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A practical guide to laser Doppler vibrometry measurements directly from rotating surfaces

B J Halkon and S J Rothberg
The Wolfson School, Loughborough University, UK

ABSTRACT
Commercially available Laser Doppler vibrometers are typically configured with a single beam to measure radial and axial vibrations or with parallel beams to measure pitch, yaw and torsional vibrations. Provided sufficient light intensity can be collected, axial and torsional vibration measurements are relatively straightforward. Radial and pitch / yaw vibration measurements are less straightforward and rotor surface roughness or treatment is critically important. Unless rotor surfaces can be considered “polished-circular”, post-processing is necessary to remove a significant cross-sensitivity to motion orthogonal to that which it is intended to measure. This paper serves as a practical guide through the optimum configurations to be used on rotors to measure all components of vibration, including subtleties associated with beam diameter and vibration amplitude on polished rotors.

1 INTRODUCTION
Vibrational performance has long been accepted as the most effective determinant of the health of rotating machinery (1, 2). Vibrations are inevitable but their consequences extend from loss of efficiency through to safety-critical failures. In addition to such concerns, the resulting generation of noise and the effect on end-user experience can affect perceptions of product quality and adherence to legislative requirements.

In terms of practical assessment, translational vibration measurements dominate with transducer selection first involving consideration of whether to measure displacement, velocity or acceleration. Vibration velocity is generally regarded as the optimum measurement parameter but traditional velocity transducers cannot match the dynamic range and frequency range of the ubiquitous piezo-electric accelerometer, even after integration of the measured signal. A choice must also be made between measurement of shaft absolute vibration, shaft vibration relative to bearings or housing absolute vibration. Measurement of any two of these options allows derivation of the third; the requirement is typically met via proximity probes for the second option and piezo-electric accelerometers for the third.

Angular vibration measurements are also possible, either by combination of translational measurements, sometimes packaged for the specific purpose, or with dedicated devices. With a wealth of important applications in rotating machinery diagnostics, methods for torsional vibration measurements are numerous. With the exception of the torsional application, however, angular vibration measurements are much less commonplace than their translational counterparts.
This paper is concerned with the application of laser Doppler vibrometry (LDV) to measurements directly from rotating surfaces. Laser vibrometers offer direct measurement of the preferred parameter, i.e. velocity, with dynamic / frequency ranges and linearity that at least match those of other options. Through non-contact operation, measurement directly from rotating parts is possible. For surfaces which are optically rough, i.e. for many surfaces of interest, there is inherent insensitivity to target shape though there are other challenges as introduced in the next section.

Laser vibrometers are now commercially available and well-established as an effective alternative to traditional vibration transducers for the measurement of translational vibration. Radial (3) vibration measurements use single-beam devices. The same is true for axial vibrations which can be measured with a stationary beam or by tracking a point on the structure during rotation (4). Established methods of angular vibration measurement are less numerous but parallel beam laser vibrometers feature particularly prominently amongst them. Pitch / yaw (5), torsional (6) and bending (7) components can be measured with inherent insensitivity to translational vibration. The use of cross-beam laser vibrometers has been reported in the past (8) as an alternative means of measuring translational vibrations although little attention has been placed on these devices for such an application more recently. They remain a legitimate option on rough surfaces but they are subject to the same challenges that are introduced in the next section.

2 LDV MEASUREMENT CHALLENGES

Despite the apparent suitability of LDV for measurements directly from rotating parts, the user of such systems, at whom this paper is targeted, must be aware of a number of issues associated with successful application.

Nowadays, commercially available systems can operate with low backscattered light from the target. Nevertheless, it is good practice to take steps to maximise return light. This may be achieved by measuring from a polished surface, in which case surface shape and/or orientation become critical to return light intensity in rotor applications. In many rotor applications, a polished surface is not available. Surfaces may even be painted black. For these situations, it is possible to treat the surface with high-gain retro-reflective sheeting. As well as ensuring that plenty of light is scattered back into the instrument, this also helps with initial alignment in the common event of non-normal laser beam incidence and, indeed, ensures that alignment is maintained during vibration. While measurements from untreated rough surfaces (rough means on the scale of the optical wavelength) can be made, this section will show how use of retro-reflective tape is very much the preferred option where measurements from a polished-circular surface are not available.

With a retro-reflective or rough surface of interest, insensitivity to target shape variation gives LDV a significant advantage over other non-contact options such as eddy current probes, with measurements from cams and geared wheels readily achievable. There are, however, two significant problems to overcome. The first, and lesser issue, is that of "pseudo-vibration", a periodic noise associated with the laser speckle phenomenon (3, 5, 8). The greater issue, and hence the primary focus of this paper, is a cross-sensitivity to motion perpendicular to the motion it is intended to measure, primarily in radial and pitch / yaw vibration measurements. For example, sensitivity to y radial displacement in an x radial velocity measurement or sensitivity to yaw displacement in a pitch velocity measurement, and vice-versa.
3 CROSS-SENSITIVITY IN LDV MEASUREMENTS FROM ROTORS

3.1 Single and parallel beam measurements
Consider the scenario shown in Error! Reference source not found.a in which the intended measurement, $u_{mx}$, is of the $x$ radial vibration velocity component, $x$, here the required alignment of the laser beam is clearly in the $x$ direction. In the presence of shaft rotation AND $y$ radial displacement, $y$, a component of the tangential velocity is also sensed by the laser beam and this results in a significant sensitivity to that $y$ radial displacement (3):

$$u_{mx} = x + \Omega_{tot}y$$

(1)

where $\Omega_{tot}$ is the total angular velocity about the $z$ axis. A similar outcome will clearly be found for a measurement of the $y$ radial vibration. This cross-sensitivity, to $y$ direction motion in an $x$ direction measurement (and vice-versa), is clearly undesirable and will need correction (3).

In a parallel beam measurement, isolation of the component of angular vibration velocity about the $x$ axis, the pitch $\theta_x$, can be achieved by a measurement with beams in a $y$ orientation with an axial separation, as shown in Error! Reference source not found.b. For exactly the same reason as cross-sensitivity is encountered in the single-beam measurement, cross-sensitivity is found in this application too. The angular velocity measured, $\Omega_{mx}$, is given by (5):

$$\Omega_{mx} = \theta_x + \Omega_{tot}$$

(2)

in which cross-sensitivity to the yaw displacement, $\theta_y$, is clear. This cross-sensitivity, to yaw motion in a pitch measurement (and vice-versa), is clearly undesirable and will need correction (5). A particularly convenient aspect of this measurement is that the beams can take any orientation within the planes shown in figure 1b i.e. the beam pair for the $x$-angular (pitch) measurement can be orientated in any direction as long as they remain parallel and in the $yz$ plane and likewise for the $y$-angular pair in the $xz$ plane. The most important practical alternative to the orientations shown is to align both beam pairs on the end of the shaft i.e. in the $z$ direction. This allows measurement if sites along the side of the shaft are not accessible.
3.2 Rough vs. polished-circular rotor considerations

These derivations effectively assume that the laser beam, with Gaussian intensity profile and of finite diameter, has minimal size and can be regarded as being a point at the actual geometric centre of the beam. Another way to consider this is that the scattered light collected in the instrument is dominated by that originating from the geometric centre of the beam. Extensive studies had repeatedly shown that this was a reasonable assumption for retro-reflective surface treatments. However, radial vibration measurements on polished surfaces exhibited no such cross sensitivity (10) and this raised a rather important practical question about how this cross-sensitivity might transition from very low surface roughness (no cross-sensitivity) to higher surface roughness and retro-reflective surface treatment ("full" cross-sensitivity as predicted theoretically and validated experimentally). Additionally, what will be the effects of factors such as vibration amplitude and incident beam diameter? These questions will be answered, with experimental evidence, in the next section.

Zero cross-sensitivity is clearly the desirable scenario since it does not require the post-processing of data that is otherwise essential and does not then encounter the shortcomings of this post-processing. Maximising the measurement conditions in which straightforward measurement without cross-sensitivity is possible is therefore a goal of the study.

3.3 Experimental investigation of rough vs. polished-circular rotors

As shown in Figure 2, experimental arrangements were realised in which the individual motion components of interest were isolated (with unwanted additional vibrations minimised) and the intended surface measurement locations were readily accessible. The shaft rotation speed was controlled independently of the vibration. In each set-up, it was the measurement in the direction orthogonal to the actual vibration which was of interest since this measurement is subject to the cross-sensitivity under investigation. For the angular vibration measurement scenario, a second set-up for measurement from the end, rather than the side, of the shaft was also arranged.

Figure 2 – Experimental arrangement for a) radial and b) angular vibration scenarios with the laser beams and rotor vibration highlighted

3.3.1 Radial vibration measurement scenarios

Rotors (diameter 15 mm, length 30 mm) with a variety of surface roughnesses between Ra 10 and 1100 nm, as shown in Table 1, were prepared. We were not able to manufacture test rotors with a variety of out-of-roundness values; out-of-roundness was kept low but varies from case to case. Rotors treated with retro-reflective tape and white paint were also investigated. Combinations of rotation and
vibration frequency and vibration amplitude, representative of the values typically experienced in real-world measurements, were considered. The effect of laser beam diameter was investigated by comparing results for three different instruments, the Polytec OFV323 (90 µm beam diameter), the Polytec OFV400 (520 µm beam diameter) and, with results shown for the first time in this paper, the Polytec PDV100 at two stand-off distances (resulting in 65 and 90 µm beam diameters).

The experimental data is used to calculate a cross-sensitivity ratio, formed from the ratio of the motion amplitude apparent in the orthogonal measurement and the correct motion amplitude from an independent measurement. This quantity is 100% for the 'full' cross-sensitivity indicated in section 3.1, referred to as the 'rough rotor' model. Measurement on the side of a polished rotor can only be accomplished when the rotor has circular cross-section and the beam is aligned to pass through its centre otherwise insufficient light intensity is collected. In such a case, zero cross-sensitivity is expected and this is referred to as the 'polished-circular rotor' model.

### Table 1 – Rotor sample roughness/roundness and cross-sensitivity ratios

<table>
<thead>
<tr>
<th>Rotor ID</th>
<th>Roughness Ra (nm)</th>
<th>Out-of-roundness (µm)</th>
<th>Vibration cross-sensitivity ratio (%), mean (standard deviation)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>PDV100 65 µm beam</td>
</tr>
<tr>
<td>A1</td>
<td>9.7</td>
<td>6.0</td>
<td>1.3 (0.6)</td>
</tr>
<tr>
<td>A2</td>
<td>11.0</td>
<td>6.7</td>
<td>3.5 (1.3)</td>
</tr>
<tr>
<td>A3</td>
<td>12.0</td>
<td>5.8</td>
<td>6.5 (3.5)</td>
</tr>
<tr>
<td>B</td>
<td>24.0</td>
<td>4.5</td>
<td>11.6 (9.1)</td>
</tr>
<tr>
<td>C</td>
<td>44.0</td>
<td>6.5</td>
<td>8.9 (8.5)</td>
</tr>
<tr>
<td>D1</td>
<td>100.0</td>
<td>23.0</td>
<td>/</td>
</tr>
<tr>
<td>D2</td>
<td>300.0</td>
<td>36.0</td>
<td>38.8 (6.8)</td>
</tr>
<tr>
<td>D3</td>
<td>310.0</td>
<td>12.0</td>
<td>12.3 (2.8)</td>
</tr>
<tr>
<td>E</td>
<td>310.0</td>
<td>1.0</td>
<td>87.8 (3.8)</td>
</tr>
<tr>
<td>F</td>
<td>1100.0</td>
<td>4.7</td>
<td>90.6 (2.0)</td>
</tr>
<tr>
<td>G1</td>
<td>White paint</td>
<td>n/a</td>
<td>98.5 (2.7)</td>
</tr>
<tr>
<td>G2</td>
<td>Retro-reflective</td>
<td>n/a</td>
<td>95.1 (3.4)</td>
</tr>
</tbody>
</table>

* calculated from only 2 data points; ▲ previously reported for fewer data points

The cross-sensitivity ratios in Table 1 are determined from the estimate of the x radial vibration velocity from the measurement in the y direction with the test instrument and the genuine velocity in the x direction. Since there is no y motion in the tests, the genuine measurement is accurately made using a Polytec OFV302 aligned in the x direction. The values were calculated from experiments with displacement amplitudes up to 100% beam diameter for the PDV100 and OFV323 and up to 50% beam diameter for the OFV400. Experimental data for the PDV100 are shown in Figure 3 and Figure 4 in which cross-sensitivity is presented as a function of surface roughness and displacement (expressed as % beam diameter). The general trends are the same as those for the other test instruments.

Figures 3a and 4a show data for rougher rotors. As for other instruments (as shown in Table 1), the cross-sensitivity ratios are consistently close to 100% (conforming to the rough rotor model) for retro-reflective tape, with the white paint surface treatment just a little short of 100%. For rotor F with a surface roughness that can be considered optically rough, the PDV100 showed closer conformance to the rough rotor model than for the other test instruments. Figures 3b and 4b show data for smoother rotors. Cross-sensitivity ratios are consistently close to zero for group A rotors at vibration displacement amplitudes close to or less than beam diameter.
Figure 3 – PDV100 (65 µm beam) effect of roughness and displacement amplitude on cross-sensitivity;
a) rougher rotors and b) smoother rotors

Figure 4 – PDV100 (90 µm beam) effect of roughness and displacement amplitude on cross-sensitivity;
a) rougher rotors and b) smoother rotors
It is for this reason that the ratios summarised in Table 1 were based on vibration displacements close to or less than 100% beam diameter. All of the other rotors, Groups B to E, for the vibration amplitudes used, are found to be in what might be described as a “transitional roughness range” where measurements conform to neither the rough nor the polished-circular rotor models.

The Group D rotors, with widely varying cross-sensitivity ratios but similar surface roughnesses, demonstrate how cross-sensitivity ratio is not a simple function of surface roughness in this transitional roughness range. This inconsistency is also apparent for rotor F measurements across the set of instruments in Table 1. The inconsistency has important practical implications. Cross-sensitivity can be resolved through simultaneous measurements but only if cross-sensitivity ratio can be independently ascertained. Consequently, reliable measurements can only be made on rotors in the group A rotor roughness range (without cross-sensitivity) or for rotors treated with retro-reflective tape (cross-sensitivity reliably at 100%) which will then require post-processing.

The difference in behaviour between the polished-circular and rough rotors can be explained in terms of light collection (3). When surface roughness is sufficiently high that diffuse scatter dominates (with which speckle patterns are associated), the ratio is close to 100% but when surface roughness is low such that specular reflection dominates, the ratio is close to zero. The difference depends on the dominant contribution to collected light intensity. For optically rough surfaces, the bright centre of the Gaussian laser beam makes the dominant contribution. For the polished-circular rotor, however, light is reflected away from the instrument by the curvature of the rotor except for the element of the laser beam that passes instantaneously through the rotor centre. In this case, the effective centre of the laser beam is no longer at its geometric centre but instantaneously at a location where rotor tangential velocity has no component, eliminating the cross-sensitivity. In this case, alignment is critically important to ensure maximum measurable vibration amplitude. Beyond the specified vibration displacement limit, diffuse scatter begins to dominate over specular reflection and measurements move towards the rough rotor model, indicated by increasing cross-sensitivity ratios for displacements in excess of 100% beam diameter, as shown in figures 3b and 4b. At intermediate values of roughness, there are significant diffuse and specular contributions which compete to make the dominant contribution to collected light intensity, resulting in ratios with intermediate values.

3.3.2 Angular vibration measurement scenarios
The same effects are apparent for each of the individual beams in the parallel pair and this will be confirmed in this summary of an experimental investigation. Rotors with lower roughness, A2, B & C, and the rotor coated in retro-reflective tape, G2, were included for the side of shaft measurement while an additional rotor with a polished shaft end (Ra 6.5 nm) was compared with retro-reflective tape for the end of shaft measurement (5). The OFV400 instrument was used with the small differences in beam diameter (550 or 605 vs. the standard 520 µm) achievable by opting for one of the alternative stand-off distances (200 or 600 vs. the standard 400 mm) not leading to significant differences in behaviour.

Figure 5a shows that, as for the radial measurements, only the rotor with Ra of 11 nm conforms acceptably to the polished-circular rotor model and displays no cross-sensitivity, in this case for vibration displacement amplitudes up to 50% of beam diameter. Interestingly, minimisation of cross-sensitivity was always found to involve centring one or the other of the parallel beams through the rotational centre rather than having the beams equidistant about it. This may not always be practical.
Side of shaft measurements with retro-reflective tape treatment (not shown) always demonstrated cross-sensitivity ratios of 100% as expected.

Figure 5 – Effect of roughness and displacement amplitude on cross-sensitivity in angular measurements (5): a) side and b) end face of shaft

Measurements from the shaft end face, as shown in Figure 5b, showed the interesting finding that the cross-sensitivity ratio is 100% for all surface roughness values and treatments. For a surface with Ra 6.5nm and one coated with retro-reflective tape, the figure shows ratios consistency close to 100% irrespective of vibration amplitude. This happens because there is no effect of surface curvature and the effective centre of the laser beam(s) remains at the geometric centre in all
cases. This leads to particularly reliable measurement of angular vibration, though one that requires post-processing to resolve individual components.

### 3.4 Resolution of vibration components in rough rotor scenarios

Having now firmly established the circumstances in which a reliable level of cross-sensitivity is encountered, that this level is 100% and that this occurs in both radial and pitch/yaw vibration measurements directly from rotating shafts, attention must be turned to resolution of the measurements. Now well-documented \((3, 5, 7)\), the procedure is identical for both radial and angular vibration measurement scenarios and begins with making a pair of measurements from two orthogonal directions and a simultaneous measurement of the shaft rotation speed.

In the absence of any fluctuations in the shaft rotation speed, the resolution algorithm alone enables complete resolution (apart from at the synchronous frequency). The resolution algorithm is formulated in terms of the alternating components of measured velocities, \(\bar{u}_{mx}\) and \(\bar{u}_{my}\), and the mean rotation speed, \(\bar{\omega}_{rot}\), and is applied frequency-by-frequency as follows (for \(x\)-radial vibration) \((3, 7)\):

\[
\dot{x}(\omega_n) = W(\omega_n)\text{FT}[\bar{u}_{mx}\bar{\omega}_{rot}\int_0^t \bar{u}_{my} dt]_{\omega_n}
\]

where \(W(\omega_n)\) is a frequency-dependent weighting factor given by:

\[
W(\omega_n) = \omega_n^2/(\omega_n^2 - \bar{\omega}_{rot}^2)
\]

and \(\text{FT}\) denotes the Fourier Transform.

In the presence of speed fluctuations, firstly initial offsets between the laser beam direction and the shaft rotation axis must be much less than vibration displacement amplitudes to have been considered negligible. Application of the resolution algorithm followed by a maximum of two iterations of a correction algorithm:

\[
\dot{x}_{m+1}(\omega_n) = \dot{x}_m(\omega_n) - W(\omega_n)\text{FT}[\Delta\omega_{rot}x_m + \bar{\omega}_{rot}\int_0^t \Delta\omega_{rot} x_m dt]_{\omega_n}
\]

can then be applied to yield improved estimates of vibration amplitudes \((5, 7)\).

With a suitable signal processing toolbox, this can be performed at the point of acquisition with results therefore immediately available as has been described and demonstrated thoroughly previously both for controlled lab-based scenarios as well as for real industrial applications \((3, 5, 7)\). There remains, however, the fundamental limitation which is that synchronous vibration components cannot be resolved.

### 4 FURTHER CONSIDERATIONS

Laser vibrometers measure relative motion between the instrument and target, and are sensitive to disturbances anywhere along the optical path. Fluctuations in the refractive index of the medium through which the laser beam passes are generally insignificant but vibration of the instrument itself or of any steering optics (usually mirrors) used to orient the probe laser beam will affect measurements. The typical approach taken when such motions are significant is to attempt to isolate the instrument or steering optics from the motions. Recent work, however, has demonstrated a technique based on additional measurements to compensate perfectly for such motions \((11)\) without the need for initial isolation.
CONCLUSIONS

Laser Doppler vibrometry (LDV) offers an attractive solution when vibration measurement directly from a rotating surface is required. This paper brings together research findings over an extended period into a definitive and practical guide aimed at the machinery vibration engineer. It will guide the industry user through the optimum configurations to be used on rotors to measure all components of vibration. This could be useful in a condition monitoring or product development application.

Two practical surface roughness / treatment ranges have been identified for radial and pitch / yaw vibration measurements from the side of a rotating shaft. Such measurements are straightforward on polished-circular rotors (Ra in the region of 10 nm) and for vibration amplitudes less than beam diameter. The second practical case is where the rotor surface is coated in retro-reflective tape. There is a significant cross-sensitivity in these measurements to motions orthogonal to the motion it is intended to measure but it is of known magnitude. The scenario conforms to the rough rotor model and a dedicated post-processing algorithm is used to resolve individual components at all frequencies other than synchronous. Pitch / yaw measurements can also be made on the end face of a rotor but these will demonstrate cross-sensitivity, regardless of surface roughness or treatment, in full accordance with the rough rotor model. Consequently they require post-processing in the same way as above.

REFERENCE LIST