An Introduction to Shake Tables for Seismic Testing of Equipment And Glossary of Vibration Terminology

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1. INTRODUCTION

Shake tables are used to simulate earthquake ground motions, and the motions of structures excited by earthquakes. By placing equipment or model structures on these shake tables engineers can determine of they can survive earthquakes or if computer models accurately predict the earthquake response of the test objects. This paper briefly reviews seismic (earthquake) table design and practice. Attachment A presents a detailed glossary of commonly used terms and concepts used in the field.

2. EARTHQUAKE MOTION AND RESPONSE SPECTRA

Seismic ground or structure motions can be presented as accelerograms – time histories of acceleration. These can be actually measured earthquakes, results of structural calculations, or artificially generated time histories having certain desirable properties. Shake tables are typically asked to reproduce these motions, within certain limits. Peak responses are typically about 3 g, 40 ips (1m/s), and +/-3" (+/-8cm). Sometimes responses several times smaller or larger than these are required.

Most shake tables do not reproduce the very slow long displacements of some earthquakes (which can reach several feet or meters). This means that most shake tables can only reproduce large earthquake motion energy above about 1 Hz. This is generally sufficient as most equipment and scale models have resonant frequencies well above 1 Hz.

Shake tables may be able to reproduce motion in only one horizontal direction (uniaxial), in one horizontal and the vertical direction (biaxial), or in both horizontal and the vertical direction (triaxial). Triaxial tables are the most realistic but also more expensive. Many tests and much research are consequently done on uniaxial or biaxial tables.

The desired motion on the shake table is often indirectly specified by a Response Spectrum. This is a plot of the maximum absolute response of a single-degree-of-freedom oscillator excited by a particular ground motion, such as an earthquake. These plots are typically acceleration response and plotted as a function of the resonant frequency of the oscillator. Multiple curves are typically presented, each one for a different value of damping of the oscillator.

Figure 1 presents a typical response spectrum, evaluated for 1% and 5% damping. Note that either of these spectra define the earthquake and one does not have to have the spectra for the actual damping of the test object (or even know the actual damping of the test object). Within a reasonable accuracy, if the table matches the 5% spectrum it will also match the 1% spectrum (or, for example, a 7.2% spectrum). In most applications either the 2% or 5% spectra are presented.

The lower the damping the greater the larger the spectra, although all spectra converge at high frequencies (to the Zero Period Acceleration or ZPA). Lower damped spectra are more variable ("hashier") than higher damped spectra. Note that the acceleration reported is spectral acceleration and not the maximum acceleration required of the table. For example, the 1% spectrum in Figure 1 has a peak value of about 10 g. This is the maximum acceleration that a 1% damped oscillator with about a 2 Hz resonant frequency would see during

this earthquake. The actual peak acceleration of the table is given by the ZPA – about 3 g.

Note that the spectra show that the peak response of this earthquake occurs for structures with resonant frequencies in the 2-5 Hz range. The fact that the 1% and 5% spectra are equal above about 20 Hz indicates that this earthquake has little energy above 20 Hz.

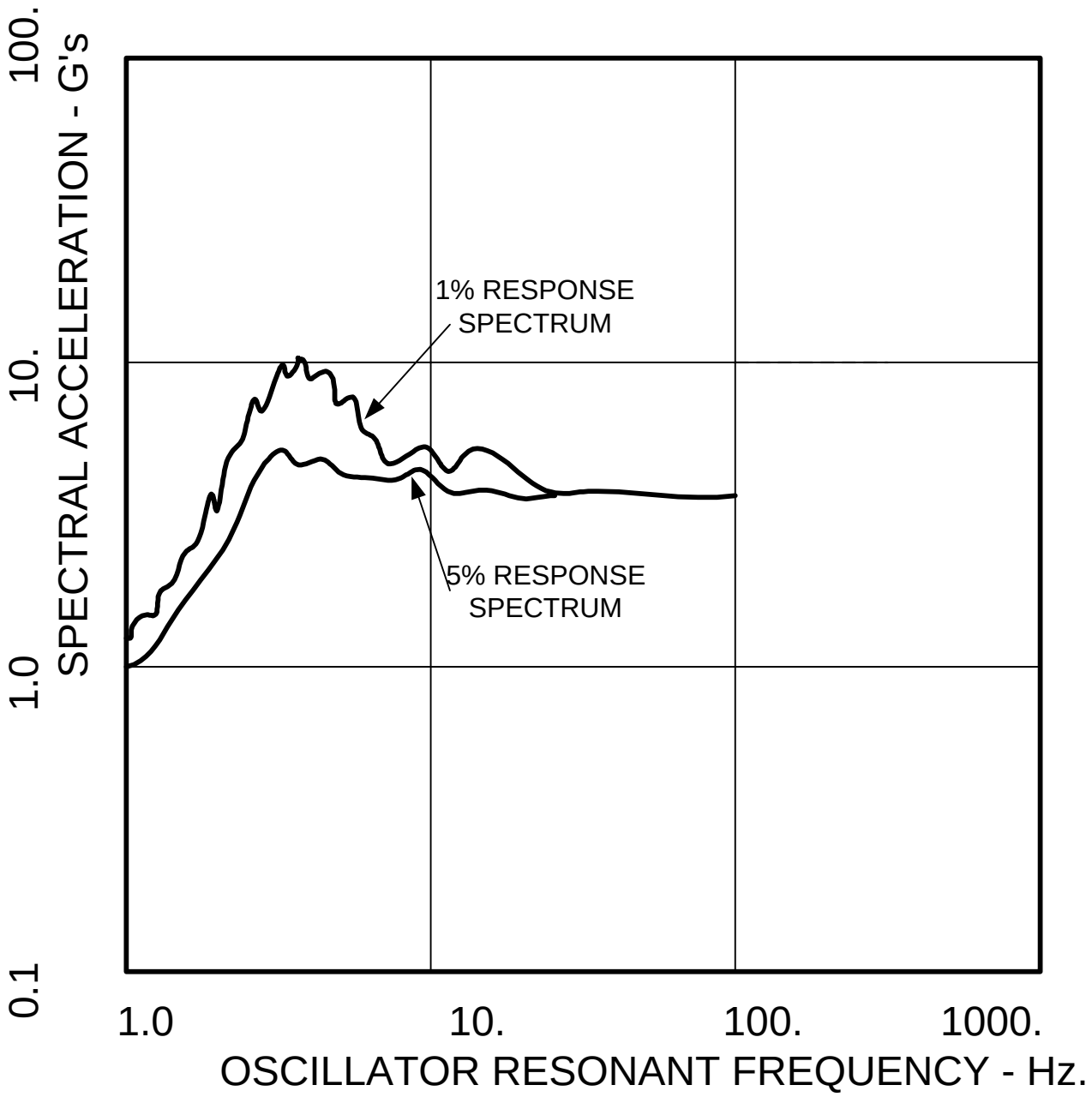

FIG. 1.: Example 1% and 5% Response Spectra

3. TESTING STANDARDS

Various industrial and government groups have issued standards, specifications, guidelines, and recommendations for testing equipment on shake tables. The following list is limited to those standards most often used in the United States (there are similar standards available in from the EC, Japan, and other countries). Most seismic testing done in the United States is done under the IEEE-344 and Bellcore Gr-63 standards.

IEEE-344

A standard of the IEEE describing procedures for the seismic qualification of electrical equipment in nuclear power plants. This standard, last issued in 1987, is also widely used for mechanical equipment.

Bellcore (Telcordia) GR-63

A standard written by Bellcore (called Telcordia since about 1999) specifying a procedure and test level for seismic qualification of telecommunications related equipment. This standard emphasizes the use of separate horizontal and vertical shake tables and defines 5 Zones (Zone 0 – Zone 4) across the United States of varying seismic severity. While used extensively for telecommunication equipment, this standard is not generally used for nuclear power plant equipment.

QME-100

An ASME standard describing procedures for the seismic qualification of mechanical equipment.

MIL-STD-167

A United States Navy Specification describing procedures for fatigue testing of equipment placed on ships and exposed to vibratory input from engines and wave action. The tests involve long duration sinusoidal step sweeps.

Mil 810

A military test standard describing test procedures for a variety of shock, impact, pyrotechnic, and vibratory fatigue applications. Such testing is typically carried

out using an electro0dynamic vibrator and typically involves high frequencies (up to 2,000 Hz).

4. TYPES OF SHAKE TABLES

Seismic tables are typically uniaxial, biaxial, or triaxial, as discussed above. They can be driven by servo-hydraulic actuators, servomotor actuators, Electro-dynamic actuators, or mechanical actuators. Servo-hydraulic actuators are the most common and can handle large tables with large test object masses and high acceleration requirements. Their disadvantage is higher noise, high oil pressure, oil leakage, maintenance, and requirement for special maintenance training.

Servomotor driven tables are cleaner and less noisy than servo-hydraulic tables and require no special maintenance training. However, they have limited payload mass capacity and can be more expensive than servo-hydraulics for larger tables.

Electro-dynamic actuators have limited stroke (except for certain newer models) and are generally limited to uniaxial tables. Hence they are seldom used for seismic qualification, except for relatively small and rigid equipment.

Mechanical actuated tables (eccentric mass and eccentric cam) can only produce sinusoidal motion and so have been largely abandoned for seismic testing. They are significantly less expensive than the other types of tables and so are sometimes used to test equipment, if the sinusoidal forcing can be justified.

5. HYDRAULIC ACTUATORS

Servo-hydraulic actuators are the most often used actuator for seismic shake tables. They consist of a piston with double-ended piston rod. A hydraulic servo valve is used to introduce oil in one side or the other of the piston (while evacuating the other) thereby causing the piston to move or exert a force in one direction or the other, under the direction of the servo controller. The piston chamber base is anchored to the laboratory foundation. One end of the piston rod is anchored to the shake table, either rigidly (as with a uniaxial table) or via ball joints (as with a multi-axes table.

The actuator is provided with hydraulic fluid under pressure. Shake table systems typically operate at 2,000 psi and can require flow rates from a few GPM to hundreds of GPM. Actuators can supply forces from about a ton to several hundred tons. Tables may have anywhere from 1 to 8 actuators.

Hydraulic actuators are typically provided with multiple high and low pressure seals, and seal drains, that limit oil leakage to a few drops per earthquake test. They will also have instrumentation that allows feedback of actuator displacement, force, and differential pressure across the piston (Delta-P). Such actuators are typically design to be very rigid and to keep strains below the material endurance limits, so as to assure years of actuator life.

6. ELECTRIC ACTUATORS

Since 1980 various manufacturers have been offering and improving all electric actuators of increasing force and performance, while reducing costs. Note that ball screw servo drives can provide high force, but do not have the fidelity or capacity to accurately reproduce earthquakes, particularly above 10 Hz. The newer all-electric drives are called direct drive hybrid servomotors as they have features found in both DC servomotors and stepping motors.

The hybrid servo motors work by using digital switching circuits to alternately energize a large number of electro-magnets on poles in the motor. An opposing set of magnetic piles on the moving element (either electro-magnets or permanent rare earth magnets) are consequently forced to move in one direction or another. Using a feedback displacement transducer the hybrid servo motor servo controller can control the force and position of the motor with great accuracy and to frequencies as high as 500 Hz.

These motors are highly engineered and reliable, as their main application is for continuous duty in manufacturing operations. Hence they are ideal for use in seismic shake tables.

These motors can not yet produce the very high forces of large servo-hydraulic actuators. The forces they can produce are limited to about 5 ton. Yet this force is adequate for small to medium sized seismic tables. Pound for pound of force capacity, these motors are 3 to 10 times more expensive than servo-hydraulic ACTUATORS. Hence they are best used for smaller tables and in cases where the noise, oil, or maintenance issue of hydraulic systems can not be tolerated.

7. SIGITAL TABLE CONTROLLERS

` A servo controller will accept a user supplied signal (program) and cause the table to follow this signal closely. Until about 1975 most shake tables accepted this fit. Since then, however, a number of firms have offered a variety of digital controllers that significantly improve this fit and make the testing process easier and faster. First, the digital controller is a signal source. It provides an earthquake time history that is connected to the servo controller. The digital controller can be provided with a library of historical earthquakes, with programs for calculating new ones, and with the ability to import digital or analog time histories supplied by others.

Second, the digital controller will record the actual motion achieved on the table and then modify the drive program to cause the table motion to more closely fit the desired motion. This is an iterative process called equalization.

Third, the digital controller will be able to record several channels of data (typically between 3 and 16) for processing, display, analysis, and documentation purposes. Hence the test object response as well as the table motion can be monitored.

These controllers typically use a standard PC for test set up and data display and storage. The PC is typically augmented by fast ADC, DAC and FFT boards and with transducer amplifiers and anti-aliasing filters. Digital controllers can control tables with 1-8 degrees-of-freedom.

8. DATA ACQUISITION SYSTEMS AND FILTERS

The digital controllers discussed in the previous section are often sufficient for all data acquisition for many shake table test labs. These controllers can be augmented by a variety of PC based data acquisition and display systems to allow even hundreds of channels of data acquisition, display, and storage. Note that in addition to the multi-channel ADC required, extra transducer amplifiers and anti-aliasing filters may be added. Anti-aliasing filters are low pass filters that prevent distortion of the sampled signal by high frequency components of the signal.

9. INSTRUMENTATION

Shake tables use a variety of transducers to control the table and to monitor the response of the test object. The most used transducers are accelerometers (including piezoelectric, piezo-resistive, capacitive servo, and strain gage accelerometers).

Displacement transducers include string pot devices, LVDT/RVDT, Laser and Ultra sonic non-contacting devices, and magnetostrictive non-contacting devices.

There are few direct velocity measurement devices. Velocity is typically found by integration of an acceleration signal. Strain is typically measured with strain gages. Occasionally crack growth gages are used.

Most instruments have associated electronics that provides a Voltage signal proportional to the sensed parameter (a few use a 4-20 ma current indication). A data acquisition system with an ADC (Analog to Digital Converter) is often used to convert these analog signals into a digital form. A few instruments directly produced digitized data.

ATTACHMENT A

DEFINITION OF FREQUENTLY USED TERMS AND CONCEPTS

Term or Concept	Definition
Accelerogram	An acceleration time history, either plotted on paper, photograph, or in digital form. The typical unit is g's. Duration is typically under 1 minute. These typically show the acceleration motion on the ground or in a structure due to an earthquake.
Accelerometer	An instrument, almost always electrical, that provides a signal (typically a Voltage) proportional to the acceleration occurring at the location of the instrument. Instruments can be based on the piezo-electric or piezo-resistive principle, strain gages, or servo accelerometers based on capacitance measurements.
Accumulator	A hydraulic device consisting of either a piston in a sealed tube, or an elastic bladder or diaphragm in a pressure vessel. A gas (typically Nitrogen) is introduced on one side of the piston or elastic element and hydraulic oil is introduced on the other side. By pressurizing the oil the gas is compressed, thereby storing energy that can later be recovered to develop high oil flow rates. Accumulators are also used to calm down hydraulic piping vibration, to maintain pressure relatively constant, or to store hydraulic oil for later use in a pressurized system.
ADC (Analog to Digital Converter)	An electronic device to turn an analog Voltage signal (or possibly a current signal) into a digital representation of that signal, typically by digitizing the signal at small evenly spaced time steps. The ADC capability is typically defined by its maximum sampling rate (which can be as high as several million samples/sec) and the number of bits in the digital representation (typically between 8 and 32 bits). An ADC typically can digitize more than one analog channel at a time (16 channels is typical, but systems are available for hundreds of channels).
Air bags	A device that looks like an automotive tire with two

	steel end caps instead of a rim. Airbags can be pressurized (typically with air at up to 100 psi) to produce a large outwards force on the end caps. This force can hold up a shake table against its dead weight. Air bags are useful because they have a relatively low spring constant and so can allow table displacement without introducing significant force change. Air bags are also used to produce isolation mounting platforms for shake tables.
Amplifier	Typically reefers to an electronic device that powers and conditions a transducer (such as an accelerometer) so as to provide a Voltage signal that can be reviewed on an oscilloscope or digitized and displayed. Amplifiers may also contain filters, attenuators, warning functions, calibration adjustment potentiometers, AC/DC features, offset adjustment, and instrument diagnostics. Amplifiers often come in banks of multiple channels (e.g. 2, 4, 8, 16 or more channels). Amplifiers can be of various kinds depending on the transducer they are designed for: charge amplifiers for piezoelectric transducers, ICP amplifiers, Voltage or current amplifiers, carrier frequency amplifiers, bridge completion amplifiers.
Anti-aliasing filter	“Aliasing” occurs when a signal is digitized at too slow a rate. If this occurs, high frequency components in the digitized signal can be interpreted as low frequency components (hence the name – “Alias …”). Sampling theory indicates that the signal must be digitized at a rate at least twice the highest frequency contained in the signal. In order to reduce the rate required, electric analog low pass filters are often used prior to digitization, to eliminate high frequency components. These are called “Anti-aliasing Filters” and are an important part of most digital data acquisition systems.
Armature	The moving element in an electro-dynamic vibrator, connected to the shake table head. It is the force created on the armature by the stationary filed coils that move the armature and shake table head. The mass of the armature and shake table head is an important parameter in shaker performance: a smaller mass can achieve higher acceleration.

Artificial earthquake	An earthquake accelerogram (time history) produced by numerical manipulation rather than by actual field measurement. A variety of mathematical techniques are available to create such artificial time histories with desired properties – such as having a specified response spectra, or representing a worst case for a particular structure. Such artificial earthquakes are often used to drive shake tables as they have more uniform and known parameters, and are often more damaging, than real earthquakes.
Ball joint (rod end, Himes Joint)	A mechanical device consisting of a metallic sphere (typically steel, bronze, or structural ceramic) in a conforming rig that allows motion of the sphere in all rotational directions but not in translation (such as a hip joint). The sphere can be lubricated with grease, or can be lined with a fluorocarbon (e.g. Teflon) or similar material or fabric and need no lubrication. These are called “maintenance free”. Ball joints are often used in shake tables to attach actuators or to provide rigid strut translation restrains such as with torque tubes. Maintenance-free ball joints are often used in shake tables, but care must be take to size them so that excessive wear gaps do not develop, or to provide a mechanism for tightening the outer ring periodically.
Bandwidth	A term use various ways, generally indicating the frequency range of operation of a device or its maximum operating frequency (e.g. “the shake table bandwidth is 50 Hz” means it can operate from some low frequency up to 50 Hz, while “the ADC bandwidth is 10 kHz” means that the ADC can digitize at up to 10,000 samples/sec.)
Bar	A unit of pressure measurement. 1 Bar is equal to 0.9869 Atmosphere, or 14.5 psi, or 100,000 Pascal
Bare wire test	A test conducted on a digital shake table control system in which the mechanical and power part of the shake table is bypassed with a single cable (the “bare wire”) that just connects the analog output of the servo controller to the digital input of the servo controller. By performing such a test the user can practice controller use without moving the table, or can run digital controller diagnostics to determine if a

	particular problem is with the digital control or in the rest of the shake table system (power supply, actuator, table, feedback instrument, etc.).
Bellcore GR – 63 (now Telcordia)	A standard written by Bellcore (called Telcordia since about 1999) specifying a procedure and test level for seismic qualification of telecommunications related equipment. This standard emphasizes the use of separate horizontal and vertical shake tables and defines 5 Zones (Zone 0 – Zone 4) across the United States of varying seismic severity. While used extensively for telecommunication equipment, this standard is not generally used for nuclear power plant equipment.
Beta (Greek letter)	A symbol typically used to signify the amount of damping in a harmonic oscillator. This term is typically reported as a fraction of critical damping, but may also be reported as the percentage of critical damping. (This can cause confusion. For example, damping of 0.5 could mean half of critical damping or ½% of critical damping, a difference of a factor of 100.) Note that damping is an important parameter in specifying a response spectrum. That is, one may speak of "the 5% response spectrum" meaning the response spectrum for oscillators with 5% of critical damping.
Biaxial (independent)	An independent biaxial shake table typically means that the table can move in the vertical and horizontal direction independent of one another and simultaneously. This is not to be confused with a vector biaxial table in which the horizontal and vertical motion are always a fixed fraction of each other. More rarely an independent biaxial table may have the ability to move independently and simultaneously in the two horizontal directions, but can not move in the vertical direction.
BNC (British Naval Connector)	A popular coaxial connector extensively used for hooking up transducers and instrumentation to data analysis systems. The bayonet and détente BNC connector is robust and nearly immune to loosening due to vibration or shock.
BSR (Buzz, Squeak, and	Such testing is typically carried out in the automotive

Rattle testing)	industry to determine if automotive components produce unacceptable noises during simulated road vibration. A very quite shake table and shake table room is required to perform these tests (typically under 60 dbA).
Chatter	During vibration a relay and similar devices may "chatter" meaning that they may temporally or permanently change state (e.g. from normally open to normally closed or vice versa). This can be a great concern in safety systems and plant operating systems. Often a chatter lasting 2 ms or greater is considered unacceptable. Digital chatter monitoring systems are often used to monitor relays during shake table testing to determine their chatter behavior.
Constant volume pump (variable volume pump)	A constant volume hydraulic pump produces peak flow continuously, dumping excess flow back to hydraulic reservoir. Hence it constantly consumes peak or near peak energy and has higher cooling requirements. A constant volume pump, however, is quieter than a variable volume pump. A variable volume pump produces just the demanded flow and so does not use peak power all the time and needs less cooling. It is, however, typically more noisy than a constant volume pump.
CPS (Cycles per second)	Refers to a cyclical behavior that repeats itself at a constant rate (e.g. the shaft rotates at 40 CPS). Note that 1 CPS and 1 Hertz (1 Hz.) have the same meaning.
Crest Factor (Peak Factor)	In a random signal (such as a vibratory motion) the Crest Factor is the maximum response above the average (RMS response). It is possible for a random signal to have an infinite Crest Factor, but most often, in vibration testing, it is defined or limited to 3 or a similar number, for practical purposes.
Cross axes motion	The motion that occurs in the directions other than the desired direction on the shake table. For example, one may want a 5-g sinusoid in the horizontal direction and no motion in the vertical direction. If, in practice, one sees 0.1g in the vertical direction one

	would say that the cross axes motion is 0.1 g, or equal to 2%. Shake tables are designed to minimize cross axes motion, but such motions can not be eliminated entirely, especially at higher frequencies where they are caused by table inaccuracies, gaps, and resonances.
Cross axes sensitivity	Sometimes this term is used synonymously with cross axes motion. More often is reefers to the amount of signal an instrument such as an accelerometer will produce when it is driven off axes. For example, if an accelerometer is vibrated perpendicular to its nominal sensitive axes and it indicates a signal equal to 2% of the actual off axes motion, then one would say that the accelerometer has a 2% cross axes sensitivity.
DAC (Digital to Analog Converter)	An electronic device to convert a digital set of values into a continuous analog signal. Typically the numbers represent an acceleration or displacement motion defined at uniform time steps. The DAC is used in a digital control system to produce an analog signal that can be used to drive analog devices, such as an analog servo controller controlling an actuator.
Damping	Refers to the ability of a vibrating structure to absorb or dissipate energy and hence reduce its vibration response or level. This term is most often quantified as a percent or fraction of critical linear viscous damping (e.g. 5% damping). The sources of true damping in a structure are many, are both linear and nonlinear, and are often not know with great accuracy. Rules of thumb based on experimental measurement of damping are most often used.
db (decibel)	A logarithmic measure of a signal or value as compared to a reference value. In vibration theory the db value of a signal is 20 times the logarithm (base 10) of the ratio of the signal to its reference. For example, if the reference is 10 Volts and the signal is 100 Volts the db value is 20. One would say “the signal is at 20 db”. If the signal were 0.1 Volts one would say “the signal is at –20 db”. Note the following often used db values: 60 db = a factor of 1000 40 db = a factor of 100

	20 db = a factor of 10 10 db = a factor of 3.162 … (SQRT(10)) 6 db = a factor of 2 3 db = a factor of 1.414 … (SQRT(2)) 0 db = a factor of 1 -3 db = a factor of 0.707 … (SQRT(0.5)) -6 db = a factor of 0.5 -10 db = a factor of 0.3162 …(SQRT(0.1)) -20 db = a factor of 0.1 -40 db = a factor of 0.01 -60 db = a factor of 0.001
DBE (Design Basis Earthquake)	Typically used in the design of nuclear power plant facilities, this is the size of the largest earthquake to which the structures and equipment must be designed to operate. Sometimes this expression is used to mean the largest earthquake that can, with reasonable probability, occur at the plant site and so is equivalent to the SSE (Safe Shutdown Earthquake). Alternately this expression can be used to mean the largest earthquake that the plant can survive without damage and so is equivalent to the OBE (Operating Base Earthquake).
Dead weight support	The mass of the moving parts of the shake table, plus the mass of the test item are dead weight that push a shake table downwards in the vertical direction. To hold the table in the center position air bags, air cylinders, springs, or air chambers in actuators are often used. These supporting devices, called dead weight supports, are useful as they remove this dead weight from the vertical actuator(s), thus allowing greater dynamic motion by the actuator. To be effective, dead weight supports must not change their force significantly over the full vertical stroke of the table. They must also be able to accept full motion in the transverse (horizontal) directions.
Delta-P	An instrument measuring the differential pressure across the piston in a hydraulic actuator. This signal is typical used as a feedback in the servo control loop to introduce damping into the system oil-column resonance, thereby allowing control and operation near the oil-column resonant frequency.
Digital Controller	Most often this term refers to an digital device,

	typically a PC with special cards and interfaces, that serves three functions. First, the controller accepts table and test object dynamic response from accelerometers and other transducers. The controller digitizes these signals and displays them. The signals can also be filtered, integrated, archived, and exported. Second, the controller will output a digitally specified time history in analog form to drive a servo controller that controls an actuator. Third, the controller will compare the actual measured table response with the desired value, and adjust ("equalize") the drive signal so as to force the table response to more accurately reproduce the desired motion. In some cases the Digital Controller will also contain the servo controller, implemented by a digital algorithm. In some cases the term Digital Controller is used to refer to the Servo Controller, if part of the servo control functions are implemented digitally (such as limit checking, parameter setting, overload protection, etc.). These "Digital Servo Controllers" most often have an analog servo loop at their heart. Hence they are better referred to as "Digitally Supervised Servo Controllers".
Double ended piston	Hydraulic actuators can be single or double ended. In a single ended piston there is only one piston shaft exiting the piston chamber. Hence the area on the two sides of the piston are different. In a double-ended piston there is a same diameter shaft existing from both ends of the chamber, hence the two sides of the piston have equal area (and the same force for the same pressure). The difference In force to pressure sensitivity of the two sides of a single ended piston make it more difficult to tune and control with a servo controller, especially for dynamic testing. Hence, shake tables almost always use double ended pistons.
Dump valve	Hydraulic power systems for shake tables often use accumulators to store energy to produce high oil flow during transient high velocity testing such as 30 second earthquakes. These accumulators represent

	a large amount of stored energy and can enable significant actuator and table motions even with the hydraulic pump turned off. In a potential accident situation it is advisable to empty these accumulators quickly. This is often done using a solenoid (or manual) valve between the high and low pressure sides of the hydraulic power supply. This dump valve allows emptying the accumulators in seconds, rather than allowing them to be active for many minutes after the pump is shut down. This dump valve is typically connected to the pump controller so as to automatically open on pump shutdown.
Durability testing	Typically used in the automotive industry, this form of testing involves exposing the test object on the shake table to long duration simulated severe road vibrations. Due to the use of time histories in which low levels of vibration have been edited out, such tests can "age" the test object at a rate of 1,000 miles per hour or more. Hence a 100 hour test can simulate a lifetime of fatigue in a typical vehicle. Durability testing is also used in shipboard tests (such as MIL-STD-167). The office and transportation vibration tests in the Bellcore GR-63 standard are durability tests. The use of 5 OBE earthquakes in seismic testing of nuclear power plant testing (IEEE-344) can be though of as a short duration durability test. Plant equipment exposed to long term operating vibration (e.g. line mounted equipment) can also be durability tested by the sinusoidal RIM standards.
Eccentric mass vibrator (Eccentric Cam Vibrator)	An actuator created by rotating one or more eccentric weights about an axis or axes. Such vibrators can produce sinusoidal forces when driven by a variable speed electric motor. While most often used to perform modal vibration tests on structures, eccentric mass vibrators can be used to drive a shake table, but are limited to sinusoidal motion. The benefit of eccentric mass vibrator actuators is their low cost compared to servo hydraulic, servo motor, or electro-dynamic actuators. Eccentric cam vibrators are similar, but create a sinusoidal displacement using an eccentric cam. Note that an eccentric cam vibrator produces an acceleration proportional to the square of the

	frequency (unless mechanically adjusted) whereas an eccentric mass vibrator produces a force proportional to the square of the frequency (unless mechanically adjusted)
Electro-Dynamic actuator	An electro-dynamic actuator is permanent magnet or electro-magnet (armature) in a stationary field coil. By varying the current in the filed coil a like varying force is induced in the armature which can be connected to a shake table. Electro-dynamic vibrators are used extensively in aerospace and military applications due to their ability to operate to 2,000 Hz and above. However, they find limited use in seismic applications since they have limited stroke (typically under +/- 1"), do not operate well below about 3-5 Hz, and are uniaxial. (Some more recent designs have longer strokes.)
Encoder	A displacement device that directly produces a digital representation (series of numbers) of a linear or rotary position. Encoders are sometimes used as feedback devices on actuators with digital controllers.
Equalization	When a drive signal is used to drive a shake table/actuator, the resulting motion does not exactly reproduce the desired drive signal. This is due to linear and nonlinear dynamic phenomena (actuator, table, and test object resonances, gaps, electrical noise, etc.). Equalization is a process in which the drive signal is modified so as to compensate for these distortions, and produce a table motion much closer to the original desired drive signal. This is a process similar to that of tuning a stereo system by ear, using a slide pot filter equalizer. While equalization can be done "by hand" using filters and attenuators, the most efficient method is to use the algorithms programmed into typical digital controllers.
FFT (Fast Fourier Transform)	A digital algorithm developed by Cooley and Tukey that allows computation of a Fourier Transform with great efficiency and reduction in computational time. The algorithm is particularly fast if the number of points in the time history is a power of 2 (hence the prevalence of powers of 2 in such data processing). The algorithm get more efficient, as compared to the standard approach, as the trace get longer, making it

	very useful in a variety of signal processing tasks. The standard approach is often called the DFT (Direct Fourier Transform) and is largely unused, except for cases when the Fourier Transform is desired in only a very limited frequency range (in which case the DFT may be faster than the FFT).
Fidelity	A shake table motion does not exactly match the desired motion, even after equalization. If the match is good (the error in match is small), one can say that the table has good (or high) fidelity. Fidelity can be measured and defined in a variety of ways. If a sinusoidal sweep is desired, one can specify the error is sine amplitude, or the value of the harmonic distortion (amplitude of the harmonics of the desired frequency). If an earthquake is desired one can compare the amplitudes on a point by point basis in the time domain (e.g. a superimposed plot) or one can look at the amplitude differences in the desired and achieved response spectra or Fourier Transform. In multi-axes tables one can look at how much of the motion in one axis “leaks” over into the other axes. Tables vary in their fidelity and generally have better fidelity at lower frequencies and when operating at less than 100% of maximum capacity. There are no single set of standards for what fidelity is required of a table. What fidelity is required is often unknown as many specifications do not address fidelity, or define it only in limited ways or for limited conditions or frequency ranges. Note that higher fidelity is often accompanied by a higher shake table price. To be cost effective, match the table fidelity specification to the application.
Fixturing	The top of a shake table is typically a flat metal surface with a uniform grid of threaded bolt holes that typically do not match the anchorage details of the test object. Most often “fixturing” must be fabricated as a transition between the test object and the table. This may take the form of a sacrificial plate that bolts to the table grid and is then tapped or welded to attach the test object, a specially made plate, beam, or bookend type fixture, braces, etc. Often fixturing is designed to be generic and can be used for a variety

	of test objects with slight modification. Fixturing must be rigid, so as to avoid changing the test object dynamics, and sufficiently strong to avoid fixture failure during the test. The mass of the fixturing must be taken into account when planning the test.
Flex plate	In lieu of a linear bearing, a table can be guided by flex plates, as is typically done in electro-dynamic vibrators, and less often in seismic tables. A flex plate is typically a thin plate of metal that is relatively flexible in one direction (out of the plane of the plate) but relatively rigid in the in plane extension and shear directions. Flex plates are most effective for low displacement applications (typically under 1" or 2.5 cm). The advantage of flex plates is their high gap free rigidity in the restraint directions/
Floor spectrum	A response spectrum defined at a particular location in a building or plant. This floor spectrum will include the effects of the structure in modifying the free-field ground motion earthquake.
Force cell	A transducer that measures the force applied to an actuator or anchor bolt. In some forms of testing (e.g. fatigue frame or pseudo-dynamic testing) an actuator is used in the ""Force Control Mode" and a force cell is used to provide feedback to the servo controller. In shake table testing it is not always possible to simulate, for example, a concrete block into which anchors are placed. In this case the anchors might be placed into a steel fixture and be supplied with an anchor bolt force cell, so as to measure the forces induced in the anchor during the test. These could then be compared to published data from concrete anchor suppliers.
Fourier Transform	A mathematical transformation mapping a time history to an equivalent frequency function, or vice versa. The Fourier transform of a time history easily shows the frequency ranges where the time history has much activity or power, shows resonant peaks, and can be used to determine transfer functions. The Fourier Transform is used extensively in digital data processing, display, filtering, and equalization.
Fragility test (as opposed	In a qualification test the test object must withstand a

to a qualification test)	given sized earthquake)e.g. the design earthquake for the site). In a fragility test the test object is exposed to ever increasing sized earthquakes until it fails (or the table limit is reached) in order to establish the largest generic earthquake that the test object can survive. This may be useful, for example, if the ultimate design earthquake has not yet been defined, or the equipment is intended for use at many different sites.
Free-field Earthquake	The size or definition of an earthquake away from any structure, before that has been the possibility of modification of the earthquake motion by the presence of the structure.
G (g)	1 g is the nominal acceleration of gravity at the surface of the earth (386.4 inch/s**2, 9.82 m/s**2). Earthquake acceleration, response spectra, and peak table acceleration capacity are most often reported in g's.
Gain	In a servo loop (as for a servo controller of an actuator) the factor by which the error between desired and actual position is multiplied before creating the correction drive signal to the actuator. Gain is found both in the electronic and hydraulic components of the actuator. Too little gain results in a sluggish responding system with poor high frequency fidelity. Too much gain will cause an actuator to go unstable (much as a "hot mike" in an acoustic system). Gain is most often set electronically in the servo controller, and may have to be adjusted if the test object mass or dynamic property varies significantly.
GERS (Generic Equipment Response Spectra)	Developed for EPRI (Electric Power Research Institute) and SQUG (Seismic Qualification User'' Group), these are a collection of fragility spectra for many varieties of equipment that demonstrate their generic ability of this equipment to withstand a moderately high earthquake. The GERS were generated by reviewing past shake table test results.
Grid (table)	A shake table top is typically covered by a uniform grid of threaded bolt holes (e.g. ½"-13 on 4"x4" grid, or ¾"-10 on 8"x8" grid). Seismic tables typically have

	a rectangular grid. Electro-dynamic tables typically have a circular grid. These holes are used to anchor the test object or the fixturing to the table top. Tapping extra holes or welding to the table top is usually not recommended.
Half-power bandwidth	The width of a resonance peak at its “half power” point which is 0.707… (SQRT(1/2)) of the peak height. This width is equal (approximately) to twice the critical damping times the resonant frequency. The width of a peak with 5% damping and 3 Hz resonance, for example, will be 0.3 Hz. This is a useful relationship, as the bandwidth can be easily measured experimentally and hence yields an estimate of the system damping.
Hard stop	A relatively rigid stop in a shake table to prevent over travel that might damage the shake table rails or actuator. Hard stops are a last resort, as impacting a hard stop can produce high accelerations on the table. Hence hard stops are often used in conjunction with a soft stop – which is a more flexible bumper that slows the table over a longer distance.
Harmonic distortion	If a table is commanded to reproduce a sine wave and does so imperfectly, the actual periodic response can be analyzed as a fundamental response at the desired frequency plus harmonic components at integer multiples of the fundamental frequency. These are called the harmonics of the response and their presence indicates a harmonic distortion. The square root of the sum of the squares of the harmonic amplitudes is called the total harmonic distortion. It is often divided by the amplitude of the fundamental to convert it to a percentage. That is, one can say the total harmonic distortion is 15%. Note that for the same response the harmonic distortion of the displacement will be much less than that of the acceleration (which accentuates the harmonics). The size of the harmonic distortion is one of the measures of performance of a table.
Hash	The absolute value of the Fourier transform of a signal is often plotted to look for the frequency distribution of the signal energy and for resonant peaks. This data is often hidden by wild fluctuations

	in the Fourier Transform called Hash. There are algorithms, which smooth the transform to reduce Hash and make the underlying features more apparent.
HPS (Hydraulic Power Supply)	In a hydraulic shake table the HPS consists of the electric motor driving the hydraulic pump, motor starter, oil reservoir, heat exchanger, control valves, oil filters, fluid height and temperature sensors, accumulators, distribution manifolds, and dump valve. The HPS provides high pressure oil at high flow rates to the actuator servo valves to move the actuator. Typical pressures are from 3,000 psi to 5,000 psi with flow rates from a few GPM to hundreds of GPM.
Hydrostatic bearing	A linear motion or rotary motion bearing that consists of two close but non-contacting surfaces that are separated by a thin layer of pressurized oil. Such bearings are known for their low friction coefficient, high stiffness, and linearity (zero gap). Care must be taken to provide good sealing to prevent oil leaks.
Hz (Hertz)	Named for the German scientist Heinrich Hertz, who first experimentally demonstrated the existence of radio waves, the Hertz is the unit of oscillation. That is, 1 Hz is 1 cycle per second.
ICP Amplifier	An amplifier designed to power and condition a piezoelectric transducer that has an internal charge amplifier.
IEEE-344	A standard of the IEEE describing procedures for the seismic qualification of electrical equipment in nuclear power plants. This standard, last issued in 1987, is also widely used for mechanical equipment.
In-cabinet spectrum	A response spectrum defined at a particular point in a cabinet in a structure exposed to an earthquake. This spectrum includes the amplification and filtering effects of both the structure and the cabinet. Hence a piece of equipment located at this point in the cabinet can be tested without the cabinet – that is, just attached to the table or table fixture.
Independence	The motion in two different directions in a multi-axes table are said to be independent if they are not

	correlated significantly. For example, IEEE-344 requires the motions to have a correlation coefficient less than 0.3 or a coherence function less than 0.5. This requirement is to ensure that the table is truly biaxial and not just moving at an angle to each axes, which might under-test modes of vibration perpendicular to this angle. Interestingly, the actual earthquake motion of locations high in a structure can be highly correlated, due to contributions for a few highly excited modes of vibration.
Intensity (Modified Mercali)	A qualitative measure of earthquake damage at a specific location, as defined by a scale of Roman Numerals (I-XII) as defined originally by the Italian Seismologist Mercali. The MMI scale I indicates just perceptible by humans, while XII indicates essentially total destruction, even of well engineered structures. The MMI scale is not to be confused with the Richter Scale, which is a measure of the total energy of the earthquake.
Isolation mass	A shake table can be constructed on an isolation mass consisting of a large mass (typically concrete or steel) that is supported on flexible springs or air bags (and possibly dampers). Such a system reduces the transmission of vibration from the operating table to the structure housing the table at frequencies above the isolation mass resonant frequency. This resonant frequency can be made as low as 0.5-5.0 Hz. While useful and effective, an isolation mass can add significantly to the cost and maintenance of a table.
KIP (kilo-pound)	An expression often used in the United States. One kip is equal to 1,000 pounds.
LB (pound)	Used in the United States to refer to both weight (force) and mass. One pound is equal to 4.448 N or 0.455 kg.
Line tamer	Due to the sudden start and stop of the oil flow in high pressure hydraulic piping and hoses, these lines will often jump, vibrate, and make noises. This effect is often also called a “water hammer”. By including an accumulator in such lines this vibration can be reduced due to the flexibility of the gas charge in the

	accumulator. This accumulator is consequently called a “line tamer”.
Linear roller or ball bearing	Linear roller or ball bearings are often used to constrain the motion of single and multi-axes tables. Roller bearings are often preferred due to their higher stiffness and load ratings. These rails can be oil or grease lubricated. Grease lubrication eliminates the possibility of oil leakage. These rails can be pre-stressed to produce an almost gap free constraint. Such rails have relatively low cost and maintenance requirements. Such rails are also available with fluorocarbon type sleeve bearings, whose advantage is lower cost and no lubrication. Such bearings, however, have larger gaps and higher sliding friction than ball or roller bearings.
LVDT (Linear Variable Displacement Transformer)	A displacement transducer based on the variable inductance caused as a magnetic material rod is passed through a field coil. Such devices are often used as displacement feedback devices for linear actuators, but have the disadvantage of wear, as the core slides against the inside of the filed coil tube. Hence many newer actuators use a non-contacting device based on the magnetostrictive principle.
Magnetostrictive displacement transducer	This transducer uses a non-contacting wire that is moved through a ring magnet. An attached electrical package sends out an electrical pulse on the wire and measures the return time of the echo that is reflected by the magnet (the magnetostrictive effect). The device then converts the time of flight to a displacement, and repeats the pulse several thousand of times per second to obtain a digital time displacement history. Often this history is past through an digital to analog converter to produce an analog Voltage representation of the signal. Such devices are used as displacement feedback transducers on many newer actuators. Their benefit comes from their low maintenance and lack of wear, as the moving components are non-contacting.
Magnitude (Richter)	A logarithmic quantitative scale that is a measure of the total energy in an earthquake, as defined by the

	American Seismologist Richter. A Richter Magnitude 3 earthquake is just perceptible by people at the epicenter, while a Richter Magnitude 6 or higher earthquake is a major earthquake. While there is no theoretical upper limit to the Richter scale, the largest historical earthquakes have been approximately Richter 8-9. A jump of one point in the Richter magnitude is equal to an approximately 30-fold increase in total earthquake energy. The Richter Scale is not to be confused with the Modified Mercali Intensity, which is a qualitative measure of local earthquake damage.
Manifold	This term typically refers to a steel or aluminum block with multiple hydraulic ports for distribution of hydraulic oil flow. In shake table systems there is a manifold from one end cap of an actuator to the other to connect the hydraulic power supply, servo valve, and piston chamber ports. Other devices, such as pressure relief valves, accumulators, and Delta-P transducers may also be connected to the manifold. A manifold may also be used separate from the actuator to accommodate large accumulator banks, dump valves, isolation valves, maintenance valves, filters, and connection to the hydraulic pump.
MAST (Multi Axes Shake Table)	MAST is a term used to describe both motion tables (which typically operate below about 1 Hz) and shake tables (which typically operate above 1 Hz) and have more than one direction of motion.
Mechanical vibrator	A vibrator (actuator) based on the use of rotating eccentric masses or a rotating eccentric cam. These can be used to drive shake tables if only sinusoidal motion is desired.
MIL-810	A military test standard describing test procedures for a variety of shock, impact, pyrotechnic, and vibratory fatigue applications. Such testing is typically carried out using an electro0dynamic vibrator and typically involve high frequencies (up to 2,000 Hz).
MIL-STD-167	A United States Navy Specification describing procedures for fatigue testing of equipment placed on

	ships and exposed to vibratory input from engines and wave action. The tests involve long duration sinusoidal step sweeps.
Modal Analysis	Refers to either the analytical or experimental determination of the modes of vibration of a linear multiple degree-of-freedom system. These modal properties include mode shapes, resonant frequencies, modal damping, modal mass, and participation factors (a measure of the sensitivity of a mode to excitation from any particular direction). Such parameters can be measured experimentally on a shake table or by field vibration tests. They can also be computed using finite element analysis software.
Mode Shape	The deflection shape that a multiple-degree-of-freedom system takes when vibrating in one mode of vibration only. This is sometimes also referred to as the eigen-vector. When vibrating in a single mode the system behaves like an SDOF system.
Motion table	This term is used to describe a table whose purpose is dominantly to position itself at various displacements and/or rotations at low frequencies and at quasi-static response levels. Such tables typically operate under 1 Hz and are not used for seismic or vibratory testing. Such tables are used for evaluation of tracking optics or in flight simulators.
N (Newton)	The SI unit of force, equal to 0.2248 Pounds.
Non-contacting displacement transducer	Such transducers measure displacement using either reflected light or laser light, or reflected ultra-sonic sound. The have the advantage of no wearing parts and not affecting the dynamics of the structure by their mass or stiffness. Some units can stand off many feet or meters. These units can sometimes have difficulties due to low frequency range or the wide “spot” area that they view to measure the displacement. They may also be more costly than contacting displacement transducers.

Nyquist frequency	A frequency equal to half the sampling rate during digitization of an analog signal. The Nyquist frequency is the highest frequency in the digitized signal that will be accurately captured. At higher frequencies Aliasing will occur and the signal will appear as a lower frequency component and corrupt the signal.
OBE (Operating Base Earthquake)	In nuclear power plant design, the size of earthquake (typically defined as a response spectrum) that can be reasonably expected to occur during the lifetime of the plant, perhaps several times. The plant and its equipment must be designed to survive such an earthquake without significant damage.
Octave	A factor of 2 in frequency (e.g. 2-4 Hz and 16-32 Hz are both 1 Octave intervals). This expression is often used to describe exponential (sometimes called logarithmic) frequency stepping as in: "Evaluate the response spectra in 1/6-th Octave steps", or " perform a sinusoidal sweep test at 0.1 Octaves/sec".
Oil-column resonance	A shake table driven by a hydraulic actuator can be approximately modeled as a mass on a spring. The mass is the mass of the shake table and any attached test object. The spring is created by the elasticity of the hydraulic oil in the piston chambers and passages between the servo valve and piston chambers. This mass-spring system has a resonant frequency (proportional to the square root of the spring stiffness divided by the mass). The table will oscillate strongly at this "oil column resonance" and be difficult to control. In addition, the capacity of the table will significantly fall off at frequencies higher than this oil column resonant frequency. Use of Delta-P feedback introduces electronic damping and makes the table much easier to control near this frequency. The oil column resonant frequency can be increased by using a shorter actuator, a higher force actuator, or reducing the table/test object mass.
Omega (Greek letter)	The symbol typically used to designate a frequency measured in radians/second, as opposed to "f" which is typically used to designate a frequency in Hz (cps).
Open loop (as opposed	If a digital controller is simply used to provide a drive

to closed loop)	signal to a shake table, without taking into account the actual table motion, it is said to be operating "Open Loop". If the table motion is taken into account (e.g. to modify the drive function, or provide for shutdown limits) then the controller is said to be operating "closed loop". If this feedback accelerometer signal is lost during a test one can say that the controller has "gone open loop". Open loop operation may be acceptable in certain situations, but can lead to damaging over-tests of structures should table or structure parameters change during the testing.
Participation Factor	In modal analysis of a multi-degree-of-freedom structure, the participation factor indicates the degree to which a particular mode of vibration is affected by ground or table motion in a particular direction. For example, a particular mode may respond strongly to shaking in the vertical and NS direction, but weakly to shaking in the EW direction. Such a mode would have large participation factors for vertical and NS directions, and a small participation factor for the EW direction.
Pascal	A SI measure of pressure, equal to 0.0001451 psi, or 0.00001 Bar.
Period (frequency)	Period is the inverse of frequency. For example a 10 Hz frequency corresponds to a 0.1 second period. Structural engineers typically use frequency. Geophysicists and seismologists will, however, often use period.
Pilot valve	A pilot valve is part of a three stage servo hydraulic valve. The pilot valve, which represents the first and second stage, provides a small (typically 1-5 GPM) controlled oil flow that activates the third stage spool of the 3 stage valve.
Planar Triaxial	If an independent biaxial table is tilted so that all three axis see motion (two horizontal and one vertical) then such a table can be referred to as a planar triaxial table. That is, the motion is restricted to a plane, but there is motion in all three axes.
Program	In the context of shake tables and their servo

	controllers, “Program” reefers to the time varying signal input into the servo controller that the user wishes the actuator to follow. Most often this will be a displacement signal, but could also be velocity or acceleration.
PSD (Power Spectral Density)	A frequency domain plot showing the distribution of energy in a time history (signal). The units of PSD are a squared quantity per unit frequency (e.g. g**2/Hz). The square root of the area under the PSD, between two frequency limits, is the RMS value of the signal, band-pass filtered at those frequencies. (That is, SQRT((g**2/HZ)*Hz) = g-rms.)
PSI (pounds per square inch)	The most popular unit of pressure used in the United States. 1 PSI equals 0.069 Bar, or 6,895 Pascals.
QME-100	An ASME standard describing procedures for the seismic qualification of mechanical equipment.
Rauomoko	The Maori god of earthquakes. Rauomoko is the unborn son of Papi, the Earth Goddess, and Raki, the Sun God. As Rauomoko struggles to be born and release himself from the womb of the Earth Goddess, he causes the earth to tremble, hence causing earthquakes. An alternate theory of the cause of earthquakes, the elastic rebound theory, postulates that motion of the earth's tectonic plates, not Rauomoko, build up strain in the plates and at their edges that is suddenly released when the rock interface forces exceed their strength or frictional limits. This sudden release of energy causes earthquakes. The elastic rebound theory is generally accepted by modern science, but ANCO Engineers still names all its shake tables in honor of Rauomoko (just in case).
Reaction mass (foundation)	Shake tables are typically anchored to a large massive foundation to minimize the ground motion and transmission of vibration to nearby floors. The foundation is typically made of lightly reinforced concrete, or possibly steel. Typically, the reaction mass (foundation) is about 10 times as massive as the maximum force of the actuator used in the shake table. For example, if a table uses a 50 ton actuator,

	the foundation should weigh approximately 500 ton. This ration can vary considerably depending on table type, force direction, soil conditions, type of testing, and the nature and uses of the area surrounding the table. In cases where a very high degree of transmitted vibration reduction is required, a floating isolation foundation (e.g. on air-bags) may be used. Such an isolated foundation significantly increases the cost of the table.
Reservoir	A hydraulic power supply has a reservoir for oil storage, typically held at atmospheric pressure. The hydraulic pump takes its suction from the bottom of this reservoir and the low pressure return flow from the shake table actuators returns to the top of the reservoir. Care must be taken to size the reservoir sufficiently large so as to provide for filling of any system accumulators while maintaining sufficient head over the pump suction to avoid aspiration of air. Reservoirs are often provided with baffles and made deep enough to allow the air in the return flow to dissipate upwards, thus avoiding aspiration by the pump.
Resistance displacement device	A displacement transducer that consists of a linear or rotary potentiometer with an applied DC Voltage. The change is measured Voltage is consequently proportional to the displacement of the potentiometer slide or rotary switch.
Resolver	A rotary displacement transducer consisting of parallel coils excited by a carrier frequency. Accompanying electronics can process the resulting signals to develop very accurate angular position measurements. Resolvers are sometimes used for position feedback in electric servo motor actuators.
Resonant Frequency	The frequency at which an oscillator will vibrate if impulsively excited. Also called a natural frequency or eigen-frequency. A multiple-degree-of-freedom system will have several resonant frequencies, one associated with each mode of vibration. An oscillator will show great amplification of response if excited with sinusoidal forcing at or near its resonant frequency.

Resonant peak	If a Fourier Transform, PSD, or Sine Sweep Response of an oscillator is obtained, there will be an enhanced response at the resonant frequency of the oscillator, called a “resonant peak”. This peak is usually easy to identify in experimental data and so serves to identify the resonant frequencies of the test object. The resonant peak will be larger and more narrow for a low damped oscillator than for a highly damped oscillator.
Response Spectrum	A plot of the maximum absolute response of a single-degree-of-freedom oscillator excited by a particular ground motion, such as an earthquake. These plots are typically acceleration response and plotted as a function of the resonant frequency of the oscillator. Multiple curves are typically presented, each one for a different value of damping of the oscillator. Response spectra (plural) or response spectrum (singular) have become the single most used description of actual earthquakes and theoretical design earthquakes. Note that while any earthquake time history has a well defined response spectrum, a given response spectrum could correspond to several somewhat different time histories.
RIM (Required Input Motion)	Some forms of seismic testing, especially for line mounted equipment, call for high level sinusoidal sweeps called Required Input Motion. Such sweeps have a defined acceleration amplitude that varies depending on the frequency.
RMS (Root Mean Square)	Applied to a series of measurements or to the amplitudes in a time history, this refers to the square root of the sum of the squares of the measurements or data points. Thus one can speak of the RMS strain at several points in a structure, or the RMS acceleration amplitude of an accelerogram.
RPM (revolutions per minute)	A popular measurement of rotation speed among motor, turbine, and engine manufacturers. 60 RPM is 1 CPS or 1 Hz.
RRS (Required Response Spectrum)	In seismic testing, a typically theoretical response spectrum that must be closely matched or enveloped during the test. The RRS may be the result of

	theoretical seismic analysis of the structure in which the equipment to be tested is to be located. The RRS has often been smoothed, simplified, combined with other spectra, and widened to account for uncertainties in analysis and multiple possible placement locations. Occasionally the RRS can be manipulated excessively, and produce a physically unreasonable or mathematically unrealizable test specification.
RVDT (Rotary Variable Displacement Transformer)	A transducer similar to an LVDT that measures rotary motion instead of linear motion. An RVDT is sometimes used as a feedback device on electric servo motor actuators.
Sampling Rate	The number of times per second that a time history is sampled (digitized) in order to produce a digital representation of the signal. The sampling rate is typical specified as N samples/second, where N can vary from 1 to millions. In seismic research the sampling rate typically varies from 100 to 1000 samples/sec. Too low a sampling rate can corrupt a signal and loose data. Too high a rate may require expensive equipment and fill up computer memory without producing useful additional information.
Sampling Theorem (Shannon)	The Shannon sampling theorem says that the sampling rate must be at least twice the highest frequency in the sampled signal. Otherwise the high frequency content in the signal will “alias” and look like low frequency energy, thereby corrupting the information in the digital signal. In practice, the sampling rate should be 3-10 times the highest frequency, to obtain optimal results.
SDOF Oscillator (Single-Degree-if-Freedom)	A linear oscillator or structural system with only one mode of vibration (such as a guided point mass tied to a massless spring). The response of linear multiple-degree-of-freedom systems can be analyzed as the linear combination of several SDOF systems. Hence the dynamics of the SDOF oscillator is fundamental to vibration analysis.
Sequence valve	When using a three stage hydraulic servo valve it is recommended to apply pressure to the pilot valves before applying pressure to the third stage and

	actuator. If the actuator has pressure before the pilot valves have sufficient pressure to control the third stage, the actuator can go momentarily unstable and cause table and test object damage. A sequence valve is a hydraulic device that blocks flow to the actuator until a preset pressure level is reached in the pressure valve. Once this (kick down) sequence valve detects sufficient pressure in the pilot line, it opens the actuator pressure line and holds it open until the pressures fall back to zero.
Servo Controller (servo loop, analog and digital)	An electronic device, typically analog at its heart, but with digital supervision, that complete a servo control loop. That is, the servo controller accepts a Voltage command from the user, compares this to the actual position of the shake table (as provided by a feedback displacement transducer), determines the error, multiples by a gain, and uses this signal to direct the table actuator to move in a direction that will decrease this gain. This is know as a proportional gain servo controller. Other feedbacks of both the integral and differential of the table motion, can be applied (creating a PID – proportional, integral, differential servo loop). Hence the servo controller gets the table actuator/table to closely follow the user supplied program (earthquake time history). A few controllers are totally digital.
Servo motor (electric)	An electric rotary or linear motor typically called a “hybrid servo motor” in that it has aspects of both a servo motor and stepper motor. Such motors can deliver high torque or force and can provide precise angular or linear positioning, which make them useful in small to medium sized shake tables. Forces up to 5 tons are possible, with frequency capacity as high as 500 Hz. Large displacements can also be provided.
Servo Valve	An electro-hydraulic device that allows an electronic signal (typically a current loop) to control the flow of oil from a hydraulic power supply to one side or the other of a hydraulic actuator. Such a valve can reverse direction over 100 times per second and can be proportional (allow little or all flow or anything in between). This allows a servo controller to control either the force or displacement of the actuator,

	according to a user supplied Voltage command (program).
Sine beat	A signal consisting of a sine wave at a single frequency multiplied by a half cosine wave at a lower frequency (the sine frequency divided by an integer, N). This produces an “N-Beat Sine Beat”. Sine beats are occasionally used as a substitute for transient type earthquake motion, as they have similar amplification properties and limit the energy to a know and narrow frequency range (such as near a resonant frequency).
Sine sweep (linear and logarithmic)	A sine sweep is a signal that changes from one frequency to another in a uniform way. The transition can be fast (some times called a “Chirp”) or slow (possibly taking hours). It can be increasing or decreasing in frequency, and it may be repeated many times. The rate of change can be linear (the same number of Hz per unit time) or “logarithmic” (the same percentage change per unit time. Note that a “logarithmic” sweep is a misnomer, as the sweep is actually exponentially increasing or decreasing. Sine sweeps are extensively used in shake table testing to provide vibratory aging or to detect resonant frequencies.
Slide pot filter	Similar to the equalizing filters that are used on some stereo systems, these filters allow the user to enhance or depress the motion of the table in various frequency ranges. The user may wish to do this to more closely reproduce a given response spectrum, or depress excessive feedback from a test object at a certain resonant frequency. THIS IS A FORM OF “HAND EQUALIZATION”.
Slip table	A term mainly used in the aerospace and automotive industry, “slip table” is essentially synonymous to “shake table top”. When using electro-dynamic actuators a horizontal table is often implemented by having a flat metal plate supported by an oiled granite or cast iron flat surfaced base. Hence the term “slip table”. The term is sometimes used to mean any shake table top, even those guided on bearings or flex plates.

Soft stop	An elastic bumper in a shake table designed to catch a table well before it reaches its maximum displacement limit and slow it down, to minimize impact shock when the table meets its end-of-travel hard stops.
Spectral Acceleration (Spectral Velocity, Spectral Displacement)	These quantities refer to the acceleration (velocity, displacement) of a response spectrum. It is important to note that these responses are not the peak motion required of a shake table to reproduce a given response spectrum. Rather these are the (theoretical) peak responses of a single-degree-of-freedom oscillator with a given damping and a given natural frequency if this oscillator was exposed to the earthquake. Clearly the oscillator can amplify over the table motion and so the spectral motions can be larger (by several factors) than the peak motions required of the table.
Spectral broadening	When a seismic analysis is done on a power plant or other structure, the resulting response spectra on each floor show distinct peaks at the structure's resonant frequencies. As no analysis is perfect, there is some uncertainty in the value of these resonant frequencies. Hence the peaks are often "broadened" about +/-15% to account for this uncertainty. These broadened response spectra are then supplied to equipment qualification personnel for reproduction on the shake table (i.e. as RRS – Required Response Spectra).
Spectrum compatible earthquake	When an RRS (Required Response Spectrum) is received and must be reproduced on a shake table, a time history must be computed that has a response spectrum similar to the RRS. Such a time history is then said to be "spectrum compatible" with the RRS. There are several computational algorithms available to develop such spectrum compatible time histories from the given RRS.
Spider	The flex plate holding the armature inside the filed coils of an electro-dynamic vibrator.
SRS (Shock Response Spectrum)	The term SRS, used by aerospace and military engineers, is the same as Response Spectrum, as used by seismic engineers. The SRS can, however,

	be report as Max SRS (meaning the maximum positive response), Min SRS (meaning the maximum negative response), or MinMax SRS (meaning the maximum absolute response). The MinMax SRS is what is equal to the Response Spectrum.
SSE (Safe Shutdown Earthquake)	In nuclear power plant design the size of the largest earthquake that can occur, within a small probability, during the life of the plant. During this earthquake there may be damage to the plant, but it must be able to shut down safely. Hence many critical pieces of safety equipment must be tested to prove that they can survive the SSE.
SSI (Soil-Structure-Interaction)	The phenomena in which a large structure rocks and translates in the surrounding soil thereby modifying the earthquake motion in its immediate vicinity and also changes the response of the structure. Such phenomena, which are more typical in relatively rigid structures such as nuclear power plant containments, can both decrease and increase the response of the structure at different frequency ranges. Both approximate methods and sophisticated computer codes can be used to determine the effect of SSI on a structure's response.
Stationarity	In practice, a time history is said to be stationary if its frequency distribution does not change greatly over time. As seismic test engineers are concerned that all modes of vibration of the test object should be simultaneously excited (so as to cause maximum stress in the object), they may require that the time history on the shake table be stationary (or close to stationary). Such a provision is required in IEEE-344, which also provides a definition of the required degree of stationarity.
Stinger	A small diameter metal rod connecting an actuator to a shake table or test object. Similar to a flex plate, the transverse flexibility of the stinger allows for misalignment or side to side vibration. When attached to a test object this arrangement allows for application of a force for modal testing.
Strain gage	A device that is bonded or welded to a material surface and experiences resistance changes

	proportional to the strain in the surface. Such gages are used in many shake table experiments to measure test item strain, or to configure transducers to measure force.
String potentiometer	A displacement transducer consisting of a rotary potentiometer attached to a drum and spring. A wire wound around the drum rotates the potentiometer to create a varying Voltage signal. The string can be attached to a moving object so as to measure its displacement. Such devices are capable of high displacement and high resolution measurements. Their frequency range, however, is limited to below about 25 Hz.
Strong motion (of an earthquake)	Many actual earthquakes, and most artificially generated earthquake time histories, have a relatively constant amplitude middle second representing a quasi steady state severe vibratory input. This is called the strong motion portion of the earthquake. Artificial earthquakes typically have a 5 second rise time, 20 second of strong motion, and 5 seconds of taper time. Real earthquakes may look approximately like this, or look quite different.
Strong motion instrument (network)	Various government and research organizations (e.g. the USGS) have installed thousands of seismometers around the world to record small and large earthquake events, to provide data for future earthquake studies, and provide information for fast emergency response. Many of these instruments are networked and their data can be accessed in seconds at a data center, or worldwide via the internet.
Three stage valve	A hydraulic valve that achieves the ability to control a high volume flow rate (up to hundreds of GPM) by using multiple stages. The first stage is typically a solenoid that either directly or indirectly (via a pressure imbalance) drives a second stage hydraulic spool/ This second stage spool produces a small (few GPM) flow that drives the large third stage spool.
Ton (tonne)	An expression used for both weight (force) and mass. In the United States a short ton is 2,000 pounds. A long ton is 2,200 pounds (which equals the SI ton or tonne). In the SI system the ton is 1000 kg or 9,820

	N.
Torque tube	Torque tubes are used in multi-axis shake table design to prevent rotations of the table but allow translations of the table. Torque tubes are passive mechanisms consisting of a torsion bar (tube) on bearings with two articulated arms with ball joints. Torque tubes are useful as the reduce the number of actuators needed to control a table. Torque tubes are useful on medium and smaller sized tables. On large tables torque tubes have to be very massive, and are subject to limits associated with the wave travel time between one end of the mechanism to the other. In such cases, extra actuators may be required instead of the torque tubes.
Transfer Function	
Triaxial (independent)	A table that can move in all three axes (vertical plus two horizontal) independently is called an independent triaxial table. Such a table provides the most realistic reproduction of a true earthquake motion.
Tri-partite graph (plot)	Response spectra re often plotted in Log-Log format with Log(frequency) as the horizontal scale and Log(velocity) as the vertical scale. In this case two slated set of grid lines can be drawn at constant displacement and constant acceleration levels. Such a plot, while initially crowded and confusing, actual contains a wealth of information and allows the user to quickly convert from acceleration to velocity to displacement.
TRS (Test Response Spectrum)	In shake table testing the TRS is the actual response spectrum achieved on the table. The success of a test depends on the TRS being close to but larger that the RRS (Required Response Spectrum) in the frequency range of interest.
Two stage valve	A servo-hydraulic valve consisting of two stages. The first is an electric solenoid driving a mechanical device, which causes a small imbalance in pressure across a hydraulic spool. The second stage is the spool, whose motion caused by the unbalance causes the direction and redirection of a larger flow of oil to an actuator (or to a three stage valve).

	Two stage valves can be used to drive actuators directly at lower oil flow rates (typically under about 50 GPM) or can be used as Pilot Valves to drive a larger third stage valve that can accommodate larger flows (up to several hundred GPM).
Uniaxial	A table that moves in only one direction due to constraints, along a straight line. This can be horizontal or vertical. It can also be a fixed combination of horizontal and vertical, in which case it is sometimes called Vector Biaxial. A multi-axial table can be commanded to move in a uni-axial direction by forcing the other directions to have zero motion.
UPS (Uninteruptable Power Supply)	A UPS is often advisable for the critical electronics (servo controller, digital controller, PC, accelerometers) controlling a shake table. Should a power transient or power loss occur without the use of a UPS, the resulting power transient in the electronics could send the table into momentary but dangerous transient motions that can damage the table and injure people.
UUT (Unit Under Test)	UUT is often used to refer to the test object that is placed on the table.
Vector Biaxial	A shake table that has motion in two directions (e.g. one horizontal and vertical) is called a biaxial table.
Vibratory aging	In nuclear power plant design this refers to the low cycle fatigue that can occur if several OBE earthquakes are experienced in the plant or during a test, or the higher number of fatigue cycles that can occur if a piece of equipment is exposed to long during operating vibration (e.g. line mounted equipment on a vibrating pipe). In automotive testing vibratory aging reefers to the fatigue that occurs due to prolonged road vibrations over the life of the vehicle.
Voice coil valve	A hydraulic servo valve consisting of a single stage in which the spool is driven by a large solenoid (voice coil). Such valves can operate to high frequencies

	(e.g. 1000 Hz).
Window (windowing)	In time series analysis using the FFT the time series is often tapered at the beginning and at the end to avoid certain numerical data distortions if the signal does not start and stop at zero. These tapers are called “Windows”. Different windows have different effects on the reselecting FFT and are useful in different applications and types of signals. The windows have names such as “Boxcar”, “Hanning”, “Hamming”, and “Cosine bell”. And “Uniform”.
Zenabi Paradox	Distantly related to the Heisenberg Uncertainty Principle, the Zenabi Paradox states that in order to perform a perfect test of a structure you must perfectly understand the structure, which would make it unnecessary to perform the test.
ZPA (Zero Period Acceleration or Zero Period Asymptote)	The response value (acceleration) of a response spectrum at high frequency (near zero period). This value represents the peak acceleration of the earthquake (or shake table) during the entire dynamic event. That is, an oscillator with a sufficiently high frequency will simply move with the earthquake, without amplification or isolation. So its peak response will equal that of the ground or table motion. The ZPA is independent of damping. For typical earthquakes the ZPA is reached somewhere above 30 Hz.