CHAPTER 26, PART I

SHOCK TESTING MACHINES

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INTRODUCTION

Equipment must be sufficiently rugged to operate satisfactorily in the shock and vibration environments to which it will be exposed and to survive transportation to the site of ultimate use. To ensure that the equipment is sufficiently rugged and to determine what its mechanical faults are, it is subjected to controlled mechanical shocks on shock testing machines. *Mechanical shock* is a nonperiodic excitation (e.g., a motion of the foundation or an applied force) of a mechanical system that is characterized by suddenness and severity, and it usually causes significant relative displacements in the system. The severity and nature of the applied shocks are usually intended to simulate environments expected in later use or to be similar to important components of those environments. However, a principal characteristic of shocks encountered in the field is their variety. These field shocks cannot be defined exactly. Therefore shock simulation can never exactly duplicate shock conditions that occur in the field.

There is no general requirement that a shock testing machine reproduce field conditions. All that is required is that the shock testing machine provide a shock test such that equipment which survives is acceptable under service conditions. Assurance that this condition exists requires a comparison of shock test results and field experience extending over long periods of time. This comparison is not possible for newly developed items. It is generally accepted that shocks that occur in field environments should be measured and that shock machines should simulate the important characteristics of shocks that occur in field environments or have a damage potential which by analysis is shown to be similar to that of a composite field shock environment against which protection is required.

A *shock testing machine* (frequently called a *shock machine*) is a mechanical device that applies a mechanical shock to an equipment under test. The nature of the shock is determined from an analysis of the field environment. Tests by means of shock machines usually are preferable to tests under actual field conditions for four principal reasons:

1. The nature of the shock is under good control, and the shock can be repeated with reasonable exactness. This permits a comparative evaluation of the equipment under test and allows exact performance specifications to be written.
2. The intensity and nature of shock motions can be produced that represent an average condition for which protection is practical, whereas a field test may involve only a specific condition that is contained in this average.

3. The shock machine can be housed at a convenient location with suitable facilities available for monitoring the test.
4. The shock machine is relatively inexpensive to operate, so it is practical to perform a great number of developmental tests on components and subassemblies in a manner not otherwise practical.

SHOCK-MACHINE CHARACTERISTICS

DAMAGE POTENTIAL AND SHOCK RESPONSE SPECTRA

The damage potential of a shock motion is dependent upon the nature of an equipment subjected to the shock, as well as upon the nature and intensity of the shock motion. To describe the damage potential, a description of what the shock does to an equipment must be given—a description of the shock motion is not sufficient. To obtain a comparative measure of the damage potential of a shock motion, it is customary to determine the effect of the motion on simple mechanical systems. This is done by determining the maximum responses of a series of single degree-of-freedom systems (see Chap. 2) to the shock motion and considering the magnitude of the response of each of these systems as indicative of the damage potential of the shock motion. The responses are plotted as a function of these natural frequencies. A curve representing these responses is called a *shock response spectrum,* or *response spectrum* (see Chap. 23). Its magnitude at any given frequency is a quantitative measure of the damage potential of a particular shock motion to a single degree-of-freedom system with that natural frequency. This concept of the shock response spectrum originally was applied only to undamped single degree-of-freedom systems, but the concept has been extended to include systems in which any specified amount of damping exists.

The response of a simple system can be expressed in terms of the relative displacement, velocity, or acceleration of the system. It is customary to define velocity and acceleration responses as $2\pi f$ and $(2\pi f)^2$ times the maximum relative displacement response, where f is frequency expressed in hertz. The corresponding response curves are called *displacement, velocity,* or *acceleration shock response spectra.* A more detailed discussion of shock response spectra is given in Chap. 23.

Of the three motion parameters (displacement, velocity, and acceleration) describing a shock spectrum, velocity is the parameter of greatest interest from the viewpoint of damage potential. This is because the maximum stresses in a structure subjected to a dynamic load typically are due to the responses of the normal modes of the structure, that is, the responses at natural frequencies (see Chap. 21). At any given natural frequency, stress is proportional to the modal (relative) response velocity.[1] Specifically,

$$\sigma_{\max} = C\nu_{\max}\sqrt{E\rho} \tag{26.1}$$

where $\sigma_{\max}$ = maximum modal stress in the structure
$\nu_{\max}$ = maximum modal velocity of the structural response
E = Young's modulus of the structural material
ρ = mass density of the structural material
C = constant of proportionality dependent upon the geometry of the structure (often assumed for complex equipment to be $4 < C < 8$)[2]

Of course, if the shock response spectrum for a test machine–generated shock is computed solely to validate that test results comply with a specified shock response spectrum, or for comparison to the shock response spectra computed from measured shocks in a service environment, then either displacement or acceleration shock response spectra are as meaningful as a velocity shock response spectrum. However, if the maximum stress in the structure subjected to the shock is of primary interest, the velocity shock response spectrum is the most applicable.

MODIFICATION OF CHARACTERISTICS BY REACTIONS OF TEST ITEM

The shock motion produced by a shock machine may depend upon the mass and frequency characteristics of the item under test. However, if the effective weight of the item is small compared with the weight of the moving parts of the shock machine, its influence is relatively unimportant. Generally, however, the reaction of the test item on the shock machine is appreciable and it is not possible to specify the test in terms of the shock motions unless large tolerances are permissible. The test item acts like a dynamic vibration absorber (see Chap. 6). If the item is relatively heavy, this causes the shock response spectra of the exciting shock to have minima at the frequencies of the test item; it also causes its mounting foundation to have these minima during shock excitation at field installations. Shock tests and design factors are sometimes established on the basis of an envelope of the maximum values of shock response spectra. However, maximum stresses in the test item will most probably occur at the antiresonance frequencies where the shock response spectrum exhibits minimum values. To require that the item withstand the upper limit of spectra at these frequencies may result in overtesting and overdesign. Considerable judgment is therefore required both in the specification of shock tests and in the establishment of theoretical design factors on the basis of field measurements. See Chap. 20 for a more complete discussion of this subject.

DOMINANT FREQUENCIES OF SHOCK MACHINES

The shock motion produced by a shock machine may exhibit frequencies that are characteristic of the machine. These frequencies may be affected by the equipment under test. The probability that these particular frequencies will occur in the field is no greater than the probability of other frequencies in the general range of interest. A shock test, therefore, discriminates against equipment having elements whose natural frequencies coincide with frequencies introduced by the shock machine. This may cause failures to occur in relatively good equipment whereas other equipment, having different natural frequencies, may pass the test even though of poorer quality. Because of these factors, there is an increasing tendency to design shock machines to be as rigid as possible, so that their natural frequencies are above the range of frequencies that might be strongly excited in the equipment under test. The shock motion is then designed to be the simplest shape pulse that will give a desired shock motion or response spectrum.

CALIBRATION

A *shock-machine calibration* is a determination of the shock motions or response spectra generated by the machine under standard specified conditions of load, mounting arrangements, methods of measurement, and machine operation. The purpose of the calibration is not to present a complete study of the characteristics of the machine but rather to present a sufficient measure of its performance to ensure the user that the machine is in a satisfactory condition. Measurements should therefore be made under a limited number of significant conditions that can be accurately specified and easily duplicated. Calibrations are usually performed with deadweight loads rigidly attached to the shock machine.

The statement of calibration results must include information relative to all factors that may affect the nature of the motion. These include the magnitude, dimensions, and type of load; the location and method of mounting of the load; factors related to the operation of the shock machine; the locations and mounting arrangements of pickups; and the frequency range over which the measurements extend.

SPECIFYING A SHOCK TEST

Two methods of specification are employed in defining a shock test: (1) a specification of the shock motions (or response spectra) to which the item under test is subjected and (2) a specification of the shock machine, the method of mounting the test item, and the procedure for operating the machine.[3]

The first method of specification can be used only when the shock motion can be defined in a reasonably simple manner and when the application of forces is not so sudden as to excite structural vibration of significant amplitude in the shock machine. If equipment under test is relatively heavy, and if its normal modes of vibration are excited with significant amplitude, the shock motions are affected by the load; then the specified shock motions should be regarded as nominal. If comparable results are to be obtained for tests of different machines of the same type, the methods of mounting and operational procedures must be the same.

The second method of specification for a shock test assumes that it is impractical to specify a shock motion because of its complexity; instead, the specification states that the shock test shall be performed in a given manner on a particular machine. The second method permits a machine to be developed and specified as a standard shock testing machine. Those who are responsible for the specification then should ensure that the shock machine generates appropriate shock motions. This method avoids a difficulty that arises in the first method when measurements show that the shock motions differ from those specified. These differences are to be expected if load reactions are appreciable and complex.

A shock testing machine must be capable of reproducing shock motions with good precision for purposes of comparative evaluation of equipment and for the determination as to whether a manufacturer has met contractual obligations. Moreover, different machines of the same type must be able to provide shocks of equivalent damage potential to the same types of equipment under test. Precision in machine performance, therefore, is required on the basis of contractual obligations and for the comparative evaluation of equipments even though it is not justified on the basis of a knowledge of field conditions.

Sometimes equipment under test may consistently fail to meet specification requirements on one shock machine but may be acceptable when tested on a different shock machine of the same type. The reason for this is that small changes of natural frequencies and of internal damping, of either the equipment or the shock machine, may cause large changes in the likelihood of failure of the item. Results of this kind do not necessarily mean that a test has been performed on a faulty machine; normal variations of natural frequencies and internal damping from machine to machine make such changes possible. However, standard calibrations of shock machines should be made from time to time to ensure that significant changes in the machines have not occurred.

SHOCK TESTING MACHINES

CHARACTERISTIC TYPES OF SHOCKS

The shock machines described below are grouped according to the types of shocks they produce. When a machine can be classified under several headings, it is placed in the one for which it is primarily intended. One characteristic shared by all shock machines is that the motions they produce are sudden and likely to create significant inertial forces in the item under test. The types of shock shown in Fig. 26.1 are classified as (*A*) through (*D*), simple shock pulses, whose shapes can be expressed in a practical mathematical form; (*E*), single complex shock; and (*F*), a multiple shock. In contrast to a simple shock pulse specification, the motions illustrated in Fig. 26.1 (*E*) and (*F*) often are the result of a shock test in which the shock testing machine, the method of mounting, and machine operations were specified.

Velocity Shocks. A *velocity shock* is produced by a sudden change in the net velocity of the structure supporting the item under test. When the duration of the shock is short compared to the periods of the principal natural frequencies of the item under test, a velocity shock is said to have occurred. Figure 26.1*A* shows a nearly instantaneous change in velocity. The shocks shown in Fig. 26.1*B, C,* and *D* are also considered velocity shocks if the above shortness criterion is met. Velocity shocks produce substantial energy at the principal natural frequencies of the item under test. This is illustrated in Figs. 26.2 and 26.3, which show the shock response spectra (computed with a zero damping ratio) for the half-sine and sawtooth acceleration pulses in Fig. 26.1*A* and *B,* respectively. Note in both cases that the values of the velocity shock response spectra are uniform at all frequencies below about $Tf = 0.2$. Hence, from Eq. (26.1), they have the potential to cause substantial damage to the basic structure of the item under test, assuming the item has natural frequencies below $f = 0.2/T$ Hz.

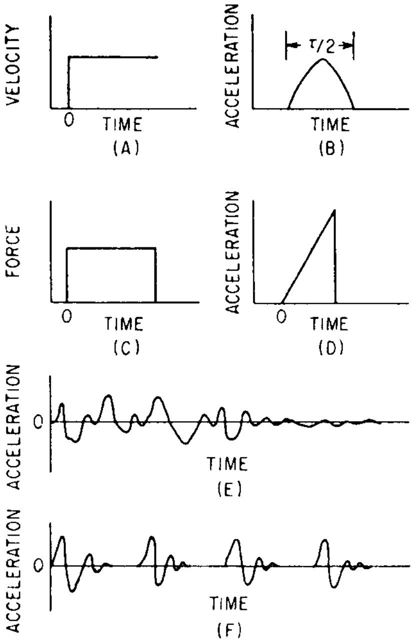

FIGURE 26.1 Characteristic types of shocks. (*A*) Velocity shock, or step velocity change. (*B*) Simple half-sine acceleration shock pulse. (*C*) Rectangular force pulse. (*D*) Sawtooth acceleration pulse. (*E*) Single complex shock. (*F*) Multiple shock.

Displacement Shocks. Some shock test machines produce a sequence of two or more velocity shocks with equal and opposite velocity magnitudes such that the test item experiences no net velocity change. For example, the half-

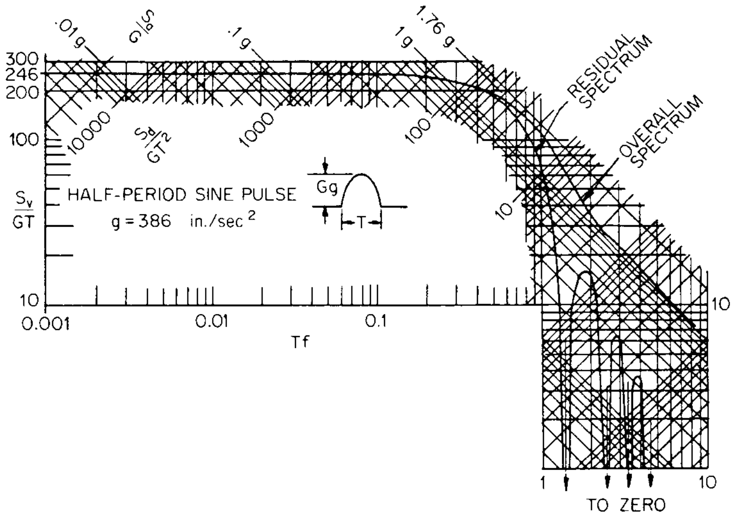

FIGURE 26.2 Residual and overall shock response spectra of the half-sine acceleration pulse shown in the inset.

sine acceleration pulse in Fig. 26.1*B* might be followed by a second half-sine pulse of equal magnitude in the opposite direction. If the time between the two equal and opposite acceleration pulses is longer than the duration of the individual pulses, a substantial displacement of the test item between the positive and negative velocity changes will occur. This type of shock is commonly called a *displacement shock.* Such shocks have a damage potential similar to that of velocity shocks.

High-Frequency Shocks. Metal-to-metal impacts that do not result in a net velocity change of the item under test create high-acceleration, high-frequency oscillations in the vicinity of the impact. Figure 26.1*E* and *F* are examples of high-

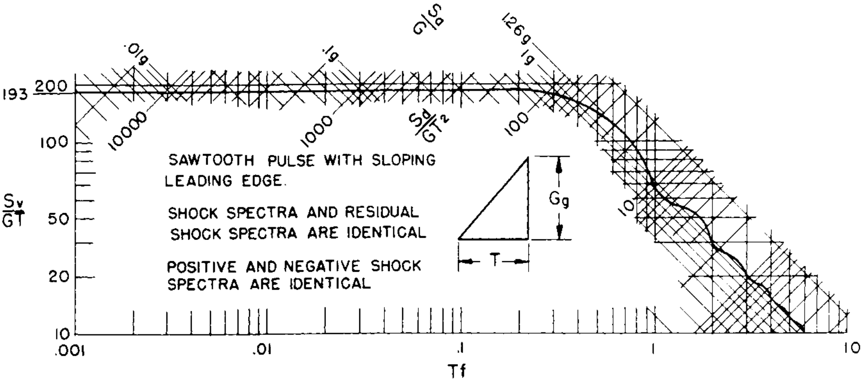

FIGURE 26.3 Shock response spectra of a sawtooth acceleration pulse shown in the inset.

frequency shocks. Since the frequency range of these shocks often exceeds the principal natural frequencies of the item under test, the shocks usually are not readily transmitted far from the point of their creation. Consequently, this type of shock lacks the damage potential of velocity shocks for all but small and/or brittle components of the item under test. Common sources of high-frequency shocks include pyrotechnic devices, which produce what are commonly referred to as *pyroshocks.* Laboratory machines and techniques for the simulation of pyroshocks are detailed separately in Chap. 26, Part II.

SIMPLE SHOCK PULSE MACHINES

Although shocks encountered in the field are usually complex in nature (for example, see Fig. 26.1*E*), it is frequently advantageous to simulate a field shock by a shock of mathematically simple form. This permits designers to calculate equipment response more easily and allows tests to be performed that can check these calculations. This technique is additionally justifiable if the pulses are shaped so as to provide shock response spectra similar to those obtained for a suitable average of a given type of field conditions. Machines are therefore built to provide these simple shock motions. However, note that the motions provided by actual machines are only ideally simple. The ideal outputs may be given as nominal values; the actual outputs can only be determined by measurement.

Drop Tables. A great variety of drop testers are used to obtain acceleration pulses having magnitudes ranging from 80,000g down to a few g. The machines each include a carriage (or table) on which the item under test is mounted; the carriage can be hoisted up to some required height and dropped onto an anvil. Guides are provided to keep the carriage properly oriented. When large velocity changes are required, the carriage may be accelerated downward by a means other than gravity. Frequently, parts of the carriage, associated with its lifting and guiding mechanism, are flexibly mounted to the rigid part of the carriage structure that receives the impact. This is to isolate the main carriage structure from its flexible appendages so as to retain the simple pulse structure of the stopping acceleration.

A typical drop table machine is shown in Fig. 26.4. The desire acceleration pulse shape is obtained using a programming device between the impacting surfaces. Devices ranging from liquid programmers to simple pads of elastomeric materials can be used. Note the shock cords that accelerate the table to create velocities beyond those that can be obtained with a free fall. Machines of this type can produce acceleration waveforms that closely approximate many different types of velocity shocks, such as the half-sine and terminal sawtooth acceleration pulses in Fig. 26.1*A* and *B,* respectively.

Air Guns. Air guns frequently are used to impart large accelerations to pistons on which items under test can be attached. The piston is mechanically retained in position near the breech end of the gun while air pressure is built up within the breech. A quick-release mechanism suddenly releases the piston, and the air pressure projects the piston down the gun barrel. The muzzle end of the gun is closed so that the piston is stopped by compressing the air in the muzzle end. Air bleeder holes may be placed in the gun barrel to absorb energy and to prevent an excessive number of oscillations of the piston between its two ends.

A variety of such guns can provide the acceleration pulses shown in Fig. 26.5*A* and *B*. The peak accelerations may extend from a maximum of about 1000g for the

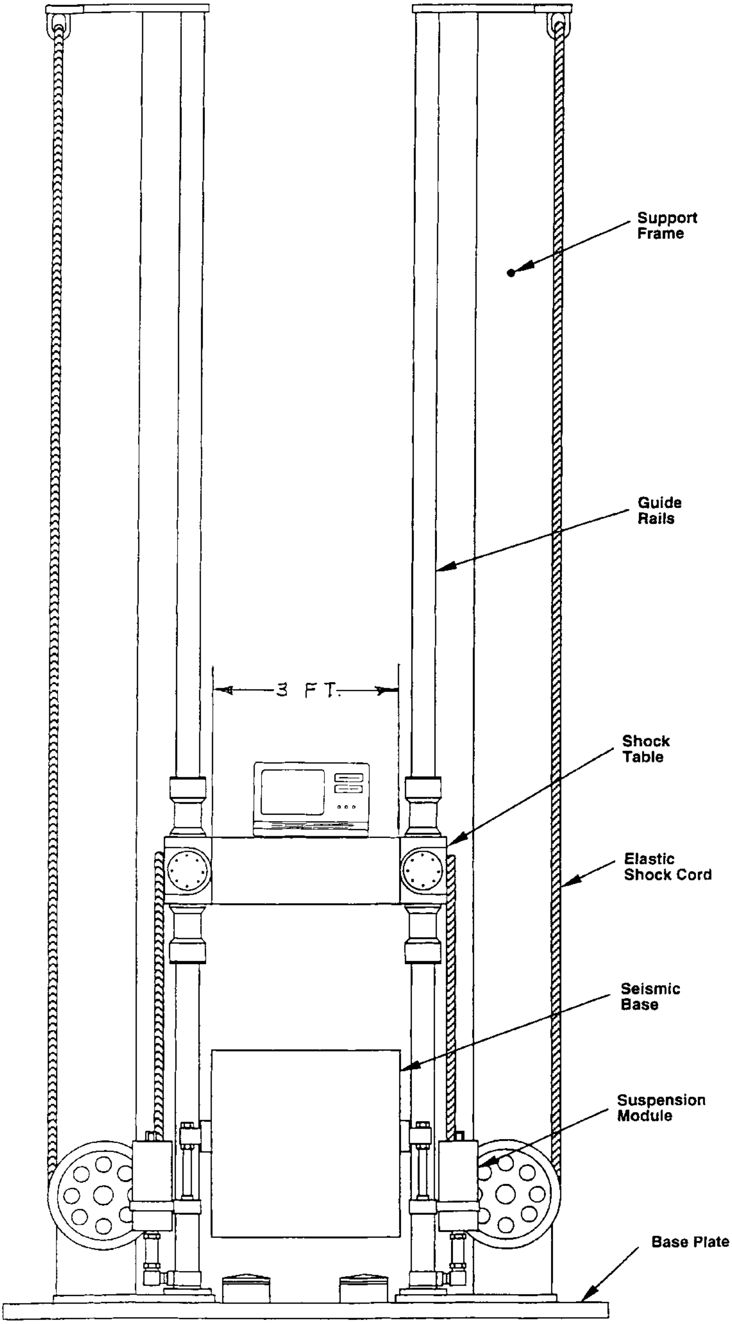

FIGURE 26.4 Drop-table arrangement for use with programming devices between the impacting surfaces. (*Courtesy of MTS Systems Corp.*)

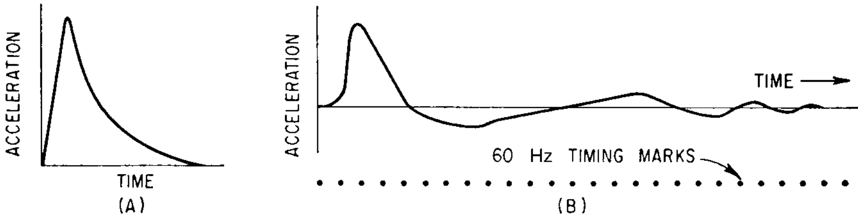

FIGURE 26.5 Typical acceleration-time curves for (*A*) 5-in. (13-cm) air gun; (*B*) 21-in. (53-cm) air gun.

large-diameter (21 in, 53 cm) guns up to 200,000*g* for small-diameter (2 in, 5 cm) guns. The pulse length varies correspondingly from about 50 to 3 milliseconds. The maximum piston velocity varies from about 400 to 750 ft/sec (122 to 229 m/sec). The maximum velocities are not dependent upon piston diameter.

High-acceleration gas guns have been developed for testing electronic devices. The items under test are attached to the piston. The gun consists of a barrel (cylinder) that is closed at the muzzle end but which has large openings to the atmosphere a short distance from the muzzle end. The piston is held in place while a relatively low-pressure gas (usually air or nitrogen) is applied at the breech end of the gun. The piston is then released, whereby it is accelerated over a relatively long distance until it reaches the position along the length of the cylinder that is open to the atmosphere. This initial acceleration is of relatively small magnitude. After the piston has passed these openings, it is stopped by the compression of gas in the short closed end of the cylinder. This results in a reverse acceleration of relatively large magnitude. (Sometimes an inert gas, such as nitrogen, is used in the closed end to prevent explosions which might be caused by oil particles igniting under the high temperatures incident to the compression.) Thus, in contrast to the previously described devices, the major acceleration pulse is delivered during stopping rather than starting. An advantage of this latter technique is that the difficult problem of constructing a quick-release mechanism for the piston, which will work satisfactorily under the large forces exerted by the piston, is greatly simplified.

Vibration Machines. Electrodynamic, hydraulic, and pneumatic vibration machines provide a ready and flexible source of shock pulses, so long as the pulse requirements do not exceed the force and motion capabilities of the selected machine. See Chap. 25 for information.

Test Load Reactions. In the above description of the output of shock machines designed to deliver simple shock pulses of adjustable shapes, it is assumed that the load imposed on the machine by the item under test has little effect on the shock motions. This is true only when the effective weight of the load is negligibly small compared with that of the shock machine mounting platform. If the effective weight of the load is independent of frequency, i.e., if it behaves as a rigid body, it is simple to compensate for the effect of the load by adjusting machine parameters. However, when the load is flexible and the reactions of excited vibrations are appreciable, the motions of the shock machine platform are complex. Specifications involving the use of these types of machines should require that the mounting platform have no significant natural frequencies below a specified frequency. The weight of this platform together with that of all rigidly attached elements, exclusive of the test load, also should be specified. Pulse shapes may then be specified for motions of this platform or for the platform together with given dead-weight loads. These may be specified as nominal values for test loads, but it is neither practical nor desirable to require that the pulse shape be maintained in simple form for complex loads of considerable mass.

COMPLEX SHOCK PULSE MACHINES

Because of the infinite variety of shock motions possible under field conditions, it is not practical or desirable to construct a shock machine to reproduce a particular shock that may be encountered in the field. However, it is sometimes desirable to simulate some average of a given type of shock motion. To accomplish this may require that the shock machine deliver a complex motion. A shock of this type cannot be specified easily in terms of the shock motions, since the motions are very complex and dependent on the nature and the mounting of the load. It is customary, therefore, to specify a test in terms of a shock machine, the conditions for its operation, and a method of mounting the item under test.

High-Impact Shock Machines. The Navy high-impact shock machines are designed to simulate shocks of the nature and intensity that might occur on a ship exposed to severe but sublethal, noncontact, underwater explosions. Such severe shocks produce motions that extend throughout the ship. Equipment intended for shipboard use can demonstrate its ability to withstand the shock simulations produced by these high-impact shock machines and thus be considered capable of withstanding the actual underwater explosion environment.

Lightweight Machines.[3–5] The lightweight high-impact shock machine, shown in Fig. 26.6, is used for testing equipment weighing up to about 350 lb (159 kg). Equipment under test is attached to the anvil plate A. Method of attachment is constrained to resemble closely the eventual field attachments. The anvil is struck on the backside by the pendulum hammer C, or the anvil is rotated 90° on a vertical axis and struck on the end by the pendulum hammer. The drop hammer B can be made to strike the top of the anvil, thus providing principal shock motions in the third orthogonal direction. Shock response spectra of shock motions generated by this machine are shown in Fig. 26.7 (these results were computed with a damping ratio of about 0.01). The spectrum for the motion at the center of the plate illustrates the amplification of the spectrum level at a natural frequency of the plate (about 100 Hz) and some attenuation at higher frequencies.

Medium-Weight Machines.[4,5] This machine is used to test equipment that, with its supporting structures, weighs up to 7400 lb (3357 kg). Shown in Fig. 26.8, this machine consists principally of a 3000-lb (1361-kg) hammer and a 4500-lb (2041-kg) anvil. Loads are not attached directly to the rigid anvil structure but rather to a group of steel channel beams which are supported at their ends by steel members, which in turn are attached to the anvil table. The number of channels employed is dependent on the weight of the load and is such as to cause the natural frequency of the load on these channels to be about 60 Hz. The hammer can be dropped from a maximum effective height of 5.5 ft (1.68 m). It rotates on its axle and strikes the anvil on the bottom, giving it an upward velocity. The anvil is permitted to travel a distance of up to 3 in. (7.6 cm) before being stopped by a retaining ring. The machine is mounted on a large block of concrete which is mounted on springs to isolate the surrounding area from shock motions. The general nature of the shock is complex, sim-

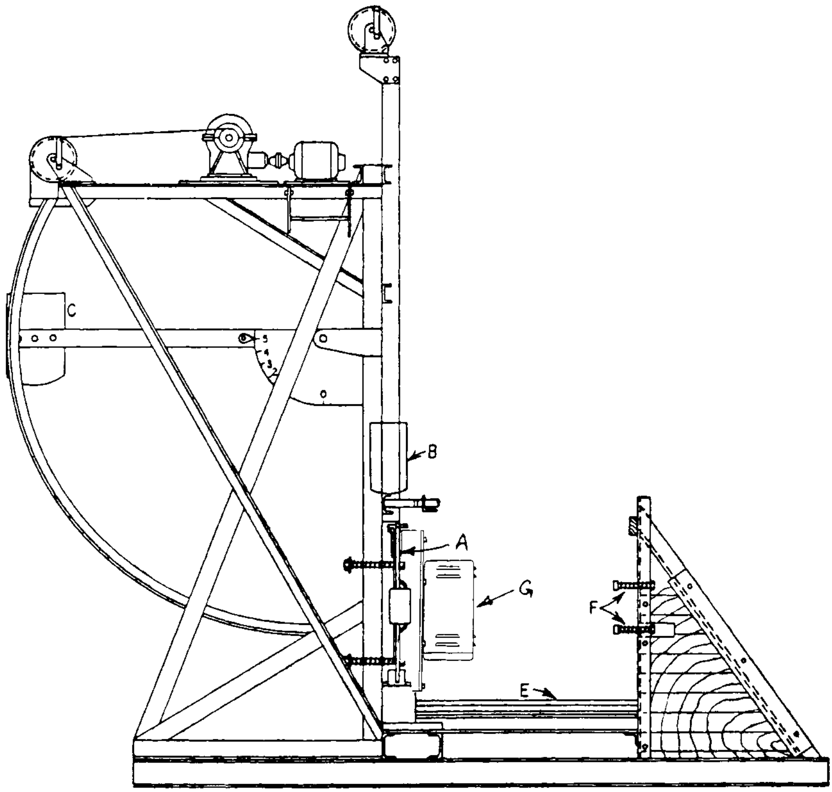

FIGURE 26.6 Navy high-impact shock machine for lightweight equipment.

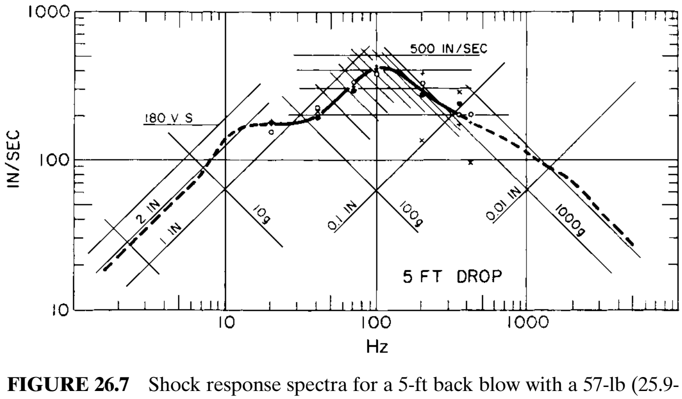

FIGURE 26.7 Shock response spectra for a 5-ft back blow with a 57-lb (25.9-kg) load on the mounting plate for four different lightweight high-impact shock machines.

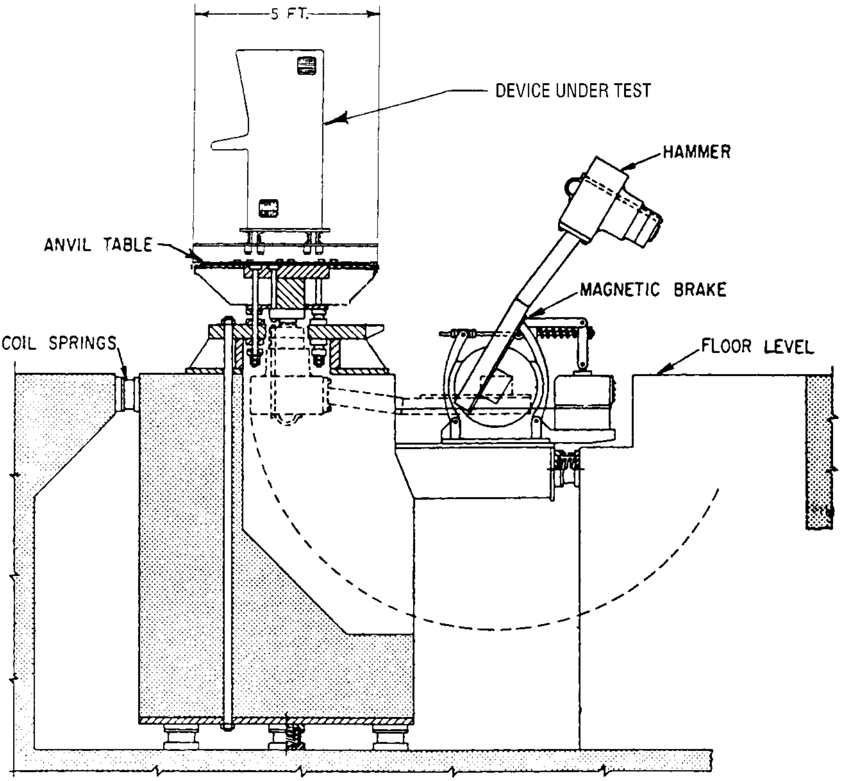

FIGURE 26.8 High-impact shock machine for medium-weight equipment.

ilar to that of the lightweight machine. Little of the high-amplitude, high-frequency components of the shock motions are transmitted to the load.

Heavy-Weight Machines.[4–6] The *floating shock platform* (FSP), and the *large floating shock platform* (LFSP) are high-load-capacity shock machines of the high-impact category. They are rectangular barges fitted with semicylindrical canopies within which test items are installed as they are aboard ship. The shock motions comprising the test series are generated by detonating explosive charges beneath the water surface at various distances.

The FSP is 28 ft (8.5 m) long by 16 ft (4.9 m) wide and has a maximum load capacity of 60,000 lb (27,216 kg). Its available internal volume is about 26 ft (7.9 m) by 14 ft (4.3 m) by 15 ft (4.6 m) high to the center of the canopy. The charges for the successive shots of the test sequence are all 60 lb (27 kg) at a depth of 24 ft (7.3 m). The charge standoff, the horizontal distance from the near side of the FSP, is shortened for each shot to a final value of 20 ft (6.1 m). Design shock response spectra for the FSP are shown in Fig. 26.9.

The LFSP is 50 ft (15.2 m) long by 30 ft (9.1 m) wide with a maximum load capacity of 400,000 lb (181,440 kg) and an internal volume of about 48 ft (14.6 m) by 28 ft (8.5 m) by 34 ft (10.4 m) high to the center of the canopy. The charge size is 300 lb (136.1 kg), and the charge depth is 20 ft (6.1 m); the standoff is decreased for each shot

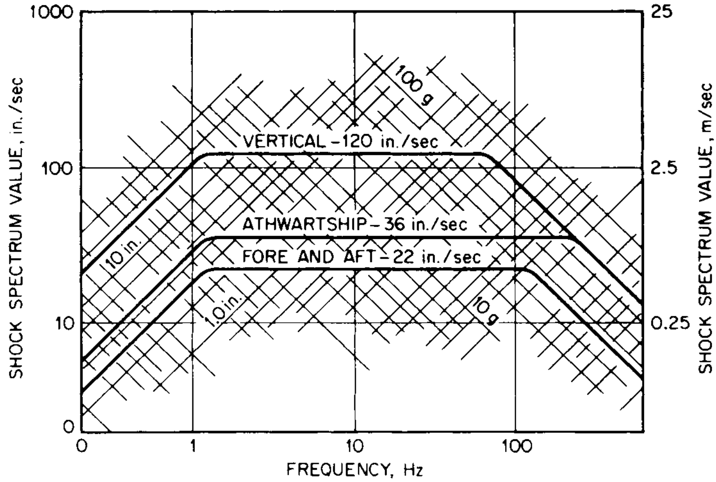

FIGURE 26.9 Design shock response spectra for the floating shock platform. The lower cutoff frequency is 1.15 Hz for all directions. The upper cutoff frequencies are vertical, 67 Hz; athwartship, 220 Hz; fore and aft, 125 Hz.

to a final value of 50 ft (15.2 m). At the crossover load of 30,000 to 40,000 lb (13,640 to 18,180 kg), the LFSP provides a shock environment equivalent to the FSP. Therefore, data in Fig. 26.9 can be used in design of equipment scheduled for LFSP shock testing.

Hopkinson Bar. When shock testing requires extremely high *g* levels for light loads (for example, calibration of accelerometers), the Hopkinson bar has proven useful. A controlled velocity projectile is impacted on the end of a metallic bar, causing a stress wave of known magnitude to travel along the bar. Often, the magnitude of the stress wave is measured as it passes the middle of the bar. The item under test is attached to the extreme end of the bar and experiences a high *g* rapid rise time acceleration when the stress wave arrives at that position. See Fig. 18.12.

MULTIPLE-IMPACT SHOCK MACHINES

Many environments, particularly those involving transportation, subject equipment to a relatively large number of shocks. These are of lesser severity than the shocks of major intensity that have been considered above, but their cumulative effect can be just as damaging. It has been observed that components of equipment that are damaged as a result of a large number of shocks of relatively low intensity are usually different from those that are damaged as a result of a few shocks of a relatively high intensity. The damage effects of a large number of shocks of low intensity cannot generally be produced by a small number of shocks of high intensity. Separate tests are therefore required so that the multiple number of low-intensity shocks are properly emulated.

Vibration Machines. Electrodynamic, hydraulic, and pneumatic vibration testing machines provide a ready and flexible source of multiple shock pulses so long as the pulse requirements do not exceed force and motion capabilities of the selected machine. They can be programmed to provide a series of different shock pulses or to repeat a particular shock motion as many times as desired and to establish the necessary initial conditions prior to each shock pulse. See Chap. 25 for more information.

ROTARY ACCELERATOR

A quick-starting centrifuge can is used to quickly attain and maintain an acceleration for a long period of time. The accelerator consists of a rotating arm which is suddenly set into motion by an air-operated piston assembly. The test object is mounted on a table attached to the outer end of the arm. The table swings on a pivot so that the resultant direction of the acceleration is always along a fixed axis of the table. Initially the resultant acceleration is caused largely by angular acceleration of the arm, so this axis is in a circumferential direction. As the centrifuge attains its full speed, the acceleration is caused primarily by centrifugal forces, so this table axis assumes a radial direction. These machines are built in several sizes. They require between 5 and 60 milliseconds to reach the maximum value of acceleration. For small test items (8 lb, 3.6 kg), a maximum acceleration of 450g is attainable; for heavy test items (100 lb, 45.4 kg), the maximum value is about 40g.

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CHAPTER 26, PART II

PYROSHOCK TESTING

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INTRODUCTION

Pyroshock, also called *pyrotechnic* shock, is the response of a structure to high-frequency (thousands of hertz), high-magnitude stress waves that propagate throughout the structure as a result of an explosive event such as the explosive charge to separate two stages of a multistage rocket. The term *pyrotechnic shock* originates from the use of propellants such as black powder, smokeless powder, nitrocellulose, and nitroglycerin in devices common to the aerospace and defense industries. These devices include pressure squibs, explosive nuts and bolts, latches, gas generators, and air bag inflators.[1] The term *pyroshock* is derived from pyrotechnic shock, but both terms are used interchangeably in the industry and its literature. A pyroshock differs from other types of mechanical shock in that there is very little rigid-body motion (acceleration, velocity, and displacement) of a structure in response to the pyroshock. The pyroshock acceleration time-history measured on the structure is oscillatory and approximates a combination of decayed sinusoidal accelerations with very short duration in comparison to mechanical shock described in Part I of this chapter. The characteristics of the pyroshock acceleration time-history vary with the distance from the pyroshock event. In the near field, which is very close to the explosive event, the pyroshock acceleration time-history is a high-frequency, high-amplitude shock that may have transients with durations of microseconds or less. In the far field, which is far enough from the event to allow structural response to develop, the acceleration time-history of the pyroshock approximates a combination of decayed sinusoids with one or more dominant frequencies. The dominant frequencies are usually much higher than that in a mechanical shock and reflect the local modal response of the structure. The dominant frequencies are generally lightly damped. However, since the frequencies are so high, it typically takes less than 20 milliseconds for the pyroshock response to dampen out and return to zero. Satellite, aerospace, and weapon components are often subjected to pyroshocks created by devices such as explosive bolts and pyrotechnic actuators. Pyroshock structural response is also found in ground-based applications in which there is a sudden release of energy, such as the impact of a structure by a projectile.

Pyroshock was once considered to be a relatively mild environment due to its low-velocity change and high-frequency content. Although it rarely damages structural members, pyroshock can easily cause failures in electronic components that are sensitive to the high-frequency pyroshock energy. The types of failures caused by pyroshock commonly include relay chatter, hard failures of small circuit components, and the dislodging of contaminants (e.g., solder balls), which cause short circuits. A significant number of flight failures have been attributed to pyroshock compared to other types of shock or vibration sources, and, in one case, an extensive database of the failures has been compiled.[2] Designers must rely on testing for qualifications of their systems and components that will be exposed to pyroshock environments in the absence of analytical techniques to predict structural response to a pyroshock. Failures can be reduced by implementing a qualification testing program for components exposed to a pyroshock environment. This chapter describes the characteristics of pyroshock environments, measurement techniques, test specifications, and simulation techniques.

PYROSHOCK CHARACTERISTICS

COMPARISON OF NEAR-FIELD AND FAR-FIELD CHARACTERISTICS

The detonation of an explosively actuated device produces high-frequency transients in the surrounding structure. The specific character of these acceleration transients depends on various parameters including: (1) the type of pyrotechnic source, (2) the geometry and properties of the structure, and (3) the distance from the source. Due to the endless combinations of these parameters, sweeping conclusions about pyroshock characteristics cannot be made; however the following paragraphs describe useful characteristics of typical pyroshock environments.

A pyrotechnically actuated device produces a nearly instantaneous pressure on surfaces in the immediate vicinity of the device. As the resulting stress waves propagate through the structure, the high-frequency energy is gradually attenuated due to various material damping and structural damping mechanisms. In addition, the high-frequency energy is transferred or coupled into the lower-frequency modes of the structure. The typical pyroshock acceleration transient thus has roughly the appearance of a multifrequency decayed sinusoid (i.e., the envelope of the transient decays and is symmetric with respect to the positive and negative peaks). The integral of the typical transient also has these same characteristics.[3] In most cases, the initial portion of the acceleration transient exhibits a brief period during which the amplitudes of the peaks are increasing prior to the decay described above (see Figs. 26.10 and 26.11). This is a result of the interaction of stress waves as they return from various locations in the structure.

A pyrotechnically actuated device imparts very little impulse to a structure since the high forces produced are acting for only a short duration and are usually internal to the structure. The net rigid body velocity change resulting from a pyroshock is thus very low relative to the peak instantaneous velocity seen on the integral of the acceleration transient. Rigid body velocity changes are commonly less than 1 meter per second. The duration of a pyroshock transient depends on the amount of damping in a particular structure, but it is commonly 5 to 20 milliseconds in duration.

Pyroshock may be subdivided into two general categories: *Near-field pyroshock* occurs close to the pyrotechnic source before significant energy is transferred to structural response. It is dominated by the input from the source and contains very high-frequency and very high g energy. This energy is distributed over a wide frequency range and is not generally dominated by a few selected frequencies. *Far-field pyroshock* environments are found at a greater distance from the source where significant energy has transferred into the lower-frequency structural response. It contains lower frequency and lower g energy than near-field pyroshock; most of the

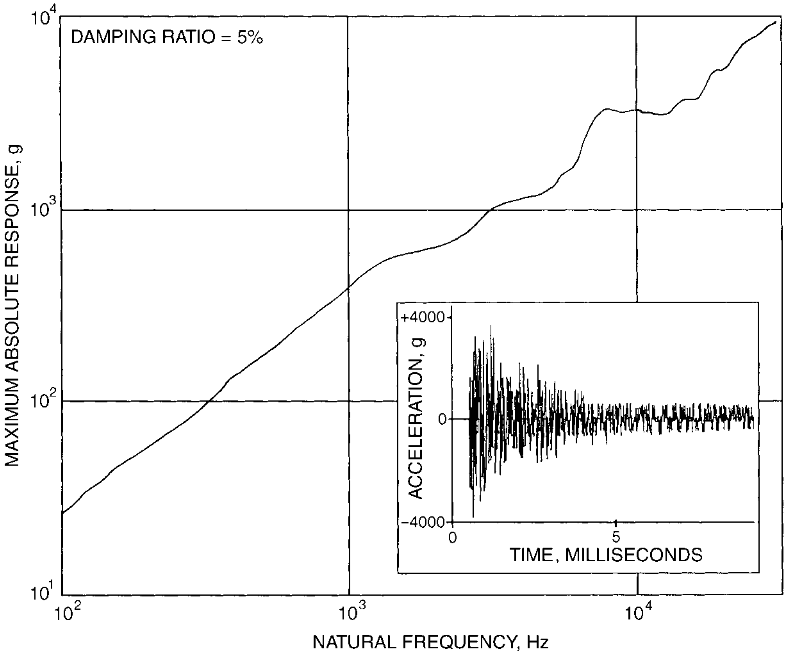

FIGURE 26.10 Shock response spectrum and acceleration time-history for a near-field pyroshock. The shock response spectrum is calculated from the inset acceleration time-history using a 5 percent damping ratio.

energy is usually concentrated at one or a few frequencies which correspond to dominant structural mode(s).

A more detailed discussion of shock response spectrum (see Chap. 23 for definition) applications is given later in this chapter, but it is introduced here as a means of describing pyroshock characteristics. Many far-field pyroshock environments have a *typical* shock response spectrum shape as illustrated in Fig. 26.11, which shows an actual far-field pyroshock acceleration transient along with its associated shock response spectrum. The shock response spectrum initially increases with frequency at a slope of 9 to 12 dB/octave, followed by an approximately constant or slightly decreasing amplitude. The frequency at which the slope changes is called the *knee frequency,* and it corresponds to a dominant frequency in the pyroshock environment. The knee frequency is often between 1000 and 5000 Hz for far-field pyroshock, but it could be higher or lower in some cases. Near-field pyroshock may also exhibit this typical pyroshock shock response spectrum except with a higher knee frequency. However, since near-field pyroshock usually has broad-band frequency content, its shock response spectrum often exhibits a more complex shape that contains numerous excursions but on average follows a 6-dB/octave slope over the entire frequency range of interest. Figure 26.10 shows an example of this type of near-field shock response spectrum.

No fixed rules define at what distance from the pyrotechnic source the near-field pyroshock ends and the far-field pyroshock begins. It is more appropriate to classify near- and far-field pyroshock according to the various test techniques that are appropriate to employ in each case.

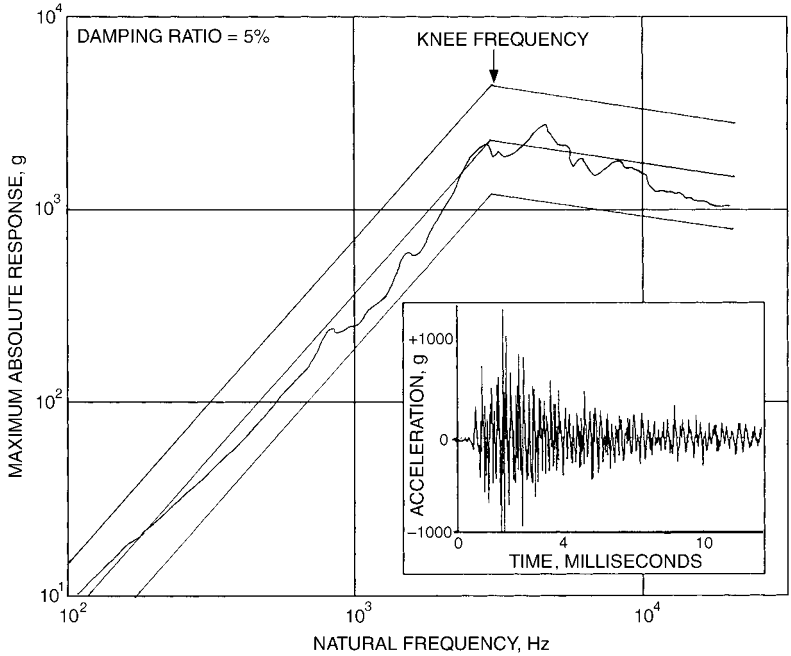

FIGURE 26.11 A typical shock response spectrum and acceleration time-history for a far-field pyroshock. The shock response spectrum is calculated from the inset acceleration time-history using a 5 percent damping ratio. The straight lines indicate tolerance bands (typically ±6 dB as shown) which might be applied for qualification test specification.

TEST TECHNIQUES FOR NEAR- AND FAR-FIELD PYROSHOCK

The pyroshock simulation techniques described in this chapter fall into two categories: (1) pyrotechnically excited simulations and (2) mechanically excited simulations. A short-duration mechanical impact on a structure causes a response similar to that produced by a pyrotechnic source. Although these mechanically excited simulations can be carried out with lower cost and better control than pyrotechnically excited simulations, they cannot produce the very high frequencies found in near-field pyroshock. Mechanically excited simulations allow control of dominant frequencies up to about 10,000 Hz (or higher for very small test items). For environments requiring higher frequency content, a pyrotechnically excited technique is usually more appropriate. The following general guidelines apply in selecting a technique for simulating pyroshock:

Near-field pyroshock. For a test that requires frequency control up to and above 10,000 Hz, a pyrotechnically excited simulation technique is usually required.

Far-field pyroshock. For a test that requires frequency control no higher than 10,000 Hz, a mechanically excited simulation technique is usually acceptable.

These guidelines are not rigid rules, but they provide a reasonable starting point when planning a pyroshock simulation test.

QUANTIFYING PYROSHOCK FOR TEST SPECIFICATION

An intrinsic characteristic of pyroshock is its variability from one test to another. That is, even though great care has been taken with the test technique, the measured response in both the near and the far fields may vary a great deal from test to test. This variability occurs in the situation where actual explosive devices are used and in the laboratory where more controlled techniques are employed. As a result, various techniques have been sought to quantify pyroshock for test specification. The purpose of these techniques is to define the pyroshock in a manner that can be reproduced in the laboratory and can provide a consistent evaluation for hardware that must survive pyroshock in field environments. All techniques require that a measurement be made of the actual pyroshock event at or near the location of the subsystem or component that will be tested. The measurement may be acceleration, velocity, or displacement, but acceleration is the most widely used measure. The measurement is then used with one of the techniques below to obtain a test specification for pyroshock. The *shock response spectrum* is considered to be conservative and a potential over-test of components and subsystems. However, components and subsystems that survive laboratory tests specified using shock response spectra generally survive pyroshock field environments, although they may be over-designed. Because aerospace systems require lightweight components and subsystems, other techniques such as temporal moments and shock intensity spectrum have been developed so that laboratory tests can more closely simulate actual pyroshock events and allow tighter design margins.

Shock Response Spectra. By far the most widely used technique for quantifying pyroshock is the shock response spectrum. This technique provides a measure of the effect of the pyroshock on a simple mechanical model with a single degree-of-freedom. Generally, a measured acceleration time-history is applied to the model, and the maximum acceleration response is calculated. The damping of the model is held constant (at a value such as 5 percent) for these calculations. An ensemble of maximum absolute-value acceleration responses is calculated for various natural frequencies of the model and the result is a *maxi-max shock response spectra.* A curve representing these responses as a function of damped natural frequency is called a shock response spectrum (see Chap. 23), and is normally plotted with log-log scales. Velocity and displacement shock response spectra may be computed (see Chap. 26, Part I), but are not commonly used for pyroshock specification. The shock response spectrum for pyroshock has a characteristically steep slope at low frequencies of 12 dB/octave that is a direct result of the minimal velocity change occurring in a pyroshock. Occasionally, a pyrotechnic device, such as an explosive bolt cutter, is combined with another mechanism, such as a deployment arm, to position components for a particular event sequence. In this case, a distinct velocity change is combined with the pyroshock event, and the low-frequency slope of the shock response spectrum will reflect this velocity change. For a typical far-field pyroshock, the low-frequency slope changes at the *knee frequency,* and the shock response spectrum approaches a constant value at high frequencies that is the peak acceleration in the time-domain as shown in Fig. 26.11. A typical near-field pyroshock may have this shape or may have the shape shown in Fig. 26.10. Conventionally, tolerance bands of ±6 dB are drawn about a straight-line approximation of the shock response spectrum for laboratory testing. An example of a typical maxi-max shock response spectrum is shown in Fig. 26.11 with the conventional ±6 dB tolerance bands.

Band-Limited Temporal Moments. The method of temporal moments may be used for modeling shocks whose time durations are too short for nonstationary models and that contain a large random contribution.[4] The method uses the magnitude of the Fourier spectrum in the form of an energy spectrum (Fourier spectrum magnitude squared) that is smoothed or formed from an ensemble average to generate statistically significant values. Temporal moments of the time-histories are used to represent how the energy is distributed in time. The moments are analogous to the moments of the probability density functions and provide a convenient method to describe the envelopes of complicated time-histories such as pyroshock. The ith temporal moment $m_i(a)$ of a time-history $f(t)$, about a time location a, is defined as

$$m_i(a) = \int_{-\infty}^{+\infty} (t-a)^i [f(t)]^2 \, dt \tag{26.2}$$

The time-history energy E is given by

$$E = \frac{1}{2\pi} \int_{-\infty}^{+\infty} |F(\omega)|^2 \, d\omega \tag{26.3}$$

where $F(\omega)$ is the Fourier transform of $f(t)$. The first five moments are used in the temporal moments technique. The zeroth-order moment m_0 is the integral of the magnitude squared of the time-history and is called the time-history energy. The first moment normalized by the energy is called the central time τ. A central moment is a moment computed about the central time, i.e., $a = \tau$. The second central moment is normalized by the energy and is defined as the mean-square duration of the time-history. The third central moment normalized by the energy is defined as the skewness and describes the shape of the time-history. The fourth central moment normalized by the energy is called kurtosis. The moments are calculated for a shock time-history passed through a contiguous set of bandpass filters. A *product model* is formed using a deterministic window $w(t)$ (see Chap. 25) and a realization of a dimensionless stationary random process with unity variance $x(t)$ as $w(t)\cdot x(t+\tau)$. A product model is then used to generate a simulation that has the same energy and moments in the mean as the original shock. Band-limited moments characterize the shock and not the response to the shock as the shock spectrum and do not rely on a structural model.

Other Techniques. Other techniques to quantify pyroshock include the shock intensity spectrum based on the Fourier energy spectrum,[5] the *method of least favorable response,*[6,7] and nonstationary models.[8,9] These techniques are not commonly used but may provide additional insight for quantifying pyroshocks. The Fourier spectrum is an attractive alternative to shock response spectrum because it is easy to compute and readily available in many software packages as a fast Fourier transform (FFT). Since the Fourier spectrum is complex, both magnitude and phase information is available. The magnitude generally has intuitive meaning, but the phase is difficult to interpret and may be contaminated with noise at the high frequencies present in pyroshock. The method of least favorable response provides a method of selecting the phase to maximize the response of the system under test. This method results in a conservative test provided that an appropriate measurement point is chosen on the structure. Stationary models for random vibration have been used for many years. Nonstationary models consist of a stationary process multiplied by a deterministic time-varying modulating function, which is a product model.[9] A nonstationary model is appropriate for pyroshock and approaches a stationary model as the time-record length is increased.

MEASUREMENT TECHNIQUES

Measurements of pyroshocks are generally made with accelerometers, strain gages, or laser Doppler vibrometers (LDV). The accelerometers are used to measure acceleration, and the strain gages and LDV are used to measure velocity. The strain gages may also be used to sense force, stress, or strain. General shock measurement instrumentation is applicable for pyroshock measurements (see Chap. 12); however, care must be taken to protect accelerometers from the high frequencies contained in pyroshocks that may cause the accelerometers to resonate and, in some cases, to fail. If accelerometers are excited into resonance, large-magnitude output results and may exceed the maximum amplitude of the data acquisition system that was chosen for the test. The result is that the data magnitude is clipped. If clipped, the data are rendered useless and the results from the test will be greatly diminished. Several mechanically isolated accelerometers are available commercially and should be used if there is a possibility of exciting the accelerometers into resonance. There is only one mechanically isolated accelerometer that can provide the wide-frequency bandwidth (dc to 10 kHz) required for pyroshock.[10,11] Other mechanical isolators generally provide a frequency bandwidth of about dc to 1 kHz. Any mechanical isolator that is used in a pyroshock environment must be well characterized over a range of frequencies and a range of acceleration values using a shock test technique, for example, Hopkinson bar testing. Strain gages are useful measurements of the pyroshock environment but are not easily translated into a test specification. Strain gages have the advantage of high-frequency response (in excess of dc to 40 kHz) provided that their size is appropriately chosen. Additionally, strain gages do not have the resonance problems that accelerometers have. The LDV provides velocity measurements that are not contaminated by cross-axis response because the LDV only responds to motion in the direction of the laser beam. The LDV is a noncontacting measurement and is easy to set up; consistent measurements of pyroshock events have been obtained with a LDV.[12,13] The LDV has the disadvantage of being very expensive per channel in comparison to the other measurement techniques, difficult to calibrate, and must have line of sight to the measurement location.

Pyroshock Test Specifications. An acceleration or velocity time-history is not adequate for specifying a pyroshock test. The time-history data must be analyzed using one of the techniques discussed above to quantify the pyroshock for a test specification. Ideally, the time-history data that are used to develop the qualification test specification should be measured during a full-scale system test in which the actual pyrotechnic device or devices were initiated. The full-scale test should be accomplished with hardware that is structurally similar to the real hardware if the real hardware is not available. A control point measurement is specified close to each component or subassembly of interest, preferably at the attachment point to measure the input pyroshock. Since full-scale testing is expensive, data from a similar application may be used to develop component or subassembly qualification test specifications. This practice may result in over-tested or over-designed components or subassemblies if a large margin is added to the test specification to account for the uncertainty in the data. If this practice is used, the test specification should be revised when better system data become available.

Once the time-history data have been acquired, the data should be scrutinized to ensure their quality.[3] The data should be free of zero-shifts and offsets. Acceleration and velocity time-histories should be integrated and the results examined. The time-history data should be low-pass filtered at a designated cutoff frequency; a cutoff frequency of 20 kHz is typical. The data must then be analyzed using the same technique as was used for analysis of the time-history data from which the test specification was derived. Test margin and tolerance bands are applied to the data analysis. For instance, if the shock response spectrum is being used, a straight-line approximation of the shock response spectrum is used as the baseline for the test specification process. A margin of +3 dB is typically added to the baseline shock response spectrum, and a customary ±6-dB tolerance is used with the baseline shock response spectrum. A typical test specification may allow the shock response spectrum from the actual test to fall outside the tolerance band at a specified number of frequency points. Pyroshock tests are highly variable, and the engineer must specify how much variability from test to test will be accepted; in some cases, a tighter, ±3-dB tolerance may be required. Additionally, the specification should require that the peak acceleration (or velocity) value and pulse durations are in agreement with the intended values for the specified input pulse. Similar approaches are used for other techniques for quantifying pyroshock.

In some cases, two or more pyroshock events, such as stage separation and an explosive actuator, may be combined into a single test specification. If the events are significantly different, the resulting test specification may be difficult or impossible to meet. A better practice is to make separate test specifications for each pyroshock event and to combine the specifications only in the case where a realizable test results.

PYROSHOCK SIMULATION TECHNIQUES

PYROTECHNICALLY EXCITED NEAR-FIELD SIMULATION

Ordnance Devices. Linear, flexible detonating charges may be used to generate pyroshocks for test purposes. An example of a test configuration using a flexible linear charge is shown in Fig. 26.12. A steel plate is suspended by bungee cords, and the test item is mounted on the plate in the same manner as it is in actual usage. Flexible linear charge is attached to the edges of the plate. The charge configuration may be varied according to experience and the desired effect.[14] For example, the charge may be attached to the backside of the plate directly opposite to the test item. A mass-mockup of the actual test item is used for the trial and error required to finalize the test configuration. In some cases, the charges may be attached to a portion of the structure where the test items are installed. Their storage, handling, and detonating constitute a hazard to laboratory personnel and facilities. However, such a fixture would normally be rather expensive because the structure would be damaged or destroyed during each shock test. The shock produced in this manner may vary greatly from test to test because actual explosives are used. However, this test configuration has the advantage of reproducing the pyroshock with realistic high accelerations and high frequencies. To ensure repeatability, the grooves generated by the charge into the surfaces of the shock plates should be machined down to eliminate the porosity which tends to absorb and modify the explosive impacts. Other disadvantages are that a qualified explosives facility (with its associated safety procedures) is required. In comparison to mechanical simulation techniques, considerable time is needed to conduct the numerous trial tests required to experimentally determine the various test parameters.

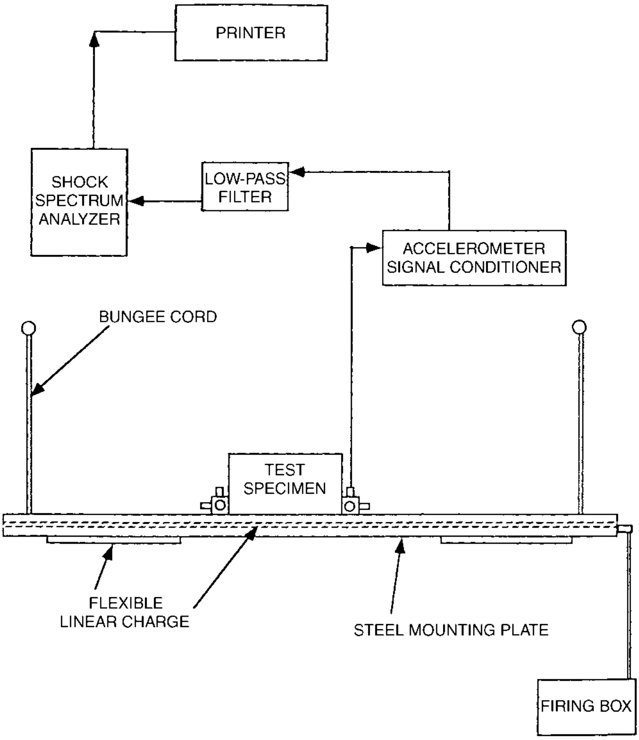

FIGURE 26.12 Ordnance-generated pyroshock simulator. (*Courtesy of National Technical Systems.*)

Scaled Tests. If the quantity of propellant or explosive is sufficiently large and the influence of the pyrotechnic device is localized, a scaled portion of the structure may be used in simulating the effects of the pyroshock as shown in Fig. 26.13 where a missile section or rocket payload section is shown. This type of test assumes that the influence of the pyrotechnic event is insignificant to other parts of the structure and isolated to the section under test. Actual pyrotechnic device firings on spacecraft equipment and scientific instruments are conducted in the scaled test. Such a test is usually an intermediate step in the design of the structure. Components in the subassembly may have been qualified with a ordnance device, and the scaled test adds another dimension of complexity to the qualification of the subassembly and its individual components.

Full-Scale Tests. In some cases, if the structure is sufficiently complex, a full-scale test may be warranted. Full-scale tests, which include multiple firings of certain critical pyrotechnic devices, are conducted to verify the structural integrity and design functions as well as to qualify items of hardware that have not been previously qualified. Full-scale tests are conducted by actuation of the flight pyrotechnic devices, which provide full-scale shock qualification. A full-scale test is usually the last test in a sequence of increasingly complex tests; the sequence is from ordnance to scaled tests to full-scale tests. The advantage of a full-scale test is that it is the real

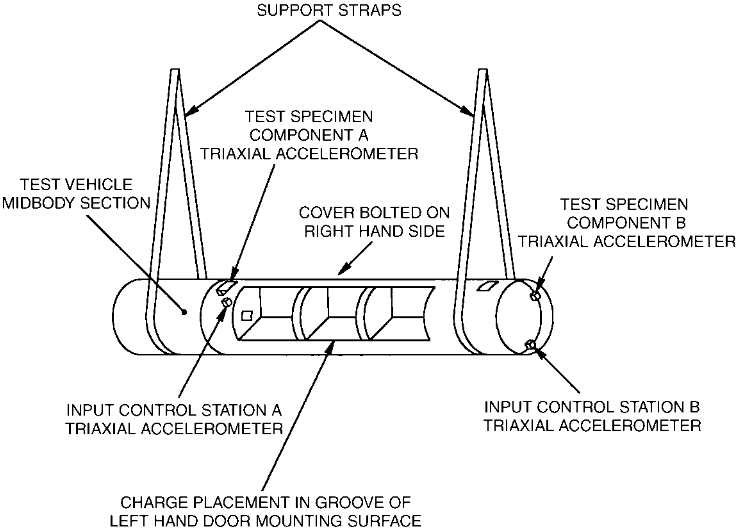

FIGURE 26.13 Scaled tests using representative structure. The test vehicle midbody section is a portion of the full-scale structure where the explosive event is located. Two input control stations *A* and *B* are used to determine that the test was properly conducted. Response measurements are made at test specimens *A* and *B*. (*Courtesy of Wyle Laboratories.*)

pyroshock event in its most complex form. The main objectives of the full-scale pyroshock test firings are: (1) to define shock response in the vicinity of potentially sensitive equipment so that component test specifications may be derived or verified and (2) to conduct full-scale qualification and thus verify the design values for shock. The disadvantage of a full-scale test is that considerable time and expense are required to obtain all the required hardware. The hardware must then be assembled, instrumented, and removed for post-test evaluation. Generally, special facilities are required for the use of explosives.

MECHANICALLY EXCITED FAR-FIELD SIMULATION

Standard Shock-Testing Machines. Shock machines such as the drop tables described in Part I of this chapter usually are not suitable for pyroshock simulation. The single-sided pulses produced by these machines bear little or no resemblance to a pyroshock acceleration transient; such pulses produce significantly greater velocity change than a pyroshock environment. A severe over-test at low frequencies can be expected if a drop table is used to simulate pyroshock environments. This can result in failures of structural members that would not have been significantly stressed by the actual pyroshock. However, in certain cases, drop tables may produce acceptable pyroshock qualification testing. For example, if a test item has significant design margin at low frequencies, then a drop table may be acceptable. Also, if the lowest natural frequency of the test item is higher than the over-tested low-frequency range, then the low-frequency over-test may be irrelevant since the affect on the test item is dominated by the peak g's of the accelera-

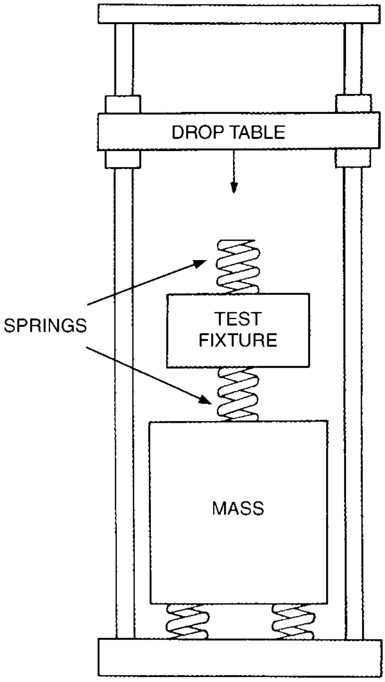

FIGURE 26.14 Bounded impact test configuration on a "standard" drop-table.

tion time-history. In these cases there is strong motivation to use drop tables due to their common availability and low test cost. If a drop table is selected as a means of conducting a pyroshock qualification test, the test item must be subjected to a shock in both positive and negative directions for each axis tested, since the drop table produces only a single-sided pulse.

Another application of a drop table for pyroshock testing is the *bounded impact method*[15] as illustrated in Fig. 26.14, which shows the test item fixture bounded by two springs (typically felt or elastomeric pads). When the drop table strikes the upper spring, the fixture oscillates at the natural frequency of the spring-mass system. This oscillation ceases when the drop table rebounds from the spring, resulting in an acceleration transient that appears as a decayed sinusoid with about two or three cycles. The velocity change is much less than for a haversine pulse, which results in a shock spectrum with the desired slope of 9 to 12 dB/octave. *Knee frequencies* up to about 2000 Hz are attainable with this method.

Electrodynamic Shakers. Pyroshock environments can be simulated with an acceleration transient produced on an electrodynamic shaker (see Chap. 25). In this method the acceleration transient is synthesized so that its shock response spectrum closely matches the test requirement. With this method a relatively complex shock response spectrum shape can be matched within close tolerances up to about 3000 Hz. The equipment limits (maximum acceleration) restrict this method to the simulation of lower-energy pyroshock environments. Even if the desired shock response spectrum is precisely met, an over-test is likely due to the high mechanical impedance of the shaker relative to the structure to which the test item is attached in a real application.

Resonant Fixtures. This section describes a variety of resonant fixture techniques used to simulate pyroshock environments. All of these methods utilize a fixture (or structure) which is excited into resonance by a mechanical impact from a projectile, a hammer, or some other device. A test item attached to the fixture is thus subjected to the resonant response, which simulates the desired pyroshock. There is no single preferred method since each has its own relative merits. Some of the methods require extensive trial-and-error iterations in order to obtain the desired test requirement. However, once the procedures are determined, the results are very repeatable. Other methods eliminate the need for significant trial and error but are usually limited to pyroshock environments which exhibit the typical far-field character as explained in Fig. 26.13.

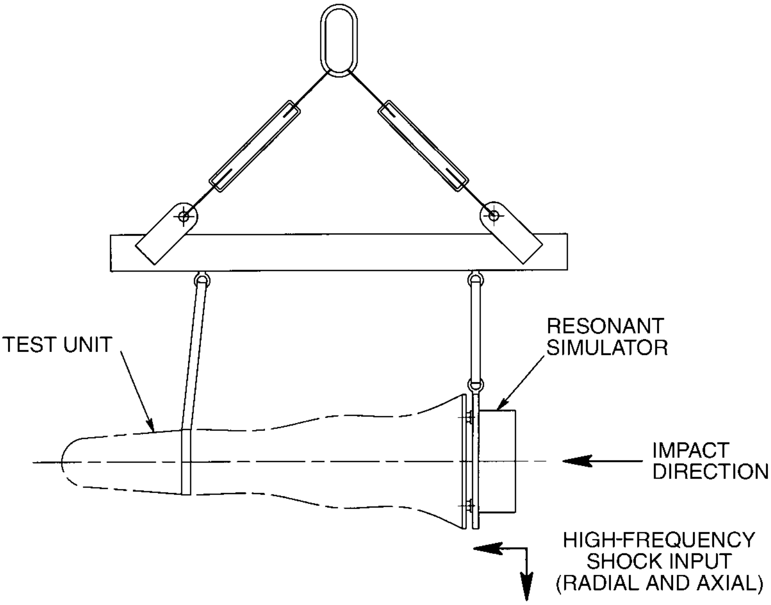

FIGURE 26.15 Full-scale pyroshock simulation with resonant fixture. Measurements at component locations confirm simulation success.

Full-Scale Tests. Some mechanically excited simulation techniques involve the use of an actual or closely simulated structure[16,17] (e.g., an entire missile payload section). The pyrotechnic devices (e.g., explosive bolt cutters) normally located on this structure would then be replaced with hardware that allow a controlled impact at this same location. Since a closely simulated structure is used, it is anticipated that the impact will cause the modes of vibration of the structure to be excited in a manner similar to the actual pyrotechnic source. In principle, test amplitudes can be adjusted by changing the impact speed or mass. This method is relatively expensive due to the cost of the test structure and because significant trial and error is required to obtain the desired test specification. Since this method applies to a specific application, it is not suited as a general-purpose pyroshock simulation technique.

In a variation of the above method[18] the pyrotechnic source and a portion of the adjacent structure are replaced by a "resonant plate" designed so that its lowest-resonance frequency corresponds to the dominant frequency produced by the pyrotechnic device and its associated structure. The resonant plate is then attached to the test structure in a manner which simulates the mechanical linkage of the pyrotechnic source, as shown in Fig. 26.15. When this plate is subjected to a mechanical impact, its response will provide the desired excitation of the test structure. A resonant fixture has successfully simulated component shock response spectra for frequencies up to 4000 Hz on a full-scale structure weighing 400 lb.[19]

General-Purpose Resonant Fixtures. Instead of developing application-specific pyroshock methods as described above, it may be desirable to implement a more general-purpose test method which can be used for a variety of test items and/or test specifications. This can be accomplished by using a simple resonant fixture (usually a plate) instead of the complex structures described above. When such a fixture is excited into resonance by a mechanical impact, its response can provide an adequate pyroshock simulation to an attached test item. Excitation of the fixture can be achieved as the result of the impact of a projectile, pendulum hammer, pneumatic piston, or the like on the fixture. The response of the fixture is dependent on a large number of parameters including: (1) plate geometry and material, (2) impact mass or speed, (3) impact duration, which is controlled with various impact materials (e.g., metals, felt, elastomers, wood, etc.), (4) impact location, (5) test item location, and (6) various clamps and plate suspension mechanisms. In theory these parameters could be varied with the aid of an analytical model, but they are usually evaluated experimentally. A significant effort is therefore required to obtain each pyroshock simulation.

Mechanical Impulse Pyroshock (MIPS) Simulator. The MIPS simulator[20,21] is a well-developed embodiment of the trial-and-error resonant fixture methods. It is universally referred to by its acronym and is widely used in the aerospace industry. Its design facilitates the easy variation of many of the parameters described above. The MIPS simulator configuration shown in Fig. 26.16 consists of an aluminum mounting plate which rests on a thick foam pad. The shock is generated by a pneumatic actuator which is rigidly attached to a movable bridge, facilitating various impact locations. The impactor head is interchangeable so that different materials (lead, aluminum, steel, etc.) may be used to achieve variation of input duration. Although a triaxial acceleration measurement is usually made at the control point near the test item, it is unlikely that the test requirement will be met simultaneously in all axes. Separate test configurations must normally be developed for each test axis. Once the test configuration and procedures are determined, the results are very repeatable. The configuration for a new test specification can be obtained more quickly if records of previous setups and results are maintained for use as a starting point for the new

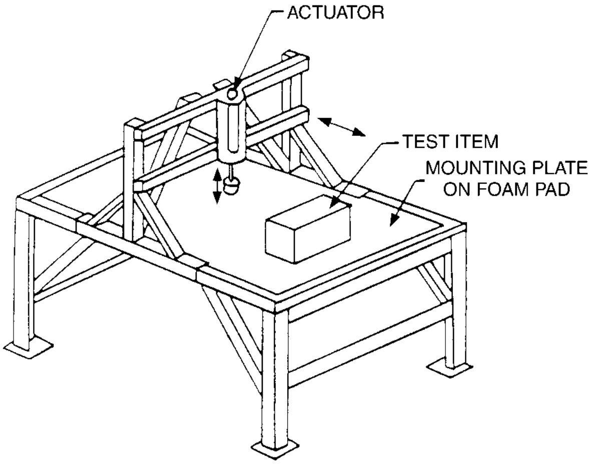

FIGURE 26.16 MIPS simulator. The mounting plate is excited into resonance by an impact from the actuator. The plate response simulates far-field pyroshock for the attached test item. (*Courtesy of Martin Marrietta Astrospace.*)

specification. Reference 19 provides some general guidelines for parameter variation, as well as results obtained from several different test configurations.

Tuned Resonant Fixtures with Fixed Knee Frequency. It is possible to greatly reduce the amount of trial and error required by the MIPS simulator and other resonant fixture test methods. In order to do this, a simple resonant fixture is designed so that its dominant response frequency corresponds to the dominant frequency in the shock response spectrum test requirement. These tuned resonant fixtures are primarily limited to pyroshock environments which exhibit more or less typical characteristics with knee frequencies up to 3000 Hz (or higher for small test items). The basic design principle is to match the dominant fixture response frequency (usually the first mode) to the shock response spectrum knee frequency. When this fixture is excited into resonance, it will "automatically" have the desired shock response spectrum knee frequency and the typical 9-dB/octave initial slope. This concept was originally developed using a plate excited into its first bending mode and a bar excited into its first longitudinal mode.[22] The methods described in the following sections require relatively thick and massive resonant fixtures compared to the structures to which the test item might be attached in actual use. Because of this, the motion imparted to the test item attached to a resonant fixture is approximately in-phase from point-to-point across the mounting surface. Whereas, the actual pyroshock motion may not be in-phase if the test item is mounted to a thin structure in actual use. The in-phase motion of resonant fixtures yields some degree of conservatism when selecting these methods for qualification testing. One significant advantage of using a thick resonant fixture is that its response is not greatly influenced by the attached test item. This allows the same test apparatus to be used for a variety of different test items.

Each of the tuned resonant fixture test methods described below produces a simulated pyroshock environment with the same basic characteristics. These similarities are illustrated in Fig. 26.17, which shows a typical acceleration record and shock response spectrum from the tunable resonant beam apparatus described later. The other methods produce pyroshock environments with initial shock response spectra slopes that are slightly less than 9 dB/octave due to a small velocity change inherent with these other methods. The shock response spectrum shown in Fig. 26.17 exhibits the desired typical shape, and the energy is concentrated at the knee frequency. The absence of significant frequency content above the knee frequency may cause the shock response spectrum to be too low at these frequencies. In practice the attached test item adds some frequency content above the knee frequency, which tends to increase the shock response spectrum. These test methods allow good control and repeatability of the shock response spectrum, especially below the knee frequency.

When using tuned resonant fixtures, the test item is usually attached to an intermediate fixture such as a rectangular aluminum plate. This adapter fixture must be small enough and stiff enough so that the input from the resonant fixture is not significantly altered. Since the resonant fixture is designed to produce the pyroshock simulation in only one direction, the adapter fixture should be designed so that it may be rigidly attached to the resonant fixture in three orthogonal orientations (e.g., flat down and on each of two edges). The acceleration input should be measured next to the test item on the adapter fixture. It is good practice to measure the acceleration in all three axes because it is possible (although infrequently) to simultaneously attain the desired test specification in more than one axis.

A number of different techniques are used to provide the mechanical impact

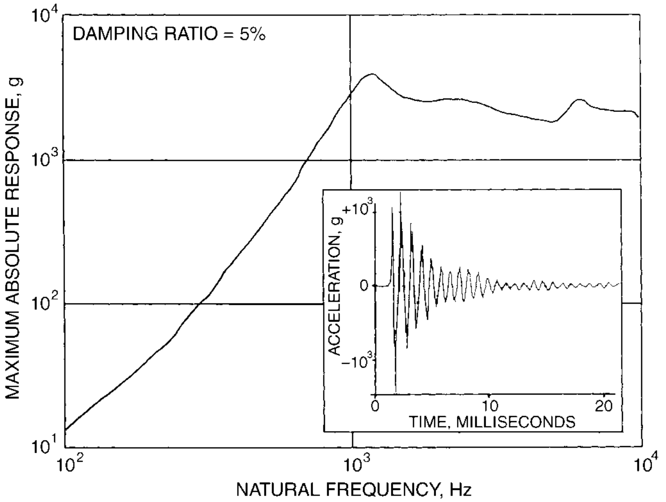

FIGURE 26.17 Typical shock response spectrum and acceleration time-history from a tuned or tunable resonant fixture test. The shock response spectrum is calculated from the inset acceleration time-history using a 5 percent damping ratio.

required by the tuned resonant fixture methods described below. Pendulum hammers of the general type shown in Fig. 26.8 have been used, as well as pneumatically driven pistons or air guns. The method which is selected must provide repeatability and control of the impact force, both in magnitude and duration. The magnitude of the impact force controls the overall test amplitude, and the impact duration must be appropriate to excite the desired mode of the tuned resonant fixture. In general the impact duration should be about one-half the period of the desired mode. The magnitude of the impact force is usually controlled by the impact speed, and the duration is controlled by placing various materials (e.g., felt, cardboard, rubber, etc.) on the impact surfaces.

Resonant Plate (Bending Response). The resonant plate test method[23, 24] is illustrated in Fig. 26.18, which shows a plate (usually a square or rectangular aluminum plate) freely suspended by some means such as bungee cords or ropes. A test item is attached near the center of one face of the plate, which is excited into resonance by a mechanical impact directed perpendicular to the center of the opposite face. The resonant plate is designed so that its first bending mode corresponds to the knee frequency of the test requirement. The first bending mode is approximately the same as for a uniform beam with the same cross-section and length. Appendix 1.1 provides a convenient design tool for selecting the size of the resonant plate. The plate must be large enough so that the test item does not extend beyond the middle third of the plate. This assures that no part of the test item is attached at a nodal line of the first bending mode. Usually, the resonant fixture with an attached test item is insufficiently damped to yield the short-duration transient (5 to 20 milliseconds) required for pyroshock simulation. Damping may be increased by adding various attachments to the edge of the plate, such as C-clamps or metal bars. These attachments may also lower the resonance frequency and must be accounted for when designing a resonant plate.

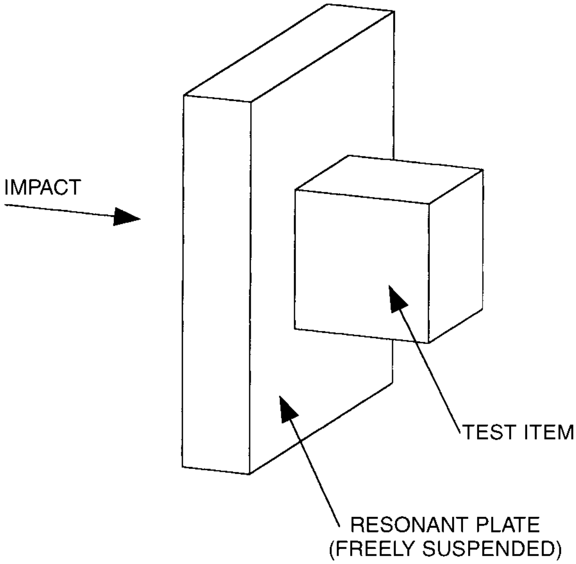

FIGURE 26.18 Resonant plate test method. The first bending mode is excited by an impact as shown. The plate's response simulates far-field pyroshock for the attached test item. The plate is sized so that its first bending mode frequency corresponds to the desired knee frequency of the test.

Resonant Bar (Longitudinal Response). The resonant bar concept[23,24] is illustrated in Fig. 26.19, which shows a freely suspended bar (typically aluminum or steel) with rectangular cross section. A test item is attached at one end of the bar, which is excited into resonance by a mechanical impact at the opposite end. The basic principle of the resonant bar test is exactly the same as for a resonant plate test except that the first longitudinal mode of vibration of the bar is utilized. The bar length required for a particular test can be calculated by

$$l = \frac{c}{2f} \tag{26.4}$$

where l = length of the bar
c = wave speed in bar
f = first longitudinal mode of the bar (equal to desired knee frequency)

The other dimensions of the bar can be sized to accommodate the test item, but they must be significantly less than the bar length. As with the resonant plate method, the response of the bar can be damped with clamps if needed. These are most effective if attached at the impact end.

Tunable Resonant Fixtures with Adjustable Knee Frequency. The tuned resonant fixture methods described above can produce typical pyroshock simulations with knee frequencies that are fixed for each resonant fixture. A separate fixture

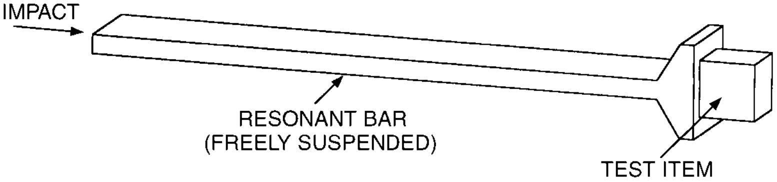

FIGURE 26.19 Resonant bar test method. The first longitudinal bar mode is excited by an impact as shown. The bar is sized so that its first normal mode frequency corresponds to the desired knee frequency in the test.

must be designed and fabricated for each test requirement with a different knee frequency, so that a potentially large inventory of resonant fixtures would be necessary to cover a variety of test requirements. For this reason tunable resonant fixture test methods were developed which allow an adjustable knee frequency for a single test apparatus.

Tunable Resonant Bars. The frequency of the first longitudinal mode of vibration of the resonant bar shown in Fig. 26.19 can be tuned by attaching weights at selected locations along the length of the bar.[24] If weights are attached at each of the two nodes for the second mode of vibration of the bar, then the bar's response will be dominated by the second mode ($2f$). Similarly, if weights are attached at each of the three nodes for the third mode of the bar, then the third mode ($3f$) will dominate. It is difficult to produce this effect for the fourth and higher modes of the bar since the distance between nodes is too small to accommodate the weights. This technique allows a single bar to be used to produce pyroshock simulations with one of three different knee frequencies. For example a 100-in. (2.54-m) aluminum bar can be used for pyroshock simulations requiring a 1000-, or 2000-, or 3000-Hz knee frequency. If the weights are attached slightly away from the node locations, the shock response spectrum tends to be "flatter" at frequencies above the knee frequency.[25]

Another tunable resonant bar method[26] can be achieved by attaching weights only to the impact end of the bar shown in Fig. 26.19. This method uses only the first longitudinal mode, which can be lowered incrementally as more weights are added. A nearly continuously adjustable knee frequency can thus be attained over a finite frequency range. The upper limit of the knee frequency is the same as given by Eq. (26.3) and is achieved with no added weights. In theory, this knee frequency could be reduced in half if an infinite weight could be added. However, a realizable lower limit of the knee frequency would be about 25 percent less than the upper limit.

Tunable Resonant Beam. Figure 26.20 illustrates a tunable resonant beam apparatus[26] which will produce typical pyroshock simulations with a knee frequency that is adjustable over a wide frequency range. In this test method, an aluminum beam with rectangular cross section is clamped to a massive base as shown. The clamps are intended to impose nearly fixed-end conditions on the beam. When the beam is struck with a cylindrical mass fired from the air-gun beneath the beam, it will resonate at its first bending frequency, which is a function of the distance between the clamps. Ideally, the portion of the beam between the clamps will respond as if it had perfectly fixed ends and a length equal to the distance between the clamps. For this ideal case, the frequency of the first mode of the beam varies inversely with the square of the beam length. In practice, the end conditions are not perfectly fixed, and the frequency of the first mode is somewhat lower than predicted. This method pro-

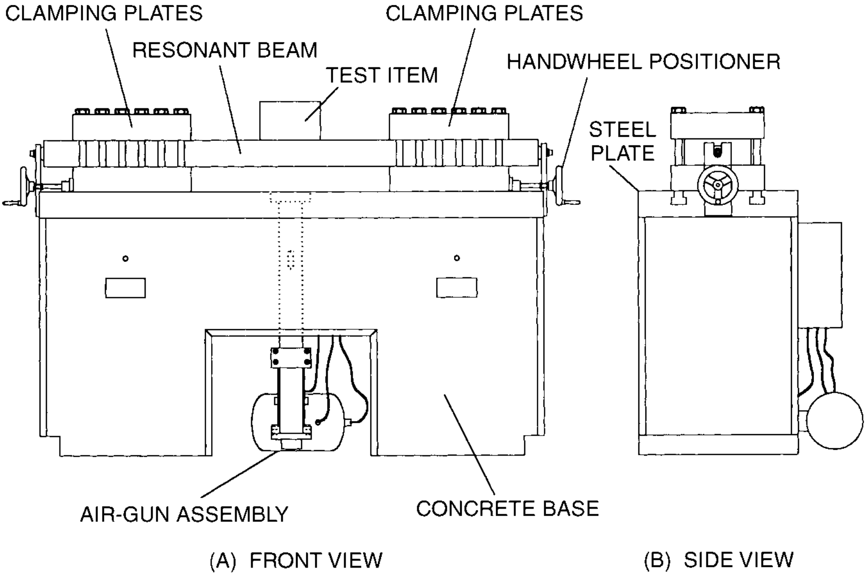

FIGURE 26.20 Tunable resonant beam test method. A beam, clamped near each end to a massive concrete base, is excited into its first bending mode by an impact produced by the air-gun.

vides a good general-purpose pyroshock simulator, since the knee frequency is continuously adjustable over a wide frequency range (e.g., 500 to 3000 Hz). This tunability allows small adjustments in the knee frequency to compensate for the effects of test items of different weights.

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