dynamic solutions

Understanding Vibration Systems

By

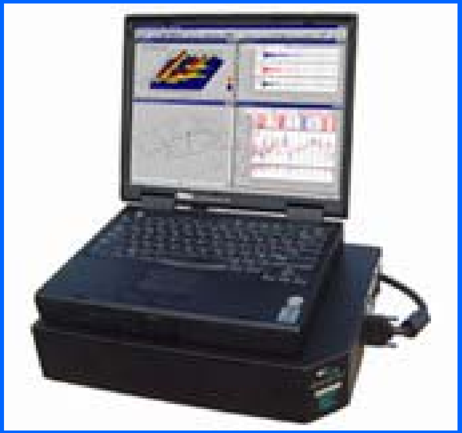
Steven Wood

Shaker System

Power Amplifier

Cooling Blower

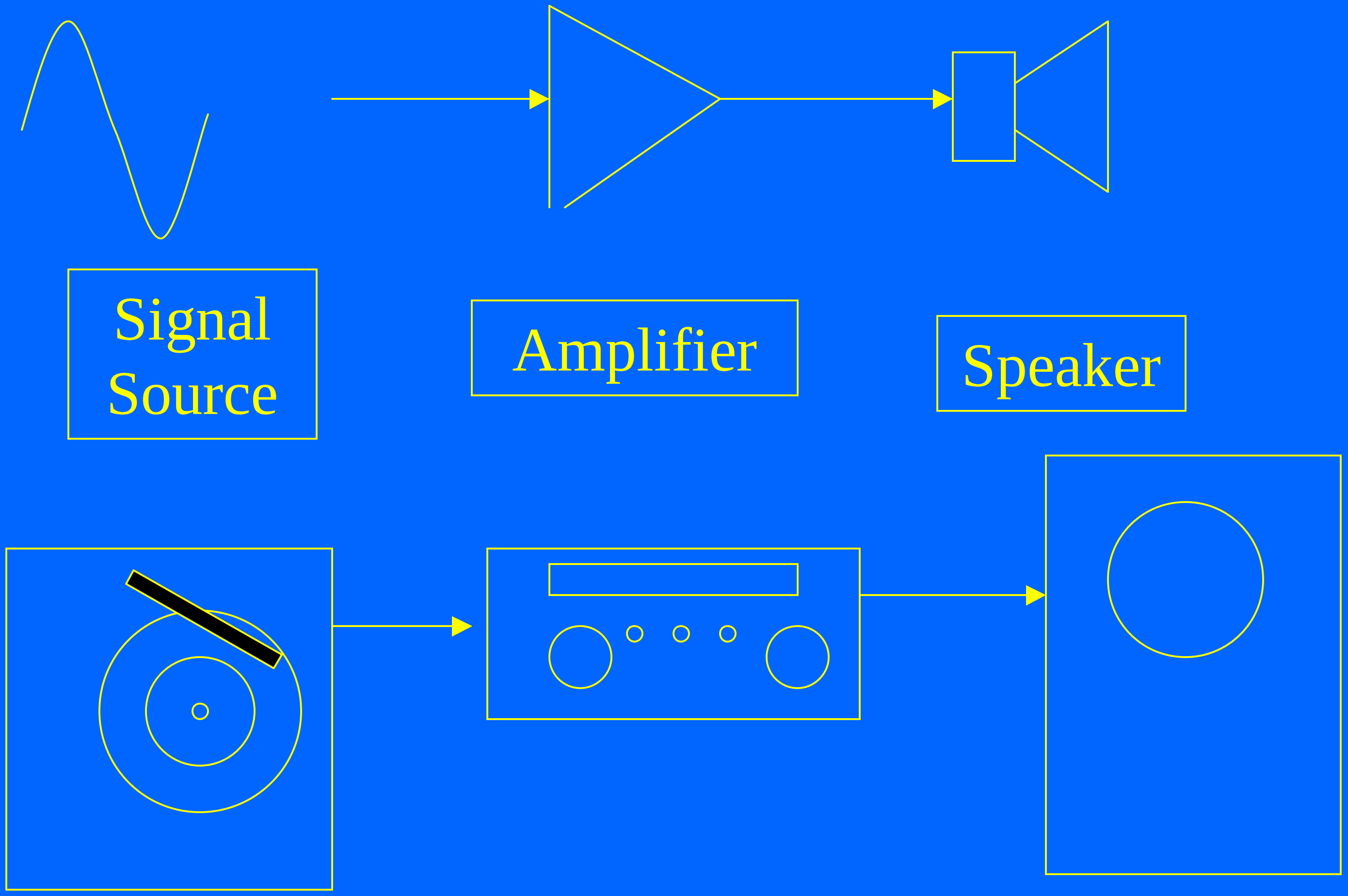
Electro-Dynamic Exciter



Vibration Controller

Accelerometer

A Simplified Shaker System

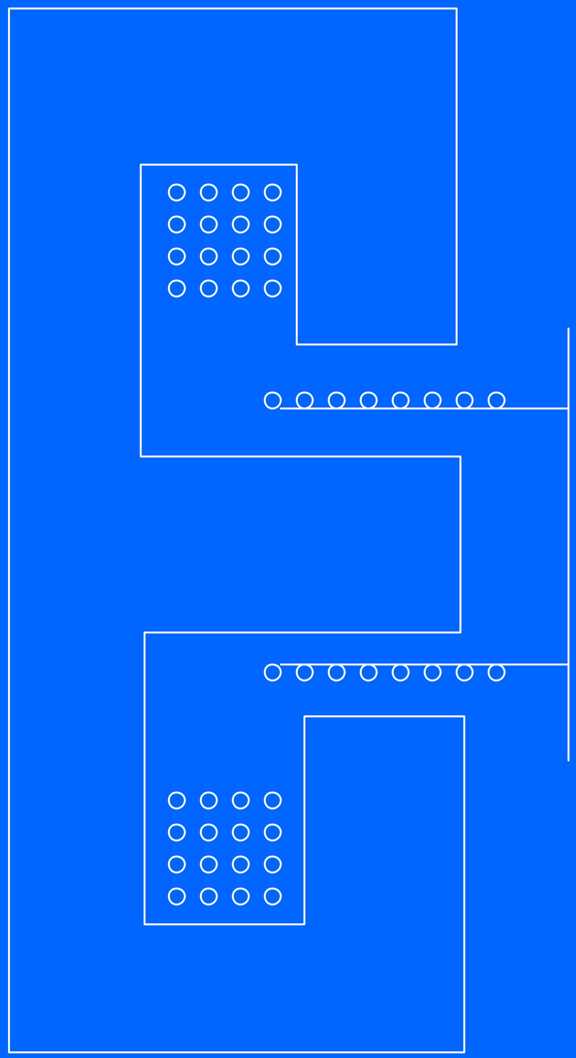


Signal Source

Amplifier

Speaker

Shaker Components

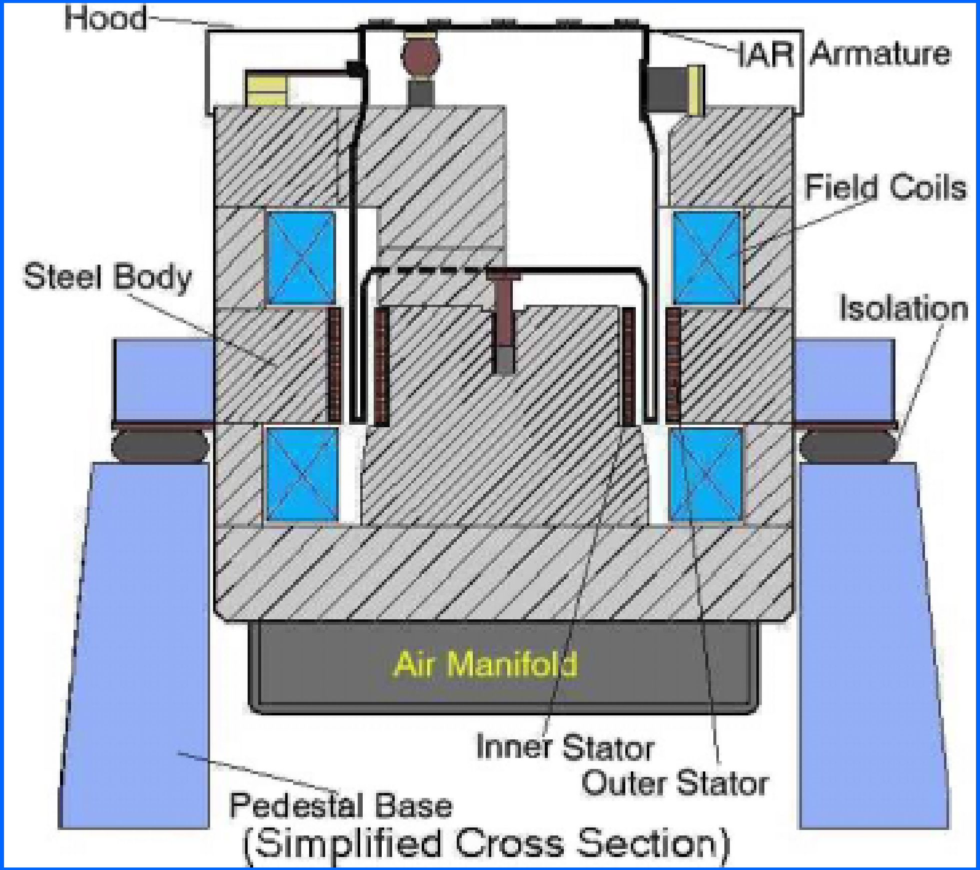


Upper and lower field coils (electromagnet) create DC magnet flux in the gap between the compensation bands and the armature assembly

Armature assemblies may be inductive or conductive.

Inductive Shaker Design

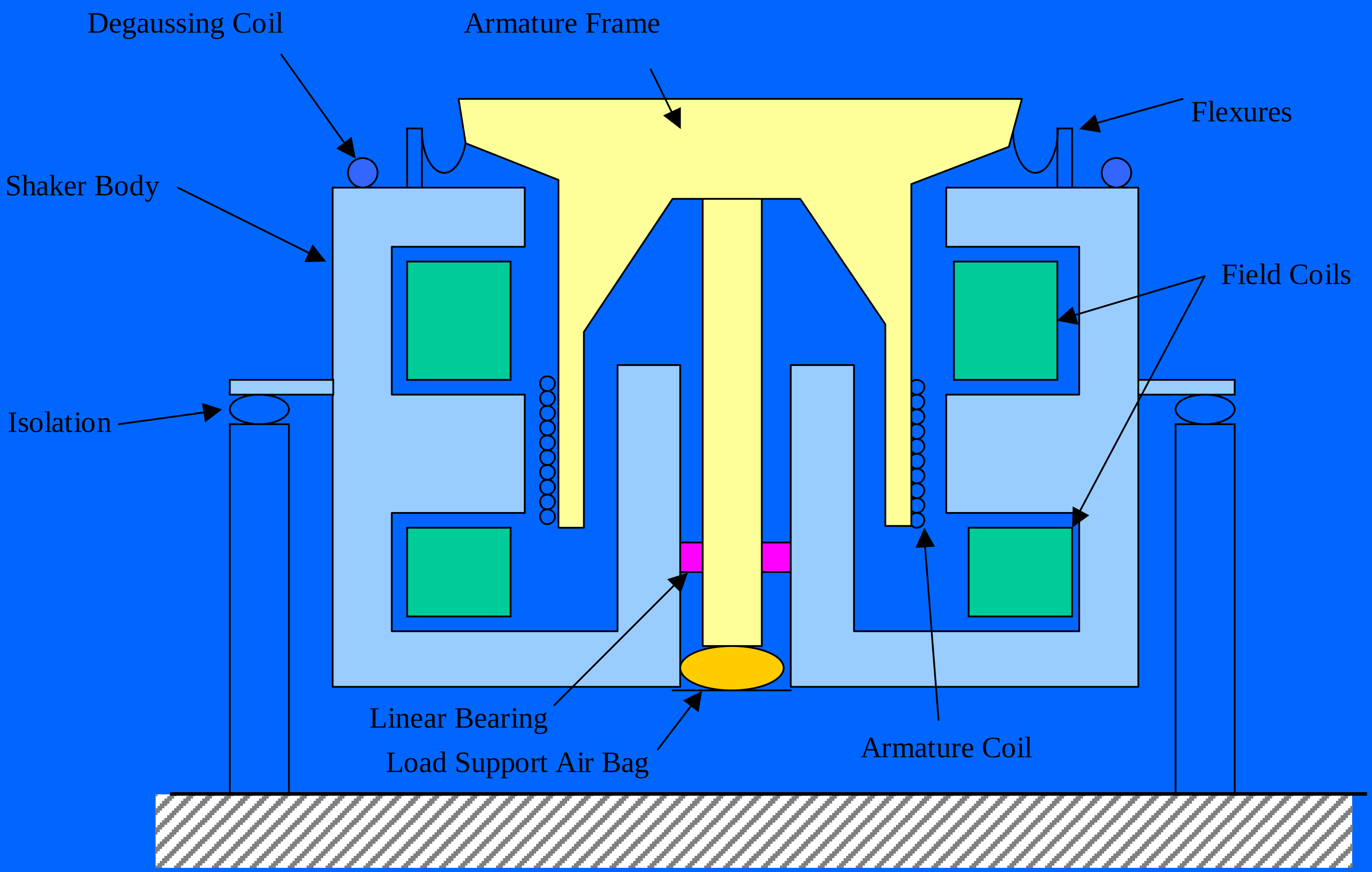
An inductive drive system consists of two stationary coils stator and field that induce current into a single-turn secondary winding on the armature. There are no direct wires or coolant lines going to the armature. Energy is transmitted magnetically or via inductive coupling.



Shaker Components Continued…

A conductive armature, as you will see on the following slide, receives its power directly from the power amplifier "direct coupled."

Conductive Shaker Design

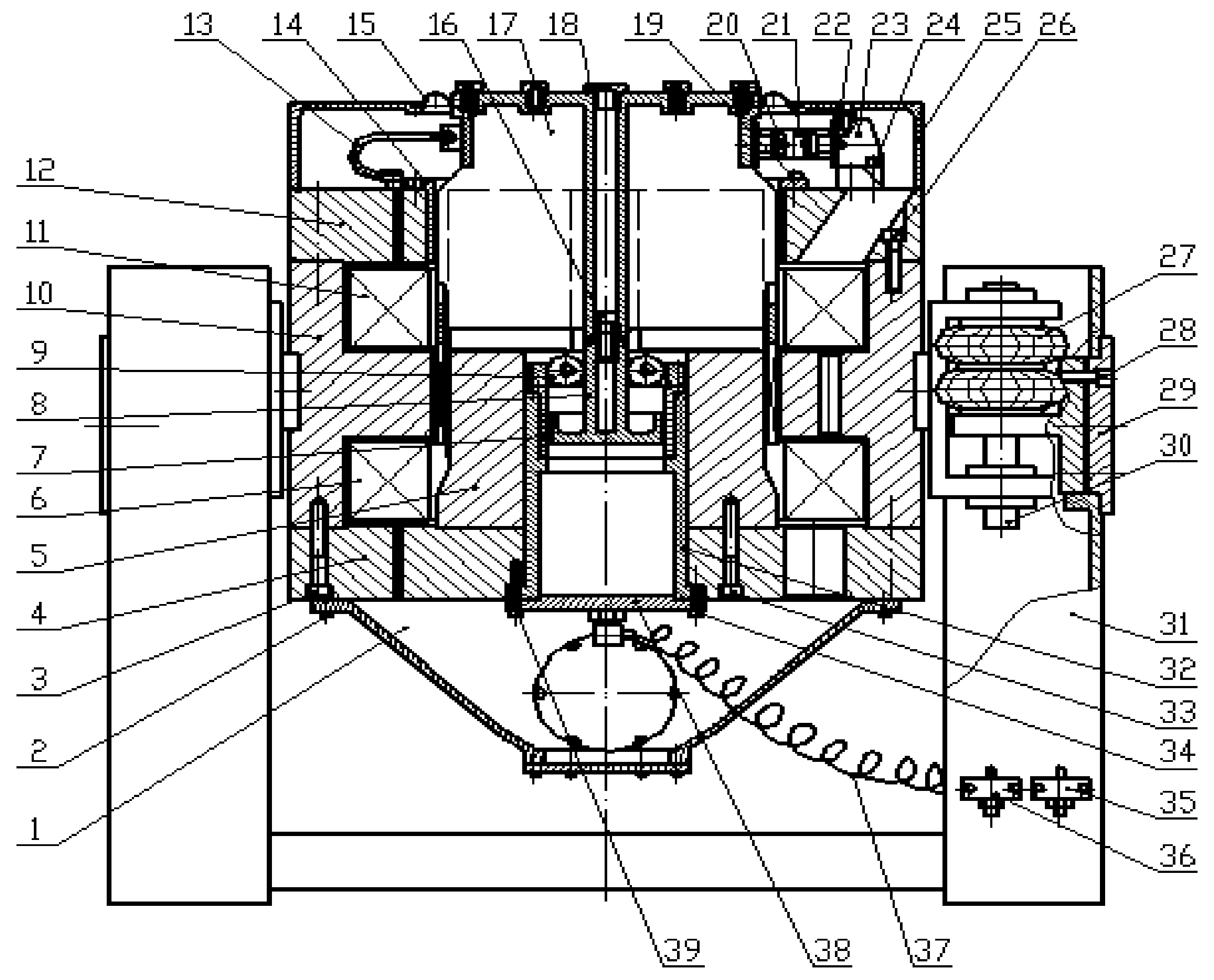


Shaker Components Continued…

- **Air Plenum (Directs the air exiting the shaker body and entering the blowers input flange)**
- **Current Lead (Provides electrical path between the Amplifier and the Shaker armature)**
- **Air Isolation Spring Regulator (Regulates air pressure to air isolation springs)**
- **Load Support Air Regulator (Regulates air pressure to rolling diaphragm load support)**
- **Compensating Rings (Converts the armature coil or “Solenoid” into a true electrical transformer) (Creates a lower impendence in the primary thereby reducing Amplifier output requirements that change with frequency)**

Shaker Components Continued…

- **Lower guidance bearing: (cross axial restraint of the armature assembly)**
- **Degaussing coils (cancels out/decreases the gauss level created by the field coils)**
- **Flexures(provide rotational restraint of armature typically below 200 Hz) Rolling Diaphragm (Load Support)**
- **Air Isolation Springs (Isolates the Shaker bodies vibration from the surrounding flooring at approximately 2 to 3 Hz)**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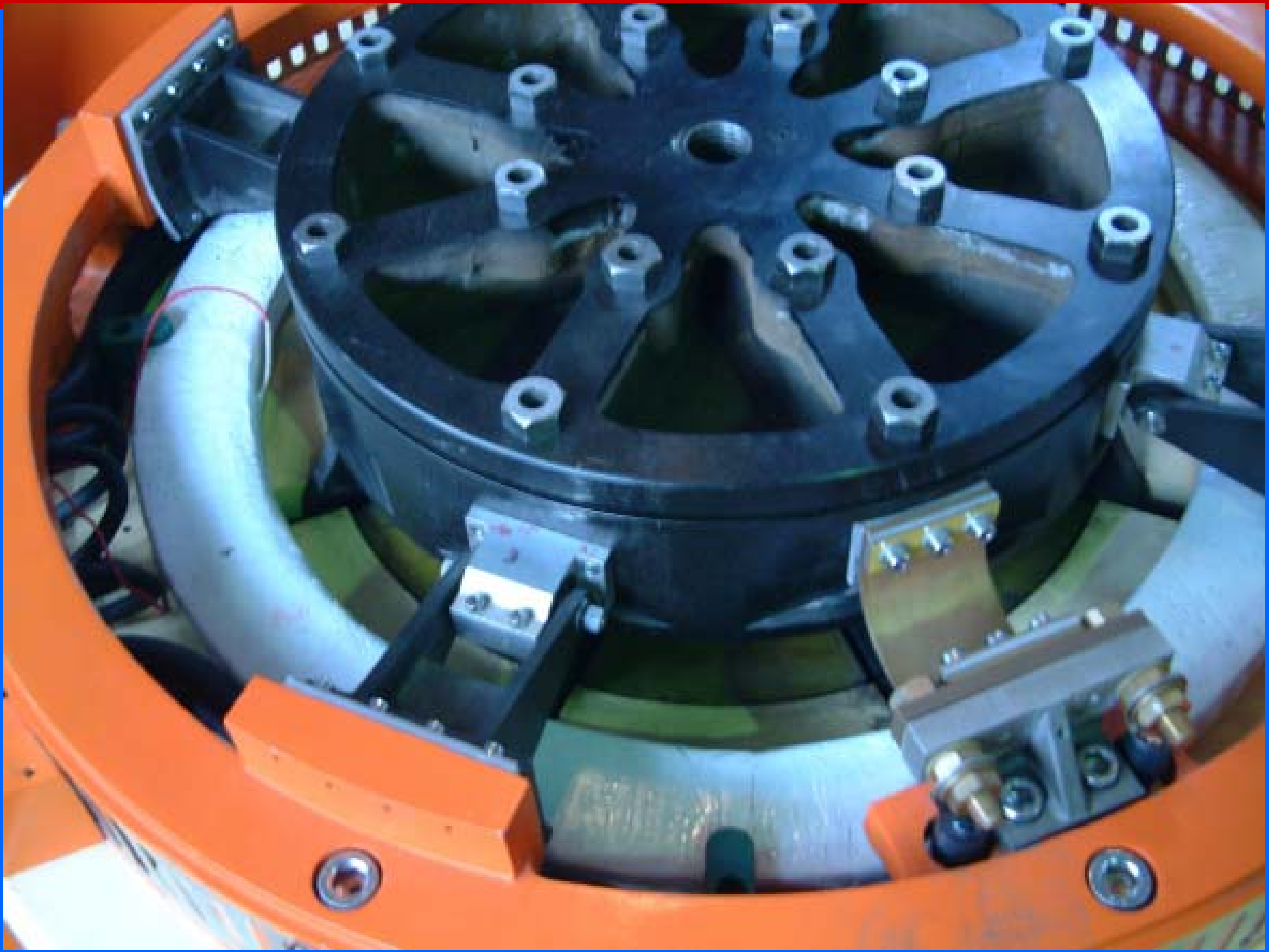
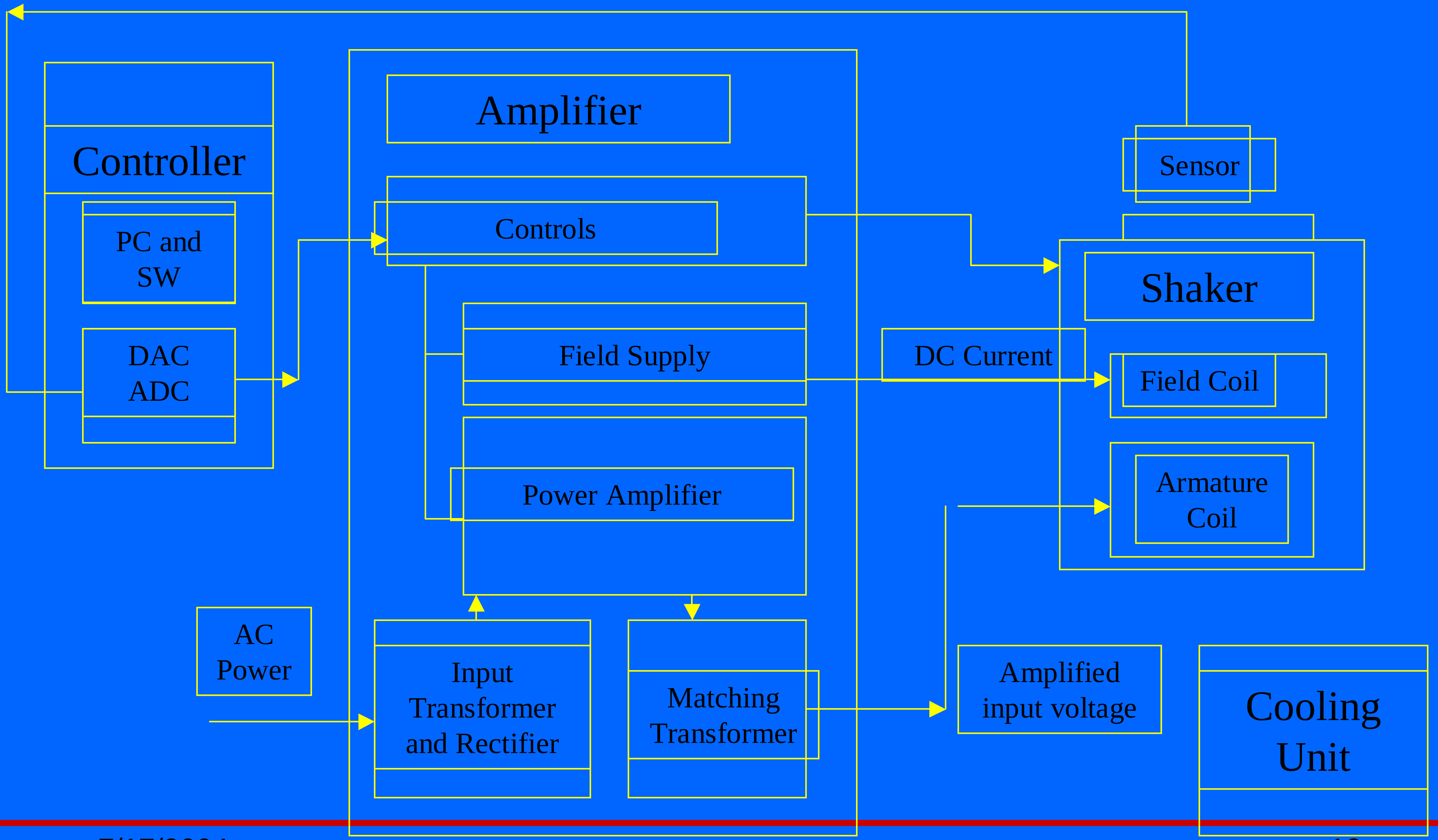


System Block Diagram



Electrodynamic Exciter

- Maximum Force?
- Maximum Displacement?
- Maximum Velocity?
- Maximum Acceleration?
- Rotational and Cross-Axial Performance?
- Uniformity of Motion?
- Armature Interface Size?

DS6600 Shaker System Specifications

Force Rating:

- Sine (5-2500Hz)--------------------- 6600 lbf
- Random (20-2000Hz)-------------- 6600 lbf
- Frequency Range------------------- 5-3,000Hz

Maximum displacement (Peak-Peak):

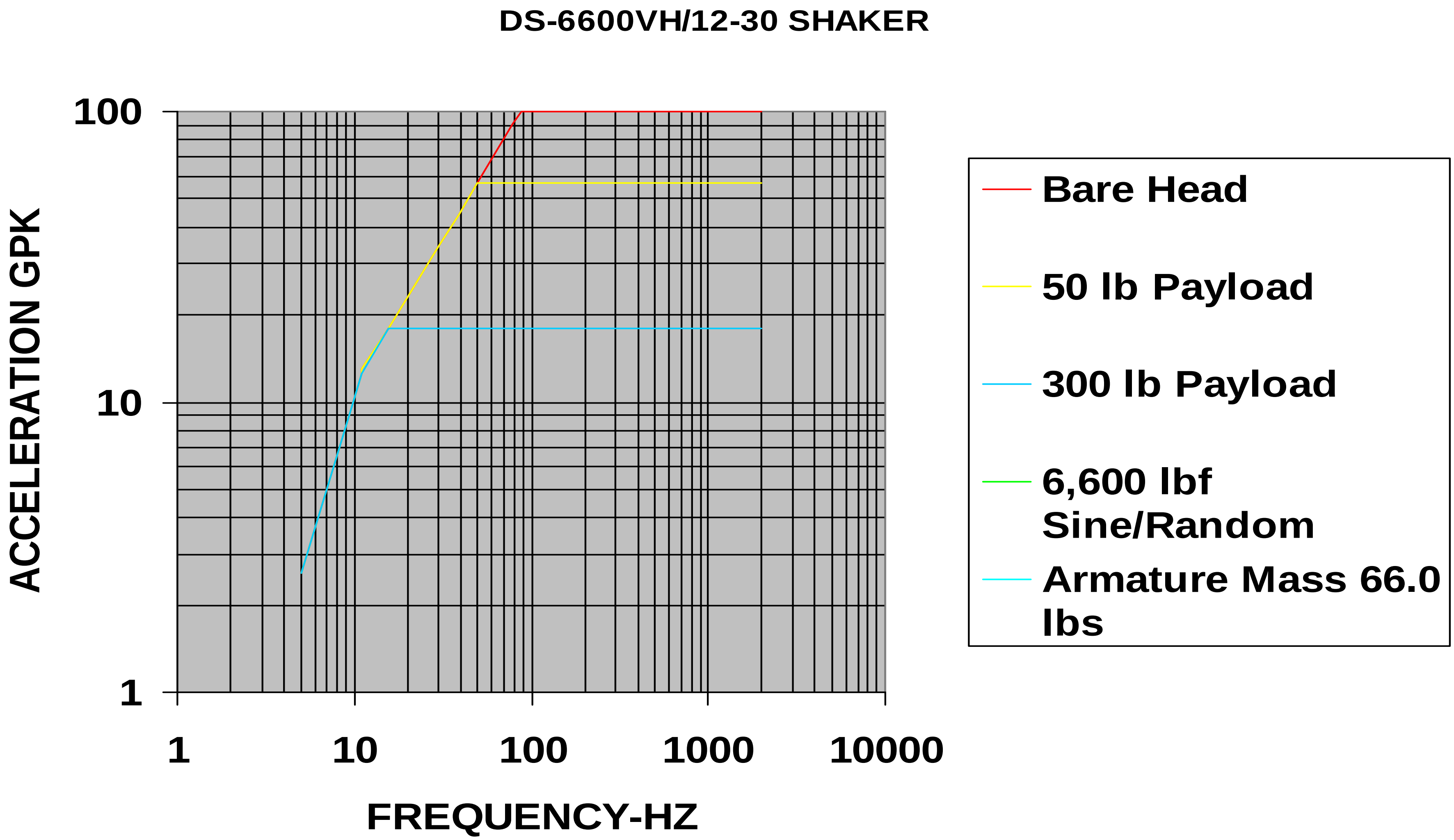
- Continuous duty -------------------- 38.1mm(1.5 in.)
- Shock -------------------------------- 50.8mm(2 in.)
- Between mechanical stops------ 55.9mm(2.2 in.)

Maximum Velocity----------------------- 1.8m/s (70.86 in/s)

Maximum Acceleration----------------- 100 gpk

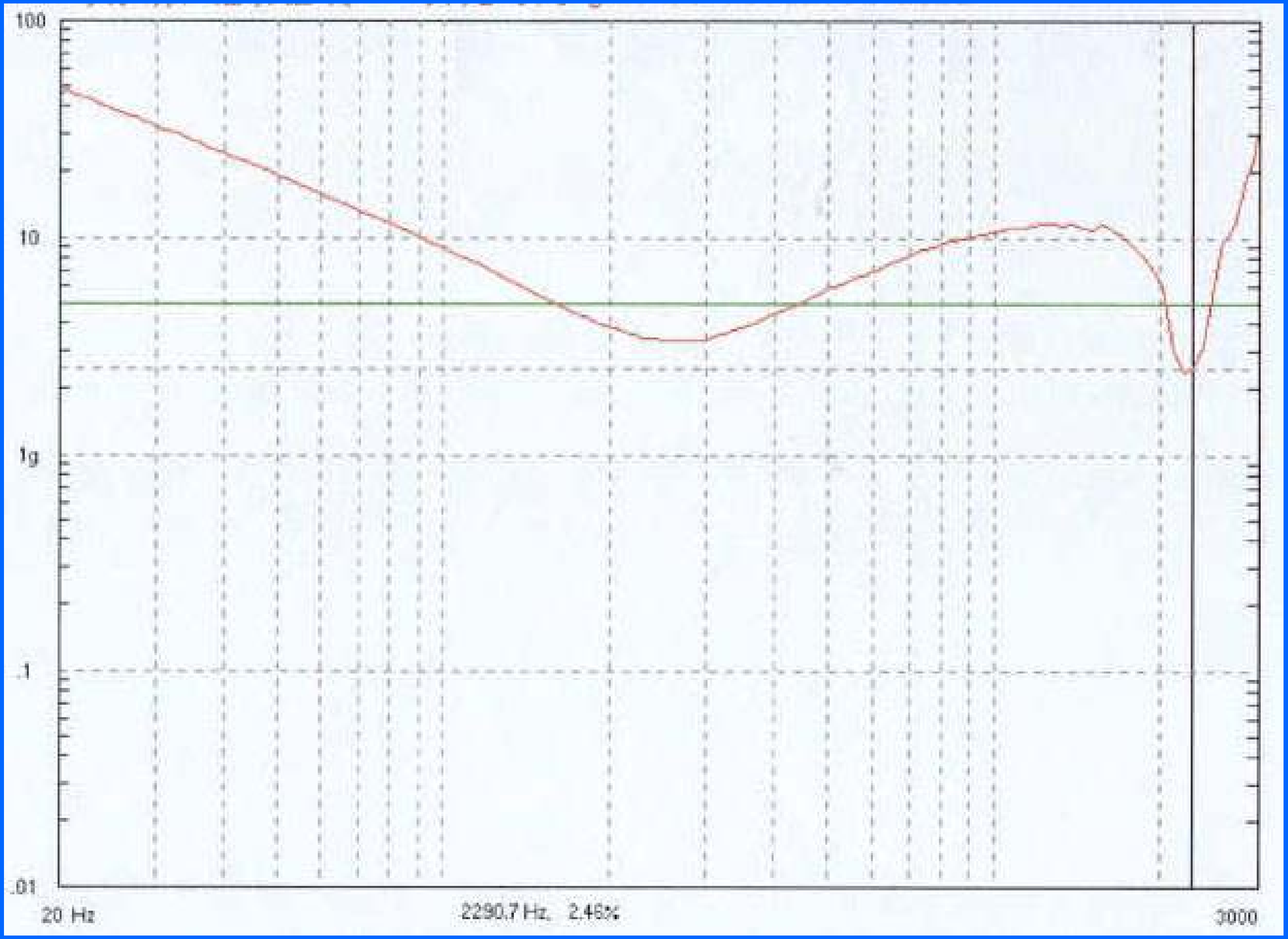
Fundamental Resonance Frequency (Bare Table): 2300Hz±5%

Body Suspension Natural Frequency-Thrust Axis: 2.5 Hz


DS-6600VH/12-30 SHAKER
100
10
1
ACCELERATION GPK
1
10
100
1000
10000
FREQUENCY-HZ
Bare Head
50 lb Payload
300 lb Payload
6,600 lbf Sine/Random
Armature Mass 66.0 lbs

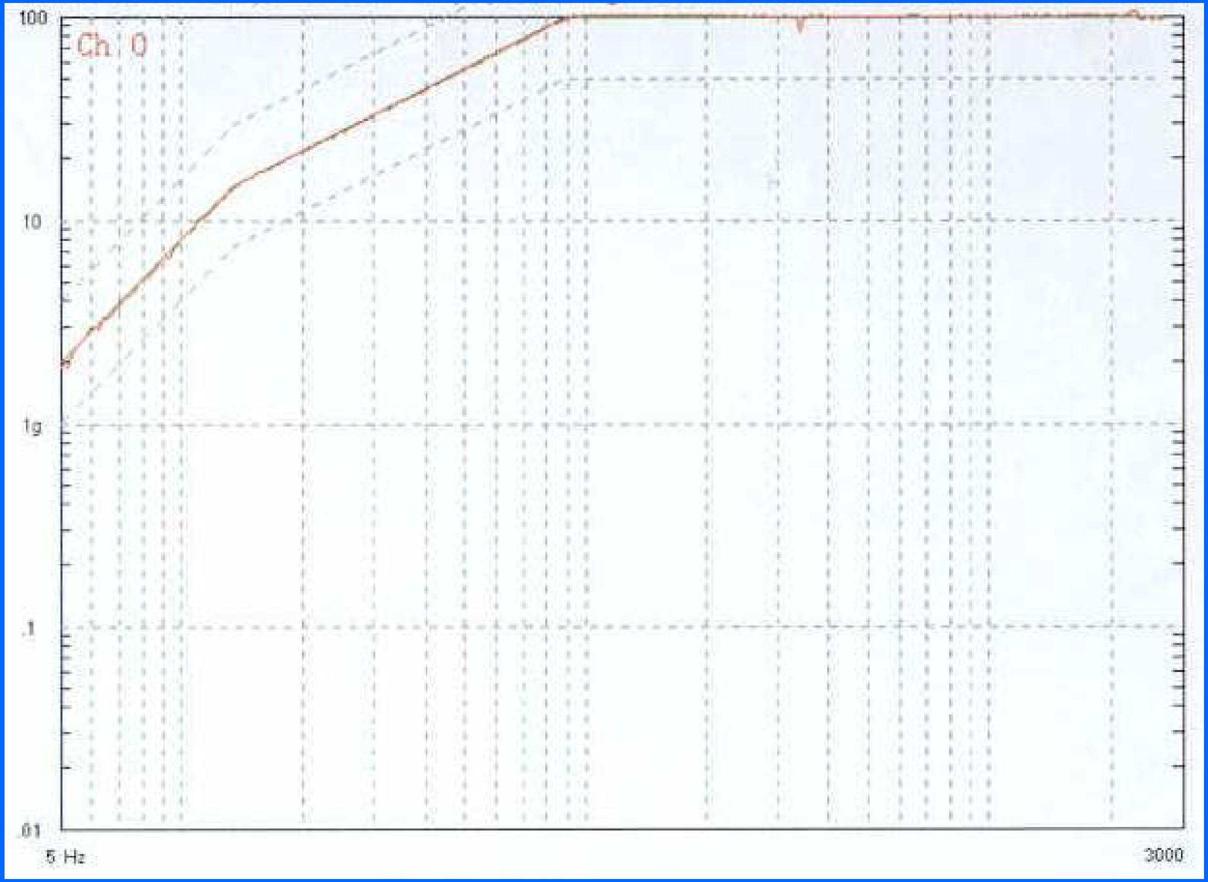
Bare Table Frequency Response

Armature Resonance: 2290.7 Hz



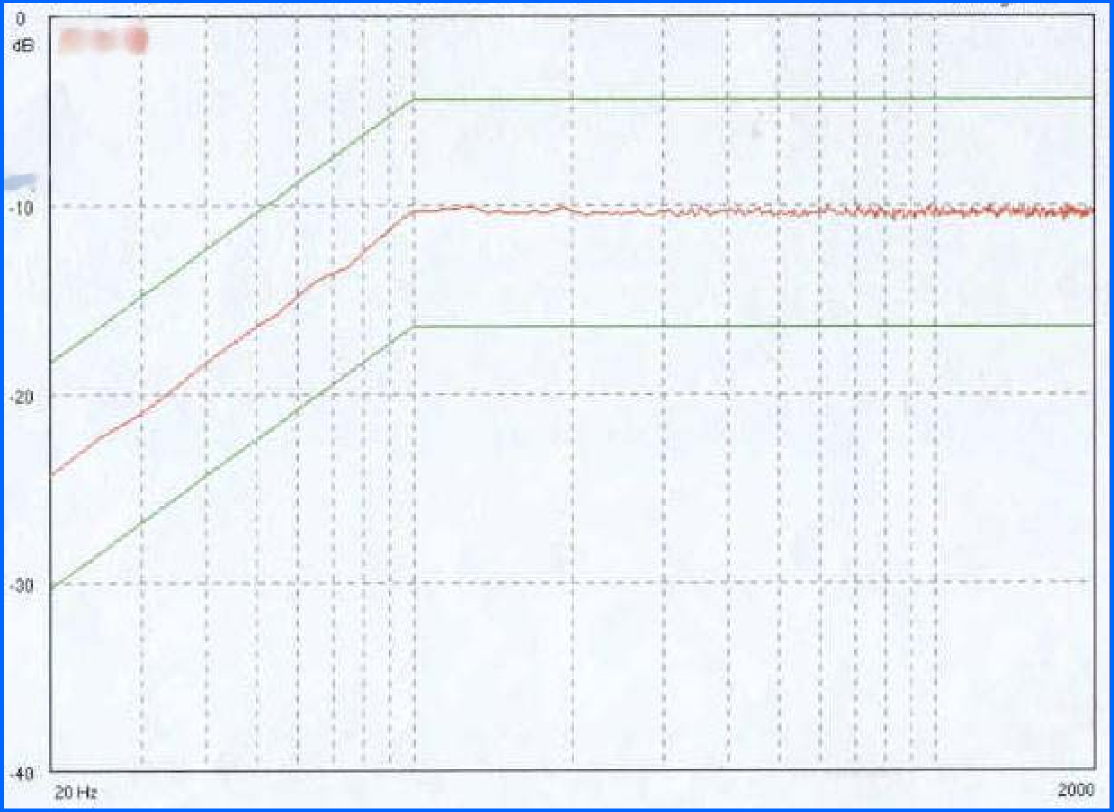
TEST: Bare Table Full Force Sine

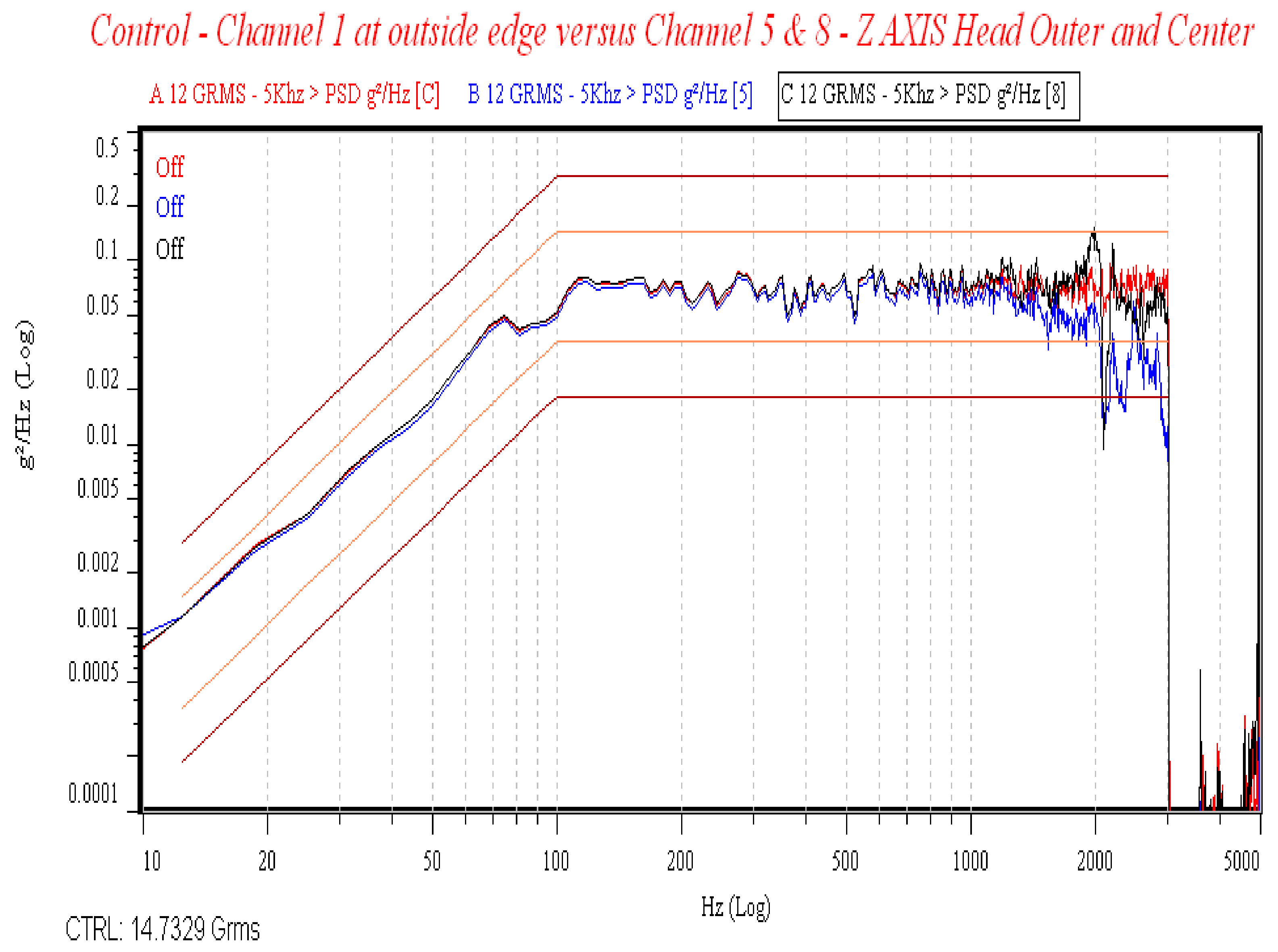
- Force Achieved: 6600 lbf.
- Acceleration: 100 G-pk
- Armature Effective Mass: 66 lbs.
- Test Duration: 7 Hrs.



TEST: Full Force Random with 440 lb. Mass

- Total Force: 6705 lbf
- Random Input: 13.25 grms
- Total Mass: 506 lbs.

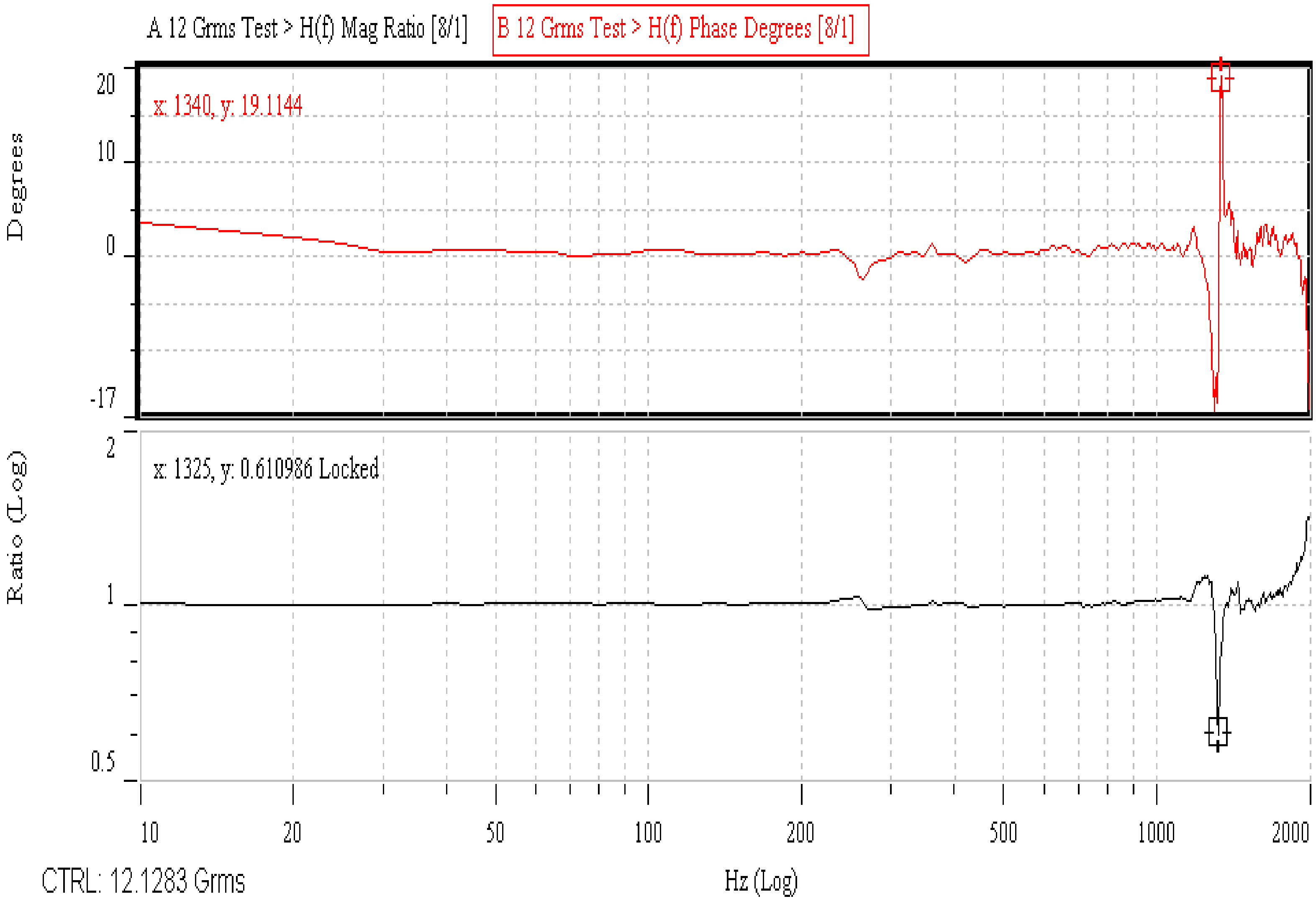




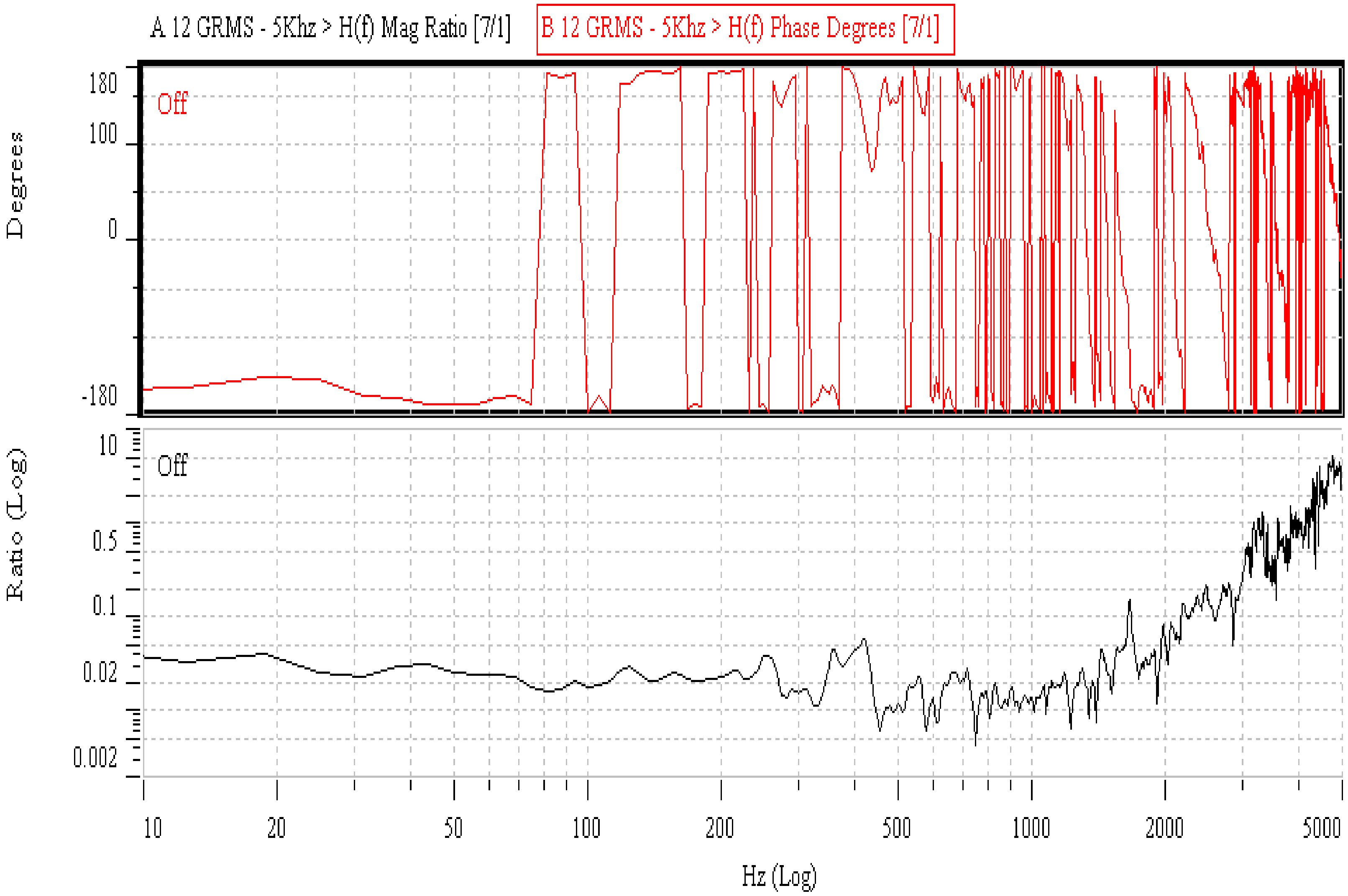
Control - Channel 1 at outside edge versus Channel 5 & 8 - Z AXIS Head Outer and Center

CTRL: 14.7329 Grms

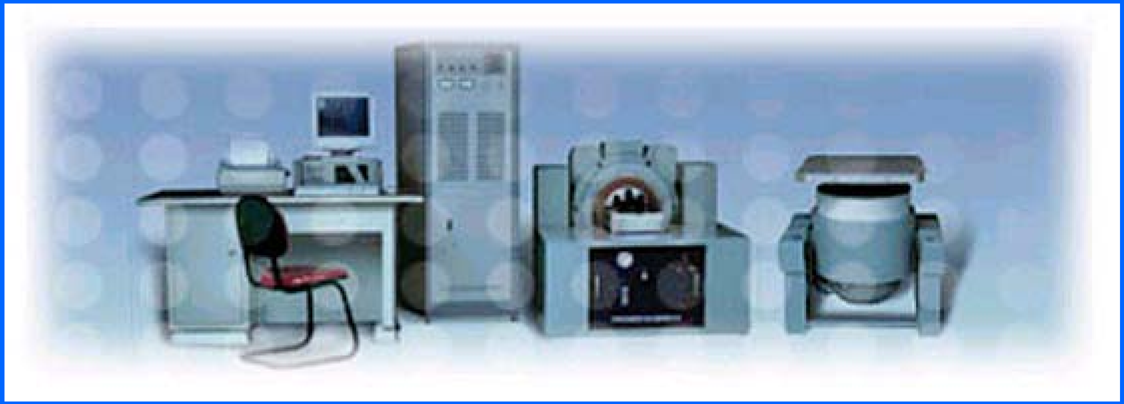
Bode - Reference Channel 1 Versus Outside Edge Channel 8 - Z Axis Opposite Egde of Head

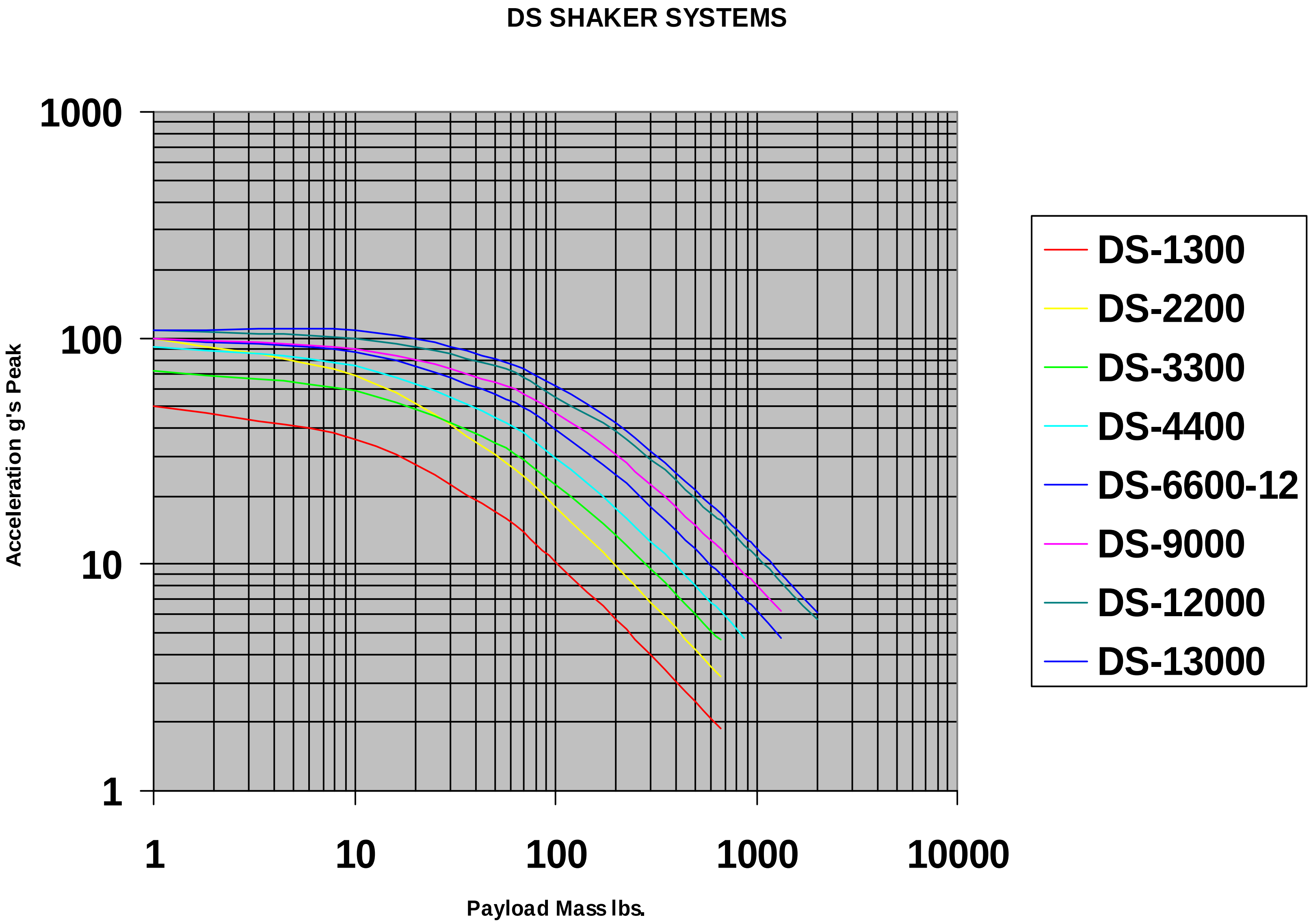


Bode - Reference Channel 1 Versus Outside Edge Channel 7 - Y Axis Opposite Side of Head



Dynamic Solutions Shaker Line



DS SHAKER SYSTEMS
Acceleration g's Peak
1000
100
10
1
1
10
100
1000
10000
Payload Mass lbs.
DS-1300
DS-2200
DS-3300
DS-4400
DS-6600-12
DS-9000
DS-12000
DS-13000

Amplifier Considerations

- Direct or Transformer Coupled?
- KVA Output?
- Voltage & Current Requirements of Exciter Armature?
- Voltage & Current Requirements of DC Field Supply?
- IGBT versus MOSFET?
- Interlocks?

Sinusoidal Input						**Amplifier Output SA-30**		
HZ		**Gpk**	**IPS**	**Inch P-P**		**Vrms**	**Arms**	**Kva**
5		2.03		1.57		40.2	30.2	1214
7		3.97		1.57		58.5	37	2165
13.5		14.88	67	1.57		100	38.5	3850
20		22.12	67			105	40.6	4263
92		100	67			95	225	21375
500		100				51.3	230	11799
800		100				76.7	208	15954
1000		100				87.3	184	16063
1500		100				87.3	119	10389
1800		100				70	76	5320
2000		100				46.6	41	1911
2500		100				38.5	44	1694
3000		100				103	93	9579
				Max Output		110	330	36300
				Max Total Used				21375
								% of Max
				Max Vrms		105		95.5%
				Max Arms			230	69.7%

Class "D" Solid State PWM Amplifiers

- Power Module: (The power module is basically a full bridge configuration consisting of switches and L-C filters. A rail voltage of 220 volts dc + or – 110 volts is brought to each half of the bridge and switched at 120 KHz. With no input voltage from the vibration controller, it has a 50% duty cycle, in phase; thus, no output voltage will appear at the output terminals. If a sine-wave, random or transient signal is present, each half of the bridge will be modulated so that the duty cycle will vary as the input signals rate. Each side is driven out of phase so that an amplified signal will appear across the output terminals. Voltage gain is the effective rail voltage times the percentage of modulation)
- Control Module: (The control module provides pre-amplification of the input signal, PWM clocking to the power module, external interlock control)

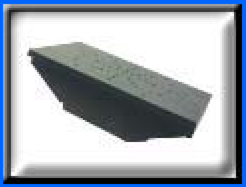
- Power supply: (provides power to the DC rail voltage supply, field supply and control power)
- Input power transformer: (distributes power to various sections of the amplifier at different voltage levels relative to the impedance tapping of the secondary legs)
- Output transformer: (takes the amplifiers output and steps up or down the voltage level in order to have a better impedance match between the amplifier and shaker)

Fixture

The Intermediate Structure That Attaches a Device Under Test (DUT) to a Shaker or Shock Test Machine

Fixture Considerations

- Useable frequency range?
- Mass?
- Temperature range?
- Ease of use?
- Specific uses?



Purpose Of Fixture

- To uniformly transmit vibration to the mounting points of the Device Under Test (DUT) to levels and frequencies of the test specification

Important Terms

- **Resonance**: Resonance, a condition where the natural frequency is equal to the forcing frequency

- **Damping**: Mitigates and reduces the effects of resonance's

- **Transmissibility**: The relationship between the input amplitude and the response amplitude. When the input and response amplitude are equal the Q is said to be 1 to 1

- **Q**: the ratio of input amplitude to response amplitude

- **Decoupling**: Occurs when the Input amplitude is greater in Q than the response amplitude. This typically occurs at frequencies greater than the natural frequency of the DUT.

Fixture Design Tips

- Use materials that have high Damping indexes. The Q of the resonance is lowered, making the fixture easier to control and decoupling rates are greatly reduced
- Use light weight alloys to eliminate fixture mass
- Modulus to density ratios effect natural frequency

Fixture Construction

- **Bolting:** Bolting is fast and simple way to construct a fixture. This method is **not** recommended for tests that exceed 250 HZ. Bolts will loosen up and decoupling will occur
- **Machining:** A fixture machined from solid stock is very good, there are no joints to work loose. This is desirable for small devices but to expensive and time consuming to build with larger devices
- **Casting:** Casting yields an excellent fixture. The monolithic construction eliminates many problems. Generally to expensive and time consuming

- **Welding:** since fixtures are typically a one of a kind proposition, welding is the preferred method of fabrication

Note: plates to be welded should be thicker than specification. This will allow for machining that may be required if the material warped due to welding

Material Choices

- **Steel:** seldom used for fixtures due to its mass and poor damping characteristics

- **Aluminum:** 6061T is widely used weighing about 2/3 less than steel but with a damping index of < .2 it is more desirable for low frequency testing or special applications were low damping is required, such as pyro-shock testing

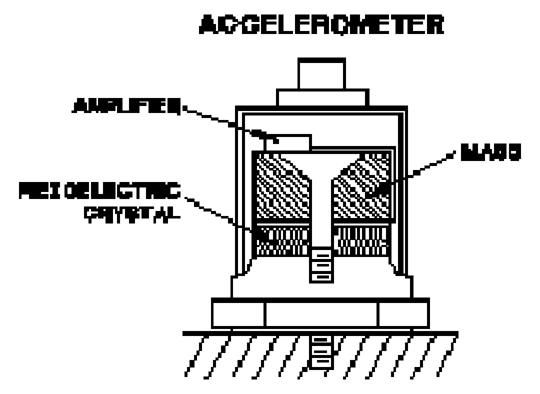
- **Magnesium:** AZ31B is the material of choice for most vibration tests due its mass 1/3 lighter than aluminum, damping index of 10.1 and is 70% more weldable than aluminum

	Weight per Cu. Inch	**Specific Stiffness**	**Damping Index**	
Steel	.283	106	< .2	
Aluminum	.098	106	< .2	
Magnesium	.065	124	10.1	

In conclusion the perfect fixture is:

- As light as possible
- Very rigid
- Highly damped
- Has perfect transmissibility within the desired frequency range (no resonance's or decoupling)
- Welded or machined

Accelerometers



Accelerometer

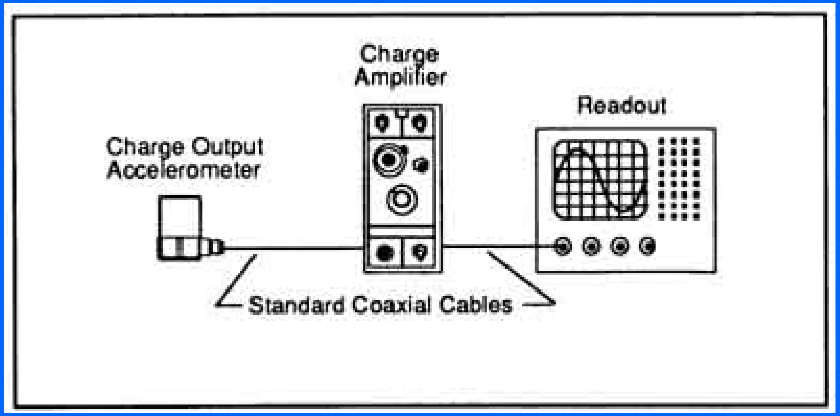
A sensor or transducer or pickup for converting acceleration to an electrical signal. Two common types are piezoresistive and piezoelectric.

- Frequency response?
- Calibration constant?
- Temperature range?
- Relative mass?

- **Piezoelectric (PE) transducer.** One which depends upon deformation of its sensitive crystal or ceramic element to generate electrical charge and voltage. Many present-day accelerometers are PE.

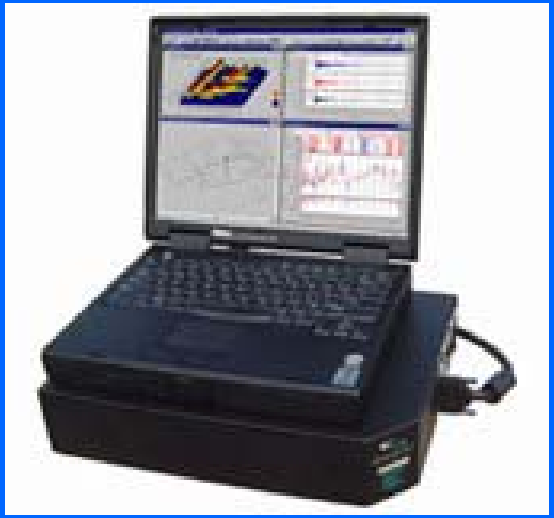
- **Piezoresistive (PR) transducer**. One whose electrical output depends upon deformation of its semiconductor resistive element, offering greater resistance change than does the wire of a strain-gage transducer, for a given deformation.

Signal conditioner: An amplifier following a sensor, which prepares the signal for succeeding amplifiers, transmitters, readout instruments, etc. May also supply sensor power



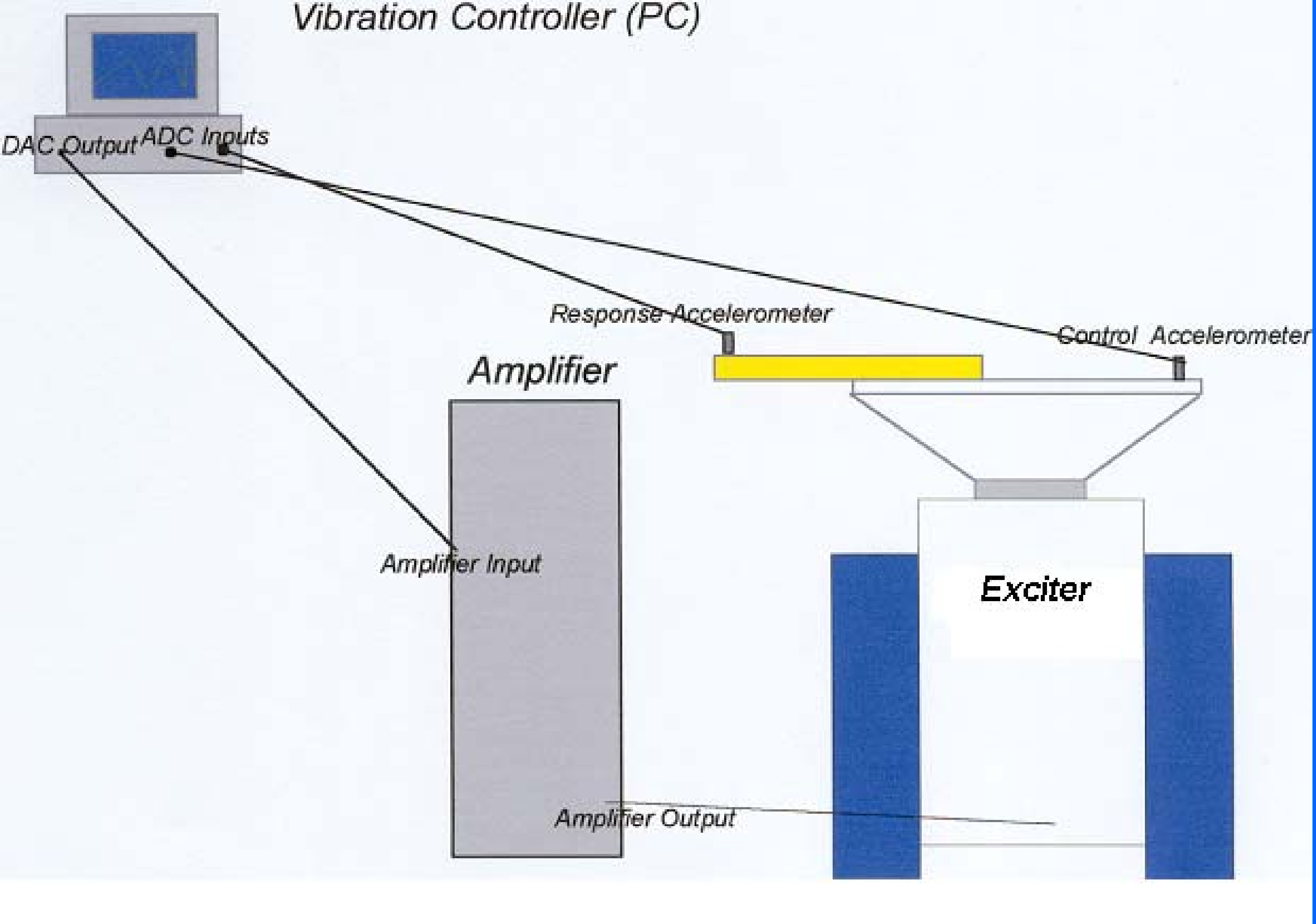
Charge amplifier: An amplifier which converts a charge input signal (as from an accelerometer) into an output voltage; A charge-to-voltage converter.

Vibration Controllers



Control System (Brains)

- **Iterative closed loop** control pre-calculates drive signals but then modifies those signals based upon resulting motion, in order to better match measured with desired motions. Evaluation and modifications take place after each excitation, repeating until the desired result is achieved. Responses are measured and fed back to the control system so as to refine or modify drive signals in order to bring responses closer to the reference or desired motions


Vibration Controller (PC)
DAC Output
ADC Inputs
Response Accelerometer
Control Accelerometer
Amplifier
Amplifier Input
Exciter
Amplifier Output

Considerations in selecting a Controller

- ADC channels required?
- Software required?
- ADC sample rate?
- Multiple DAC outputs?
- Hardware quality?
- Engineering features? (Transfer functions, phasing, coherence, limiting, safety/abort, multiple graphics etc)

Input control signal. Originates in a control sensor; Sometimes selected between or averaged between several sensors. Used to regulate shaker intensity. (May originate in a force sensor for force-controlled testing.)

Response signal. The signal from a "response sensor” measuring the mechanical response of a mechanical system to an input vibration or shock.

Open loop: control provides pre-computed or preconceived drive signals to the exciter system without modifying or refining those signals based on observation of the resulting motion.

Averaging: summing and suitably dividing several like measurements to improve accuracy or to lessen any asynchronous components.

Hardware Overview

- **A/D converter. (ADC)** A device that changes an analog signal such as voltage or current into a digital signal (consists of discrete data values).

- **Anti-aliasing filter**. A low pass filter designed to stop frequencies higher than the ½ the sample rate, in order to minimize aliasing

- **Tracking filter**. A narrow band pass filter whose center frequency follows an external synchronizing signal.

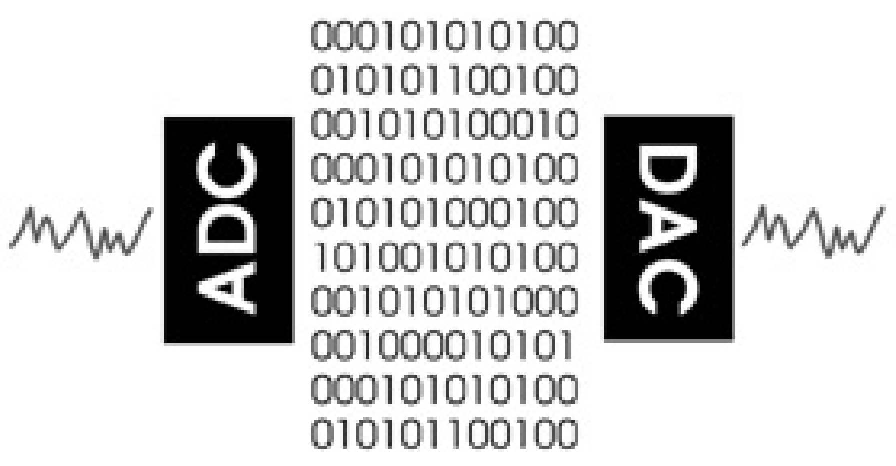
- **Constant-bandwidth filte**r. A band pass filter whose bandwidth is independent of center frequency. Filters simulated digitally by an FFT process are constant bandwidth.

- **Constant percentage filter**. A band pass filter whose bandwidth relates (1/3 ´, 1/10 ´, etc.) To center frequency. May be synthesized digitally.

- **DSP** - digital signal processor. A microprocessor optimized for digital signal manipulations.

- **MUX:** Multiplexer - A device that selects multiple inputs into an aggregate signal

- **D/A converter (DAC) -** A device that converts a digital signal (discrete values) into an analog voltage



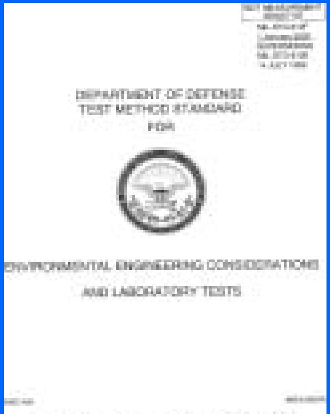
- **Peak**. Extreme value of a varying quantity, measured from the zero or mean value. Also, a maximum spectral value. Peak times .707=RMS

- **RMS** or **root-mean-square** value. The square root of the time-averaged squares of a series of measurements. Refer to a textbook on electrical engineering. In the exclusive case of a sine wave, s, the RMS value, is 0.707 ´ the peak value. Peak = RMS x 1.414

- **Averaging**. Summing and suitably dividing several like measurements to improve accuracy or to lessen any asynchronies

Testing Applications

- Mil-Std testing
  - (Sine, Random and Shock Applications)
- SAE standards
- Transportation crash simulation
- Package testing
- Production testing
- Road load testing
- Failure analysis
- Environmental stress screening
- Fatigue & fragility testing
- Buzz, squeak & rattle (BSR)


DEPARTMENT OF DEFENSE
TEST METHOD STANDARD
FOR

ENVIRONMENTAL ENGINEERING CONSIDERATIONS
AND LABORATORY TESTS

More Applications…

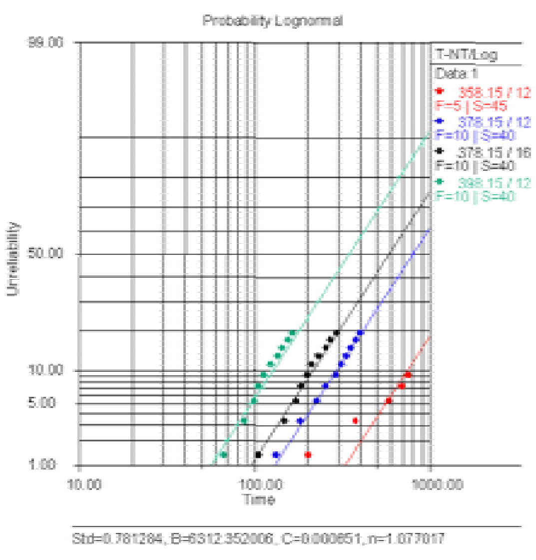
- Product development & qualification
- Accelerated life testing
- Accelerated stress screening
- Nebs (GR-63-core)
- RTCA/DO-160 requirements

Accelerated Life Testing

An activity during development of a new product. Prototypes are subjected to stress levels (including vibration, usually random) that are much higher than those anticipated in the field. The purpose is to identify failure-prone, marginally-strong elements by causing them to fail. Those elements are strengthened and tests are continued at higher levels. Sometimes called test, analyze & fix testing (TAAF) or highly accelerated life test (HALT).

Accelerated Stress Testing

A post-production activity on a sampling (100% at first) of units. The intent is to precipitate hidden or latent failures caused by poor workmanship and to prevent flawed units from reaching the next higher level of assembly or the customer. Intensity is typically half that achieved in accelerated life testing.



Environmental Stress Screening (ESS)

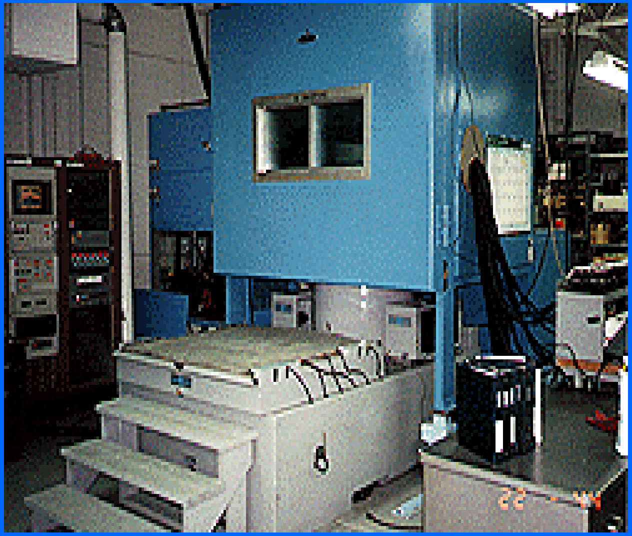
A post-production process in which 100% of produced units are subjected to stresses more severe than anticipated in service. The object is to precipitate latent defects into recognizable failures, so that that particular unit does not proceed further in production nor reach the customer. **Hass.** Highly accelerated stress screening.

Life Cycle Testing

Subjecting products to stresses similar to those anticipated in actual service while collecting engineering data related to life expectancy, reliability, specification compliance, or product improvements.

Usually aimed at determining the products' mean time between failures or MTBF stress screening.

A modern electronics production tool for precipitating latent defects such as poorly-soldered connections. Utilizes random vibration + rapid temperature ramping.



Reliability

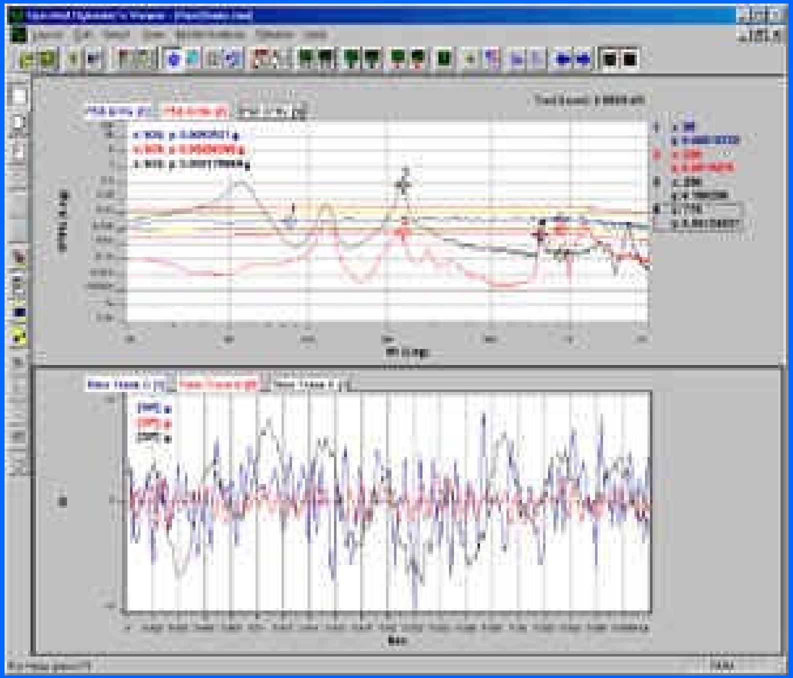
The likelihood or probability that an equipment will "do its job" for a specified length of time (say 1000 hours) under specified circumstances (such as cycling in a specified manner over certain temperature limits, experiencing a particular vibration spectrum, etc.). Reliability defined in this way can be determined experimentally. Take 1000 units. Operate them under specified conditions. At the end of 1000 hours, how many are still operating correctly?

Fragility Test

Expensive but highly useful dynamic tests of several samples (to account for variations in tolerances, material properties and manufacturing processes) at potentially destructive frequencies, to determine fragility.

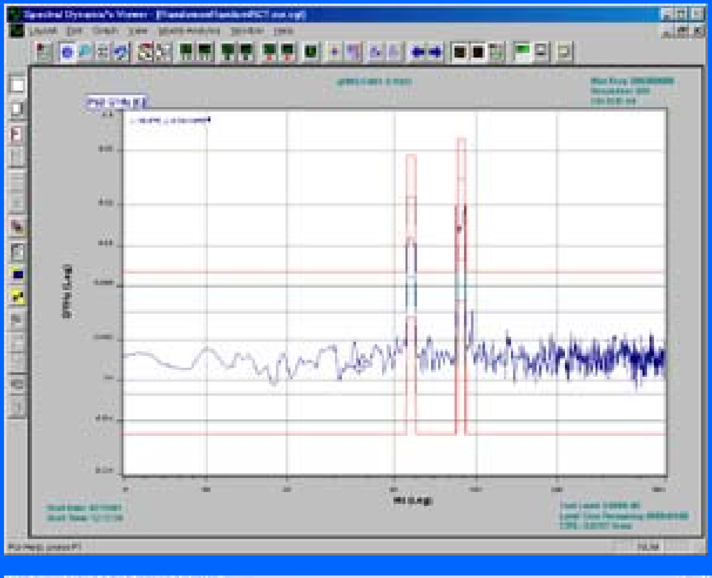
Random Vibration

One whose instantaneous magnitudes cannot be predicted. Adjective "Gaussian" applies if they follow the Gaussian distribution. May be broad-band, covering a wide, continuous frequency range, or narrow band, covering a relatively narrow frequency range. No periodic or deterministic components.



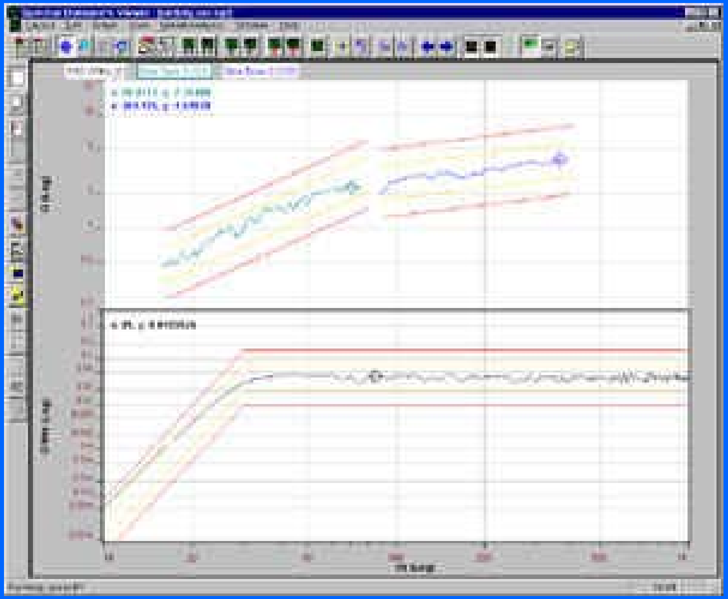
Random on Random

Combined environment of broad band random with narrow band swept random bandwidths



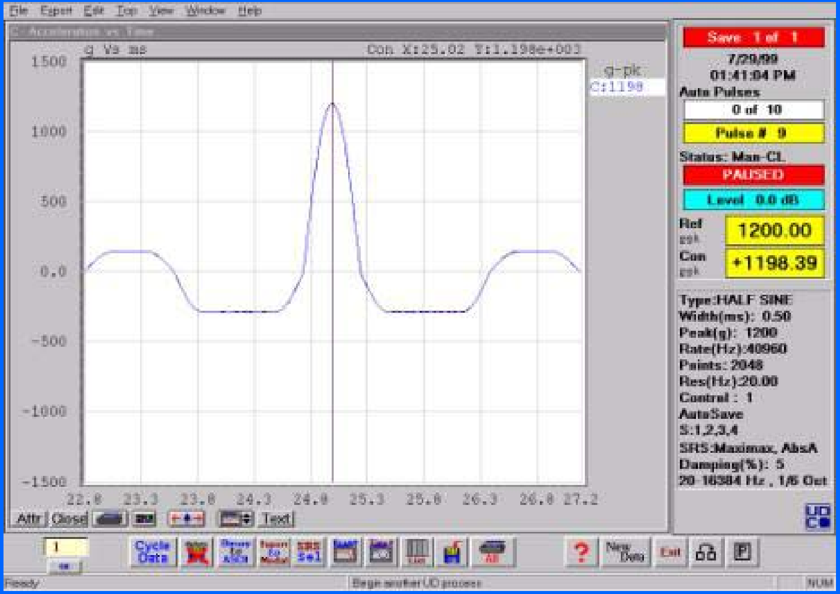
Sine on Random

Combined environment of broad band random with discrete stationary or swept sine tones.



Classical Shock Pulse

An ultra-simple shock pulse, one that is never seen in the "real world" yet is often specified in test requirements. Such pulses contain much more low-frequency energy than do "real world" shock events. Such pulses are said to be "mathematically tractable". They have been studied to death.



Save 1 of 1
7/29/99
01:41:04 PM
Auto Pulses
0 of 10
Pulse # 9
Status: Man-CL
PAUSED
Level 0.0 dB
Ref gpk 1200.00
Con gpk +1198.39

Type:HALF SINE
Width(ms): 0.50
Peak(g): 1200
Rate(Hz):40960
Points: 2048
Res(Hz):20.00
Control : 1
AutoSave
S:1,2,3,4
SRS:Maximax, AbsA
Damping(%): 5
20-16384 Hz , 1/6 Oct

Examples include the half-sine pulse, the square pulse, the triangular pulse, the trapezoid and the sawtooth. The first four, which are symmetrical, are being specified less with each passing year. Only the sawtooth is required in MIL-STD-810F.

Shock Pulse

Complex waveform: Time domain waveform with multiple frequencies and amplitudes. Seismic, Pyrotechnic event.

Shock pulse, haversine: A practical variation on the obsolete half-sine pulse, whose abrupt transitions at beginning and end cannot be achieved in test labs. Practical testing requires some rounding, and the result is called a haversine pulse. Another definition: an inverted cosine offset by half its amplitude. A continuous haversine resembles a sine wave.

Bounce Test

A shaking of unrestrained (loose) cargo. The cargo is repeatedly thrown a short distance into the air and then falls onto the vibrating platform.

Impact Test (bump test)

A broad frequency range of structural responses is caused by a deliberate impact.

Stepped Sine Testing

MIL-STD-167: Sine shaking in a series of dwells. Frequency is incrementally increased or decreased.

Swept-Sine Testing

Sine shaking whose frequency is smoothly and continuously varied. Commonly required for sequentially identifying resonance's.

Vibration Basics and Shaker Selection

Determining Shaker Sizing

Proper Shaker selection requires application of Newton's Second Law of Motion:

Force = Mass x Acceleration (F=MA)

- Vibration systems have output forces ratings defined in terms of:

Sine force: lbs (kN) peak

Random force: lbs (kN) rms

Shock force: lbs (kN) peak

Applying Newton's Law In Shaker Selection

Suitability of a Specific Test System can be evaluated in terms of the following:

Force Requirement (lbf)

- UUT + Fixture + Armature x G = F x 1.30= Desired Force Shaker System

Maximum Displacement

- Determined by test environment

Maximum Velocity

- Determined by test environment

F=ma

Determining Moving MASS

- The mass value (M) in the initial formula of F = MA **must include all moving masses** attached to the shaker armature surface including the armature mass itself: shaker armature + head expander or slip plate with its driver bar + test specimen + specimen interface fixture, including bolts and bearing stiction if the system is driving a horizontal plate using hydrostatic bearings.

Determining and Evaluating Mass

Test Articles, Slip Tables, Head Expanders and Fixtures

- Size, Mass and Frequency Response
- Overturning Moment/Guidance Issues

  (UUT+Fixture) x CG x G x Q= lbin
- Slide Plate: L x W x PSI (14) x effective area= lbin
- Desired Resonance:

  Frequency x (L x W)/ 209000=Thickness

Specimen Specifics

In addition to your test specification, the following test article data is required to determine the appropriate system for your test requirements:

- Specimen Description
- Specimen Test Mass
- Specimen Dimensions
- Specimen Center of Gravity (CG)
- Specimen Mounting Considerations

Fixture Specifics

Test fixtures effect mass and resonance and must be considered carefully. The following concerns should be addressed in selecting a shaker system:

- Do your fixtures exist or will they require design and fabrication?
- What are or will be the approximate dimensions (estimate if necessary) of the fixturing?
- What is or will be the approximate mass (estimate if necessary) of the fixturing?
- Are there any mounting issues (bolt pattern, size)?
- Will a head expander be required?

F=ma
Test Specifications

- The maximum **Acceleration** for the F = MA estimate is derived from the test specification:
  - for Sine vibration (G-peak)
  - for Random vibration (G-rms)
  - for Classical Shock pulses (G-peak)
- The operator must be cognizant of the maximum displacement and velocity of any given test parameter to insure they don’t exceed the systems capabilities

Evaluating the Test Specifications

- Waveform:
  - Sine
  - Random
  - Classical Waveform Shock
  - SRS Shock
  - Mixed Mode (Sine on Random and Random on Random)
- Time Replication
- Test Magnitude
- Test Frequency Range
- Test Duration
- Three Axis Testing Required ?

Understanding Random Vibration

Random vibration stated force ratings are determined with guidance of ISO 5344. ISO 5344 specifies use of a flat 20 Hz to 2000 Hz spectrum with a test load of three to four times the armature mass. This is done to achieve continuity of ratings between different manufacturers. By use of the non-resonant three to four time armature mass load the resonant frequency of the shaker armature under test typically will fall below 2000 Hz. This enables the system to gain free energy at the higher frequencies.

Real World Random Vibration

Typical “real life” Random tests don’t always have test loads of three to four times the armature weight and test input profiles are gaussian in nature rather than flat. Narrow band Random profiles that don’t excite the armature resonance and have test fixtures that are highly damped may require system de-rating of up to 30%.

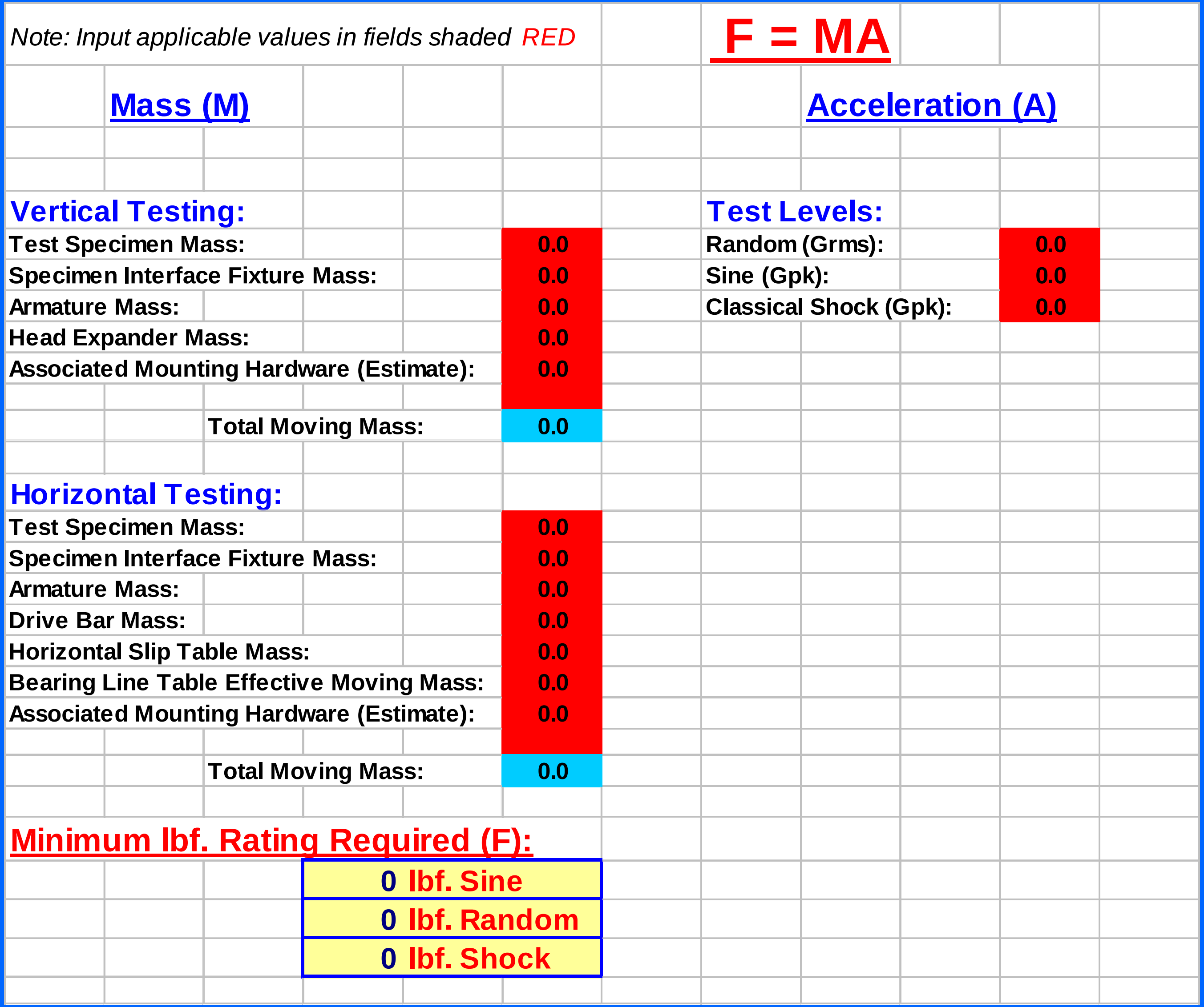
Effects of Resonance

- **Every mechanical structure has a resonant frequency**, which may result in a significant dynamic force absorber at certain frequencies. This phenomena must be taken into account during the estimating process. The force rating defined by the manufacture is rated at the armature surface. If the test system has associated fixtures, head expanders, slip tables, etc. that act as force absorbers and have been defined as a control accelerometer locations, then the shaker may be over driven. **It is always advisable to have monitor accelerometer attached to the armature surface** to determine the “true force” that is being achieved.

F=ma
Calculating Required Force

- Multiply the TOTAL MOVING MASS by the ACCELERATION (G) LEVEL determined by your test specification
- Include a safety margin for transmissibility, etc.
- Use our Microsoft Excel® Shaker Selection Calculator (next slide) for determining the minimum system force rating requirements needed for your application
- It is always recommended that you verify your calculations with a sales engineer prior to purchasing a system

Shaker Selection Worksheet



Note: Input applicable values in fields shaded RED

F = MA

Mass (M)

Acceleration (A)

Vertical Testing:

Test Specimen Mass:	0.0
Specimen Interface Fixture Mass:	0.0
Armature Mass:	0.0
Head Expander Mass:	0.0
Associated Mounting Hardware (Estimate):	0.0
Total Moving Mass:	0.0

Test Levels:

Random (Grms):	0.0
Sine (Gpk):	0.0
Classical Shock (Gpk):	0.0

Horizontal Testing:

Test Specimen Mass:	0.0
Specimen Interface Fixture Mass:	0.0
Armature Mass:	0.0
Drive Bar Mass:	0.0
Horizontal Slip Table Mass:	0.0
Bearing Line Table Effective Moving Mass:	0.0
Associated Mounting Hardware (Estimate):	0.0
Total Moving Mass:	0.0

Minimum lbf. Rating Required (F):

0	lbf. Sine
0	lbf. Random
0	lbf. Shock

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