Towards laser Doppler vibrometry from unmanned aerial vehicles

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Abstract. Laser Doppler vibrometers are technically well suited to general application but they offer special benefits in a variety of challenging measurement scenarios which are now well documented and accepted. An interesting and potentially powerful example of such a challenging measurement scenario is one where the laser vibrometer is mounted on/in an unmanned aerial vehicle in order that autonomous measurement campaigns can be undertaken in remote and/or harsh environments. One important challenge to overcome in such a scenario is the measurement sensitivity to vibration of the instrument itself or indeed of any steering optics used to point the probe laser beam toward the target of interest. In this paper, recently reported means by which this measurement sensitivity can be rectified by simultaneously obtained correction measurements will be developed. Specifically, this development is intended to lead towards laser Doppler vibrometry from unmanned aerial vehicles (UAVs) with correction of instrument motion being presented herein for the first time from a single, rather than a pair of, uniaxial accelerometers.

1. Introduction

Laser Doppler vibrometers (LDVs) measure target surface 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 quite recently [2]-[4], however, little attention had been given to i) a quite fundamental aspect of operation which is that the measurement is of <u>velocity relative to the instrument itself</u> and ii) measurement scenarios in which interpretation of the data must consider instrument or laser beam steering optic motion. Instead, practical application of LDV has typically either involved mounting of the instrument on a stable platform, i.e. on a tripod, or, in the case of significant levels of ambient ("base motion") vibration, the use of passive or active anti-vibration mounting arrangements [5]. Often such measures will be sufficient to yield high quality outcomes but an alternative, in which the instrument vibration can be fully compensated for across a broad frequency range, would be clearly preferable. Such compensation would be particularly beneficial where the measurement campaign involves the mounting of the instrument onto a platform in which the vibration level might be comparable with that of the target of interest, for example when making measurements from unmanned or other aerial vehicles.

Previously, comprehensive vector-based mathematical treatments of the velocity measured for both scenarios in which significant levels of i) base motion vibration [2] and ii) steering optic vibration [3] have been presented. Substantial experimental investigations have conclusively verified both scenarios providing practical compensation schemes based on traditional contacting vibration measurement transducers which can be conveniently located on the instrument or steering optic itself. For realistic vibration levels for both target and instrument/steering optic vibration, reductions of at least 37/47 dB, respectively, were demonstrated. Ultimately in both cases, real-world measurements were presented, in accordance with conventional noise and vibration engineering paradigms, showing that the required accelerometer compensation measurements yield a substantially enhanced understanding of the dynamic characteristics of the systems under test.

More recently, these earlier contributions have been reviewed in such a way that the practising vibration engineer might readily realise the measurement error reduction benefits [4]. In the case of instrument vibration correction, which is the primary focus of *this* article, the recommendation up to now, given the need to determine the instrument vibration in the direction of the probe laser beam, was to mount a pair of accelerometers equidistant around the probe laser beam axis. A single compensation accelerometer was shown to be viable in the case of only translational vibration, with angular vibration components present resulting in reduced correction performance. A single correction accelerometer would, of course, be optimal, indeed certain commercially available systems come complete with a mounting location for just such a single "compensation sensor". In this paper, therefore, a revised scheme for complete correction of LDV measurements, taken in the presence of substantial instrument vibration, based on the use of a single accelerometer is presented for the first time. A further, novel contribution of this paper is to make use of variable capacitance "DC response" accelerometers, rather than the previously utilized traditional general-purpose piezoelectric equivalent, for correction.

2. Accelerometer relative calibration

When embarking on a new instrument vibration correction measurement campaign, the first step is to "calibrate" the *correction* transducer(s). Additionally, where a "true" target vibration reference measurement is required (to prove the principle of the instrument vibration correction technique [4]) and this measurement is to be from a contacting transducer (rather than another, "Fixed LDV" [2]), this also applies to the *target* transducer. Indeed, the full measurement chain must be calibrated and this initial transducer "accelerometer relative calibration" stage takes two distinct forms: amplitude and phase relative (to the LDV) calibration.

Firstly, and consistently with all traditional measurement campaigns, the actual sensitivity of the accelerometer must be determined. In traditional measurement campaigns, this is achieved using an accelerometer calibrator such as the B&K Type 4294. Such devices generate a controlled amplitude single frequency component, e.g. a sinusoid at 159.2 Hz (1000 rad/s), against which the output of the accelerometer(s) can be verified, and the sensitivity(ies) accordingly adjusted. In the case of instrument base motion correction, however, the LDV will be used as the reference vibration (velocity) signal with the vibration being (arbitrarily) generated using a broadband (white) noise signal amplified to drive an electrodynamic shaker on which the accelerometers are mounted. Figure 1 shows the typical experimental arrangement in which the LDV probe laser beam is directly in line with the accelerometer sensitive axis (and, of course, positioned at the optimal stand-off distance).

Using a frequency domain integration approach [2],[3] to convert the accelerometer signal into velocity for direct comparison with that of the LDV, the RMS of the difference between the two signals within the frequency range of interest (2.5 – 100 Hz in this case) can be determined. The ratio of these two values for the accelerometer and the LDV can clearly be used to revise the accelerometer sensitivity such that the ratio ultimately becomes 1. Typically, this calculation is performed for a minimum of five averages and for two distinct levels of vibration amplitude. Figure 2 shows typical example accelerometers vs. LDV data *after* amplitude calibration. The curves may be challenging to differentiate from one another when reproduced in greyscale; that, however, is the very point – that, for each of the two vibration levels shown, the (integrated) accelerometer signals are indistinguishable from that of the LDV.

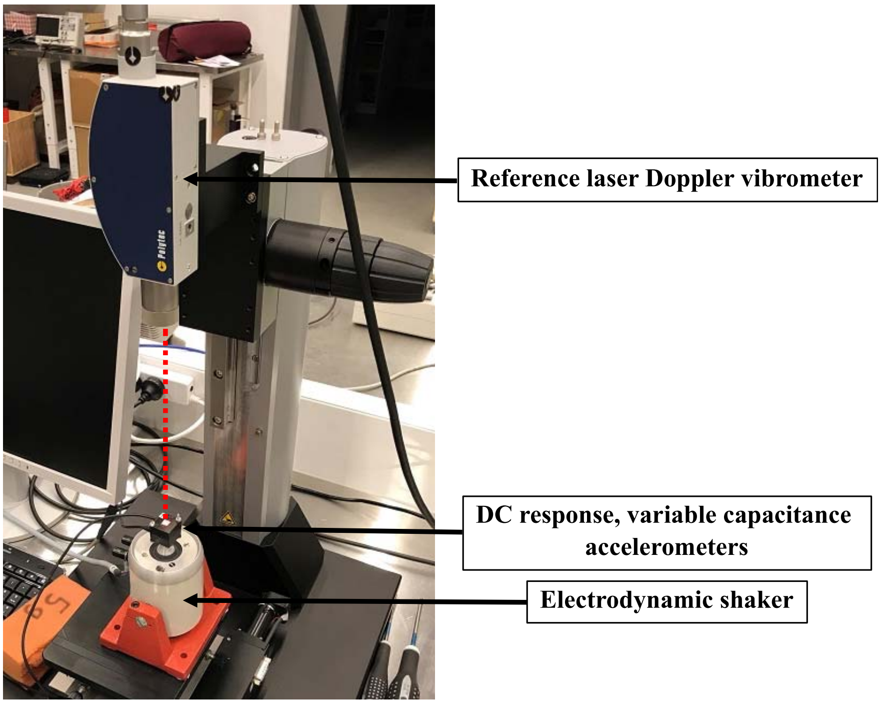

Figure 1. Typical accelerometer calibration experimental arrangement (with laser beam path highlighted)

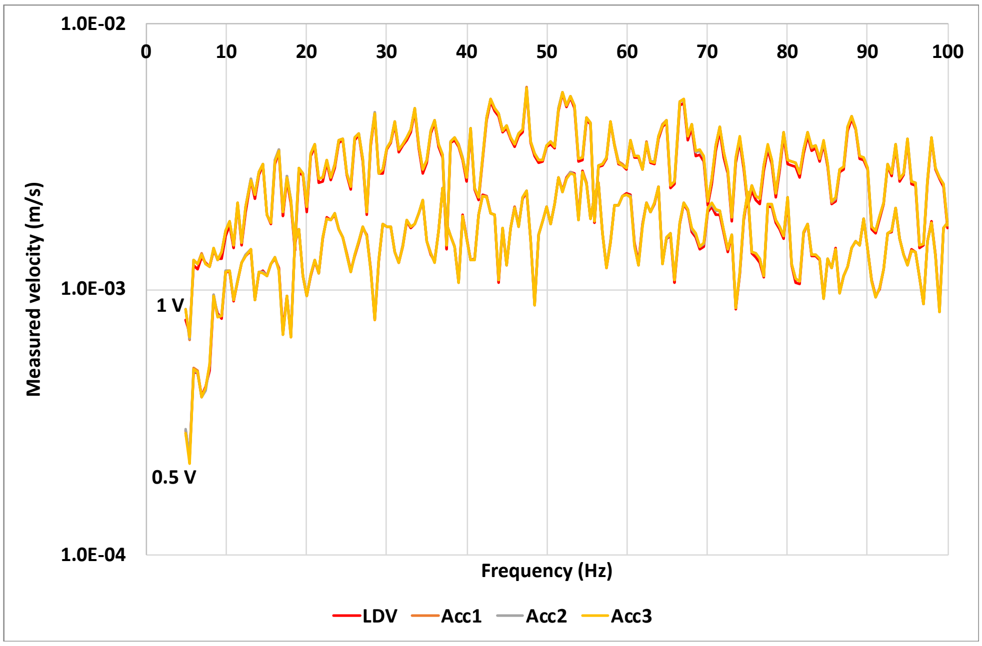

Figure 2. Typical *amplitude* difference comparisons LDV vs. accelerometers

In addition to *amplitude* calibration, *phase* differences between the accelerometer and LDV, mostly attributed to relative time delays between the signal conditioning electronics in each, also need to be accounted for. Broadband calculations are again performed in frequency domain processing. In this case, the absolute unwrapped phase differences between the accelerometer and LDV signals are averaged on a frequency-by-frequency basis for a minimum of five averages. The ratio of the mean of these values to the mean angular frequency of the frequency range of interest (2.5 – 100 Hz) is the effective time delay between the two signals. Figure 3 shows typical phase difference data *prior to* time delay correction. Again, in greyscale these various signals will be challenging to differentiate from one another but, again, this is indeed the very point – the three similar accelerometers should be expected to have nominally the same characteristics with respect to the LDV. The effect of the finite time delay can be seen in these curves as the underlying upward slope. In essence, the algorithm determines the gradient of the slope from which the time delay is derived (τ = slope gradient / 2π); clearly some noise immunity is necessary. Taking the mean for two different vibration levels yields values per accelerometer as shown in Table 1 below. These values are then readily incorporated into the subsequent frequency domain data processing when using the accelerometers to correct the measured, vibrating LDV signal. This will be described in the following subsection.

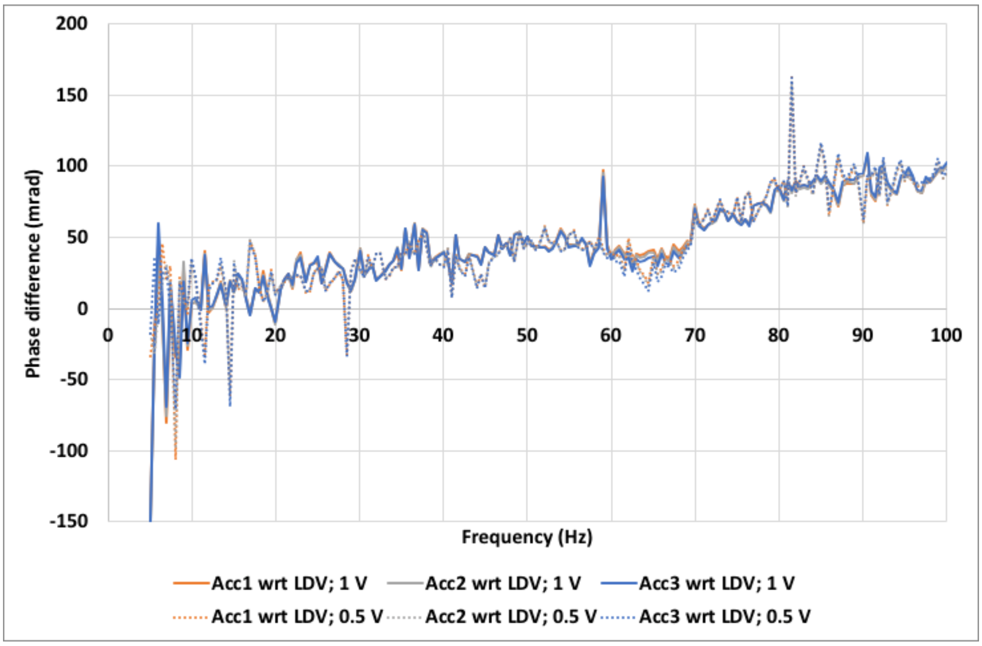

Figure 3. Typical *phase* difference comparisons LDV vs. accelerometers

Table 1. Example accelerometer vs. LDV time delays

Acc. model	Acc. s/n	Time delay (ms)		
		1V	0.5V	Mean
770F-10-U-120	10046	0.137	0.139	0.138
770F-10-U-120	10047	0.136	0.139	0.138
770F-10-U-120	10048	0.139	0.143	0.141
3225F	15763	-0.044	-0.046	-0.045

3. Instrument vibration correction

Sensitivity to instrument vibration (in the direction of the laser beam) was readily confirmed by a straightforward experiment, with an arrangement as set out in figure 4. Here, a "Vibrating LDV" sensor head was mounted on an electrodynamic shaker and excited with a broadband signal. The speaker cone, being relatively lightweight and of small radius of curvature, was fitted with a Dytran 3225F "teardrop" piezoelectric accelerometer to provide the 'true' "Vibrating target" measurement. With nominally zero target vibration, the true accelerometer reference measurement is clearly reflective, as shown in figure 5, of the target vibration whereas the LDV measurement is not. The LDV measurement is 100% sensitive to the vibration of the instrument itself as expected and previously shown in significant detail [2],[4].

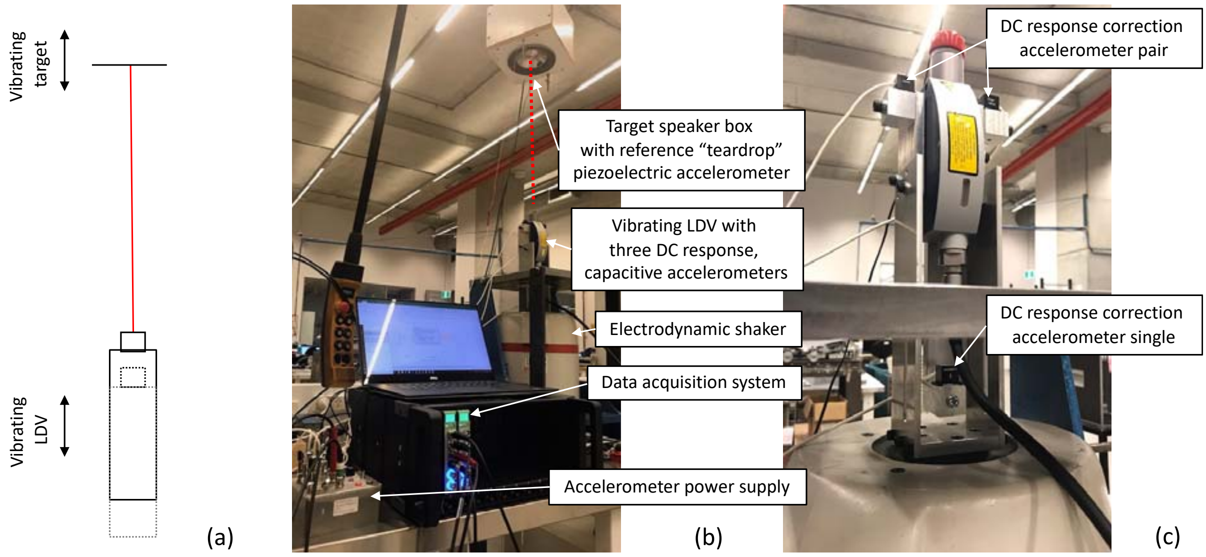

Figure 4. Experimental arrangement (a) schematic, (b) overall setup and (c) correction accelerometers

Making use of the same experimental arrangement but now arranging both instrument *and* target vibration (of absolute levels representative of those likely to be experienced in a practical real-world measurement scenario), figure 6 clearly shows that the signal measured by the LDV (long dash curve) is substantially different to the true target vibration (short dot curve) as expected. Here the most significant, approximately one order of magnitude, differences are seen to be between c5 and c20 Hz.

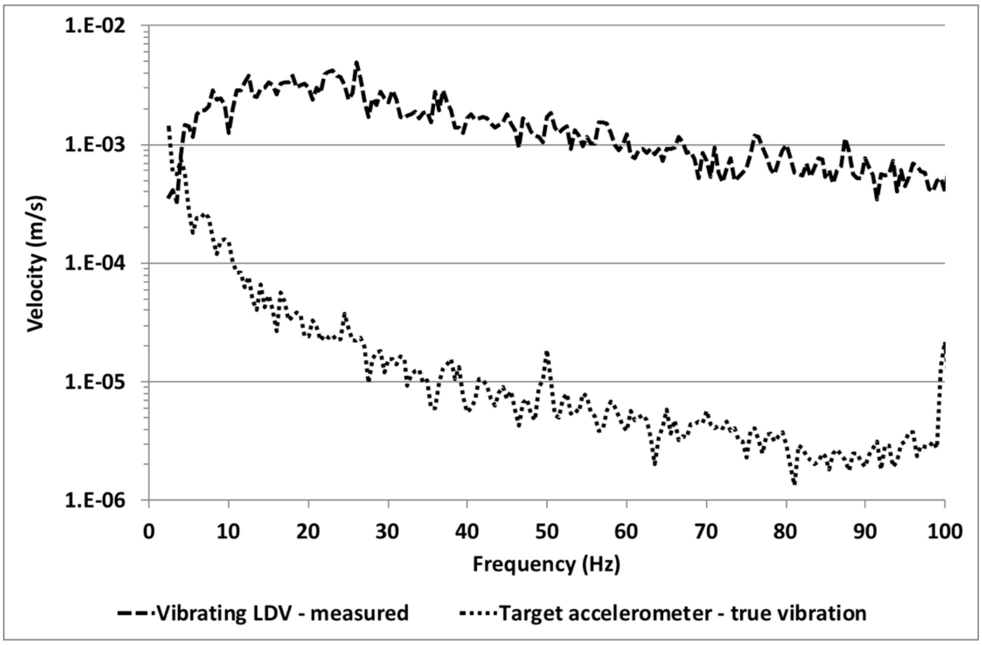

Figure 5. LDV vs. true target vibration velocity: instrument vibration, no target vibration

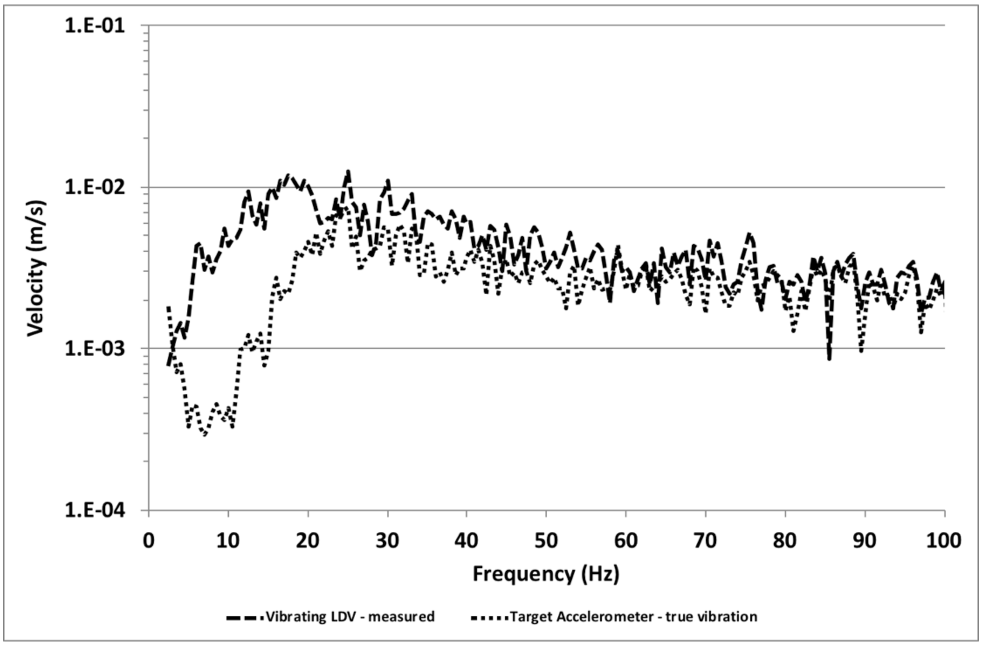

Figure 6. LDV vs. true target vibration velocity: instrument vibration and target vibration

As set out in significant theoretical and experimental detail previously [2], for complete correction of the erroneous LDV measurement, a simultaneous measurement of the instrument velocity at some point along the laser beam axis is required. This can be straightforwardly shown as:

$$U_{corr} = U_m - U_0 \tag{1}$$

where U_m is the measured velocity, U_{corr} the corrected velocity and U_0 the required correction measurement. Given that positioning a single transducer *forward* of the instrument would clearly result in a blocking of the laser beam, the required correction measurement was previously obtained by a pair of accelerometers positioned equidistant about, with their sensitivity axes parallel to, the laser beam axis.

Figure 4c shows a practical example of this accelerometer pair positioning strategy where a simple bracket and a pair of mounting blocks are used to provide accelerometer mounting locations. In other commercially available instruments, mounting is often even more straightforward since the laser beam optical axis is typically normal to a flat surface which is the front of the sensor head body. There is such a surface on the Polytec NLV-2500 Compact Laser Vibrometer used in this study but it is not sufficiently expansive for the relatively large footprint Endevco 770F-10-U-120 variable capacitance accelerometers. Figure 4c also shows an alternative instrument vibration compensation sensor arrangement based on a single accelerometer mounted on the laser beam axis but *behind* the instrument sensor head. This alternative option is presented and compared with the previously proven accelerometer pair here for the first time.

Integrating these accelerometer measurements in the frequency domain, incorporating the finite time delays as set out in Table 1 and subtracting the appropriate correction measurement in accordance with equation (1) leads to *corrected* LDV signals as shown in figure 7. Here, as expected, complete correction of the LDV measurement is shown for both cases of the accelerometer pair (bold solid curve with +) and the single accelerometer (bold solid curve); indeed, they are indistinguishable from one another. The dB reduction in the error is 17.5 dB in both cases. Phase error, as shown in figure 8, is comfortably within 100 mrad between 20 and 100 Hz; below 20 Hz phase error is larger as would be expected.

There is a small exception to the excellent agreement between the corrected LDV signal and the true vibration reference measurement and that is in the low frequency region below c10 Hz. Rather than this being a problem with the compensation algorithm, this is certainly as a result of the comparatively poor low frequency performance of the target piezoelectric accelerometer in that low frequency range (it is performing quite acceptably with respect to its specification – it is simply not intended to provide as reliable a result as a DC response accelerometer in this low frequency range). When the accelerometer signal is integrated, any error in the measured data below 20 Hz is multiplied by a relatively large number (1/ω) and the resulting velocity can be seen to "tick up" whereas the corrected LDV measurement is more reliable since both the LDV and the correcting DC response accelerometers have very reliable low frequency performance. Future studies will make use of an additional DC response accelerometer or another LDV for the "true" reference vibration measurement such that a better agreement is achieved.

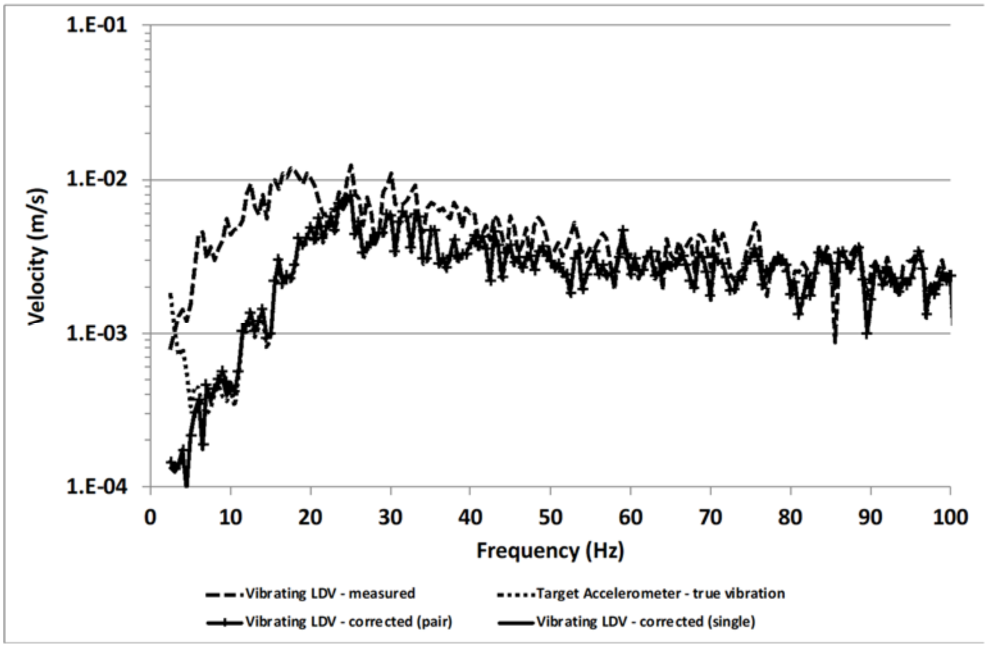

Figure 7. Corrected LDV measurement for a pair and a single correction accelerometer

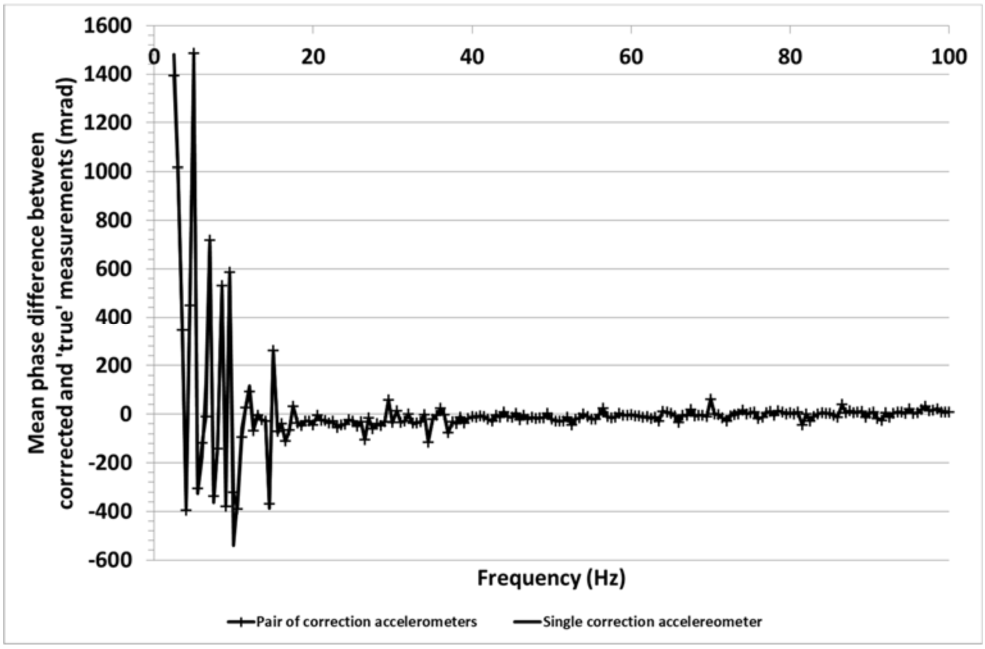

Figure 8. Mean phase difference between corrected LDV and true vibration measurements

4. Conclusions

This paper has reviewed the practical means by which an erroneous LDV measurement, due to significant levels of instrument vibration, can be corrected by subtracting a simultaneous measurement of the instrument vibration at some point along the axis of the laser beam. The means by which the required correction accelerometers should be calibrated both in terms of amplitude *and* phase (finite time delay) has been presented with newly obtained measurement data included herein for the first time. A measurement scenario, with typical real-world levels of instrument and target vibration, was presented, again incorporating data presented herein for the first time. Recommendations for the practical application of this, readily deployable by the practising noise and vibration engineer, are included. Novelties in this article include the use of DC response accelerometers to provide the correction measurement and, the use of a single accelerometer, rather than a pair, mounted behind the instrument sensor head. For the vibration levels used, error reduction of 17.5 dB was achieved between uncorrected and corrected measurements with phase agreement within 100 mrad between 20 and 100 Hz.

In order to achieve better correction at frequencies down to DC, which is important for applications such as seismic measurements and handheld application, correction measurement transducers with excellent low frequency performance should be utilised. Similarly, comparison measurements of the true vibration, for the sake of confirming the validity of the technique, should have equally excellent low frequency performance. In future, a DC response accelerometer or another LDV will be used to determine the true target vibration. The piezoelectric accelerometer used in this study was chosen for its small footprint and light mass which made for easy and reliable attachment to the light speaker cone domed surface. However, it has the problem of relatively unreliable low frequency performance after integration to velocity (for comparison with the LDV measurement) which causes the signal to "tick-up" as shown in figures 6 and 7 at frequencies below 5-6 Hz. In order to move "towards LDV from unmanned aerial vehicles", future research will also investigate the extension of the technique presented herein to the measurement of *transient*, rather than only stationary, vibration signals where time, rather than frequency, domain processing will clearly need to be developed and deployed.

5. References

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