APPLICATIONS OF LASER DOPPLER VIBROMETRY IN DESIGN AND NON-DESTRUCTIVE TESTING

D J Berry, Managing Director

Ometron Ltd, Worsley Bridge Road, London SE26 5BX

ABSTRACT

The application of scanning laser doppler vibrometry (LDV) as a technique for aiding the design and for non-destructive testing (NDT) of a wide range of structures is assessed. A new instrument called VPI Sensor is described and evaluated. VPI Sensor is capable of testing structures as large as bridges, buildings and aircraft. The random/RMS NDT method, which appears to have great potential for in-field detection and monitoring of damage, is described.

1. INTRODUCTION

Optical techniques for full-field measurement of vibrational displacement are already widely used by a variety of industries. They are generally sensitive, offering high spatial resolution without the loading effects of contacting transducers such as accelerometers.

Scanning Laser Vibrometry offers specific advantages over established methods of experimental vibration analysis and modal testing using discrete, contacting accelerometers. Because the measuring technique is non-contacting, tedious attachment procedures for a large number of accelerometers are avoided and there is no risk of affecting the true dynamic response of the test structure. Alternative full field non-contacting techniques based on holography or electronic speckle pattern imaging (ESPI) have dynamic range limitations for the measurement of low frequency, large amplitude vibrations and are intrinsically more vulnerable to unstable measuring conditions because the primary measurement parameter is displacement rather than velocity.

The principles behind the LDV technique are very simple. In the same way that sound waves reflected from, or emitted by, a moving object are subject to a frequency change (the well-known Doppler effect heard on ambulance sirens, etc.); a beam of light reflected from a moving surface is also changed in the frequency. Although the fractional change in frequency of the light wave is very small (typically 1 part in 10^8 or less) it can be measured very accurately using optical interferometry in conjunction with electronic frequency measurement. The velocity of the moving surface is derived from these frequency changes.

Scanning LDV accommodates a very wide dynamic range, typically less than 10^{-9} to 10^{1} m of vibrational displacement amplitude. Noise equivalent velocity is generally around 10^{-6} ms^{-1} per root Hertz. This means that much smaller displacement amplitudes can be measured at higher frequencies and much larger displacements at lower frequencies than some other optical techniques such as electronic speckle pattern interferometry (ESPI).

Scanning LDV can be used in extreme environments such as the mapping of the vibration characteristics of hot running exhaust and other situations such as nuclear power plant where close access to the test surface might be hazardous.

2. THE VPI SENSOR

Design Features

The Sensor has been designed for optimum ease of use in a wide range of non-ideal operating conditions. It employs a highly sensitive coaxial optical system and is a Class II laser product. These together with the following features serve to illustrate the high level of performance and versatility that can be achieved with LDV.

The sensor is a modular laser doppler vibrometer with built-in x, y beam positioning mirrors. There are inputs for control of the mirrors with an external computer.

The 9000 Series Console developed by Ometron can also be used. Programs are available for full field (25° x 25°) scan control and digitised colour coded display of up to over 65,000 measurements in each scan. The test surface can either be under single frequency or random/service loading conditions. At a single frequency the amplitude, phase, real and imaginary components of velocity can be displayed. Under random or service loading and in conjunction with an FFT analyser, up to 32 frequency lines of information can be recorded at each point in a scan and later displayed as up to 32 maps of operating deflection shape. Sophisticated software is available for manual beam positioning and autostepping through up to 512 points without the need for an external computer. A handset is used to move the beam and fix the grid of points.

The Sensor measures the velocity of surfaces that have a retroreflective coating up to 200 m away with only a 1 mW laser beam. Flat white surfaces can be up to approximately 40 m from the Sensor. This means that at closer distances large structures can be tested with little or no surface preparation. A lower power laser ensures a safer working environment than usually associated with other long range optical systems.

The velocity amplitude can be in the range 0 ±1 ms^{1} from DC to 100 kHz. The minimum detectable velocity is typically in the order of 3×10^{6} ms^{1}.

The Sensor can accommodate large variations in reflectivity of the test surface both in time and space. This is because the dynamic range of the amplitude of the doppler signal is very large. The velocity information is obtained from changes in the frequency and not the amplitude of the doppler signal. A wide range of surface finishes and operating conditions can be tolerated. In particular, laser speckle effects which can seriously degrade the quality of interferometric data from rough surfaces, are typically of little or no significance.

Accuracy of output of the Sensor is approximately ±3% of full scale for each of the three ranges (0-0.01, 0-0.1, 0-1.0 ms^{1}). A frequency coded square wave signal is provided with high intrinsic calibration accuracy (0.01%) for special requirements using external signal analysers.

Measurement Principle

The Sensor is based on a Michelson interferometer in which a laser beam is divided into reference and signal beams (See Figure 1). The sub 1 mW signal beam is directed onto a vibrating test surface, and back-reflected light is recombined with the internal reference beam. When the test surface moves, the path difference between the routes followed by the reference and signal beam changes, resulting in intensity modulation of the recombined beam due to interference between the reference and signal beams. One complete cycle of intensity modulation corresponds to a surface movement of $\lambda/2$ = 3.16 x 10^7 m, half the wavelength of the helium neon laser source; hence the frequency F_d of intensity modulation corresponding with a surface velocity, v, is given by $F_d = 2v/\lambda$. We shall refer to F_d as the Doppler frequency associated with a surface velocity v, since the intensity modulation of the recombined beam may alternatively be seen to arise through interference between a reference beam and a signal beam, the frequency of the latter being shifted by an amount $F_d = 2v/\lambda$, in accordance with the Doppler effect, following reflection from a surface moving with velocity v.

The recombined beam is shared between two independent detection channels in such a way that the interferometric path difference presented to one channel is effectively one quarter of a wavelength longer than that presented to the other. This configuration results in a 90° phase shift between the signals from the two channels (denoted 'sin' and 'cos'), the direction of motion of the surface determining which signal leads the other in phase. The sin and cos signals at frequency F_d are fed to a dual channel balanced modulator where they are respectively modulated by internally generated sin and cos signals at a carrier frequency F_c. Summation of the two modulated outputs yields a single, frequency shifted output at $F_c + F_d$ + or $F_c - F_d$, depending on the direction of motion of the surface. In this way, electronic mixing results in essentially the same shifted Doppler signals as those obtained using optical frequency-shifted techniques, and established frequency tracking methods can be used to derive an analog voltage representing the instantaneous velocity of the moving surface.

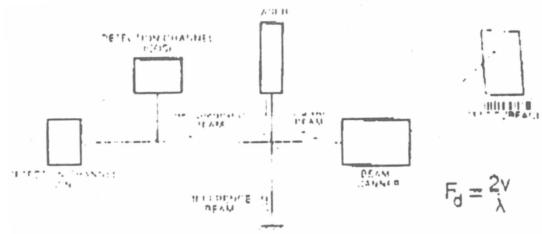

Figure 1 VPI Sensor system schematic

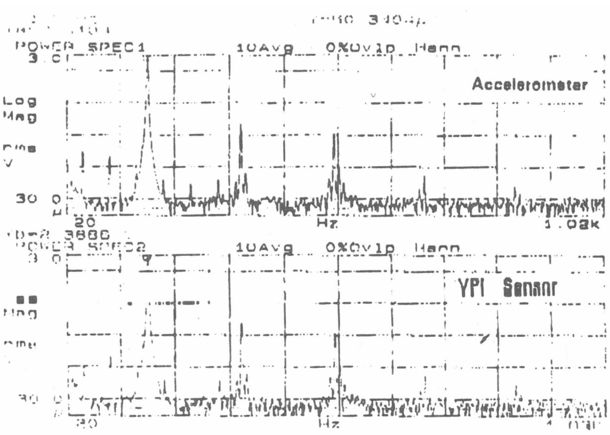

Figure 2 VPI Sensor compared to Accelerometer

4 APPLICATIONS

The Sensor can be used as a non-contacting accelerometer. Figure 2 demonstrates close agreement between data from the Sensor and an accelerometer. A flat plate was excited at 171 Hz and the laser focussed on to the back of the accelerometer. There are many situations where a non-contacting Sensor is more convenient such as high temperature or lightweight structures and areas difficult or dangerous to access:

- Running engines and exhausts
- Power and chemical plant.
- Satellite, hard disk reader arms, turbine blades and other lightweight components
- Bridges and buildings
- Tires and other objects such as continuously running machinery difficult to attach accelerometers to.
- Rotating parts with and without a derotator.

The VPI Sensor can be used as a means of detecting defects in materials and structures. The VPI RapidScan System is a new implementation of vibration pattern imaging instrumentation. It contains the performance features of VPI Sensor with high speed data acquisition. VPI RapidScan can be used with broadband excitation to detect structural defects, such as delaminations in composite and honeycombe materials. In the example defects due to debonding are revealed in a satellite dish (Figure 3).

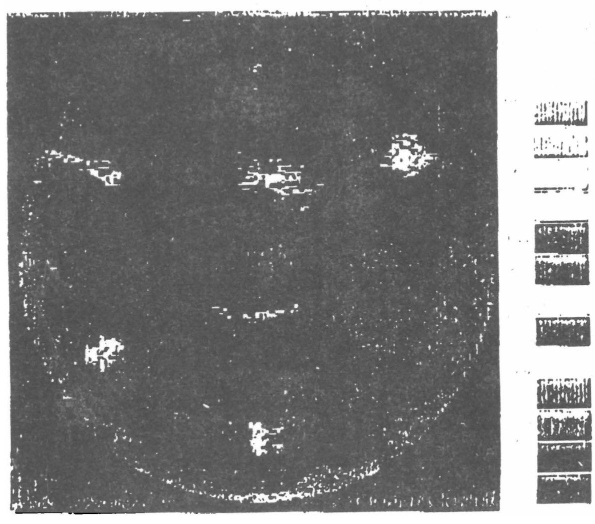

Figure 3 VPI RapidScan provides a vibration signature of a satellite dish and highlights structural defects.