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Reprint of: Taking laser Doppler vibrometry off the tripod: correction of measurements affected by instrument vibration

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ABSTRACT

Laser Doppler vibrometers (LDVs) are now well-established as an effective non-contact alternative to traditional contacting transducers. Despite 30 years of successful applications, however, very little attention has been given to sensitivity to vibration of the instrument itself. In this paper, the sensitivity to instrument vibration is confirmed before development theoretically and experimentally of a practical scheme to enable correction of measurements for arbitrary instrument vibration. The scheme requires a pair of correction sensors with appropriate orientation and relative location, while using frequency domain processing to accommodate inter-channel time delay and signal integrations. Error reductions in excess of 30 dB are delivered in laboratory tests with simultaneous instrument and target vibration over a broad frequency range. Ultimately, application to measurement on a vehicle simulator experiencing high levels of vibration demonstrates the practical nature of the correction technique and its robustness in a challenging measurement environment.

1. Introduction

The laser Doppler vibrometer (LDV) is now well-established as an effective non-contact alternative to traditional contacting transducers such as the ubiquitous piezoelectric accelerometer. LDVs measure vibration velocity and are technically well-suited to general application but they have repeatedly proved invaluable in a variety of challenging measurement scenarios. Commercial LDVs have now been available for more than 30 years but, despite so much successful application, almost no attention has been given to a quite fundamental aspect of LDV operation which is that the measurement is of velocity relative to the instrument itself. Consequently, measurements are directly affected by instrument vibration in the direction of the laser beam and this cannot be distinguished from the intended measurement.

While instrument vibrations can be a factor in general application, they are particularly important in specific scenarios including handheld measurements such as in a clinical application [1], measurements taken within a moving structure such as a vehicle cabin [2], and measurements taken from a moving vehicle [3,4]. To date, the routine approach taken is to attempt to isolate the instrument to minimise its vibration, often by mounting on a tripod with compliant feet, but this is not always convenient or adequate. This paper shows for the first time how to compensate for instrument vibrations, contributing significantly to the advancement of LDV as a user-friendly technique. This comprehensive study includes a confirmation of the measurement sensitivity to such motions, a theoretical basis for the proposed scheme of additional measurements for correction in the presence of complex instrument motions, and laboratory tests to confirm its effectiveness. Finally, the system is taken out of the laboratory and successfully implemented on a flight simulator platform undergoing extreme vibrations.

2. Understanding the velocity measured during instrument vibration

2.1. Extent of the problem

The sensitivity to instrument vibration in the direction of the laser beam was confirmed by a simple experiment, as outlined in Fig. 1, in which two simultaneous LDV measurements were made on a (nominally) stationary target. The “Vibrating” LDV (Polytec OFV4000 set-up for translational vibration measurement) is mounted on a shaker and excited; the excitation is broadband and primarily in the direction of the laser beam. A “Fixed” LDV (Polytec PDV100) (i.e. not excited) is tripod mounted and used to provide the ‘true’ measurement. As shown in Fig. 2, the true measurement is at an extremely low level, as expected, but the measurement from the vibrating instrument shows significant sensitivity to instrument vibration in the direction of the

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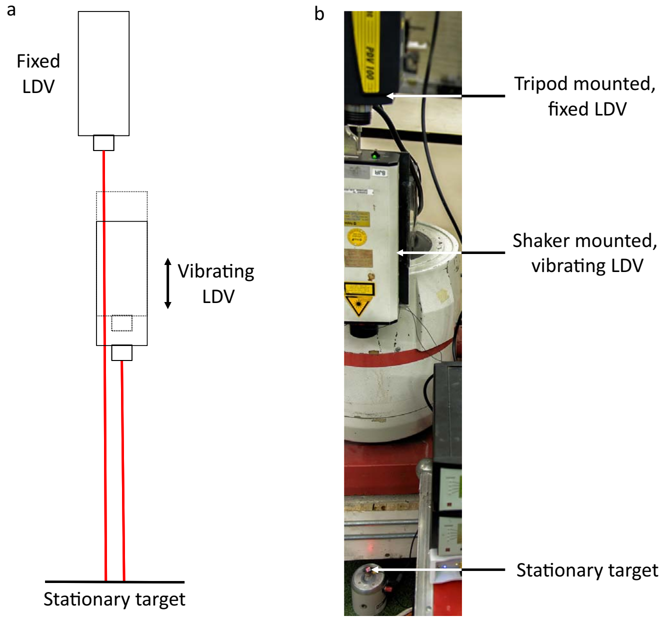

Fig. 1. Experimental arrangement showing vibrating and fixed LDVs to demonstrate sensitivity to instrument vibration; (a) schematic and (b) physical set-up.

laser beam, as suggested in Section 1.

The fundamental requirement for correction is an independent measurement of the instrument velocity in the direction the laser beam at some point along the laser beam path. However, such a measurement is impractical because it would obscure the laser beam so one or more compromise locations have to be chosen where one or more absolute motion sensors can be attached. This proposal relies on the reasonable assumption that the region of the optical head of the vibrometer including the laser beam aperture and any sensor locations moves as a rigid body for the frequency range of interest. In the first stage of this investigation, an accelerometer was attached to the front face of the optical head and its output integrated to velocity for easy comparison, which is shown in Fig. 3.

Fig. 3 illustrates two important issues. Firstly, the visual comparison between the two measurement spectra is reasonable overall. This supports the observation that the LDV measurement sensitivity to the instrument's own motion in the direction of the laser beam is 100%. At the same time, the comparison is far from perfect because of the compromise required in locating the accelerometer. The mean of the absolute percentage differences at individual spectral lines is still 100.4% from 2.5 to 100 Hz. Given that, as shown in Fig. 2, the apparent target velocity is two orders of magnitude higher than the true velocity in these tests, the single correction measurement already offers a valuable improvement in measurement accuracy and similar compensations have been reported in literature previously [5,6]. However, the remaining error is far too large to present as a satisfactory outcome and, for this reason, this paper shows for the first time how an ideal means of determining the required instrument motion can be found to provide accurate and practical correction that is effective for arbitrary, six degree-of-freedom instrument vibration.

2.2. Mathematical determination of the required correction

Using a vector-based approach and with reference to Fig. 4, the arbitrary velocity at the location of Accelerometer 1, $\vec{V_1}$, can be written in terms of the arbitrary velocity at some chosen point, O, along the laser beam path, $\vec{V_0}$, and the arbitrary angular motion around the chosen point, $\vec{\theta}$:

$$\vec{V_1} = \vec{V_0} + \vec{r_1} \times \vec{\theta} \tag{1}$$

where $\vec{r_1}$ is the position vector for the accelerometer location relative to the chosen point along the laser beam path.

The required correction velocity, U_0, is the component of the total velocity in the laser beam direction, defined by the unit vector $\hat{x}$, and can be written as:

$$U_0 = \hat{x}\,.\quad \vec{V_0} \tag{2a}$$

From Eq. (1):

$$\hat{x}\,.\,\vec{V_0} = \hat{x}\,.\,\vec{V_1} - \hat{x}\,.\,(\vec{r_1} \times \vec{\theta}\,) \tag{2b}$$

$U_1 = \hat{x}\,.\,\vec{V_1}$ is the measurement made by Accelerometer 1 (after integration), while $\hat{x}\,.\,(\vec{r_1} \times \vec{\theta}\,)$, in which $\vec{\theta}$ is currently unknown, is responsible for the difference apparent in Fig. 3. Additional measurements of the instrument vibration are clearly required but the question is: how many measurements and at which location(s)? If an additional measurement, U_2, is made at a location defined by position vector $\vec{r_2}$ then:

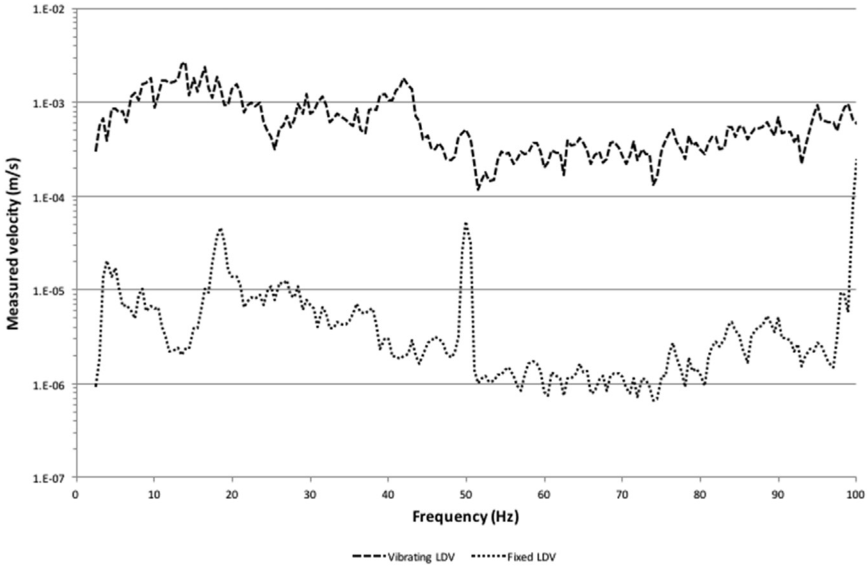

Fig. 2. Comparison between measurements from the vibrating LDV and from the fixed LDV on a (nominally) stationary target.