Optics and Lasers in Engineering 50 (2012) 1596–1601

Contents lists available at SciVerse ScienceDirect

Optics and Lasers in Engineering

journal homepage: www.elsevier.com/locate/optlaseng

Torsional vibration measurements on rotating shaft system using laser doppler vibrometer

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ARTICLE INFO

Article history:
Received 3 November 2011
Received in revised form
24 May 2012
Accepted 29 May 2012
Available online 22 June 2012

Keywords:
Torsional vibration
Laser torsional vibrometer
Measurement
Model
Shaft system

ABSTRACT

In this work, a laser torsional vibrameter was used to measure the torsion vibration of a rotating shaft system under electrical network impact. Based on the principles of laser Doppler velocimetry, the laser torsional vibrometer (LTV) are non-contact measurement of torsional oscillation of rotating shafts, offering significant advantages over conventional techniques. Furthermore, a highly complex shafting system is analyzed by a modified Riccati torsional transfer matrix. The system is modeled as a chain consisting of an elastic spring with concentrated mass points, and the multi-segments lumped mass model is established for this shafting system. By the modified Riccati torsional transfer matrix method, an accumulated calculation is effectively eliminated to obtain the natural frequencies. The electrical network impacts can activize the torsional vibration of shaft system, and the activized torsion vibration frequencies contained the natural frequencies of shaft system. The torsional vibrations of the shaft system were measured under electrical network impacts in laser Doppler torsional vibrometer. By comparisons, the natural frequencies by measurement were consistent with the values by calculation. The results verify the instrument is robust, user friendly and can be calibrated in situ. The laser torsional vibrometer represents a significant step forward in rotating machinery diagnostics.

1. Introduction

Torsional and bending vibrations are both important in rotating shaft systems. Due to the turbine rotor failures at Southern California Edison's Mohave station in 1970 and 1971 [1], industry's attention was focused on the shaft's torsional vibration caused by the transmission operation in a turbine-generator. Typical torsional vibration problems in automotive, marine propulsion and industrial applications include oscillation of crankshafts, drive-shafts, and component wear in gear boxes. In these cases shaft cracking, coupling deterioration and gear failure can result [2,3]. Fundamental to the study of turbo-generator shaft torsional vibrations, as occurs in subsynchronous resonance and high speed reclosing, is the calculation of the characteristic frequencies and responses of the vibrations.

This Application Note describes and examines the use of two Torsional Vibration Meters Type 2523 in a critical, severely time-limited, trouble-shooting situation [4]. Torsional Vibration Meters Type 2523 was introduced in Instruction Manual [5]. Bently Nevada Corporation has a Torsional Vibration Signal Conditioner (TVSC) [6] which can produce a square wave signal with variable periods representative of torsional vibrations. It was used to detect the crack in rotor shaft [6], which also requires the installation of a toothed wheel on the shaft. Wang and Davies [7] used a magnetic sensor to sense the passage of teeth of a geared wheel installed on the engine shaft. The frequency of the signal varies as the engine speed changes. The system uses a fast counter and is interfaced to a personal computer.

All of the above systems require further measurements to produce information about motion in the x and y directions and are difficult to install, or are not flexible. There was therefore a real need for a torsional vibration transducer which was user friendly and could provide data immediately in on-site situations. The laser torsional vibrometer (LTV) [8] extended the application of this technology, achieving accurate non-contact measurement of the torsional vibration of rotating components and overcoming the limitations of conventional instrumentation [9]. Measurements with the LTV are unaffected by the shape of the target, allowing use on components of arbitrary cross-section. Use on the side of a shaft or on the end-face is possible and this is advantageous where access is restricted. Additionally, the system uses a minimum of optical components and has straightforward signal processing requirements [10,11]. Often retro-reflective tape is applied to the target shaft to facilitate use of a low-powered laser. The Torsional Vibration Meter Type 2523 [12] was designed for making torsional vibration measurements where it is not

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http://dx.doi.org/10.1016/j.optlaseng.2012.05.018

feasible to mount a transducer onto a rotating object. Bruel & Kjaer developed the Type 2523 based on a design by the Institute of Sound and Vibration Research, University of Southampton. It is an easy to use, highly accurate, reliable vibration measuring system.

2. Measurement principles for laser torsional vibrometer

Laser light has an inherent property that makes laser technology ideally suited for use in the torsional vibrometer. When a laser beam is split and subsequently recombined, a well-defined phase relationship still exists in the recombined beam, even if its component beams have traveled different distances. This is known as temporal coherence, and the maximum path difference over which it holds true is the coherence length.

A schematic of the electronic and optical components in the laser torsional vibrometer is shown in Fig. 1. The heart of the system is a low power (< 1.5 mW) laser. The laser beam is split into two equal-intensity parallel beams separated by a distance *d*.

$$d = \boldsymbol{R_A} \cos\alpha_A + \boldsymbol{R_B} \cos\alpha_B \quad (1)$$

where $\boldsymbol{R_A}$ is transient rotating radius of point A, and $\boldsymbol{R_B}$ is that of point B. The beams strike the shaft surface at point A and B. The instantaneous velocity at each of points A and B, with respect to the axis of rotation, is $\boldsymbol{V_A}$ and $\boldsymbol{V_B}$, respectively. The shaft itself also has an instantaneous velocity of $\boldsymbol{V}$. Each beam sees only the velocity in one direction:

$$\begin{aligned} V_A &= -\boldsymbol{V_A} \cos\alpha_A - \boldsymbol{V} = -\omega \boldsymbol{R_A} \cos\alpha_A - \boldsymbol{V} \\ V_B &= \boldsymbol{V_B} \cos\alpha_B - \boldsymbol{V} = \omega \boldsymbol{R_B} \cos\alpha_B - \boldsymbol{V} \end{aligned} \quad (2)$$

and is thus frequency-shifted:

$$f_A = \frac{2V_A}{\lambda} \text{ and } f_B = \frac{2V_B}{\lambda}$$

where λ is the wavelength of laser. This signal contains the required angular vibration information. It is not practical to demodulate the signal directly. When the beams arrive at the photodiode they heterodyne, producing an output current that is modulated at the beat frequency f_D, that is, the difference between the frequencies of the Doppler-shifted beams:

$$\begin{aligned} f_D &= f_B - f_A = \frac{2}{\lambda}(V_B - V_A) \\ &= \frac{2\omega}{\lambda}(\boldsymbol{R_B} \cos\alpha_B + \boldsymbol{R_A} \cos\alpha_A) = \frac{2\omega d}{\lambda} \end{aligned} \quad (3)$$

Thus, the beat frequency is directly proportional to the shaft speed (ω) and is independent of any solid body motion of the shaft. If the plane of the laser beams is not perpendicular to the shaft axis, then f_D is also a function of cos θ, where θ is the angle between the plane of the laser beams and the plane perpendicular to the axis of shaft rotation.

The laser torsional vibration meter is designed to simplify the measurement of torsional vibration. The fitting and calibration of conventional torsional transducers requires substantial machinery downtime. Attachment of the retroreflective tape is quick, thus minimizing machinery downtime and simplifying the measurment process.

3. Signal extraction of torsional vibration

A simplified block diagram of the signal processing electronics in the laser torsional vibration meter is shown in Fig. 2. The signal from the torsional vibration transducer consists mainly of a frequency proportional to the rotational speed of the target. It is both frequency and amplitude modulated. The amplitude is modulated as a result of the random position of the glass spheres on the retroreflective tape. The frequency is proportional to the rotational speed and, in the case of torsional vibrations, the signal is parallel to a filter bank and to an amplitude detector. From the filter bank, the signal passes to a fast comparator that changes it to a square wave.

The signal then travels to two phase-locked loops in parallel for demodulation of the frequency-modulated signal. If the laser light has been frequency modulated due to the rotational speed, that is, only the carrier wave is present, then the signal from the phase-locked loops only has a DC component. If the carrier wave

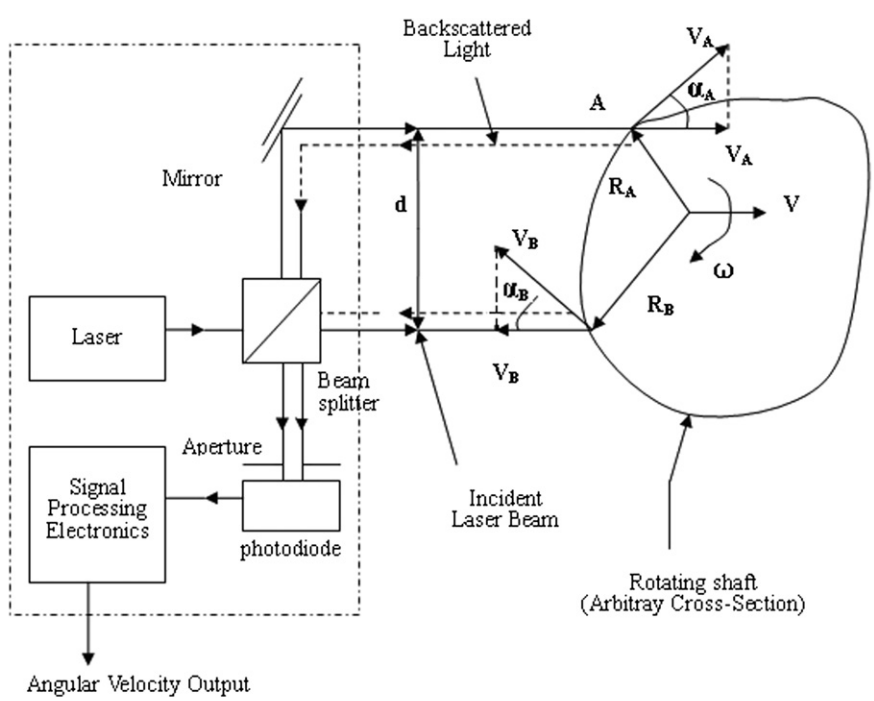

Fig. 1. A schematic of the arrangement of the electronic and optical components within the laser torsional vibrometer.