Making waves in vibration measurement with laser Doppler vibrometry

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ABSTRACT
The impact of the invention of the laser cannot be over-stated. In vibration and acoustics engineering, the laser Doppler vibrometer has revolutionised the means by which scientists and engineers can interpret and control the natural and man-made environment, both on and off the planet. Combining high sensitivity, dynamic and frequency ranges, non-invasiveness and high spatial resolution, laser Doppler vibrometers (LDVs) have received significant and increasing attention in both research and industry. This paper will briefly investigate the origins, working principles and evolution of LDVs, focusing on industrially relevant, practical applications. Particular focus will be on overcoming specific challenges associated with making successful measurement campaigns in challenging scenarios, including directly from rotating equipment and from vibrating platforms, a UTS topic of interest.

INTRODUCTION
With now well over 50 years of research and development into non-contact velocity measurement techniques based on the (laser) Doppler effect, the undeniably successful instrument variant that has become commonly known as the laser Doppler vibrometer (LDV) is no longer a novel device (Rothberg et al., 2017). Widely deployed both in research and in industry, the wide array of alternative optoelectronic configurations proposed, both in the scientific literature and by the commercial system manufacturers, has led to a veritable plethora of increasingly challenging and complex measurement applications. Many such applications have led to substantial contributions to the significant technological advances that have been realised in common engineered products and in more exclusive or elaborate domains alike. Examples include the near eradication of brake squeal in transport applications through to determination of the dynamics of insect antennae and appendages with sub-picometre resolution!

BRIEF FUNDAMENTALS, OPPORTUNITIES AND CHALLENGES
LDVs measure surface vibration velocity at a point in the direction of the incident laser beam by mixing a backscattered, frequency-shifted target with a mutually coherent reference beam in the internal interferometer arrangement. Specific optical arrangements enable resolution of up to all six degrees of freedom with or without rotation, of wholefield vibration when coupled with scanning mirrors or of micro-structures when coupled with microscopes. Traditionally HeNe (633 nm – red, visible) laser sources were commonplace; more recently diode (1540 nm – near infra-red, invisible) sources are becoming increasingly available. Commercially available systems are engineered to be laser safety class 2; for 633 nm this equates to a laser power of <= 1 mW while for 1540 nm this equates to <= 10 mW (infra-red is absorbed in water, of which the eye consists, hence extra power can be tolerated). Measurements do not have to be made with the instrument orthogonal to the target surface/vibration direction, provided the optical nature of the surface results in *some* light being backscattered into the instrument optics. Traditionally, surface treatment is employed to maximise the optical signal level. With the introduction of the higher power laser source, measurements can now be made on untreated target surfaces over distances up to ‘00s m.

Light scattered from such rough surfaces is, however, in the form of a speckle pattern in the far field. Speckles have varying amplitude *and* phase and as the target (or instrument) moves, the associated illumination of alternative surface scatterers results in the speckles moving across the photodetector introducing additional velocity content (i.e. noise) to the signal. Recent manufacturer developments have introduced multiple detector arrangements to combat this effect. A second challenge (which can be leveraged as a benefit) is sensitivity to path length fluctuations in the fluid medium through which the laser beam passes to and from the target surface. So-called Refracto-vibrometry makes use of this phenomenon to determine refractive index changing pressure fluctuations in water and in air. Finally, since LDVs make a measurement of the target surface vibration velocity *relative* to the instrument sensor head, any vibration of the *instrument* is indifferentiable from that of the *target*. Recent work has, however, resolved this even for scanning LDV (Halkon and Rothberg, 2020) and for transient vibration signals (Darwish et al., 2022). Ongoing efforts will apply these capabilities to various challenges of national importance.

MEASUREMENTS DIRECTLY FROM ROTATING EQUIPMENT

Their non-contact, non-invasive nature and inherent insensitivity to target shape variation (including shaft run-out) makes LDVs ideally suited to rotating machinery vibration measurements. Their dynamic and frequency ranges being at least comparable with alternative, typically contacting transducers and their direct measurement of the preferred parameter, velocity, further compounds the choice. The "icing on the cake" from an industrial application standpoint is the significantly reduced equipment downtime required and direct access to the vibrating component of interest, i.e. measurement of angular velocity directly from the shaft rather than having to infer or derive it from e.g. a measurement from a nearby strain gauge or from an accelerometer on a nearby non-rotating part (Halkon et al., 2020). Axial vibration measurement, for example for out-of-plane rotating blades, have long been of interest and the inspiration for increasingly sophisticated approaches including the continuous, shaft-synchronised scanning of the laser beam to directly extract blade vibration shapes. Torsional (or angular) vibration measurements, using a parallel beam pair optical set-up, is already well-established with applications including the use of pairs of instruments to yield differential vibration measurement outcomes such as shaft twist/torque, belt stretch and gear pair backlash for example. Radial and bending (pitch/yaw) measurements have also been successfully demonstrated, including with the inherent sensitivity to the orthogonal vibration resolved (except for the synchronous frequency component which remains a challenge). With all scenarios, there are important practical considerations for the user and these have been addressed in detail in recent years (Rothberg et al., 2017; Halkon et al., 2020).

MEASUREMENTS FROM VIBRATING PLATFORMS

The 100% sensitivity of an LDV – a *relative* vibration transducer – to its own vibration can be simply shown by mounting the sensor head to a shaker with the vibrating and sensitive axes aligned. Similarly, sensitivity to vibration of optical components used to steer the laser beam is readily demonstrated. Making use of a general, vector-based model of the measured velocity, practical schemes have been conceived and experimentally implemented to offer full compensation for the additional velocity in the LDV signal. Target vibration signals, even when fully masked and even in the presence of scanning of the laser beam, have been recovered. An *absolute* vibration measurement, akin to that achieved with an accelerometer but without the need to instrument the target and with all of the benefits of remote, non-invasive high dynamic/frequency ranges and spatial resolution is obtained. Focus has been on offering accessible solutions to the practising vibration engineer with the correction measurement(s), therefore, being realised with contacting transducers carefully mounted to the vibrating sensor head, for example as shown in Fig 1. Signal processing techniques have evolved from being frequency-domain based, suitable for application to statistically stationary vibrations, through to, more recently, time-domain based, suitable for vibrations that are transient in nature for example human speech signals and structural response to ambient excitation. The potential that is unlocked by harnessing this capability has applications that are wide-ranging and significant.

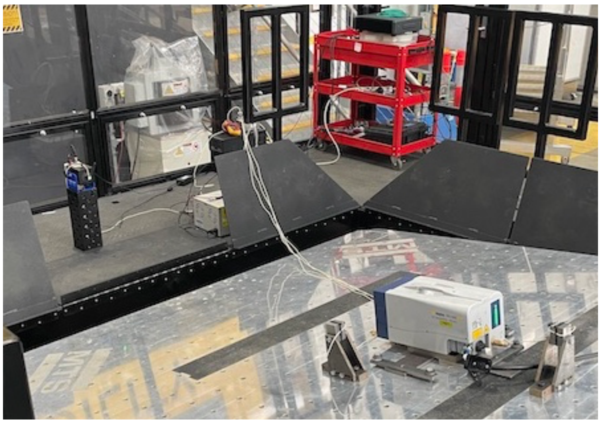

Figure 1: Experimental arrangement showing 6 DoF base vibration compensation at UTS Tech Lab

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