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Restoring high accuracy to laser Doppler vibrometry measurements affected by vibration of beam steering optics

Ben J. Halkon, Steve J. Rothberg *

Wolfson School. Mechanical, Electrical and Manufacturing Engineering, Loughborough University, Loughborough, Leicestershire LE11 3TU, UK

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ABSTRACT

Laser Doppler vibrometers are now well-established as an effective non-contact alternative to traditional contacting transducers. Wide-ranging applications include those where beam steering optics are required to reach locations that are difficult to access but no attention has yet been given to measurement sensitivity to the vibration of those optics. In this paper, a thorough mathematical treatment of this sensitivity to steering optic vibration and its correction is set out. A very practical scheme requiring a single correction measurement, from the back-surface of the mirror at the incidence point and aligned with the mirror normal, delivers an error reduction typically in excess of 30 dB. After validation in the laboratory, the scheme is then applied to a genuinely challenging measurement scenario on a single cylinder racing motorcycle. Correction is theoretically perfect for translational mirror vibrations but angular mirror vibrations require an adapted scheme using a triplet of accelerometers arranged around a circular path on the mirror back-surface and this is set out theoretically.

1. Introduction

The laser Doppler vibrometer (LDV), the basis for which is the detection of the Doppler frequency shift that occurs when light is scattered by a moving surface, is now well-established as an effective non-contact alternative to traditional contacting vibration transducers such as piezoelectric accelerometers [1]. Commercially available LDVs are technically well suited to general application but they offer special benefits in a variety of challenging measurement scenarios including those in which the measurement point of interest is difficult to access. In such cases, steering optics (typically mirrors) are often used to direct the probe laser beam to the point of interest with the required orientation. Practically, this means positioning the steering optic in close proximity to the measurement point which generally necessitates its mounting at a convenient location near to or even within the structure of interest, without opportunity for vibration isolation. Valve motions in reciprocating engines have been the most commonly reported application [2–4] in which this issue is of particular importance. When the laser beam is incident at a point on any surface at which there is a change in the laser beam direction, the LDV measurement will be sensitive to the vibration of that surface. Consequently, any vibration of a steering optic will result in erroneous measurement content due to Doppler shift that occurs both outbound to and inbound from the target. The specific novel contributions made in this paper will enable complete correction of measured vibration by application of a vector-based approach to determine the sensitivity of LDV measurements to steering optic vibration.

* Corresponding author.
E-mail address: s.j.rothberg@lboro.ac.uk (S.J. Rothberg).

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Building on the previously reported proof-of-principle [5], the objectives of this paper are to show theoretically and confirm experimentally how the measured velocity for such scenarios will include a component proportional to the vibration velocity at the point of incidence on an optical device whenever a change in beam direction occurs (through reflection or refraction). The required correction to the LDV measurement is set out theoretically and then demonstrated experimentally for a laboratory-based set-up, in which translational vibration of the steering mirror is arranged. While previously only the effect of steering mirror vibration was explored, this paper extends this to, for the first time, a thorough treatment of the real-world scenario where both steering mirror and target vibration are present. Additionally, a previously unreported genuinely real-world measurement on a single cylinder racing motorcycle engine mounting bracket, in which a steering mirror was needed to direct the laser beam to an inaccessible measurement location, is described with the required correction due to the vibration of the steering mirror being applied. Finally, the paper extends the mathematical description of the LDV measurement, for the first time, to include not just translational but also angular vibrations of a steering mirror. The error associated with angular vibrations in a measurement corrected for only translational vibrations is quantified. Ultimately, a scheme for correction of both translational *and* angular steering mirror vibration is proposed theoretically for future practical implementation.

LDV is a technique that has built its reputation on real world measurements with high accuracy. The practical steps proposed in this paper, like those proposed in a recent study of the effects of vibration of the instrument itself [6], are essential to restoring that accuracy in the kind of challenging applications that are the trademark of LDV and represent a significant and important contribution to the vibration engineering community.

2. Modelling the measured velocity

To enable general determination of the velocity measured for any arrangement, knowledge of the points of incidence on all moving surfaces, at which a change in laser beam direction occurs, is required [7]. For the arrangement under consideration here, this means both the vibrating steering optic and the target itself. The modelling task begins with a vector description of the outgoing laser beam direction and an arbitrary point through which the laser beam passes, as shown in Fig. 1, for the laser beam direction:

$$\hat{b}_1 = -\hat{x} \tag{1}$$

An arbitrarily chosen point, denoted A, along the line of the laser beam can be written in vector form:

$$\overrightarrow{OA} = \begin{bmatrix} \hat{x} & \hat{y} & \hat{z} \end{bmatrix} \begin{bmatrix} x_A & y_A & z_A \end{bmatrix}^T \tag{2a}$$

For an arrangement in which a plane mirror is used to align and position the laser beam onto the point of interest on the target surface, mathematical description of the mirror location, incident point and its normal are required. With reference to Fig. 1, an arbitrary reference point on the mirror (in the absence of vibration), denoted B, can be expressed generally as:

$$\overrightarrow{OB} = \begin{bmatrix} \hat{x} & \hat{y} & \hat{z} \end{bmatrix} \begin{bmatrix} x_B & y_B & z_B \end{bmatrix}^T \tag{2b}$$

The figure shows the path taken to the target (dotted line) in the absence of mirror vibration. The beam is shown steered through 90°, though this is just an arbitrary choice. The plane of the target (in the absence of vibration) includes the origin, O, of the global coordinate system though this is, again, just an arbitrary choice.

When the mirror undergoes arbitrary six degree-of-freedom vibration, the level of which is significantly exaggerated in

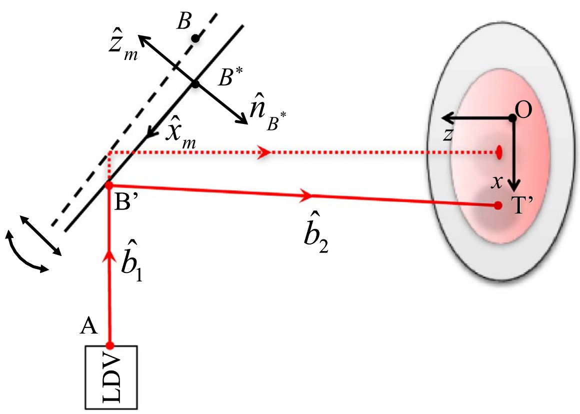

Fig. 1. Schematic showing translational vibration measurement using an angled steering mirror; beam deviation significantly exaggerated for the sake of clarity.