
Chapter 1	
What are vibration and shock?	1
1.0 Preliminary discussion	
1.1 Definitions of terms	
1.2 Vibration concerns - railroading	
1.3 Vibration concerns - aircraft	
1.4 Vibration concerns - ships	
1.5 Vibration concerns - automotive	
1.6 Vibration and shock as environments	
1.7 Random vibration	
1.8 Machinery vibration	
1.9 Wind-induced vibration	
1.10 Seismic events	
1.11 Fatigue failures	
1.12 Electrical failures	
1.13 Vibration and shock – definitions	
1.14 Vibration sources and effects	
1.15 Mechanisms	
1.16 Your automobile as an example	
1.17 Machine elements	
1.18 Buildings and offices	
1.19 Remote vibration monitoring	
1.20 Isolation	
1.21 Aeroacoustics	
1.22 Transportation	
1.23 Effects on equipment	
1.24 Effects on humans	
1.25 Another word on reliability	
1.26 DeciBel scaling	
1.27 Mechanical shock	
Chapter 2	
Introduction to Classical Sinusoidal Vibration	17
2.0 Why study sinusoidal vibration?	
2.1 Unidirectional motion	
2.2 Sinusoidal vibration	
2.3 Trigonometry review	
2.4 Displacement, velocity, acceleration	
2.5 Swept-frequency mathematics	
2.6 Frequency range	
2.7 Mass? Weight?	
Chapter 3	
Resonance Effects	25
3.0 Concentrate on resonances	
3.1 Forcing frequency = natural frequency	
3.2 Useful electro-mechanical analogs	
3.3 A little more math	
3.4 A hand-held f_n experiment	
3.5 Effect of varying static deflection	
3.6 Have you access to a shaker?	
3.7 Transmissibility graph	
3.8 Half power bandwidth	
3.9 Critical damping	
3.10 Mass and weight are not synonymous	

Chapter 4	
Torsional Vibration	35
4.0 Introduction	
4.1 What is torsional vibration?	
4.2 Comparing to SDoF system	
4.3 Torsional displacement, velocity, acceleration	
4.4 Electro-mechanical analogs	
4.5 Torsional shaking and shocking	
Chapter 5	
Control of Dynamic Motion	41
5.0 Too much vibration	
5.1 Absorb vibratory energy	
5.2 Treat the path	
5.3 Interrupt path with passive isolation	
5.4 COTS equipment	
5.5 Avoid too-soft isolators	
5.6 Isolating shakers	
5.7 Elastomeric and helical isolators	
5.8 Force/deflection curve	
5.9 Locating the isolators	
5.10 Damping creates difficulty	
5.11 Pneumatic isolators	
5.12 Active vibration isolation	
5.13 Reduce ambient vibration how much?	
5.14 Passive dynamic absorbers	
5.15 Tips for designers	
5.16 Redesigning with lesser "Q"	
5.17 PWB ruggedizing without redesign	
Chapter 6	
Displacement and Velocity Measurements	53
6.0 Analogy with humans	
6.1 Why do we need instrumentation?	
6.2 How do we describe an event's severity?	
6.3 Linearity	
6.4 Distributions	
6.5 Importance of measurement certainty	
6.6 Metrology terms	
6.7 Visual displacement indicators	
6.8 Displacement sensors and recorders	
6.9 Non-contact displacement-sensing lasers	
6.10 Velocity sensors	
Chapter 7	
Acceleration and Force Sensors	63
7.0 Strain gage(SG) and piezoresistive (PR) accelerometers	
7.1 Piezoelectric (PE) accelerometers	
7.2 Capacitive accelerometers	
7.3 Tri-axial accelerometers	
7.4 The hand-held accelerometer	
7.5 Servo or force-balance accelerometer	
7.6 Signal conditioning	
7.7 Cable disconnect	
7.8 Accelerometer mechanical errors	

7.9	<i>Static calibration</i>	
7.10	<i>Dynamic calibration</i>	
7.11	<i>Sensitivity</i>	
7.12	<i>Avoid accelerometer bracket resonance</i>	
7.13	<i>Mounting devices</i>	
7.14	<i>Mounting method effects</i>	
7.15	<i>Base bending sensitivity</i>	
7.16	<i>Temperature changes affect sensitivity</i>	
7.17	<i>Lateral or “cross-axis” sensitivity</i>	
7.18	<i>How many accelerometers?</i>	
7.19	<i>Effect of mass loading</i>	
7.20	<i>Protect accelerometers</i>	
7.21	<i>Torsional acceleration</i>	
7.22	<i>Acceleration vs. velocity</i>	
7.23	<i>Integration</i>	
7.24	<i>Force sensors (load cells)</i>	
7.25	<i>Smart sensors</i>	
 Chapter 8		
	Acceleration and Force Signals	85
8.0	<i>Data acquisition – avoiding errors</i>	
8.1	<i>Networked data</i>	
8.2	<i>Readout instruments</i>	
8.3	<i>The time domain – meters and scopes</i>	
8.4	<i>The frequency domain – spectrum analysis</i>	
8.5	<i>Virtual instruments</i>	
8.6	<i>Bits? resolution?</i>	
8.7	<i>Electrical measurement errors</i>	
8.8	<i>Signal conditioning</i>	
8.9	<i>Ground loops</i>	
8.10	<i>High-impedance cables</i>	
8.11	<i>Amplification inside sensor case</i>	
8.12	<i>Thermal effects</i>	
8.13	<i>Data insurance</i>	
 Chapter 9		
	Calibration	99
9.0	<i>Do you use the word “calibrate” properly?</i>	
9.1	<i>Why must we calibrate?</i>	
9.2	<i>Static calibration</i>	
9.3	<i>Relatively crude checks</i>	
9.4	<i>Absolute calibration</i>	
9.5	<i>Accelerometer calibrations at NIST</i>	
9.6	<i>Hand-held calibrators</i>	
9.7	<i>Specialized shakers</i>	
9.8	<i>Comparison calibration</i>	
9.9	<i>Random vibration calibration</i>	
9.10	<i>Calibrating at temperature extremes</i>	
9.11	<i>“Chatter ball” calibration</i>	
9.12	<i>Gravity calibrating an accelerometer</i>	
9.13	<i>Hammer calibrating an accelerometer</i>	
9.14	<i>Measuring transverse sensitivity</i>	
9.15	<i>Shaker calibrating a force sensor</i>	
9.16	<i>Gravity calibrating a force sensor</i>	
9.17	<i>Hammer calibrating a force sensor</i>	

- 9.18 *Microphone calibration by pistonphone*
- 9.19 *Comparison calibrating a microphone*
- 9.20 *Calibrate how often?*

Chapter 10

Continuous Systems 111

- 10.0 *The Continuous System Model*
- 10.1 *Calculating first bending f_n*
- 10.2 *Effect of damping*
- 10.3 *Identifying natural frequencies*
- 10.4 *Superposition*
- 10.5 *Beams and plates*
- 10.6 *Printed wiring cards*
- 10.7 *Plate damping*
- 10.8 *Force measurements*
- 10.9 *Units of force*
- 10.10 *Dynamic ratios*
- 10.11 *More damping applications*
- 10.12 *Phase changes*
- 10.13 *Active shape control*
- 10.14 *Fatigue failures*
- 10.15 *Axial resonances*

Chapter 11

Analysis of Complex Motion 127

- 11.0 *Review of sinusoidal vibration*
- 11.1 *Complex vibration*
- 11.2 *Spectral displays*
- 11.3 *Machinery monitoring*
- 11.4 *Unbalance*
- 11.5 *Dynamic unbalance*
- 11.6 *Bearings*
- 11.7 *Misalignment*
- 11.8 *Gear mesh*
- 11.9 *Machinery health monitoring (MHM)*
- 11.10 *Spectrum analysis*
- 11.11 *Digital analysis problems*
- 11.12 *Aliasing*
- 11.13 *Leakage*
- 11.14 *Windowing*
- 11.15 *Waterfall display*
- 11.16 *Automobile vibrations*
- 11.17 *Helicopter vibrations*
- 11.18 *Time synchronous averaging*
- 11.19 *An introduction to random vibration*

Chapter 12

Test types - Mechanical Shakers 149

- 12.0 *Climatic vs. dynamic testing*
- 12.1 *Why climatic environmental tests?*
- 12.2 *Developmental testing - preview HALT, HASS*
- 12.3 *Pre-production testing*
- 12.4 *Production sample testing*
- 12.5 *Reliability demonstration testing*
- 12.6 *Choosing a shaker*

12.7	<i>Mechanical shakers</i>	
12.8	<i>Direct drive type shakers</i>	
12.9	<i>Thumpers</i>	
12.10	<i>Reaction type shakers</i>	
12.11	<i>Mechanical shakers for ESS</i>	
12.12	<i>Need for multiple shakers</i>	
Chapter 13		
	Electrohydraulic Shakers	157
13.0	<i>Hydraulic actuators</i>	
13.1	<i>Electrohydraulic (EH) shakers</i>	
13.2	<i>Shaker limitations</i>	
13.3	<i>Multi-axis shakers</i>	
13.4	<i>Package/Transportation testing</i>	
13.5	<i>Simulating transport vibration</i>	
13.6	<i>Torsional shaking</i>	
13.7	<i>NEBS seismic testing</i>	
Chapter 14		
	Multiple Electrohydraulic Shakers	161
14.0	<i>Arguments against single axis shaking</i>	
14.1	<i>Multi-axis seismic testing</i>	
14.2	<i>Freight transport</i>	
14.3	<i>Automotive transport</i>	
14.4	<i>Road simulation - NVH testing</i>	
14.5	<i>Suspension development tests</i>	
14.6	<i>Buzz, squeak & rattle testing</i>	
14.7	<i>“CUBE” shakers</i>	
14.8	<i>“Man-rated” shaker systems</i>	
Chapter 15		
	Electrodynamic Shakers	169
15.0	<i>ED shakers – theory, history and uses</i>	
15.1	<i>Construction details</i>	
15.2	<i>Degaussing or demagnetizing coil</i>	
15.3	<i>Wanted and unwanted armature motions</i>	
15.4	<i>Guidance</i>	
15.5	<i>Spare armature</i>	
15.6	<i>Isolating the shaker</i>	
15.7	<i>Long-stroke shakers</i>	
15.8	<i>Single-turn driver coil</i>	
15.9	<i>Cooling of shaker</i>	
15.10	<i>Quieting the cooling blower</i>	
15.11	<i>Electrodynamic shaker system</i>	
15.12	<i>Stroke, force and velocity limits</i>	
15.13	<i>Worker safety</i>	
15.14	<i>Capabilities chart</i>	
15.15	<i>Narrow-band random de-rating</i>	
15.16	<i>Remote control of shaker</i>	
15.17	<i>Combined environmental testing</i>	
15.18	<i>Torsional shakers</i>	
15.19	<i>Piezoelectric shakers</i>	

Chapter 16	
Multiple Electrodynamic Shakers	181
16.0 Multiple shakers, single axis	
16.1 Multiple shakers, multi-axis	
16.2 Two-axis ED shaker	
16.3 Multiple single-axis shakers	
16.4 Earthquake simulation	
16.5 Tilted fixtures are not multi-axis	
Chapter 17	
Power Amplifiers for Electrodynamic Shakers	187
17.0 Focus on power amplifier	
17.1 Theory - what does the power amplifier do?	
17.2 History: vacuum tubes to transistors	
17.3 Switched vs. linear power amplifiers	
17.4 History: motor-generator sets	
17.5 Why consider early shaker systems?	
17.6 Shaker demand for current and voltage	
17.7 Wideband ratings	
17.8 Narrowband ratings	
17.9 Noise and distortion	
17.10 Effect of power amplifier distortion	
17.11 Shaker armature centering	
17.12 Need for maintenance	
Chapter 18	
Standards for Sine Testing	197
18.0 Military test standards	
18.1 Aircraft vibrations	
18.2 Shipboard vibrations	
18.3 Aircraft test frequency range extended	
18.4 Random vibration required	
18.5 Tailoring of military test standards	
18.6 Commercial test standards	
18.7 International organizations	
18.8 COTS equipment	
18.9 Nuclear power plant seismic tests	
18.10 Telecom seismic tests	
18.11 "Cookbook" standards	
Chapter 19	
Control of Sinusoidal Vibration Testing	205
19.0 Why perform sinusoidal vibration tests?	
19.1 Resonance search tests	
19.2 Resonance dwell tests – fatigue	
19.3 Manual control of swept-sine tests	
19.4 Sine testing automated	
19.5 Why the oscilloscope?	
19.6 Tracking filter	
19.7 Sine testing – digital control	
19.8 Remote control of shaker	
19.9 Shortcomings of motion control	
19.10 Constant motion not found in "real world"	
19.11 Tuned or passive vibration absorbers	
19.12 Crankshaft torsional absorbers	

19.13 Force control	
19.14 Response control at CG	
19.15 Multiple control accelerometers	
19.16 Response control strategy	
Chapter 20	
Introduction to Random Vibration	219
20.0 Introduction to random vibration	
20.1 Sources of random vibration	
20.2 Aerospace (vibration source)	
20.3 Rocket liftoff	
20.4 Land and sea vehicles	
20.5 Musical instruments - complex spectra	
20.6 Hash and trash	
20.7 Continuous spectrum - a difficult concept	
20.8 Road inputs to automobiles	
20.9 Random vibration video demonstration	
20.10 Simulating random vibrations in the lab	
20.11 What is PSD? ASD? g^2/Hz ?	
20.12 Conversion: g^2/Hz to 'tustins'	
20.13 PSD/ASD in m^2/s^3	
Chapter 21	
Measurement and Analysis of Random Vibration	229
21.0 Review the familiar sine wave	
21.1 Fourier transform pair	
21.2 Review the complex wave	
21.3 Random vibration in the frequency domain	
21.4 Random vibration in the time domain	
21.5 Gaussian distribution	
21.6 Meaning of term RMS	
21.7 True RMS (TRMS) metering	
21.8 Variance	
21.9 More on amplitude probability density	
21.10 Is your field vibration Gaussian?	
21.11 Is your test vibration Gaussian?	
21.12 A mixture of sinusoids?	
21.13 How can we examine a spectral "slice"?	
21.14 Function of bandpass filter	
21.15 Earthquakes are random vibrations	
21.16 Don't stack your resonances	
Chapter 22	
Random Vibration Testing Standards	237
22.0 Why are standards not effective?	
22.1 Military Standard 810, IEC, ASTM	
22.2 Earthquake (seismic) testing - NEBS	
22.3 How do we interpret what standards say?	
22.4 Focus on frequency domain	
22.5 "Real world" spectra not so simple	
22.6 Interpreting dB tolerances	
22.7 Shaker force requirement; spectrum area	
22.8 Multiple sine + random testing	
22.9 Analyzing narrow bandwidth peaks	
22.10 Spectral graphs misleading	

- 22.11 *Statistical degrees of freedom*
- 22.12 *Don't forget the time domain*
- 22.13 *Clipping*
- 22.14 *Multiple zones*

Chapter 23

Controlling Random Vibration Tests and Screens 249

- 23.0 *Random vibration test practice*
- 23.1 *What are the control tasks?*
- 23.2 *Analog control*
- 23.3 *Why study old analog technology?*
- 23.4 *Computer control*
- 23.5 *Modifying a computer for shaker control*
- 23.6 *How computer controls tests*
- 23.7 *Consider not specifying g^2/Hz*
- 23.8 *Data acquisition*
- 23.9 *Test spectrum based upon field data*
- 23.10 *Averaging*
- 23.11 *"Real world" data not stationary*
- 23.12 *Much realism is lost*
- 23.13 *Reproducing the time domain*
- 23.14 *Shaker compensation*
- 23.15 *Forget about PSD*
- 23.16 *Early idea now possible*
- 23.17 *Varying intensity*
- 23.18 *What if I must test to a spectrum?*
- 23.19 *Sine-on-Random (SoR) tests*
- 23.20 *Narrow-band Random on Random (RoR)*
- 23.21 *Unwanted high-frequency vibration*
- 23.22 *Remote shaker control*
- 23.23 *Gunfire testing*
- 23.24 *Vibration test mishap at JPL*
- 23.25 *Intense noise testing*

Chapter 24

Environmental Stress Screening 267

- 24.0 *What is ESS?*
- 24.1 *Hardware vs. software reliability*
- 24.2 *Military services pioneered ESS*
- 24.3 *ESS analogy*
- 24.4 *Why Is ESS needed?*
- 24.5 *Treadmill analogy*
- 24.6 *Latent defects precipitated*
- 24.7 *Relates how to electronics?*
- 24.8 *Overstressing required*
- 24.9 *Automotive electronics ESS*
- 24.10 *Focus on random vibration*
- 24.11 *A final production step*
- 24.12 *Not simulation but rather stimulation*
- 24.13 *Most effective stimuli*
- 24.14 *Random vibration is needed*
- 24.15 *Is ESS helping us?*
- 24.16 *Does ESS lessen product useful life?*
- 24.17 *How do we define useful life?*
- 24.18 *Extensions to HASS and to HALT*

24.19 *Are uniformity and repeatability essential?*

24.20 *Electronic maintenance stressing*

Chapter 25

Accelerated Testing and Screening 279

25.0 *You intend to prevent failures?*

25.1 *Why worry about reliability?*

25.2 *Commercial product marketing today*

25.3 *HALT helps us to achieve field reliability*

25.4 *Brief review of failures and reliability*

25.5 *HALT stimulates aging*

25.6 *Thermal stressing and cycling*

25.7 *Random vibration*

25.8 *Combining thermal + vibration stresses*

25.9 *Environmental stress screening – ESS*

25.10 *Highly accelerated stress screening – HASS*

25.11 *Less popular stimuli*

25.12 *Detecting a failure*

25.13 *Can we stop screening?*

25.14 *Root cause failure analysis needed*

25.15 *Failure mechanisms*

25.16 *Multi-axis testing and screening*

25.17 *Pneumatic vibrators used for ESS*

25.18 *Segmented table? Rigid table?*

25.19 *Non-coherence; chaos*

25.20 *Spectrum; low-frequency content*

25.21 *Larger displacement offered*

25.22 *Our own lab or “go outside”?*

25.23 *Fluorinert transmits heat and vibration*

25.24 *Acoustical excitation for screening*

25.25 *Thermal ramping*

25.26 *Arguments against HALT*

25.27 *A few thoughts on fatigue failures*

25.28 *Test time exaggeration factors*

25.29 *Virtual testing*

25.30 *Further study*

Chapter 26

Attaching Test Articles to Shakers 303

26.0 *Function of fixture*

26.1 *Coupled system*

26.2 *Hire a professional*

26.3 *Understanding fixture behavior*

26.4 *Extremal control*

26.5 *Fixture transmissibility*

26.6 *Resonant fixtures*

26.7 *Standard fixture configurations*

26.8 *Special-purpose fixtures*

26.9 *Fixture fabrication*

26.10 *Too many interfaces*

26.11 *Welding*

26.12 *Fixture materials*

26.13 *Damping fixture resonances*

26.14 *Fixture mechanical impedance*

26.15 *Force-controlled testing*

- 26.16 Bolting to DUT and to shaker
- 26.17 Control accelerometer location
- 26.18 Fixture criteria
- 26.19 Experimentally evaluating a fixture
- 26.20 Lissajous patterns aid fixture evaluation
- 26.21 Fixture care (maintenance)
- 26.22 Fixtures for buzz, squeak & rattle testing
- 26.23 Fixtures for ESS, HALT and HASS
- 26.24 Heat transfer consideration

Chapter 27

Attaching Oversized Loads 325

- 27.0 Table expanders
- 27.1 Shaker horizontal - auxiliary supports
- 27.2 Support from beneath - slip plate
- 27.3 Axial resonance
- 27.4 Avoid slip plate
- 27.5 Bolted connections in shear
- 27.6 Increasing fixture-to-slip plate friction
- 27.7 Problems with high center of gravity
- 27.8 Hydrostatic bearings
- 27.9 Support from above
- 27.10 Combined environment testing
- 27.11 Connecting shaker to load CG

Chapter 28

Measuring and Quantifying Mechanical Shock..... 333

- 28.0 What is shock? How different from vibration?
- 28.1 Shock excites all resonances
- 28.2 Instrumentation: equipment limitations
- 28.3 "Fairing" a shock pulse
- 28.4 Choosing a shock accelerometer
- 28.5 High frequency filter cut-off effects
- 28.6 Low frequency filter cut-off effects
- 28.7 Accelerometer limitations
- 28.8 Over-ranging
- 28.9 Factory shock
- 28.10 Laser measurement of displacement
- 28.11 MIL-STD-810F pyroshock
- 28.12 Accelerometer mounting and cabling
- 28.13 Accelerometer cable
- 28.14 Windowing
- 28.15 Inexpensive shock recorders
- 28.16 Mechanical shock time history recorder
- 28.17 Accelerometer-based recorders
- 28.18 Concealable recorders
- 28.19 Shock calibration
- 28.20 Hopkinson bar shock calibration

Chapter 29

SRS - the Shock Response Spectrum 347

- 29.0 Time domain review
- 29.1 Why do we need SRS?
- 29.2 Designer and test lab use SRS
- 29.3 History of SRS

29.4	<i>Studying earth motion</i>	
29.5	<i>Early studies of shipboard shock</i>	
29.6	<i>Understanding the SRS</i>	
29.7	<i>The maximax spectrum</i>	
29.8	<i>Electronic SRS analysis</i>	
Chapter 30		
	Mechanical Shock Testing	357
30.0	<i>Shock test standards</i>	
30.1	<i>Moving carriage machine</i>	
30.2	<i>Hard disk drive testing</i>	
30.3	<i>Packaging fragility tests</i>	
30.4	<i>Drop testing</i>	
30.5	<i>Drop package machines</i>	
30.6	<i>Hammer machines</i>	
30.7	<i>Barge tests</i>	
30.8	<i>More recent navy shock testers</i>	
30.9	<i>Explosive pyro tests</i>	
30.10	<i>Classical pulses on shakers</i>	
30.11	<i>SRS tests on shakers</i>	
30.12	<i>Reproducing the time domain</i>	
30.13	<i>Automotive crash tests</i>	
30.14	<i>Railroad crash tests</i>	
Chapter 31		
	Introduction to Modal Testing	375
31.0	<i>Review of continuous systems</i>	
31.1	<i>What is a mode?</i>	
31.2	<i>Modal analysis vs. modal test</i>	
31.3	<i>Modal analysis</i>	
31.4	<i>Modal testing</i>	
31.5	<i>Disagreement between analysis and test</i>	
31.6	<i>Continuously exciting the physical model</i>	
31.7	<i>Shaker exciting the physical model</i>	
31.8	<i>Coupling shaker to load</i>	
31.9	<i>Shock exciting the physical model</i>	
31.10	<i>Transducers used in modal testing</i>	
31.11	<i>Boundary conditions</i>	
31.12	<i>Sources of error in modal testing</i>	
31.13	<i>Modal test hints</i>	
31.14	<i>Automobile modal test example</i>	
31.15	<i>TEDS sensors</i>	
31.16	<i>Piezoelectric actuators</i>	
31.17	<i>Scanning laser metrology</i>	
31.18	<i>Modal testing of operating machinery</i>	
Chapter 32		
	Buzz, Squeak and Rattle Testing	393
32.0	<i>Buzz, Squeak and Rattle (BSR), Itch</i>	
32.1	<i>Sound quality measurements</i>	
32.2	<i>Loudness - sones and phons</i>	
32.3	<i>Buzz, Squeak and Rattle (BSR) shaking</i>	
32.4	<i>Sine sweeping</i>	
32.5	<i>Structural stiffness is important</i>	
32.6	<i>Sound limits</i>	

32.7 Enclosures needed

32.8 Warning re aliasing

32.9 Remote control of shaker

32.10 BSR solutions

Chapter 33

Think, then test 403

33.0 Concluding chapter

33.1 Good testing

33.2 Tips to improve laboratory operations

33.3 Shaker system maintenance

33.4 Study past failures

33.5 Require dynamic testing

Conclusion 411

Appendix A 413

Appendix B 415

Definitions of Terms - Glossary 417

Index 433