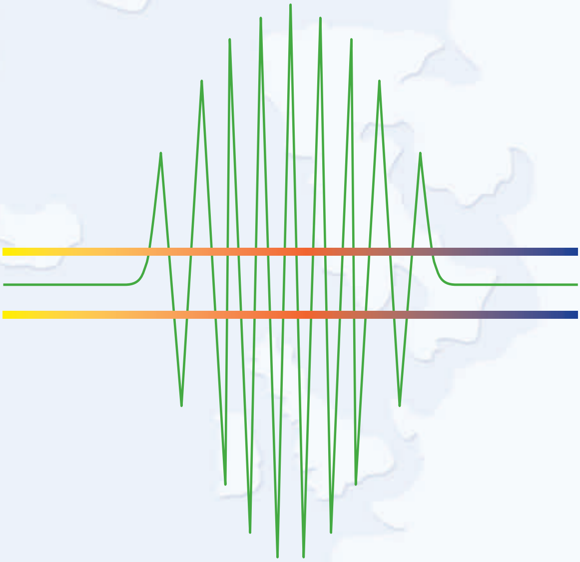
THERMOTRON®



Fundamentals of Electrodynamic Vibration Testing Handbook

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Written and published by
Thermotron Industries,
Holland, MI

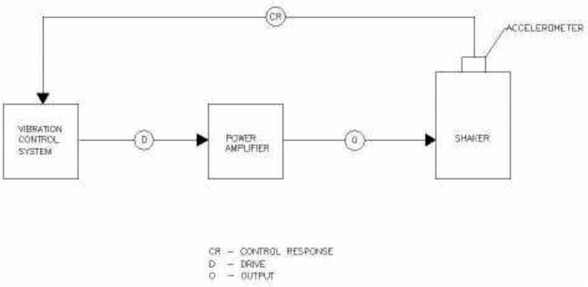
Introduction

Vibration testing is performed for a variety of reasons: to determine if a product can withstand the rigors of its intended use environment, to insure the final design will not fall apart during shipping, for Environmental Stress Screening to weed out production defects, or even as a form of Accelerated Stress Testing. Vibration tests are commonly used to improve the reliability of military hardware, avionics instrumentation, consumer electronics, automotive components, and telecommunications gear.

Electrodynamic vibration systems are capable of performing many different tests that specify sine, random, shock, sine-on-random, random-on-random and other complex waveforms as well as replicating data that is collected from real world conditions.

Breaking the electrodynamic vibration system down into its discrete components, we are quite simply left with something analogous to a stereo system – a big and powerful, industrial strength stereo system. Using a vibration control system (synonymous with the CD player), a signal is sent through an amplifier (similar to the amplifier used for a home stereo), to the shaker (something like a speaker, but made mostly out of steel and weighing several tons), where the armature (comparable to the stereo speaker's woofer or voice coil) moves up & down or back & forth in a magnetic field. An added element to the vibration system is an accelerometer that senses the output of the shaker and sends this signal back to the controller for fine tuning. The controller in turn sends a drive signal back to the amplifier which provides accurate, closed-loop control and spectral shaping of the test being performed.

This resource presents fundamental concepts and the basic elements that comprise an electrodynamic vibration system.



A. Electrodynamic Shakers

Size & Force (F=ma)

When sizing an electrodynamic shaker for a specific application you need to first take into account two essential factors. What is the moving mass (armature, fixture and product) and what acceleration level needs to be achieved? Multiplying these two factors together provides the force required to perform the test function. In the event that the shaker is attached to a sliptable, the mass of the slip plate and driver bar attachment must be accounted for. When a shaker interfaces with an environmental test chamber, the mass of the thermal barrier must be added to the total moving mass. Don't forget to account for miscellaneous mass that might otherwise be overlooked such as: head expanders or plates, bolts & nuts, cables, etc. Force can be expressed in the English units, lbf or the metric equivalent, kN. It is not uncommon for the manufacturer of vibration systems to derate actual shaker force capabilities to 80% of their true value as a measure of conservative safety.

Displacement, Velocity & Acceleration

The three functional limits to electrodynamic shaker performance are displacement, velocity and acceleration. Displacement limits shaker operation at the lowest frequencies, and acceleration limits the shaker performance at the highest frequencies. Velocity limits shaker performance in a band between the other two limits. As an example, Thermotron's DS-2250 vibration system has a displacement limit of 2" peak-peak, a velocity limit of 100 inches per second, and an acceleration limit of 100 g's. Each of those limits applies over a different frequency range.

An example of a Force calculation
F=ma

	Vertical	**Horizontal**
Product Mass	25 lb	25 lb
Fixture Mass	40 lb	40 lb
Cables Mass	2 lb	2 lb
Head Expander Mass	60 lb	NA
Slipplate Mass	NA	65 lb
Armature Mass	23 lb	23 lb
Total Mass	150 lb	155 lb
Acceleration Level	10 g	10 g
Force Required	1500 lbf	1550 lbf

Displacement of an electrodynamic shaker is a function of how far up and down the armature is capable of traveling. Most shaker systems are limited to 2” (50 mm) peak-to-peak travel. This means that an armature can travel up one inch (25 mm) and down one inch (25 mm) from its center position. It is standard practice to protect the shaker from overtravel situations by utilizing sensors that shut the system down before the mechanical limits of the shaker are exceeded.

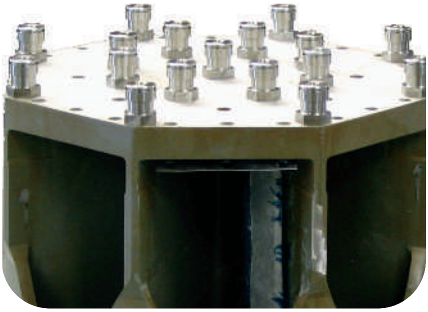
Velocity is the speed at which the armature can move. Velocity limits for electrodynamic shakers can reach 100 inches per second (2.5 m/sec). The higher the velocity limit, the greater the shaker’s capability of attaining a wider range of shock pulses.

Acceleration is expressed in terms of gravitational units or g’s. A single g is equal to the acceleration due to gravity 32 ft/sec^2 (9.8 m/sec^2), 2 g’s is twice the acceleration due to gravity and so on. When the term grms is encountered, it is used to specify the rms (root mean square) g level of a random acceleration profile. Sine and shock acceleration levels are expressed in terms of g pk, where pk stands for peak. The acceleration component of a vibration test is typically prescribed by the test specification.

Frequency Range

Electrodynamic shakers operate through a wide frequency range that is typically from 5 Hz to 3,000 Hz. Most test specifications in the automotive and transportation industry emphasize low frequencies (ie: below 1,000 Hz) while military vibration specifications normally call for testing out to 2,000Hz and electronics industry specs can go as high as 3,000 Hz.

Armatures



above: A 16” armature

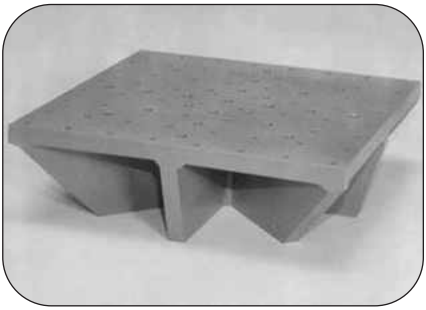
Among the general rules of thumb for armature design and construction are:

- A lightweight armature is favorable and will permit testing at higher g levels.
- The armature structure should provide a significant amount of stiffness.
- Material of construction is often magnesium or aluminum.
- Magnesium has a very high strength-to-weight ratio and provides superior damping, making it a favored material.
- Smaller lighter armatures may be appropriate for testing smaller products, while larger armatures can eliminate the need to use a head expander, reducing system mass and improving transmissibility.

Centering & Support

The armature needs to remain centered in its travel. Using an optical sensor to locate the armature and an automated pneumatic fill & drain system, the armature, bare table or loaded, will stay true to its course. Merely centering the armature at the beginning of a test is neither adequate nor safe. Advanced systems possess the ability to continuously center the armature while a test is in progress. Another feature of most shakers is a centerpole and bearing shaft that helps to keep the armature properly aligned during operation. It is good practice to load fixture and product weight over the center of the armature to avoid overturning moments. In the event the payload center of gravity cannot be located over the center of the armature, additional guidance may need to be added to the system to prevent shaker damage.

Head Expanders & Plates



above: Head expanders are used for large or multiple products

If large or multiple products extend too far beyond the edge of the armature, the product could be damaged or overtested. Using a head expander or head plate to increase the armature mounting area and properly tie the fixturing and products should alleviate this potential problem.

Head expanders and plates should be designed for proper stiffness (ie: gusseted and welded) and should not be bolt-together structures since bolted joints reduce energy transmission. Favored materials of construction are magnesium or aluminum.

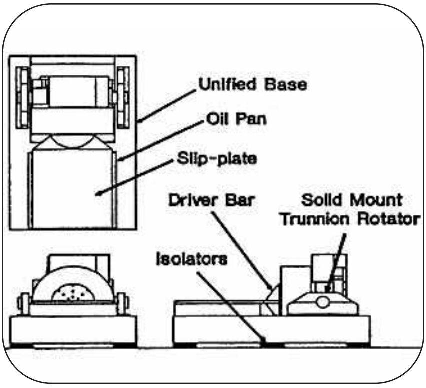
Fixturing

In addition to acting as a mounting interface between the shaker and the product to be tested, a vibration fixture needs to be rigid and lightweight. The vibration fixture should also transmit a uniform distribution of energy from the armature to the test item. In many cases, vibration is applied in three orthogonal axes. Specialized vibration fixture designs permit the fixture to be rotated for testing in the X, Y, and Z axis. It is common to find the weight of a fixture to be two to three times heavier than the products to be tested. Fixtures should mount easily to the armature and products should mount easily to the fixture. Quick changes from product to product and axis to axis help to maximize equipment utilization and improve lab productivity.

Sliptables

A sliptable assembly is used when vibration is required in the horizontal axis. For this purpose, the shaker is mounted in a trunnion which allows the shaker to be rotated 90°. A single piece table construction with a solid trunnion limits the relative body motion of the shaker and improves low frequency/high displacement performance of the overall system by solidly linking all of the reaction mass of the shaker to the sliptable base. The solid trunnion and base configuration also limits the potential problems associated with

above: A Thermotron horizontal sliptable available in various sizes.



above: Sliptable assembly.

misalignment which can plague a two piece system. Beyond the standard oil film systems, several options such as guideline tracking and hydrostatic bearings, are available to further control true and consistent horizontal vibration performance.

Cooling

Shakers consume significant electrical power which is converted to heat. Cooling of field coils and armature coils is mandatory in an electrodynamic vibration system. Shakers up to 15,000 lbf are typically air-cooled, while high force shakers (20,000 lbf and above) are liquid-cooled. Air-cooled shakers can be set up to exhaust warm air outside the facility during warm months. Provisions can be made to damper the warm air back into the facility during colder months. The blower for an air-cooled shaker can be mounted outdoors or it can be placed in a sound deadening package and remain indoors.

Chamber Interface

When integrated with a chamber to perform combined environment tests, the shaker needs to be equipped with certain items. A thermal barrier, using sheets of G10 material and/or flexible silicon rubber will protect the shaker from being exposed to the temperature extremes of the test chamber. Properly designed, this flexible seal will also provide a protective barrier against moisture. Casters and track are one way to roll the

above: Thermotron combined AGREE system. This system allows for electrodynamic and repetitive shock shakers.

shaker under a chamber. Another option is to utilize an air-glide system that floats the shaker on a cushion of compressed air.

Applications where the shaker remains fixed in its position and the chamber rolls back and forth present another viable option.

The ability to generate and run sophisticated combined environment tests from a single user interface can be a huge advantage. This simplifies data entry and synchronizes the individual pieces of equipment so they work in concert to carry out a fully integrated test.

Vibration Isolation

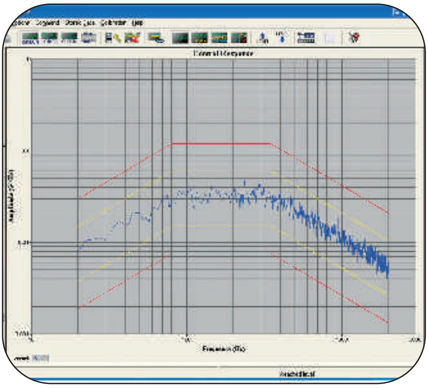
Electrodynamic shakers are capable of generating high forces over a wide range of frequencies. To limit the amount of unwanted vibration energy from being transmitted into the floor and throughout the facility, pneumatic mounts between the shaker and the floor are filled with compressed air to isolate the transmission of this energy. Shakers are relatively heavy pieces of equipment and, as such, are typically mounted on the ground floor of the facility.

Noise Levels

An electrodynamic shaker running a full force random profile can be as loud as a jet engine. While performing a sine sweep to find a resonance point, the shaker can start out as a low-pitched hum and rise to an ear piercing scream. It is for these reasons that a sound enclosure should house the shaker system. It is a wise idea to place the control and amplifier console outside of the room for purposes of safety and comfort.   A multi-pane window providing a view from the control room into the shaker room is advised for those situations where visual access to the product under test is critical.

B. Vibration Test Types

Random



above: A typical NAVMAT profile.

Random vibration is used to closely approximate real world application environments. A wide range of frequencies are excited simultaneously at closely controlled energy levels. There are many examples of random vibration profiles which plot power spectral density (in units of g^2/Hz) vs. frequency.

Test specifications with frequencies up to and greater than 2,000 Hz are considered broad band. Random vibration test specifications with upper frequencies less than 500 Hz are referred to as narrow band. Full system force is not achievable for narrow band, and the performance must be derated to protect the equipment.

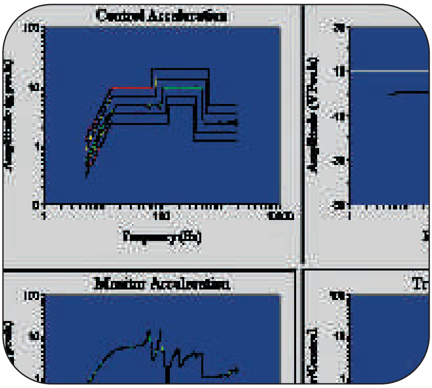
One very popular random vibration test specification is NAVMAT P9492 called out in the Navy Manufacturing Screening Program. This spectrum slopes up from 20 to 80 Hz at +3dB/octave to 0.04 g^2/Hz, remains flat at 0.04 g^2/Hz from 80 to 350 Hz, and rolls off at -3dB/octave from 350 to 2000 Hz. The overall grms value for this profile is 6.0 grms.

Real Data Acquisition & Playback (RDAP)

above: Thermotron's Real Data Acquisition and Playback allows actual test data to be recorded in the field and replicated on the shaker, as in the case of recording engine vibrations in a car.

RDAP is a more recent development which allows actual vibration data to be recorded in the field and replicated on the shaker in the lab. This method of testing provides very accurate feedback regarding how a product will perform under normal operating conditions. Recorded vibration levels can be stepped-up to higher levels to accelerate the stress testing process if so desired.

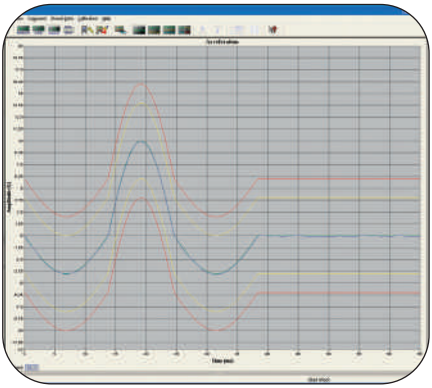
Sine with Resonant Search & Dwell



During sine testing, energy is output at a single frequency. A sine sweep test is a useful engineering development technique which is performed as a means to locate the resonance of a product. The resonance, or natural frequency, is the point where small vibration levels cause the system to exhibit high amplitude levels. Dwelling at the resonance point is a common practice to determine if a product can withstand a higher level of stress.

Sine vibration performance for electrodynamic shakers is dictated by a curve which is limited by maximum displacement (typically 2” [50 mm] peak-to-peak at low frequency, maximum velocity up to 100 inches/sec [2.5 m/sec]) through mid-range frequencies, and maximum acceleration (a function of shaker capacity and moving mass) at the higher frequencies.

Classical Shock



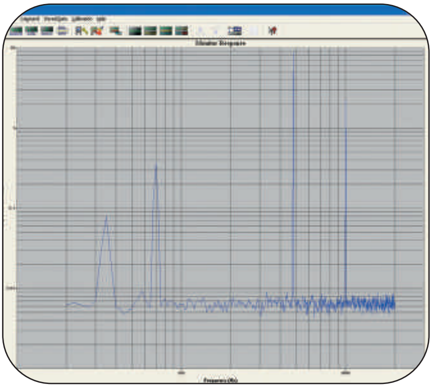
Shock conditions, such as sudden and severe impacts, are encountered by a variety of products as a result of transportation, mishandling, and actual use environments: dropped cell phones, automobile collisions, aircraft landings and missile launches are all examples. Most electrodynamic vibration systems have the capability of performing shock. The armature is given an initial displacement (preloaded) and a pulse of energy is delivered by the amplifier which translates into a particular waveform. Classical shock pulses are determined by shape, amplitude and duration. The most common are half sine, sawtooth, triangular, and trapezoidal.

Shock Response Spectrum (SRS)

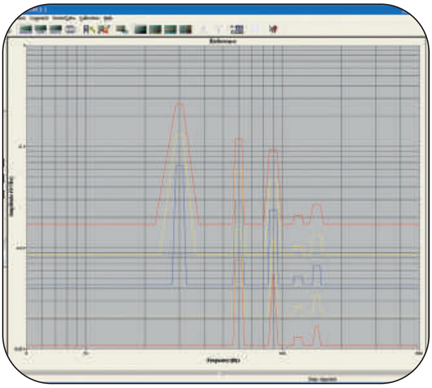
SRS Testing is a way to synthesize a complex waveform that can be used on an electrodynamic shaker in a controlled manner with repeatability. This avoids the inconsistencies of shock test machines that limit the shape of the excitation pulse. SRS is a useful tool for estimating the potential damage of a shock pulse. SRS tests are used to qualify equipment installed in nuclear power plants as well as to simulate seismic, pyrotechnic, gun fire and aircraft take-off and landing vibrations.

Sine-on-Random

Certain applications involving rotating equipment in moving vehicles require a vibration profile that combines fixed or swept sine and random vibration. Sine-on-Random software simulates the vibration environment experienced by helicopters, automobiles, and trains where the sine component of a rotor or a reciprocating piston engine is placed on top of a broadband random vibration profile indicative of the moving vehicle.



Random-on-Random



Random-on-Random profiles combine fixed or sweeping narrow bands of random superimposed on a background broadband random spectrum. This vibration signature is typical of tracked vehicles, propeller aircraft and turbine engines.

C. Amplifier Console

The electronics for an electrodynamic shaker have become so compact that the inverters, magnetic field power supply, vibration controller, electrical interconnects, and any optional instrumentation can fit into one console commonly and collectively referred to as the amplifier.

Inverters

Inverters supply the armature drive current. Due to their exceptional efficiency, class D solid state switching inverters have become the industry standard for electrodynamic shakers. These inverters are of modular design and amplifiers are configured with one or more modules.

Currently two types of power devices are used for shaker inverters: the IGBT (Insulated Gate Bipolar Transistor) and the MOSFET (Metal Oxide Semiconductor Field Effect Transistor). The target application for these devices is not shaker inverters and no significant advantage exists for one device over the other. Rather, advanced shaker inverters have the ability to communicate with the vibration controller which in turn is able to tune inverter parameters providing optimum system dynamic range, power consumption, etc.

Magnetic Field Power Supply

Commonly referred to as the field supply, this benign component supplies the current to energize the field coils located in the shaker body. High performance field supplies also possess the ability to communicate with and be tuned by the vibration controller.

Console Design

A manufacturer should possess the ability to supply a power panel that complies with appropriate UL, CE, or CSA standards, including interlocked access doors. These interlocks will prevent accidental personnel exposure to high voltages. It is also expected that the amplifier be protected from over temperature and over current conditions. Finally, appropriate cabinet design and circuitry includes RFI/EMI suppression to minimize interference from the vibration system's amplifier.

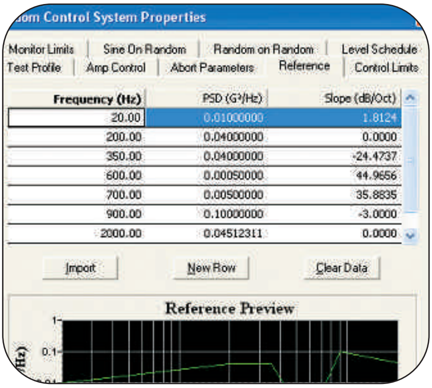
D. Vibration Controllers & Instrumentation

above: Thermotron's VIO module box, part of the vibration control system.

Vibration controllers have come to adopt the power and speed afforded by today's personal computers. It is important that the operating systems and interface be robust and familiar to the user. USB and Ethernet connections provide quick and easy access to data and peripherals that make the tasks of data mining and manipulation quick and effective. Vibration controllers will be capable of reproducing the various vibration test types listed previously (random, sine, shock, etc.) as long as they are loaded with the appropriate software.

Software

Outfitting a control system with the software to provide a comprehensive suite of vibration tests is normally an ala carte affair. Digital vibration controllers can be configured with software to meet sine, random, shock (half sine, sawtooth, triangular and square wave), shock response spectrum (SRS), sine-on-random, random-on-random, and real data acquisition and playback as the application dictates.



Frequency (Hz)	PSD (G²/Hz)	Slope (dB/Oct)
20.00	0.01000000	1.8124
200.00	0.04000000	0.0000
350.00	0.04000000	-24.4737
600.00	0.00050000	44.9656
700.00	0.00500000	35.8835
900.00	0.10000000	-3.0000
2000.00	0.04512311	0.0000

above: Thermotron's vibration controller allows the user to set control limits for the safety of the equipment.

It is vital to the safe performance of the vibration system and protection of the product under test that certain safety measures be in place. The control software should be capable of performing a loop check at the beginning of each test to insure that all systems are in operating order. High and low tolerance and abort limits should be set at prescribed levels that will provide warning and automatic shutdown when these out-of-range limits are exceeded.

Dynamic Range

The dynamic range of a system is the largest signal amplitude that the entire system can process divided by the inherent noise of the system. It is also used to indicate the number of bits (resolution) of the data converters used in a vibration controller. There are roughly 6 decibels (dB) of dynamic range per bit.

Inexpensive professional audio grade 24 bit data converters are making their way into vibration controllers. The target market for these converters are not vibration controllers, and they do not provide the best solution for the application. It is important to remember the vibration controller is part of a control system consisting of itself, an amplifier, and a shaker. Therefore, the dynamic range of the system is subject to the "chain is only as strong as its weakest link" principle - meaning the dynamic range of the system cannot be better than the dynamic range of any single component of the system.

Since state of the art inverters and shakers are hard pressed to provide 60 dB of dynamic range, a vibration controller with 10 to 12 bit data converters used in conjunction with a properly designed programmable input amplifier can outperform a vibration controller with 24 bit converters. The high resolution data converters are essentially using their "extra" bits as a limited programmable input amplifier when used in vibration controller applications.

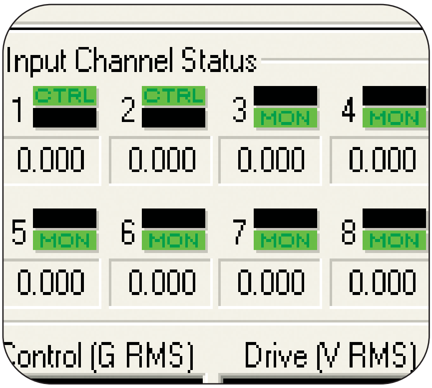
High performance vibration controllers also possess the ability to communicate with the amplifier's inverters and field supply to maximize system dynamic range.

Spectral Resolution

Spectral resolution, commonly referred to as lines, or bins, is the number of frequency segments that a random vibration profile is divided into. The higher the spectral resolution, the greater the number of points used to calculate and control the test frequency spectrum.

Current hardware and software algorithms make it a simple matter for a controller manufacturer to add absurd amounts of lines. For any random vibration profile, the time it takes to acquire the data is directly proportional to the number of lines. There is no known way to sidestep this physical constraint. This added acquisition time adversely effects the time it takes the controller to correct any errors in the random vibration profile. Experts in the field rarely use more than 800 lines. For example, a controller will take 20 times longer to correct a 16,000 line test than it would for an 800 line test. The number of lines are user selectable. In the hands of a novice user, this "feature" of many lines could actually be detrimental.

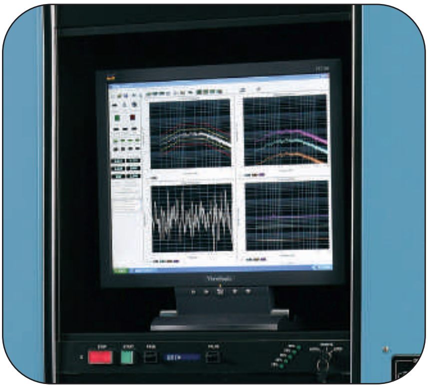
Data Acquisition



above: Thermotron's vibration control software allows up to eight channels of input.

Most controllers are capable of accommodating multiple accelerometer inputs. These accelerometers can be used to monitor or control the vibration response characteristics at various locations on the product under test, the fixture, or the armature. The results of data acquired during vibration testing can be used to prove the vibration test was completed successfully. Data acquired in this manner can also be used to determine how and why a product may have failed.

In addition to monitoring, it is also beneficial in certain circumstances to control the vibration spectrum based on more than one input accelerometer signal. The vibration controller should have the capability of supporting various control strategies such as multipoint averaging, maximum or minimum, etc.



above: Close-up of Thermotron's vibration controller located in the console.

E. Accelerometers

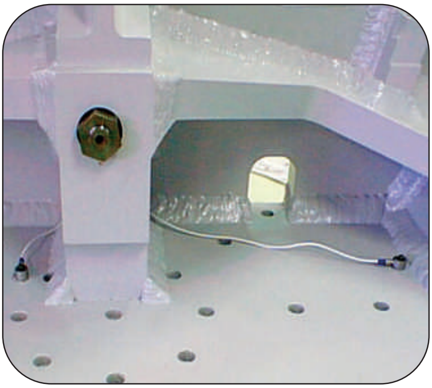
Advantages & Size

above: Typical accelerometers in various sizes.

An accelerometer is a device that senses the motion of the surface to which it is attached, providing an electrical output signal. Piezoelectric materials are used in accelerometers that produce a "charge" proportional to the motion. Years ago larger velocity type pickups were used to measure vibration. These were bulky and had a limited frequency range. Accelerometers are now made mechanically smaller and have a wide frequency range (2-10,000 Hz). Typical weights of accelerometers used on shakers range from a few grams (miniature accelerometers) to 10 or 20 grams (general purpose accelerometers).

Mounting

For accurate measurements, it is important that accelerometers be mounted correctly on shaker systems. The mounting surfaces between the accelerometer and surface should be smooth and clean. The two most common methods of mounting accelerometers are threaded stud mounting and adhesive mounting. Sometimes a non-conductive spacer is required to prevent unwanted ground-loop interference.



above: Accelerometer mounted to a fixture on a shaker.

Stud mounting is the preferred method because the accelerometer is tightly coupled to the surface being measured, assuring excellent transmissibility, especially at high frequencies. A torque wrench set to the manufacturer's specification is used to ensure repeatability and prevent thread damage. A thin layer of grease can be used to fill any voids resulting in a joint with improved stiffness. This type of mounting is typically used on control accelerometers mounted on fixtures.

Adhesive mounting is used when it is impractical or impossible to use the stud mounting method. This technique is frequently used when measuring the vibration response from a product under test. For this type of measurement miniature accelerometers with smooth, flat surfaces are well suited. A common and reliable adhesive used is cyanoacrylate also known as “Crazy Glue” or “Instant Bond.” Removing the adhesive mounted accelerometer requires great care. Solvents should be used to soften the bond, supplemented by a light shearing torque.

Types & Conditioning

Throughout the years two accelerometer types have been used:

*1)	Charge Mode*
*2)	Voltage Mode*

Charge mode accelerometers produce a high impedance charge from internal crystals. Each accelerometer has its own sensitivity in pC/g (pico coulomb per g). This charge must be converted to a voltage for vibration measurement readout and analysis. Special low noise cables are used for charge mode accelerometers to eliminate the adverse effects of electrical noise and cable movement.   Devices called charge amplifiers are connected to these accelerometers to convert the charge signal to a low impedance voltage signal. Charge amplifiers can be simple in-line devices or complex instruments with sensitivity dials and various outputs for monitoring and analysis.

The most popular accelerometers used today are the voltage mode accelerometers. Voltage mode accelerometers have an internal amplifier that converts the high impedance charge signal to a low impedance output voltage signal. A voltage mode accelerometer has its sensitivity expressed in mV/g (millivolts per g). The charge amplifier is replaced by a current source, typically 4 mA, that powers the internal amplifier. The internal amplifier allows the accelerometer to be conveniently coupled to read-out instruments (scopes, analyzers, meters, etc). The low output impedance eliminates the need for expensive low noise cable.

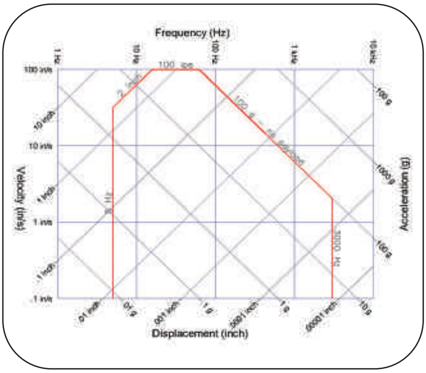
Sensitivity & Environments

As mentioned earlier, each accelerometer has its own output sensitivity, either in pC/g or mV/g. The sensitivity depends on the piezo-electric properties of the crystal used. Typically smaller accelerometers have low sensitivities (0.5 pC/g, 1 mV/g, etc.) and a wider frequency response. Larger accelerometers have higher sensitivities (10 pC/g, 100 mV/g, etc.) but a lower frequency range. Sensitivity and frequency response are two important properties to consider when selecting accelerometers.

Another factor that should be considered is the environment in which the accelerometer will be operated. Humidity and extreme temperatures can affect sensitivity. Rapid change in temperatures can cause thermal transients. For this reason care should be taken when selecting accelerometers to be used under extreme environmental conditions. Typical temperature limits are -55°C to + 121°C for voltage mode devices. Since charge mode accelerometers do not have internal electronics, they can be designed for operation at substantially higher temperatures. Typical temperature ranges for charge mode accelerometers are from -55°C to + 250°C.

F. Universal Vibration Calculator

A version of the calculator can be downloaded from the Thermotron website at:
http://www.thermotron.com/resources/univconv.html
This tool will allow you to quickly and conveniently calculate important vibration parameters and make common unit conversions.



above: A nomograph.

G. References, Resources & Websites

Vibration Test Specifications by Industry

Aerospace
RTCA
http://www.rtca.org

Automotive
SAE
http://www.sae.org

Electronics
IPC / JEDEC
http://www.ipc.org

Defense
MIL-STD
http://www.dscc.dca.mil

Telecommunications
Telcordia
http://telecom-info.telcordia.com

General Test Specifications

JIS
http://www.jsa.or.jp

IEC
http://www.iec.ch

IHS
http://www.ihs.com

Trade Publications

Evaluation Engineering
http://www.nelsonpub.com

IEST Journal
http://www.iest.org

Sound & Vibration
http://www.SandV.com

Test & Measurement World
http://www.tmworld.com

TEST Engineering & Management
http://www.mattingley-publ.com

Testing Technology International
http://www.ukintpress.com/testing2.html

Technical Organizations

American National Standards Institute (ANSI)
http://www.ansi.org

American Society for Quality (ASQ)
http://www.asq.org

American Society for Testing and Materials (ASTM)
http://www.astm.org

Institute of Environmental Sciences and Technology (IEST)
http://www.iest.org

International Standards Organization (ISO)
http://www.iso.ch

Shock and Vibration Information Analysis Center (SAVIAC)
http://saviac.bah.com

MIL-STD Search
http://astimage.daps.dla.mil/quicksearch

Education and Training

Equipment Reliability Institute
www.equipment-reliability.com

Q1. What provisions are included for lifting the shaker?
A1. Heavy duty eye bolts or lifting ears are attached to the shaker body. Straps or chains capable of supporting the weight of the shaker are attached to the eye bolts or lifting ears. A forklift hoists the shaker up by the straps or chains and gently moves and lowers the shaker into place.

Q2. How do we deal with the noise issue?
A2. Electrodynamic shakers are extremely loud. Under the right conditions, the vibration system can sound like a jet engine ready for take off. They should be housed in an enclosure that has very good absorbing qualities. If the shaker is combined with a chamber, the space below the chamber can be enclosed with sound absorbing panels. Baffled air inlet ducts must be incorporated to supply the required flow of cooling air.

Q3. Where should the control console and amplifier be located?
A3. The control and amplifier should be located in a quiet area. Some installations have separate, dedicated control rooms for this equipment, while others simply locate the controls outside the

deadened booth. In the case of a combined environment facility, the amplifier and control instrumentation can be located next to the chamber if the area is large enough.

Q4. What networking connections need to be made?
A4. Shaker controls have become quite sophisticated. They can be run as stand-alone devices or be connected to a local area network via Ethernet. They can also be remotely accessed via the internet if so desired. PCs used to drive the control algorithms are available with multiple USB connections that will support peripheral appliances that will enhance data transfer and storage as well as other test and measurement instruments.

Q5. Where should the cooling blower be located?
A5. In a normal installation, the blower is mounted in a remote outdoor location, say on the roof of the building. The cooling air is drawn through the shaker body and ducted out of the building. The warm air can be diverted back into the building during cold months and used as a heat source. Some blowers are mounted inside the building. In this case, a quiet package or sound deadening enclosure built around the enclosure should be considered.

Q6. Do we need a special floor that will support the weight of the shaker and eliminate vibration transmission?
A6. Many low and medium force shakers feature vibration isolation systems that prevent energy from being transmitted directly into the facility floor. It is not uncommon for a shaker's mass to exceed 6,000 lbm (2,700 kg). A mass of 10,000 lbm (4,500 kg) or more can be expected if a concrete filled granite topped sliptable is included.

Q7. Should the shaker roll or be stationary?
A7. If the shaker is used strictly for vibration testing at ambient conditions, it should be left in a stationary configuration. When combined with a chamber, consideration has to be given to whether to move the shaker or the chamber for product loading. The installation can be configured either way, but it is more common to move the shaker. If the chamber is moved, provisions may need to be made for flexible refrigeration lines, and in extreme cases, raising and lowering the chamber.

Chambers can also be designed with several different door configurations. When equipped with vertical lift doors or horizontal sliding doors, moving the chamber becomes much more challenging.

Q8. What is the best way to move a shaker around?

A8. Some shakers have v-groove casters and mating sections of reinforced steel track that allow them to be moved back and forth (usually into and out from under a test chamber). An automated power tow can greatly ease the rolling around of shakers. Shakers are also available with an air-glide transport system that permits the equipment to be easily maneuvered on a cushion of compressed air.

I. Handy Equations & Engineering Reference

Shaker Force

The shaker force required is independent of frequency and is calculated by the following force equation using weight in place of mass and acceleration in normalized units of standard g's.

Shaker **Force** = (**Payload** mass + **Fixture** mass + shaker **Armature** mass) X **Acceleration** (g's)

Units:
Sine: pounds force peak = (pounds + pounds + pounds) X g's peak
Random: pounds force rms = (pounds + pounds + pounds) X g's rms

Shaker Displacement & Velocity

The required shaker displacement is a strong function of low frequencies. The table below of sinusoidal motion equations can be used to calculate the required displacements and velocities for sinusoidal vibration. Random displacements and velocities must be calculated from acceleration spectral density information.

The universal vibration calculator should be used to calculate displacements and velocities requirements for random vibration testing.

Sinusoidal Equations of Motion

Acceleration, velocity, displacement and frequency are related by two independent equations, therefore specifying any two fully defines the motion.

	Known Values					
	g & f	**v & f**	**D & f**	**D & g**	**v & g**	**D & v**
g (g's) peak acceleration		$f\,v/61.45$	$f^2D/19.56$			$v^2/193.0D$
v (inch/sec.) peak velocity	$61.45\ g/f$		πfD	$13.89\ (gD)^{1/2}$		
D (inch) pk-pk displacement	$19.56\ g/f^2$	$v/\pi f$			$v^2/193.0\ g$	
f (Hz) frequency				$4.423\ (g/D)^{1/2}$	$61.45\ g/v$	$v/\ \pi D$

J. Handy Conversion Factors & Material Properties

	Converting From	*Converting To*	*Multiply By*
Force	lbf	N	4.448
	Ton Force	kN	8.896
Density	lb/in^3	kg/m^3	27,680
	lb/ft^3	kg/m^3	16.018
Pressure	lbf/in^2	kPa	6.895
Volume	ft^3	m^3	0.02832
	in^3	cm^3	16.39
	ft^3	in^3	1,728
Velocity	in/Sec	m/Sec	0.0254
Power	Hp	Watt	746
Volume Flow	ft^3/Min	m^3/Sec	0.0004719
Acceleration	g	m/Sec^2	9.807

Item	*Density*	*Metric Density*
Magnesium	0.065 lb/in^3	1,799.2 kg/m^3
Aluminum	0.098 lb/in^3	2,712.6 kg/m^3
Stainless Steel (304)	0.286 lb/in^3	7,916.5 kg/m^3
G-10 PCB Material	0.065 lb/in^3	1,799.2 kg/m^3

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