Practical Aspects of Successful Laser Doppler Vibrometry based Measurements

Kevin Bo GATZWILLER[1], Kevin Bernard GINN[1], A. BETTS[2], Steve MOREL[2]
[1] Brüel & Kjær Sound and Vibration Measurement A/S, Skodsborgvej 307, DK-2850 Nærum, Denmark
[2] Image Automation Ltd, Kelvin House, Worsley Bridge Road, London SE26 5BX, England

Laser Doppler Vibrometry provides for highly accurate and versatile non-contact vibration transduction in applications where it is impossible or undesirable to mount a vibration transducer onto a vibrating object. Typical applications include vibration measurements on: rotating surfaces, targets submerged in water, light weight structures, remote targets and targets behind layers of glass. Use of Laser Doppler Vibrometry in such applications requires attention to a number of practical issues that are of paramount importance for a successful result. This paper will discuss these issues in detail and show how to deal with them such that measurement accuracy, precision and reliability is maximized. Furthermore, practical single point Laser Doppler Vibrometry applications will be used to highlight the theoretical discussions.

Keywords: **Non-contact, Measurement, Vibration, Laser Doppler Vibrometer, Transducer, Doppler Effect**

1. INTRODUCTION

Laser Doppler Vibrometry (LDV) has become well established as an accurate, fast, efficient and cost-effective means of measuring mechanical vibration. Not only does LDV excel in many applications due to lack of physical contact with the test specimen, but also, by reason of the high optical sensitivity of modern LDVs, the surface measured does not need to be specially modified or prepared in advance.

LDV based measurements have been successfully used in a number of different applications, including vibration measurements on: Light structures, hot structures, inaccessible parts, surfaces which must not be marked, very small surfaces, high voltage surfaces, radioactive surfaces, living tissue, wet surfaces, rotating surfaces (sides or ends of shafts), continuous surfaces moving with constant velocity (e.g measurement of the speed of a rotating disc) and shock. However, it is not just in demanding RDT&E applications that Laser Doppler Vibrometers have been prevailing. Increasingly, LDV instruments are finding a new role in quality control. Examining the resonance characteristics of a metal casting, for example, can indicate whether the component has been machined correctly. Laser Doppler Vibrometry sensing is a robust technique for the measurement of mechanical vibration without surface contact. A key additional advantage of being non-contact is that LDV instruments can investigate panels and components considered to be inaccessible using other techniques.

LDV's, can be set up quickly and require minimal preparation or modification of the part under test. Current designs are compact, robust, cost effective and can be used as a simple non-contact transducer or as part of a full modal analysis solution. Finally, extremely wide stand-off range can be achieved with LDVs based upon the Homodyne principle, providing measurement capabilities up to a distance of over 200m (650 ft).

2. OPERATING PRINCIPLE OF LDVs

Laser Doppler Vibrometers are based on an interferometer such as a Mach-Zender, Fabry-Perot, or Michelson interferometer. The latter is used in the Brüel & Kjær Laser Doppler Vibrometers Types 8329, 8333 and 8334 and will be used here as examples of the operating principle of LDVs.

In a Michelson interferometer, a laser beam is divided into a reference beam and a signal beam. The signal beam is directed onto a vibrating test structure, and the back-reflected light is recombined with the internal reference beam. When the test structure moves, the frequency of the signal beam is shifted, resulting in intensity modulation of the recombined beam due to interference between the reference and signal beams. One complete cycle of the intensity modulation corresponds to a surface movement of $\lambda/2 = 0.316$ mm, half the wavelength of the helium neon laser source (where λ is the wavelength of the source, 0.633 mm). The frequency of this modulation (referred to as the Doppler frequency, F_d) is given by $F_d = 2v/\lambda$, where v is the surface velocity. The recombined light is split into two paths, and a quarter-wave plate used so that the two signals are in quadrature (sine and cosine) allowing the direction of motion to be determined. This allows both the speed and direction of motion to be determined. A balanced detection scheme, with two detectors in each channel, is used for low noise and high sensitivity.

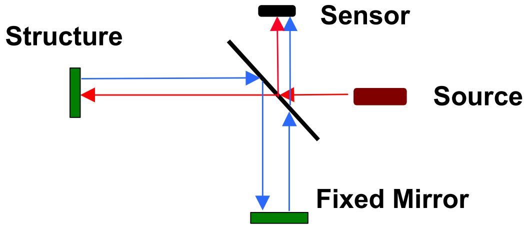

Fig.1 Schematic overview of a Michelson Interferometer. Detector principle is Homodyning. In a practical LDV implementation, "Sensor" would be a photodetector and "Source" would be a laser.

Hardware implementation of this measurement principle in Laser Doppler Vibrometers Types 8329, 8333 and 8334 yields a rugged and environmentally tolerant instrument incorporating no perturbing acoustooptic devices (i.e., Bragg cells).

3. MEASURING ON HIGH TEMPERATURE SURFACES

As previously discussed, the key application area of a single point Laser Doppler Vibrometer, is the ability to measure on targets that are difficult or impossible to access by traditional contact transducers. One such measurement situation is obviously occurring when the target is extremely hot - above temperatures where any contact vibration transducer can be used. At such high temperatures, the target may glow – emitting visible red/white light. What happens with an LDV measurement when this occurs?

During measurement, an LDV is "looking" for wave lengths of exactly 633 nm. The entire optical system is based upon processing this single wave length - all other wave lengths are effectively filtered out (Laser Doppler Vibrometers Types 8329, 8333 and 8334 are carefully designed so that filters are not necessary – the coatings of the optics suffice).

This means that it is highly unlikely that any infrared wave lengths can interfere with the measurement - unless radiation at frequencies of exactly 633 nm exists together with the infrared waves. And even if that latter is the case, the intensity backscattered into the Laser Doppler Vibrometers Types 8329, 8333 and 8334 due to this added "noise" will generally be extremely low compared to intensity due to the 633 nm laser light radiated from the instrument. Unlike the wanted signal, the glow will not be coherent, therefore it can only degrade fringe content, and increase the noise level. In the extreme case it would saturate the detector (with DC), leaving no headroom for the fringes (AC).

Any "noise" signals at 633 nm will therefore have to be very high intensity in order to give confusion at the output from the LDV. There are many practical examples that demonstrate this very high collector efficiency. The classic example is hot engine/exhaust measurements, where highly accurate and reliable vibration measurements can be conducted without any such "noise" problems.

4. MEASURING ON ROTATING TARGETS

Laser Doppler Vibrometers Types 8329, 8333 and 8334 can be used to measure lateral vibrations (unbalance) of rotating shafts. Unlike proximity probes, the LDV based measurement does not interpret any changes in the geometry of the shaft as a vibration. Imperfections on the shafts surface will not influence the measurement. The laser will only detect vibrations of the centre of rotation of the shaft, in the direction of the laser beam. This may not be intuitively obvious. The following mathematical proof will hopefully help.

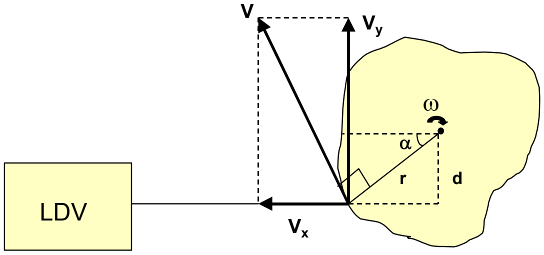

Fig.1. Laser Doppler Vibrometers Types 8329, 8333 and 8334 do not interpret changes in the distance to the surface of an irregularly shaped target as vibration. When correctly aimed, only axial vibrations will be detected.

Consider a shaft with an irregular geometry, as shown in Fig.6. The shaft is rotating at an angular frequency of w, corresponding to a tangential velocity of V at the point where the laser beam is incident, at a distance r from the axis of rotation, and at a vertical distance d below it. The tangential velocity can be resolved into two components Vx, and Vy perpendicular to each other. The component in the direction of the beam, Vx is then expressed as

$$Vx = V\sin\alpha \quad \text{where } \alpha \text{ is as indicated.}$$

Since $V = r\omega$ then

$$Vx = r\omega\sin\alpha$$

r can also be expressed in terms of α and d, as

$$r = \frac{d}{\sin\alpha}$$

Therefore

$$V_x = \frac{d\omega \sin\alpha}{\sin\alpha} = d\omega$$

which is wholly independent of r.

Consequently, for a shaft with no axial vibration any Doppler shift in the laser beam is proportional only to the shaft rotation speed ω, which is a DC component, and the distance "off axis" of the laser beam. The laser does not interpret the changing distance to the target surface as a vibration.

A practical point results from this analysis. When making axial vibration measurements on rotating shafts it is important to ensure that d is zero or nearly zero by carefully aligning the laser beam so that it lies in an imaginary straight line passing through the centre of the shaft. This is important since the DC rotation component can often have considerably larger magnitude than the axial vibration itself, and in some cases may overload the laser doppler vibrometer.

5. NOISE FLOOR WHEN MEASURING ON ROTATING TARGETS

The ability of LDVs to measure low level velocities is dependent on the target's surface velocity characteristics. If the particle scatterers within the laser beam spot only have a velocity in the direction of the incident laser beam then the laser speckle pattern which they form on the photo-detector surface remains essentially stationary and no Doppler frequency broadenings occur.

However, if the scatterers move out of the beam and are replaced by others, such as when measuring on a rotating component, the speckle pattern (see one of the following sections dealing with the issue of speckle) on the photodetector will move.

This has two effects: 1. The noise floor level of the LDV output will be raised. 2. Peaks associated with the rotational speed of the shaft will appear – and, if the shaft also exhibits torsional vibration, peaks at the torsional frequencies will appear as well. The latter will, as discussed in the foregoing section, only apply if the LDV measures off the centre of rotation (that is, $d \neq 0$ in Fig. 1)

The speckle pattern produced by the target surface will also move on the photo-detector if the particle scatterers "tilt" within the laser spot. In particular at high amplitudes of linear vibration, all target surfaces have an inherent tilt associated with the motion. This means that there will be a rise in the noise floor of the output from the LDV in such circumstances as well.

Changes to the lower measurement limit of a Laser Doppler Vibrometer due to target rotation are dependent on the rotational speed. Therefore it is not possible to accurately specify the noise floor of the instrument under such conditions. Consequently, the specifications of Laser Doppler Vibrometers Types 8329, 8333 and 8334 are only concerned with targets which do not rotate.

6. MEASURING THROUGH LAYERS OF GLASS

One of the important features of an LDV, is the ability to measure at a target behind one or several layers of glass. The usefulness of this feature in a practical measurement situation, is significantly magnified for an LDV that provides for high optical sensitivity. This obviously means that even a poorly reflective target can back-scatter sufficient energy. There are four points to bear in mind when doing this:

1) The window should be on a slight tilt to the sensor (say one or two degrees). This prevents reflections from the window entering the LDV. Bear in mind that this needs to allow for the cone-angle of ± 12.5 degrees for a scanning vibrometer. Remember that uncoated glass typically reflects 4% per surface, which is often much greater than the back-scatter from the target.

2) The window itself should be flat - like ordinary float glass. Otherwise, it may be difficult to achieve the best spot size (because a non-flat window will act like a lens).

3) The proximity of the LDV sensor to the window should be less than that of the target to the window. This is so that the beam is not coming into focus on the window itself (where the sensor would detect both movements in the window and become sensitive to dirt on the window.)

4) The window must be clean. This is to prevent problems with scatter and loss of signal. If the window is very dirty and cannot be cleaned it may need replacing.

The following Fig. 2 summarises the points above.

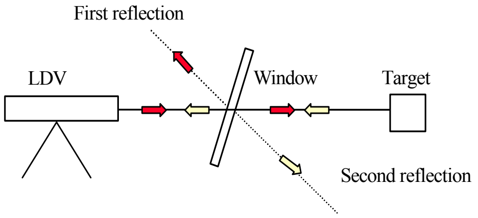

Fig.2 A typical set-up with one of the Laser Doppler Vibrometers Types 8329, 8333 or 8334 measuring

through one layer of glass. The LDV is tilted to avoid measuring on reflections.

If possible, whenever measuring through glass and other non-air media, it is recommended to place a handheld calibrator as the target *prior* to the actual measurement and then perform a measurement with the calibrator turned on. Now, it is known exactly what should be measured. It is advantagous to perform this measurement in the time domain because any noise added to the signal is immediately seen here. If this “medium validation” measurement is performed with the expected result, it is determined that the medium (glass, water, etc.) does not interfere with the subsequent “real” measurement. Normally, any such transparent non-air medium does not pose problems.

7. SPECKLE NOISE

When the measuring laser beam illuminates an optically rough (in terms of the wavelengths of light) surface, the light reflected back to the LDV sensor has a granular appearance, referred to as a laser speckle pattern. The smaller the spot on the test surface, the coarser the speckle pattern. As the measuring beam moves to a different point on the test surface the speckle pattern changes completely. It is this effect which gives rise to so-called laser speckle noise. This has the effect of causing the Doppler signals to vary in amplitude, as seen in Fig. 3.

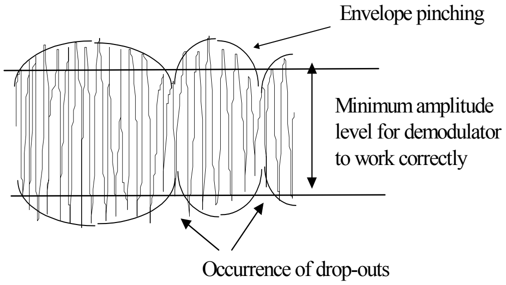

Fig. 3. Relationship between Doppler signal and drop-outs. When the Doppler signal amplitude comes below the threshold value, drop-outs will occur.

Speckle occurrence is affected by displacement. The speckle pattern will vary to a greater extent as displacement increases in the direction of the laser beam. Likewise a lateral displacement, perpendicular to the laser beam, will introduce further speckle. Thus alignment of the LDV, so that the instrument is measuring perpendicular to the surface, minimizes speckle noise.

When the measuring laser beam is correctly focused, the Doppler signal amplitude is maximized (which obviously is advantageous), but subject to large variations when the measuring beam moves across the test surface because the speckle pattern is at its most coarse, and the intensity of light collected by the detection system fluctuates strongly (which is not good from a speckle noise point of view). In a practical measurement situation, one has normally to find a compromise between the need for sufficient intensity at the photo-detector and speckle “averaging” by slightly defocusing.

An LDV operates like an FM radio receiver, with high intrinsic immunity to fluctuations in Doppler signal amplitude - the vibration information is associated with the frequency modulation while the amplitude modulation is associated only with the amount of light being back-scattered into the LDV.

However, the demodulation circuits cannot function correctly unless the Doppler signal amplitude exceeds a minimum threshold value. Failure of the demodulation circuits to derive an analogue velocity waveform from a Doppler signal of insufficient amplitude is termed "drop-out". Fig. 4 shows good and bad velocity outputs, “drop-out” is observed in the bad velocity signal.

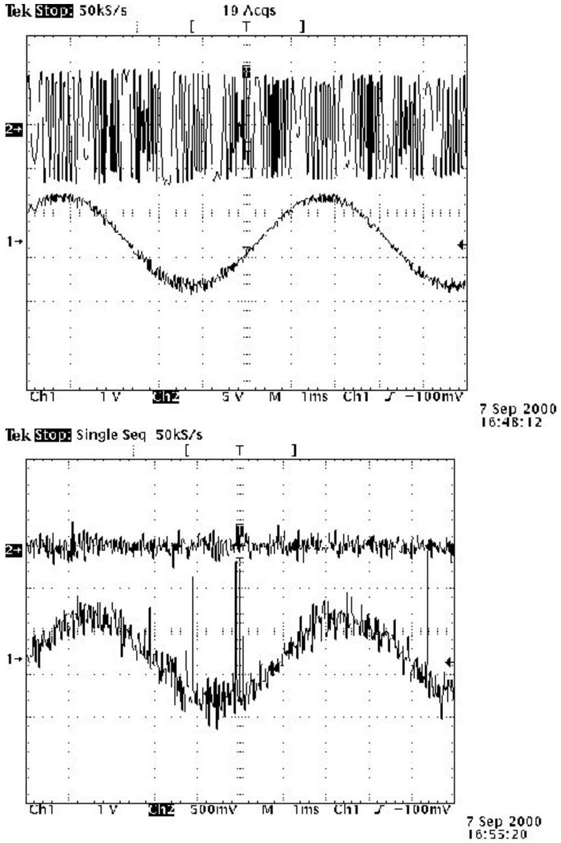

Figure 4. Two print-outs from an analyzer showing good and bad instantaneous velocity outputs from an LDV. In both print-outs, top curve shows the “raw” Doppler signal and bottom curve shows the

concomitant instantaneous velocity. The second print-out shows significant drop-outs in the demodulated velocity output signal.

Since drop-out is a consequence of insufficient Doppler signal amplitude, it is most likely to occur when operating conditions are least favorable, that is, the working distance is long or between optimum values, the test surface scatters very little light back towards the sensor, the measuring beam is out of focus. Improvements to any of these operating conditions will reduce drop-out effects.

Analyzing the output from a single point LDV in the frequency domain, the speckle noise/drop-out phenomena will manifest themselves as sudden "rises" of the noise floor (naturally, the energy content of the transient spikes will be broad-banded) potentially masking the signal one is trying to measure. More often than not, this is rather annoying and the user has to attempt to control the occurrence of speckle noise to ensure a successful measurement.

8. WORKING WITH MIRRORS

In a LDV based measurement, a mirror can serve two purposes: Firstly, it allows the user to "bend" the laser beam, and secondly, it extends the depth of focus because of the increase in working – stand-off – distance. The Brüel & Kjær mirror set UA 1554 has been specifically designed for use with a single point LDV. For such an LDV measurement application, mirror(s) need to be flat to be diffraction limited, this simply means that ordinary mirrors won't work very well. Ideally one would want a flatness of λ/8 (where λ is the wavelength of the laser light) over the area of incidence of the beam on the mirror. In practice there is no need for the whole mirror to be this flat, only the area of incidence. On the Laser Doppler Vibrometers Types 8329, 8333 and 8334 , which have a maximum aperture of 11mm, this would be up to 11 mm diameter maximum (11*√2 mm for a mirror at 45 degrees), otherwise you wouldn't be able to achieve focus on the specimen.

The other point to consider is reflectivity. This should be as high as possible to maintain the most amount of optical intensity back-scattered into the LDV. Obviously, the higher number of mirrors needed, the greater this issue will become.

The Mirror Kit Type UA 1554 has been designed with both issues in mind (diffraction and reflectivity), ensuring optimum performance and is therefore an obvious choice in applications requiring one or several mirrors.

9. NO MASS LOADING WHEN MEASURING WITH AN LDV

When a contact transducer, such as an accelerometer, is mounted onto a vibrating specimen the increase in overall mass, combined with a change in the local stiffness, will inevitably alter the dynamic properties of the structure. Moreover, the added mass of the contact transducer will also provide for a reduction in the resonance frequencies of the structure. Depending upon the application, these issues may have far reaching consequences if they are not dealt with properly.

A key benefit of an LDV based measurement is that neither of these issues will occur - the result is a unique increase in overall measurement accuracy and the assurance that even when measuring on a large number of Degrees-of-Freedom (DOF), inherently, larger changes in dynamic properties will not occur. Obviously, the heavier the contact transducer(s) mounted on the test specemen, the more significant mass loading will become. Fig. 5 shows the theoretical relationship between accelerometer mass and the thickness of a plate for a specified change in the acceleration level over a specified frequency range.

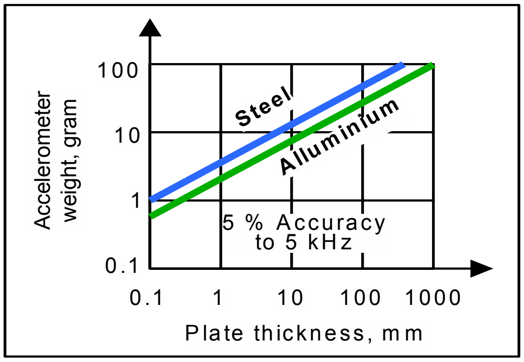

Fig. 5. Theoretical relationship between accelerometer mass and the thickness of a plate for a specified change in the acceleration level over a specified frequency range.

10. MEASURING AT HIGH ALTITUDES

Laser Doppler Vibrometers Types 8329, 8333 and 8334 have been specified to measure at altitudes up to 3,000 m (10,000 ft). It is, however, possible to perform measurements at higher altitudes. The following will highlight an important issue associated with the use of Types 8329, 8333 and 8334 at altitudes higher than 3,000 m (10,000 ft)

Laser Doppler Vibrometers Types 8329, 8333 and 8334 uses a HeNe gas laser as light source. It is the HeNe gas laser that causes the maximum altitude restriction. The laser is specified up to 10,000 ft, i.e. ca. 3,000 m. The seals of a gas laser are not 100% tight. This is also the reason why it is generally recommended to operate a gas laser at least once per week for one hour in order to keep it operational for the maximum period of time. At higher altitudes the ambient air pressure is lower and He-Ne gas will leak easier from the laser.

Therefore, if Laser Doppler Vibrometers Types 8329, 8333 and 8334 are to be used at altitudes of more than 3000 m, the LDV should be used often (e.g. just switch on the LDV every second day and leave it on for about 15 min) and be aware that the lifetime of the laser might become less than the standard >10,000 hours. Other components than the laser will not be effected when measuring at high altitudes.

11. MAXIMUM OPERATING TEMPERATURE

Laser Doppler Vibrometers Types 8329, 8333 and 8334 are designed to minimise the effects of temperature variation. Performance is guaranteed for typical operating conditions (for example from +5˚C to +35˚C for the Type 8329), and LDVs may be used with care to obtain measurements even outside this range. HeNe laser power supplies typically incorporate over-temperature sensors, and automatically shut down when overheating is detected (usually at around 45˚C). This should be avoided where possible, but does not itself cause any damage. The instrument should be switched off and allowed to cool down; then it will operate normally again.

All the electronic components in the Types 8329, 8333 and 8334 are rated to temperatures higher than that of the HeNe laser. However, there are potential temperature stability issues with the optics in going beyond the stated maximum operating temperature range. The LDV will not stop functioning but performance may degrade. The performance of the frequency-to-voltage converter inside the LDV will not be affected, so accuracy will not be impaired, but dynamic range will be reduced.

12. LASER COHERENCE REPEAT LENGTH

The laser coherence repeat length is the required distance of the target from the laser cavity to ensure stability of the laser beam at the target.

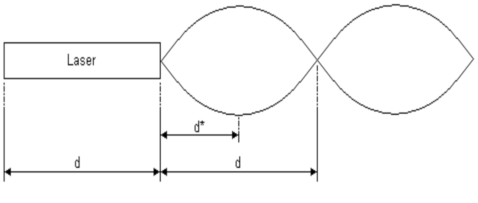

Figure 6. Coherence repeat length of laser

At optimum working distances d, the Doppler signal is of optimum amplitude and stable with time. At the intermediate distances d*, the Doppler signal amplitude varies between large and small values.

Laser coherence occurs at distances where the light frequencies emitted by the laser are all in phase with one another. This occurs at distances which are multiples of the laser cavity length (d, figure 5). At intermediate distances, beating will occur between the different frequencies. The cycle time from high amplitude to low amplitude and back again increases dramatically as the laser warms up. Before the laser is fully warmed up this can be from a few seconds to a minute or so, and the rapid fluctuation is a quite obvious indicator that the set up is sub-optimal. As the laser reaches normal operating temperature the cycle time becomes hours

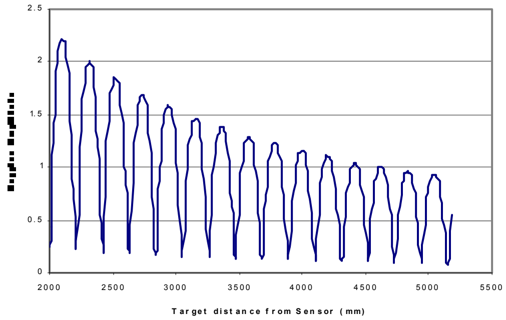

Figure 7. Variation in Doppler amplitude according to distance

Figure 7 shows the variation in laser power over distance for a matt white surface. The cyclical nature of the curve is an indication of the stability of the Doppler amplitude, as related to the laser cavity length. Each peak thus defines an optimum good working distance while each trough defines a worst-case working distance.

The overall Doppler amplitude is inversely proportional to the distance from the LDV sensor to the target. Thus:

$$V_{doppler} \propto 1/r$$

Doubling the target distance will result in a halving of the Doppler amplitude. In the chart above, the Doppler amplitude at 2.5 m is approximately 1.8 V, whereas at 5.0 m the amplitude is reduced to 0.9 V.

Different types of finishes and surfaces will produce Doppler signals of differing amplitudes for the same working distance, due to variations in the physical properties of different surfaces. However, the general concepts regarding working distances and the inverse relationship between distance and relative Doppler amplitude apply.

In many cases it is not necessary to set up a measurement to an exact working distances in order to obtain a stable velocity output. This is unavoidable for non-flat structures spanning more than one optimum working distance. In these cases there is little to be gained in favouring any particular working distance. Where the velocity output exhibits "dropout", then setting the LDV sensor to a good working distance will improve the stability of the sensor.

Where it is necessary to configure the LDV sensor for a good working distance, then the optimum distances are calculated by the equation:

Working distance = laser cavity length + (n x Y mm)

where:

n is an integer ≥ 1

Y= 138.5 mm - length of the laser cavity tube inside Type 8329

Y = 210 mm - length of the laser cavity tube inside Types 8333 and 8334

Note that HeNe laser manufacturers allow a tolerance of typically around +/-1% in the cavity length. The above formula therefore gives a useful figure for distances of less than 5 metres, while the instruments themselves can be used at up to 200m - depending upon the application. At over 5m or so it is better to find a good distance by a practical test; set the equipment up at one position, and then move up to one repeat length towards (or away from) the target in order to find where best results are obtained

13. CONCLUSION

Successful LDV measurements depends upon a number of pratical issues that have to be dealt with in order to maximize signal accuracy, consistency and reliabilty. It has been seen how to deal with the most important issues governing signal drop-outs: Stand-off distance, focus, target reflective quality and laser warm-up time. Furthermore, practical issues related to achieving best measurement results when measuring through layers of glass, when measuring on rotating targets and when measuring at high altitudes has been discussed. Finally, it has been shown that an LDV based measurement, unlike a traditional accelerometer based measurement, is inherently insensitive to the mass loading effect. A mathematical model was used to quantify the mass loading effect when mounting an accelerometer with a certain weight.

14. REFERENCES

[1] Operating Manual, Ometron VH300+