From The Big Bang To Cleaner Teeth – Doppler Shift – A Practical Engineering Tool

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Introduction. Many basic engineering techniques rely on fundamental science that is so well embedded and accepted, that it becomes effectively ‘invisible’ to the average user. Doppler Shift is one such physical phenomenon that is widely used throughout science and engineering, but often without being noticed.

Probably the most familiar scientific application of Doppler is the measurement of the speed of stars, to identify the expansion of the Universe since the ‘Big Bang’. But in engineering and R&D, it can and is being used as a powerful vibration measurement tool. Using laser-based interferometric techniques, with Doppler Frequency Shifting in one path of the interferometer, velocities and displacements as subtle as those of the hearing mechanisms of flies and as fierce as the motion of Formula 1 engines valves can be measured.

This paper describes the basics of Doppler Shift and its use within Laser Doppler Vibration and Velocity measurement instruments. It will cover the extremely wide performance capabilities of the technique and the practical advantages of such instruments, with some practical examples of how and where they are currently being used. Of these examples, many are unique and would not be practical or even feasible without the availability of such tools.

Basics:
In the 19th century, Christian Andreas Doppler observed the effect that now carries his name. He proposed that there is an ‘apparent change in frequency and wavelength of a wave that is perceived by an observer moving relative to the source of the waves’ (i).

In practice, this effect may be seen in waves in front of a vehicle or vessel moving through water. If the water is flowing against the moving vehicle, the waves are compressed and of shorter wavelength relative to those in static water. If the flow is in the direction of the vehicle, the wavelength is longer than in static water.
It can also be observed for frequencies and wavelengths in the audible sound range, such as the rising and falling tone of sound waves coming from a train whistle or car horn as it travels towards, passes and then moves away from the observer.

The Doppler effect can also be observed optically. For example, astronomers use the apparent blue or red colour shift of stars to calculate their velocity towards or away from the Earth, tracing star movements back to the ‘Big Bang’ at the start of the Universe.

Note that the speed is relative, because the Earth is also moving and hence has a velocity related frequency shift of its own. Effectively the same basic method of velocity measurement is utilised within a frequency-shifted Laser Doppler Interferometer.

**Laser Doppler Interferometry:**
In a conventional laser interferometer, coherent light travels from a source and is separated into two paths, one used as a measurement arm and one as a reference arm, then recombined at a detector, where differences in the two paths show as interference fringing effects. These differences are subtle distance changes, which, observed over time provide velocity information, but can be difficult to interpret especially with relation to directionality.
By superimposing a known ‘carrier’ frequency modulation into the reference arm, relative plus/minus frequency shifts can easily be measured to provide velocity information. This is the configuration used in a range of commercial heterodyne laser vibrometers.

The carrier frequency is selected to provide better velocity resolution than could be obtained by comparing the signal against the laser frequency (~10^{14} Hz). Additionally, by exploiting polarisation effects, direct displacement changes can also be obtained.

Such instruments measure (out-of-plane) motion along the axis of the laser beam and offer a very wide dynamic range, being able to resolve sub-μm/s velocities (up to ±30 m/s), ultra small displacements (pm to >± 100 mm) and frequencies over the near-DC to 30 MHz range. Versions using triple beams can give tri-axis vibrational information, including the scanning and mapping of whole surfaces, to understand complex structural vibration behaviour.

An associated technique, Laser Surface Velocimetry, uses converging beams from a split single laser source to measure inplane or transverse motion.
Again, Doppler frequency shifting is a key part of the design, enabling speed and vibrational velocity to be measured down to zero or reverse speeds. The method is immune to the colour or temperature of the test piece, so it has found wide acceptance in the steel, paper and other industries for the measurement of hot, cold, rough or otherwise ‘difficult’ surface materials.

Both Laser Doppler Vibrometers (LDV’s) and Laser Surface Velocimeters (LSV’s) have the major advantages of being non-contact and hence zero-mass loading (important for small light structures), work from a variety of ‘normal’ engineering surfaces and are easily targeted, operated and easy to use.

With such a wide performance and advantages for working from otherwise ‘difficult’ or challenging structures, it will come as no surprise that such instruments are being exploited in many different engineering applications.

Application Examples:
Because of the small size of the measurement laser spot (typically ~100 µm at ~1m standoff, down to 1 µm through a microscope), LDV’s lend themselves to measuring from extremely small, lightweight structures.

Examples in the natural world include work on dragonflies and moths to characterise the vibrational deflection shapes of their wings (used for developing remote surveillance ‘insects’ for military and ‘search & rescue’ tasks) and the response of their sensory organs. Micro sensors based on the same technology employed by crickets and spiders to sense predators and prey are being developed (3).

A better understanding of the hearing function has been achieved using LDV, leading to improvements ENT surgical techniques and smaller and better hearing aids resulting from studies of human and insect hearing (4, 5, 6, 7).
Motions can be very small. For example, the human stapes bone (saddle & anvil) in the middle ear moves approximately 2nm under normal volume conditions. The hair cells in the cochlear (inner ear) move fractions of this value, typically around 100 picometers (1 ten millionth of a millimetre!). Velocities are down to a few microns/second. Both can be readily resolved with laser Doppler vibrometry.

In manufacturing, there are many examples of movements at the same scale. The successful development of PC and laptop hard-drives has relied heavily on laser vibrometry to optimise the basic design of the dynamics of the data read/write head, disk rotation stability and shock resistance of the whole assembly\(^{(8)}\). Data projectors use resonating micro-tilt mirrors operating in the ultrasonic frequency range as a core to their operation\(^{(9)}\).

But not all laser Doppler-based vibration measurements are so subtle, with sub-micron movements.

Current Formula 1 engines rev to ~20,000 rpm and this causes extreme stress on the rotating and other linear motion mechanical parts of the engine. A typical F1 head has 4 valves (2 inlet/2 exhaust) that open and close ~8mm, over 160 times a second.
Problems that can present include not following the cam profile accurately (leading to excess lift or ‘bouncing’ off the top and closing side of the cam) and seating bounce and/or overstressing of the valve stem at closure. The use of a pair of differential LDV’s is now the norm for developing such engines \(^{(10)}\). One laser measures the valve motion, with the second monitoring and subtracting the background vibration of the cylinder block. If the two laser spots are targeted at the centre and edge of the valve head, then ‘mushrooming’ distortion can be seen and measured.

LDV is also used for NVH (Noise, Vibration and Harshness) testing and optimisation of vehicles, both ground and air based.

Probably the most extreme example of NVH was the destructive vibration affecting the rear panels of the Thrust SSC land speed recorder holder mentioned above. The panels were subjected to high temperatures and \(~170\) dBA of noise, which was causing cracks in, and pulling rivets from, the titanium alloy panels \(^{(11)}\). These were so severe that it was estimated that, when the record was captured, the vehicle only had a further three possible runs before it would be forced to retire.

Laser Doppler Vibrometry can now offer a test procedure for assessing such stress and damage cracks in metal and composite panels \(^{(12, 13)}\). Using scanning techniques and ultrasonic excitation, a map of the suspect surface is measured and the resulting data and images can highlight both the location and extent of the damage.
This can provide a quick and effective condition monitoring method for the inspection of airframes, vessels and vehicles.

One unusual and uniquely effective use of LDV has been in the assessment and development of motorised toothbrushes, drills and ultrasonic dental scalers \(^{14}\).

Dentists now commonly use scalers for the removal of plaque and other scale on teeth, being more effective and gentler than traditional scrapers, particularly near and below the gum line. But early designs tended to fail prematurely due to suspected mis-location of the critical vibration nodes and anti-nodes.

Attempts were made to try and analyse the motion using high-speed video microscopy, but the true behaviour was finally seen using scanning Laser Doppler Vibrometry, initially in one axis and subsequently using 3D LDV.

This work \(^{3}\) showed that the scaler probes had a vibration anti-node or ‘hotspot’ at the bend, rather than at the tip, of the probe that was the cause of the early failure. Vibration data and modelling was used to adjust the scalers’ length, shape and vibrational frequency for better efficiency, lifetime, and effectiveness.
The same LDV methods were used on motorised toothbrushes to visualise and measure head movement, both in loaded and unloaded conditions. Again, by careful optimisation of the design, improved cleaning of teeth is achieved.

Conclusion:
By basing a testing instrument (Laser Vibrometry) on a basic physical phenomenon (Doppler Shift), it has been possible to build a practical tool with applications in a wide range of research, development, quality assurance, faultfinding and production testing. It is equally applicable to automotive, aerospace, civil, mechanical, medical and natural engineering and any other discipline where motion or vibration need to be assessed or measured.

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(1) http://en.wikipedia.org/wiki/Doppler_effect
(2) http://www.polytec.com/eur/158.asp
(3) http://www.cilia-bionics.org/
(4) Centre for Biomimetics, Reading University
(5) Guys & St Thomas Hospital, London
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And to colleagues and customers not mentioned above.