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Synchronized-scanning laser vibrometry

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Synchronised-Scanning Laser Vibrometry

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ABSTRACT

The use of Laser Vibrometers incorporating some form of manipulation of the laser beam orientation, typically using two orthogonally aligned mirrors, has become increasingly popular in recent years with considerable attention being given to the operation of such scanning Laser Vibrometers in continuous scanning mode. Here the laser beam orientation is a continuous function of time, making it possible, for example, to track a single point on a moving target such as a rotating bladed disc. A recently derived comprehensive velocity sensitivity model has been developed to incorporate time-dependent beam orientation enabling confident and detailed analysis of data obtained in such measurements. The model predicts the measured velocity for arbitrary mirror scan angles and arbitrary target motion and is shown to be especially valuable in revealing the sources of additional components that occur in continuous scanning and tracking measurements on rotors.

The development of the comprehensive velocity sensitivity model and of sophisticated measurement hardware and software has resulted in proposal of the exciting new Synchronised-Scanning Laser Vibrometry technique. Introduced for the first time in this paper, the measurement involves the probe laser beam tracking the rotating structure and simultaneously scanning the region of interest to provide modal data under operating conditions, i.e. during rotation. Such a measurement is inconceivable by any other means and the system that has been created has the potential to provide data of fundamental importance in the design and development of a wide range of devices from hard disk drives to gas turbines.

Keywords: laser Doppler vibrometry, scanning, tracking, synchronised-scanning, vibration measurement, rotating machinery, mode shapes, operational deflection shapes

1. INTRODUCTION

The principle of Laser Doppler Vibrometry (LDV) relies on the detection of a Doppler shift in the frequency of coherent light scattered by a moving target, from which a time-resolved measurement of the target velocity is made. The Laser Vibrometer is now well established as an effective non-contact alternative to the use of a traditional contacting vibration transducer. Laser Vibrometers are technically well suited to general application but offer special benefits where certain measurement constraints are imposed, for example by the context, which may demand high frequency operation, high spatial resolution or remote transducer operation, or by the structure itself, which may be hot, light or rotating. Measurements on such structures are often cited as important applications of LDV¹ and scanning LDV is of particular current interest.

Commercial scanning Laser Vibrometers incorporate two orthogonally aligned mirrors and can operate point by point or in continuous scanning mode. Continuous scans are conveniently arranged for by driving the beam deflection mirrors with continuous time variant signals, enabling the target velocity profile along a pre-determined path to be determined in a single measurement. Post-processing of the Laser Vibrometer output signal results in a series of coefficients that describe the operational deflection shape or, where a frequency response function is obtained, mode shape²⁻⁵. A special case of continuous scanning is the tracking mode in which the probe laser beam remains fixed on a single point on a

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target such as a rotating bladed disc⁶ or a windscreen wiper blade⁷. Throughout the remainder of this document, “scanning” LDV refers to operation in continuous scanning mode.

Recent work resulted in the extension⁸⁻¹⁰ of a totally general theoretical description of the velocity measured by a single laser beam incident in an arbitrary direction on a rotating target undergoing arbitrary motion¹¹ to the particularly challenging application of continuous scanning Laser Vibrometer measurements on rotating targets with flexible cross-sections. The original velocity sensitivity model was written in terms of laser beam orientation angles, whilst the more recent version was reformulated to make use of mirror scan angles, which is especially useful as it is these that the user would seek to control in a real scanning system. The advanced technique of circular scanning on rotating targets was investigated as a means of illustrating the effectiveness of the model for the analysis of actual scan configurations. In particular, the origins of the additional components that occur in measured data due to instrument configuration were easily revealed using the velocity sensitivity model.

1.1. Velocity measured by a dual mirror scanning Laser Vibrometer

With reference to Figure 1, a typical scanning measurement is performed by the introduction of two orthogonally aligned mirrors, separated by some distance d_s , into the beam path.

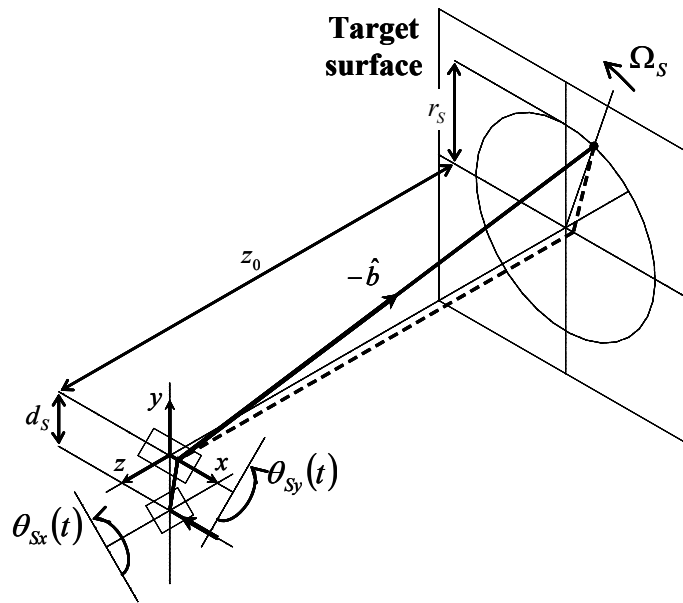


Figure 1 – The dual mirror scanning arrangement

The mirror scan angles, θ_{sx} and θ_{sy} , are defined as positive if in an anticlockwise sense and “zero” when the resulting laser beam direction, described by the unit vector \hat{b} , is along the scanning system optical axis (z axis). Expressing the orientations of the mirror surfaces as unit vectors, it is possible to calculate the laser beam direction for any combination of mirror scan angles and thereby derive an expression for the velocity measured, U_m , in a scanning Laser Vibrometer measurement on a rotating target of flexible cross-section undergoing 6 degree-of-freedom vibration⁸⁻¹⁰:

$$\begin{aligned}
 U_m = & \sin 2\theta_{sx} [\dot{x}_r(P_0) + \dot{x}_f(P)] \\
 & - \cos 2\theta_{sx} \sin 2\theta_{sy} [\dot{y}_r(P_0) + \dot{y}_f(P)] \\
 & + \cos 2\theta_{sx} \cos 2\theta_{sy} [\dot{z}_r(P_0) + \dot{z}_f(P)]
 \end{aligned} \tag{1}$$

in which $\dot{x}_f(P)$, $\dot{y}_f(P)$, $\dot{z}_f(P)$ are the vibration velocity components in the x , y , z , directions due to cross-section flexibility (the point P represents the instantaneous point of incidence of the laser beam on the arbitrarily deformed

target) and $\dot{x}_r(P_0)$, $\dot{y}_r(P_0)$, $\dot{z}_r(P_0)$ are the resultant vibration velocity components in the x , y , z directions due to rigid body vibration (the point P_0 represents the corresponding point on the undeformed target). These components are given by:

$$\dot{x}_r(P_0) = \dot{x} - (\dot{\theta}_z + \Omega)(y_0 - y) + (\dot{\theta}_y - \Omega\theta_x)(z_0 - z) \quad (2a)$$

$$\dot{y}_r(P_0) = \dot{y} + (\dot{\theta}_z + \Omega)(x_0 - d_s \tan 2\theta_{sx} - x) - (\dot{\theta}_x + \Omega\theta_y)(z_0 - z) \quad (2b)$$

and

$$\dot{z}_r(P_0) = \dot{z} + (\dot{\theta}_x + \Omega\theta_y)(y_0 - y) - (\dot{\theta}_y - \Omega\theta_x)(x_0 - d_s \tan 2\theta_{sx} - x) \quad (2c)$$

Here, \dot{x} , \dot{y} , \dot{z} and x , y , z are the translational vibration velocities and displacements, $\dot{\theta}_x$, $\dot{\theta}_y$, $\dot{\theta}_z$ and θ_x , θ_y , (θ_z) are the angular vibration velocities and displacements and Ω is the total rotational angular velocity of the target. $(x_0 - d_s \tan 2\theta_{sx}$, y_0 , $z_0)$ is the position of an arbitrary known point that lies along the line of the beam. In this case, the incidence point of the laser beam on the y deflection mirror is a convenient known point to consider⁸⁻¹⁰.

The development of equation (1) is significant since it can be conveniently employed to make the analysis of complex measurement configurations more straightforward. In particular, applications in which the laser beam is scanned can be investigated by considering time dependent mirror scan angles and, therefore, corresponding time dependency in the known point position and laser beam orientation.

1.2. Circular scanning Laser Vibrometer measurements on rotating targets

The scanning system used was custom-built incorporating a Polytec OFV3020 Laser Vibrometer and a pair of GSI Lumonics M3 galvanometers and is shown in Figure 2. Each galvo can rotate an attached mirror through $\pm 15^\circ$ mechanical ($\pm 30^\circ$ optical). A two-channel function generator was used to generate the cosine and sine functions necessary to perform a circular scan. The galvos are mounted relative to the Laser Vibrometer in the same manner as was shown schematically in Figure 1, which is equivalent to the arrangement employed in both the Ometron Type 8330 and Polytec PSVx00 commercial scanning Laser Vibrometers. The target used was a light ($\varnothing 110\text{mm} \times 2\text{mm}$), aluminium rotor with rigid cross-section mounted to a DC motor. The target rotation frequency was controlled using a stable DC power supply and measured using a Polytec OFV4000 Rotational Laser Vibrometer.

A circular scanning Laser Vibrometer measurement can be performed by deflecting the laser beam through suitable angles around two orthogonal axes simultaneously, typically by using cosine and sine functions⁸⁻¹⁰ of the form:

$$\theta_{sx} = -\Theta_{sx} \cos(\Omega_s t + \phi_s) \quad (3a)$$

and

$$\theta_{sy} = \Theta_{sy} \sin(\Omega_s t + \phi_s) \quad (3b)$$

where Ω_s and ϕ_s are the scan angular frequency and initial phase and Θ_{sx} and Θ_{sy} are the x and y mirror scan amplitudes which, taking into account the distance between the target to x mirror and target to y mirror difference, are given by:

$$\Theta_{sx} = 0.5 \tan^{-1} \left(\frac{r_s}{z_0 + d_s} \right) \quad (4a)$$

and

$$\Theta_{sy} = 0.5 \tan^{-1} \left(\frac{r_s}{z_0} \right) \quad (4b)$$

where r_s is the desired scan radius. Substituting equations (2a,b&c), (3a&b) and (4a&b) into equation (1) immediately results in a totally general description of the velocity sensed in a circular scanning measurement on a rotating target. This comprehensive velocity sensitivity model is especially useful since it enables prediction of the effects of the dual mirror scanning arrangement and of translational and angular misalignments between the scanning system and target rotation

axes have on the measurement. Such factors may lead to significant additional components in the velocity measured; the influence of the misalignments, in particular, is of importance as small misalignments are inevitable.

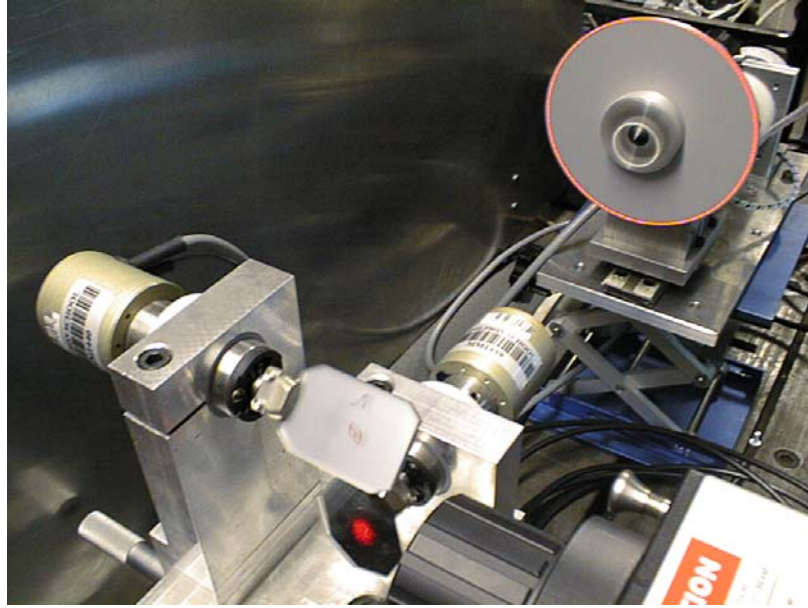


Figure 2 – Custom-built scanning Laser Vibrometer

As illustrated in Figure 3, translational misalignment can be accounted for in the velocity sensitivity model by including the constants x_{0m} and y_{0m} in the intended known point x and y coordinates. Similarly, angular misalignment is represented by including the constants θ_{xm} and θ_{ym} in the angular vibration displacement parameters. Setting the flexible and rigid vibration components to zero in equation (1) and using small angle approximations enables the measured velocity (ideally zero, of course) to be predicted for this “no target vibration, arbitrary misalignment” circular scan^{9,10}:

$$\begin{aligned} \frac{U_m}{\Omega} = & \left[\theta_{xm} x_{0m} + \theta_{ym} y_{0m} \right] \\ & + \frac{r_s}{z_0 + d_s} \left[y_{0m} + \theta_{xm} (z_0 + d_s) \right] \cos(\Omega_s t + \phi_s) \\ & - \frac{r_s}{z_0} \left[x_{0m} - \theta_{ym} z_0 \right] \sin(\Omega_s t + \phi_s) \\ & - \frac{r_s^2}{2z_0(z_0 + d_s)} d_s \sin 2(\Omega_s t + \phi_s) \end{aligned} \quad (5)$$

This equation shows that components at DC, 1x and 2x scan frequency dominate the measurement, as illustrated in Figure 4 (no small angle approximations). As shown in equation (5), the amplitude of the components at DC and 1x scan frequency are misalignment dependent whereas the amplitude of the component at 2x scan frequency is insensitive to variations in misalignment. It is possible to perform an experimental validation of each element of the velocity sensitivity model separately and such comprehensive validations have been shown previously^{9,10}.

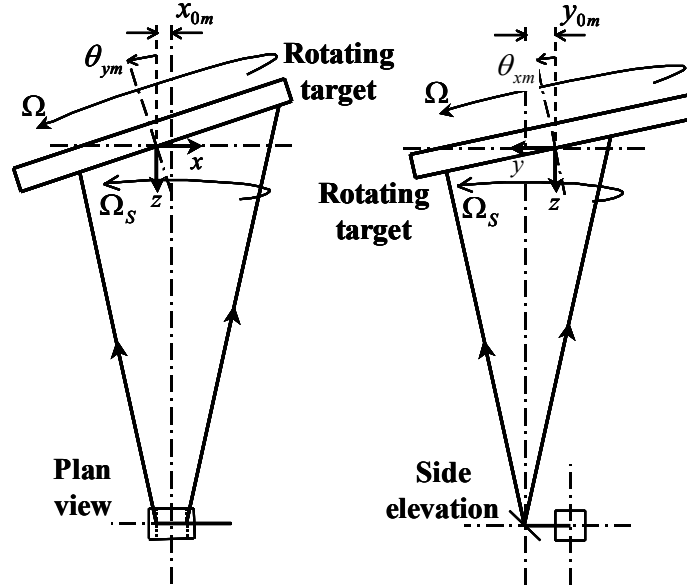


Figure 3 – Translational and angular misalignment between the scanning system and target rotation axes

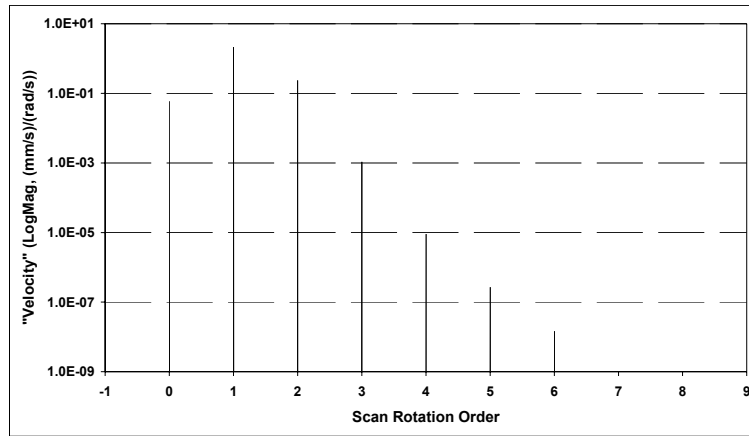


Figure 4 – Additional measurement components that occur due to misalignment between the dual mirror scanning system and target rotation axes; corrected mirror drive signals
 $(r_s = 100\text{mm}, d_s = 50\text{mm}, z_0 = 1\text{m}, x_{0m} = y_{0m} = 2\text{mm}, \theta_{xm} = \theta_{ym} = 15\text{mrad})$

2. MEASUREMENT TECHNIQUE DESCRIPTION

2.1. Circular tracking Laser Vibrometry

Circular tracking Laser Vibrometer measurements can be arranged for by setting the scan frequency equal to the target rotation frequency. Here, the probe laser beam remains fixed on a single point on the target during rotation and the measured velocity then relates to that particular point only. Such a measurement is especially advantageous if the target is non-continuous in cross-section as is, for example, a bladed disc. The dedicated tracking system specifically developed to enable such measurements is illustrated in Figure 5. The system is based on a custom-built scanning system described in section 1.2 but makes use of a bespoke arbitrary function generator that is synchronised to the target rotation, rather than a standard, variable frequency, dual channel function generator, to drive the x and y mirror galvos.

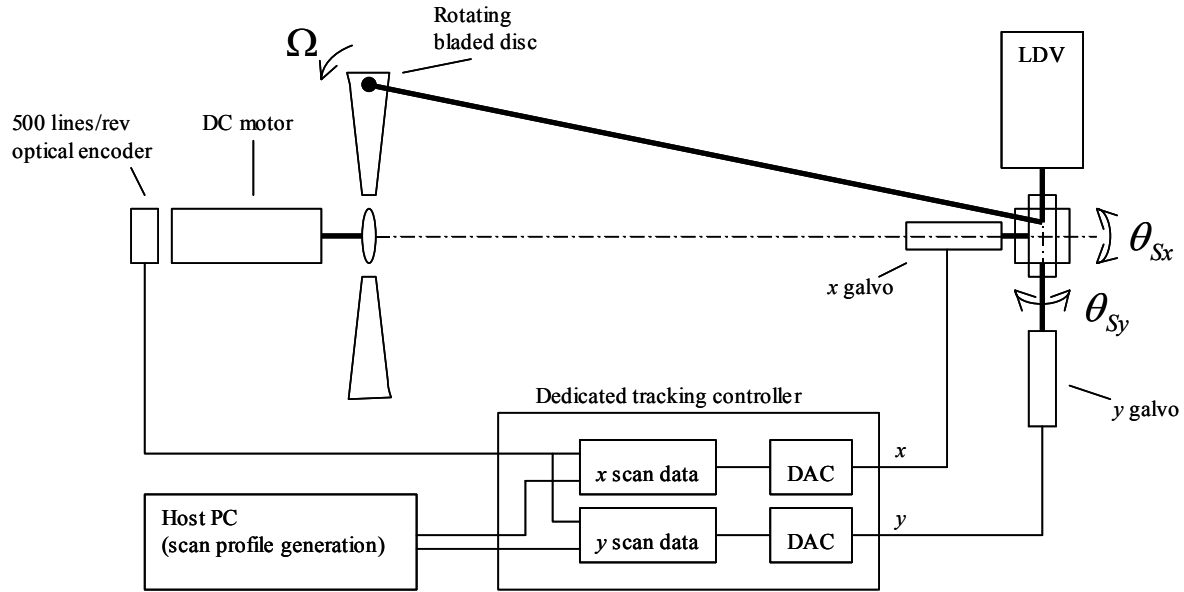


Figure 5 – Tracking system schematic diagram

The dedicated tracking controller makes use of the output from a 500 lines/rev optical encoder that is mounted to the target shaft, thereby providing a real-time measurement of rotation angle, to synchronise the generation of the pre-defined x and y mirror scan angle waveforms. The x and y mirror scan angle waveforms, which contain 500 data points – one data point per encoder line, are pre-defined in software on the host PC before being uploaded to the controller. Each waveform is stored on a low-cost 20MHz processor and the value corresponding to a particular rotation angle is fed into a similar 20MHz processor which converts the digital number into an equivalent output voltage. The two output voltages are directly connected to the x and y galvos and the mirrors subsequently rotated through the necessary angle. Modulation of the amplitude and phase of the output voltages during a tracking measurement is possible via the host PC software interface and enables the interrogated point to be adjusted sequentially such that a number of discrete measurement points can be addressed and the vibration velocity profile across, for example, the surface of a blade can be obtained^{6,7}. Such a measurement would yield very useful data, difficult to obtain by any other means, but it would be time-consuming and is prone to problems associated with not making measurements simultaneously.

2.2. Synchronised-Scanning Laser Vibrometry

The major step forward in Laser Vibrometry technology, presented for the first time in this paper, is to synchronise the tracking and continuous scanning configurations described separately earlier. In this Synchronised-Scanning technique, the scan amplitude and/or frequency are/is continuously modulated during tracking to perform a synchronised scan across a region of interest on the rotating structure. The comprehensive velocity sensitivity model allows the complexity in the measured velocity to be readily accommodated but the challenges in hardware for scan control are significant.

2.2.1. Theoretical description: line scan

The Synchronised-Scanning technique is best explained with reference to a measurement on a rotating bladed disc as shown in Figure 6. Since the intention is to measure the operational deflection shapes of the blades it is necessary to scan the probe laser beam up and down the blade whilst the blade is under operating conditions, i.e. rotating. The intended scan profile, in de-rotated form, is also shown in Figure 6. Line scans of this form have successfully yielded modal data in previous studies^{2,4} but, of course, on non-rotating structures. With reference to equations (3a&b) and (4a&b), the necessary mirror scan functions have the generic form:

$$\theta_s(t) = \Theta_s \cos(\Omega t + \phi_s) \quad (6)$$

in which Θ_s is the scan amplitude and Ω is the scan frequency (equal to rotation frequency for tracking).

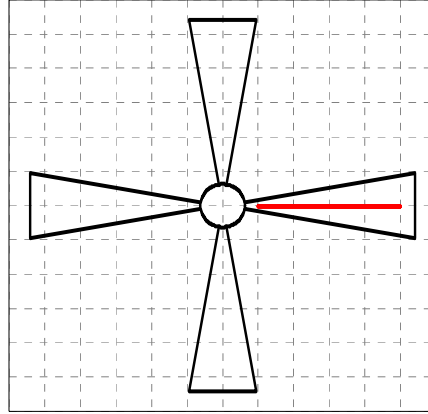


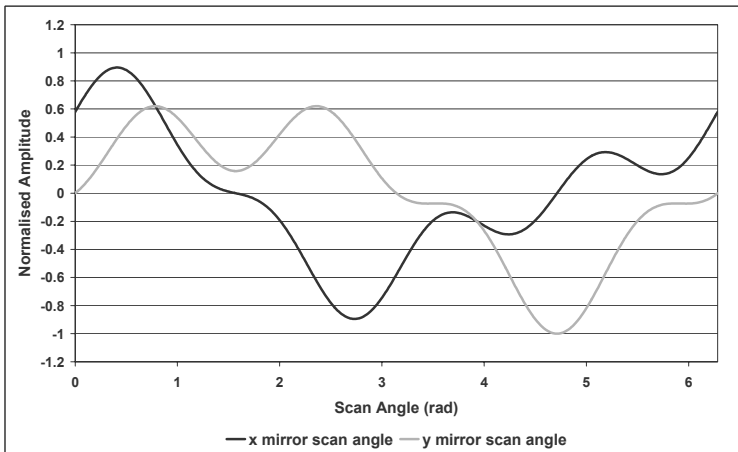
Figure 6 – Bladed disc showing intended scan profile along the length of one of a blade

To achieve the line scan of the blade, r_s , which would be constant in a circular tracking measurement, becomes a function of time, thereby modulating the scan amplitude:

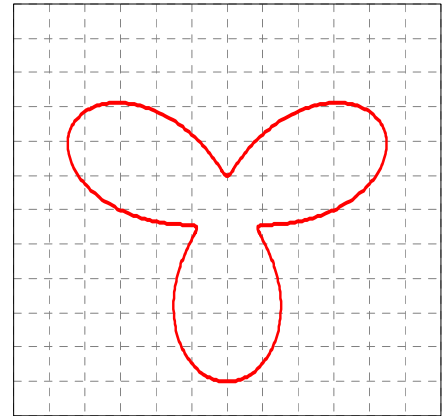
$$r_s(t) = \bar{r}_s + \Delta r_s \cos(m\Omega t + \phi_{r_s}) \quad (7)$$

where \bar{r}_s and Δr_s are the mean and time dependent components of the scan radius, m is the number of radius cycles per revolution and ϕ_{r_s} is the initial phase. Note from equation (7) how synchronised line scans require higher frequency operation of the scanning mirrors.

The result is mirror scan angle functions such as those illustrated in Figure 7a and a scan profile in space of the form shown in Figure 7b. This sophisticated measurement technique may be employed to provide valuable data relating to, for example, the cantilever bending mode of vibration of a blade under operational conditions.



(a)



(b)

Figure 7 – (a) normalised mirror scan angles and (b) scan profile for a synchronised line scan ($m = 3$)

2.2.2. Theoretical description: area scan

Whilst the synchronised line scan would yield data for a cantilever bending mode, it would yield lower quality information for a torsional mode; the scan may even be performed along a nodal line in which case the measured vibration velocity would be zero. For such a case, a two-dimensional synchronised scan, such as that shown in Figure 8,

would be beneficial. Again, previous work^{4,5} has shown how mode shape data can be obtained from an area scan of this nature but, of course, on a non-rotating structure.

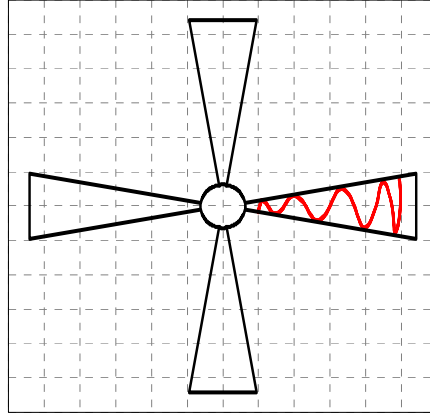


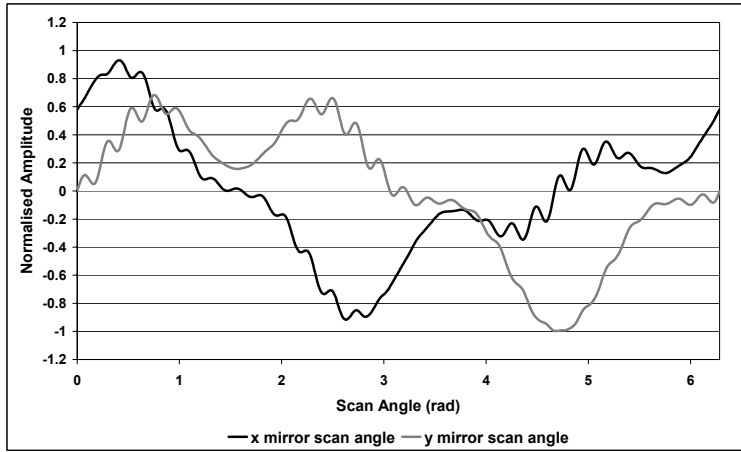
Figure 8 – Bladed disc showing intended scan profile across the area of one of a blade

The area scan can be achieved by considering a simultaneous phase modulation of the mirror drive signals:

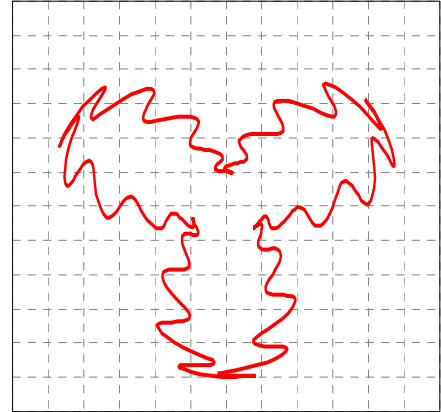
$$\phi_s(t) = \overline{\phi_s} + \Delta\phi_s \cos(mn\Omega t + \phi_{\phi_s}) \quad (8)$$

where $\overline{\phi_s}$ and $\Delta\phi_s$ are the mean and time dependent components of the scan phase, n is the number of phase cycles per radius cycle and ϕ_{ϕ_s} is the initial phase. Note how synchronised area scans require even higher frequency operation of the scanning mirrors than synchronised line scans.

The result of the combined scan radius and phase modulation is the correspondingly more complex mirror scan angles illustrated in Figure 9a and a scan profile in space of the form shown in Figure 9b and, in a de-rotated form, in Figure 8.



(a)



(b)

Figure 9 – (a) normalised mirror scan angles and (b) scan profile for a synchronised area scan ($m = 3$, $n = 9$)

The experimental arrangements, shown in Figure 10, use a bladed disc with the shape of that shown in Figure 6 and Figure 8. The disc is not visible in Figure 10 because of the speed at which it is rotating but the figure does illustrate the scan profiles well. The photographs were achieved by holding the camera shutter open long enough for the bladed disc to

complete several rotations, to show the path of the laser beam as it scans up and down and across the blade surface in synchronisation with its rotation.

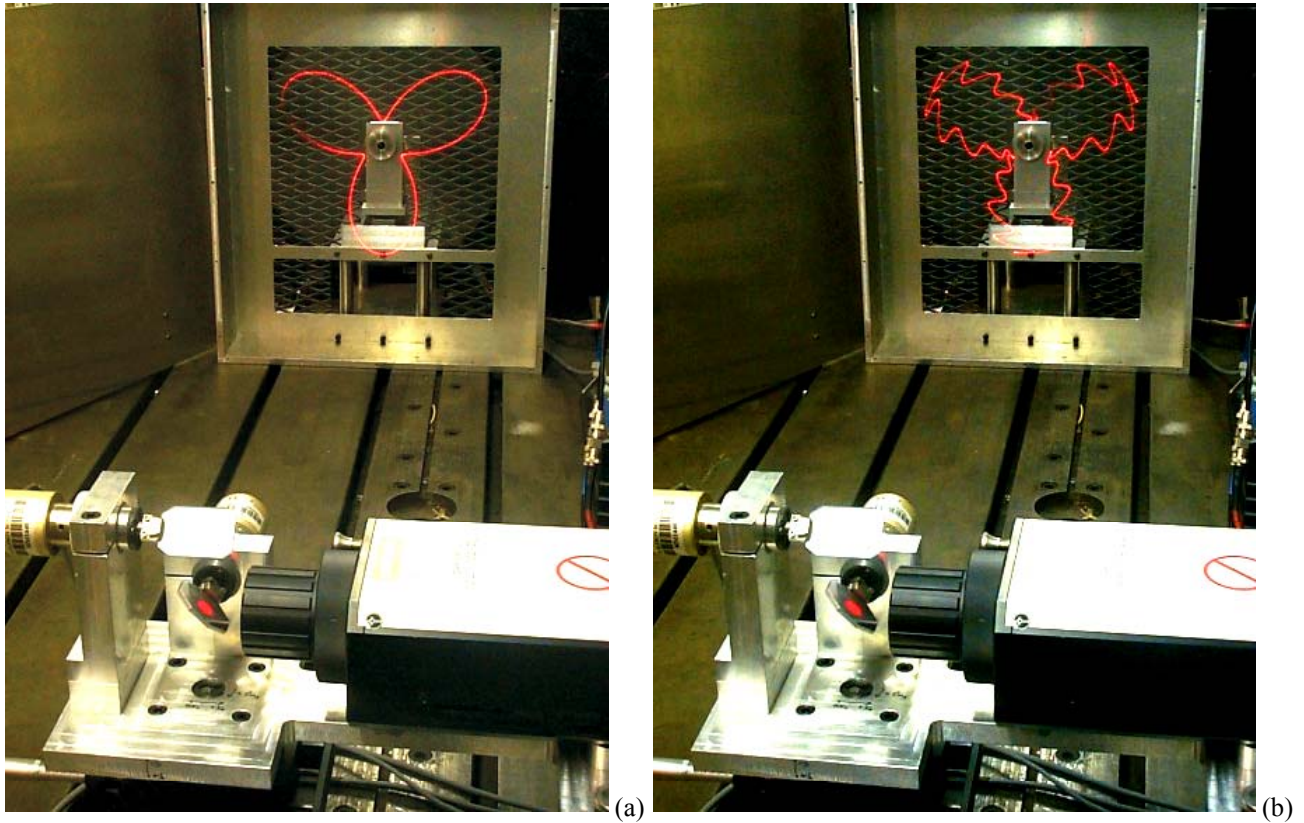


Figure 10 – Actual experimental profile for a synchronised (a) line scan ($m = 3$) and (b) area scan ($m = 3, n = 9$)

The values chosen for m and n were chosen principally for the purposes of illustration and the selection of optimum scan profile parameters would be an important part of the further work that should be conducted in order to explore the full potential of this seemingly powerful measurement technique. Its feasibility, however, has been demonstrated and the acquisition of useful information is the subject of this next subsection.

2.3. Operational deflection shape extraction

Consider the form of the measured velocity from a line scan measurement, such as that described in section 2.2.1, on a rotating blade oscillating in its first flexural mode. In a simple, perfectly aligned tracking measurement, the measured velocity will be of the form of that shown in Figure 11. As described in section 1.2, the data contains additional components at DC and 1x scan frequency (which, in this case, is equal to rotation frequency) due to small but inevitable misalignments between the scanning system and target rotation axes and an additional component at 2x scan frequency due to the dual mirror scanning system. Importantly, however, the data shows that, provided there is a sufficient separation between the scan and vibration frequencies, the measurement constitutes a respectable, unambiguous measurement of the vibration velocity. The small sidebands at the vibration frequency $\pm\Omega$ are generally very low level and therefore below the speckle induced noise¹² ($\approx 0.013(\text{mm/s})/(\text{rad/s})$, broken line in Figure 11b) that occurs in a real measurement.

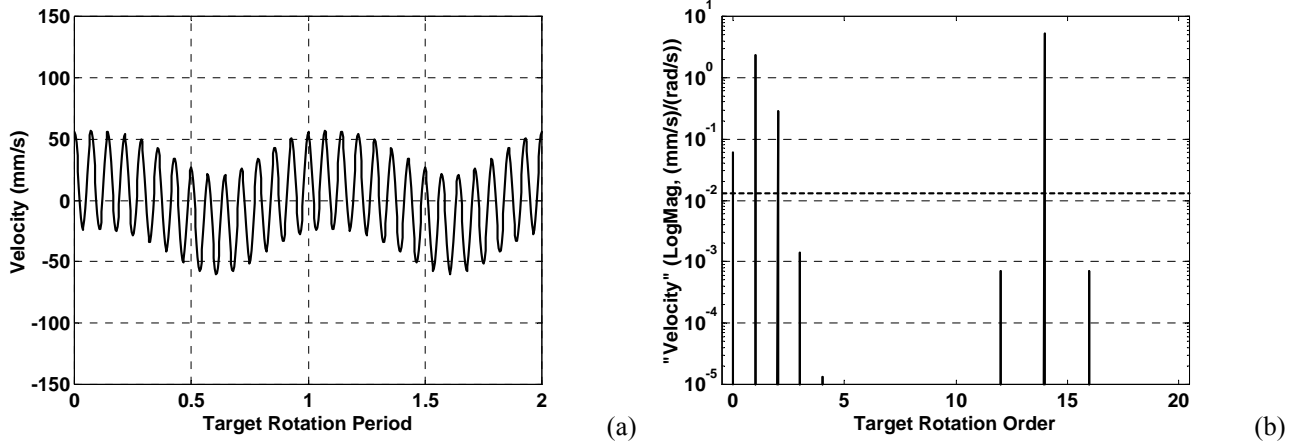


Figure 11 – Simulated tracking measurement on a rotating blade undergoing first cantilever bending mode vibration in the (a) time and (b) frequency domain
 $(r_s = 110\text{mm}, d_s = 50\text{mm}, z_0 = 1\text{m}, x_{0m} = y_{0m} = 2\text{mm}, \theta_{xm} = \theta_{ym} = 15\text{mrad})$

In a Synchronised-Scanning measurement, the processing of the data is more complex since the operational deflection shape modulates the measured velocity as the laser beam changes position on the target surface. In such a measurement, the measured velocity will be of the form of that shown in Figure 12; again, additional components (at DC, 1x, 2x, 3x and 4x scan frequency) are present as a result of the misalignments, the dual mirror scan system and the line scan. In this case, however, information relating to both the vibration velocity and the operational deflection shape is present in the components at the vibration frequency and the sidebands at the vibration frequency $\pm\Omega$, $\pm2\Omega$, $\pm3\Omega$ etc.. Extraction of the operational deflection shape is achieved by relating the amplitudes and phases of the vibration peak and sidebands to a polynomial series in terms of r_s .

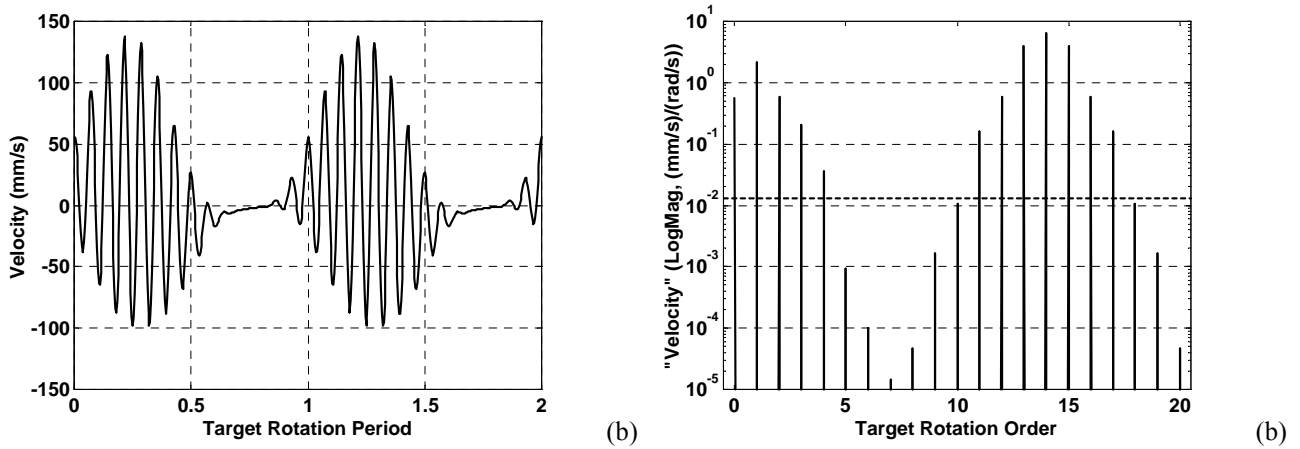


Figure 12 – Velocity measured in a simulated synchronised line scan measurement on a rotating blade undergoing first cantilever bending mode vibration in the (a) time and (b) frequency domain
 $(\overline{r_s} = 110\text{mm}, \Delta r_s = 0.727\overline{r_s}, m = 1, d_s = 50\text{mm}, z_0 = 1\text{m}, x_{0m} = y_{0m} = 2\text{mm}, \theta_{xm} = \theta_{ym} = 15\text{mrad})$

In an equivalent *real* synchronised line scan measurement, the output from which is shown in Figure 13, strong correlation with the simulated data is apparent, thereby confirming the value of the comprehensive velocity sensitivity model for enabling confident data interpretation for any measurement configuration. Worthy of note is the fact that the additional component levels are lower than those in the simulated measurement, confirming that the misalignment quantities used in the simulation are (intentionally) pessimistic. Furthermore, the underlying speckle noise can be

observed but at a level that is insignificant compared with that of the vibration peaks of interest. This data confirms the potential of the exciting new Synchronised-Scanning technique for the acquisition of data of fundamental importance in rotating machinery design, i.e. modal data from structures such as bladed discs under operating conditions.

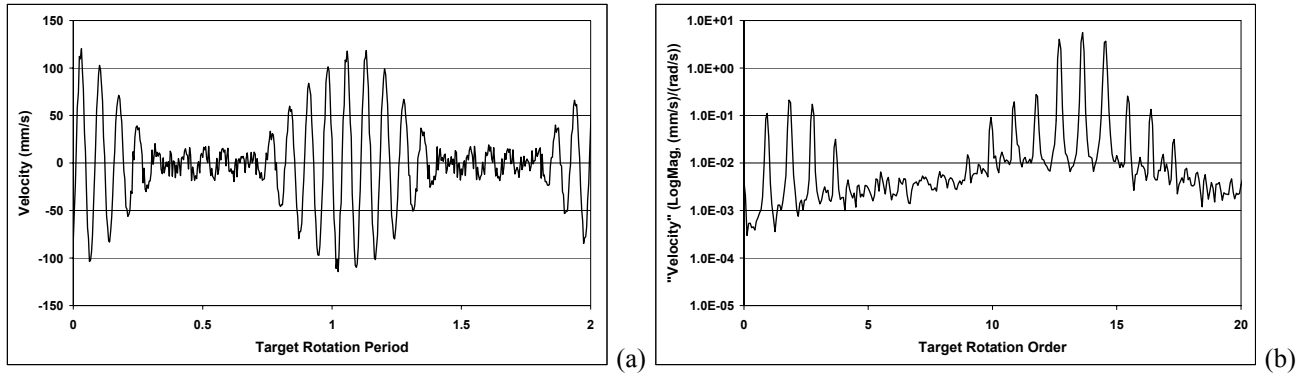


Figure 13 – Velocity measured in an actual synchronised line scan measurement on a rotating blade undergoing first cantilever bending mode vibration in the (a) time and (b) frequency domain
 $(\bar{r}_s = 110\text{mm}, \Delta r_s = 0.727\bar{r}_s, m = 1, d_s = 50\text{mm}, z_0 = 1\text{m}, x_{0m} = y_{0m} = \theta_{xm} = \theta_{ym} = \text{arbitrary})$

3. CONCLUSIONS

The Synchronised-Scanning technique is the latest exciting and innovative new development of the scanning Laser Vibrometry technique for vibration measurements directly from rotors under operating conditions. The previous section outlined how the Synchronised-Scanning Laser Vibrometry system combines the mathematical basis of the comprehensive velocity sensitivity model with measurement and scanning hardware and a dedicated tracking controller. Combining the ability to track a single point on a rotating structure with the ability to scan a structure to retrieve modal data, Synchronised-Scanning Laser Vibrometry opens up a host of new measurement possibilities. The feasibility of meeting the hardware and software requirements of the system has already been demonstrated, whilst the comprehensive velocity sensitivity model, the mathematical basis of the necessary post-processing, has been validated and applied to a number of existing scanning configurations. The comprehensive velocity sensitivity model has already proved valuable but post-processing of the data obtained from the complex profiles used in synchronised scans simply could not be contemplated without it. Such measurements are inconceivable by any other means and the innovative new system will provide data of fundamental importance in the design and development of range of devices from hard disk drives to gas turbines.

4. ACKNOWLEDGEMENTS

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