Accelerometers, geophones and seismometers – which to choose?

Report by John Shelton, AcSoft Ltd, Svantek UK Ltd

Recent years have seen a large increase in measurements of vibration, for a variety of applications, such that the diary of the busy acoustic consultant is just as full of vibration surveys, as noise measurements. Be it for health and safety applications, such as hand-arm and whole-body vibration, annoyance, such as ground vibration, or damage, such as building or blasting vibration, the methodology still seems more an art than a science.

All acousticians should have a firm grip on the performance of their sound level meters, and know how to use and calibrate them. Sadly, this does not always appear to be the case with vibration instrumentation.

Several instrumentation standards exist, the key one being BS EN ISO8041:2005, along with procedural standards such as BS 6472:2008, but sometimes it can appear very confusing. Can I calculate PPV from a spectrum? Can I measure VDV with a geophone? Should PPV measurements use W_d weighting?

This brief article goes back to basics, and addresses some of the more common questions we get asked, if only for a quiet life!

Transducers

Vibration transducers can be split basically into two types – accelerometers and geophones (or seismometers). Accelerometers have an output proportional to, er, acceleration, and geophones have an output proportional to velocity. So how can both be used to measure vibration?

There's a basic relationship between acceleration and velocity – the former being the rate of change, or the differential, of velocity. Therefore we can easily convert between the two by *integrating* an acceleration signal to yield a velocity signal. This is normally done in the time domain, using a filter (called an integrator), but it can also be done in the frequency domain by dividing an acceleration spectrum by $2\pi f$, where f is the frequency. This effectively slopes the spectrum by -6dB/octave, so a velocity spectrum will appear to have a lot fewer high frequency components!

A typical triaxial geophone

Accelerometers

The majority of accelerometers for our applications are piezoelectric devices. A small piezoceramic crystal is sandwiched between the base and a seismic mass, so when the base is accelerated, the crystal is stressed, causing a proportional charge output. Because it is a simple mass/spring system, it will have a fundamental resonance – the crystal is very stiff, so this will be high, some kilohertz for most devices. Below that resonance, the response is virtually flat and linear, making an excellent transducer.

To make a sensitive accelerometer, make the mass and/or crystal bigger – but, this brings the resonance down, so there's a trade-off to be made. Thankfully, most requirements for sensitive accelerometers are at low frequencies!

The output of the crystal is a charge, which requires a specialised charge amplifier, with extremely high input impedance, in order to drive our measuring system. These used to be separate boxes, with specialised low-noise cabling, but nowadays, the charge amplifier is built into the accelerometer itself, and this uses a 'phantom' powering system known as IEPE (integrated electronic piezo-electric), also known by a variety of proprietary names such as ICP®, CCP etc. At least IEPE is standardised! This means that long cables can be driven, and as long as your instrument can provide the powering, you should be in business. But always check that you have an IEPE accelerometer rather than a charge accelerometer first!

Due to being a capacitor, such accelerometers do not have a DC response, and will roll-off at low frequencies. Make sure you select one suitable for your task, if you want to measure down to 0.5Hz for example.

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A typical triaxial accelerometer

A portable low frequency field vibration calibrator

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Accelerometers are rugged and will measure in any axis, but being a mass stuck to a piece of glass, the crystal can crack, not always obviously. This is particularly true for the sensitive ones with big seismic masses, so don't drop them on a concrete floor!

Geophones

A typical geophone is a moving coil device. Think of a loudspeaker backwards. A magnet is suspended in a coil (sometimes vice-versa), attached to the base of the transducer. As the base is moved, a current is induced in the coil, which can then be used as an output proportional to velocity.

Like an accelerometer, the geophone is a resonant device, but this time, the resonance is low frequency due to the mass (magnet) being suspended. Typically, this is around 3-4Hz, and the usable linear range is above this. This potentially gives an issue with measuring low frequency vibration – we are often interested in measuring vibration at just the frequencies that a geophone has a resonance. However, the design of geophones is a mature art, and careful damping and linearization will provide excellent performance.

Geophones are normally designed to operate in one axis, either vertical or horizontal, so they must be oriented to their design axis. If you have a triaxial unit, it will have one vertical, and two horizontal coils. Stick it to a wall instead of a floor, and you'll probably lose any signal, so they should always be mounted in the same orientation – on a bracket for example.

Conditioning an active geophone is very specific, but recent devices also support the IEPE system, already dominant in accelerometers.

A big plus of geophones is their lower price, and they are very rugged – hence their popularity in the mining engineer's toolkit – no fiddly microdot connectors!

Choose your weapons

The choice of transducer would seems to depend on what you want to measure – an accelerometer for measuring acceleration (VDV, MTVV, etc) and a geophone for measuring velocity (PPV). This complicates the instrumentation, so it would be nice to use one for the other.

We can get velocity by integrating the accelerometer output, so this would appear to be the ideal solution. Well, it works well, but the integrating can cause some side-effects. If you consider that the integration process emphasises low frequencies (think of the -6dB/octave slope in the spectrum), any noise present at low frequencies in the amplifier chain, or extraneous environmental effects can cause spurious results. Some accelerometers, due to their physical design, can be sensitive to temperature transients. This shows up as a very low frequency signal, which, when integrated, generates a large velocity output. Try blowing on your accelerometer and see what happens! This also applies to poor or badly maintained cables.

Careful design of high pass filters can mitigate these effects, but these can introduce phase errors, which might be important when trying to measure the peak amplitude of the velocity signal (PPV). It's interesting but beyond the scope of this article to compare the raw output of an integrated accelerometer and a geophone for the same signal and measure its peak!

Of course, integrating the acceleration signal in the frequency domain is a lot easier, but generally will not yield a PPV value, almost all spectra being RMS values.

A geophone is excellent for its design purpose. We could calculate acceleration by differentiating the signal, but often they have a limited dynamic range, compared to accelerometers, so this can result in noise being amplified. Also, as their resonance is often bang in the middle of the frequency range of interest, the phase performance becomes very significant, and needs careful design.

So which is best? Without resorting to Harry Hill to find out, it's probably best to start with an accelerometer, and integrate to velocity when you need to. This will cover the majority of applications with one transducer. But if your application is for PPV only, then the geophone may make a better choice. But either way, make sure you know the performance characteristics and limitations.

Future technologies

New technologies such as MEMS (MicroElectroMechanical systems) are now looking promising for use in both sound & vibration transducers. Recent developments at NPL have shown that a microphone meeting Class 1 is attainable, and the same can be said for accelerometers. MEMS accelerometers have been used for years in airbag sensors, and you've probably got one in your smartphone, so it knows when to change the display if you tilt it from vertical to horizontal.

The use of MEMS for measurement accelerometers is on the way and they have an advantage in their low price and stability/ruggedness. Already MEMS devices are being used for hand-arm and whole-body vibration, and very linear high sensitivity devices for ground vibration are on the near horizon.

A nice feature of MEMS accelerometers is their DC response – it makes calibration easy – by turning them upside-down the change should be 2g! Their low noise floor and lack of low-frequency resonance also makes integration easier

Calibration

No acoustician worth their salt will leave the house without a sound level calibrator. Its use is written into countless standards, and is your only contact with reality. Historically, this is due to microphones having often large dependencies on environmental effects, so field calibration was a must.

These days, microphones are very stable, and if you see a difference in sensitivity over a few measurements, then something is wrong somewhere.

Somewhat bizarrely, the same calibration habit doesn't seem to have caught on with vibration measurements. Perhaps this is due to the complexity and cost of vibration calibrators, or simply a belief that a transducer that looks like a hex nut couldn't possibly get damaged!

BS EN ISO 8041:2005 is the instrumentation standard which is cross-referenced in nearly every standard for human vibration measurement. It defines the performance of instrumentation (much like BS EN 61672 for sound level meters), and significantly almost forgets to mention geophones, concentrating on accelerometers as transducers (the Germans are ahead of us here – they have bolted that down in DIN 45669 for example).

The standard has a lot to say about calibration, for type approval, periodic calibration and field calibration, but very few practitioners seem to be aware. This is probably down to the limited availability of a practical calibrator which allows checks on performance at the frequencies of interest (often below 80Hz).

Most field calibrators operate at 159.15Hz – an odd frequency until you consider it is 1000 radians/second, which makes converting from acceleration to velocity and displacement easy, e.g. $10ms^{-2}$ acceleration is $10mms^{-1}$ at that frequency. These are handy devices (but often three or four times the cost of a sound level calibrator) and can be used to check the complete measurement chain, albeit at a high frequency – you just have to assume your filters and low frequency response is OK.

Another limitation is that ground vibration transducers are often large (high sensitivity), so such calibrators cannot be used – there is not enough power available.

The ISO standard recommends calibration at 15.91Hz and 79.6Hz for low frequency vibration instruments, *in the field*, as well as periodic calibration, for example. This allows the whole-body weighting filters and RMS/RMQ detectors to be checked too. This requires a much bigger vibration exciter, and such devices are now coming to market to address this need for field calibration.

Geophones give a particular problem. Vertical geophones can be field calibrated in the same way as accelerometers, but horizontal geophones cannot be mounted on a vertical calibrator, so the only solution is to send them to a laboratory equipped with a horizontal slip table – time consuming and expensive.

A new working group has been set up to address the issues of vibration transducers, but the standardisation wheels grind exceeding slow.

Conclusion

Hopefully this article will have given some insight into some of the issues practitioners should consider before equipping themselves with vibration instrumentation and heading out into the unknown. There are many more issues not covered here, but browsing the standards appropriate to the measurement will provide a wealth of information. Hopefully future articles in Instrumentation Corner will enlighten further!

***John Shelton** is a member of the IOA Measurement & Instrumentation Committee, and AcSoft Ltd is a sponsor member of the Institute.* ◘