

Application Note

On the Working Principle of Torsional Vibration Meter Type 2523

by N. A. Halliwell, S. J. Rothberg and T. J. Miles, Loughborough University of Technology, P. G. Eastwood, Acoustic Technology Limited (ATL) Conditioning Monitoring Division, C. J. D. Pickering, University of Southampton and K. Gatzwiller, Brüel & Kjær

Abstract

With the advent of the Torsional Vibration Meter Type 2523, a new, advanced laser-based technique for fast, easy and accurate measurement of torsional vibrations was introduced to the market. Some of the astonishing features offered by this new (later patented) technique included: No sensitivity to translational vibrations of the rotating specimen and/or the laser transducer part of the instrument and no sensitivity to the cross-sectional geometry of the shaft. In this Application Note, the basic optical design of the instrument is introduced along with a derived mathematical explanation of some of the important features offered by the technique and implemented in the Torsional Vibration Meter Type 2523. Furthermore, to verify the performance of the instrument, results from comparison measurements are presented and evaluated.

The concept of the Torsional Vibration Meter Type 2523 was originally conceived by a team led by N.A. Halliwell at the University of Southampton (Institute of Sound and Vibration Research) and subsequently described in a "Letter to the Editor" that first appeared in a technical publication. A part of this Application Note is based on this "Letter to the Editor" and appears by courtesy of Academic Press Incorporated Ltd., London, England.

* The original title of this "Letter to the Editor" is: "The Laser Torsional Vibrometer: A New Instrument". It appeared in *Journal of Sound & Vibration* (1984), 93(4), 588-592.

Introduction

The measurement of torsional vibrations of rotating machinery components in general provides problems



Two Torsional Vibration Meters Type 2523 being prepared for a marine application. The operating principle ensures that the instrument can be employed even in severe environments with maintained confidence in the results

for traditional contacting transducers. For many on-site situations their use requires extensive machinery "down-time" and special arrangements for fitting and calibration, etc. However, with the laser based Torsional Vibration Meter Type 2523, an advanced non-contact means of measuring torsional vibrations has become commercially available — allowing the vibration engineer to accurately measure torsional vibrations on any visible part of a rotating specimen.

The following sections provide a thorough explanation of the basic operating principle of the instrument. As previously indicated, it will,

amongst other things, be seen that the instrument can be operated while hand-held and that it allows the engineer to simply "point" the laser beams at the surface of interest. It will also be seen how the unique optical design employed in the instrument means that the instrument is for all practical purposes insensitive to operator body movement and will respond only to torsional vibrations. Further to this, it will be examined how the instrument can operate successfully on rotating components of arbitrary cross-section and as such should prove to be of particular value in studies of gear vibration.

One of the main considerations in the implementation of the dual-beam laser technique into an instrument was to ensure that the optical design could withstand the often harsh environments met in industrial applications. It is therefore worthwhile to notice that in addition to the lack of need for on-site focusing and on-site calibration, the Torsional Vibration Meter Type 2523 is compact, robust and easy to set-up.

More information on the features and benefits of the Torsional Vibration Meter Type 2523 can be found in references [1] and [2]. These references contain pertinent specifications as well, including, of course, environmental specifications.

The Dual Laser Beam Principle

The optical geometry for the Torsional Vibration Meter Type 2523 is shown schematically in Fig.1. With reference to this figure, the theory will be developed for the system operating on the side of a shaft of arbitrary cross-sectional area which is rotating about an axis defined by the unit vector \vec{z} which is assumed to be perpendicular to the plane of the cross section. The shaft itself is allowed to vibrate as a rigid body with an instantaneous velocity vector \mathbf{V} .

The laser beam is divided into two equal intensity parallel beams of separation d , which impinge on the shaft surface at points A and B in a direction defined by the unit vector \vec{i} . The instantaneous shaft surface velocities, with respect to the axis of rotation, at these points are \mathbf{V}_1 and \mathbf{V}_2 , respectively. The laser is a low powered (2mW) solid state diode* which produces invisible light at a wavelength λ of 780nm. The essentially single frequency light from this laser undergoes a Doppler shift f when scattered by the moving surface and the light collected in direct backscatter is shifted by an amount given by [5]

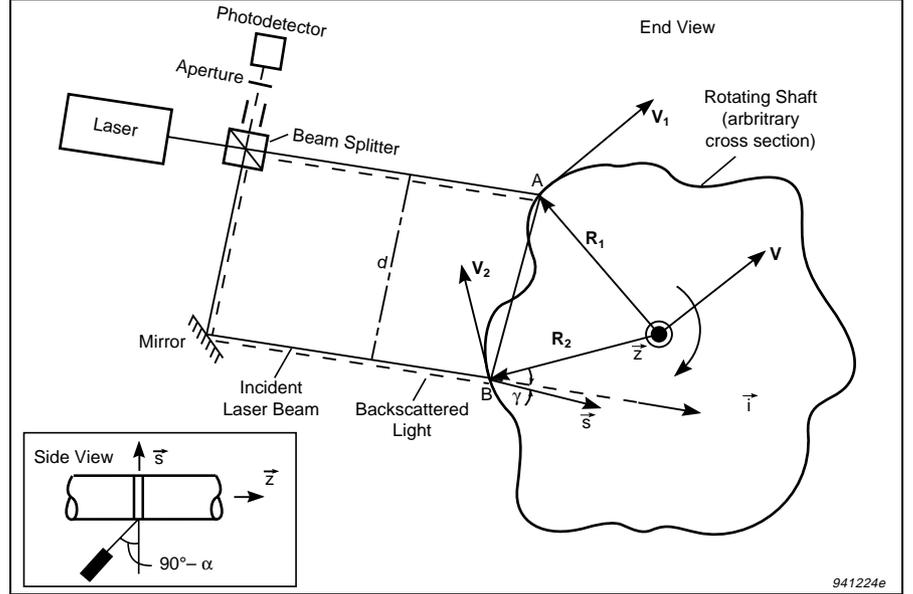


Fig.1 Optical geometry of the Torsional Vibration Meter Type 2523

$$f = \frac{2\mu U}{\lambda} \quad (1)$$

where U is the instantaneous velocity in the direction of the incident laser beam, λ is the laser wavelength, and μ is the refractive index of the medium ($\mu = 1$ for air). Accordingly, light backscattered from the points A and B undergoes Doppler shifts f_a and f_b given by

$$f_a = \left(\frac{2\mu}{\lambda}\right)\vec{i} \cdot (\mathbf{V} + \mathbf{V}_1) \quad (2)$$

$$f_b = \left(\frac{2\mu}{\lambda}\right)\vec{i} \cdot (\mathbf{V} + \mathbf{V}_2) \quad (3)$$

respectively. When this backscattered light is mixed onto the surface of a photodetector, heterodyning takes place and the output current from the detector is modulated at the difference or "beat" frequency f_d given by:

$$f_d = f_a - f_b = \left(\frac{2\mu}{\lambda}\right)\vec{i} \cdot (\mathbf{V}_1 - \mathbf{V}_2) \quad (4)$$

Considering the vector $\mathbf{V}_1 - \mathbf{V}_2$, one can write

$$\mathbf{V}_1 = 2\pi N \cdot (\mathbf{R}_1 \times \vec{z}) \quad (5)$$

$$\mathbf{V}_2 = 2\pi N \cdot (\mathbf{R}_2 \times \vec{z}) \quad (6)$$

where N is the shaft revolutions per second. Thus

$$\begin{aligned} \mathbf{V}_1 - \mathbf{V}_2 &= 2\pi N \cdot (\mathbf{R}_1 - \mathbf{R}_2) \times \vec{z} \\ &= 2\pi N \overline{\mathbf{BA}} \times \vec{z} \\ &= 2\pi N \overline{\mathbf{BA}} |\sin \alpha| \end{aligned} \quad (7)$$

where \vec{s} is a unit vector perpendicular to $\overline{\mathbf{BA}}$ and z , and α is the included angle between the latter. Substituting in equation (4) gives

$$f_d = \left(\frac{4\mu\pi}{\lambda}\right) N |\overline{\mathbf{BA}}| \sin \alpha \vec{i} \cdot \vec{s}$$

and finally

$$f_d = \left(\frac{4\mu\pi}{\lambda}\right) N |\overline{\mathbf{BA}}| \sin \alpha \cos \gamma \quad (8)$$

where γ is the angle between \vec{i} and \vec{s} . If the instrument is held so that the plane of the incident laser beams is parallel to the shaft cross-section, then $\alpha = \pi/2$ and $|\overline{\mathbf{BA}}| \cos \gamma = d$ and hence

$$f_d = \left(\frac{4\mu\pi}{\lambda}\right) N d \quad (9)$$

In interpreting equation (8), it is helpful to consider this position as a reference and note that a lateral tilt of the laser beam plane with respect to $\overline{\mathbf{BA}}$ produces in general a value of $|\overline{\mathbf{BA}}| \cos \gamma$ other than d , whilst a rotation of this plane produces a non-zero value of α . For hand-held use, clearly the latter is more crucial as a large error is produced for a small change in this angle. It should be re-

* For safety reasons, a laser radiating low power was chosen instead of a high power output laser. This, however, implies that a piece of retro-reflective tape must always be attached around the measurement object to ensure sufficient light back-scattered into the laser transducer. Special retro-reflective paint is available as well.

membered, however, that human body movement will produce erroneous results only below a frequency of 30 Hz and therefore for most practical purposes the instrument (or more correctly: the laser transducer part of the instrument) can be operated hand-held.

Note that with this optical geometry the beat frequency is insensitive to radial and axial shaft (or operator) movement and for constant values of the angles α and γ will only respond to variations in shaft speed, i.e. torsional vibrations.

The instrument will also perform successfully if the laser beams are simply pointed at the end of a rotating shaft. Many practical measurement situations have shown this to be a crucial advantage. The theory presented is general and it is only necessary to note that end of shaft use immediately produces a finite value of α in equation (8) which in this case corresponds to the angle between the plane defined by the shaft end and the incident laser beam plane. Further to this, provided that the end of the shaft is perpendicular to the axis of rotation, the sensitivity to rotation of the incident laser beam plane is removed as in this case the $\sin\alpha$ term in equation (8) is unity.

The output current from the photodetector is modulated at the beat frequency, given by equation (8), and is then analysed by a suitable Doppler signal processor which is essentially a frequency-to-voltage converter. A time-resolved voltage analogue of the beat frequency variations (i.e. torsional vibrations) is produced and is "available", after suitable amplification and filtration, at the AC output connector on the rear panel of the Torsional Vibration Meter Type 2523.

This latter point emphasises a further advantage of the optical geometry in that immediate control of the mean value of the beat frequency is provided. For side or end of shaft use, suitable adjustment of the angles α and β provides this control. This is

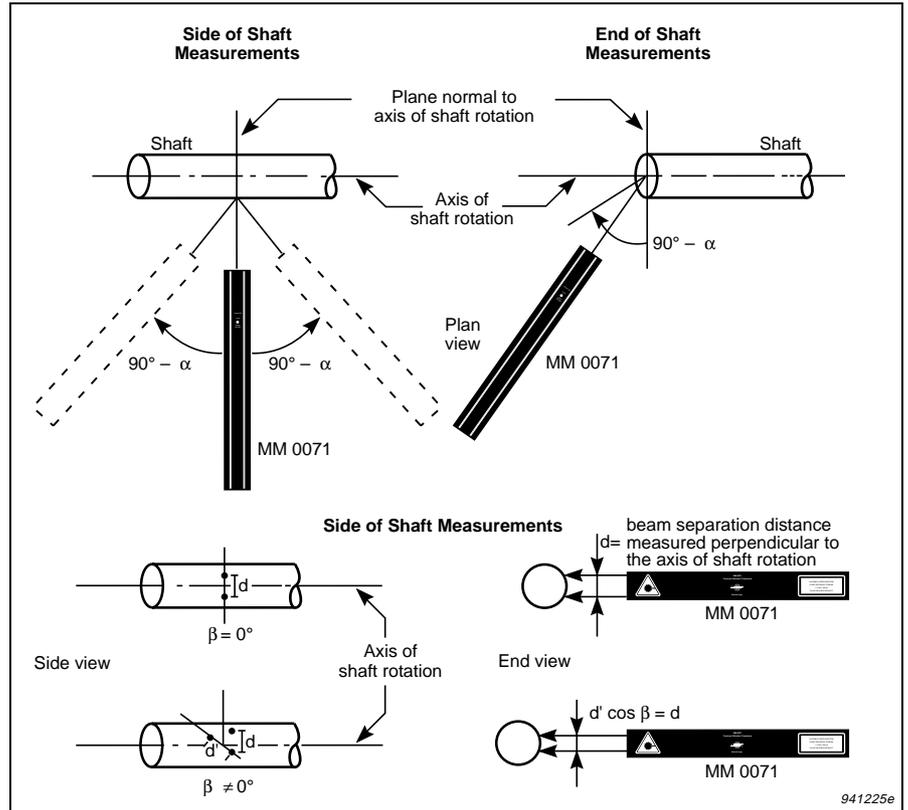


Fig.2 Tilting and/or pivoting the laser transducer enables the operator to choose an optimum direction of measurement for the job at hand. It also provides for high shaft speed measurements and measurements on shafts with small diameters

an important point which provides measurement versatility in that a large range of shaft diameters and rotational speeds can be accommodated by tilting or pivoting the laser transducer [2]. The standard operating ranges of the Torsional Vibration Meter are as follows: Detectable rotational speed range from 30 RPM to 7200 RPM and angular displacement dynamic range from 0.01° (RMS) to 12° (RMS) [1, 2]. These specifications are valid for shaft diameters up to 500mm*. When tilting the laser

* Measuring on shafts of a larger diameter can still be accomplished; however, the signal-to-noise ratio will decrease. Measurements on shafts with different diameters have indicated that the signal-to-noise ratio will decrease by 3 dB for every doubling of the diameter so that, for instance, a diameter of 1000mm will raise the noise floor 3dB.

transducer part of the Torsional Vibration Meter as described above, measuring on shaft diameters down to approximately 8mm is possible. When tilting and/or pivoting, the laser transducer, RPM values up to approximately 35000 can be measured. The dynamic range of the instrument will obviously be limited in a situation where the laser transducer is either tilted or pivoted. Fig.2. shows the principles of tilting and pivoting of the laser transducer. Note that d is the beam separation distance measured perpendicular to the axis of shaft rotation — and therefore the distance used in the formulas (1) to (9). The distance d' is equal to the (constant) distance between the two laser beams.

Results and Comparison with Traditional Techniques

The accuracy and consistency of the Torsional Vibration Meter is obviously of paramount importance for obtaining reliable measurements. One of the key factors in this respect can be found when looking closer at the previously derived mathematical equations.

From equation (9) it can easily be found that the accuracy of the instrument is directly depending upon the parallelism between the two laser beams and the stability of the wavelength of the laser light. Hence, one of the first steps in the factory calibration procedure, includes, amongst

other things, adjustment of the parallelism of the two laser beams to within $1/60$ of a degree. The wavelength consistency of the radiated laser light is an inherent property of a laser source. The Doppler Signal Processor is subsequently calibrated by aiming the laser transducer at a

shaft rotating with a smooth and constant RPM, while monitoring the RPM output on the rear panel of the Torsional Vibration Meter Type 2523. The output is then calibrated to give 1V per 1000 RPM. The constant $(4\mu\pi/\lambda)d$ is hereby defined and thereby is also the amplitude of the measured torsional vibrations defined. Finally, the calibration procedure includes a linearity check. Known values of "artificial" torsional vibration are generated by a frequency modulated HF generator and fed into the instrument part of the Torsional Vibration Meter Type 2523. Relating the known inputs to the measured outputs, a measure of the linearity is produced.

However, from a user's point of view it might be more interesting to validate the performance of the Torsional Vibration Meter Type 2523 by comparison with traditional torsional vibration transducers or, alternatively by a known "checking" method. During the development phase, a number of different comparison measurements and calibrations were carried out to serve the purpose of validation. In the following, three representative cases from these measurements are used to elaborate on the performance of the Torsional Vibration Meter Type 2523.

In the first case, a small, brushless DC motor, driven by a sinusoidal voltage, produced known values of torsional vibrations. When the driving frequency was varied, it was possible to achieve a dynamic range of 80 dB for torsional displacements, which encompasses the range which is typically found in practice. The standard cross-beam laser vibrometer [3] was used to calibrate the displacements produced. A comparison of the results between the two vibrometers is shown in Fig.3. Agreement to within 0.5 dB was demonstrated for the range tested.

In the second case, tests were conducted by measuring the torsional displacements of the crankshaft of a six-cylinder turbocharged diesel engine. The tripod-mounted instrument was arranged so that the crankshaft velocity was measured on its side surface. For comparison, an alternative measuring system, a Rolls-Royce Torsigraph, was fitted to the engine. This device consisted of a slotted disc, fixed to the end of the crankshaft, which rotated in sympathy with the latter. A transducer monitored the slot passing frequency from the disc and variations in this frequency were

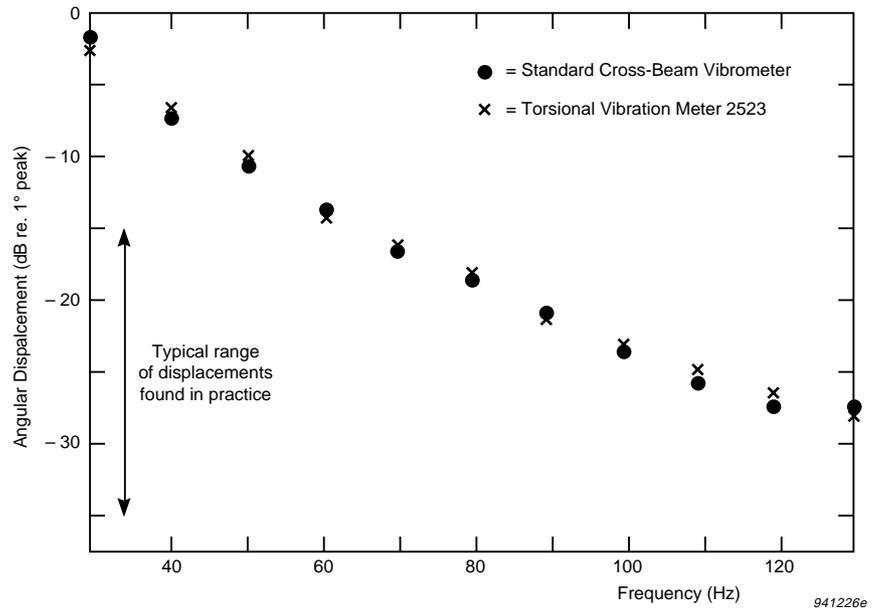


Fig.3 Comparison of results obtained by using the Torsional Vibration Meter Type 2523 and the Standard Cross-Beam Vibrometer

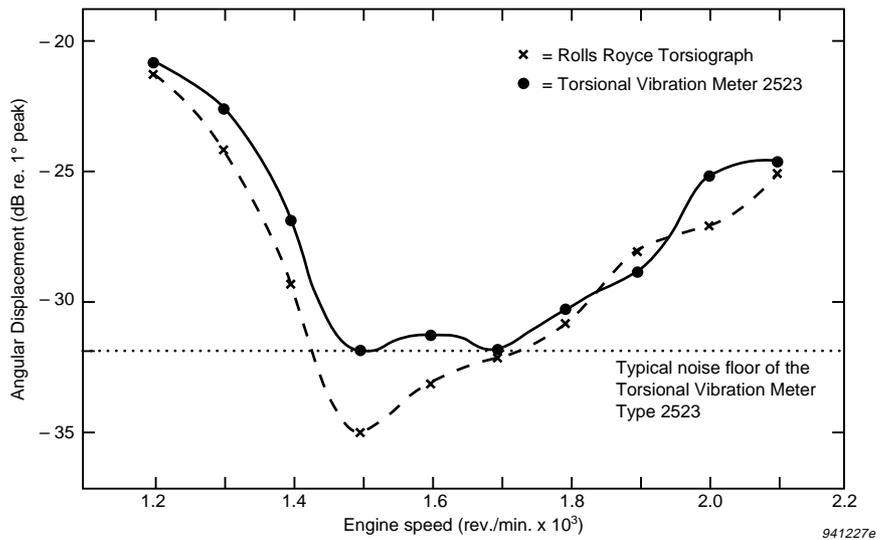


Fig.4 Measurements of the sixth rotation order angular displacements of the crankshaft of a six-cylinder turbocharged diesel engine

then demonstrated to provide torsional vibration data.

Outputs from both systems were processed with a Dual-Channel FFT Analyzer and the spectra displayed on an X-Y plotter. Measurements were taken at intervals of 100 RPM in the range 1200 to 2100 RPM at both no-load and full-load conditions. It is usual to measure torsional vibrations in degrees peak (i.e. displacement) and consequently the output from the Torsional Vibration Meter Type 2523 was converted to give an output signal that is propor-

tional to angular displacement. This is achieved simply by operating the instrument in the Angular Displacement Mode (the Torsional Vibration Meter Type 2523 features a built-in integrator to provide for two modes of operation*: Angular Velocity Mode and Angular Displacement Mode).

Fig.4. shows an examination of the variation of the sixth order of rotation versus engine speed under a full-

* The desired mode of operation is selected by two push buttons on the front panel of the instrument part of the Torsional Vibration Meter Type 2523.

load condition. Not surprisingly, discrepancies can be noted at certain RPM values. Many traditional torsional vibration transducers are known for their sensitivity to rigid body motion of the transducer housing and sensitivity to translational motion of the shaft onto which the transducer is mounted.

The last case to be presented here — and probably the most interesting of the three cases — is connected to the use of a well-known checking* method: The Hoke's Joint. The principle of this method is that of a driven shaft and a driving shaft, connected by a Hoke's Joint. Fig.5. shows the set-up schematically. Torsional vibrations will be generated in the driven shaft due to the time-variant torque transmission characteristics of the Hoke's Joint — the amplitude of the generated torsional vibrations will depend upon the angle ϕ . The generated second order and fourth order of torsional vibrations can easily be calculated [6] and therefore, when measuring the torsional vibrations of the driven shaft, a comparison can be carried out in a easy and straightforward manner. The result of such a comparison is shown in Fig.6. where the X-axis represents negative and positive inclination angles ϕ and the Y-axis represents angular displacement in degrees peak. The solid line shows the theoretical curve with calculated values of the generated torsional vibration, whereas the three dotted lines shows the measured values of second order torsional vibration at three different rotational speeds. Note that the three dotted lines are overlaying.

The curves explicitly demonstrate the accuracy and consistency of the

* The term "checking" is deliberately used in stead of the term "calibration" to indicate that the Hoke's Joint method is not based on a traceable calibration device that has been calibrated by absolute means. However, in the technical absence of an ideal calibration method, the Hoke's Joint provides a sufficiently accurate means of producing known values of torsional vibration.

Conclusions

Extensive laboratory and field tests have shown the Torsional Vibration Meter Type 2523 to be an accurate and reliable instrument for easy non-contact measurements of torsional vibration. By examination of the opti-

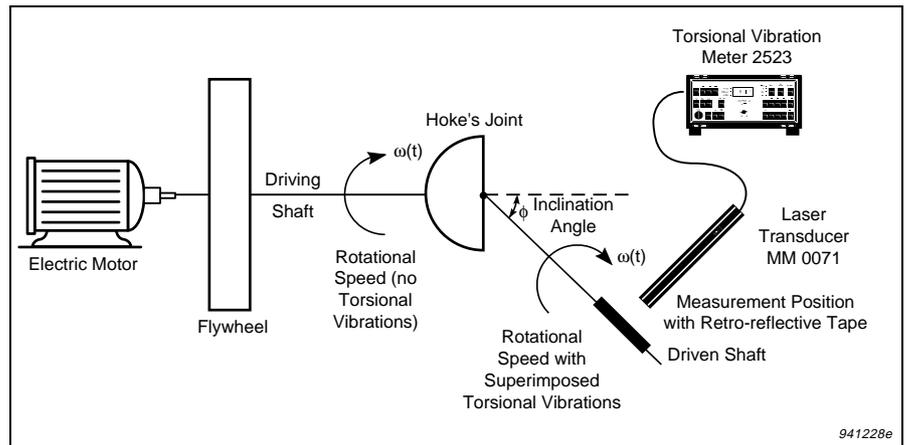


Fig.5 Principle of the Hoke's Joint checking method for torsional vibration transducers

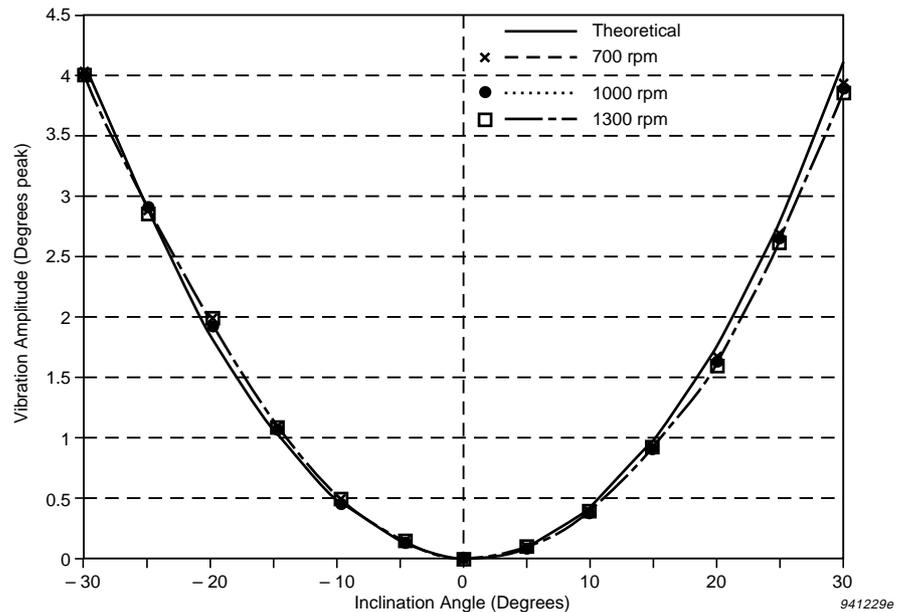


Fig.6 A comparison between the measured values of 2nd order torsional vibration (at different RPM values) and the corresponding theoretical curve for 2nd order torsional vibrations. Note that the measured values are independent on the shaft speed (the curves are overlaying)

Torsional Vibration Meter Type 2523. Note especially that the theoretical curve is independent of the rotational speed and that the arbitrarily chosen rotational speeds, in accordance with this, all provide the exact same meas-

ured result. This demonstrates the capability of the Torsional Vibration Meter Type 2523 to precisely measure the torsional vibration, superimposed onto any rotational speed.

cal geometry, it has been shown that the Torsional Vibration Meter Type 2523 provides the vibration engineer with an instrument that simply can be "pointed" at the rotating surface of interest. Also, it has been shown

how the instrument offers the advantages of insensitivity to operator or shaft translational movement, versatility of use, and operation irrespective of the component cross-section.

References

- [1] Brüel & Kjær Product Data: *Torsional Vibration Meter* — Type 2523, BP 0958.
- [2] Brüel & Kjær Instruction Manual: *The Torsional Vibration Meter Type 2523*, BE 1111.
- [3] N.A. Halliwell, H.L. Pullen and J. Baker, 1983 Proceedings of the Society of Automotive Engineers, paper 931321: *Diesel Engine Health: Laser Diagnostics*.
- [4] N.A. Halliwell, 1979 Journal of Sound & Vibration 62, 312-315, *Laser Doppler Measurement of Vibrating Surface: A Portable Instrument*.
- [5] J.B. Abbiss, T.W. Chubb and E.R. Pike, 1974, Optics and Lasers Technology 6, 249- 261: *Laser Doppler Anemometry*
- [6] B.I.C.E.R.A: *A Handbook on Torsional Vibration*, compiled by E.J. Nestorides of the B.I.C.E.R.A. Research Laboratory, Cambridge, At the University Press, 1958.



WORLD HEADQUARTERS:

DK-2850 Naerum · Denmark · Telephone: +45 45 80 05 00 · Fax: +45 45 80 14 05 · Internet: <http://www.bk.dk> · e-mail: info@bk.dk
Australia (02) 9450-2066 · Austria 00 43-1-865 74 00 · Belgium 016/44 92 25 · Brazil (011) 246-8166 · Canada: (514) 695-8225 · China 10 6841 9625 / 10 6843 7426
Czech Republic 02-67 021100 · Finland 90-229 3021 · France (01) 69 90 69 00 · Germany 0610 3/908-5 · Holland (0)30 6039994 · Hong Kong 254 8 7486
Hungary (1) 215 83 05 · Italy (02) 57 60 4141 · Japan 03-3779-8671 · Republic of Korea (02) 3473-0605 · Norway 66 90 4410 · Poland (0-22) 40 93 92 · Portugal (1) 47114 53
Singapore (65) 275-8816 · Slovak Republic 07-37 6181 · Spain (91) 36810 00 · Sweden (08) 71127 30 · Switzerland 01/94 0 09 09 · Taiwan (02) 713 9303
United Kingdom and Ireland (0181) 954-236 6 · USA 1 - 800 - 332 - 2040
Local representatives and service organisations worldwide
BO0426-11