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TRACEABILITY AND UNCERTAINTY OF LOW-FREQUENCY VIBRATION MEASUREMENTS

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Measurements of vibration in the range 20 Hz to 50 mHz are of interest to consultants, manufacturers and researchers in such fields as ground vibration, impact testing of safety equipment and human exposure to vibration. However, if the vibration transducers and the voltmeters or recorders used with them have not been specifically calibrated in this range the reading error cannot be corrected. In some cases measurements may not be legally acceptable. This paper briefly discusses low frequency measurement errors and uncertainties and the chain of traceability through calibrations performed at the National Measurement Laboratory.

1 INTRODUCTION.

Vibration measurements are often made to check compliance with a clause in a contract. But having made the measurements, how "sure" can we be that the results really show whether the measured object complies with the contract, especially if the measured values are very close to the limits? The ISO Guide [1] is of little help in deciding what is "sure enough". However, unless the measurer is able to justify a claimed *level of confidence*, the values may not survive a legal challenge. The problem is analogous to that of geometric tolerances, the subject of a series of ISO standards.

Figure 1 demonstrates the sort of problem that can arise. A hypothetical contract requires vibration of some type of machine to be less than "Vlimit". Results are shown from (hypothetical) measurements on two machines. The points indicate measured values, and the solid bars show uncertainties at, say, the 90% level of confidence. The set of results indicated by open points appear to have failed the specification, but the uncertainty bars show that there is more than a 10% probability that the machine is within specification. Results from the other machine, indicated by filled points, seem to indicate compliance with the specification, but there is more than a 10% chance that it does not comply.

It would be easier to make a decision about compliance if the uncertainty bars did not overlap the Vlimit. Maybe the client will accept a lower level of confidence, 80% say, or 50%? The alternative is to attempt to reduce the band of uncertainty, at the given level of confidence. More care in calculating corrections and total uncertainty may achieve this; perhaps additional repeat readings are needed. The actual (calibrated) sensitivity of the measuring instrument at each frequency should be used, and the calibration uncertainty, as well as other sources of uncertainty, needs to be correctly factored into the overall uncertainty calculation.

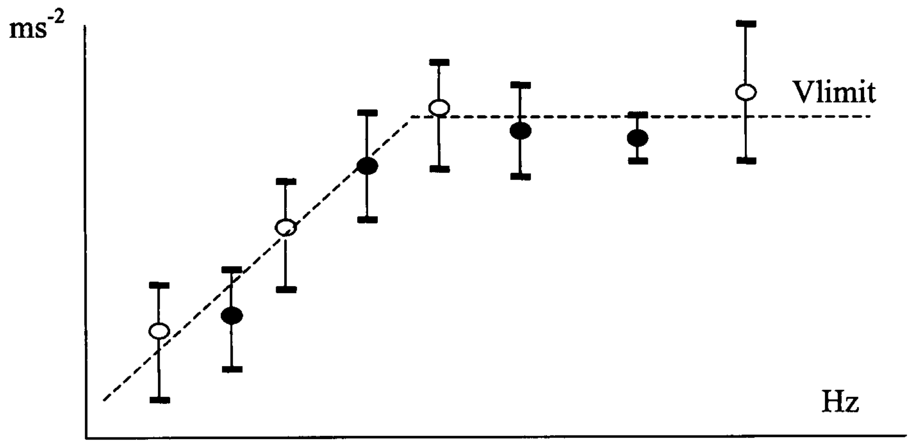

Figure 1 - Measured vibration values close to a specified limit.

2. INSTRUMENT SELECTION.

When purchased new, any reputable vibration measuring instrument will have a manufacturer's certificate of calibration. However, the calibration will be for a limited number of frequencies (sometimes only one), and the accuracy specification often does not extend over the full range of frequencies, particularly low frequencies. Often a user does not have the freedom to choose an accelerometer which responds to d.c., and must use an available piezoelectric accelerometer.

3. LOW-FREQUENCY RESPONSE.

Piezoelectric accelerometers are capacitive devices. Although in principle they do generate a charge output from a constant "dc" acceleration input, the charge tends to decay rapidly through leakage paths and load resistance. Sometimes the low-frequency rolloff can be estimated from the time constant, but in most cases the behaviour at low frequencies is dominated by the characteristics of the conditioning amplifier, or by high-pass coupling through the power unit. This can be clearly seen in figure 2, where a low frequency calibration of a piezoelectric accelerometer/charge amplifier combination is compared to a calibration done on the charge amplifier by itself. Figure 3 shows a similar calibration done on a different set. Here a rise in frequency response can be seen before rolloff that is typical of some accelerometer systems.

4. CALIBRATION UNCERTAINTIES.

Most working-grade accelerometers are calibrated by comparison with a reference accelerometer. In making such a comparison, one of the major sources of uncertainty is likely to be in measuring the ratio of the two voltage outputs, particularly if the ratio differs hugely from unity. Voltmeter corrections should be applied, from the calibration certificate of the meters. The maker's "accuracy" specifications for the meters in the ranges used should be considered as standard uncertainties [1], unless otherwise specified. At very low frequencies, thermal transients can introduce large unknown errors, i.e. uncertainty, so thermal shielding against drafts etc is a good idea.

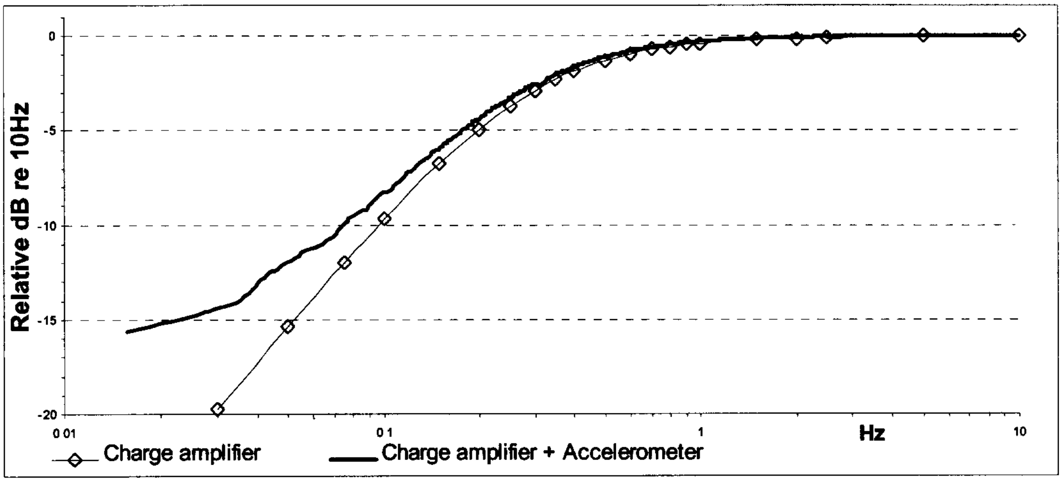

Figure 2 – Frequency response of a Bruel & Kjaer 4371 accelerometer with a Bruel & Kjaer 2651 charge amplifier using a LLF setting of 0.3Hz, and the response of the charge amplifier by itself.

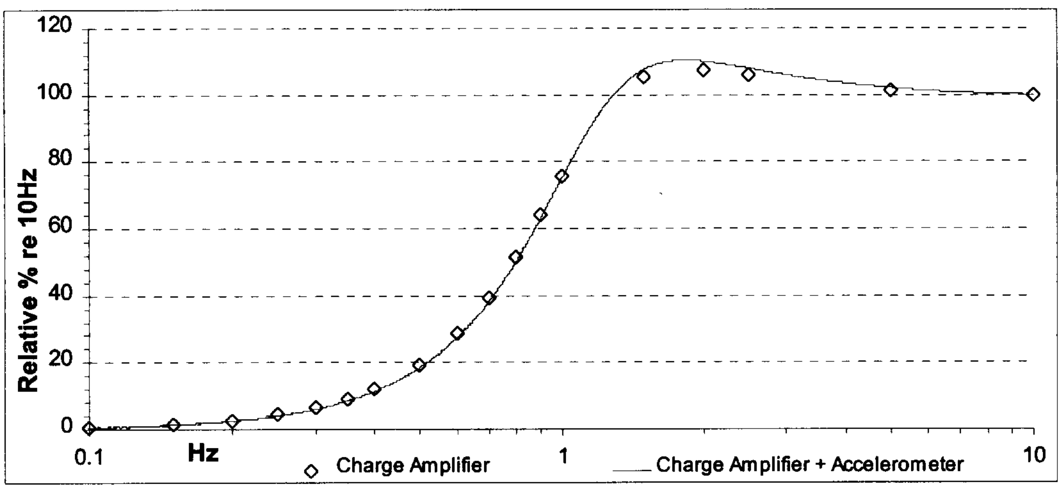

Figure 3 – Frequency response of a Bruel & Kjaer 4367 accelerometer with a Bruel & Kjaer 2634 charge amplifier, and the response of the charge amplifier by itself.

The main uncertainty remaining is that of the calibration of the reference accelerometer. In reports issued by NML, reference accelerometer sensitivity is always accompanied by an uncertainty, $\mathbf{U_{cal}}$, generally expressed as a percentage. This is always an expanded uncertainty, with a coverage factor **k** to give a confidence level of 95%, ie the chance is 95% that any sensitivity value given does not differ from the "true" sensitivity by more than the quoted uncertainty. To use $\mathbf{U_{cal}}$ in the subsequent comparison calibration, it must first be divided by **k** to get the equivalent "standard" uncertainty. This is then combined with the other uncertainties to obtain $\mathbf{u_c}$ for the comparison calibration. The combined uncertainty $\mathbf{u_c}$ can then be multiplied by a (different) **k** to find the uncertainty of the sensitivity of the working-grade accelerometer at the 95% confidence level. Sometimes it may be preferable to keep $\mathbf{u_c}$ as it is, for factoring into uncertainty calculations for later measurements with the accelerometer.

5. CALIBRATION METHODS AT NML

At the National Measurement Laboratory several methods are utilised for accurate calibrations down to about 50mHz. These methods are all traceable back to the fundamental definitions of frequency, voltage and length.

Generally, for frequencies greater than 1Hz, a calibration is performed by comparing the output of a test accelerometer with that of a reference undergoing the same excitation. In the range 1 to 80Hz, the reference takes the form of two Sundstrand Q-flex servo accelerometers permanently fixed to a horizontally orientated air-bearing shaker table on which the test accelerometer is placed..

For any calibration to have meaning, the reference must have been calibrated beforehand to a more accurate definition of acceleration. Our references at the National Measurement Laboratory are periodically calibrated "absolutely", for frequencies less than 3kHz, by the use of laser interferometry with a method known as "Fringe Counting" [2].

An absolute calibration gives traceability to two of the primary units. *Length* is derived from the stable wavelength of a HeNe laser that is known accurately to at least 6 significant figures (632.817nm ± 0.002 in laboratory conditions). *Frequency* is linked directly to the NML standard caesium clock, accurate to 1 part in 10^{12}, via a 10MHz feed into the acceleration laboratory to two HP 53131A counters. The resultant uncertainty in the frequency measurement is ~1 in 10^7.

Voltage at low frequency is linked back to periodic calibrations of a SR830 digital lock-in amplifier or a DP6100B DSP with a HP3458A precision voltmeter using DC sampling. The HP3458A has been calibrated in turn from the NML AC/DC transfer standard which, in turn, refers back to the Josephson volt, recognised world wide and intercompared regularly.

Below 3Hz a different technique is sometimes used. The main requirement for a calibration is having a known acceleration to excite the transducer with. A very convenient source of stable acceleration is Earth's gravitational field. An apparatus was developed [3] that utilizes an air-bearing mounted, vertically rotating flywheel. The accelerometer under test is bolted to the center of the flywheel with its sensitive axis in a vertical plane. When rotated, the accelerometer would experience a sinusoidally varying orientation with respect to the direction of gravity. This method is used to produce SHM excitation with a constant acceleration amplitude of ±1g down to about 50mHz.

Using Earth's gravity, the units of time and length are already combined in the form of acceleration. Gravity surveys have been done in many places in Australia and throughout the world. One such survey [4] has been carried out at the NML site in Sydney and a designated gravity station is located within the building. This station is utilized mainly for calibration and verification of gravity meters and for the national standards of Force and Barometry. A typical apparatus for conducting gravity measurements utilises a Michelson interferometer, in a similar fashion to absolute accelerometer calibrations mentioned above, to gauge the acceleration of a freely falling reflector in an evacuated tube. The local value of g at the NML gravity station is 9.7963763 m/s^2 and is known to 0.2 PPM. So, a value for local gravity is also traceable back to the fundamental standards of time and length. Traceability of voltage is again carried out through the SR830 lock-in amplifier and back up the chain as before.

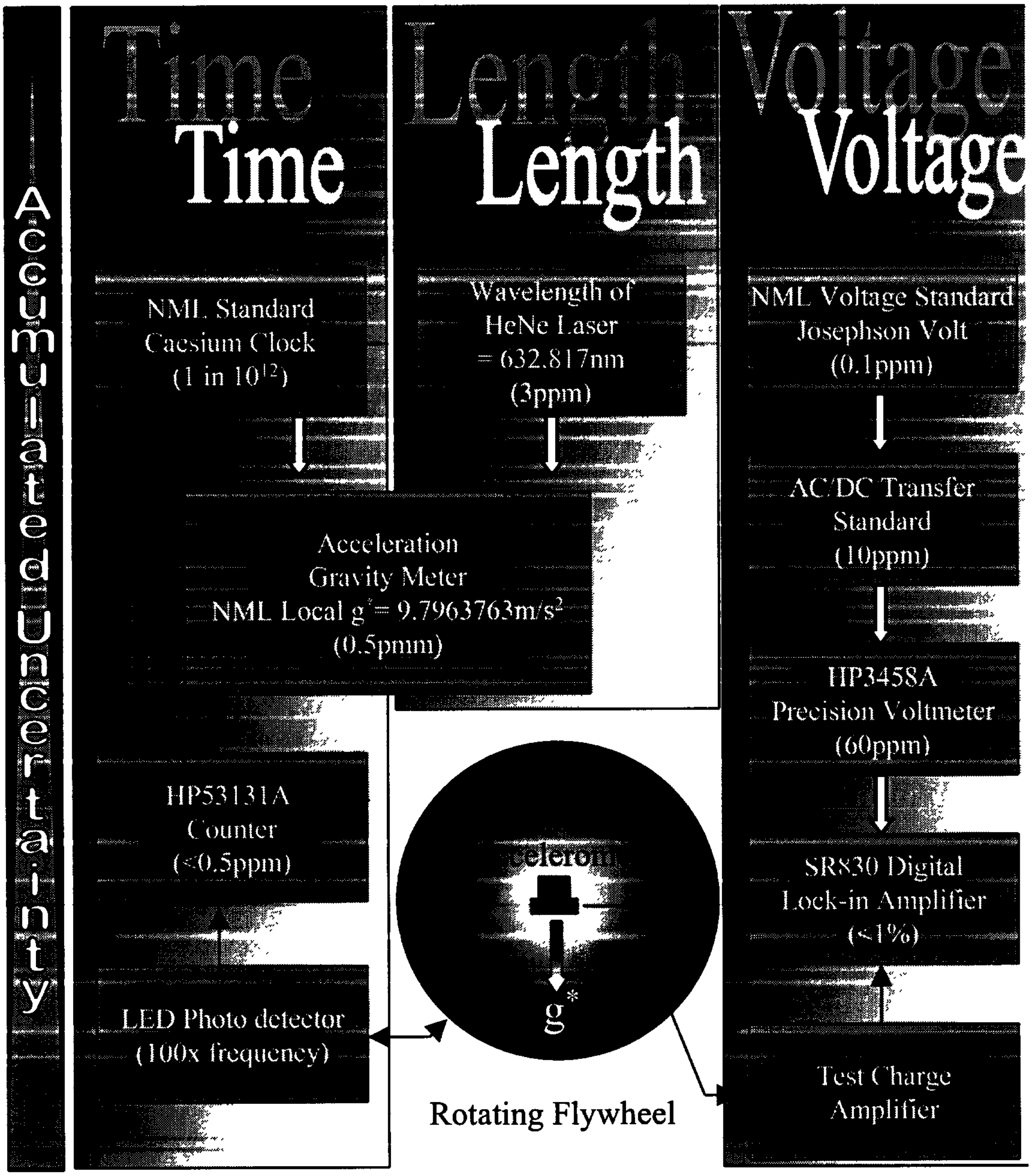

Figure 4 - Path of traceability to primary physical standards. The diagram shows how the calibration of reference accelerometers at NML enables measurements in the field to be traceable right back to the physical standards of length, time interval and voltage. Approximate or estimated values for accuracy of the equipment are given for an assumed accelerometer response of 20mV/g. In the diagram a large solid arrow indicates a direct connection, hollow arrows are periodic calibration.

Figure 4 shows, diagrammatically, the "traceability path" for a calibration by flywheel that enables field measurements to be traceable right back to the physical standards of length, time interval and voltage. At every stage of the chain, sources of uncertainty must be taken into consideration and are accumulated.

When uncertainties are combined in a simple model, it is typical to add them in the form $\mathbf{u_c} = \sqrt{(\mathbf{u_1}^2 + \mathbf{u_2}^2 + \ldots \mathbf{u_n}^2)}$ [1], where $\mathbf{u_{1..n}}$ is the standard uncertainty of each component expressed as a percent. Thus, the larger uncertainties dominate the result, so that uncertainties relating to the definition of the units are generally insignificant against the much larger uncertainties of the calibration measuring equipment and the statistical uncertainty (type A) of the measurement.

6. COMPLIANCE?

Many acceleration measuring systems sent to NML for calibration are also tested for compliance to a standard. A common example is SAEj211/1, "Instrumentation for Impact Test" [5] illustrated in Figure 5 below. The policy at NML is that if the 95% uncertainty bands fall entirely within the specification the instrument is said to comply. If the uncertainty bands fall entirely outside the specification the instrument does not comply and if they overlap from either above or below the result is called indeterminate and we cannot say either that it complies or does not comply. For this reason great care is taken to ensure that the calculations are done correctly and that sources of uncertainty are minimised.

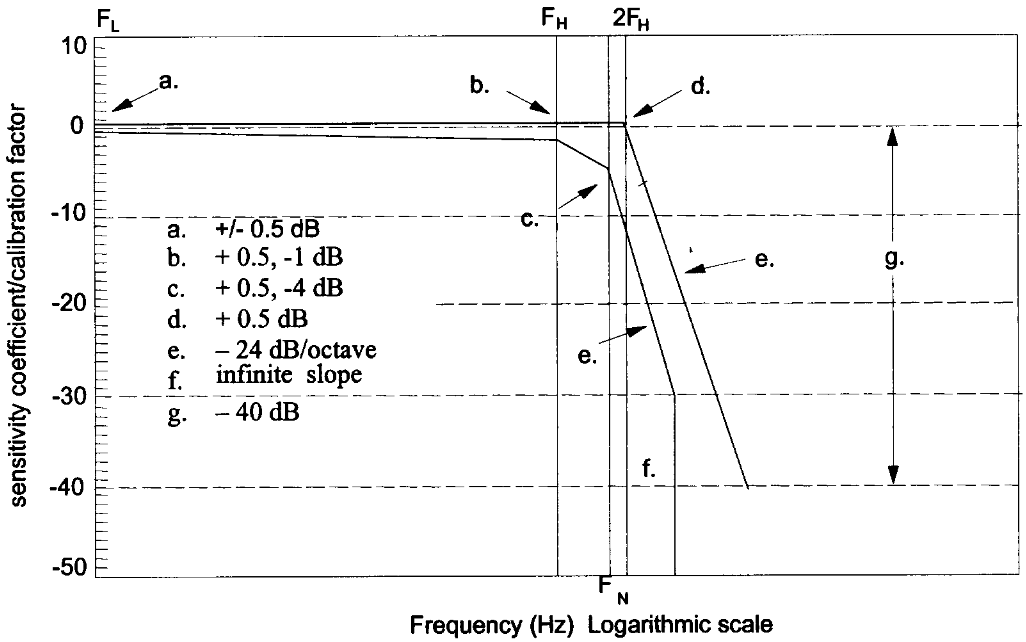

Figure 5. Requisite data channel dynamic accuracy conditions as required by SAEj211/1, Instrumentation for Impact Test. F_L, F_N, and F_H are determined by the selected frequency class, 600 Hz or 1000 Hz.

7. CONCLUSION

Careful estimates of uncertainty can help to assure the practitioner, and his client, that compliance has been demonstrated to within agreed levels of confidence. Such estimates must include the component of uncertainty inherent in the calibration of the measuring instruments. When measuring low frequency vibrations, the true frequency response must also be included.

References

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