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CORRECTION OF LASER DOPPLER VIBROMETER MEASUREMENTS AFFECTED BY SENSOR HEAD VIBRATION USING TIME DOMAIN TECHNIQUES

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Abstract. *Despite widespread use in a variety of areas, in-field applications of laser Doppler vibrometers (LDVs) are still somewhat limited due to their inherent sensitivity to vibration of the instrument sensor head itself. Earlier work, briefly reviewed herein, has shown it to be possible to subtract the instrument vibration via a number of means, however, it has been difficult up to now to truly compare the performance of these. This is compounded by the constraint that a frequency domain based approach only holds for stationary vibration signals while, particularly for in-field applications, an approach that is also applicable to transient signals is necessary. This paper therefore describes the development of a novel time domain post-processing based approach for vibrating LDV measurement correction and compares it with the frequency domain counterpart. Results show that, while both techniques offer significant improvements in the corrected LDV signal when compared to a reference accelerometer measurement, the time domain based correction outperforms the frequency domain based method by a factor of eight.*

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1 INTRODUCTION

Laser Doppler vibrometers (LDVs) have become indispensable tools both within industrial and research domains, especially where non-contact operation is advantageous [1]. Despite the considerable amount of published research, in-field applications of LDVs - which might include their incorporation into unmanned aerial vehicles for example - remains arguably limited, at least partly due to their sensitivity to vibration of the instrument itself. However, if this limitation was eliminated, it could enable remote vibration measurement campaigns in hazardous environments, for example facilitating the more accurate and rapid detection of remnant mines or structural health monitoring of remote infrastructure.

LDVs are based on an interferometric optical arrangement, meaning they measure target surface vibration *relative* to the instrument; conversely, more traditional contacting vibration transducers measure *absolute* surface vibration. In other words, instrument vibration, usually caused by the surrounding environment, is indistinguishable from that of the target in the resulting measurement. A common solution to this problem is to isolate the LDV using passive [2] or active anti-vibration mounting arrangements [3]. However, such solutions can be too heavy, ineffective or costly. The contemporary solution [4–6] is to independently measure the instrument vibration and use this information to correct the LDV measurement, thereby recovering the intended target vibration measurement.

Correction by measuring the instrument vibration has previously been carried out conveniently and effectively in the frequency domain [4–6], however, this is only appropriate for the statistically stationary signals that are typically encountered. Oftentimes, however, and in particular in field based measurement campaigns, vibration profiles may be transient in nature and an alternative, time domain based approach may, therefore, be more appropriate. Correction based in the time domain has previously been carried out using either an internal damper, which the reference beam is incident upon or an external accelerometer [7–9]. However, until now, no comparison has been been made of the two types of approach due to alternative experimental setups or effectiveness metrics. The development of a novel, post-processing, time domain based approach and its comparison with the frequency domain based alternative is, therefore, the focus of this article.

2 FREQUENCY DOMAIN BASED PROCESSING

It has been rigorously shown, both mathematically and experimentally, that correction of erroneous LDV measurements requires the subtraction of an independent simultaneous measurement of the instrument/optical element vibration [4, 5]. In the case of a single beam LDV, this measurement is conveniently achieved in practice using a single, ‘correction accelerometer’ mounted somewhere along the laser beam axis, generally on the back of the housing. To experimentally confirm the validity of the correction, a second ‘reference accelerometer’ is typically mounted to the target at the measurement location to offer a ‘true’ target vibration measurement. For statistically stationary velocity signals, frequency domain processing is a convenient means by which subtraction of the correction accelerometer signal can be realised while simultaneously performing the required integration and temporal alignment. The framework for this frequency domain based processing approach for the correction of erroneous LDV measurement is already well-established and the description is therefore intentionally kept brief in what follows.

2.1 Sensitivity adjustment and time delay correction

Accelerometer sensitivities are adjusted, with reference to the LDV, using a broadband frequency domain based relative calibration procedure. By necessity, this includes integration, readily achieved in the frequency domain, of the accelerometer signals. Ratios of the vibration levels over the frequency range of interest are used to revise the accelerometer sensitivities. Furthermore, due to inevitable differences between accelerometer and LDV signal conditioning electronics, finite time delays, independent of the sensitivity adjustment, exist between the digitised signals. Again, taking the LDV as the reference, these can be similarly readily estimated in the frequency domain from the signal phase differences [4, 5].

2.2 Instrument vibration correction

Among other typical practical measurement factors, including the accuracy of the positioning of the correction transducer to accurately determine the instrument vibration in the laser beam direction, the mean error reduction achieved depends upon the relative levels of instrument and target vibration. For vibration levels and frequency ranges of relevance to 'real-world' measurement campaigns, that is an RMS of $1\ \mathrm{mm\,s^{-1}}$ to $10\ \mathrm{mm\,s^{-1}}$ over the frequency range 2.5 Hz to 100 Hz, comparison of the LDV signal to the reference accelerometer typically yields a significant mean error reduction between 15 and 30 dB [4–6]. As previously derived [6], the mean error reduction, R, is calculated using:

$$R = -10\log_{10}\left(\frac{\mathrm{MSE_{corr}}}{\mathrm{MSE_m}}\right)\ \mathrm{dB} \tag{1}$$

where $\mathrm{MSE_m}$ and $\mathrm{MSE_{corr}}$ are the mean square error of the LDV signal before and after correction, respectively, when taking the reference accelerometer signal as the 'true' vibration signal. For N spectral lines, the general formulation is:

$$\mathrm{MSE_{signal}} = \frac{1}{2}\sum_{n=1}^{N}(A_{\mathrm{signal}}(n) - A_{\mathrm{true}}(n))^2 + (B_{\mathrm{signal}}(n) - B_{\mathrm{true}}(n))^2 \tag{2}$$

where $A_{\mathrm{signal}}(n)$ and $B_{\mathrm{signal}}(n)$ are the real and imaginary parts, respectively, of either the measured or corrected LDV signal at the nth spectral line. Similarly, $A_{\mathrm{true}}(n)$ and $B_{\mathrm{true}}(n)$ are the equivalents for the reference accelerometer signal.

3 TIME DOMAIN BASED PROCESSING

While there are some earlier studies in which erroneous measurements from LDVs subject to instrument vibration are resolved in real time or using time domain based techniques [7–9], they are few in number and diverse in approach with each employing a different metric to gauge the efficacy of the correction. This makes it somewhat difficult to contextualise the relative performances as well as to compare each with the established frequency domain based approach previously described. An early approach used a purely mechanical means to perform the compensation, incorporating an internal damper into the optical arrangement, upon which the reference beam was incident [7]. However, this system performance is unlikely to be consistent over a sufficiently wide frequency range as a result of damper resonances. Other known solutions employ a correction accelerometer, with the compensation being performed either in real-time [8] or in post-processing [9]. In the former, it is unclear where the accelerometer was mounted geometrically, only that it was mounted to the probe laser beam optics. Recent work

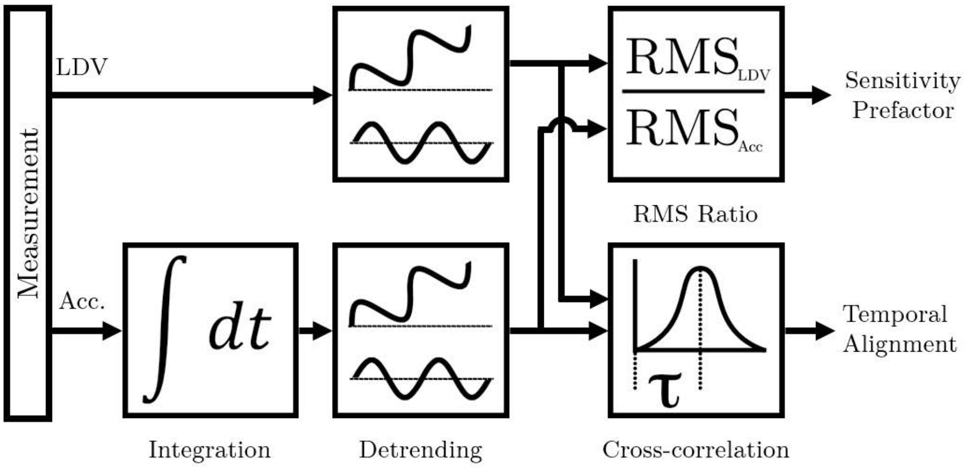


Figure 1: The time domain based accelerometer calibration procedure with "Acc." representing either the correction or the reference accelerometer signal.

has shown that the accelerometer must be on the laser beam axis for complete correction in the presence of arbitrary six degree-of-freedom instrument vibration [5]. In the latter, some useful enhancements to the preceding frequency domain based approach are introduced, in particular the means to undertake signal time delay compensation using time series data.

Offering complementarity to the earlier approaches, the method proposed herein is entirely based in the time domain and, for the moment, is performed in post-processing on recorded signals. In this respect, it does not differ to the frequency domain based approach, previously summarised, and, as such, the required experimental arrangement is common. While the motivation for the novel approach is to extend current capability to processing of *non-stationary* signals, in order to directly compare with the frequency domain equivalent, using the same previously defined metric, R, *stationary* vibration signals only are considered herein.

3.1 Sensitivity adjustment and time delay correction

As for the corresponding stage in the frequency domain based processing approach, accelerometer sensitivities and signal finite time delays are determined with the LDV taken as the reference. Figure 1 schematically depicts the time domain based processing calibration procedure for a single accelerometer; this can be replicated for as many accelerometers as are required. Again, the accelerometer signals must first be integrated and this is straightforwardly achieved here using the cumulative trapezoidal method. However, the integration of accelerometer signals commonly leads to the introduction of errors such as a DC offset and drift. Detrending is intended to remedy this and is achieved by subtracting a least squares fit of a first order polynomial from the integrated signal. Since this might remove genuine as well as spurious signal content, the LDV signal is subjected to the same for consistency.

With the accelerometer and LDV signals both represented as velocities, an RMS ratio can then be used to revise the accelerometer sensitivities; all subsequent measurements acquire signals accordingly adjusted. Meanwhile, the finite time delays between the LDV and accelerometer signals which occur as a result of differences between the signal processing electronics in the measurement chain, are estimated using a cross-correlation function as follows [9]:

$$r_{xy}(\tau) = \frac{1}{T}\int_0^{\infty} x(t)y(t+\tau)dt \qquad (3)$$

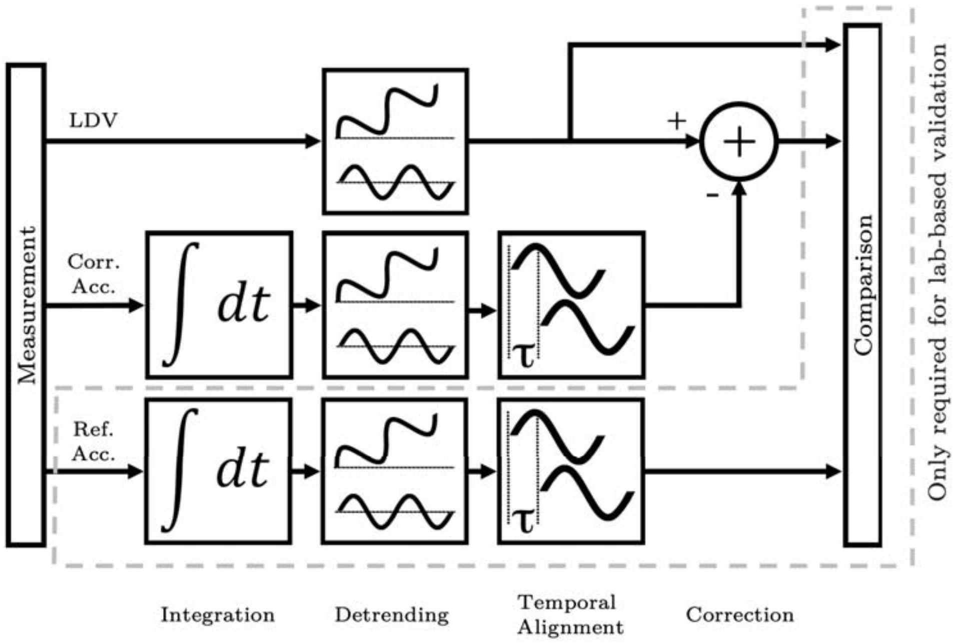


Figure 2: The time domain processing correction procedure with “Corr. Acc.” and “Ref. Acc.” representing the correction and reference accelerometer signals, respectively.

where τ is the time delay between the signals, x and y are the two signals, t is time and $r_{xy}(\tau)$ the cross-correlation function in which the peak will occur at the time delay between the signals.

3.2 Instrument vibration correction

Figure 2 schematically depicts the time domain based processing correction procedure. The first, “Integration”, and second, “Detrending”, steps are consistent with those previously described. The third, “Temporal alignment”, step incorporates the finite time delay in the accelerometer signals. This is achieved by time-shifting each accelerometer signal relative to the LDV signal by the amount previously determined, τ. Since this is only possible in integer units of the time step, a high sample frequency is required to maximise the accuracy of the temporal alignment between the signals. This time-shifting results in regions at the start and at the end of the measurement duration where samples for all three signals are not present and these regions are therefore truncated. The total original measurement duration may therefore need to be slightly longer than that which is ultimately required.

The final signal processing step in Figure 2, “Correction”, refers to the LDV signal correction and is given mathematically by [4]:

$$U_{\mathrm{corr}}(t) = U_{\mathrm{m}}(t) - U_0(t) \tag{4}$$

where $U_{\mathrm{m}}(t)$ is the measured LDV signal, $U_0(t)$ is the integrated correction accelerometer signal and $U_{\mathrm{corr}}(t)$ is the fully corrected LDV signal.

Ultimately, and only possible in the lab-based experimental validation approach described herein, the “Comparison” step in Figure 2 determines the efficacy of the correction procedure. This is achieved by comparing the corrected LDV signal with the final reference accelerometer signal. The performance metric used here is the previously described mean error reduction, R, given by (1). To calculate this in the time domain, an appropriate formulation of the MSE should be used, given by [6]:

$$\mathrm{MSE}_{\mathrm{signal}} = \overline{\left(U_{\mathrm{signal}}(t) - U_{\mathrm{true}}(t)\right)^2} \quad (5)$$

where $U_{\mathrm{true}}(t)$ is the reference accelerometer, $U_{\mathrm{signal}}(t)$ is either the measured or corrected LDV signal and $\overline{(\cdot)}$ signifies the time average. Direct comparison can now be made between processing techniques in both the time and frequency domains.

4 EXPERIMENTAL VALIDATION

4.1 Setup

An experimental setup, common with that implemented in earlier work [4–6], depicted in Figure 3 was arranged, whereby independent control of the target vibration and of the LDV vibration was possible. The target vibration is the measurement of interest while the base vibration simulates the effect of a vibrating platform on the LDV measurement. Both target and base vibrations were created using electrodynamic shakers independently powered and driven using uncorrelated broadband white noise signals up to 200 Hz, generated by a Siemens PLM Simcenter SCADAS Mobile data acquisition system.

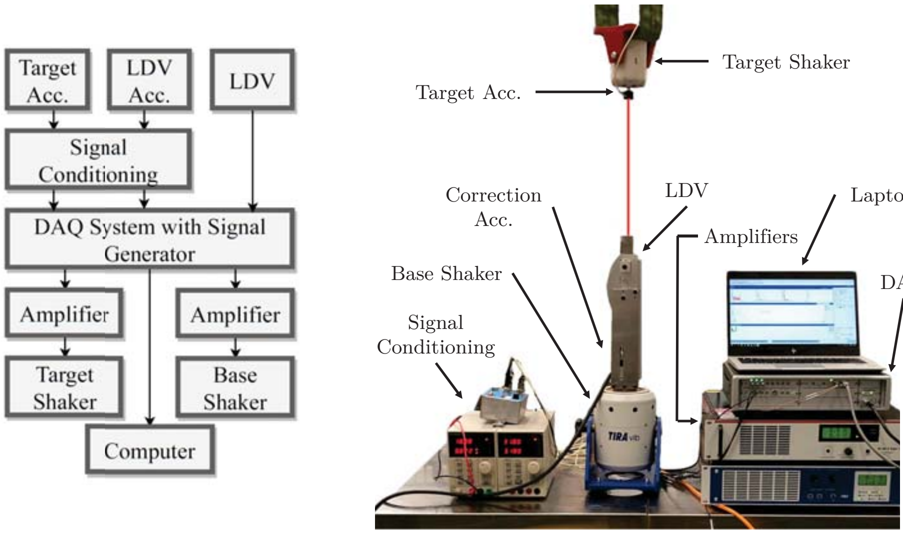
Mounted to the base vibration shaker, using a custom-made aluminium mounting bracket such that the LDV sensitive direction was aligned with the shaker vibration direction, was a Polytec Compact Laser Vibrometer NLV-2500-5. The bracket also contained an Endevco 770-10-U-120 (200 $\mathrm{mV/g}$ nominal) DC-response accelerometer, rigidly mounted with synthetic beeswax. This correction accelerometer was aligned with the probe laser beam axis to be optimally effective [4]. The target shaker was suspended from above using an overhead crane, providing isolation from the large base motion shaker. Mounted to the shaker spigot was a second similar Endevco accelerometer providing the 'true' vibration measurement.

4.2 Data collection and processing

The Siemens acquisition system was used to record the various time data throughput vibration signals at the maximum sampling frequency of 204.8 kHz for a duration of 8 s. This extremely high oversampling factor assists in the accurate temporal alignment of the three signals in the time domain, as previously mentioned. The acquired data were processed as five separate 1.6 s segments for both processing methods. In the frequency domain, these acquisition parameters lead to a spectral resolution of 0.625 Hz and a bandwidth of 102.4 kHz. The DC component was excluded from the calculation of R in frequency domain processing. The mean error reduction for both the time and frequency domain based approaches was averaged over the five segments with the standard error of the mean taken as the uncertainty in each result.

4.3 Results comparison

Frequency domain based accelerometer calibration for the model and conditioning used yielded a time delay of -138.5 ± 13.2 µs with the corresponding time domain based method value of -125.0 ± 1.1 µs in agreement. Since the estimation using the time domain based method yielded a lower uncertainty, a time delay of -125.0 µs was subsequently used for both correction procedures. It should be noted that, due to the necessary signal truncation following time domain based temporal alignment, comparisons between time and frequency domain approaches are not of *exactly* identical signal content. In this case, however, the difference is only 26 out of over 300,000 samples and it is therefore unlikely this will significantly affect the

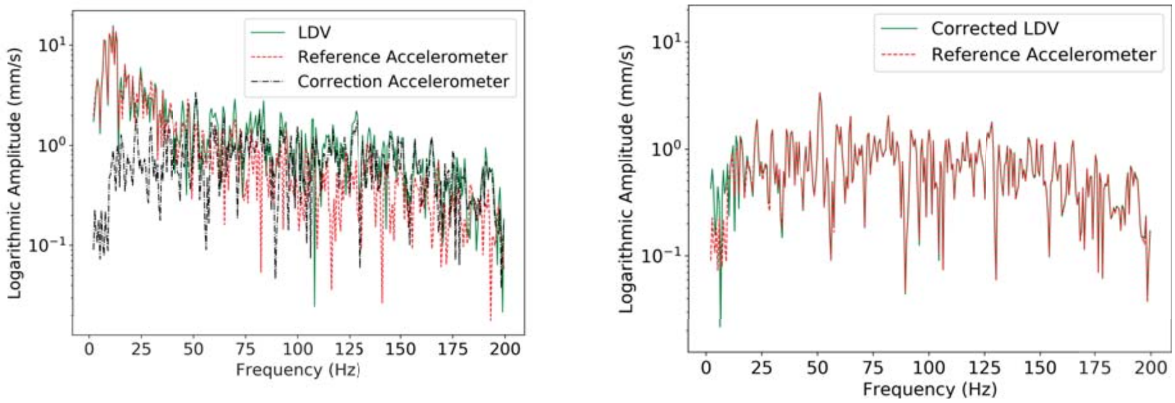


(a) (b)

Figure 3: Experimental setup used to simulate a LDV target vibration measurement during base motion vibration: (a) block diagram representation and (b) physical setup.

results.

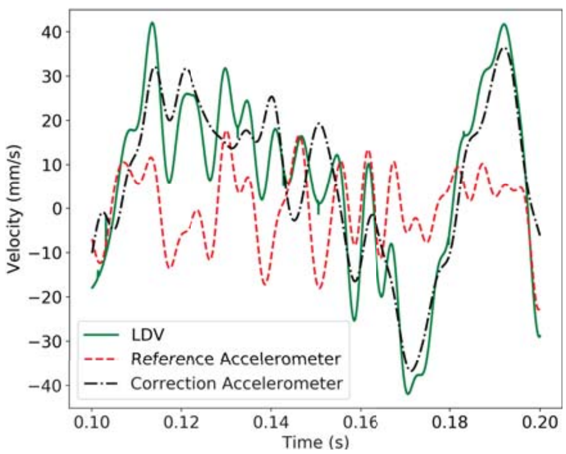
As can be seen qualitatively by comparing Figure 4 (a) and Figure 4 (b), this frequency domain based processing method yields significant improvements in the corrected versus the uncorrected LDV signal over the range 25 Hz to 200 Hz. However, the performance below 25 Hz is relatively poor, likely due to the lower signal level in this range owed to the shaker-amplifier dynamic characteristics.



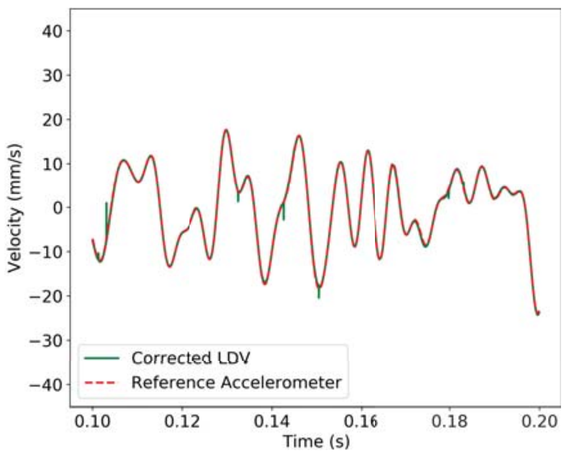
(a) (b)

Figure 4: Frequency domain processing spectra for a 1.6 s segment in the range 0.625 Hz - 200 Hz: (a) all signals before correction and (b) corrected LDV and reference accelerometer signals.

As can be seen in Figure 5 for a 100 ms segment of data, the time domain based processing method proposed here also offers significant improvement in the corrected versus the uncorrected LDV signal. However, in the time domain, the effect of speckle noise [1] is apparent, manifested as instantaneous spikes not present in the reference accelerometer signal.



(a)



(b)

Figure 5: A 100 ms segment of data from time domain processing: (a) all signals before correction and (b) corrected LDV and reference accelerometer signals.

The quality of the correction for the two alternative methods can be compared quantitatively using the mean error reduction, R, which can be seen in Table 1. Here it is shown that the time domain processing method outperforms the established frequency domain based processing method by a factor of eight.

Table 1: The mean error reduction for the five 1.6 s segments along with their logarithmic uncertainties calculated as the standard error of the mean.

	R
Frequency Domain	$25.3^{+1.8}_{-1.3}$ dB
Time Domain	$34.5^{+2.1}_{-1.4}$ dB

5 CONCLUSIONS

While correction of LDV measurements in the presence of instrument vibration has typically been carried out in the frequency domain and for *stationary* vibration signals only, extension to vibration signals that are *transient* in nature requires an alternative, time domain based approach. Furthermore, the direct comparison of existing time domain based approaches with the established, frequency domain approach is challenging. In this paper, therefore, the totally general theoretical basis for complete measurement correction was extended to include a completely time domain based approach.

Validation using a conventional experimental arrangement consisting of a vibrating LDV instrumented with a correction accelerometer and a vibrating target similarly instrumented to provide a true vibration reference measurement, has been shown. Throughput time data for statistically stationary vibration signals have been acquired and processed in both frequency and time domain processing. It has been shown that, while both approaches lead to significant improvements in the quality of the corrected LDV measurement, the time domain based approach described here yields a mean error reduction value, R, eight times higher than the previously described frequency domain based approach.

This improvement is a significant finding and offers a viable alternative to the established frequency domain equivalent for *stationary* vibration signals, provided time data signals can be acquired with a high oversampling factor. Moreover, it now extends the capability to perform complete correction of LDV measurements in the presence of *transient* instrument vibration, such vibrations being more likely to occur in real-world in-field applications for example in measurement campaigns from unmanned aerial vehicles.

Future investigations will explore the sensitivity of the time domain based approach to reduced sample frequency signals and identify the sources of the performance gap. Improved frequency domain approach performance, including the estimate of accelerometer signal time delays, will be realised. Ultimately, however, deployment of the time domain based approach for transient signal processing will be the most significant follow-up to the work presented here.

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