Accelerometer Calibration
Using a **Laser Doppler Dispacement Meter**

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What is Acceleration? Figure 1 illustrates classical sinusoidal vibration, with instantaneous single-frequency vibratory displacement x, velocity *v* and acceleration a, all plotted on a common time base2. Note that *v* is the time derivative, the rate of change of displacement with time, the slope of the displacement vs. time graph2. Note also that a is the next time derivative, the rate of change of velocity with time, the slope of the velocity vs. time graph.

Figure 1 can be summarized by three equations:

$$x = X\sin 2\pi ft$$
$$v = x = 2\pi fX\cos 2\pi ft$$
$$a = v = x = -4\pi^2 f^2 X\sin 2\pi ft$$

If one wishes the details of a vibration time history (comparable to Figure 1), an analog or digital oscilloscope or recording oscillograph is useful. However, few requests for vibration and shock data specify the time history. Most specify some statistical measure such as the peak value (comparable to X) or the root mean square (RMS) value.

The maximum values of the above three equations are observed at a moment when the sine or cosine term equals unity, so that:

$$X = X$$
$$V = 2\pi fX$$
$$A = 4\pi^2 f^2 X$$

Only rarely are metrologists asked for X, the zero-to-peak displacement. They are usually asked for *D*, the peak-to-peak displacement. Since *D = 2X,* the three equations change to:

$$D = 2X$$
$$V = \pi fD$$
$$A = 2\pi^2 f^2 D$$

X and *D* can be stated in in2. or mm, *V* in in/sec or mm/s and *A* in in/sec2 or mm/sec2. Divide *A* by 386 in/sec2 or 981 mm/sec2 to get *A* in multiples of the earth's gravitational constant.

Displacements Tiny at High Frequencies. In theory, if we can accurately measure X or *D* or *V* or *A*, and if all waveforms are sinusoidal, we can calculate the other terms. However, a serious problem exists at higher frequencies, where the displacement values X and *D* tend to be very small. For example, if we decide to sinusoidally shake an accelerometer at a peak acceleration *A* = 10 g at a frequency of 1,000 Hz, our peak-to-peak displacement *D* = 0.0002 in. = 0.005 mm. At a frequency of 2,000 Hz, *D* will be only 1/4 as large. At a frequency of 20,000 Hz, *D* will be only 11400 as large, -0.5 !1in. or 0.0125 !1m.

How can we accurately read such a small dynamic displacement? A microscope? A typical 50X microscope with calibrated reticle is somewhat useful for an absolute accelerometer calibration

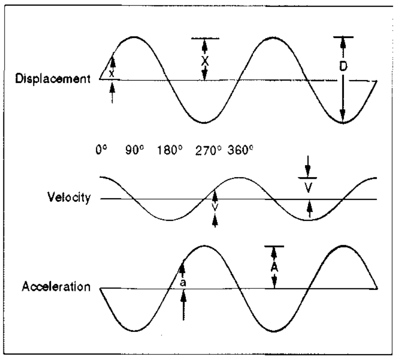

Figure 1. Sinusoidal displacement, velocity and acceleration time histories.

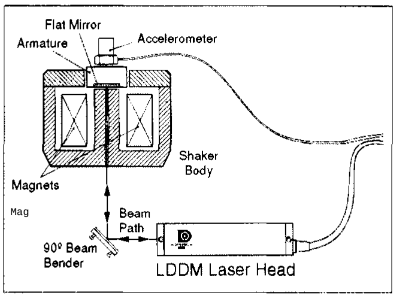

Figure 22. An accelerometer is mounted on the armature of an electrodynamic shaker2. A horizontallaser beam from the LDDM hits the 45° x 45° mirror, and is then reflected up to a flat mirror on the bottom of the shaker armoture and back to the LDDM via the 45° mirror2.

around 50 Hz, with acceleration *A* = 10 g, displacement *D* = 0.08 in. -0.2 mm. But it is useless at 1000 Hz with a *D* of 0.0002 in. or 0.005 mm.

Consequently, most laboratories and their clients have in past years settled for comparison calibration. Comparison calibration at The National Institute for Standards and Technology (NIST) is very accurate, with :t1% uncertainty. However, subsequent comparison calibrations against transfer standards, (each of which contributes uncertainty), is seldom better than :t2% .Subsequent calibrations of working accelerometers (each of which contributes still more uncertainty) is seldom better than :t2% .When this is added to the uncertainties of ancillary equipment and usage, uncertainties are seldom better than :t5%2.

Need for Accelerometer Calibration. Accelerometers and accompanying signal processing and readout functions should be recalibrated on schedule, typically every six months. They should also be recalibrated before (and immediately after) important vibration and shock investigations and tests2. Accelerometers should also be checked immediately if struck or dropped.

Absolute vs. Comparison Calibration2. Metrologists prefer absolute calibration for its greater accuracy. Unfortunately,

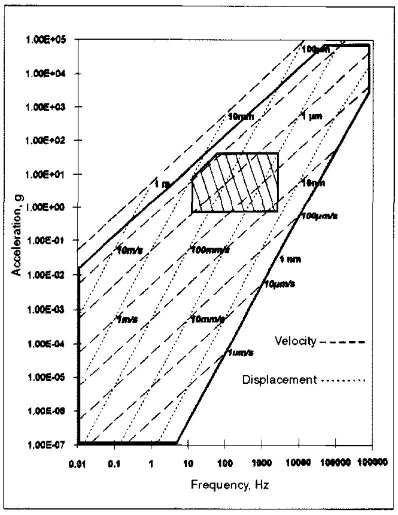

Figure 32. The large polygon show2.' the displacement, velocity and acceleration levels which the LDDM can measure in one large dynamic range (no switching required)2. The smaller polygon show.'i the displacement, velocityand acceleration levels demanded by typical vibration testing specifications2. A range of constantvelocity lines assists the reader in evaluating ony maximum or mjnjmum velocit}' limitations imposed by the in.'itrument2.

absolute calibration of accelerometers above 40 to 50 Hz has been difficult2. Absolute calibration is based upon the primary standards of mass, time and length maintained in the USA by NIST, in the UK by NPL (National Physical Laboratory), in Germany by PTB (PhysikalischTechnische Bundesanstalt), etc.

Imagine that you are holding a "standard" accelerometer, just recalibrated at a facility once or twice removed from NIST's :t1 % uncertainty. Its sensitivity is known in picocoulombs per g, but with an uncertainty of perhaps :t2%. If you now calibrate the test accelerometer by the usual "comparison" route, you will mount the test accelerometer and standard accelerometer back-to-back on a suitable fixture driven by an electrodynamic shaker. You will compare their electrical outputs over the needed range of frequencies and accelerations:

$$V_s = S_s a \text{ and } V_t = S_t a$$

where *V* = accelerometer output voltage, s = accelerometer sensitivity, and a = the applied acceleration for the standard and test accelerometers. Assuming that the accelerations are equal:

$$V_s/V_t = S_s/S_t$$

Since S_s is known, you can calculate S_t with a possible uncertainty of ±2.5%:

$$S_t = S_s V_t/V_s$$

There are at least three sources of error in this procedure: 1. error in the "known" sensitivity of the standard accelerometer; 2. errors in measuring signals *Vs* and *Vt;* and 3. Slight differences in the motion of the two accelerometers. These errors can always be reduced somewhat, but we recommend that you avoid them entirely by switching to absolute calibration.

Lasers to the Rescue. Fortunately, la

ser technology now makes it possible to accurately read peak-to-peak displacement D on the order of 0.05 pin. or 1.2 nm (see Figures 2 and 3). Thus the frequency of absolute accelerometer calibration can be greatly extended. Notice the larger shaded area of Figure 3 and compare it with the much smaller area demanded by typical vibration testing specifications.

The Optodyne LDDM measures phase shift (between the outgoing and the re turn laser light beams of Figure 2). This phase shift develops an electrical signal that is proportional to vibratory (or transient) displacement. The LDDM is thus distinctly different from laser velocimeters and vibrometers (LDV), which develop an electrical signal (must be averaged over time) that is proportional to vibratory velocity (must be above the LDV's minimum velocity). LDV signals must be electrically integrated to obtain displacement. The LDDM can measure smaller displacements. and with more favorable signal/noise ratios than the LDV.

Rather than compare with NIST's mass (not needed here), time and length standards, Optodyne uses a crystal-controlled clock as a fundamental frequency standard. Optodyne's length standard is based on a laser whose wavelength is checked against an NIST standard.

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