Chapter 1 What are vibration and shock?

1.0 Preliminary discussion

Along with theory and facts, this book gives you a little history that you are not likely to get elsewhere. You today are standing on the shoulders of pioneers.

Vibration and shock are relatively new fields, possibly 99% of all progress to date having occurred since 1940. This text shows you and tells you a little about the "early days".

Are you responsible for teaching others about vibration and shock technology? Then what you read here should be very useful. It collects (valuable to me and hopefully to you) 50 rich years of experience.

For some readers, specialists, this book may not adequately discuss their small segment of the vibration and shock "world". They may dismiss this book as "a survey". In a sense they are correct. This book *is* primarily intended for newcomers to the field. But it also fills some long-standing needs, since everyone has gaps in his knowledge. The author has often been thanked for clarifying a topic that had for as much as twenty years concerned an individual.

Why are *you* reading this book? Before we commence discussing vibration (and mechanical shock), let's take a few minutes to discuss why vibration (and shock) might interest you. You probably are involved with some form of equipment. Long useful life of that equipment is doubtless important to you. Vibration and shock may reduce that life.

In school, you probably spent a lot of time and effort learning how things are supposed to work. But very little (if any) time learning how things fail. Vibration and shock often accelerate failure, so by lessening (controlling) vibration and shock we can defer failure. That's one way this book can help you.

You may need to know if vibration is excessive. Or if some change has reduced or increased an existing vibration. Thus you may need to learn how to accurately measure vibration.

Perhaps you will (in a test laboratory) use shakers to simulate transportation or service vibration. Or to perform ESS, HALT or HASS. Product reliability is probably important to you and to your organization. How does your organization measure reliability? (If you didn't measure it, how could you tell if reliability were improving or getting worse?) Perhaps you will ask this question of your engineering department leaders.

1.1 Definitions of terms

There is a CD-ROM in a pocket inside the rear cover of this book. It contains a glossary that defines many vibration and shock terms. I suggest that you use the glossary to look up any terms you are not familiar with.

1.2 Vibration concerns – railroading

There once was a time when no one worried much about vibration. Consider the locomotive of Figure 1-1, for instance. Most failures in that era involved fatigue, and the most common cure was to make the part stronger (and heavier). Hooray! That extra ton gave better traction.

As time has passed, trains (and other vehicles) have gotten much lighter and much faster. See Video Clip 1-1 on the CD in a pocket in the rear of this book.

Figure 1-1 Early-day railroad locomotive

Figure 1-2 came from the Transportation Technology Center at Pueblo, Colorado, a commercial test facility that was formerly operated by the American Association of Railroads. Electrohydraulic shakers (see Chapters 13 and 14) shake pieces of rolling stock, test couplings, etc.

Video clip 1-1 High speed passenger train

Figure 1-2 Getting ready to shake a gondola car

1.3 Vibration concerns – aircraft

Let's shift to another area of engineering, where an extra ton would greatly compromise performance. Flight hardware is valued for strength without excessive mass. Aircraft engineering "got into" vibration measurement and testing a few years before the automobile industry. At the same time that vehicle weight went down, horsepower came up! No wonder that vibration intensity and concern increased markedly.

In flight, have you noticed airplane wings flexing? That is perfectly normal. Actually, the fuselage also bends slightly. Studying such motions (one at a time) is called modal analysis. We'll learn about modes in Chapter 10 and study modal testing in Chapter 31. Meantime, Animation 1-1 (on the CD) presents a computer-generated modal animation of the British *Concorde*.

Figure 1-3 Passenger jet airplane
(courtesy Boeing)

Insert CD-ROM (from pocket inside back cover) into appropriate slot. Go to Animation 1-1 to view an aircraft body bending vertically, one of its many response modes. You will see this animation again in Chapter 31 on modal analysis. You will use this CD-ROM for numerous animations and video clips.

Animation 1-1 Modal analysis

The author's first "modal" vibration test experience (see Chapter 31) was on the XB52, developmental model of the highly successful B52 aircraft shown in Figure 1-4. Had anyone predicted that B52s would still be operational fifty years hence, he would have been laughed at. It appears that we developed a VERY successful airplane. Grandsons are literally piloting the specific aircraft flown by their grandfathers.

Ask yourself: were B-52s overdesigned? They could have been lighter, permitting greater bomb loads and/or more fuel and thus greater range. Would they then have lasted 50+ years?

Few jet aircraft passengers ever think about vibration. But flying in a helicopter (Figure 1-5) is different. One is very conscious of vibration, mainly the main rotor blades passing over the cabin. Passengers and crew of propeller-driven aircraft sense propeller vibration.

Figure 1-4 B-52 aircraft
(courtesy Boeing)

Figure 1-5 Naval helicopter in flight
(courtesy US Navy)

Figure 1-6 Naval ship taking evasive action
(courtesy US Navy)

1.4 Vibration concerns – ships

Today, equipment aboard combat ships must not produce much hull vibration (must be quiet), Figure 1-6, even when maneuvering. Potential enemies listen carefully for identifying sounds. Further, the ship's noise must not interfere with its own sonar.

This is especially true of submarines, Figure 1-7. Reducing machinery noise and vibration receives particular attention in Chapter 5.

Figure 1-7 Submarines and their crews keep quiet!
(courtesy US Navy)

1.5 Vibration concerns - automotive

Automotive electronics, just like consumer electronics, is rapidly increasing in complexity. Yet it also must meet the rigorous automotive environmental requirements that approach those called for by the military.

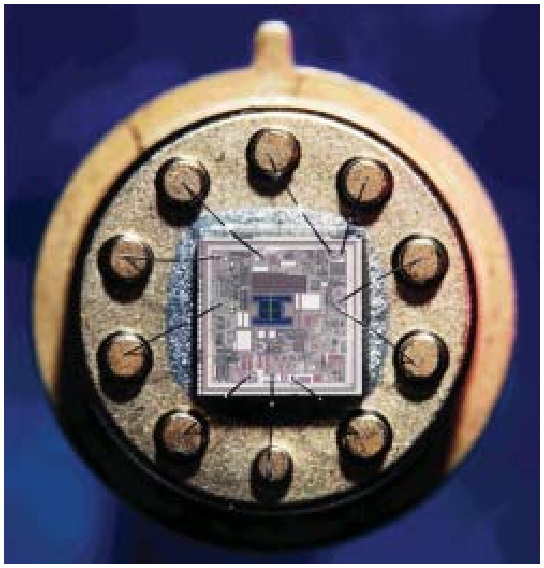

Figure 1-8 PR accelerometer on integrated chip

Many mechanical and hydraulic components are being replaced by electromechanical or even completely electronic components. Microcircuits are replacing relays, switches and traditional mechanical functions with higher-reliability components while eliminating the cost and weight of copper wire. Example: the airbag crash sensor of Figure 1-8. The Analog Devices ADXL-50 combines a micromachined PR (see Chapter 7) accelerometer with signal conditioning and other functions.

1.6 Vibration and shock as environments

We will go into the field and measure the environments of vibration (Chapters 6-9) and shock (Chapter 28). And we will try to replicate field vibration and shock in our test laboratory, using shakers (Chapters 12-16) and shock test apparatus (Chapter 30). Among other goals, we want to find out if our hardware will survive the man-made environments of vibration and shock. We will perform dynamics tests per Chapters 18, 23 and 30 having somewhat the same goals as did engineers performing the climatic test of Figure 1-9.

Figure 1-9 Climatic test on MIL vehicle

1.7 Random vibration

In the early days of aircraft, just getting into the air was quite an accomplishment. Soon, however, aircraft were required to reliably carry airmail and airfreight, to safely and comfortably carry passengers, to reliably carry out military missions. These demands necessitated control of in-flight vibrations. We will consider control (lessen, moderate, decrease) of vibration in Chapter 5.

Intense random vibration can't be seen in Video Clip 1-2, but it is present. High velocity, turbulent airflow over all surfaces creates random vibration of the skin. The aircraft structure carries that random vibration to all the “black boxes” on board. Another path is acoustic. Unless on-board equipment is rugged, it can misoperate and/or suffer damage.

Video clip 1-2 Jet aircraft in flight

In the early days of our space programs, “mission success” only required something as simple as acquiring the proper orbit. That was not easy, particularly early in the “Space Race”. Far too many vehicles exploded at ignition or during liftoff, Figure 1-10. Or they went “off course” and had to be destroyed. Random vibration was often the culprit, but this was not known until about 1955. More realistic random vibration testing led to much higher reliability. See Chapters 22 and 23.

Figure 1-10 Rocket liftoff

We want present and future spacecraft to accomplish such diverse activities as viewing distant galaxies, detecting specific wavelengths of radiation, measuring crop yields, etc. Today’s and tomorrow’s spacecraft carry increasingly complex systems and subsystems. More hardware. And they are required to function for not hours or days but for years. Vibration (Figure 1-11) and acoustic tests (launch vehicle as well as the satellite payload) are among the many tests required prior to launch.

The costs of failure, including vibration-induced failure, have risen. This book deals with ways to reduce the number of failures. Acoustic (Chapter 23) and vibration testing (Chapters 19 and 23) and shock (Chapter 30) testing are among the tools.

Figure 1-11 Vibration test on satellite

1.8 Machinery vibration

Less dramatic, perhaps, but no less important to continued operation of various kinds of machinery, is the unique vibration “signature” of installed machinery. Changes in that signature are used by machinery health monitoring (sometimes called condition monitoring) specialists to warn of impending failure, as with the gears of Figure 1-12. See Chapter 11

Figure 1-12 Gear train as vibration source

A little closer to the experience of most of us: automobile vibrations. We’ll be considering engine and drive train vibrations. See Chapters 6 through 11 for more on vibration measurements and analysis.

1-9 Wind-induced vibrations

You have perhaps observed wind causing outdoor structures to vibrate. Examples (not discussed further in this text) might include electric power transmission lines, car radio whip antennas, the sailboat rigging of Figure 1-13, or the sails themselves.

Figure 1-13 Wind-induced vibrations

One of the most dramatic examples of wind-induced vibration was the 1940 failure of the recently opened Tacoma (Washington State) Narrows Bridge. Video Clip 1-3 shows the bridge oscillating at different times in two of its “favorite” modes. On this particular day (over several hours) the wind speed remained critical long enough that resonant response reached destruction. Many movie cameras recorded the collapse.

Video clip 1-3 Tacoma narrows bridge

1.10 Seismic events

Earthquakes are an ever-present danger in certain areas of the globe. They are multi-directional and their random vibration typically covers a continuous frequency spectrum, perhaps 2 to 35 Hz, with greatest intensity (at least in California) around 8 Hz. They vary tremendously in intensity, so that logarithmic scaling (see Section 1.19) is needed.

Many occur in unpopulated areas and so do little damage. Figure 1-14 helps to locate one California event. Figure 1-15 shows one very dramatic adverse effect of that event. Vital equipment that will be used in telecommunications centers, electric power plants - especially nuclear plants, etc. should be subjected to simulated earthquakes. See Chapters 14, 18 and 30.

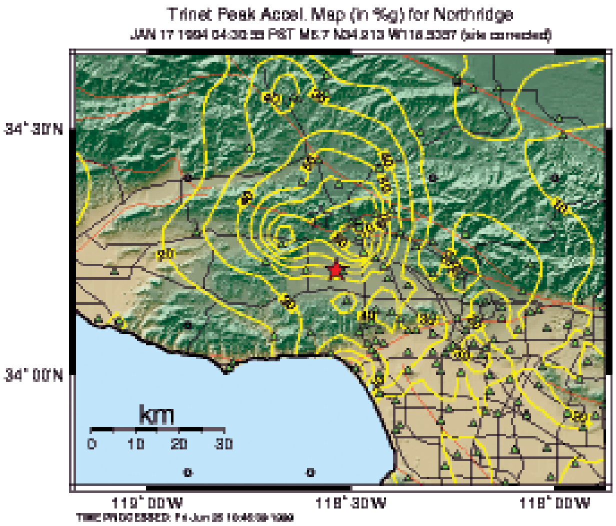

Figure 1-14 Epicenter of Northridge, California earth quake – 1994

Figure 1-15 One result of the 1994 Northridge (Los Angeles) earthquake

1.11 Fatigue failures

Many people, when discussing vibration-induced failures, limit their thinking to fatigue failures. Figure 1-16 suggests an experiment. File a very small nick in a paper clip, somewhere in its central area. Then bend the paperclip back and forth a few cycles, cyclically stressing that central area. It will not surprise you that the wire cracks and breaks at the "stress riser" you have created. We will further discuss fatigue testing in Chapters 12 and 19. However, there are many other vibration-induced failure modes; we will discuss some of them throughout this book.

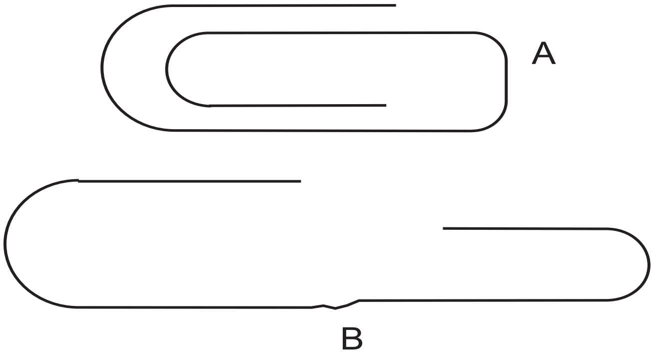

Figure 1-16 Demonstrating fatigue failure

1.12 Electrical failures

Intermittent electrical conductors and connections that momentarily "open" or "short" (even for a microsecond) when they should remain "closed" or "open", can create difficulty. Nearly every electrical or electronic part is somehow connected to other parts and to the apparatus is which it functions. When performing vibration and shock tests, we apply power to the DUT (device under test) and monitor DUT test points as well as DUT outputs to be sure that operation is not affected. Any intermittent connections even as short as 1 microsecond between a component and a wiring board, between a wiring board and a "black box" or inside the connectors of Figure 1-17, can be "bad news". Interconnect reliability detectors (event detectors), offered by AnalysisTech of Wakefield, Massachusetts (Figure 1-18) and other firms, are useful.

1.13 Vibration and shock - definitions

In this and subsequent Chapters we will examine three general classes of mechanical motion and force:

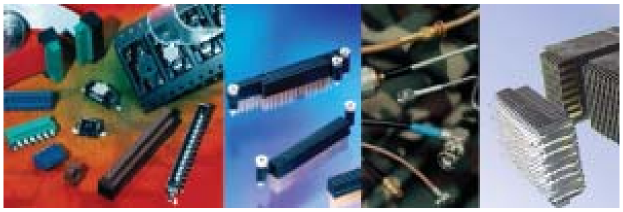

Figure 1-17 Variety of electrical connectors

Figure 1-18 Event detector

1. continuous and cyclic (such as sinusoidal and omplex vibration),

2. continuous but non-cyclic (such as random vibration) and

3. neither continuous nor cyclic (such as mechanical shock).

What is vibration? Here is one definition: "Vibration is one possible motion in a mechanical system, an oscillating motion about some reference or equilibrium position." If we wish to measure, control (and possibly simulate) vibratory motion, we need to understand its basic nature.

Most dictionary definitions seem to focus on highly repetitive sinusoidal vibration. According to *WWW Webster on-line,* as of 1997, Main Entry: *vi·bra·tion*

Pronunciation: vI-'brA-sh&n. Function: noun. Date: 1655

1 : a periodic motion of the particles of an elastic body or medium in alternately opposite directions from the position of equilibrium when that equilibrium has been disturbed (as when a stretched cord produces musical tones or particles of air transmit sounds to the ear)

1 b : the action of vibrating : the state of being vibrated or in vibratory motion: as
(1) : OSCILLATION (2) : a quivering or trembling motion : QUIVER
2 : an instance of vibration
3 : vacillation in opinion or action : WAVERING
4 : a characteristic emanation, aura, or spirit that infuses or vitalizes someone or something and that can be instinctively sensed or experienced, often used in plural. b : a distinctive, usually emotional atmosphere capable of being sensed, usually used in plural
- vi·bra·tion·al /-shn&l, -sh&-n&l/ adjective
vi·bra·tion·less /-sh&n-l&s/ adjective

If we mention that we're involved with vibration, in some non-engineering gatherings, we can get some strange looks. Some people think about definitions 3 and 4, whereas we probably mean 1 or 2.

My favorite, by columnist Ann Landers: "Vibration is a motion that can't make up its mind in which direction it is going." Her definition is broad enough to include random as well as complex vibration.

1.14 Vibration sources and effects

Where does vibration come from? Vibration can be generated by almost any motion or mechanical force, including, but not limited to: the combustion and rotation of your automobile engine and drive train, irregularities in road surfaces, reaction (propulsion) forces of rockets, turbulent gas or liquid flow in pipes or ducts, also by acoustical energy from rocket or other engine exhausts, aerodynamic flow over your automobile, over aircraft, missiles, buildings, bridges, electrical power lines, through wind musical instruments or by gunfire. Bowing a stringed musical instrument creates vibration. Many of these vibrations also generate sounds. Horseback riding, walking and jogging excite vibrations in our bodies.

Vibratory motion can be helpful or it can be detrimental. Vibratory massagers, paint mixing, vibratory conveyors, the loosening of stuck parts, agitation of liquid concrete to allow entrained air to escape and the deliberate compacting of loose materials are examples of helpful vibration.

Fatigue-induced mechanical failures, broken leads and solder joints on electronic equipment, failure of aircraft or automotive structural components, bridge collapses, also unwanted buzzes, squeaks and rattles, are among the harmful effects vibration can cause.

Roadway-induced vibration and shock, the subject of Video Clip 1-4, are very unpopular. Not only are they uncomfortable for driver and passengers, they necessitate much maintenance and can lead to accidents as well as to premature scrapping of vehicles.

Video Clip 1-4 Roadway-induced vibration and shock

1.15 Mechanisms

Vibratory energy in machines, vehicles and structures may be generated by any change in force or motion. Here are some examples of (generally unwanted) vibration-producing mechanisms:

- Unbalanced rotating elements, *e.g.* fan blades,
- Oscillating components, *e.g.* pistons and valves
- Rough mating surfaces of gears and bearings,
- Fluid flow causing turbulence in pipes
- Air flow over aerodynamic surfaces,
- Forces induced by handling, transportation
- Thrust forces of rocket propulsion systems
- Forces generated by pumps

1.16 Your automobile as an example

Your automobile can introduce you to vibration measurement and analysis. How is vibration described? What are the sources? Aside from roadway-induced motions, consider the engine of Figure 1-16. Describing engine vibration is not simple.

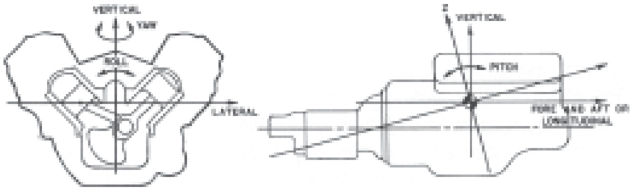

Figure 1-19 Automobile engine generates vibrations

Flexible supports (engine mounts) isolate the engine from the frame. But these mounts are not very effective when the engine idles. We will learn why in Chapter 5.

Please recognize and consider the repetitive, cyclic nature of the engine-induced forces. These forces will attempt to shake not only the engine but also the vehicle, driver and passengers. Automotive engineers will try to minimize that shaking. Engine and drive train motions and forces are coupled to the driver and passengers

- mechanically via the vehicle structure: vibration
- acoustically via air: sound or noise.

What causes those motions and forces? The rotating crankshaft and flywheel, imperfectly balanced, are one source. Piston reaction forces are another. Forces pass through the crankshaft bearings and cause the engine to shake. At idling speed, if we look at and touch the engine, we can see and feel large dynamic displacements.

Unbalance vibration occurs at a certain frequency, the number of events per minute or per second. To state frequency in cycles per second (cps) or the *Systeme Internationale* (SI) term hertz (Hz), divide the number of RPM by 60. Thus at l800 revolutions per minute (RPM) an unbalanced rotor generates vibration at a frequency of 1800 cpm (cycles per minute) or 30 Hz.

Chapter 3 introduces resonance, which at certain engine speeds magnifies existing vibration. A common non-automotive example of resonance is pushing a child on a swing. If you push, even gently, at the proper frequency, the child's motion eventually becomes large.

This simplified discussion is placed here in Chapter 1 to introduce some technical terms we will be using later. Engine vibration forces occur at several frequencies; the most obvious is at "1 x rpm" or "first order". When any exciting or forcing frequency f_f coincides with any of the natural frequencies f_n of the engine or vehicle, we have resonance. Your automobile frame is fairly stiff; that is, its natural frequencies are relatively high. It is common practice to mount the engine on relatively soft vibration isolators or engine mounts to isolate the frame from some engine vibrations and to avoid exciting some frame resonances.

However, this soft mounting allows relatively large engine vibratory displacements when the engine rotates slowly.

1.17 Machine elements

Rotating elements within a machine may be statically or dynamically unbalanced. Unbalance forces pass through bearings, causing the machine's frame to vibrate. That vibration, as well as vibration caused by gears, by bearings and by misalignment of bearings, all contribute to the machine's overall vibration signature. Measurement of that vibration is suggested by Figure 1-20.

Figure 1-20 Measuring a machine's vibration

1.18 Buildings and offices

Modern (as compared to older) office buildings are characterized by low mass and by lack of structural damping. But where do architects tend to install powerful blowers, pumps, compressors, etc.? On the roofs. The upper floors (which should bring high rents) are sometimes vacant due to building vibration and accompanying noise. Fans and other mechanisms inside office machinery can cause subtle malfunctions and fatigue failures. (See "The Business Machine Vibration Environment", by Skinner and Zable of IBM, in *The Journal of Environmental Sciences,* Sept/Oct 1978).

1.19 Remote vibration monitoring

Compressor stations on unattended gas pipelines may be 100 to 200 miles from maintenance personnel. Remotely monitored vibration signals warn of imminent bearing or gear failure or of "thrown" turbine blades.

Machine tool vibration can cause chatter, poor finishes and excessive rejects. Remote sensing can monitor automatic manufacturing equipment. Without monitoring, lost production, scrap, production machinery downtime and maintenance costs can skyrocket.

The US Navy is experimenting with monitoring (from shore) vibration of propulsion systems and other machinery aboard unmanned ships.

1.20 Isolation

Machine tool users often find that isolation (as suggested by Figure 1-21) against vibration and shock is helpful. This somewhat resembles the cushioning of your automobile suspension and of the engine mounts.

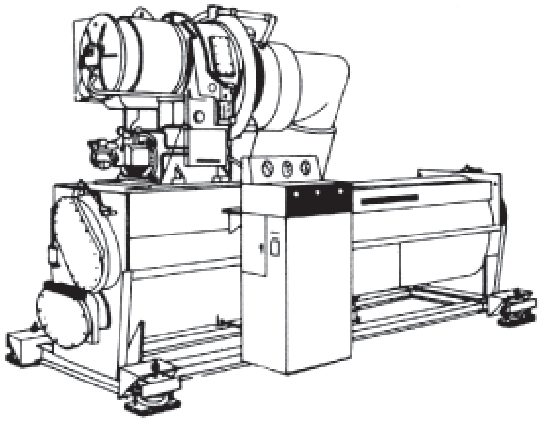

Figure 1-21 Machine tool isolated from factory floor

"Cold-header" bolt-making machines were once lagged down to concrete floors. They often tore loose due to severe shocks. Floating such machines on rubber mounts or on springs dissipates energy by allowing the machine to deflect slightly with each stroke.

Weaving looms were once bolted to the floors of soft wooden buildings. Shuttle acceleration and deceleration forces were dissipated by building motion. However, when looms were moved to concrete-floored buildings, loom maintenance costs soared. Flexibility was restored by floating the looms on soft pads.

1.21 Aeroacoustics

High velocity aerodynamic flow across aircraft and missile skin surfaces usually leads to turbulence. To a lesser extent, this occurs when your automobile travels at high speed, especially into the wind. Turbulence causes oscillating forces in the skin, generating vibratory motion of the skin and structural members. Forces are transmitted to components, equipment and passengers directly by mechanical coupling. Forces (noise) are also coupled indirectly by acoustic coupling.

Troublesome aeroacoustic forces can also be generated by the turbulent flow of wind around buildings. Tall building sway has been known to damage those buildings (most notably Boston's John Hancock Building - Figure 19-16) and cause personnel discomfort. We earlier discussed (Video Clip 1-4) wind-induced bridge vibration. Wind flow over electrical power transmission lines can result in vibration which occasionally causes dramatic fatigue failures of the lines and their support towers.

1.22 Transportation

Transport vibration and shock costs billions of dollars annually. Rough factory handling can be followed by truck or rail travel, then by more rough handling upon receipt. Until recently, amazingly little was known about these environments. (See "An Assessment of the Common Carrier Shipping Environment," by Ostrem and Godshall, 1979, Forest Products Laboratory, U. S. Dept. of Agriculture, Madison, WI; see also pg. 83, Part 2, *Shock and Vibration Bulletln 50*. Modern, very compact instruments (Section 28.18) that sense and record vibration and shock are nowadays revealing what happens *en route*.

1.23 Effects on equipment

We know that sustained vibration and repeated shocks often cause damage. Mechanical fasteners (bolts, machine screws etc.) loosen under vibration and shock. Rotating component unbalance, such as automobile tires or jet engine fans, can damage the component or the supporting structure. Vibration can cause fatigue of connectors, solder joints, circuit boards, component leads and other electrical/electronic elements.

1.24 Effects on humans

Sustained vibration at certain frequencies annoys, and sometimes physically damages people. It can cause a truck driver's painful back and can eventually incapacitate him. Vibration White Finger (VWF) industrial disease, (Raynaud's Syndrome) involves long exposure to severe hand vibration, especially when combined with cold weather. See NIOSH (Cincinnati, Ohio) Technical Report by D. Wasserman, 1982, NIOSH videotape #177. Also Wasserman & Wasserman "The Nuts & Bolts of Human Exposure to Vibration" in *Sound & Vibration* magazine, January 2002. See also Figure 1-22. Tool and hand vibration are measured simultaneously to gauge the benefit of cushioned gloves. To guard against VWF, lightly grip vibrating tools, wear "cushioned" gloves and stay warm. VWF can lead to impaired finger circulation, to gangrene and to amputation.

Sustained very low frequency sounds and/or vibrations can cause illness. Little data has been scientifically gathered, and no standards exist. (See AGARD monograph No. 151 "Aeromedical Aspects of Vibration and Noise" by John C. Guignard and P. C. King, NATO 1972, available from the National Technical Information Service as AD-754631).

Automobile interiors have become so quiet that drivers and passengers hear (and complain about) small vibration-induced sounds collectively called BSR (buzz, squeak and rattle). A new engineering specialty has sprung up; see Chapter 32.

Figure 1-22 Vibration White Fingers

1.25 Another word on reliability

With ever-increasing complexity and sophistication of (and our dependence upon) modern equipment, the costs of failure become less and less acceptable. Since vibration is a major cause of failure, it becomes increasingly important that we understand and control the vibration environments to which equipment, structures and people are exposed.

1.26 DeciBel scaling

Before we discuss deciBels, can we agree that it's convenient for all our paper money to be same size? Nice that a $1000 bill is not 1000 X the height and 1000 X the width of a $1 bill. Somewhat similarly, we want all our graphs to be on standard size graph paper.

How can we show maxima up to 1000g and readable minima down to 0.001g on the same graph?

The magnitudes we encounter in vibration, shock and sound measurements can vary over a huge dynamic range. Logarithmic scaling of amplitudes is very useful, almost a necessity. Logarithmic scaling “compresses” large values that would drive an ordinary meter off scale (or plotter off the paper). And it “expands” small values that would not lift an ordinary meter’s pointer (nor a plotter pen) off zero. See Figures 1-23 and 1-24; the same rotating machinery data is first plotted with linear scaling of magnitude of velocity while the second is plotted with logarithmic scaling of magnitude. We will examine the details of what these graphs represent when we get into Chapter 11.

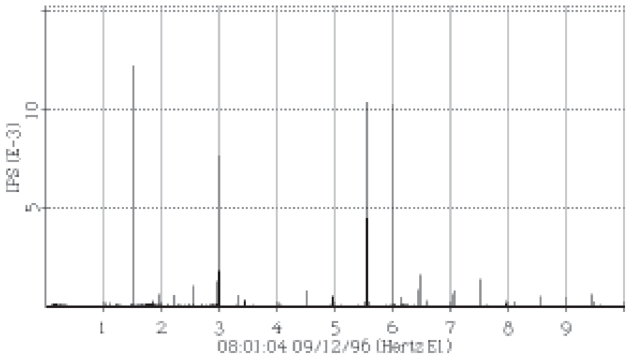

Figure 1-23 Spectrum with linearly-scaled ordinates

Notice the tiny contributions at certain frequencies, Figure 1-23. They are so small that we cannot evaluate them. Yet (see Chapter 11) they may be important to our understanding of machine condition.

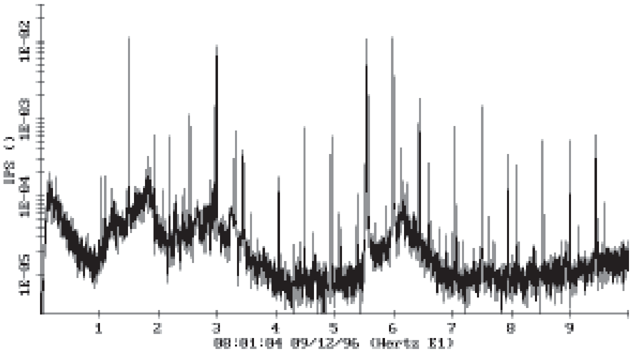

Figure 1-24 Spectrum with logarithmically-scaled ordinates

With the logarithmic scaling of amplitudes in Figure 1-24 we can evaluate those tiny peaks. We could have seen them in Figure 1-23 by greatly in- creasing the “gain” or amplification. But then each of the large contributions would have driven the pen off the paper.

The magnitudes we encounter in vibration, shock (and sound) measurements can vary over a huge dynamic range. DeciBel scaling is the most common way to implement log scaling of magnitude. The original unit, the Bel, was simply the base 10 logarithm of a sound power ratio. That unit was later subdivided by 10 to get dB. Like logarithmic scaling, dB scaling “compresses” large values that would drive an ordinary meter or plotter off scale. And it “expands” small values that would not lift an ordinary meter’s pointer or a plotter’s pen off zero.

The original “classic” relationship is :

$$\text{number of dB} = 10\log_{10}\frac{P}{P_0}$$

However, we are much more likely to be measuring voltage or a voltage-like quantity such as displacement, velocity, acceleration, force, pressure, strain. etc. How can deciBells relate voltages? Since power is proportional to voltage squared, we can say that

$$\text{number of dB} = 10\log_{10}\frac{E^2}{E_0^2}$$

$$\text{or number of dB} = 20\log_{10}\frac{E}{E_0}$$

The denominator P_0 or E_0 is our standard or reference value, against which we are comparing some new or unknown value in the numerator, P or E. We must always state what that reference value is, *e.g.* 20 µPa (micropascals) for acoustics.

Use the “power” equation for sound power measurements, for power spectral density random vibration measurements, etc.

Did the statement that power is proportional to voltage^2 agree with your previous knowledge? It is worth exploring. Let’s (in our imaginations: see Figure 1-25) double the voltage in a simple circuit, and see if power quadruples.

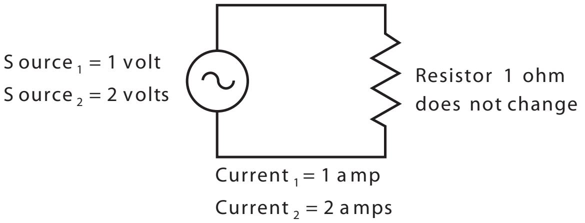

Figure 1-25 Exercise to prove +6 dB means power x 4

Insert power quadrupling into the earlier x10 “power” equation or insert voltage doubling into the earlier x20 “voltage” equation. Either way, you should get +6 dB.

Tables similar to Table 1-1 are commonly found in Electrical Engineering and other handbooks.

Notice the colored line pertaining to +6 dB in our “voltage doubling” imaginary experiment. Note that a halving of voltage or quartering of power can be described as -6 dB.

Table 1-1 Decibel relationships

Volts, amps etc. ratio	Power ratio	No. of dB -< >+	Power ratio	Volts, amps etc. ratio
1.00	1.00	0.00	1.00	1.00
0.89	0.79	1.00	1.26	1.12
0.79	0.63	2.00	1.59	1.26
0.71	0.50	3.00	2.00	1.41
0.50	**0.25**	**6.00**	**3.98**	**1.78**
0.35	0.13	9.00	7.94	2.82
0.62	0.10	10.00	10.00	3.16
0.18	0.03	15.00	31.62	5.62
0.10	0.01	20.00	100	10.00
0.03	0.00	30.00	1000.00	31.60

Note in the upper window of the cardboard calculator (Figure 1-26) that the slider has been positioned for 20 dB. In the second window we see a voltage or current ratio of 10:1 or 1:10. Note in the third window a power ratio of 100:1 or 1:00. Does this agree with Table 1-1?

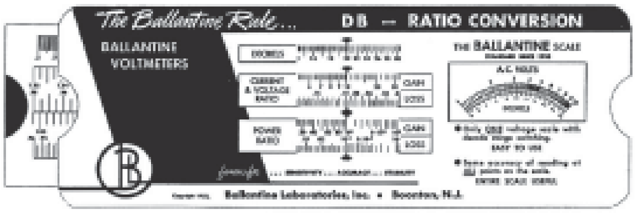

Figure 1-26 Cardboard deciBel calculator

Even a common multimeter (Figure 1-27) may have a deciBel scale. Note that the angle subtended by 0 to +6 dB is equal to the angle subtended by a doubling of voltage or current. Does this agree with Table1-1?

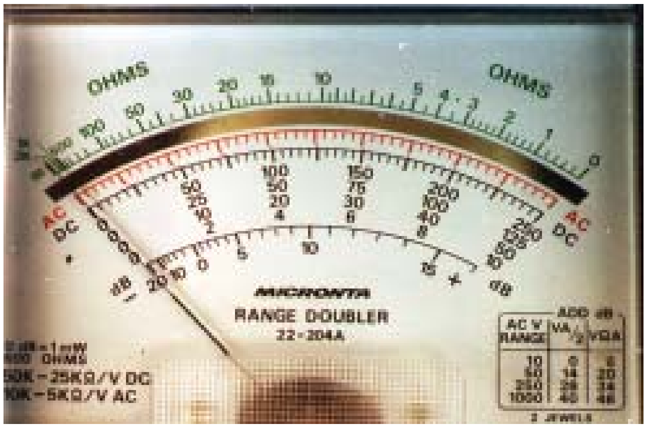

Figure 1-27 dB scale on common multimeter

Practically any dynamic quantity can be used as the dB reference. These are commonly used:

- Vibratory displacements of 1 mm or 0.001 inch (often called 1 mil) or 1 inch,
- Vibratory accelerations of 1 mm/s^2 or 1g,
- Vibratory velocities of 1 mm/s or 1 in/sec,
- Vibratory forces of 1 dyne or 1 newton or 1 pound, etc. have all been used. 20 micropascals or 20 µPa is almost always used for noise regulations..

Consider the air pressure measurements (Figure 1-28) that are appropriate for checking automobile, truck or bus tires. Such a gage is

- far too gross and
- far too slow to respond for acoustics (pressure) measurements as in Figure 1-29.

Figure 1-28 Distant cousin to a microphone

Figure 1-29 suggests acoustic measurements, where dB scaling is common.

Figure 1-29 Noise test in hemi anechoic room

DeciBel scaling does not "come naturally" to mechanical engineers and technicians, though it does to electrical and electronic engineers and technicians. I had to work pretty hard to come up with dB applications to mechanical systems. High performance aircraft speed might be given in dB compared with Mach 1, the speed of sound.

Bordering on the ridiculous, Figure 1-30 and Table 1-2, automobile speed might be compared with, say, 60 miles/hour, calling that 0 dB.

If we don't like negative dBs, we can define 1 mile/hour as our 0 dB reference as shown in Table 1-3. You'll encounter deciBel scaling in later chapters where we discuss electrical measurements (of, for example, motion and force). Also the "slope" and the "flatness" of random vibration spectra. Perhaps I should have waited and introduced deciBel scaling at that time, when you will need it. But I wanted to get some of the math out of the way early.

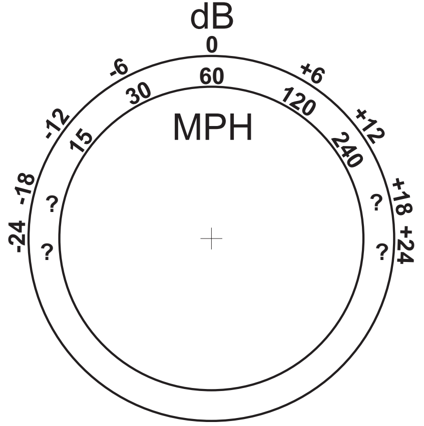

Figure 1-30 Ridiculous automobile speedometer in dB

AUTOMOBILE SPEED

miles/hour	deciBels
120	+6
60	0 = ref
30	-6
15	-12
10	
5	
1	

Table 1-2 Concept of automobile speed in dB

miles/hour	deciBels
1	0 = ref
2	+6
4	+12
10	+20
100	+40
1000	+60

Table 1-3 Concept of automobile speed in dB

Another engineering field in which logarithmic scaling is used: seismology or the study of earthquakes. The reference was set low so that the smallest recorded 'quakes are positive. A tremor or a disturbance 1000 times greater would be assigned a "Richter scale" number of 3. 10,000 times greater will be Richter 4. The largest earthquake ever recorded, something over 8, was then more than 10^8 or 100,000,000 times greater than the reference. Thus logarithmic scaling is necessary.

1.27 Mechanical shock

Mechanical shock, discussed in Chapters 28, 29 and 30, can be severe. Shock (such as in the event of Video clip 1-5) events are usually (compared to vibration) quite brief. That weapon's real function requires surviving impact with earth.

Video Clip 1-5 Weapon strikes earth — shock !

In Chapter 30 we will deal with mechanical shock testing, exemplified here by the automotive passenger-restraint shock test of Figure 1-31.

Figure 1-31 Automotive sled test

My thanks to Randall H. Collier, P.E., of Baton Rouge, Louisiana, for reading a draft of this chapter and for offering his advice on it.

In this first chapter I have tried to give you a sampling of what is contained in the remaining 32 chapters. And to impress you with the variety of uses in which vibration and shock technology is being used.