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An international review of laser Doppler vibrometry: Making light work of vibration measurement

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ABSTRACT

In 1964, just a few years after the invention of the laser, a fluid velocity measurement based on the frequency shift of scattered light was made and the laser Doppler technique was born. This comprehensive review paper charts advances in the development and applications of laser Doppler vibrometry (LDV) since those first pioneering experiments. Consideration is first given to the challenges that continue to be posed by laser speckle. Scanning LDV is introduced and its significant influence in the field of experimental modal analysis described. Applications in structural health monitoring and MEMS serve to demonstrate LDV's applicability on structures of all sizes. Rotor vibrations and hearing are explored as examples of the classic applications. Applications in acoustics recognise the versatility of LDV as demonstrated by visualisation of sound fields. The paper concludes with thoughts on future developments, using examples of new multi-component and multi-channel instruments.

1. Introduction

Laser (Doppler) Vibrometry (LDV) has its origins in fluid velocity measurements reported by Yeh and Cummins [1] at Columbia University in 1964. Their seminal paper described measurement of "Doppler shifts in the Rayleigh scattered light at [flow] velocities as low as 0.007 cm/s" at a time when the laser was still in its infancy. Helium Neon (HeNe) lasers were pioneered at Bell Telephone Laboratories, first in the infra-red in 1960. The now familiar red HeNe laser used by Yeh and Cummins had been developed in 1962 and it remains prevalent in commercial laser Doppler instruments more than 50 years after those first experiments.

This review paper begins with an introduction to the principle of operation and a historical perspective on how the laser Doppler vibrometer (also generally abbreviated to LDV) has reached its current state of maturity. The effects of laser speckle have been and remain a concern in LDV and Section 2 sets out the state-of-the art. Scanning LDV has been an extremely important development with wide application and this technique is considered before considering applications in structural heath monitoring, MEMS, rotating machinery, hearing and acoustics. The paper concludes with thoughts on future development.

Detection of the Doppler frequency shift that occurs when light is scattered by a moving surface is the basis of LDV [2]. This frequency shift is directly proportional to the surface velocity and so its detection enables convenient and non-contact measurement of vibration velocity. Detection is not entirely straightforward as the laser has a frequency typically 6 or 7 orders of magnitude higher than the Doppler shifts, which are typically in the low MHz range. Scattered light from the target has to be mixed interferometrically with a mutually coherent reference beam to produce a beat in the collected light intensity at the difference in frequency between the target and reference beams, i.e. down in the MHz range where demodulation is possible electronically.

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Such a configuration still leaves a directional ambiguity in the measurement because demodulation only identifies the modulus of the frequency shift. Early proposals achieved the necessary discrimination by introducing a known frequency pre-shift to the reference beam [3–5]. This modifies the frequency of the intensity beat to be less than or greater than the pre-shift frequency depending on the direction of the target velocity. Quadrature detection has also featured in commercial instrumentation as a means to discriminate direction but frequency shifting by Bragg cell reigns supreme as the preferred method in today's commercial instrumentation.

Flow measurements in fluids received much attention through the 1960s and 70s but it was not until the latter part of this period that Brian Moss and his team at the Atomic Energy Research Establishment at Harwell in the UK gave serious consideration to vibration measurements on solid surfaces using the laser Doppler technique [6]. Graham Bank and his team at the loudspeaker manufacturer Celestion of Ipswich in the UK added a scanning head to the Harwell instrument to provide a “3-D isometric view of the complete vibrating surfaces of the test object frozen in time” [7]. The Harwell instrument was developed by Ometron and became the first commercially available scanning LDV system. Volkswagen in Germany followed Celestion's example with its own scanning system [8]. A further significant innovation from this period was the introduction of a parallel beam instrument [9] for torsional vibration measurement on rotors. By the end of the 1980s, the growing maturity of LDV was evidenced by there being four prominent instrument suppliers. Polytec was an established supplier of laser-based test instruments whose Laser Vibrometers had built an excellent reputation through successful application in the emerging hard disk industry. Dantec's core business was in fluid flow measurements when they introduced their Laser Vibrometer. Ometron's instrument worked exceptionally well at low light levels and was unique in using quadrature detection for direction discrimination. Finally, Brüel & Kjær, as a leading provider of traditional noise and vibration instrumentation, though, unlike their competitors, without any track record in laser-based instrumentation, released their first Laser Vibrometer. Polytec and Ometron were already offering scanning variants at this point and Polytec's range included a differential instrument.

A variety of optical configurations have been proposed in the scientific literature and by commercial providers. Fundamentally, however, instruments can be categorised as having a single probe beam for translational vibration measurement, or a pair of probe beams for differential vibration measurement. Multiple single beams or multiple pairs are of course possible. Scanning heads can be readily added to single beam instruments to automate the relocation of the beam in sequential point-to-point measurements across a structure. A pair of probe beams enables the classic differential measurement in which the relative velocity between two parts of a structure or device is determined. Configuration of the pair of beams as a V (cross-beams) is used for in-plane vibration measurement while a parallel beam arrangement enables angular vibration measurements including torsional vibrations. All instruments can be used for measurements on rotating and non-rotating structures. In all cases, orientation of the beam(s) determines the component of velocity measured with the corollary that it is the small but inevitable misalignments that usually determine measurement accuracy.

The first commercial instruments claimed particular advantages over traditional instrumentation, such as accelerometers or strain gauges, particular for measurements on hot, light, or rotating structures where traditional contacting instrumentation would change structural dynamics or be difficult to attach. Thin and soft structures could be added to the list but this would still neglect the special benefits now routinely exploited where high frequency operation, high spatial resolution or remote transducer operation is required. There are also several important limitations: limited access limits line of sight and makes measurement challenging, particularly on complicated 3D geometries, and measurement quality depends on the properties of the surface, which will be considered in the next section.

2. Laser speckle and pseudo-vibration

Despite 30 years or more of fairly relentless success for LDV, laser speckle has prevailed as its nemesis. When a coherent laser beam is incident on a surface that is optically rough, i.e. the surface roughness is large on the scale of the laser wavelength (from 633 nm for the red HeNe laser to 1500 nm for an infra-red laser), the component wavelets of the scattered light become dephased. This condition is satisfied by many of the surfaces encountered in traditional engineering structures. The dephased, but still coherent, wavelets interfere constructively and destructively, thus resulting in a chaotic distribution in backscatter of high and low intensities, referred to as a “speckle pattern”. Statistically the speckles have intensities with a negative exponential probability distribution, whilst their phases are uniformly distributed between 0 and 2π [10]. Light collection is generally a summation over several speckles. Small adjustments in the position of the incident beam are sometimes necessary to avoid low signal amplitude resulting either from low overall backscattered intensity (from an uncooperative surface) or from an unfavourable summation of speckles over the photodetector(s). Such an unfavourable summation might be through a dominance of darker speckles or, more subtly, as a consequence of the phasor addition of each speckle in the collection. However, it is when speckles start to move or evolve in response to target motions (other than directly in line with the laser beam) that speckle effects can really become problematic.

Summation on the photodetector over a changing population of speckles has two important effects on the Doppler signal: amplitude modulation and phase modulation. The amplitude modulation can mean the varying signal amplitude drops occasionally to a very low level and so-called ‘signal drop-outs’ occur. This is a longstanding [11] and ongoing [12,13] challenge. Even when adequate signal amplitude is maintained, however, dynamic changes in the sampled speckle pattern cause noise in the photodetector output phase which results in ‘speckle noise’ in the vibrometer output. Its precise origins have been explained [14] together with introduction of the more general term ‘pseudo-vibration’ [15].

The frequency content of pseudo-vibration is worthy of further consideration. Both signal drop-out (evident as spikes in the output) and pseudo-vibration (through changes in randomly phased speckles) contribute measurement noise across a broad frequency band. In particular, where the surface vibration (or whole body motion such as rotation) causing these effects is itself periodic, the resulting noise is pseudo-random with a spectrum comprising peaks at a fundamental frequency and higher order harmonics. These frequencies will generally be those of greatest interest making the noise difficult to distinguish from the genuine vibration. While decreasing the effects of signal drop-out is possible [12], particularly in the recent proposal of diversity reception [16], pseudo-vibration remains largely uncontrolled. To date the most successful mitigation has been to introduce a small side-to-side motion of the probe laser beam(s) sufficient to break the periodicity of the noise [17]. This spreads a slightly increased level of noise more evenly across the full spectrum, reducing spectral amplitudes at the important harmonic peaks at the expense of raised levels elsewhere in the spectrum. Manufacturers are yet to provide expected pseudo-vibration levels for their instruments but levels have been published in the literature in a format that can be widely applied by the user [18] and so-called ‘pseudo-vibration sensitivities’ have been quantified for a range of instruments and measurement scenarios [19]. A proper solution for pseudo-vibration, however, should be a priority for future research.