Principle of Laser Doppler Vibrometry

A laser-Doppler Vibrometer (e.g., Polytec’s Micro Motion Analyzer 400) detects the Doppler shift of laser light, that is reflected from the test object ("O") shown in the following figure.


**Figure 1:** Michelson interferometer - principle of operation (Polytec, Inc.; http://www.polytec.com/usa/158_942.asp).

A laser beam is divided at a beam splitter into a measurement beam (passing straight through the splitter towards the tested object "O") and a reference beam, which is deflected 90° upwards and propagates towards the reference mirror "RM". Both beams return reflected to the beam splitter. Now 50% of energy in the reference beam passes straight through the splitter while 50% of the measurement beam is reflected 90° downwards. The beams interfere in the path between the splitter and the detector. The distances the light travels between the beam splitter and each reflecting surface are $x_R(t)$ and $x_M(t)$ for the reference mirror "RM" and object "O" respectively.

The corresponding optical phase of the beams in the interferometer is:
reference: \( \phi_R(t) = 2 \frac{2\pi}{\lambda} x_R(t) \); measurement: \( \phi_M(t) = 2 \frac{2\pi}{\lambda} x_M(t) \)

which gives the phase difference

\[
\phi(t) = \phi_R(t) - \phi_M(t) = 2 \frac{2\pi}{\lambda} [ x_R(t) - x_M(t) ] = 4\pi \frac{\Delta L(t)}{\lambda}
\]

The photodetector measures the time dependant intensity \( I(t) \) at the point where the measurement and reference beams interfere

\[
I(t) = I_M I_R R + 2 K \sqrt{I_R I_M R} \cos[2\pi t f_o + \phi(t)] = I_M I_R R + 2 K \sqrt{I_R I_M R} \cos[2\pi f_o t + 4\pi \frac{\Delta L(t)}{\lambda}]
\]

where \( I_R \) and \( I_M \) are the intensities of the reference and measurement beams, \( K \) is a mixing efficiency coefficient and \( R \) is the effective reflectivity of the surface.

If the difference of the light path lengths, \( \Delta L(t) \), changes continuously, the light intensity \( I(t) \) varies in a periodic manner, according to above equation. A displacement \( \Delta L(t) = \lambda/2 \) causes the phase change \( \phi(t) = 2\pi \).

The rate of change of phase \( \phi(t) \) is proportional to the rate of change of position which is the velocity \( v(t) \) of the vibrating surface. This relationship is commonly expressed as a formula for the Doppler frequency \( f_D \):

\[
f_D = 2 \frac{v(\xi)}{\lambda}
\]

Due to the sinusoidal nature of the signal on the detector's output, a direction of the velocity \( v(t) \) can not be determined in the setup shown in Figure 1. The most common way to achieve a directional sensitivity is introduction of a known optical frequency shift into one arm of the interferometer to obtain a virtual velocity offset. This can be done by means of an acousto-optic modulator (Bragg cell) incorporated into one arm of the interferometer. The Bragg cell is driven at frequencies \( f_B \) of 40 MHz or higher and generates a carrier signal at the so called RF drive (center).
frequency. The movement of the object frequency modulates the carrier signal. The object velocity determines sign and amount of frequency deviation with respect to the center frequency $f_0$. This type of interferometer is called heterodyne interferometer. Its structure is shown in Figure 2.

With the introduction of a shift frequency $f_B$ the intensity at the detector changes to:

$$I(t) = I_M I_R R + 2K \sqrt{I_R I_M R} \cos[2\pi (f_B - f_D) t + \phi(t)]$$
The heterodyne solution has significant advantages. As only high frequency AC signals are used (i.e., the $\phi(t)$ term in the above equation is neglected) to detect the Doppler frequency and the object's velocity, there is no disturbance from low frequency noise present in the instrumentation (e.g., from power supplies). Non-linear effects of the photo detector as well as of all signal pre-processing stages do not affect the integrity of the Doppler modulation content.

For further information see the website (Polytec, Inc.):