Shock & Vibration
OVERVIEW

ENGINEERING eBOOK

Steve Hanly

Editor's Note:

Shock & Vibration Overview by Steve Hanly was originally published in 2016 on Midé Technology's website. The eBook has been updated to reflect Slam Stick's rebranding to enDAQ. The eBook is also now located on enDAQ.com. enDAQ is a division of Midé Technology.

To learn more about Slam Stick's rebranding to enDAQ, please visit our website.

Updated: January 2020

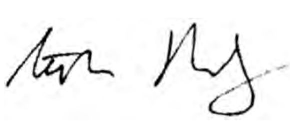
Why I Wrote This eBook

Over the last couple years, we've learned a great deal about shock and vibration to support our enDAQ (formerly Slam Stick) data logging line and its customers. We've had a lot of questions on various aspects of shock and vibration testing, so I'm excited to share with everyone what we've learned!

This eBook provides a practical overview on some of the key components of shock and vibration testing. Everything will be covered from sensor selection to analysis. Engineers have limited time, so links will be provided to supplemental information and suppliers to keep this eBook as quick hitting and brief as possible. You'll learn:

- **Sensor Selection**
  We'll go through different accelerometer types and alternatives to accelerometers.
- **Data Acquisition System Selection**
  Learn what to look for in a data acquisition system.
- **Equipment Setup**
  We'll discuss best practices of equipment setup (sensors, electronics, and wiring).
- **Analysis Overview**
  We'll define some theoretical background on vibration followed by some analysis examples such as FFTs, PSDs, and spectrograms for real world data and applications.
- **Response Spectrums**
  We'll give some background on how to use response spectrums and modal analysis as part of the design process.
- **Simulating Shock and Vibrations in the Laboratory**
  We'll give some different methods of exciting and testing your system in a controlled environment.
- **Analysis Software Options**
  We'll discuss different software options available to the vibration test engineer.

If you're new to shock and vibration measurement or if you just need a quick refresher, use this as a guide. We'll update this book, so please send suggestions and best practices you've learned. I hope you enjoy it.



Stephen Hanly, VP of Product, Midé Technology

Table of Contents

Vibration Introduction

All bodies possessing mass and elasticity are capable of vibration, which basically means everything you see and touch can vibrate and are impacted from shock events. As the world around us gets increasingly more automated with more and more powerful machinery, vibration and its destructive strength is on the forefront of any mechanical engineer's mind during the design and testing process.

I'm sure everyone knows what vibration is—the device in your pocket probably reminds you far too frequently throughout the day! But here's the technical definition: vibration is an oscillating motion about a point of equilibrium. Mechanical shock is a sudden change of acceleration that generally excites a structure's resonance. A shock event is basically a type of vibration where the excitation is non-periodic; much of the test setup and analysis between shock testing is similar to vibration testing. Plus, the tendency for shock events to induce a vibratory response in the structure makes it worthwhile to discuss the shock and vibration testing together. Mechanical shocks and vibrations have become very pervasive in our ever day lives, so measuring and measuring and understanding their impact on your system is an important part of mechanical design.

Shock and vibration measurement can be defined as "the *art* and science of measuring and understanding a structure's response to a dynamic environment." Shock and vibration testing goes beyond simply data acquisition, it is only effective when you are able to understand what the data means for your application. And it takes some creative skill to properly gather and analyze your shock and vibration data.

Shock & Vibration Measurement

What, Why, Who, When, & Where?

Before we can get into sensor selection, we need to answer some key questions:

1) What frequency range do you care about?

The frequency range will drive hardware. I've seen far too many engineers have the wrong sensor and even the wrong DAQ (data acquisition) system for their application that can lead to erroneous results.

2) What amplitude range is of interest?

Obviously, you'll need to select a sensor with a measurement range that includes the amplitudes you or your customer care about, but it also heavily influences your DAQ selection. Very small vibrations/accelerations like those in seismic applications will require not only a very low noise and high sensitivity accelerometer, but you'll also need a DAQ system with very low noise and ultra-high resolution. On the higher amplitude end, it's important to bear in mind what type of acceleration levels the DAQ hardware will see. When measuring a wider range, resolution will also be important.

3) Who needs the data and why?

You'll need to lean towards higher quality systems if your customer has a test standard they need to have the system qualified to. The United States military has a testing standard, MIL-STD-810 (vibration is section 514.6 and shock is 516.6) for example, you won't be able to qualify your system to meet such a standard with low quality equipment. On the other hand, if you just need a rough handle of the shock and vibration levels in your environment to get started in the design process or if you're trying to satisfy a curiosity, lower quality systems may be adequate. There are other applications, such as health monitoring, that aren't necessarily looking for absolute vibration values. Rather, relative vibration levels and how it changes with time is important.

4) Where is the test environment?

Will this be in the lab or in the field? If testing will be limited only to the lab then more complicated test equipment can be used. Conversely though, if the testing is done in the field, ease-of-use will be a driver of your hardware selection. The type of environment will also heavily influence sensor selection such as temperature range, humidity, electromagnetic noise, and even corrosive or radioactive conditions.

5) When is the test date?

All too often engineers realize they need testing once a problem has already presented itself. Lead time of equipment now becomes incredibly important especially because they can have 6 to 8-week lead times. Often the engineer won't have that time available to wait.

6) When will the vibration analysis need to be completed?

This may drive your software selection. If you have a limited time to perform the analysis you may want to go the route of simpler and cheaper software packages to give you that quicker overview of the data. On the other hand, if you have a development effort that has a heavy emphasis on analysis and the time available to support that analysis effort then a more complex software package may be warranted. Along that same vein, it may be worthwhile to use a programming language like MATLAB or Python to develop your own analysis scripts specific to your analysis needs.

SENSOR SELECTION

Accelerometers

Accelerometers are by far the sensor of choice for shock and vibration measurement. Accelerometers mount directly to (or in) the vibrating structure and proportionally converts mechanical energy to electrical when experiencing acceleration. Acceleration is generally represented with the gravitational constant ‘g’ which equals 9.81 m/s^2. There are three main types of accelerometers:

1) Piezoelectric Accelerometer

Piezoelectric accelerometers are the most popular and widely used for industrial applications. They typically use lead zirconate titanate (PZT) sensing elements that product electric charge or output under acceleration. Piezoelectric accelerometers have very low noise and offer superior performance over capacitive MEMS or piezoresistive accelerometers in all vibration and most shock applications. Piezoelectric accelerometers come in many different variants: triaxial or single axis, high sensitivity for seismic applications down to low sensitivity for shock testing, and even have some types that can handle extreme environments including nuclear. The major downside of piezoelectric accelerometers is that they are AC coupled so they can’t measure the gravity vector or sustained accelerations. This also prevents the engineer from integrating the data for velocity or displacement information because of their intrinsic decay properties (although it can be integrated for higher frequency vibration). But again, piezoelectric accelerometers are generally the preferred choice for industrial testing applications for their performance benefits.

Because piezoelectric accelerometers are so popular there are many different companies that sell these including: Measurement Specialties, Meggitt's Endevco Corporation, PCB Piezotronics, Bruel & Kjaer, and Dytran. Generally, the cost of a piezoelectric accelerometer will be in excess of $1,000 and they typically have long lead times of over 4 weeks.

2) Capacitive MEMS Accelerometer

MEMS (micro-electro-mechanical systems) accelerometers more than likely refer to *capacitive* accelerometers. MEMS is just the fabrication technology. This fabrication technology has brought capacitive accelerometers into the mainstream though! They are by far the cheapest and smallest accelerometer options (as the name implies!); and capacitive MEMS accelerometers are the type found in your smart phone. These accelerometers can be mounted directly to printed circuit boards which has made capacitive MEMS accelerometers the preferred choice for electrical engineers. Their low cost (typically less than $10) and small size has made them popular but capacitive MEMS accelerometers have much poorer data quality, especially on the higher frequency and amplitude end. They should generally be avoided for industrial applications, but they are a DC coupled and a great option for human-based applications. Their low cost and power consumption also make them a good choice for health monitoring.

Capacitive MEMS accelerometers are very easy to purchase and have short lead times. Using one will require some electrical design on your part though. The leading manufacturers of capacitive MEMS accelerometers include Analog Devices, Bosch Sensortec, and InvenSense.

3) Piezoresistive Accelerometer

Piezoresistive accelerometers are the premier type for shock testing. Piezoresistive accelerometers are strain gauge based so they require amplifiers and temperature compensation, but they have a very wide bandwidth (0 hertz to several thousand hertz) and low noise characteristics. Piezoresistive accelerometers can be gas or fluid damped which protects the accelerometer and prevents it from reaching its internal resonant frequency. Because they are DC coupled their output can be integrated to calculate velocity and displacement during shock events. Again, they are the premier type for shock testing, but piezoelectric accelerometers are preferred for vibration testing.

The same companies that sell piezoelectric accelerometers also offer piezoresistive options. Piezoresistive accelerometers also tend to be in excess of $1,000 each and have longer lead times of over 4 weeks.

Figure 1 provides a reference table that recommends an accelerometer type for different applications. If you want to dive a bit deeper into accelerometer selection check out our enDAQ blog post. Endevco also has a nice white paper on selecting the right accelerometer.

Application	Piezoelectric	Capacitive MEMS	Piezoresistive
Static Acceleration (0 Hz, 1 g) Gravity, Sensor Orientation		✓	✓
G- Force (0 Hz, <25 g) Rocket, Centrifugal, Aircraft		✓	✓
Seismic (<1 Hz, <1 g) Earthquake, Waves, Bridges	✓		
Low Frequency Vibration (<5 Hz, <25 g) Human Motion, Robotics	✓	✓	✓
General Vibration (5 Hz to 500 Hz, <25 g) Electric Motor, Car Suspension	✓	✓	
High Frequency Vibration (>500 Hz, <25 g) Gear Noise Analysis, Turbine Monitoring	✓		
General Shock (<100 Hz, <200 g) General Testing, Shock Absorber Testing	✓	✓	✓
High Impact Shock (<250 Hz, >200 g) Drop Testing	✓		✓
Extreme Shock (>1,000 Hz, >2,000 g) Vehicle Crash Testing, Metal on Metal			✓

Figure 1: This table provides a quick checklist on which accelerometer types work best for different testing applications.

Vibration Meters

Vibration meters offer real time vibration analysis in a handheld unit so that maintenance decisions can be made quickly in the field. They either wire to a traditional accelerometer or some even, like the one shown in Figure 2, incorporate the accelerometer into the unit cutting down on wiring requirements and complexity. Vibration meters typically don't allow the user to log long duration events (they may give you access to the last couple thousand points for some analysis), but they give RMS and peak-to-peak levels in real time. They also will typically have an algorithm to rate the overall vibration of your bearing or machine. Vibration meters can be a bit pricey at around $1,000 which sometimes won't include the cost of the accelerometer (the Fluke 805 is over $2K that has the embedded accelerometer). If you are looking to do some more in depth vibration analysis or any shock testing, a vibration meter is probably not your best option. But for that quick go/no-go vibration testing of a piece of machinery, a vibration meter is unbeatable. Fluke is the leader in hardware and software for vibration meters. Here is their vibration testing homepage.

Figure 2: The Fluke 805 vibration meter incorporates an accelerometer directly into the main electronics handheld unit to cut down on complexity and wiring.

Data Loggers

An often-overlooked option for shock and vibration measurement is to use a data logger that combines the accelerometer with the data acquisition system, power, and memory into one package. This is the preferred option for engineers who need ease-of-use and portability. Apps on your smart phone can be considered simple data loggers but they tend to have a maximum sample rate of 100 Hz and poor data quality. Higher end data loggers like enDAQ's S4 line (formerly Slam Stick X) effectively bridge the gap to the more expensive shock and vibration measurement systems by incorporating a high quality piezoelectric accelerometer as opposed to the cheaper capacitive MEMS accelerometers found in most vibration data loggers.

Figure 3: The enDAQ S3 sensor is incorporates the accelerometer, power, and data acquisition electronics into one small handheld package.

Shock and vibration data loggers generally have much shorter lead time (a few days) and lower cost ($500 to $2,000) than building your own vibration measurement system. There are a lot of different companies that make shock and vibration data loggers and a lot of different options. Here's a post comparing 6 different products.

Non-Contact Displacement Sensors

Although accelerometers are the most popular choice in shock and vibration measurement, displacement sensors measure the displacement of a vibrating structure. Calculating between displacement, velocity, and acceleration is accomplished with integration/differentiation (here's a calculator for simple harmonic motion applications). The downside to using these is that it's measuring *relative* motion between two structures. These are near impossible to use in the field because a fixed mounting and distance is required between the sensor and equilibrium position of the vibrating structure. They can also be quite a bit more expensive and complex than accelerometer-based systems. That being said, displacement sensors can be preferred in some applications that prevent the use of accelerometers such as rotating components (although a data logger could be used), or when the accelerometer's mass would too greatly influence the motion of the system. Generally, displacement sensors should be avoided for shock testing for fear of damaging the sensors.

Figure 4: Laser displacement sensors (and capacitive sensors) offer a sensor option that allows direct measurement of displacement without contacting or interfering with your test article.

Laser displacement sensors (KEYENCE is the leader) and capacitive displacement sensors would be the two main sensor types that would be useful for vibration testing. These systems will typically be upwards of $5,000 and lead times over 4 weeks.

Microphones

Sound is not often thought of as a way to measure vibration, but it should be! After all sound, by definition, is a vibration that travels through the air in the form of pressure waves. Microphones offer a cost-effective means of measuring high frequency vibration and is especially useful to determine how a system's vibration changes with time. Health monitoring applications can greatly benefit from using a microphone on cost and simplicity.

Microphones aren't limited to applications where cost is a concern. Some acoustics applications will use high end microphones for vibration testing and analysis. You'll notice a lot of the accelerometer companies also offering high end microphones, like PCB Piezotronics. Microphones and acoustic analysis can be a great option for some applications, but if you need absolute shock and vibration data, not relative change, then microphones probably won't work. They also won't be able to analyze modal shapes and specific/discrete points along your structure. But again, they are very effective for overall frequency analysis.

Strain Gauges

Often times the end goal of vibration testing is determining the stress and strain in your structure. Strain gauges can be an effective sensor type to directly measure the strain of your test article. A change in capacitance, inductance or resistance is proportional to the strain experienced by a strain gauge so that mechanical energy can be converted to an electrical signal. Strain gauges do present some challenges though. They can be very sensitive to temperature change, material properties of your structure, and the adhesive used. Instrumenting a structure with strain gauges is very much an art and difficult to do. They also require strain gauge amplifiers which are also difficult to work with. That being said, strain gauges are cost effective (from a material point-of-view, not labor), and allow the engineer to directly measure the strain in his/her structure.

Data Acquisition (DAQ) System Selection

Now that you have the sensor, something needs to capture and record the sensor's output! Data acquisition systems do just as the name implies: collect/acquire data. The global leader in DAQ systems is National Instruments, but there are many other options out there too. National Instruments offers unparalleled customization options with both their modular hardware and their software program, LabVIEW. Measurement Computing offers some more cost-effective alternatives to National Instruments, but they're less well-known and trusted. For the more advanced user there are systems like m+p International's VibRunner that can capture 100s of channels for modal analysis applications on larger structures. Something like this will cost tens of thousands of dollars, whereas low-channel systems will cost hundreds or thousands of dollars.

1) Sensor Mating

The sensor selection will often dictate the type of DAQ system that will work based upon the sensor's output. Does the sensor have a digital output? Is it 0 to 30 volts, is ±5 volt? Low sensitivity sensors may require amplification of their output. It will simplify your shock and vibration measurement system setup significantly too if the DAQ system can provide the excitation voltage to your sensor to power it so that clunky power supplies can be avoided.

2) Sample rate

It's good practice to sample at a rate 10 times greater than the upper interested frequency range to accurately capture the vibration profile. For most shock and vibration measurement applications a DAQ system will need a sample rate of at least a few thousand hertz, but it all depends on what frequency range that your or customer is concerned about. Take for an example an excerpt of vibration data recorded on a test aircraft shown in Figure 5. The data sampled at 2,500 Hz is made up of many different frequencies ranging from 50 to 600 Hz. Now if this same dataset is sampled only at 500 Hz (shown in the dashed red line), the vibration environment looks much different and would be inaccurately represented.

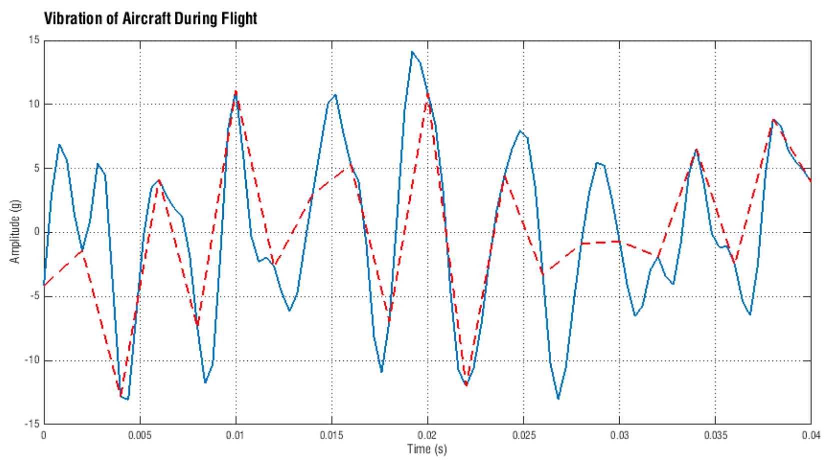


Figure 5: An excerpt of vibration data was sampled at 2,500 Hz on an aircraft during a test flight. When sampled at only 500 Hz the dataset becomes grossly misrepresented.

General guidelines on sample rate are over 10,000 Hz for shock testing, over 5,000 for general vibration, and around 1,000 Hz for slower vibration or movement.

3) Resolution

Resolution is generally specified as bits which can then be used to calculate the resolution in acceleration units. For example, let's say that an accelerometer system has 16-bit resolution. This means that it has 2^{16} (65,536) acceleration levels or bins it can measure. Figure 6 illustrates the importance of resolution on a simple 60 Hz sine wave with two lines of different resolutions. 5-bit resolution provides 2^5 discrete acceleration levels that can be detected while 5-bit resolution only provides 2^3 or 8 discrete levels.

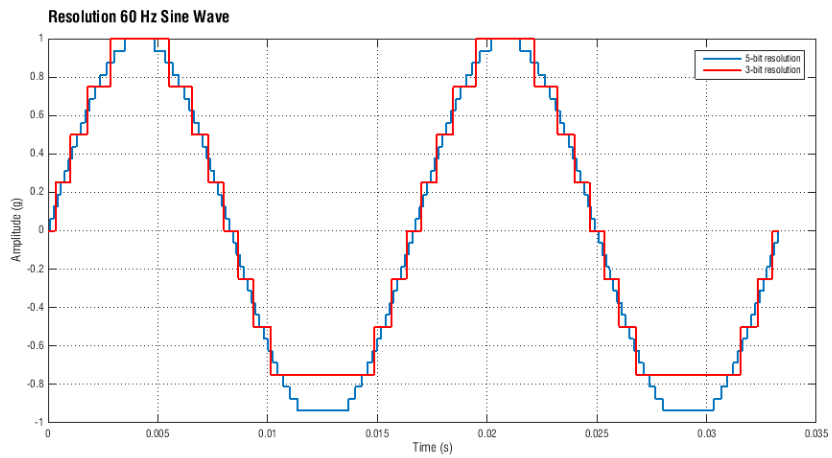


Figure 6: Two 1g sine waves are plotted on each other with different resolutions.

When looking for a DAQ system they will typically have a resolution on the order of 16 or 24 bits. The lower quality shock and vibration data loggers however may only have a resolution of 12 bits or less which may not be adequate for your application.

4) Filtering

Filtering can be used to remove unwanted frequency content and should be an important part of your evaluation of different DAQ systems. High pass filters remove lower frequency vibration and is inherent to all piezoelectric accelerometers (resistor and capacitor in series) which gives these accelerometers the AC response. Low pass filters are more important however to prevent aliasing which can't be filtered out in software. Aliasing causes a signal to become indistinguishable or to look like a completely different signal as shown in Figure 7. It's important to realize that an analog lowpass filter is needed to prevent aliasing. Once a signal is aliased, it can't be filtered out digitally in software.

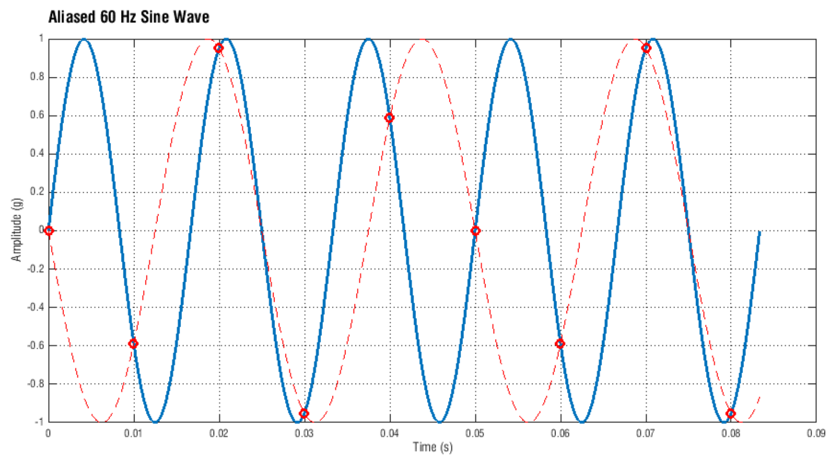


Figure 7: A 60 Hz sine wave when sampled at 100 Hz can erroneously make the vibration profile look like a 40 Hz signal.

Now the question remains as to what *type* of filter should you use? An ideal filter would uniformly pass all frequencies below a specified limit and eliminate all above that limit. This ideal filter would have a perfectly linear phase response to the same upper frequency limit. But ideal filters don't exist; there is some compromise that needs to be made on a filter's amplitude and phase response. There are four main different types of filters:

1) Butterworth

A Butterworth filter is known for its maximally flat amplitude response and a reasonably linear phase response. The Butterworth filter is the most popular for vibration testing.

2) Bessel

The Bessel filter has nearly perfect phase linearity, so it is best suited for transient events like shock testing. It has a fairly good amplitude response but its amplitude roll-off is slower than the Butterworth or Chebyshev filter.

3) Chebyshev

The Chebyshev has a faster roll-off in the amplitude response which is achieved by introducing a ripple before the roll-off. They have a relatively nonlinear phase response.

4) Elliptic

The Elliptical filter has the steepest roll-off in the amplitude response, but it has a ripple in both the pass band and stop band. In addition, its phase response is highly nonlinear. This is only used for applications where phase shift or ringing is not of a concern. It should generally be avoided to the common test engineer because of its tendency to distort complex time signals.

In Figure 8 the performance of these filters are compared for a 1,000 Hz cut off frequency and 5th order filters. The plots were generated in MATLAB using the Signal Processing Toolbox and the analog filter functions. Figure 9 takes a closer look at the filter performance in the passband (0 to 1,000 Hz). The Chebyshev and Elliptical filters offer that sharper amplitude roll off but at the expense of large ripples in the passband and nonlinearity. Butterworth filters offer the best of both worlds with a relatively sharp amplitude roll off. Bessel has the best phase response and a reasonably good amplitude response but note how early it begins filtering. In the stopband it still allows over 10% of the single until roughly 2.5x the cut off frequency.

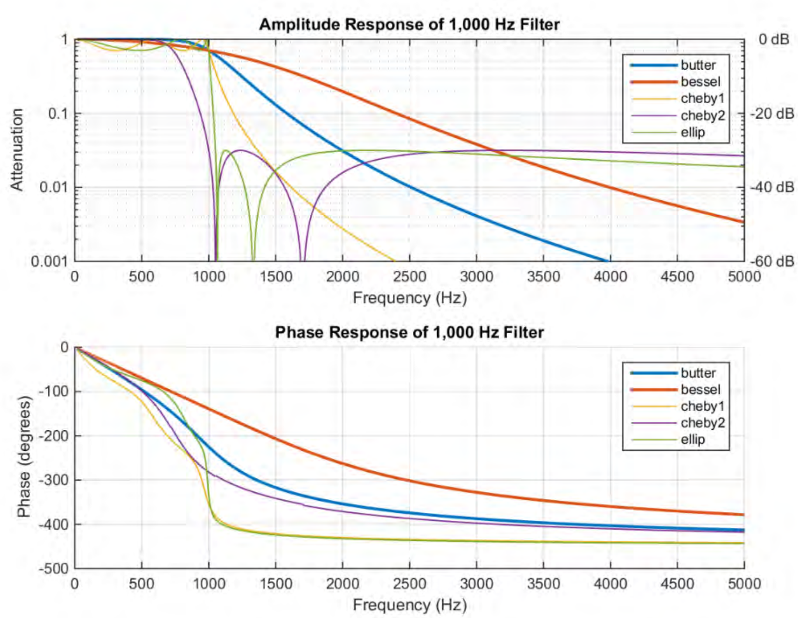


Figure 8: Different filter types are compared on their amplitude response and phase for a 1,000 Hz 5th order filter.

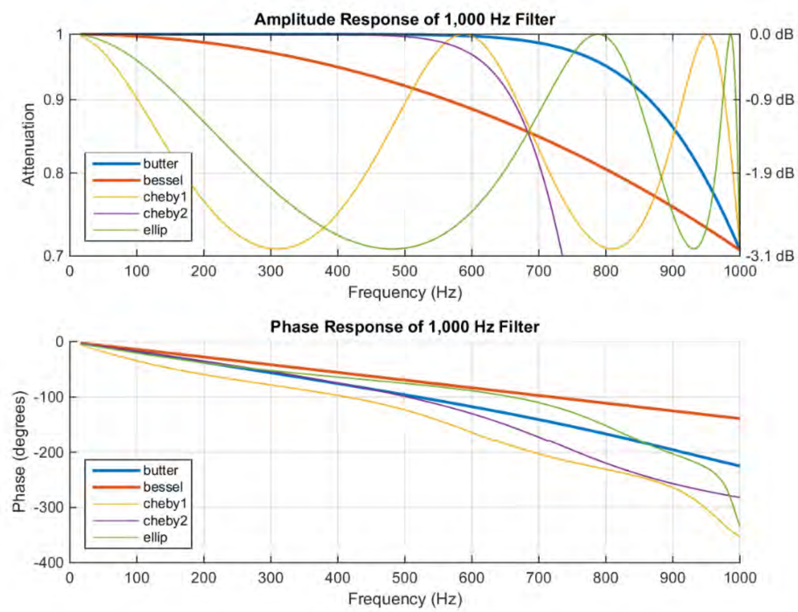


Figure 9: Different filter types are compared in the passband on their amplitude response and phase for a 1,000 Hz 5th order filter.

Which filter you choose will depend on your application, but in general, the Butterworth filter is best for vibration and the Bessel is best for shock testing. And above all, you should avoid a system that does not offer some low pass filtering to avoid aliasing.

EQUIPMENT SETUP

Accelerometer Mounting

The method of mounting the accelerometer to the vibrating structure and the coupling between the sensor and the measurement point is a critical factor in obtaining accurate results. Mounting types and methods influence the resonant frequency of the accelerometer. If/when the accelerometer’s mounting results in a reduction of its natural frequency the bandwidth (or useful frequency range) is reduced. Accelerometers, piezoelectric in particular, have a very high amplification factor at resonance, too, so it’s important to avoid using a mounting method that shifts the resonance into the frequency range of your vibration environment. There are six main mounting methods listed below. Their frequency response is compared in Figure 10.

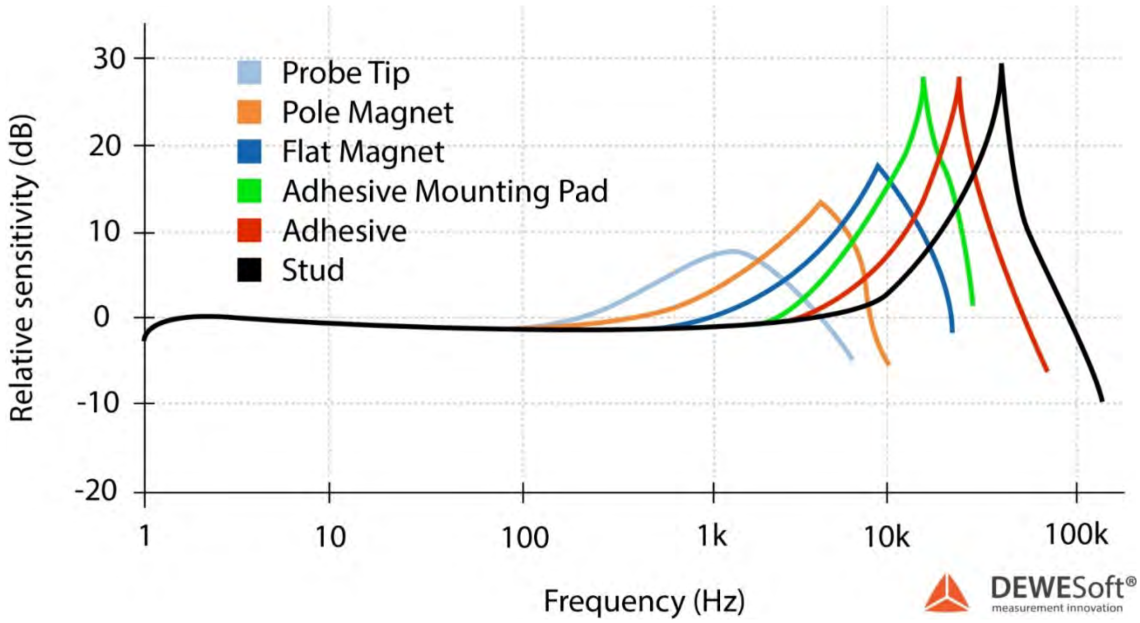


Figure 10: The frequency responses for some common mounting methods are compared.

1) Stud Mounting

This represents the best mounting method in terms of accelerometer performance and will maximize the frequency response of the accelerometer. It's important to torque the accelerometer down to the manufacturer's specifications. Inadequate mounting torque can reduce the frequency response. Perhaps the most important factor when stud mounting is to use a coupling fluid such as grease, oil, petroleum jelly or beeswax. Using a coupling fluid solves a lot of mounting problems including inadequate mounting torque, surface flatness, and surface roughness. Figure 11 provides a comparison on the frequency response for when an accelerometer is under torqued and/or no coupling fluid is used. The data presented is from an excellent [MEGGITT/Endevco presentation and resource on accelerometer mounting].

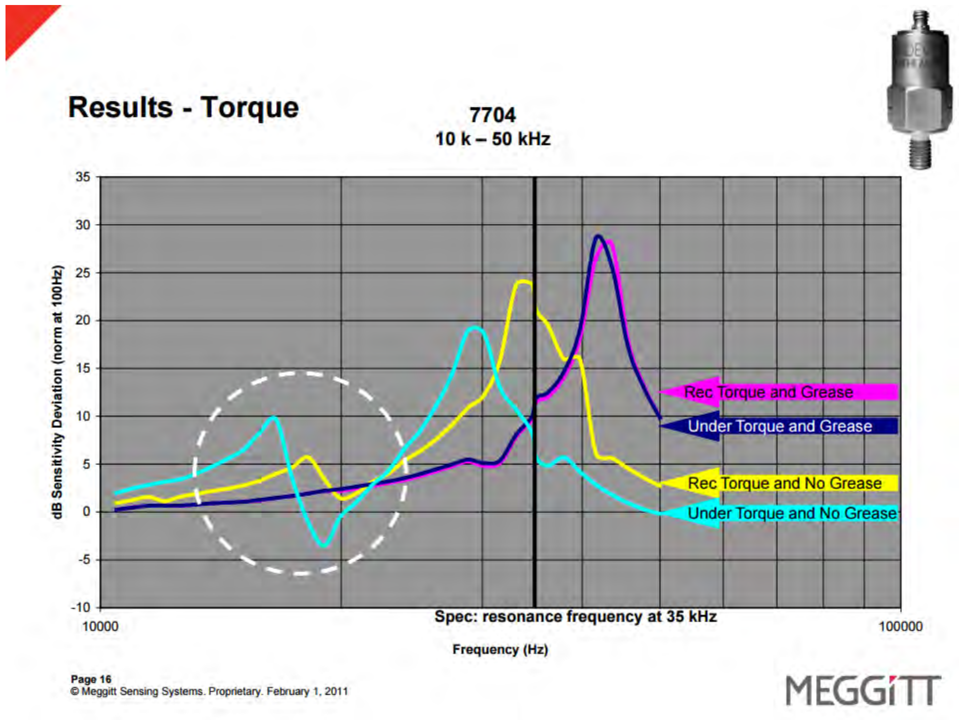


Figure 11: The frequency response of an accelerometer can be greatly reduced when not using a coupling fluid.

2) Adhesive

There are several different adhesives to consider when mounting your accelerometer. Surprisingly though, the most important parameter for accelerometer performance is not the adhesive type, rather it is the thickness of the adhesive that plays the largest role. Figure 12 provides a few plots of the frequency response of different adhesives (data is taken from that same Endevco presentation) which illustrates what little difference there is.

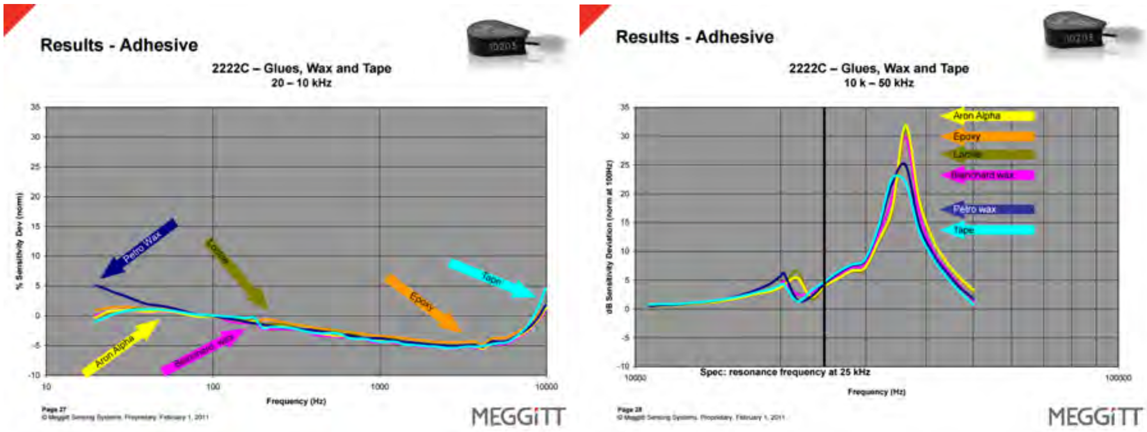


Figure 12: The frequency responses of different adhesives are compared which shows that the adhesive itself has little impact on the performance.

a. Loctite or Epoxy

Loctite or a two-part epoxy offers a permanent mounting option which improves repeatability and testing time. There are many different types of Loctite, but 454 is a popular type for accelerometer testing. Must times the accelerometer can also be dismounting with a small shear load from the tap of a hammer (be careful not to damage the sensor or test article though!). Accelerometer manufacturers will recommend using a de-bonding agent like Acetone and gently twisting the accelerometer.

b. Wax or Duct Seal Putty

Wax or duct seal putty are other popular adhesives that aren't as effective as Loctite or epoxy but still offer surprisingly good frequency response. The major benefit of using this type of adhesive is that removal of the accelerometer is much easier. Hi-Test, who does much of the shock and vibration testing for large military systems, recommends using duct seal putty for shock testing because it can mechanically filter out high frequency (and thus low energy) vibration content that could risk exciting an accelerometer's internal resonance. Petroleum wax would have similar benefits but note that this can have adverse effects for an application that is interested in higher frequency vibrations. Blanchard wax is a much stiffer adhesive and may be preferred for these applications.

c. Double Sided Tape

Double sided tape is often thought to not be strong or stiff enough to be used as an effective mounting method for accelerometers. They do offer the lowest frequency response of all the adhesives but for many applications it is still plenty effective enough. enDAQ has had good luck with the 3M 950 adhesive transfer tape for its products (a 5 yard roll is actually included with each unit). Endevco's study found that the thickness of the adhesive is the most important factor, and this is only 0.005" thick (0.1 mm). If the 950 tape is adequately compressed, then there is no discernable difference in the enDAQ sensor's performance compared to mounting with bolts. The downside of this particular tape is that it's quite tacky and can be difficult to remove. 3M offers an adhesive eraser wheel which is effective at removing this tape and other adhesives.

3) Adhesive Mounting Pad

Adhesive mounting pads offer the very high frequency response of adhesives and stud mounting but allow the engineer to easily swap out accelerometers. For large structures when you may be doing modal analysis it is much easier to instrument the structure with adhesive mounting pads first (no wiring, and less expensive) then attach the accelerometers for your test. At the end of testing the accelerometers can easily be taken off and brought to the next test. If, after analyzing the data, the team determines more testing is needed then having the mounting pads remain on the structure ensures that the tests can be repeatable. Adhesive mounting pads also help prevent epoxy from damaging expensive accelerometers. Here are some accelerometer mounting bases from PCB, but there are many accessory options out there.

4) Magnetic Mounting Base

For ferrous magnetic structures a magnetic mounting base allows easy and mess-free accelerometer mounting. There are two types of magnetic bases: flat, and curved. Flat offers the best frequency response. You should use caution with magnetic mounting bases to not damage your structure or injure yourself. But these are a great solution for short term testing applications. Here are some accelerometer magnetic mounting bases from PCB.

5) Handheld or Probe Tip

Some applications can be difficult to reach for proper mounting and/or have sensitive coatings or materials that prevent adhesives or bolting. A probe tip can be utilized to press the accelerometer to the structure by hand. This obviously drastically reduces the measurable frequency range to less than 100 Hz or so. Because humans can't remain perfectly still either, they are not recommended for frequency ranges less than 10 Hz.

Wiring

One of the biggest pains of vibration measurement is typically how to deal with wiring. Wiring can sometimes require modifications to the test environment to accommodate the wiring from sensors to DAQ systems to a power source. This can limit where testing occurs and can sometimes require special "test samples" that are systems specifically designed for testing, not field use. Often test data is required on site, on a fielded unit, not a glorified laboratory!

Figure 13: Wiring is often a necessary evil in vibration testing, but it can create a headache for the engineer.

Wiring also can introduce mechanical, electrical, and electromagnetic noise so great care should be taken to mitigate the chances of the wiring introducing such noise. Generally, a reduced cable length offers the best practice of minimizing unwanted noise and is where a high quality vibration data logger offers unique benefits.

1) Ground Loops

Unwanted differences in the electrical potential between the sensor and the instrumentation will result in erroneous DC offsets and voltage drops. The entire measurement chain should be grounded at only one point (which is the very purpose of grounding!). To prevent these ground loops there should be sufficient insulation between the accelerometer body and ground. Unfortunately, this insulation may mechanically dampen the coupling of the accelerometer which will also influence vibration data. Another way to mitigate this issue is to shorten the cable length as much as possible.

2) Electromagnetic Noise

In particular EMI laden environments (like those found on surface ships) electromagnetic noise can greatly sully the data quality. Again, the best practice is to avoid long cable lengths where possible, but sometimes special cabling may be needed that is has reinforced shielding to offer EMI protection. This of course comes with an added price tag but of only a few hundred dollars in most instances.

3) Mechanical Noise

Cable motion will literally induce mechanical strain on the accelerometer which the accelerometer will measure and erroneously report as vibration in your structure. This strain and acceleration will influence the data quality of the sensor as it tries to measure the vibrating structure directly without interference. To prevent this motion which causes erroneous data the cable should be secured as close as possible to the accelerometer. O-rings, cable clamps, and adhesive cable clamps are typically used.

4) Risk of Losing Connection

The last challenge wiring presents is the possibility that you may lose connection during a test. So, strain relieving your cabling is very important to prevent mechanical noise but also to help ensure connection is not lost. In large setups there can be a concern about wire mismatching where the engineer may think he/she is analyzing data from one accelerometer when in fact he/she may be looking at data from a completely different area of the structure. It’s very important to double check that all accelerometers are properly wired, labeled, and strain relieved to prevent losing or confusing data sources.

MEGGITT offers a nice resource on sensor wiring and cabling that is worth a read.

Environmental Concerns

The largest environmental concern is temperature. All sensors will have some temperature dependence, especially piezoelectric accelerometers and strain gauges. Therefore, temperature compensation will be needed to offset these effects. Some sensors will have the necessary hardware to compensate the output integrated into the sensor package, but in some instances, the engineer may need to add a temperature sensor and perform their own compensation. In addition, there are some other sensor concerns, especially for accelerometers.

1) Base Strains

Many piezoelectric accelerometers are using a piezoelectric element with a tip mass mounted to the base and measuring shear. Therefore, when the surface the accelerometer is mounted to experiences strain, this can often appear as "acceleration" in your data. Accelerometer manufacturers are aware of this and design their sensors to minimize the effect, but base strains can still result in erroneous data.

2) Acoustic Noise

As we've mentioned, noise is simply pressure waves that can excite the accelerometer and your structure. Normally though these induced vibrations are much less than the actual inherent structural vibrations, but it is something to consider.

3) Transverse Vibrations

Accelerometers are sensitive to vibrations acting in directions perpendicular or orthogonal to the main axis of interest. This transverse sensitivity is typically less than 5% for single axis accelerometers. Triaxial accelerometers typically have a little higher transverse sensitivity.

4) Magnetic Fields

The magnetic sensitivity of accelerometers is very low but should be considered in especially extreme environments like naval ships.

5) Humidity

Most accelerometers are sealed to ensure reliable operation in humid environments, but this humidity can cause issues at the cable connections especially. Especially humid environments may require special accelerometers that come pre-wired to ensure accurate data. Data loggers and vibration meters may need special housings or accessories for these environments.

6) Corrosive Substances

Most accelerometers should be constructed of high-quality materials that are resistant to corrosive agents, but plastic housed accelerometers or data loggers may be susceptible. It's important to ensure these substances do not come in contact with your equipment.

A final concern about the environmental impacts on your test setup is what the DAQ electronics will need to experience and survive. Often engineers may overlook the survivability of these electronics which is fine for testing in the laboratory but testing out in the field may require robust electronics and/or special accessories and cases to dampen shock and vibration levels that the electronics are subjected to.

ANALYSIS OVERVIEW

Single Degree of Freedom Vibration

To understand why vibration analysis is useful and what it entails, we must first think of a simple mass spring damper model shown in Figure 14.

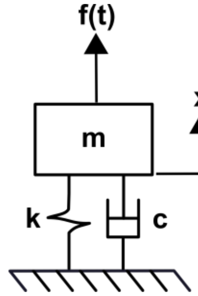


Figure 14: A simple single-degree-of-freedom system is represented where m is the mass, k is the spring constant, c is the damping coefficient, x represents the displacement from equilibrium and f defines the force acting on the mass as a function of time.

As review, some simple equations which describe the motion of this system and define key parameters are listed in Table 1. For those that are unfamiliar, there are plenty of resources out there that can provide more information on free vibration of single degree of freedom systems.

Table 1: Equations for a Single Degree of Freedom System

Equation	Description
$m\ddot{x} + c\dot{x} + kx = F(t)$	Differential equation of motion
$w_n = \sqrt{\frac{k}{m}}$	Natural frequency as radians per second
$f_n = \frac{w_n}{2\pi} = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$	Natural frequency as hertz
$\xi = \frac{c}{2\sqrt{km}}$	Damping ratio
$Q = \frac{1}{2\xi}$	Quality factor

To understand why a vibration test engineer cares about these parameters, let's take a look at a transmissibility plot shown in Figure 15. Transmissibility looks at how a SDOF system responds to a base excitation with a given damping and natural frequency. When the excitation frequency is much larger than the system's natural frequency, the system isolates that base vibration. When the system's natural frequency is much larger than the base excitation frequency the system will neither amplify nor dampen an input vibration. The worst-case scenario is when the input frequency is equal to the system's natural frequency which will amplify that input by a factor approximately equal to Q.

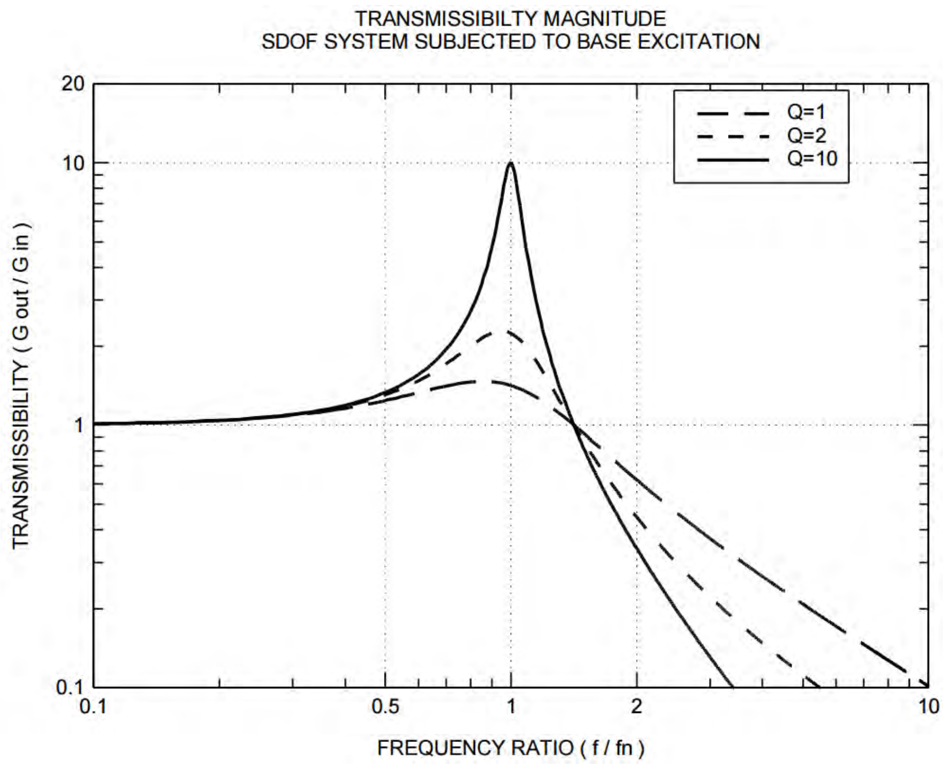


Figure 15: The transmissibility illustrates how a SDOF system will respond to a base excitation. This plot was taken from Tom Irvine's vibrationdata publications that have some supporting information.

Most systems in the real world can't be represented by a SDOF system, but every structure, no matter how complex, can be factored down to individual single-degree-of-freedom (SDOF) systems. And most real-world excitations are not perfect sine waves but rather a collection of sine waves. Nevertheless, vibration analysis is used to predict how a system will react to a given input and provides the tools for an engineer to ensure survivability of his/her system. But all this is only made possible when the vibration environment is understood and known, which is why we do vibration testing!

Simple Analysis in the Time Domain

When analyzing vibration data in the time domain (amplitude plotted against time) we're limited to a few parameters in quantifying the strength of a vibration profile: amplitude, peak-to-peak value, and RMS. A simple sine wave is shown in Figure 16 with these parameters identified.

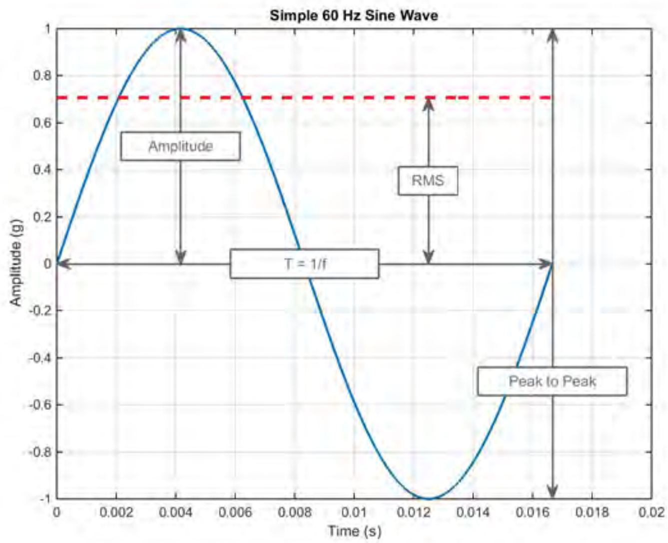


Figure 16: A simple 60 Hz sine wave is shown with the amplitude, peak-to-peak, RMS, frequency, and period identified.

1. The **peak or amplitude** is valuable for shock events, but it doesn't take into account the time duration and thus the energy in the event.
2. The same is true for **peak-to-peak** with the added benefit of providing the maximum excursion of the wave, useful when looking at displacement information, specifically clearances.
3. The **RMS** (root mean square) value is generally the most useful because it is directly related to the energy content of the vibration profile and thus the destructive capability of the vibration. RMS also takes into account the time history of the wave form.

Vibration is an oscillating motion about equilibrium so most vibration analysis looks to determine the rate of that oscillation, or the frequency which is proportional to the system's stiffness. The number of times a complete motion cycle occurs during a period of one second is the vibration's frequency and is measured in hertz (Hz). For simple sine waves the vibration frequency could be determined from looking at the waveform in the time domain, but as we add different frequency components and noise, we need to perform spectrum analysis to get a clearer picture of the vibration frequency.

Fast Fourier Transform (FFT)

FFT Background

Any waveform is actually just the sum of a series of simple sinusoids of different frequencies, amplitudes, and phases. A Fourier series is that summation of sine waves, and we use Fourier analysis or spectrum analysis to deconstruct a signal into its individual sine wave components. The result is acceleration/vibration amplitude as a function of frequency, which lets us perform analysis in the frequency domain (or spectrum) to gain a deeper understanding of our vibration profile. Most vibration analysis will typically be done in the frequency domain.

A discrete Fourier transform (DFT) computes the spectrum, but nowadays this has become synonymous with the fast Fourier transform (FFT) which is just an efficient algorithm for the DFT. enDAQ has a blog of FFT basics and one on vibration analysis which provides more information. The most important thing to understand though is that the number of discrete frequencies that are tested as part of a Fourier transform is directly proportional to the number of samples in the original waveform. With N being the length of the signal, the number of frequency lines or bins is equal to N/2. These frequency bins occur at intervals (Δf) equal to the sample rate of the raw waveform (Fs) divided by the number of samples (N), which is another way of saying that the frequency resolution is equal to the inverse of the total acquisition time (T). *To improve the frequency resolution, you must extend the recording time.*

$$\Delta f = \frac{1}{T} = \frac{F_s}{N}$$

The lowest frequency tested is 0 Hz, the DC component; and the highest frequency is the Nyquist frequency (Fs/2).

Constructed Sine Wave and FFT Example

To illustrate how an FFT can be used, let's build a simple waveform with three different frequency components: 22 Hz, 60 Hz, and 100 Hz. These frequencies will have amplitude of 1g, 2g, and 1.5g respectively. The following figure shows how this waveform looks a little confusing in the time domain and also illustrates how the signal length affects the frequency resolution of the FFT.

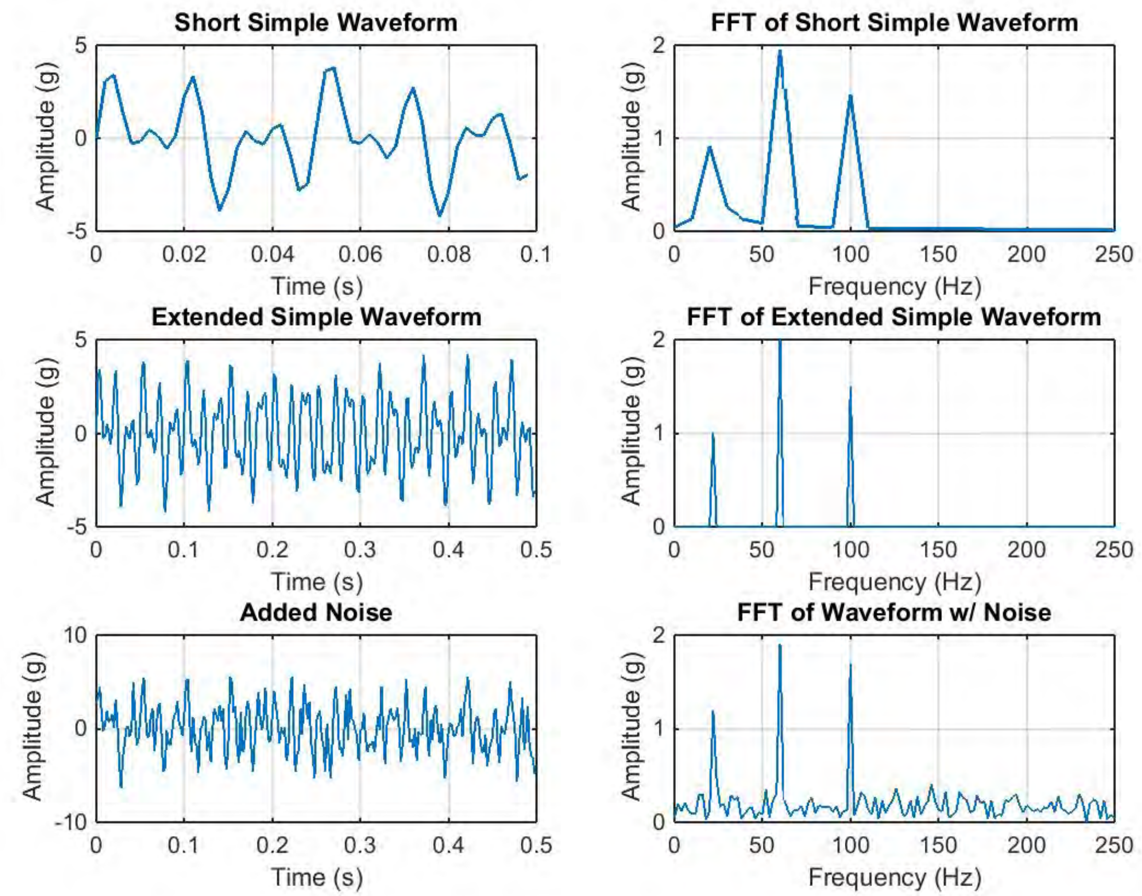


Figure 17: Constructed waveform with 22, 60, and 100 Hz frequency components is shown at varying sample lengths and with noise to illustrate usefulness of FFT analysis.

If we sample this wave at a 500 Hz rate (500 samples per second) and take an FFT of the first 50 samples we're left with a pretty jagged FFT due to our bin width being 10 Hz (Fs of 500 divided by N of 50). The amplitudes of these frequency components are also a bit low. But if the range is extended to the first 250 samples as shown then the FFT is able to accurately calculate both the frequency and amplitude of the individual sine wave components.

Not that the "pure" waveform didn't look confusing enough in the time domain, but if broadband noise is added as shown in the bottom plots then the waveform becomes even less distinguishable. This is the power of an FFT: it is able to clearly identify the major frequencies that exist to help the analyzer determine the cause of any vibration signal.

Windowing

Fourier transforms perform an integral from negative infinity to positive infinity, but one can only acquire data over a discrete time period. So, a Fourier transform must repeat the signal infinitely to perform the transform. When the acquired data begins and ends at 0, or if there are an integer number of cycles, then this infinite repetition will cause no problems. But if these are not true, there will be leakage in the frequency domain because the signal is distorted as shown in Figure 18.

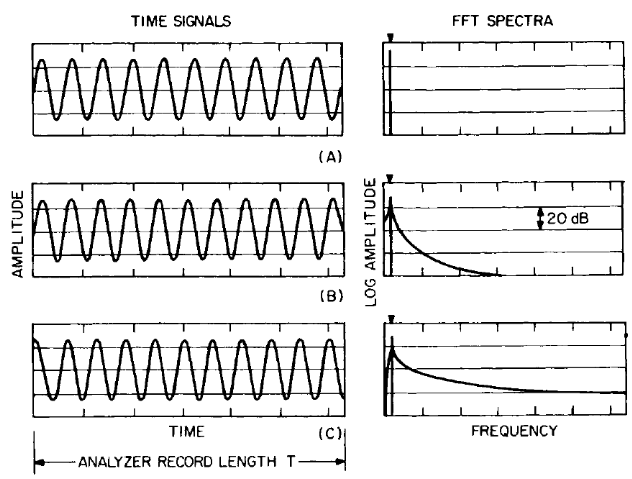


Figure 18: The time-window effects are shown when using a FFT analyzer without windowing (or rather a uniform window) are shown. (A) represents an integer number of cycles so that the spectrum has a clear spectral line. (B) and (C) represent time signals where there are a half integer number of periods, but with different phase relationships, which gives a different discontinuity and spectral leakage.

Remember that a Fourier transform looks to calculate a series of sine waves to represent the data. If there is a discontinuity in the data (by not beginning and ending at 0 or not having an integer number of cycles) then the FFT analyzer will need many terms to approximate the apparently discontinuous signal.

In order to minimize this error, windows are used to better make the signal appear periodic for the FFT process. The most common windows are the rectangular window, the Hanning window, the flattop, and the force/exponential window (used for impact testing). The important thing to understand is that all windows distort the data. They are a necessary evil sometimes but aren't always required if the vibration tester can satisfy Fourier's request by completely observing the signal in one sample of data. For more information check out enDAQ's blog on Fourier transform leakage. When looking at software packages, an option for windowing is important for many applications.

Spectrogram and FFT Comparison

Car Engine

In real world applications there will typically be many different frequency components of a vibration profile as well as mechanical and electrical noise. Let's look at some data taken on a passenger car engine while it was idling and do some vibration analysis. This data was generated with an enDAQ sensor as part of a how-to video series if you're interested in some more details about the test setup.

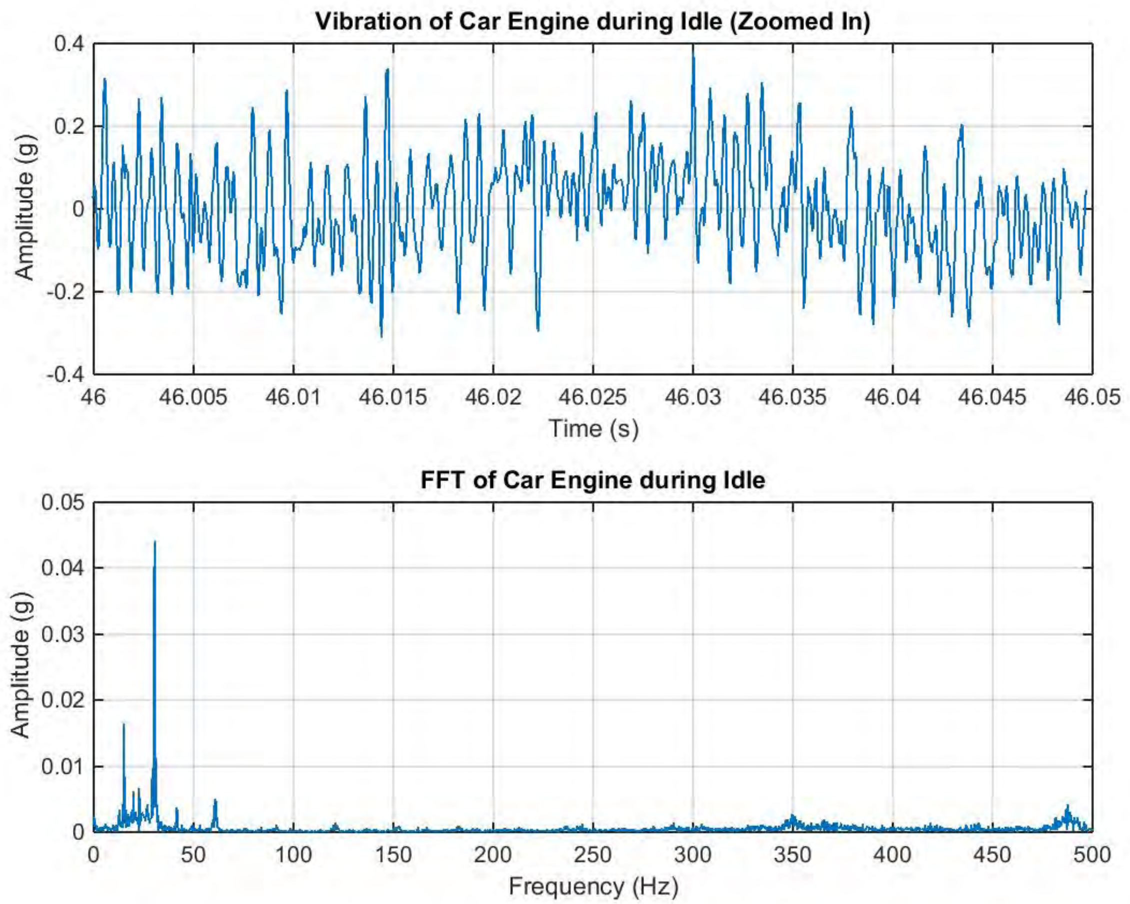


Figure 19: A car's engine during idle clearly shows the 30 Hz dominate frequency which equals twice the crank shaft rotation frequency of 15 Hz (900 RPM) where a peak is also visible.

We can use spectrum analysis of the vibration profile to indicate what the engine's crank shaft rotation speed was. This is a 4-cylinder 4-cycle engine. The engine operates with two pairs of pistons moving out of phase with each other and two piston combustions per crank shaft rotation, so the dominant frequency of the engine's vibration will be twice the crank shaft rotation speed (here's a nice video on how a 4-stroke engine works). In the FFT there is clearly a dominate frequency at 30 Hz or 1,800 RPM which tells us that at idle the crank shaft is rotating at 900 RPM (or 15 Hz) where there is also a peak in the FFT. The use of an FFT in our vibration analysis gave clues on what was causing the measured vibration.

In many applications the vibration frequency will change with time and you can run into trouble if you only look at the FFT. Let's zoom out of the area where the car engine is running at a relatively fixed rate and compute an FFT of the entire signal. In this test the engine sat off for a period of time, idled, then the engine was revved before letting it idle again and finally turning it off. The vibration frequency changed pretty dramatically throughout the test, but the FFT doesn't capture that. We know from the previous plot that when it was idling there was a fairly significant dominant vibration frequency of 30 Hz, but this peak gets muted when you try and look at the FFT of a changing vibration environment.

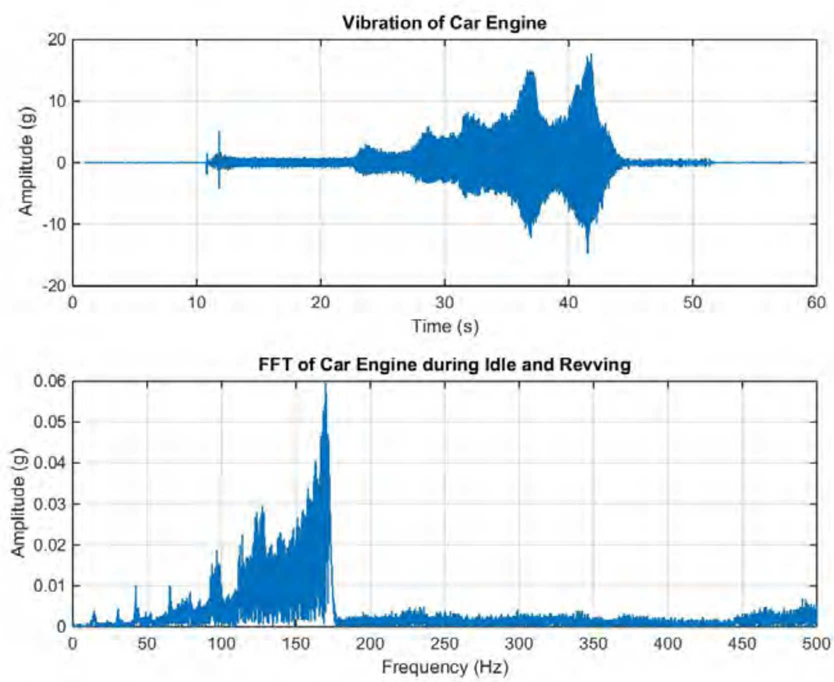


Figure 20: The time history and FFT are shown from an enDAQ sensor mounted to an engine block while it was revved to change the dominate frequencies.

In this example, and others where the vibration frequency changes with time, we need a spectrogram. A spectrogram works by breaking the time domain data into a series of chunks and taking the FFT of these time periods. These series of FFTs are then overlapped on one another to visualize how both the amplitude and frequency of the vibration signal changes with time. Turn this three-dimensional surface plot of FFTs on its side, add a color scale to represent the amplitude (often works best when you look at the color/amplitude on a logarithmic scale) and you're left with a spectrogram!

Back to that car engine example where the engine was revved for a bit. The spectrogram shown below illustrates how the dominate frequencies change with time in relation to when the car engine was idled and revved. Using a spectrogram, the analyzer gains a much deeper understanding of the vibration profile and how it changes with time.

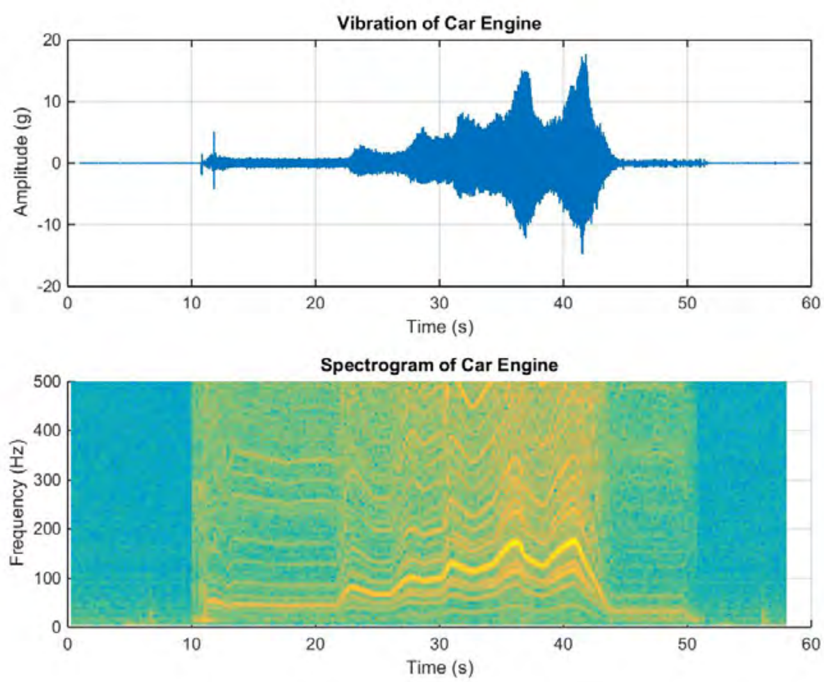


Figure 21: Spectrogram of car engine shows how crank shaft speed change (when engine is revved) affects vibration frequencies which become apparent in spectrogram.

Power Spectral Density (PSD) Examples

A lot of vibration in the real world, especially during transit, can be called “random” vibration because it is motion at many frequencies at the same time. FFTs are great at analyzing vibration when there are a finite number of dominant frequency components, but power spectral densities (PSD) are used to characterize random vibration signals. A PSD is computed by multiplying each frequency bin in an FFT by its complex conjugate which results in the real only spectrum of amplitude in g^2. The key aspect of a PSD which makes it more useful than a FFT for random vibration analysis is that this amplitude value is then *normalized* to the frequency bin width to get units of g^2/Hz. By normalizing the result, we get rid of the dependency on bin width so that we can compare vibration levels in signals of different lengths.

PSDs are powerful because the area under the curve (or integral) in the frequency domain represents the RMS vibration level for that frequency range. And RMS vibration is related to the energy in the environment. PSDs are also often used in test standards because of how they cancel out the effect of bandwidth of a frequency spectrum. Let's go through an example from MIL-STD-810G. Figure 514.6C-5 (page 312 from the standard) describes the typical acceleration levels that jet aircraft cargo are exposed to as shown below.

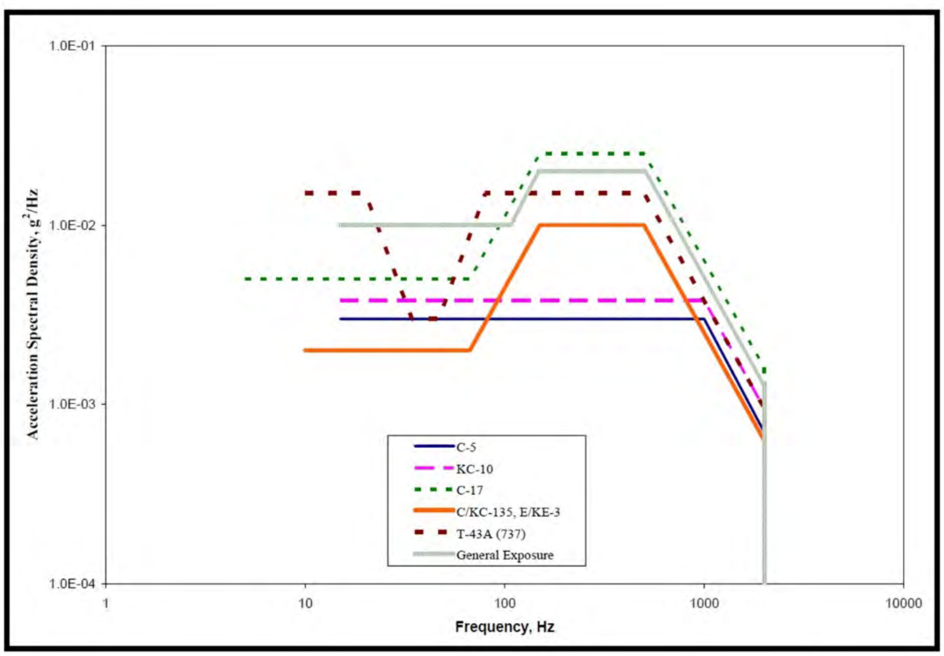


Figure 514.6C-5. Category 7 - Jet aircraft cargo vibration exposure.[1]

Figure 22: Typical vibration levels that jet aircraft cargo will be exposed to.

If you were developing something for the government that was going to be transported with a jet aircraft, you would be required to do some testing on your device/equipment to prove it can survive prolonged exposure to those vibration levels. Most shaker control systems will have these exposure profiles built in but they can also be constructed easily given some known PSD levels and rise/decline rates. Let's take a look at some data captured by an enDAQ sensor when it was being excited with these vibration levels. All this data is available to download.

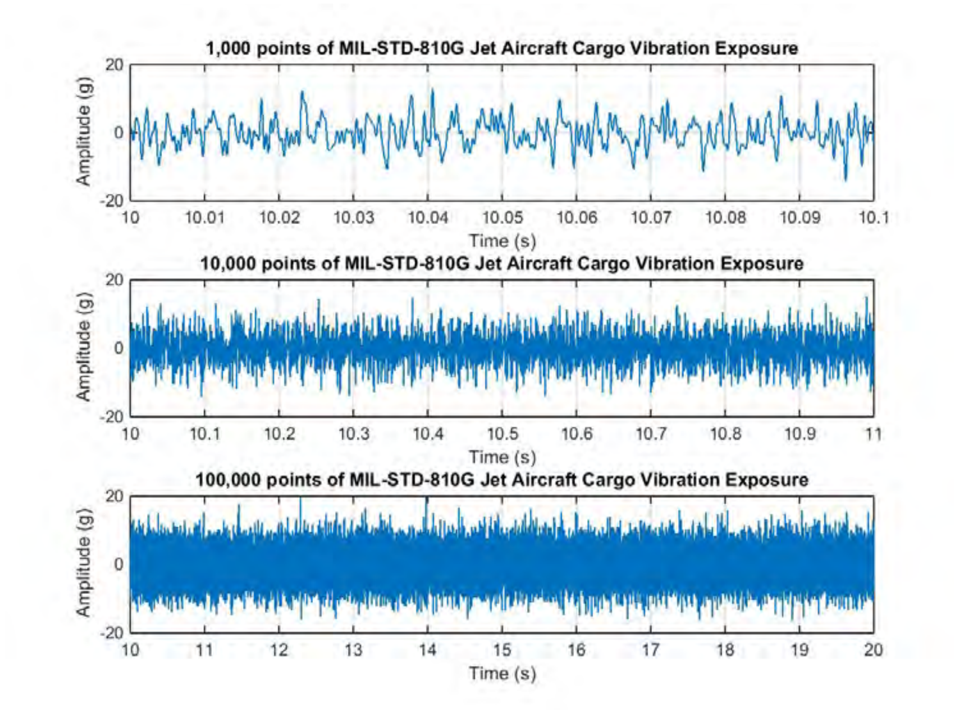


Figure 23: Raw acceleration data from an enDAQ sensor when exposed to random jet aircraft cargo vibration levels.

Obviously, the raw data in the time domain doesn't tell us much although the amplitude of the vibration in the time domain of nearly 20g is surprising. Let's compute both FFTs and PSDs of these signals to see how the signal length affects the amplitude for the FFT but not the PSD.

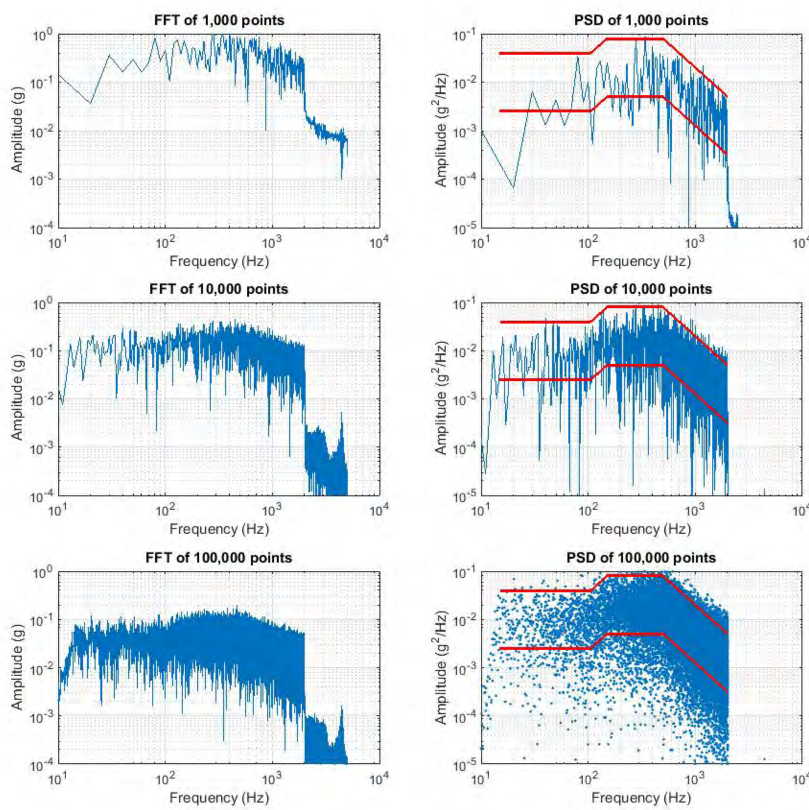


Figure 24: The amplitude of the PSD doesn't change with different signal lengths but the FFT does.

The red lines in the PSD are the input error bounds that the shaker is trying to keep the signal within. As you see, the PSD of different signal lengths just fills in this area, but the amplitude doesn't change overall. The FFT amplitude however shifts down as the bandwidth is increased. This normalization that occurs in a PSD calculation makes it so much more desirable to be used when analyzing random vibration signals.

Now let's put ourselves in the shoes of someone buying equipment to be integrated into a larger system. We will want to make sure this equipment can handle the vibration levels in this environment so we may require a test organization to quantify that environment. An enDAQ sensor (formerly Slam Stick) recently recorded data on a commercial flight to do just this. Its aim was to understand the type of vibration levels humans were exposed to during flight. Check out the data below along with a PSD (again this is all available to download).

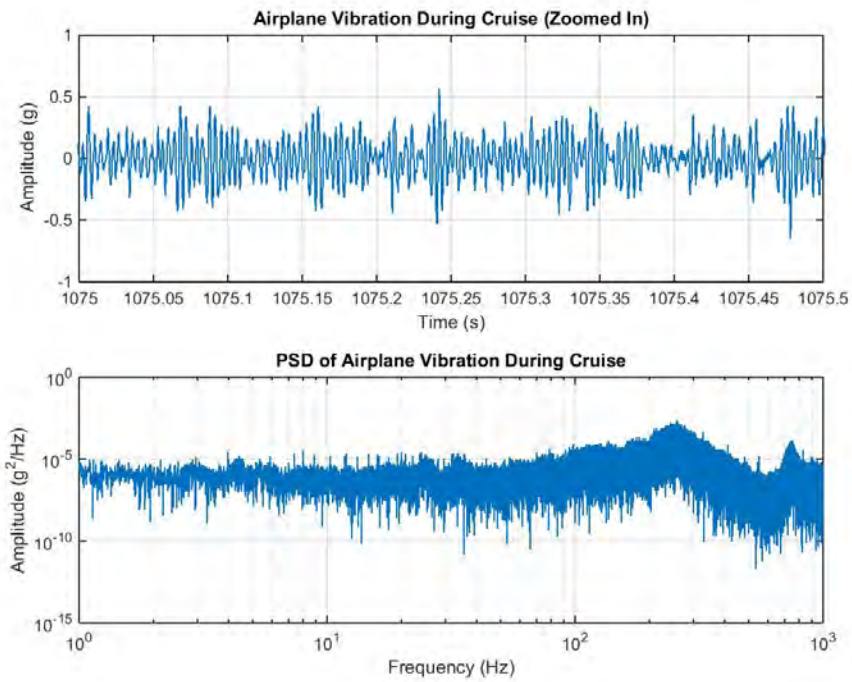


Figure 25: Random vibration levels on the seat of a commercial airliner.

There is definitely a resonance of that seat around 250 Hz, but there is surprisingly steady broadband vibration of 10^{-5} g^2/Hz from 1 Hz to 1 kHz. This PSD could be used to program an exposure profile in a laboratory shaker to allow an engineer to do some in-house testing ahead of a field test. Because this was from *actual* data in the *actual* environment, the engineers have confidence that their system can survive. It's incredibly valuable to go out and actually measure the environment than to simply rely on some test standard. These test standards will recommend using the standard's data as a guide, but they typically try and encourage the engineer to go out and get the *actual* vibration data. Nothing beats the real data!

RESPONSE SPECTRUMS

Vibration Response Spectrum

The vibration response spectrum (VRS) is used to quantify how a system will respond for a given vibration input. It takes the vibration input, in the form of a PSD, and plots what the response will be as a function of a system's natural frequency. The vibration response spectrum calculates the transmissibility functions for a range of frequencies. Engineers use this in the design process to understand what natural frequencies to avoid or target for their system.

Let's use the airplane seat vibration data as an example. If we were an engineer designing a component for that seat, like the personal video screen, we would need to understand what natural frequencies to avoid. Taking a look at the raw data and the PSD (Figure 26) it's obvious that 250 Hz should be avoided, but how bad would a system with that natural frequency respond in that environment?

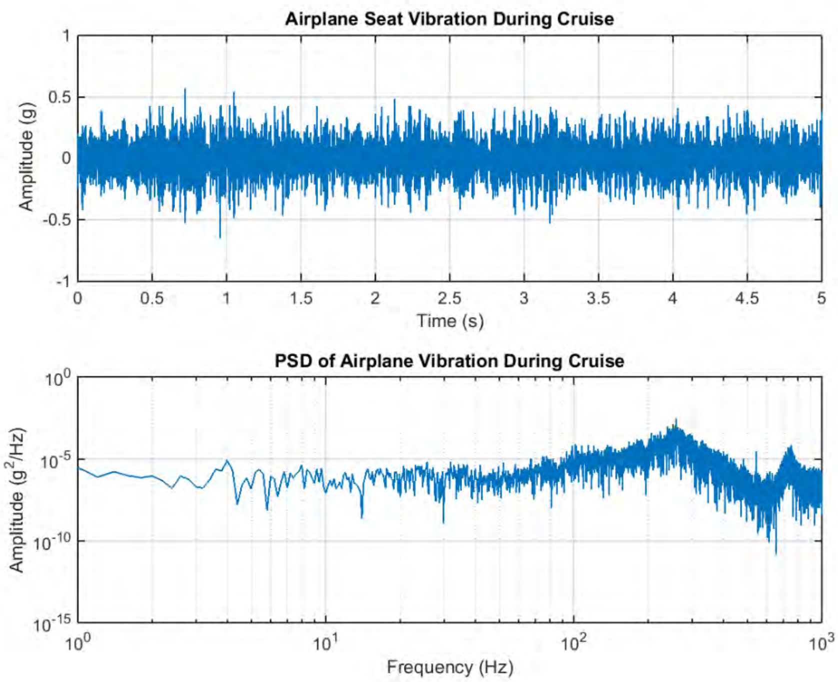


Figure 26: The raw data and a corresponding power spectral density are shown for 10,000 data points recorded with an enDAQ sensor on the base of a commercial airplane seat.

Using the VibrationData Toolbox published by Tom Irvine & enDAQ, the transmissibility ratio for a 250 Hz single-degree-of-freedom system can be calculated, shown in Figure 27. This assumes the system has a quality factor (Q) of 10. The response of such a system would amplify the vibration amplitude by 100 times! The overall RMS vibration level of a 250 Hz is nearly 0.8g RMS compared to the 0.1g RMS level of the base vibration. That's a significant increase in the vibrational environment that the screen would have to survive.

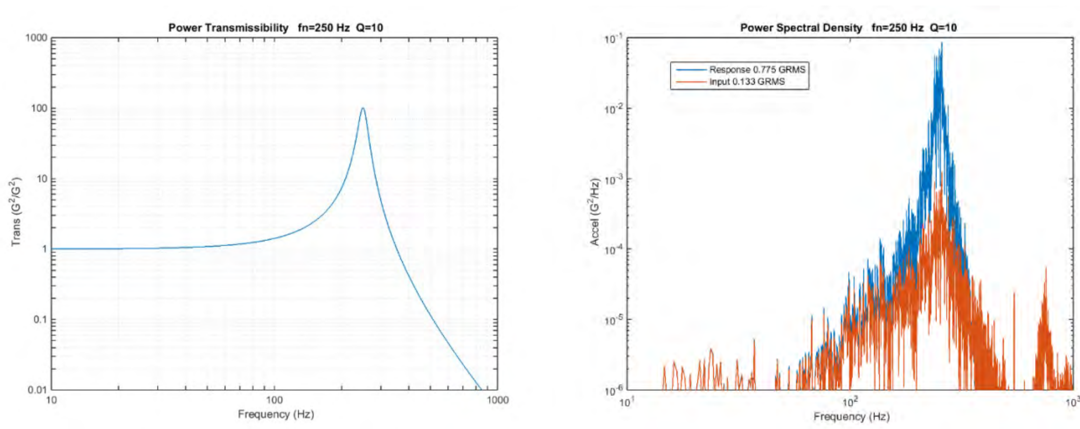


Figure 27: Transmissibility of 250 Hz SDOF system with the airplane seat input vibration profile is shown on the left. The corresponding power spectral density of such a system in that environment is shown on the right.

What about other frequencies besides 250 Hz? How would those systems respond? That's where the vibration response spectrum comes in: it calculates the response acceleration (measured by RMS) for a range of natural frequencies as shown in Figure 28. It also uses a Rayleigh distribution to determine the n-sigma peak to use as a safety factor during the design process.

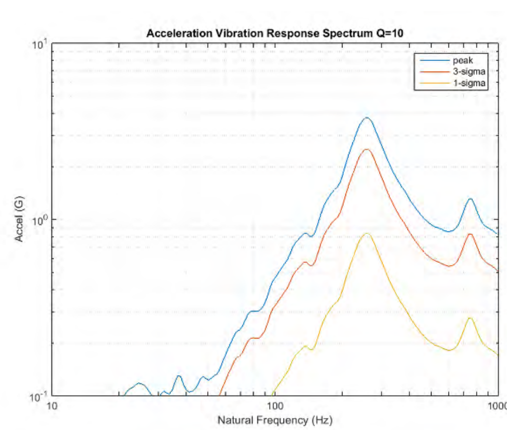


Figure 28: The vibration response spectrum for the airplane seat data calculates the response for different natural frequencies of a candidate system.

From the vibration response spectrum, the engineer knows to either us some isolator mounts with a natural frequency below 100 Hz to dampen the vibrations or a stiff mount in excess of a couple hundred hertz natural frequency to at least not amplify the vibration levels in the environment.

Let's take this example a step further and develop a test standard PSD from the experimental data. That data that was captured with the enDAQ sensor represents actual data, but can a simplified PSD be developed off that experimental data? Again, using the MATLAB GUI package, a simplified PSD can be created that envelopes the maximum expected flight level plus some margin. This is a more prudent approach because conditions experienced experimentally may vary in the future (the weight of the passenger in the seat, temperature in the cabin, engine speed etc.). Using a trial-and-error approach the script derives the least possible PSD that meets the VRS requirement of the raw data shown in Figure 29.

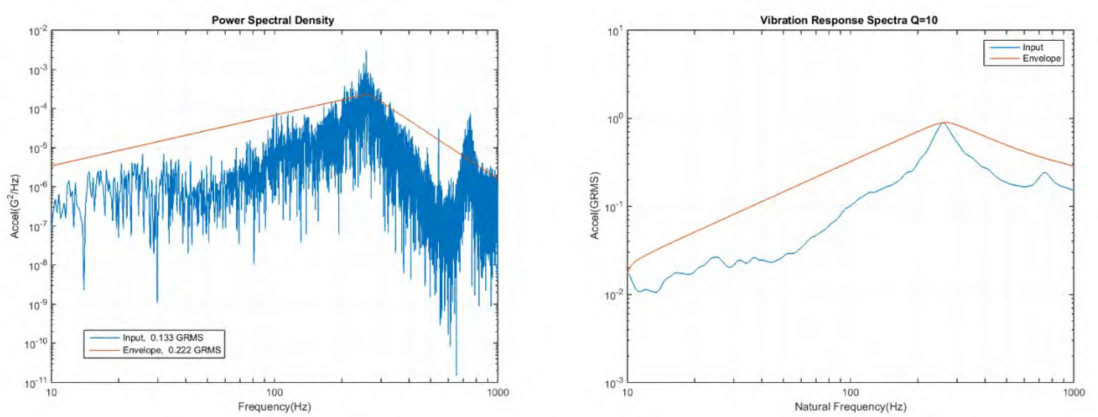


Figure 29: An enveloped PSD is calculated using a vibration response spectrum to ensure it meets or exceeds the VRS of the experimental data.

The vibration response spectrum of the simplified PSD is shown in Figure 30. It still envelopes the same levels as that shown in Figure 28, but it does so more conservatively. This PSD may be distributed to customers so that they can design their components accordingly and test them to appropriate vibration levels. Note the relative displacement shown in Figure 30. If isolator mounts are used, then it's important to ensure they can withstand the expected relative displacement levels so they don't bottom out.

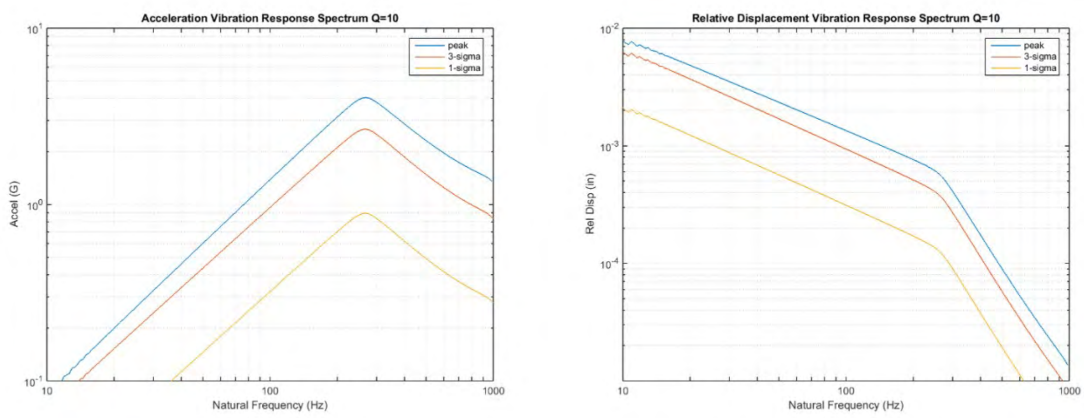


Figure 30: The vibration response spectrum of the simplified PSD is shown along with the relative displacement.

Tom Irvine's 16th webinar goes through the vibration response spectrum in much more detail and is a great reference if interested in the vibration response spectrum. More detail is available on his VRS tutorial.

Shock Response Spectrum

Similar to the vibration response spectrum, a shock response spectrum is used to calculate the response for a given shock excitation. The math and use case is very similar in both instances: it enables the engineer to design his/her system avoiding certain natural frequencies that would amplify the shock input.

Let's look at an academic example of designing a system to survive a 1g, 1 second half sine pulse. We'll explore the response from seven different resonant frequencies (and corresponding spring stiffness) ranging from 0.063 Hz to 4.0 Hz. The system is shown in Figure 31, this information is all taken from the vibrationdata SRS educational animation page.

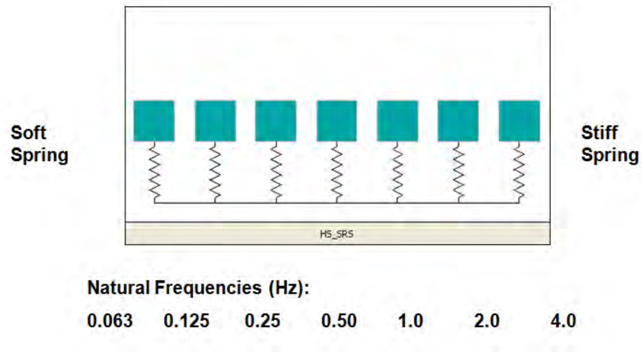


Figure 31: A seven spring system is shown with natural frequencies increasing by a power of 2 between each other.

Figure 32 shows six frames of the response out of these springs as they experience the shock input. The full video is available to download on [Tom Irvine's vibrationdata page]. One can see the spring on the far-left experience very little overall motion but it had to withstand a significant amount of relative motion and spring compression. On the far right the spring tracks the base input with very little spring compression. The middle systems experience widely oscillating acceleration throughout the input and then after the shock impulse has ended.

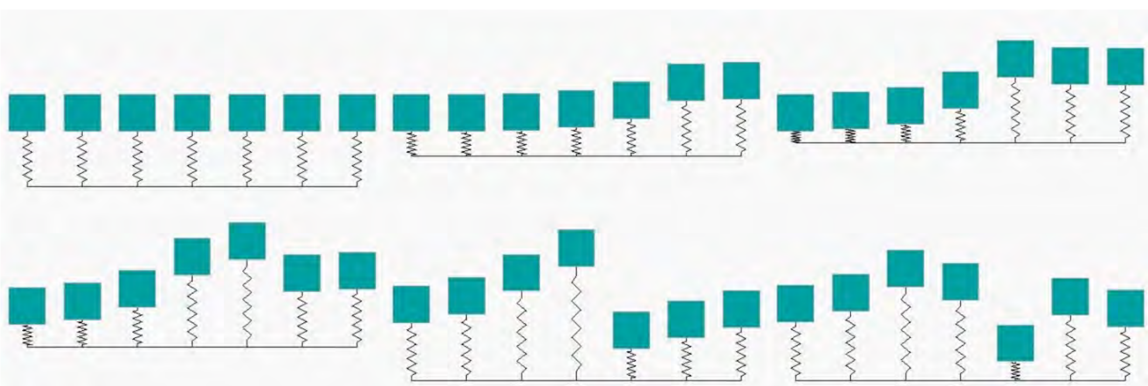


Figure 32: From top left to bottom right the frames are spaced approximately 0.25 seconds apart as the base input goes through a 1 second half sine pulse.

Using the [VibrationData Toolbox] published by Tom Irvine & enDAQ, we can calculate the response out of these systems shown in Figure 33. Notice how the stiffest spring tracks the input nicely and then quickly rings out after the base excitation is done. The softer springs also oscillate after the base input is finished but they do so much more slowly and experience their maximum acceleration levels when the input is already finished. Figure 34 plots the relative displacement the springs need to endure during the event and afterwards. This illustrates that if you go the route of a damper, you need to ensure it has enough spring compression available for your environment.

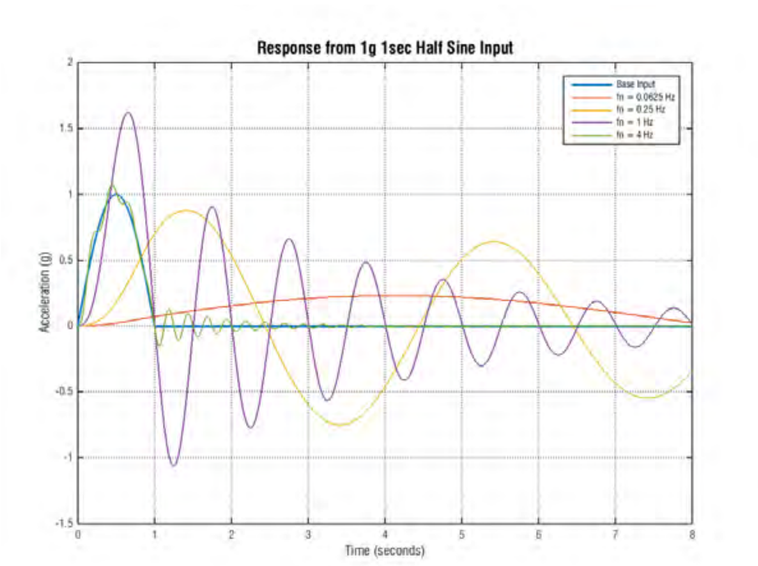


Figure 33: Response from different springs for the given base input of 1g, 1 second half sine pulse.

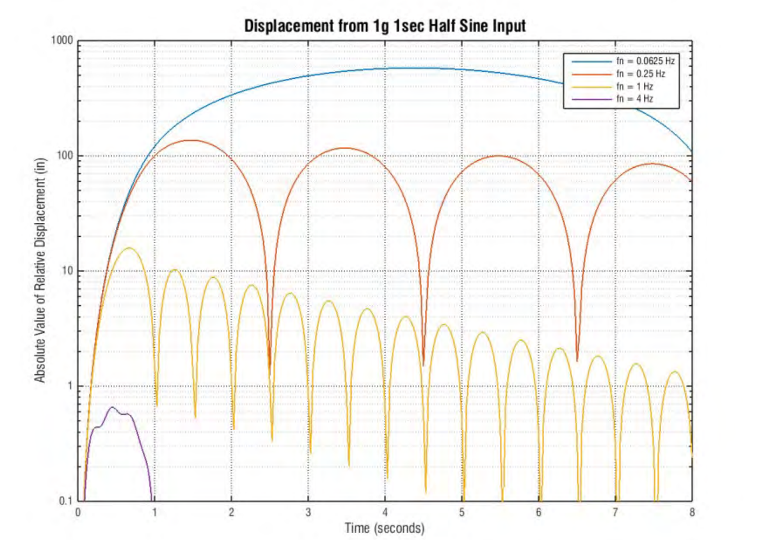


Figure 34: The absolute value of the relative displacement between the masses and the base input is plotted on a logarithmic scale to illustrate the much larger spring compression that the softer springs need to endure.

Instead of testing each spring, a shock response spectrum can be used to calculate the response for a range of natural frequencies, plotted in Figure 35. This plot can be used by the design engineer to determine frequencies that should be avoided in his/her design. This example is an academic one but even so, an engineer may be surprised that for a 1 second half sine input, the worst natural frequency a system could have is around 0.8 Hz, not the 0.5 Hz of the input. In real world applications you will have real test data that will have many frequency components. As always, with these analyses your analysis can only be as good as the raw experimental/input data.

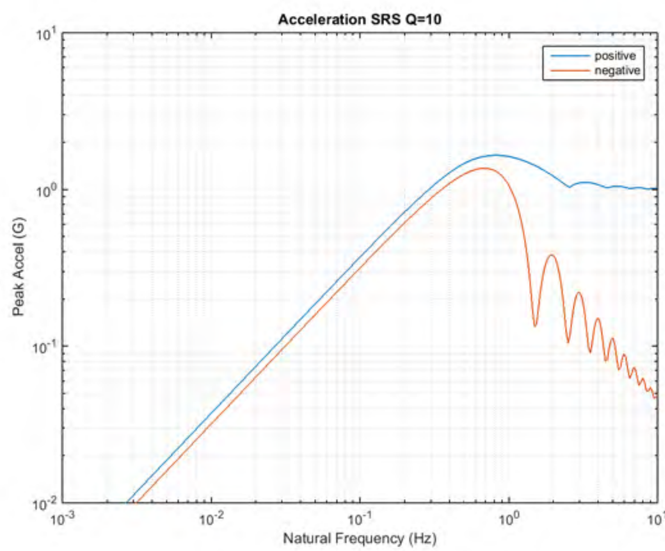


Figure 35: The shock response spectrum is shown for a 1g 1 second half-sine pulse input.

Tom Irvine's 23rd webinar covers the classical shock pulse and the shock response spectrum if you are interested in more information. Beyond the more basic shock response spectrum, a look at the pseudo velocity shock response spectrum may be a prudent exercise if/when designing a system to survive shock.

Modal Analysis

Modal analysis is the logical next step of vibration testing and looking at response spectrums. It allows the engineer to determine key dynamic parameters of their structure:

- Modal resonant frequency
- Modal damping
- Mode shape

Picture a flat plate supported in the center with an accelerometer positioned in one of the corners. Then excite the plate with a sinusoidal sweep of different frequencies but fixed amplitude and measure the response from the accelerometer. If you do this an accelerometer may measure the type of response shown in Figure 36. You may expect that the output from the accelerometer would also be fixed because of the fixed input levels, but this is the whole beauty of modal analysis! The response amplifies as the force is applied with a rate of oscillation closer to the resonant frequencies in the system.

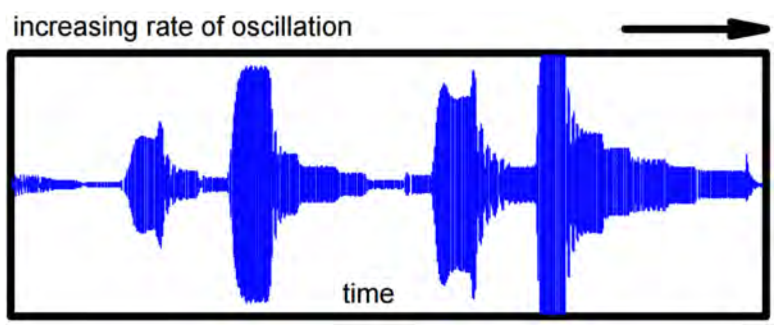


Figure 36: Response from accelerometer on a plate measuring acceleration as the plate is excited with a range of different frequencies, but a fixed force amplitude.

If a frequency response function is applied to the data the resulting plot is a function of frequency shown in Figure 37. This allows the engineer to directly see where the resonant frequencies lie but with curve fitting, you can also determine the damping characteristics of each mode.

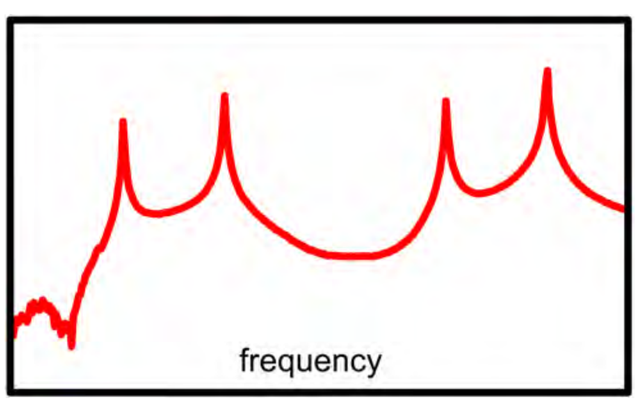


Figure 37: Frequency response function from a modal analysis test.

If a grid of accelerometers is placed around the plate and the same exercise is repeated, you can begin to start seeing modal shapes at each one of these resonant frequencies. The first four modes of this representative plate are shown in Figure 38: a first bending mode, a twisting mode, the second bending mode, and a second twisting mode. For an interesting video on the modal shapes of a plate, check out this video.

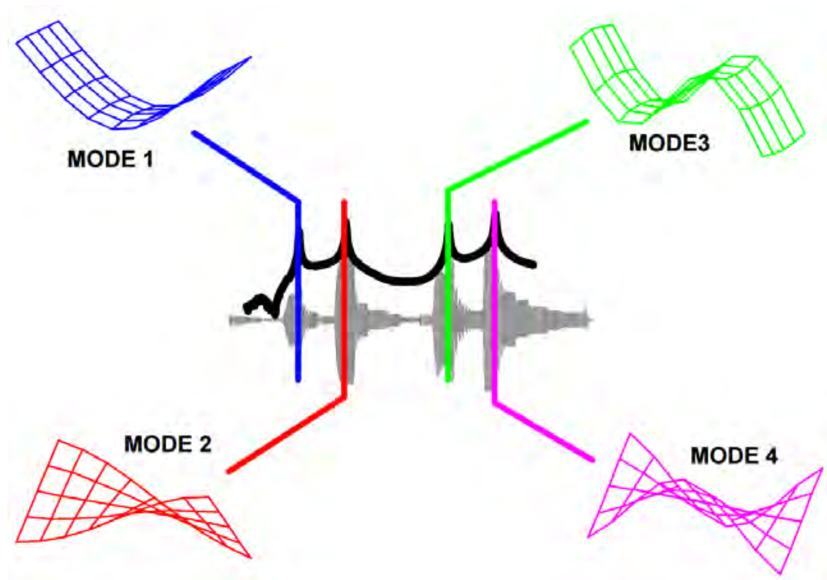


Figure 38: Mode shapes emerge at each resonant frequency which provides more information on the dynamic characteristics of your structure.

Understanding a structure's mode shapes help the engineer better design his/her structure. Performing experimental modal analysis also helps the engineer correlate or validate a finite element model so that they can have more confidence in their design and optimize it for a particular operational environment.

Modal analysis is a very powerful tool, but it typically requires a fairly expensive and complex test setup (many wired accelerometers, a shaker and/or impact hammer, large data acquisition system, and a powerful software package). So, it has its limitations and is traditionally reserved for expensive and/or large structures for testing and design. A typical design engineer for a smaller or lower volume product/system may not be able to afford this type of analysis and testing.

For hardware and software, m+p International seem to offer some of the best that we've come across but there are other options too. Typically, though, a modal analysis setup will cost tens of thousands of dollars. But the information it provides is arguably easily worth the cost for some applications!

If you are interested in finding out more on modal analysis, check out Dr. Peter Avitabile's Modal Space articles (the previous images are from this collection of articles). He has been doing modal analysis for 40 years and "grown up" with the industry, so finding an expert with more experience than him is very difficult, if not impossible! Brüel and Kjaer also have a two part Structural Testing document (part 1 is mechanical mobility measurement. Part 2 is modal analysis and simulation). These documents were written back in 1988, but they are still applicable even today, especially the fundamentals. The most thorough and modern resource we've come across is available from the Modal Shop, *The Fundamentals of Modal Testing*.

Simulating Shock & Vibrations in the Laboratory

Shock and vibration testing in the field is a great way to get operational data on your system's response to its environment and/or to quantify the environment you intend to operate in. But as the design process advances and prototypes are constructed it will be advantages to do some controlled shock and vibration testing in the laboratory. There are a couple main purposes of laboratory testing:

- Qualification testing
  - During design process
  - To meet test or regulatory standards
- Fatigue testing
- Modal analysis
- Evaluating performance characteristics

General Shock and Vibration Testing

There are two main types of vibration shakers/exciters for general shock and vibration testing: electrodynamic (ED) and hydraulic. Figure 39 provides a plot comparing the operating ranges of these two types of exciters. Electrodynamic is much more common because of the wider frequency range, their linear behavior, and their wide range of operating conditions (shock and SRS pulses in addition to vibration). But for maximum displacement and lower frequency ranges a hydraulic shaker would be preferred.

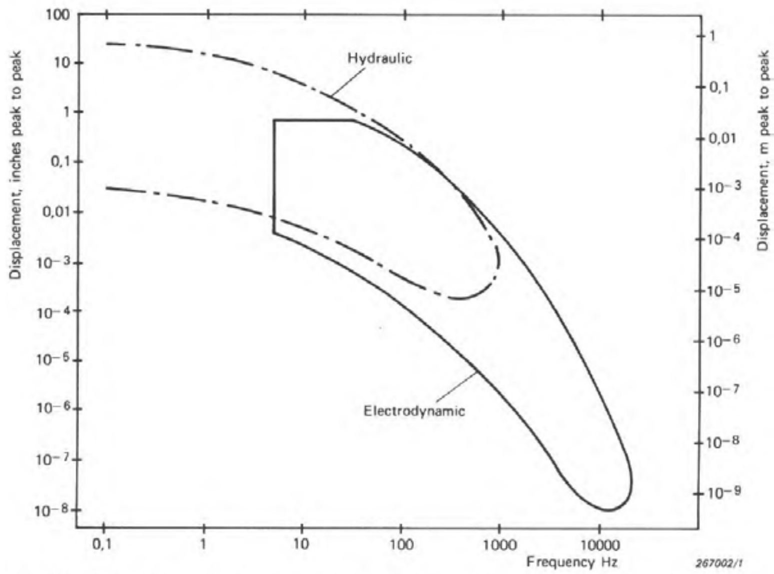


Figure 39: The useful operating regions of hydraulic and electrodynamic vibration shakers. This plot is from the Brüel and Kjaer's Mechanical Vibration and Shock Measurements. This book was published in the 80s so the performance ranges have changed since then slightly, but this data is still effective at highlighting the difference between the two types of vibration shakers.

At enDAQ, we use a Brüel and Kjaer electrodynamic shaker for our shock and vibration testing, including calibration of our enDAQ sensors. Specifically, we have the LDS V455 permanent magnet shaker shown in Figure 40. There are other companies that sell shakers such as Data Physics, and Unholtz-Dickie. The trouble with buying these larger general-purpose shakers in your company's lab is the typically high costs they require. These types of industrial shakers will cost tens of thousands of dollars and that doesn't include the high cost of the amplifier and software to run the shaker (tens of thousands for these too).

Figure 40: The LDS V455 is a good general-purpose shock and vibration shaker. It has a useable frequency range of 5 Hz to 7.5 kHz, a peak-to-peak displacement maximum at 0.375", and a maximum sine force peak at 100 pounds-force.

Modal Testing

Shakers are also used extensively in modal testing. In these test setups, typically a much smaller shaker is needed to excite the range of modal frequencies you may be interested in. For this type of testing the Modal Shop offers the best range of solutions, including rental services. Figure 41 provides an image and performance plot of one of their mini shakers. This shaker is ideal for general purpose testing on small components and also very useful as an excitation source for modal testing.

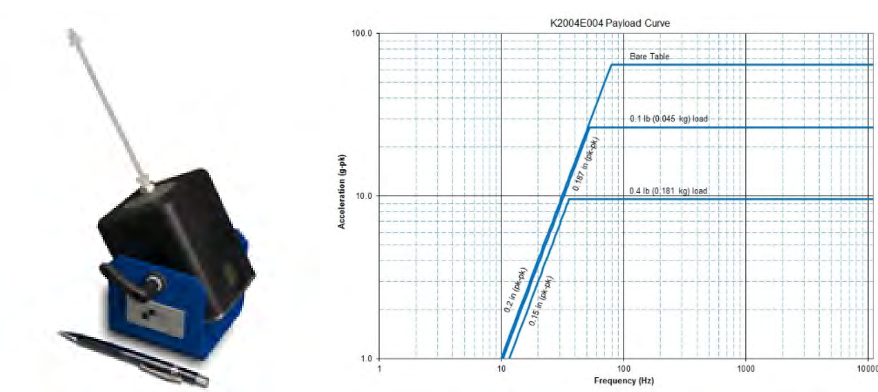


Figure 41: The Modal Shop's 2004E mini-shaker is pictured with its payload curve.

Their shakers may also work as general vibration and shock exciters for smaller systems to qualify your product/design as shown in Figure 42, but their equipment is best suited for smaller test setups and/or modal testing.

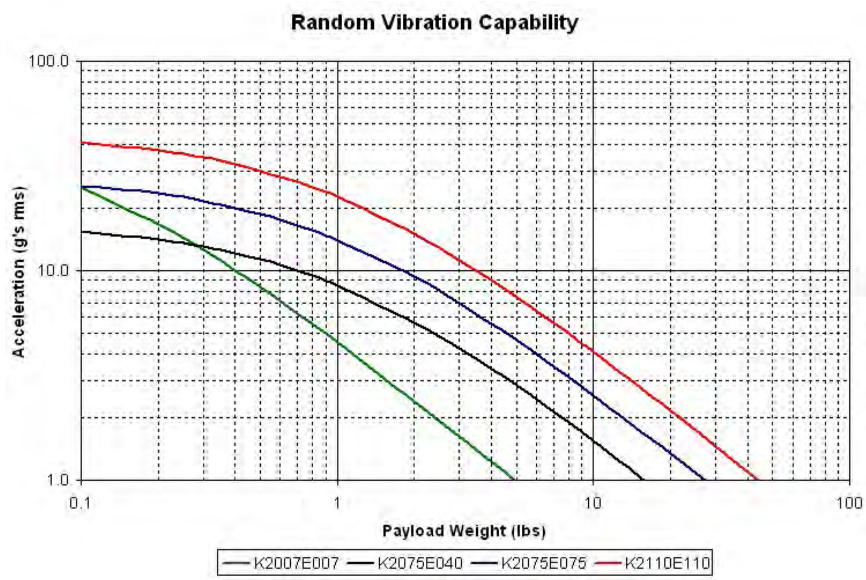


Figure 42: The Modal Shop's general-purpose vibration shakers performance range is dependent on payload mass and maximum acceleration levels desired.

Another form of exciting your structure for the purpose of modal testing is using an impact hammer. These offer a much more cost-effective means of performing your testing (a typical impact hammer will cost just under $1,000) and are the preferred method for many experts. An impact hammer will provide a nearly constant force over a broad range of frequencies (specified by the type of tip you use), and, therefore, these are capable of exciting a broad range of resonances and modal shapes. These hammers will come force-instrumented so that the frequency response function can be calculated using output of modal accelerometers instrumented throughout your structure.

Figure 43 provides some performance specifications of one of PCB Piezotronics' impact hammers that cost $760. The Modal Shop (owned by PCB) also offers a variety of impact hammers which can be purchased or rented.

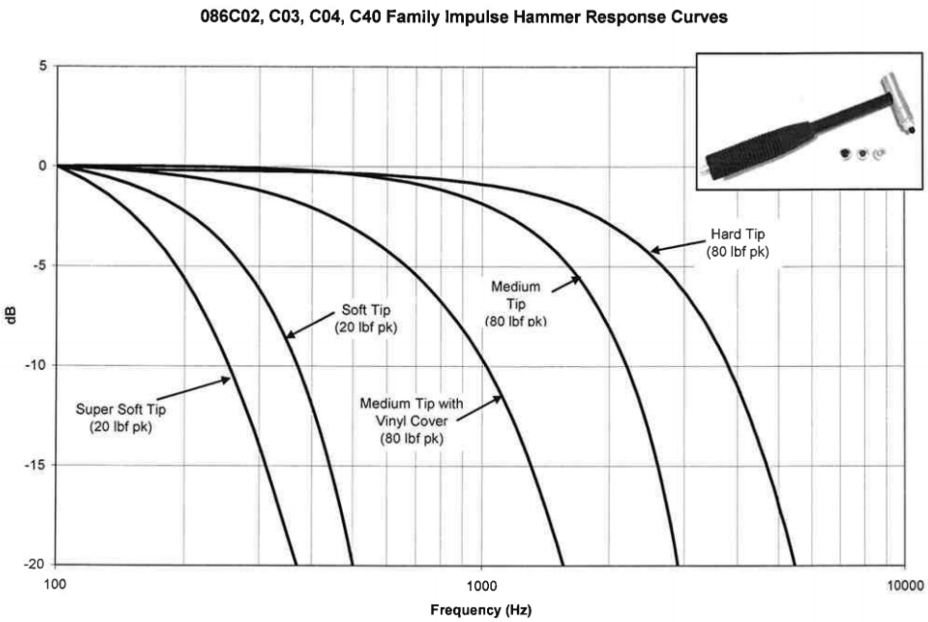


Figure 43: PCB's model 086C03 impact hammer and its performance is shown.

Testing Labs

Performing shock and vibration testing in a simulated environment can be very expensive and require complex equipment and setups. But there are test laboratories that can offset some of these costs (although their services will still be several thousand dollars). enDAQ has had experience with both National Technical Systems (NTS), and Dayton Brown. For larger systems, like those being qualified for naval ships, Hi-TEST laboratories offers shock and vibration testing services. This includes their MIL-S-901D shock testing capabilities that consist of exploding a charge underwater to subject a test setup to a large displacement shock event. Midé, which enDAQ is a product line of, has been down there a couple times for our bulkhead shaft seal and stern tube seal product lines as well as for some of our general R&D programs. It is both exciting and nerve racking to witness those tests!

Analysis Software Options

Setting up test hardware and knowing what/how to analyze the vibration data is meaningless without the means to perform that analysis. Software is also typically needed to acquire the vibration data in the first place. There are a wide variety of software packages available to the test engineer, but he/she needs to answer two questions before settling on a software option or combination of options:

- Do you need to analyze data in ***real-time,*** or ***post-process*** the shock and vibration data?
- Do you prefer developing ***your own analysis and simulation programs***, or using a ***standalone graphical user interface***?

If the products you will be using acquire the data and export it then the software will "only" need to do the post-processing. This would be the case for a data logger. But for applications that require real-time (or near real-time with a buffer) data streaming and analysis will limit the options available. Real-time data streaming and processing is needed for typical modal analysis, and for controls applications (where an action is taken based upon recorded data).

Writing custom analysis and simulation programs will require some advanced knowledge of the computing language and analysis fundamentals but is the preferred path for most post-processing analysis applications. Standalone graphical user interfaces (GUIs) are nice for providing that initial overview of your data and performing some analysis. In many applications though there will be a need for doing analysis based upon certain conditions specific to your test. For example, if I performed a two-hour long test on an aircraft component, I may want to develop a script that looks through the data and runs FFTs if/when certain conditions are met. Doing this fairly simply analysis that has a couple if-statements may be more difficult in a standalone GUI.

Most times a combination of standalone GUIs and custom analysis scripts will offer the best of both worlds to complete your analysis. There are a lot of options out there, but it can be difficult to go through and compare them. Below we've condensed the list to a few more well-known software packages.

MATLAB

MATLAB is a programming language specifically developed for linear algebraic operations. Because of this initial core design and focus, it is a hugely popular tool for data analysis. Engineers would have used MATLAB is college and entered the workforce already with a knowledge and preference for this (MathWorks is smart with their pricing to offer significant discounts to universities and students).

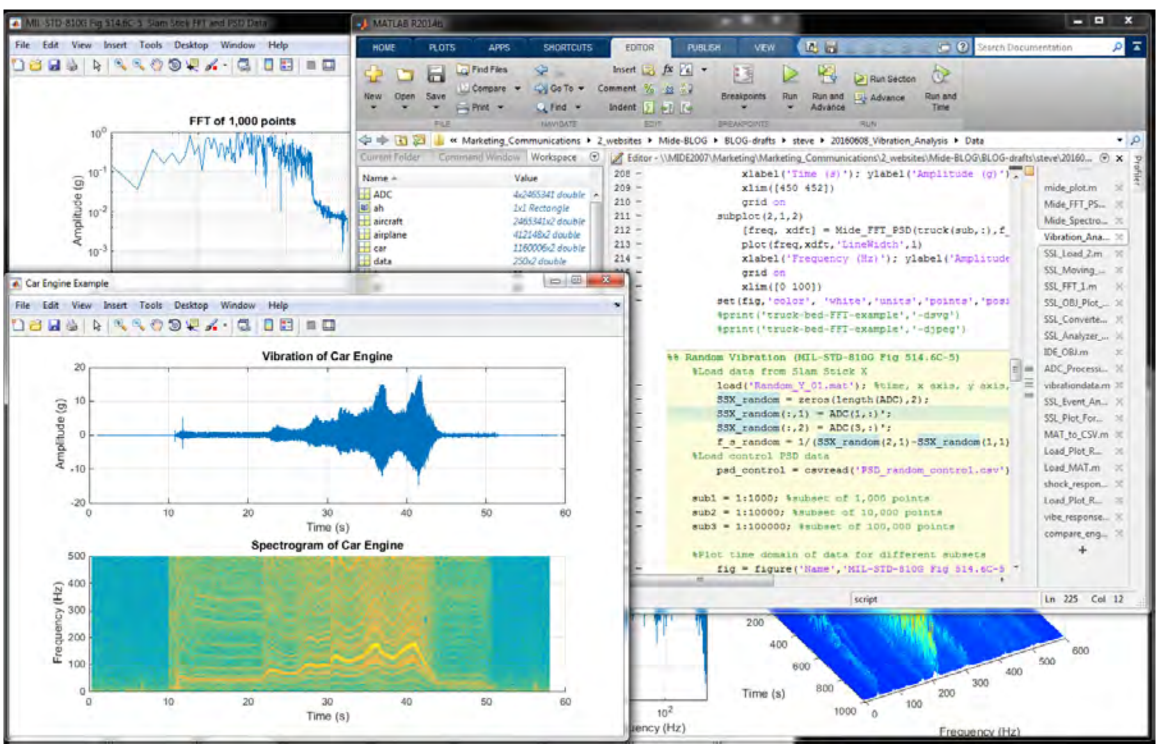


Figure 44: MATLAB is the most common programming tool used by vibration analysts.

The big disadvantage of MATLAB is that it's not free—a commercial license will cost $2,150. They also charge more, typically $1,000, for additional toolboxes (here's a full price list of the MATLAB products). I'd recommend the signal processing toolbox for vibration analysis. Don't worry though, I didn't use any functions in that toolbox for this analysis or the ones covered in my vibration analysis basics blog.

If code base programming seems daunting, MATLAB does have their Simulink block diagram environment. This is a compelling product that can help reduce human programming induced errors and allow teams of analysts to integrate their algorithms a little easier. A single commercial license is $3,350 (in addition to a MATLAB license). Simulink also lets engineers interface with hardware such as National Instruments, Raspberry Pi and Arduino, but these hardware supports will cost you. Simulink is great for analyzing data in real time (another couple thousand dollars) and offers incredible customization in addition to built-in analysis capabilities.

Python

Python is a free, open source, and very versatile programming language. Their NumPy and SciPy packages have similar functions to MATLAB. Python is a pretty elegant and intuitive programming language compared to MATLAB. It was created to be a generic language that is easy to read, and they definitely succeeded with that! Python is universally accepted as the better alternative to MATLAB for other programming needs besides data analysis.

But if you ask what's better, MATLAB or Python for vibration analysis, you may start a heated debate because they both have benefits and disadvantages. We recently did some testing to compare MATLAB and Python for vibration analysis and came to the conclusion that for basic analysis (including FFTs) Python can match and even beat MATLAB computation times, but the programmer may need to do a bit of digging to find and download all the necessary libraries. But these libraries will be free!

As a MATLAB user I found the Anaconda distribution of Python and its most popular libraries very helpful. The Spyder development environment, shown in Figure 45, has a similar interface and feel to MATLAB for those with MATLAB experience.

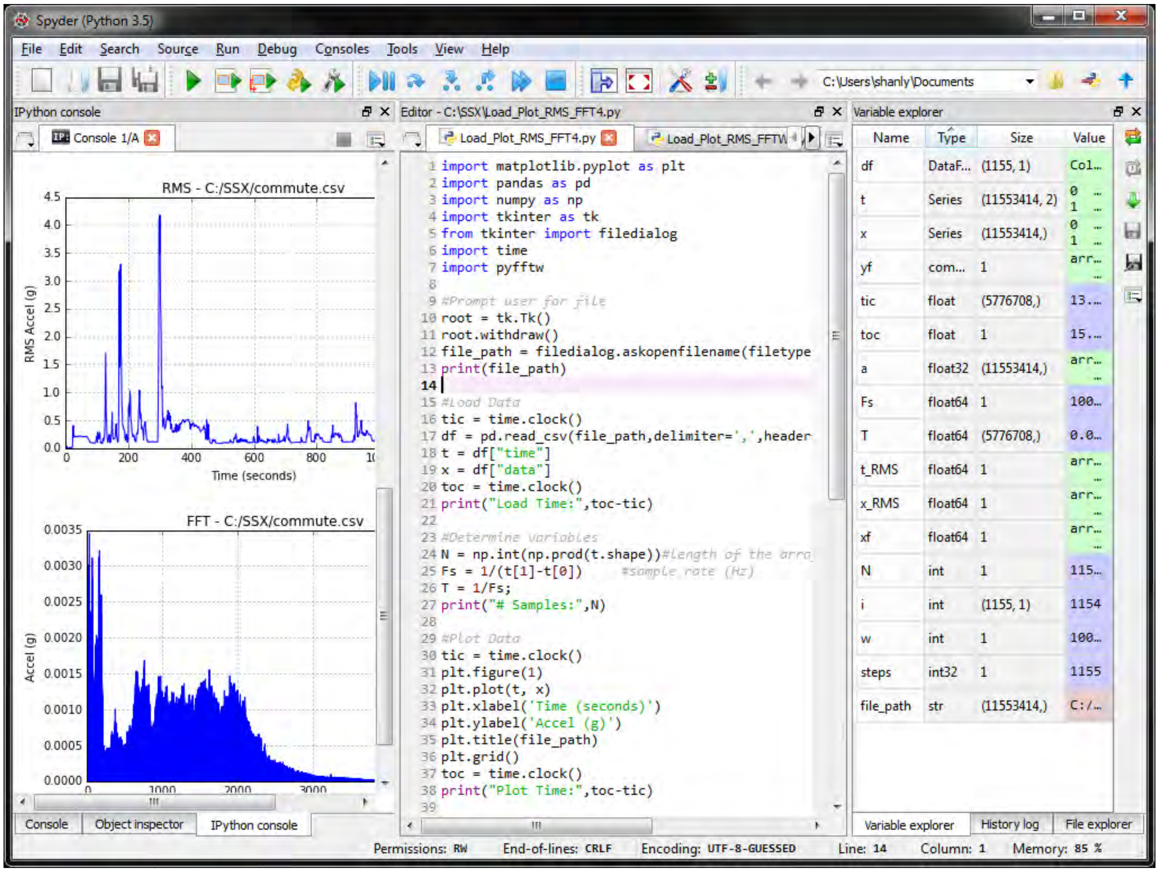


Figure 45: The Spyder Python development environment is shown. It has a similar interface to MATLAB.

Python is gaining popularity because it's free and the community is generating a wide variety of versatile libraries that are publicly available through [GitHub](). A quick search finds the [PyDAQmx library]() that interfaces with National Instrument's drivers. Again, Python is free so it's becoming a compelling alternative, especially as they offerings and capabilities continue to grow and improve.

LabVIEW

Most engineering companies will likely have a couple LabVIEW licenses to interface with their National Instruments data acquisition hardware and analyze data in real time. [LabVIEW]() is a development environment specifically designed for engineers and scientists analyzing data. As such, it's a popular tool for vibration testing! As we've discussed, National Instruments is the world leader in hardware for data acquisition, so it makes sense that their software is also very popular and pairs well with their hardware. Designing analysis programs with LabVIEW may be easier to those with less programming knowledge because of the graphical programming language they use, shown in Figure 46.

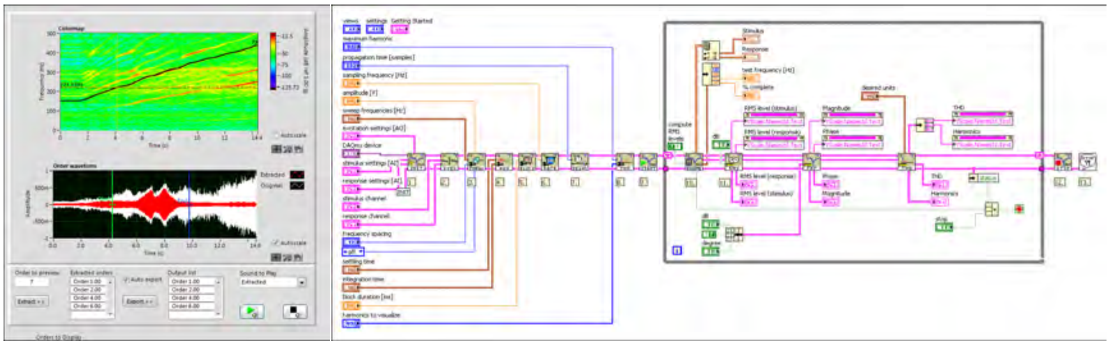


Figure 46: LabVIEW's block diagram design environment is shown next to a representative analysis window.

A full [LabVIEW license costs $2,999] and vibration customers may be interested in their [Sound and Vibration Toolkit] for another $1,999. It can definitely get expensive quickly but is a great solution for data analysis, especially in real-time controls applications.

Standalone Vibration Analysis Software

There are a wide range of standalone software packages available for purchase, but let's first identify a couple free ones.

Tom Irvine's & enDAQ's VibrationData Toolbox

Through a partnership with Tom Irvine we can bring you his legendary MATLAB Signal Analysis and Structural Dynamics Package to those without a MATLAB license in the **VIbrationData Toolbox**. He provides the source code to this package on his website (and updates it frequently). This offers great versatility because it has a nice GUI which is easy to work with, but all the source code is available if you need to take the next step and perform your own custom analysis. In nearly all of his webinars he will go through an example that uses these software packages so you can quickly see the power and ease of use of these analysis options.

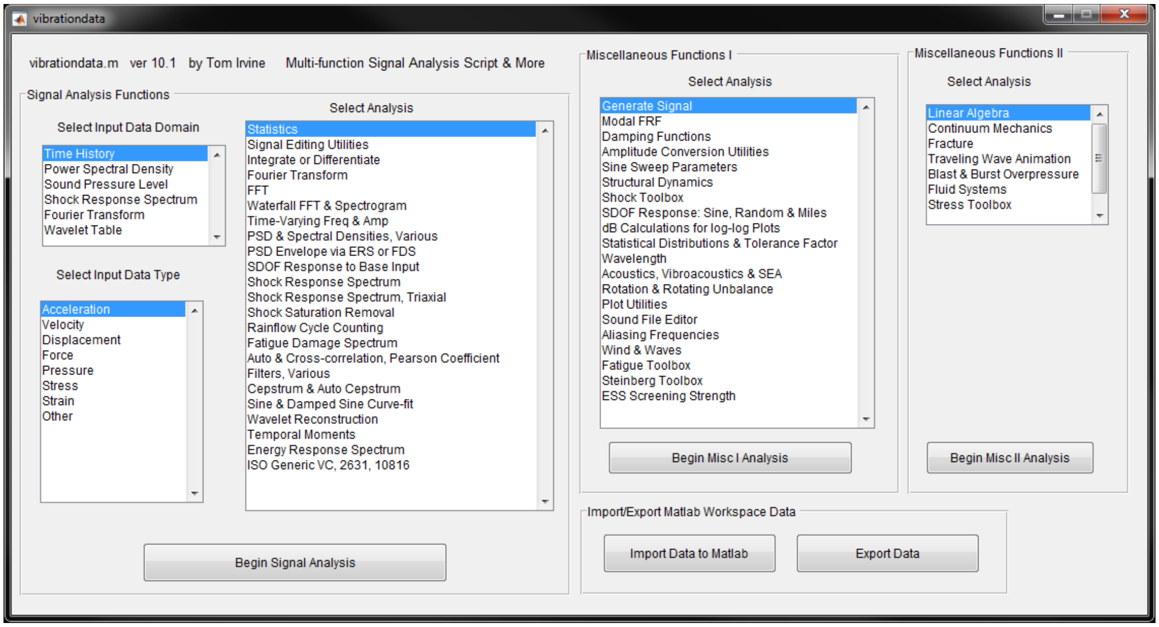


Figure 47: Vibrationdata's MATLAB signal analysis GUI window is shown with a broad range of analysis capabilities.

enDAQ Lab

enDAQ Lab is available for free along with some example recording files. This software currently only works with enDAQ sensor recording files, but enDAQ has plans to open this up to other import files in the future. The software only has basic analysis capabilities, but it covers the major ones typically needed: FFT, PSD, spectrogram, unit conversion, and general plotting. Data can be exported to MATLAB or CSV (readable by Excel, Python, and other software) for follow on analysis.

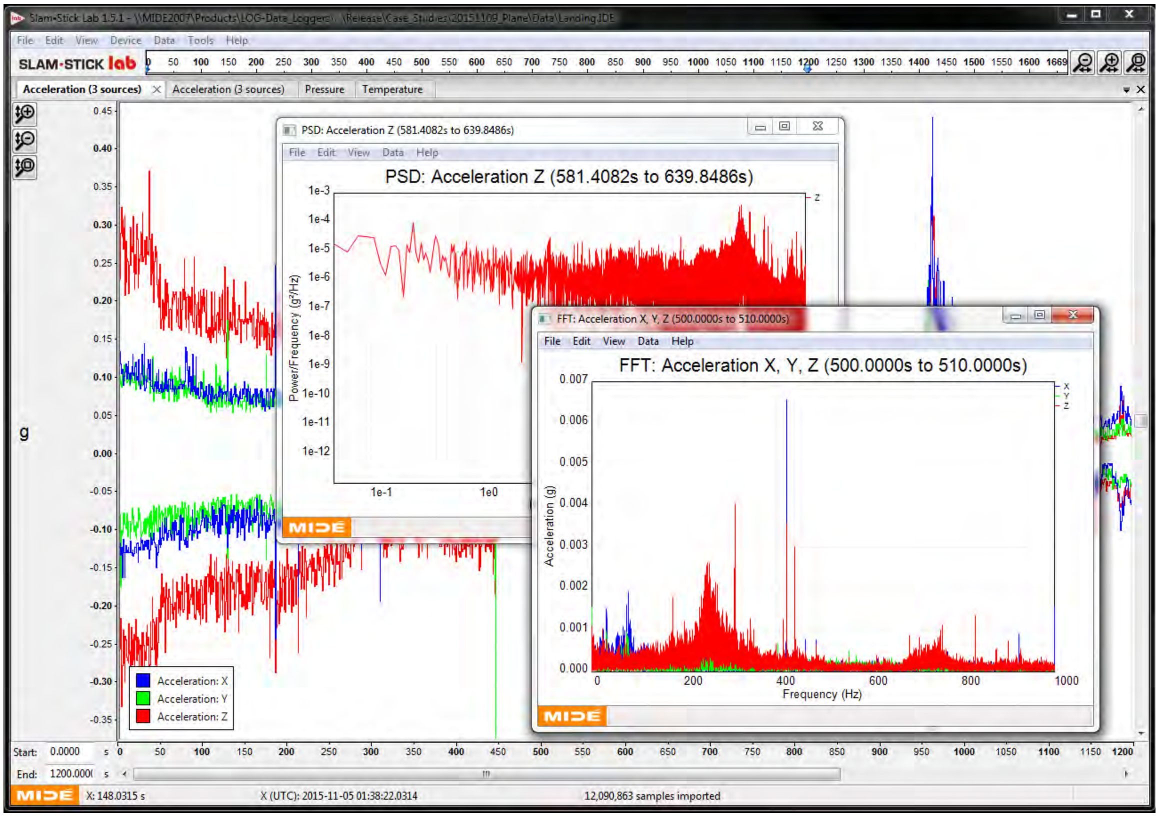


Figure 48: enDAQ Lab software is a free standalone GUI for analyzing enDAQ sensor recorded data.

The following represent a select few of many different standalone GUIs available on the market for vibration analysis. These will typically cost around $5K or more but offer some unique benefits over writing your own code, namely a time savings advantage.

m+p International

This company specializes in vibration testing, specifically modal. They have a variety of hardware products for data acquisition but also some software packages for post processing and analyzing data in real-time. Their m+p analyzer can interface with their hardware for real time analysis but is also useful in handling large datasets and post processing vibration data.

VibrationVIEW

Vibration Research's VibrationVIEW software is another alternative to post processing and analyzing vibration data in real time.

Brüel and Kjaer

Bruel and Kjaer have a couple different software packages that are very impressive for both post processing and analyzing vibration in real time.

ProAnalyst

Xcitex's ProAnalyst software is unique in that it uses video for determining vibration levels and analyzing them. Seems like a very powerful tool that can simplify the hardware setup! The costs don't seem too ludicrous either, only $1,795 for their introductory edition. It quickly starts climbing towards $10K and beyond though for the professional edition and different toolkits. I do like how they come right out and list the pricing instead of requiring you to fill out a form!

FEMtools

For modal analysis and validating CAD models with experimental data, FEMtools is a very powerful tool. It can also be used for general post processing of time history vibration data.

CONCLUSION

Before you can dive into vibration measurement and analysis it's important to ask yourself and answer those first couple questions: what frequency and amplitude is of interest, who needs the data and why, where is the test environment, when is the testing, and when does the analysis need to be completed by?

Remember that shock and vibration testing is an ***art and a science***. It's not always very straightforward, but that creates some opportunity as the engineer to impart their own personality into testing and analysis. It lets the engineer have fun, so go out and have fun with your vibration testing!

Resources

Avitable, Peter. *Modal Space (in our own little world).* 2014. Web.

- Full PDF
- UMASS Lowell Structural Dynamics and Acoustic Systems Laboratory

Broch, Jens Trampe and Joëlle Courrech. *Mechanical Vibration and Shock Measurements*. Naerum, Denmark: Brüel & Kjaer, 1980. Print.

- Amazon Link

Harris, Cyril M and Allan G Piersol. *Harris' Shock and Vibration Handbook*. New York: McGraw-Hill, 2002. Print.

- Amazon Link

Irvine, Tom. *Shock and Vibration Signal Analysis.* 2005. Web. 12 September 2005.

- Full PDF
- vibrationdata Blog by Tom Irvine

McConnell, Kenneth G. *Vibration Testing*. New York: Wiley, 1995. Print.

- Amazon Link

Technical Papers

- Brüel & Kjaer
- Meggitt's Endevco
- PCB Piezotronics

Join the Conversation

enDAQ is committed to providing high quality technical content to the engineering community. In order to keep our Engineering Blog current and accurate we welcome all feedback—please Subscribe to our blog today.