On the Use of Tracking Filters During Sine Vibration Testing

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Sinusoidal vibration testing has evolved over the years for many good reasons. Initially, from a military standpoint, a predominant part of vibration excitation was from propeller driven aircraft. Here, system resonances could easily be excited during runup, or in the more unfortunate circumstance, during sustained operation at flight speed. Although there initially was only rudimentary instrumentation to measure and analyze field and test data, the approaches have been relatively consistent for over 40 years. In the mid to late 50s and throughout most of the 60s swept spectrum analyzers and then tracking filters were used to measure the 'sine' values of signals. When real-time analyzers and FFT analyzers were introduced in the late 60s and early 70s, attempts were still made to quantify the peak sinusoidal signals present. Through the addition of several 'safety factors' a series of MIL-STD sine criteria, such as MIL-STD-202, was developed.

Early shaker designs were aimed at sine testing as well. It was only in the early 60s that shaker manufacturers introduced designs with flexures aimed at random vibration testing in addition to swept sine testing. Several other advances in testing and analysis led to additional requirements for analyzing and testing with sine components. Thus today's sine requirements include satellite shakedown, phase resonant dwell and MIL-STD-810's sine-on-random definitions as well as swept sine testing.

What is a Tracking Filter?

A swept sine test starts out with a 'pure' sine signal being sent from the control system to the shaker amplifier. From that point onwards this signal has a tough journey. The amplifier, often a Class D switching amplifier, drives the shaker. The control accelerometer sees the combined response of the shaker armature and flexures, the test fixture, the Unit Under Test (UUT) and the attachment method for the accelerometer. The accelerometer response includes the dynamic response of the UUT, rattling or loose parts, cable whip, complex modal interaction, harmonic distortion and signal conditioning considerations. More often than not, what started out as a pure sine signal ends up as anything but.

The control accelerometer at least has the advantage of being held (or attempting to be held) at a reasonable signal level. Other mounted response accelerometers may be exhibiting signal levels down in the noise or extremely high resonant responses. It is not unusual for response transducers to exhibit swings of over 100 dB during a swept sine test on a dynamic structure. So how do we make sense of all the possible detriments to the theoretical pure sine response?

In the mid 1950s, during a ground vibration test on a prototype aircraft at General Dynamics in Ft. Worth, a controversial circumstance arose. The testing crew identified the “first mode” at 5 Hz. This was quickly disputed by the dynamicists, the “second story” guys. Their claim was that the first mode should not appear until about 10 Hz. Closer examination of the aircraft's response at 5 Hz proved that the dynamicists were correct, much to the consternation of a young test engineer named Laurie Burrow. The signal at 5 Hz turned out to be a small component of 5 Hz and an overwhelming dose of the 2nd harmonic, 10 Hz. Laurie realized that they needed a way to look at just the test frequency values free from noise and distortion components. And it needed to track the test sweep automatically, with no operator intervention. Thus the idea of a narrowband tracking filter, capable of operation down to 1 Hz or less was born. Laurie spent much of the next six months in the library searching for ways to implement a solution. He finally found it by putting together two unrelated concepts. These were a single sideband modulator and a wide range 90° phase splitter. And so was born the first inherently-tuned (can't lose lock) narrowband tracking filter. Less than 10 years later, Laurie left General Dynamics and bought back the rights to his design, thus founding Spectral Dynamics Corporation of San Diego.

What started out as crystal filter plug-ins, with a 100 kHz intermediate frequency, evolved into solid state circuits with a zero intermediate frequency design. Then as digital control systems replaced analog designs, the hardware tracking filters were replaced at Spectral Dynamics (SD) by a unique, proprietary implementation of a digital approach. This approach continues today in both PC-based and workstation-based control and analysis systems at SD. Examples of these filters are shown in Figures 1 and 2.

Note that a tracking filter needs a constant amplitude sine reference signal to point it to the correct frequency. This is called a COLA (Constant Output Level Adapter), a term developed 40 years ago during analog tracking filter days. The performance of a tracking filter is in many ways dependent on the quality of the COLA, as discussed later on.

Pretenders to the Throne

Implementing a true digital tracking filter is both expensive and difficult. This is partly true because of the fact that true tracking filter technology requires several items which can be considered holdovers from an analog world. More on this later. It also requires dedicated hardware for each channel which, if not done correctly, can significantly raise the cost of such hardware.
So it is not surprising that most manufacturers of digital control systems have attempted to replicate a tracking filter using concepts they know well, such as the FFT. And, since random control systems require FFT processing anyway, using an FFT approach to implement a tracking filter is virtually free. Unfortunately, the concepts of a bin-centered FFT analysis and that of a continuously sweeping sine tone are mutually exclusive as will be seen. What may not generally be recognized is that conducting a good, accurate, effective swept sine vibration test can be much more difficult than conducting either a random or a shock test. Many factors go into performing an acceptable swept sine vibration test and good tracking filters are one of those critical factors. An example of an FFT-based tracking filter used by a non-American based control system manufacturer is shown in Figure 3. It is obvious that the FFT approach to filtering does not achieve the desired objective and this filter shape meets none of the following criteria. The characteristics of a good tracking filter should include:

- A flat shape over the specified bandwidth
- A sideband-free shape of at least 70 dB
- A rolloff of at least 80 dB per octave from the center frequency
- Selection of fixed and variable bandwidths
- Operation down to 0.1 Hz for seismic applications
- Unity gain at the center frequency
- Perfect phase match, channel-to-channel across the passband

Some examples of tracking filter use include:

**Remove Distortion Components.** One of most obvious needs for signal filtering is when distortion takes place and affects the accelerometer response. The example, shown in Figures 4 and 5 of a satellite qualification test, shows three distinct types of distortion often encountered in sine testing. If the goal of the test is to measure, reproduce and possibly control the sine level stated in the specification, then these types of distortion must be removed from the measurement.

**Look Inside “Rattling Response” for the Sine Component.** Many years ago Wayne Tustin suggested that since it was very easy to fool a sine test and thus get away with an undertest, tracking filters should always be used. He gave the example of just tossing his car keys on the shaker near the control accelerometer. The resulting rattling would be picked up by the control transducer and add some high but inconsequential peaks to the signal, thus forcing the controller to reduce the drive until the rattle subsided. This, of course, would be an undertest throughout the rattling interval. The simple use of a good tracking filter during this test will completely eliminate this trickery. Figure 6 shows a typical time domain signal for a 1 g test both with and without filtering for a particularly bad case of the rattles.

Rattling noise and complex modal response can add many undesirable signals to the control accelerometer. In Figure 7 we see the control accelerometer during a swept sine test displayed both as broadband peak (control) and fundamental (auxiliary 2) in a display expanded from 100 to 2,000 Hz. For this test, the tolerance bands were set at ±1.5 dB and the abort bands at ±3 dB. Note that at many frequencies near 100 Hz, the true sine
Figure 7. Control accelerometer signal shown in both broadband peak (white trace) and fundamental (black trace) formats.

Figure 8. Control accelerometer shown with (white trace) and without (black trace) tracking filters from 2 to 2000 Hz.

Figure 9. Broadband peak response measurement during 5 to 100 Hz sweep.

Figure 10. Fundamental (tracking filter) response measurement during 5 to 100 Hz sweep.

level of the test is about 3 dB low due to rattling. But at 349.8 Hz the true level of the fundamental sine component drops by 17 dB from the specification! Surely this is an undesirable undertest which can easily be corrected through the use of tracking filters.

Improve Control Dynamic Range of a Test. Quite often the noise encountered in instrumentation during a vibration test is of broadband nature. Depending on the sensitivity of the control transducer and the required frequency range, this may or may not hinder completion of a successful vibration test. In a swept sine test, if noise is encountered, the use of tracking filters can have a wonderfully positive effect. Figure 8 shows a critical sine test being performed on an aerospace structure. It was too late in the program to change instrumentation, so the test engineer needed an immediate solution. His problem was high noise levels in the instrumentation which prevented him from starting the test at 5 Hz. The frequency range of the test required by the specification was 5 to 2000 Hz. However, if possible, it was desired to begin the sine sweep at 2 Hz. The control and response accelerometers were each 100 mV/g but there was background noise on each channel of about 3 mV RMS. The shape of the test profile began with a constant displacement segment of 0.5 mm p-p which created a test level below the background noise at 5 Hz.

Note that at 2 Hz the desired test level of 0.004 g is nearly 20 dB below the measured noise floor. But, by using a constant percentage bandwidth tracking filter, the test is accurately controlled from 2 to 2000 Hz, even with ±1.5 dB control tolerances and ±3 dB abort limits up to 60 Hz. The use of good tracking filters has enabled the control system to work well below the existing noise floor and successfully complete a very difficult test.

Improve Frequency Response Function Measurements. Much sine testing, especially of expensive aerospace structures such as satellites, is performed to check for any changes in structural dynamics. A good sine test offers a wonderful way to measure responses over a very wide dynamic range and to check for nonlinear behavior. However, some structures include very light items such as antennas and solar panels and at the same time very heavy items such as panels supporting banks of batteries. These can interact in a very complex way during a sine sweep. So if an accurate assessment of dynamic structural response at key points on the structure is required, it makes no sense to include rattling or higher mode responses in the measurement. However, if broadband peak or RMS measurements are used, measured responses will bear no relationship to true dynamic response or to computer modeling predictions.

Figure 9 shows a response measurement made on a satellite during a 0.6 g qualification test. Note that the response reaches 10 g at a position about 5 ft above the control plane and shows a generally jagged response. This display was done with a broadband peak computation and shows nearly 60 dB of dynamic range.

Figure 10 shows the same measurement using a tracking filter to process the stored data. These data exhibit a classical structural response, free from noise interference. Note also that the measurement dynamic range has increased dramatically to about 120 dB.

Other Criteria for Successful Sine Testing

As important as tracking filters are for conducting a successful sine control test, there are other factors which can also be critically important and which will contribute to the effectiveness of the tracking filter. These include:

A Smooth, Continuous Sine Sweep. For optimum results, the system must be able to place the filter directly over the resonant peak or critical frequency. This requires resolution of less than 0.1 Hz anywhere in the sweep. An FFT approach will create frequency spacings of 1.25 Hz if 1,600 lines are used to
This also creates a block length of 800 msec, which is an eternity during a fast moving swept sine test. So the use of 16 bit or even 32 bit lookup tables to try and resolve frequency cell positioning is insufficient in most applications.

**Autoranging of Input Signals.** During a sine sweep, response signals will vary over a very wide range depending on the dynamics of the UUT. In order to avoid input overloading during brief periods of high responses, it may be tempting to set every channel on the 10 V input range. But this will virtually assure that during most of the sweep, the majority of inputs will be down in the noise floor, even if 20 or 24 bit A/D converters are used. The only foolproof way to avoid overload or a poor S/N ratio, developed over 40 years of sine testing, is to autorange every input continuously during the sweep.

**Fast, Real-Time Level Measurements.** In order to understand what is happening on the UUT during a swept sine test, an accurate determination of the signal level must be available now. This requires dedicated DSP hardware and an architecture that avoids running back to the host CPU for every decision. If autoranging is to be successful, the quickest possible intelligence about the level and level direction of each input is crucial. Note that since a pure sine signal is very predictable, the use of good tracking filters permits accurate determination of signal level and frequency in 1/4 of a cycle, even when sweeping at 4 octaves per minute at 2,000 Hz.

**Conclusions**

The use of good tracking filters permits repeatable swept sine testing and meets the intent of every sine specification published today. Additional benefits in terms of improved signal-to-noise testing and better dynamic response measurements are available when using tracking filters during sine and sine-on-random testing.

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