig 2b suggests the correction performance to be a function of frequency. This outcome was initially unexpected but quickly found to be consistent with a result where there exists a finite time delay between the accelerometer and LDV signals due to the alternative signal conditioning electronics therein [2]. While excellent *amplitude* agreement was ultimately found, the *phase* difference exhibits a symptomatic ramp function with increasing frequency.

For stationary signals with which vibrations engineers are typically concerned, such time differences, once determined on the benchtop prior to or immediately following the measurement campaign, can be conveniently removed in frequency domain post-processing. Given the LDV measures vibration velocity, the resulting acceleration signal must, of course, be integrated prior to subtraction and this is similarly readily achieved in the frequency domain. A significantly improved measurement is ultimately achieved as can be seen in Fig 4, with the measured and true vibration signals again included for reference in Fig 4a. The mean dB error reduction in Fig 4b shows the significant improvement, equating to an average across the frequency range shown in excess of 33 dB.

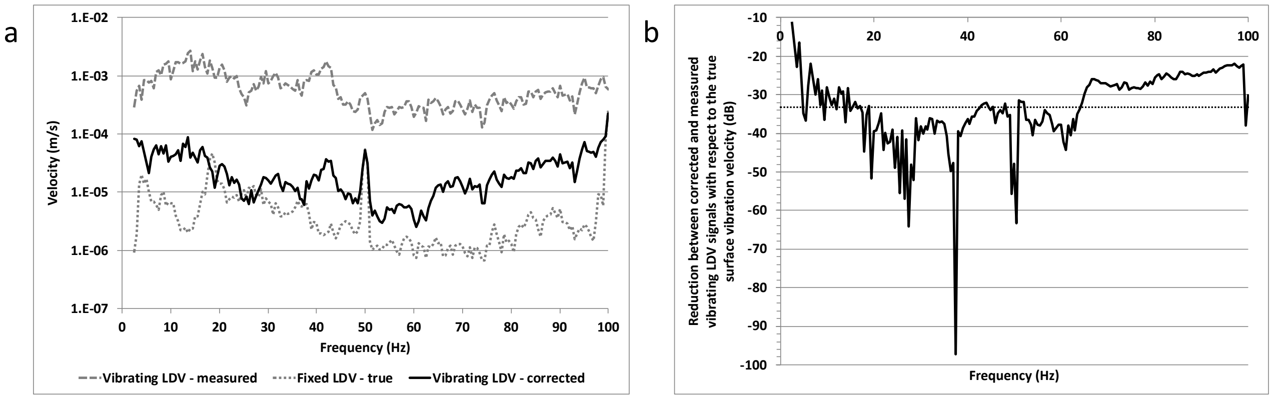

Figure 4: Correction with two accelerometers and time delay adjustment; (a) amplitude and (b) dB reduction.

For the more real-world relevant scenario in which the target itself is also vibrating, in this case with a level 80x10^{-3} g RMS broadband, it can be shown that the improvement between measured and corrected signals is excellent as shown in Fig 5 [2]. The only exception would be at very low frequency, i.e. below c 10 Hz but neither the accelerometer nor the LDV measurement performance are expected to be reliable in this region. Overall, the mean dB error reduction in Fig 5b shows the significant improvement, equating to an average across the frequency range shown in excess of 37 dB.

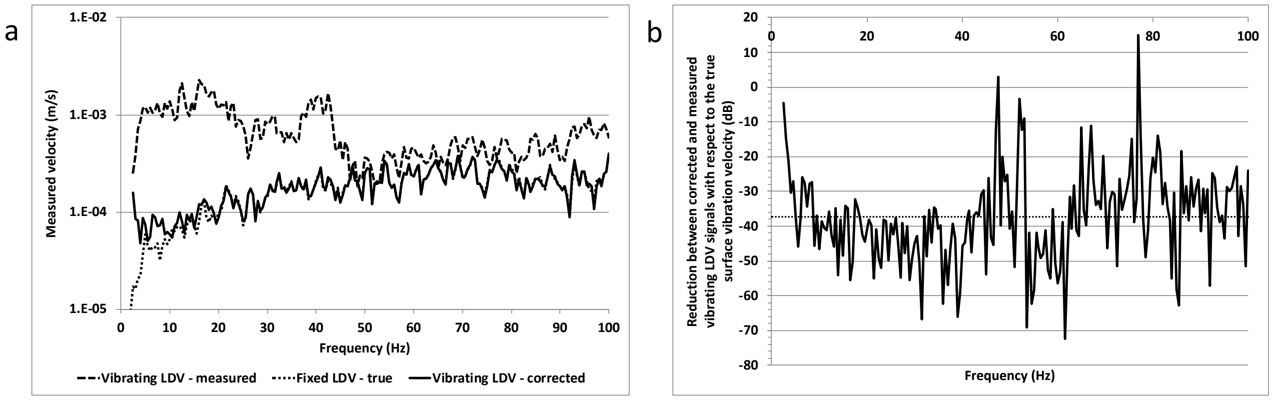

Figure 5: Correction for scenario with instrument *and* target vibration; (a) amplitude and (b) dB reduction.

2.2 Steering optic vibration

Sensitivity to laser beam steering optic vibration can readily be investigated by employing an experimental arrangement such as that shown in Fig 6 [3]. The steering mirror orientation shown results in a 90° angle through which the beam is steered to direct it toward the target; alternative angles were also investigated. Target and steering mirror translational motions were generated independently by small electrodynamic shakers with linear bearings maintaining directional isolation. Both true vibration signals were determined using piezoelectric accelerometers, in the case of the steering mirror mounted on the back-surface of the mirror directly behind the point of laser beam incidence.

As can be seen in Fig 6b for a scenario in which the target is nominally stationary while the steering mirror is undergoing 50x10^{-3} g RMS broadband vibration, sensitivity to steering mirror vibration is apparent. The measurement is two to three orders of magnitude higher than actual target vibration. Application of a general vectorial velocity sensitivity framework shows the sensitivity to be to the component of mirror vibration in the direction of the mirror normal [3]. Indeed, the LDV probe beam is Doppler shifted twice at the mirror surface, once on the way to and again on the way back from the target surface. The general framework shows the required correction which is completely general and easy to implement provided the mirror orientation can be determined.

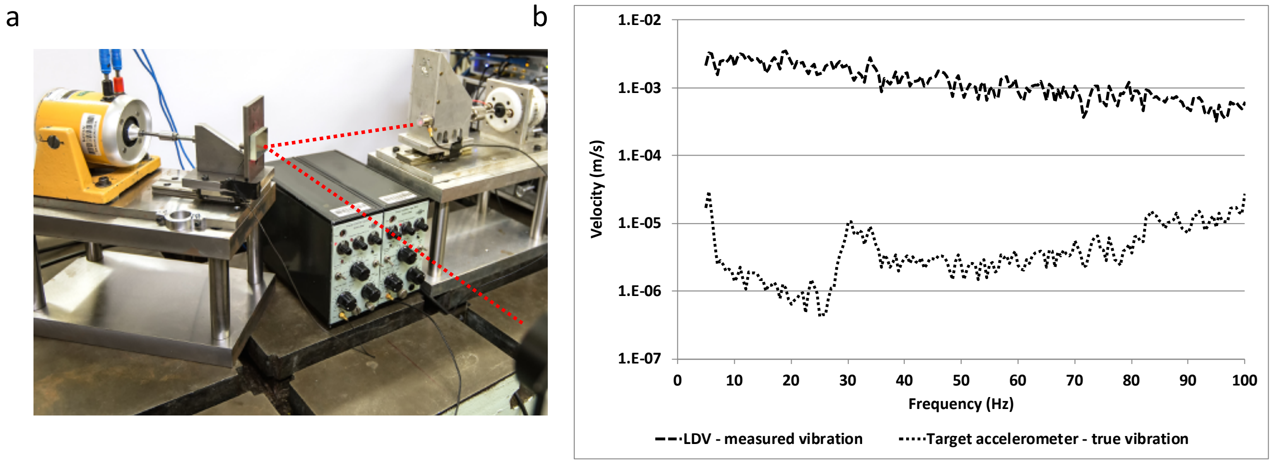

Figure 6: Steering mirror vibration sensitivity confirmation; (a) arrangement and (b) measured data.

As for the previous investigation, finite time delays between the accelerometers and LDV signals were determined in advance and incorporated as necessary into the frequency domain post-processing. Similar improvements in the LDV measurement were realised as shown in Fig 7. For the scenario in which only the steering mirror is vibrating, shown in Fig 7a, a mean error reduction in excess of 35 dB is realised. For the more general scenario, in which the target is also undergoing vibration – 30x10^{-3} g RMS broadband here – Fig 7b shows the equivalent error reduction, this time with an average for the frequency range shown in excess of 47 dB.

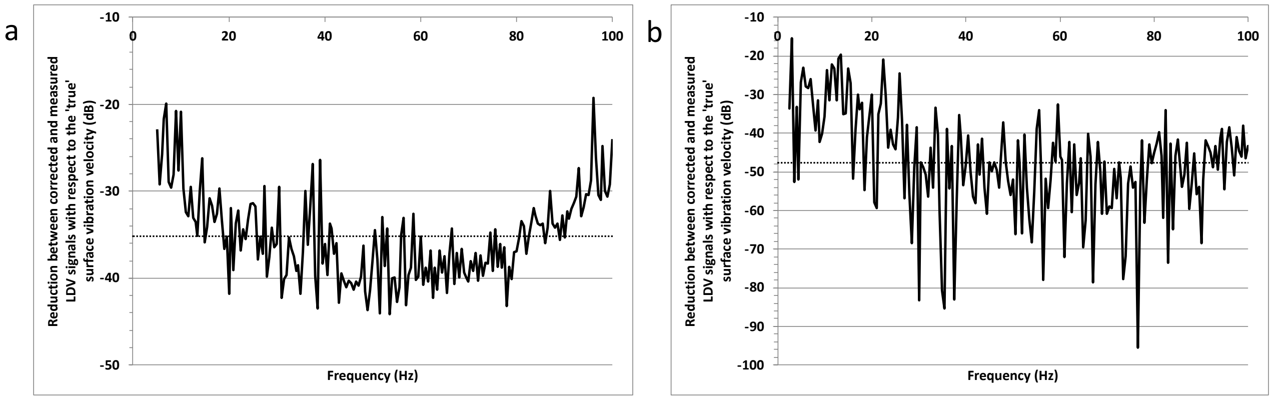

Figure 7: Correction for; (a) steering mirror vibration only and (b) both steering mirror and target vibration.

3. Real-world measurement scenarios

3.1 Measurements from a vibrating vehicle simulator

An example real-world measurement scenario in which instrument vibration is likely to be significant relative to that under investigation would be where the LDV is operated within a vehicle while measuring the vibration of a component or assembly also within that vehicle. While the measurement will be of the *relative* vibration velocity between the vibrating instrument and target, it is the *absolute* target vibration that is required. Fig 8a shows just such a scenario, on a vibrating platform vehicle simulator, where the vibration of a mounted display was of interest. Utilising exactly the same procedure as deployed in the laboratory-based equivalent described in subsequent 2.1, a potentially crucial improvement in the LDV measurement is realised as is shown in Fig 8b. The corresponding error reduction in the frequency range shown is in excess of 24 dB. These results are presented for the first time in this article. While, in this case, inclusion of the accelerometer on the target surface enables determination of the true vibration, this may not always be possible, particularly, for example, where the mass of the accelerometer is significant relative to the target surface of interest and its addition would therefore result in a change in vibration behaviour.

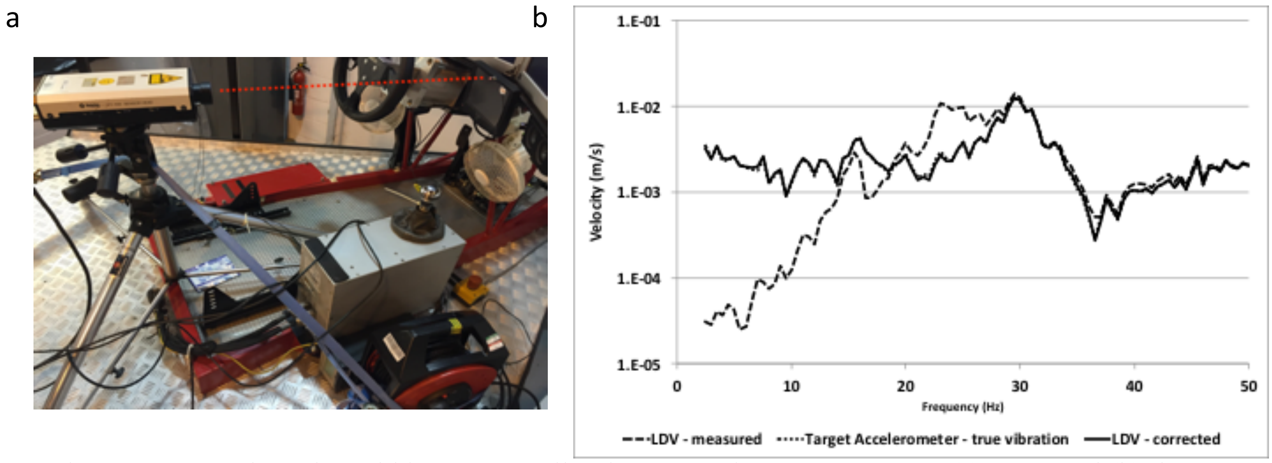

Figure 8: Example real-world instrument vibration correction measurement; (a) setup and (b) data

3.2 Measurements on a racing motorcycle engine

An example real-world scenario in which the correction of the LDV measurement is erroneous due to the vibration of a steering mirror used to divert the probe laser beam onto a hard-to-get-to location of interest is shown in Fig 9. Here a mirror is mounted to the bed of a dynamometer on which a single cylinder racing motorcycle is being tested. The mirror is being used to deflect the probe laser beam onto an engine mounting high up inside the motorcycle system and difficult to otherwise probe, certainly with the preferred measurement orientation which is in the vertical direction. Furthermore, the mounting is of cylindrical geometry and it is therefore challenging to attach a traditional contacting transducer to the preferred location. The LDV, however, is readily deployable albeit with care required to compensate for the inevitable vibration of the steering mirror.

Again, exactly as set out previously, the measurement is corrected using an accelerometer mounted to the back side of the mirror. Despite the required correction being completed in post-processing, the results are equivalent in nature to those typical of this kind of NVH measurement campaign, i.e. in the form of a "waterfall analysis" or Campbell diagram, as shown in Fig 9b. Here a structural resonance peak at approximately 190 Hz can be seen to persist through-out the engine speed run-up with it reaching a maximum at the closest 1x engine rpm (11605 rpm). In this case there is no true vibration for comparison, but analysis shows the mirror vibration to be of significance, particularly at 0.5 x and 1 x engine frequency. Without the important correction of the LDV measurement, there is a risk of data misinterpretation. The results, presented in this form for the first time in this article, enable the engineering team to make a better-informed decision about the handlebar vibration issue.

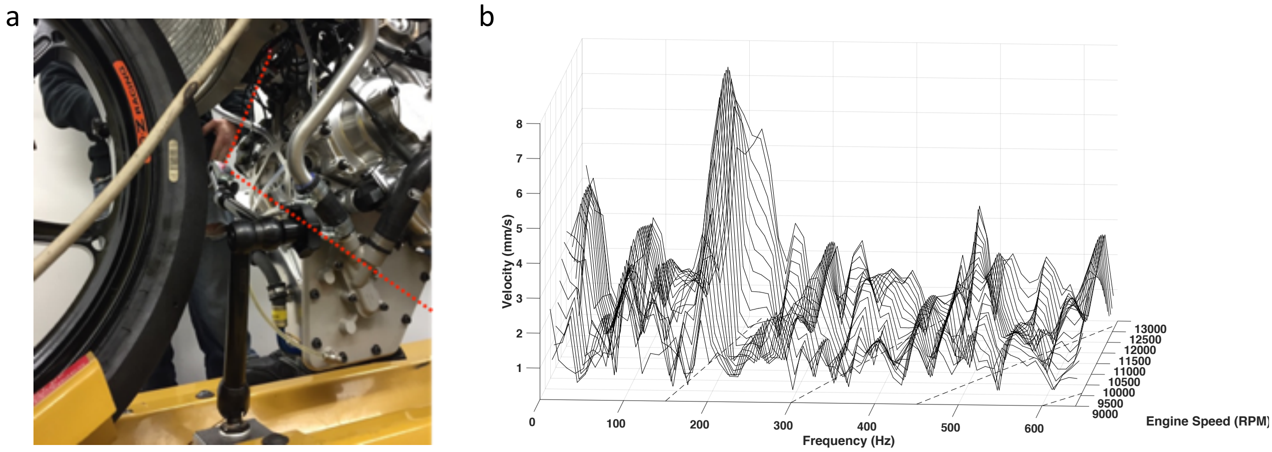

Figure 9: Example real-world steering mirror vibration correction measurement; (a) setup and (b) data

3.3 Measurements from an unmanned aerial vehicle

A potentially interesting extension to the correction of instrument vibration body of work would be the investigation of making vibration measurements of remote structures of interest from a vibrating platform such as a helicopter or, indeed, an unmanned aerial vehicle (UAV). Theoretically, correction of the LDV measurements, adversely affected by the vibration of the UAV itself, can be corrected in the same manner as that describe in subsection 2.1 and deployed in subsection 3.1. Some initial proof-of concept work, reported herein for the first time, has been completed. As can be seen in Fig 10a, successful indoor flight trials have been undertaken with a Polytec PDV-100 Portable Digital Vibrometer.

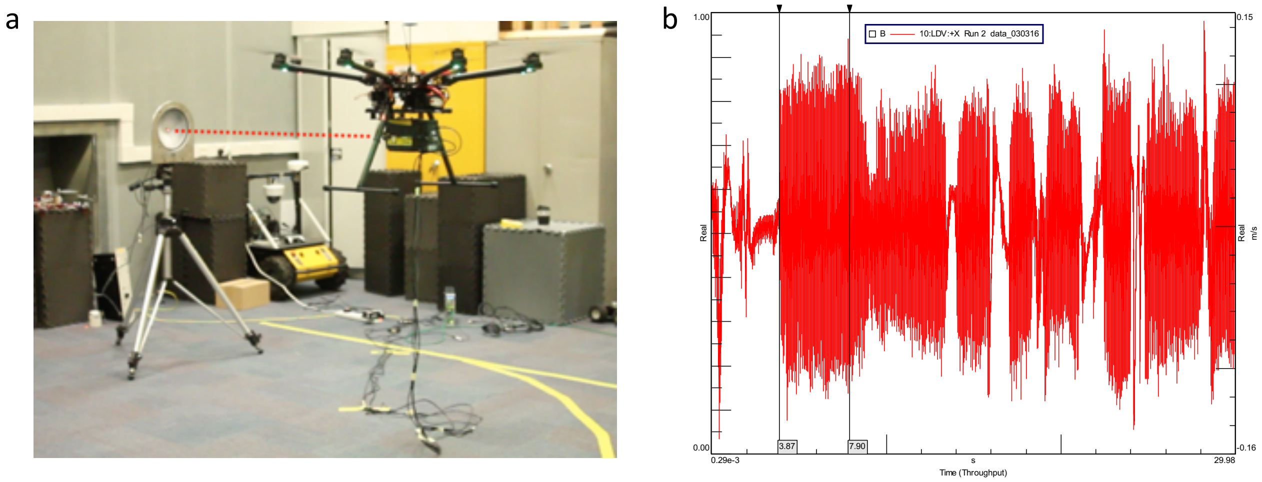

Figure 10: Novel UAV-mounted LDV measurement for remote sensing applications; (a) setup and (b) data

Initial testing was completed indoor rather than outdoor for safety and regulatory reasons. The target structure of interest was simply a 150 mm diameter loudspeaker which could be driven with broadband noise. An IEPE piezoelectric accelerometer was mounted to the surface of the speaker cone to provide a reference vibration measurement. The PDV-100 was powered and the signals collected from the vibrometer analogue output and the two IEPE piezoelectric correcting accelerometers via an umbilical cable to the ground-based acquisition system. The airframe used was a DJI-S1000 octocopter with an A3 flight controller and approximately 7 kg payload capability. The PDV-100 mass is approximately 2.6 kg. Longer term it is envisioned that a data logger acquisition system can also be mounted on the airframe with battery power for both the UAV, the LDV and the acquisition system being on board.

For the moment, however, this novel LDV application remains sufficiently challenging justifying the need for further research. The trade-off with indoor flight trials is that GPS is not available to assist with the UAV stability of position and pointing. For a relatively small target it was therefore not possible to maintain the laser beam pointing for a sufficiently long enough time to be able to extract meaningful measurement data for correction. A typical example of the output is shown in Fig 10b where the segments of low signal level indicate periods where the probe laser beam “fell” off the target surface. Future work will likely involve the use of lightly grounded / tethered UAVs to progress the data post-processing which, for the transient rather than stationary signals expected, will require time rather than frequency domain processing, ideally in real time rather than post-acquisition.

4. Conclusions

This paper has presented a comprehensive review of two recent important extensions of the huge range of capabilities of the now readily accepted laser Doppler vibrometer (LDV). Firstly, the fundamentally important issue of LDV sensitivity to instrument vibration in the direction of the probe laser beam is shown and the means by which this can be completely corrected across the entire frequency range of interest is described. Correction requires that a pair of measurements are made from locations equidistant about the laser beam with the mean of these two measurements being the correction signal that must be subtracted from the measured signal. This convenient correction works for arbitrary six-degree-of-freedom instrument motion and yields measurement error reductions of over 30 dB in all cases. Correction performance at extreme frequencies is simply a function of the performance of both the LDV and correcting accelerometers. Future research will involve the use of high sensitivity DC response accelerometers such that correction can be achieved at the low frequencies and low vibration levels the like of which are important in seismic sensing application where the impact of environmental vibration presents significant challenges and contaminates the measured LDV signal.

The second of the two techniques described involves complete correction of the erroneous measurement that results when a vibrating steering optic (typically a mirror) is used to direct the probe laser beam into a hard-to-get-to measurement location. Generally, it is practically challenging to mount the steering optic in a useful location while also isolating it from the surrounding vibration. Examples of such measurements include the use of mirrors to direct beams onto valvetrain components within internal combustion engine test rigs or similar. Again, complete correction is shown to be possible by the application of a single correction accelerometer at the back surface of the mirror in line with the laser beam reflection. Here, measurement error reductions are again at least 30 dB.

Lastly, the paper sets out three practically challenging and of interest real world measurement applications, two of which show conclusively the potential of the both techniques addressed herein to offer significant benefits in vibration engineering. The third, significantly more challenging scenario, described in this paper for the first time, presents a novel and exciting opportunity for future investigation.

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