Application Note

Measuring Torsional Operational Deflection Shapes of Rotating Shafts

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Abstract

With the advent of the laser-based Torsional Vibration Meter Type 2523, general torsional vibration measurements were not only greatly facilitated but, moreover, the unique concept of the instrument opened up for a number of new innovative measurement techniques, including the possibility of measuring Torsional Operational Deflection Shapes on rotating shafts. This Application Note describes the concept and the basic technique of measuring torsional operational deflection shapes using the Torsional Vibration Meter Type 2523, the Multichannel Analysis System Type 3550 and the Operational Deflection Shapes Software WT 9380, running on a Personal Computer. Applying the Torsional Operational Deflection Shapes technique to a demonstration model, the features and benefits of the technique are discussed.

The Torsional Vibration Meter Type 2523 used in a *TODS measurement*

Introduction

Today, a multitude of advanced techniques in the field of studying mechanical vibrations are available to the design engineer. Well-known examples of this are the Finite Element Method, Experimental Modal Analysis, and Operational Deflection Shapes.

The purpose of these techniques, employing one or more of them at different stages in the design process, is obviously to enable the design engineer to create products that have better performance towards minimized vibrational problems.

The **Finite Element Method** (FEM), is an analytical computer-based method for modelling different physical properties, such as structural dynamics.

Experimental Modal Analysis (EMA), is defined as the process of extracting the modal parameters, i.e. modal frequency, mode shape and modal damping from a series of mobility measurements with the aim of creating a non-parametric input/output model: The Modal Model.

Operational Deflection Shapes (ODS), designates the periodic motion pattern of a vibrating structure at a specific frequency and under a particular stationary, operating condition.

Torsional Operational Deflection Shapes

An ODS is an observation, or visualization, of a particular dynamic behaviour. It gives, in contrast to FEM and EMA, no information about the inherent dynamic properties of the structure. Still, the ODS of a vibrating structure can provide very useful information to aid in the understanding of the dynamic behaviour of a machine, a component or an entire structure, in particular when searching a solution to a dynamic problem[1].

Torsional Operational Deflection Shapes (TODS) are defined similar to ODS, with the exception that TODS designates the operational deflection shapes of structures vibrating in a rotational, or angular, degree of freedom.

Determining the ODS, or TODS, of a structure requires the measurement and analysis of the response signals from the vibrating structure.

Measuring Torsional Vibrations

Measurement of torsional vibrations, particularly in the field, has heretofore posed several practical problems. Conventional torsional vibration transducer systems have required the insertion of sensors such as strain gauge sensor modules, gear tooth wheels or optical encoders requiring the 'breaking" of shafts unless located at a shaft end, or have been restricted to accessible portions of the shaft system. Signal conditioning and processing add to the problems by limiting the frequency range and dynamic range of the measurement. Furthermore, calibration is usually difficult to perform[2].

The Torsional Vibration Meter Type 2523, however, provides a fast and easy means of measuring torsional vibrations anywhere on a visible part of a rotating shaft, eliminating practically all the above mentioned problems and furthermore fulfilling one of the most important demands for measuring torsional operational deflection shapes, namely the ability to move the Torsional Vibration Transducer to a set of measurement positions.

The Torsional Vibration Meter Type 2523, built on a concept conceived by Professor Neil A. Halliwell at Loughborough University (and formerly Southhampton University, ISVR), is based on a patented dual laser beam principle where the two laser beams are radiated from a laser transducer and pointed towards the shaft, rotating with at least 30 RPM. The frequency of the two back-scattered laser beams will, due to the rotation of the shaft, be Doppler shifted. When back-scattered into the laser transducer and heterodyned on a photo detector, the difference in the amount of Doppler shift in the two
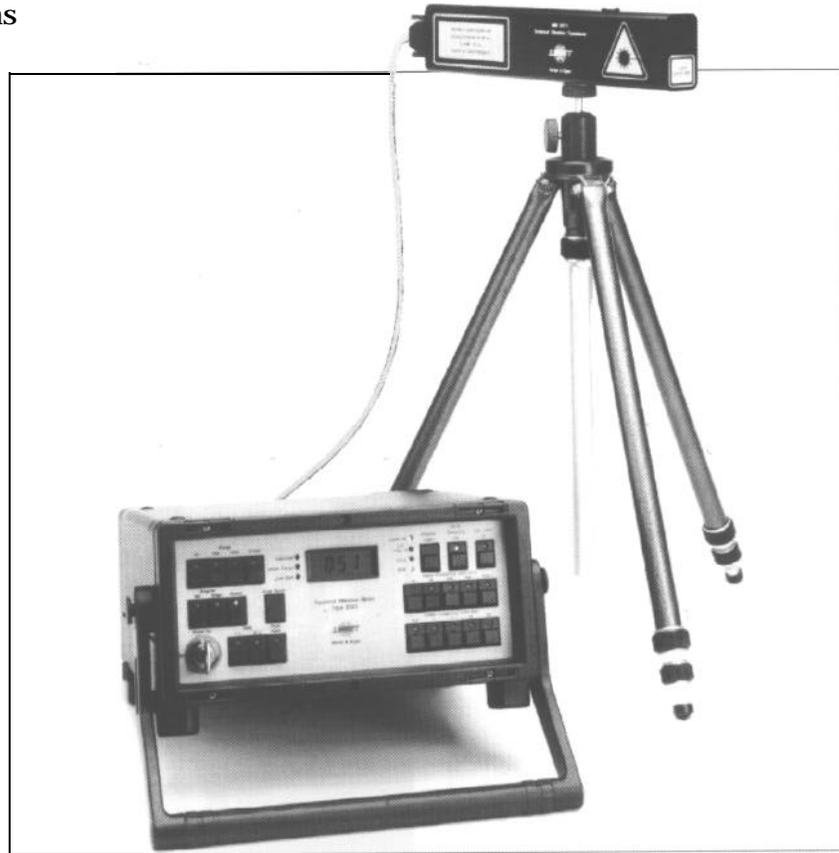

Fig. 1   Torsional Vibration Meter Type 2523

laser beams is then directly proportional to the rotational speed of the shaft. Any torsional vibrations in the shaft, superimposed onto the steady rotational speed of the shaft, will be detected as well, causing the heterodyned signal on the photodetector to be frequency modulated at the same frequency as the frequency of the torsional vibration measured.

The Torsional Vibration Meter uses a small, low power, solid state laser, providing safe and easy operation but also requiring retro-reflective tape to

be attached around the shaft[3]. Fig. 1 shows the instrument.

In practical situations, where shafts are operating in a dynamic environment, whirling, axial vibrations and torsional vibrations may be added to the dynamic behaviour. However, the dual laser beam design principle of the Torsional Vibration Meter Type 2523 ensures that even in such complex situations, only the torsional vibrations will be contained in the measured output signal.

Problems Associated with Torsional Vibrations

Torsional vibrations in rotating shafts are well-known as sources of numerous vibration problems. Typical problems within the automotive industry and the marine engine industry include:

Lack of powertrain smoothness and quietness.
The shafts in the drivetrain of passenger cars are excited to torsional vibrations by the inertia and gas forces of

the engine, the cardan joints and the gear mesh. Torsional resonance phenomena in the driveshaft, halfshaft, etc., can create wear and fatigue problems along with reduced passenger compartment comfort[4].

The general trend in the automotive industry towards reducing fuel consumption, and the concomitant necessity of weight optimized constructions, have meant that these vibration problems tends to increase.

Gear rattle noise.
In an automobile, the inherent revolutionary fluctuations (torsional vibration) of the combustion engine are transmitted to the input shaft of the gearbox through the flywheel and the clutch disk. In the gear box, these revolutionary fluctuations produce circumferential vibration in each gear set, and due to the backlash of these gear sets, the surfaces of the gears hit each other, thereby generating rattle

noise[5]. Especially in cars fitted with manual gearboxes, rattling noise is a significant contributor to the overall noise level in the passenger compartment.

Reduced engine performance.
Torsional vibrations occurring at the crankshaft are one of the major sources of combustion engine vibration leading to increased mechanical shear stresses and higher noise levels radiated from the engine[6].

Furthermore, crankshaft torsional vibrations will typically excite the auxiliary drives via the belt. Resonance phenomena may then occur in the belt drive or, at generators, compressors and steering pumps, creating excessive belt wear or very unpleasant noise and vibrations[4].

Car engines are usually fitted with a so-called harmonic balancer, usually mounted at the "free" end of the crankshaft. Correctly chosen (tuned), the balancer will dampen the tor-sional vibration amplitudes when the crankshaft torsional natural frequency is excited. Wear of this damper increases engine wear and car compartment noise.

Reduced reliability of ship propulsion systems.
Shafts in a marine propulsion system are excited to torsional vibrations by the inertia and gas forces of the engine. Again, as in the automotive industry, the common problems associated with this include wear and excessive mechanical shear stresses in the shafts with the possibility of shaft failures.

Furthermore, the majority of larger marine diesel engines are fitted with a torsional damping device in order to prevent the build-up of large vibration amplitudes and torsional stresses at critical speeds. A decline in the performance of this damper inevitably results in increased engine wear[7].

Obviously, these vibrational prob-lems often makes the measurement and analysis of torsional vibrations play an important role when designing against (or trouble shooting) vibrational problems in rotating machinery. Expanding a normal, i.e. a one-plane, torsional vibration measurement with a TODS measurement can be extremely useful in many applications.

The most important benefit of a TODS measurement is that it provides an animated picture of the torsional deformation at critical frequencies (typically a harmonic component close to a torsional natural frequency) under operating conditions.

A visualization of the torsional deformation shape provides a better understanding of the vibrational problem and consequently, this can help in creating the basis for a better solution to the problem.

The Torsional Operational Deflection Shapes Demonstration Model

In order to illustrate how a typical TODS measurement can be performed, a special TODS Demonstration Model was built, as seen in Fig.2.
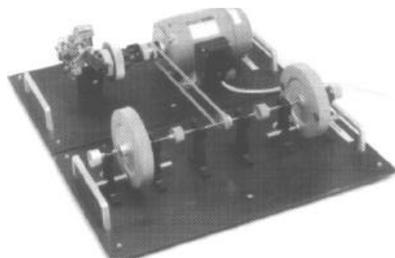
Fig.2   TODS Demonstration Model

This model consists of a thin steel shaft with two aluminium flywheels, rigidly mounted at the ends of the shaft. The shaft, symmetrically built and supported by six roller bearings, is made to rotate, at variable speed, by means of an electric motor.

This mechanical system will possess a number of natural frequencies (in the translational as well as in the torsional degrees of freedom), of which the first torsional natural frequency is excited by the following system: two permanent magnets are mounted in two of the bearing housings and two other magnets are positioned at equal
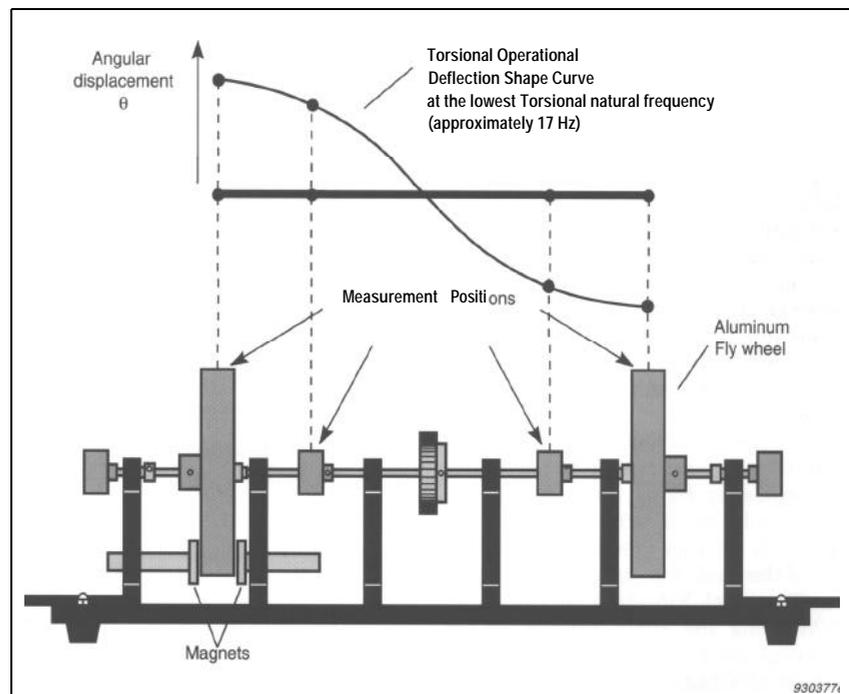
Fig. 3   TODS of the Demonstration Model

distance, on one of the aluminum flywheels.

When the shaft is rotating, the speed of rotation, and thereby the excitation frequency, can be fine-tuned to coincide exactly with the first torsional natural frequency, thereby creating a (stationary) torsional resonance situation where the torsional operational deflection shape will be as seen in

Fig.3, i.e. the two ends of the shaft will have the same torsional vibration amplitude, but a phase difference of approximately 180° (the actual phase difference will depend upon the precision with which the excitation frequency is tuned to coincide with the torsional natural frequency). The nodal point is found to be in the middle of the shaft due to the symmetrical design. This torsional resonance situation results in a superimposed dynamic shear stress in the shaft as shown in Fig.4.

Naturally, the various excitation sources of "real" machinery depend upon the type of machinery in question. The principal, automotive, torsional vibration excitation sources are the nature of the combustion process, the transmission components and the cardan joints. Nevertheless, the basic principles, as they are explained above, of the TODS Demonstration Model apply for "real" rotating machines as well.
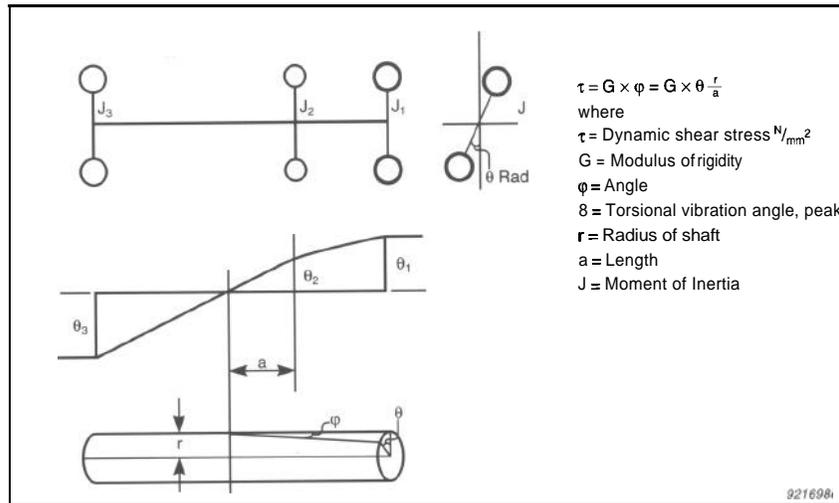

$$\tau = G \times \varphi = G \times \theta \frac{r}{a}$$

where
τ = Dynamic shear stress $^N/_{mm}^2$
G = Modulus of rigidity
φ = Angle
θ = Torsional vibration angle, peak
r = Radius of shaft
a = Length
J = Moment of Inertia

Fig. 4   Calculating the Superimposed Shear Stress τ

Measuring a Basic Torsional Operational Deflection Shape

The Torsional Vibration Meter Type 2523 measures the torsional vibrations in a single plane giving a calibrated output in millidegrees/second (angular velocity) or in millidegrees (angular displacement). Thus, when measuring the Torsional Operational Deflection Shape, subsequent measurements must be performed at different planes along the shaft where the phase of the torsional vibration between the different planes must be determined as well. A Brüel & Kjær Tacho Probe MM 0024 is used to obtain this phase information. Fig. 5 shows the set-up.

The Torsional Operational Deflection Shape measurement is therefore performed by fixing and aiming the tacho probe at an arbitrary point on the shaft (in this case a point at the end of the shaft was used) and moving the Torsional Vibration Meter Type 2523 along the shaft, measuring at different positions. At each point, the Torsional Vibration Meter Type 2523 will provide the torsional vibration amplitude (in millidegrees or degrees/ second depending upon the mode of operation). The B channel of the Multichannel Analysis System Type 3550 is connected to the AC output of the Torsional Vibration Meter Type 2523 and the A channel is connected to the Tacho Probe MM 0024.
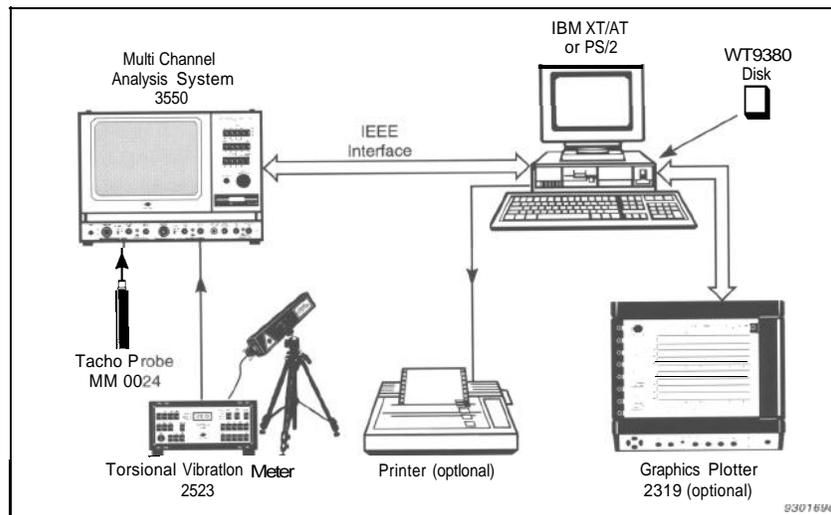

Fig. 5 TODS set-up with instruments

At the frequency of interest, i.e. the torsional natural frequency being excited, the Complex Spectrum of the Multichannel Analysis System Type 3550 will provide the vibration amplitude as well as phase information. However, no manual data interpretation is required: the Personal Computer, running the WT 9380 Operational Deflection Shapes Software, is used for complete analyzer control, transfer of transmissibility data, data processing

and deflection shape presentation (animation).

The direct TODS measurement result, i.e. the absolute torsional vibration measured at the four measurement positions and the relative torsional vibration between the four measurement positions, can be displayed if requested. The relative torsional vibration (amplitude and phase) between the measurement positions forms the basis for the compu-.

ter to create the TODS animation.

A printout of the direct TODS measurement result, measured on the TODS Demonstration Model, is shown in Fig. 6a. Fig. 6b shows the associated deflection shape. As previously discussed, the output of the Torsional Vibration Meter Type 2523 is proportional to the angular velocity and therefore the field "Data Type" is assigned "Velocity". The WT 9380 Operational Deflection Shapes Software automatically calculates, by digital differentiation and integration respectively, the corresponding torsional acceleration and the torsional displacement values at the four measurement positions. The DOF (Degrees of Freedom) column specifies the four measurement positions. The suffi 2 designates that the measurements are performed in a torsional degree of freedom.

The first torsional natural frequency of the TODS Demonstration Model, which is excited as explained above, can be calculated prior to the measurement in order to facilitate the search for the lowest torsional resonance.

The calculation is performed by determining the eigenvalues of the KM matrix, where K designates the (torsional) stiffness matrix of the shaft and M designates the inertia of mass matrix of the shaft. Doing so, this gives a value of the lowest torsional natural frequency of approximately 18 Hz which corresponds well with the measured value (17 Hz).

Fig. 6a Operational Deflection Shape #1

Fig. 6b Associated deflection shape

The WT 9380 Operational Deflection Shapes Software

The Operational Deflection Shapes Software is a complete software package, designed to assist the vibration engineer in developing the ODS or TODS of a structure on a Personal Computer.

For ease of use, the menu-driven software has one main module, the Main/Display Model Module, for displaying the ODS data and two sub-modules. The first sub-module, the Measurement Module, is for analyzer set-up, measurement transfer, etc. The second sub-module, the Model/Geometry Module, defines the geometry, i.e. coordinates, constraints, etc., of the structure to be measured. The software's module structure is shown in Fig. 7.

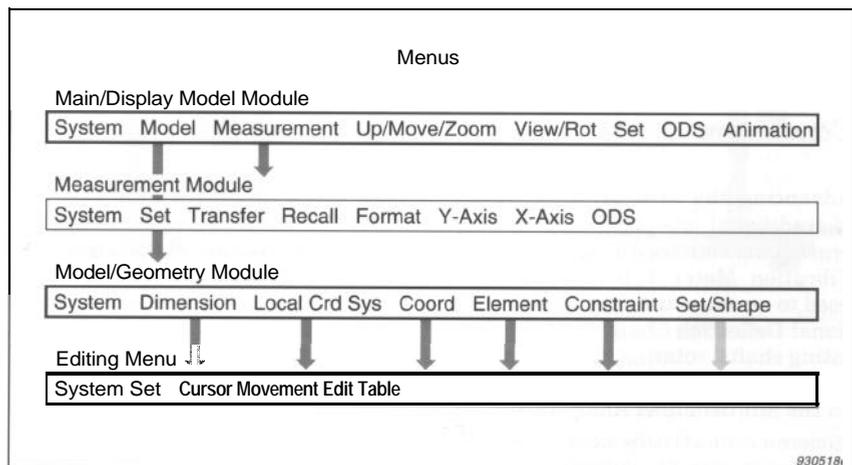Obviously, the geometry of the measured structure must be defined

Fig. 7 Structure of the WT 9380 software

before carrying out the actual measurement. The three-dimensional geometry of the TODS Demonstration Model is shown in Fig. 8. As can be seen in the figure, the geometry is based on four sets of points and each set, consisting of eight points, defines a (constrained) circle, having only one (torsional) degree of freedom. These four circles are then connected to one another by a total of 24 lines. Each of the four "circle point" sets defines one of the four measurement points on the TODS Demonstration Model.

During the TODS measurement, the Operational Deflection Shapes Software is used in the Measurement Module mode, providing full analyzer control (set-up and data transfer). Between the measurements at the four different measurement points, the operator, after having moved the laser transducer, is prompted to accept (or reject) the new measurement before the Multichannel Analysis System transfers the data to the Personal Computer.

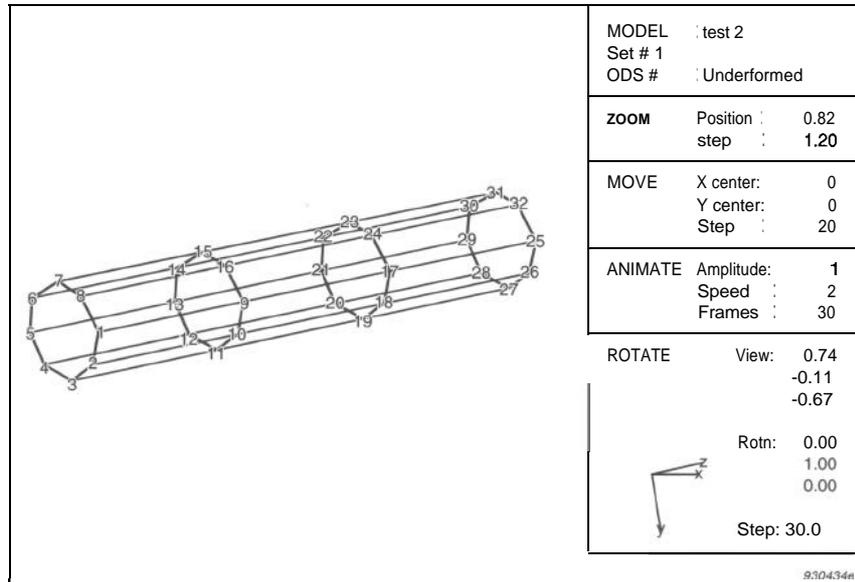Note that the geometry seen in Fig.

MODEL	: test 2	
Set # 1		
ODS #	: Underformed	

| **ZOOM** | Position : | 0.82 |
| | step : | **1.20** |

MOVE	X center:	0
	Y center:	0
	Step	20

ANIMATE	Amplitude:	1
	Speed :	2
	Frames :	30

ROTATE	View:	0.74
		-0.11
		-0.67
	Rotn:	0.00
		1.00
		0.00
	Step: 30.0	

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Fig. 8   Geometry of the TODS Model shaft

8 has been simplified in comparison to the model: the two flywheels of the model are not defined in the   geometry. This was done in order to clarify the animated deflection shape.

Expanding the Basic TODS measurement

The basic TODS measurement, using the Torsional Vibration Meter Type 2523 and the MM 0024 Tacho Probe as described in the foregoing, can be refined by applying several additional techniques.

TODS Order **Tracking**[1], also possible with the Multichannel Analysis System Type 3550, can be used for concentrating each harmonic of the TODS into one frequency line only, thus avoiding any problems with Smearing, Leakage and Picket Fence Effect. Although the frequency axis is resealed into an order axis, the MM 0024 Tacho Probe, now also being used to control the sampling rate of the analyzer, provides the necessary information for reading out the various orders in Hertz or RPM.

Advancing the measurement capabilities even further: using two Torsional Vibration Meters Type 2523 and differential analysis of the two AC Signal Outputs in the Multichannel Analysis System Type 3550, a direct real-time measure of the "twist" between two planes on the shaft is obtained. Employing a   tacho probe, such as the MM 0024, the   signal-to-noise ratio of the measurement can be improved by applying synchronous time domain averaging (Signal Enhancement) of the two AC Signal   Output[2] time signals – before subtraction and subsequent frequency analysis.

Using the User Definable Functions in the Type 3550 Multichannel Analysis System, such a real-time "twist" measurement with two Torsional Vibration Meters Type 2523 is easy and straightforward to perform.

Conclusion

Advancing the analysis possibilities of traditional one-plane torsional vibration measurements, the Torsional Vibration Meter Type 2523 can be used to measure the Torsional Operational Deflection Shape (TODS) of rotating shafts, rotating at a critical frequency. The instrumentation is based on the Multichannel Analysis System Type 3550, controlled by a Personal Computer running the Torsional Operational Deflection Shapes Software WT 9380.

Measuring the TODS of a rotating shaft means that torsional vibration problems can be investigated by viewing the deflection shape and thereby guide the vibration engineer in   making optimal design modifications to control vibration and lessen wear and fatigue. Employing a TODS Demonstration Model, where the lowest torsional natural frequency was excited during rotation, a typical TODS measurement was described and the result, in terms of the animated deflection shape was shown.

[1] Order tracking can also be performed when using only one Torsional Vibration Meter Type 2523, i.e. when performing a normal single plane torsional vibration measurement.

[2] The Torsional Vibration Meter Type 2523 has two BNC signal output sockets on the rear panel: The DC Signal Output and the AC Signal Output. The AC Signal Output is for obtaining an AC output of the measured torsional vibration velocity (or displacement) in the frequency range chosen on the front panel of the instrument.

Acknowledgements

References

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