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FPL DYNAMIC COMPRESSION TESTING EQUIPMENT FOR TESTING PACKAGE CUSHIONING MATERIALS[1]

By

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Abstract

A dynamic compression testing system, consisting essentially of a pendulum, abutment, and electronic recording equipment, was built by the Laboratory for testing package cushioning materials. The tests simulate the loading of an item in a cushioned package when the package is impacted. The characteristics, limitations, and theoretical aspects of each component of the instrumentation are presented in detail, particularly in regard to acceleration measurements. The recording equipment is also suitable for measurements of dynamic loads and strains.

Introduction

For the past several years, the U.S. Forest Products Laboratory has conducted research on the various characteristics of package cushioning materials that are of importance in protecting packaged items from damage during shipment.

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[1] This Note is a revision of Forest Products Lab. Rpt. 2120 of the same title, issued in 1958.

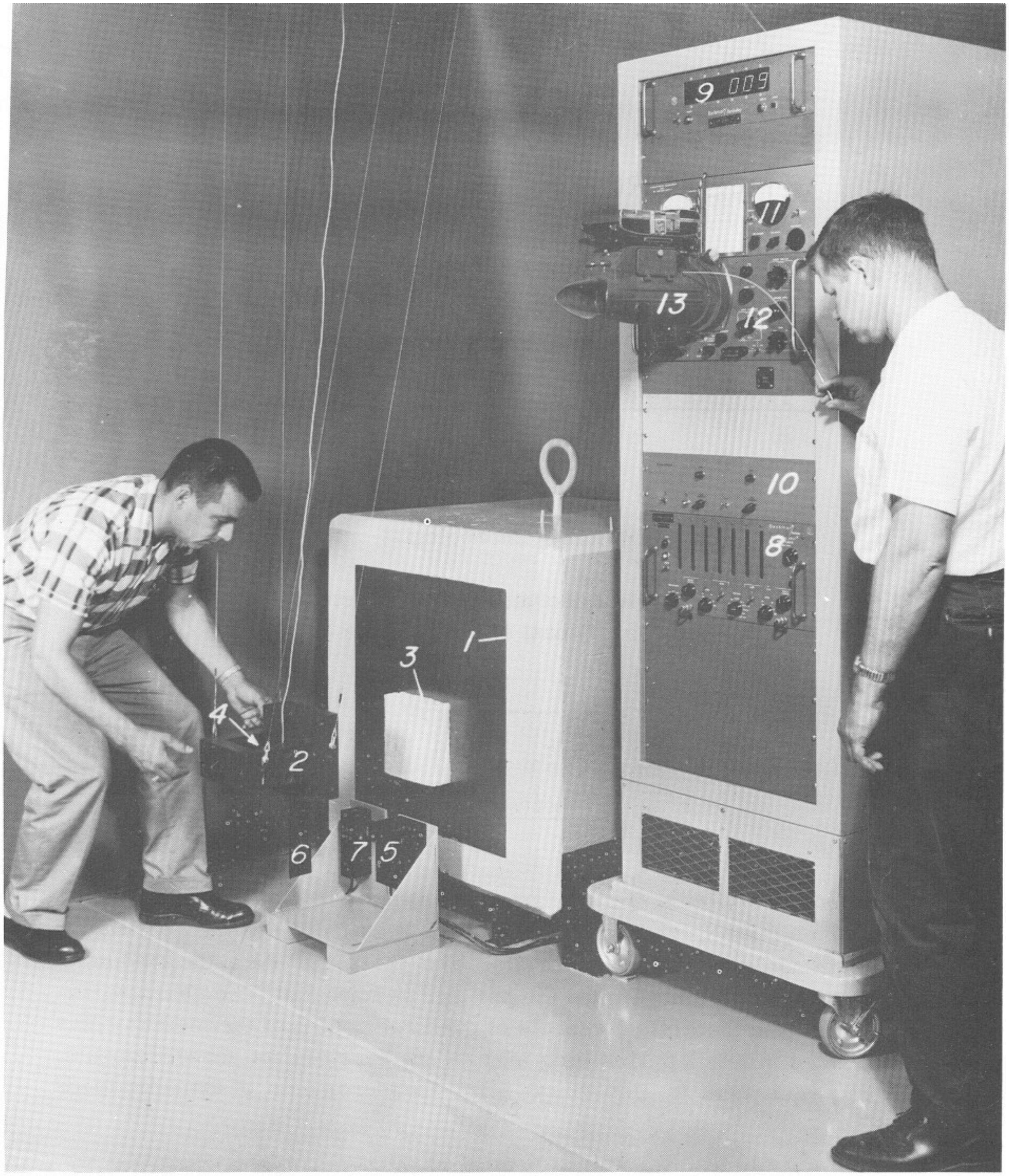

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Figure 1.--Pendulum impact test of cushioning material: (1) Steel-concrete abutment; (2) Loading pendulum; (3) Specimen of cushioning material: (4) Accelerometer; (5) Box housing photoelectric tubes; (6) Interrupter arm; (7) Light source: (8) Electronic counter; (9) Electronic counter display unit; (10) Thyrotron circuits; (11) Junction andcalibration box for two-channel recording system; (12) Cathode-ray oscilloscope; and (13) Land process camera.

Much of the earlier work has involved "static," or slowly applied, compression tests of the materials, but more recently dynamic, or rapidly applied, compression tests have been conducted. Two principal facts that have caused this transition are: (1) Dynamic compression tests simulate more accurately the loading action of an item in a cushioned package when it is dropped, and (2) unpublished work has indicated that poor agreement exists frequently between static and dynamic compression test data. To facilitate dynamic testing, the Laboratory, under the sponsorship of the Air Force Packaging Evaluation Agency (MOSPR) Headquarters, Mobile Air Material Area, Brookley Air Force Base, Ala., has built the system described in this publication.

Although the primary purpose for building this equipment has been for testing the dynamic compression characteristics of relatively soft cushioning material, the basic recording equipment of the system can be used for other types of dynamic tests. A brief summary of these is presented in the report.

Apparatus

The basic units of the system consist essentially of a loading pendulum, a 2-ton, steel-concrete abutment, and recording equipment. A test consists of drawing the pendulum to a predetermined height and allowing it to swing against a specimen of cushioning material which is mounted on a vertical face of the abutment. The loading action of the pendulum simulates that of an item in a cushioned package when the package is dropped upon a rigid surface. The principal components of the equipment are shown in figure 1.

The various components can be grouped either as testing or recording equipment. The remaining portion of this section deals with details of the various components.

Mechanical Testing Components

Pendulum--Two different pendulums, each capable of being loaded with various weights, are employed. One, an especially lightweight, yet stiff, head is used to simulate lightweight items. The second head, which is much more robust, is used to simulate medium and heavyweight items.

The lightweight pendulum (fig. 2, left) weighs 2.45 pounds unloaded, is made of sandwich material consisting of aluminum facings glued to a resin-impregnated, paper-honeycomb core material, can be loaded from 2.45 to 11.0 pounds, and can withstand up to 100 pounds per square inch of compressive stress.

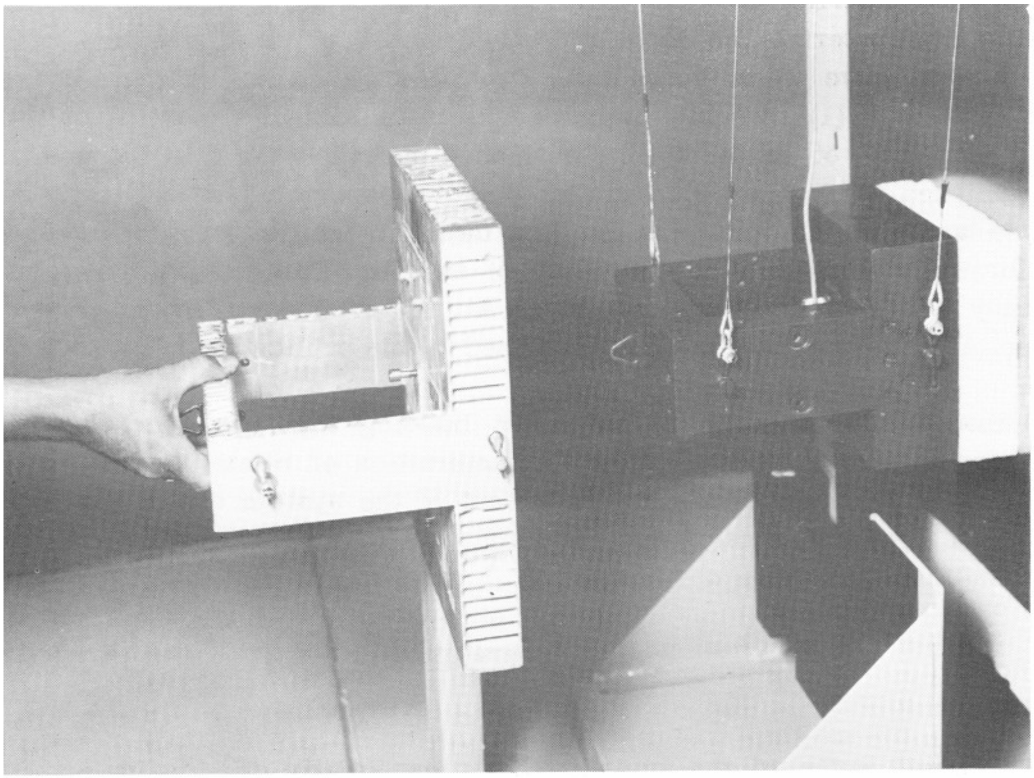

Figure 2.--Loading pendulum used to simulate packaged items. M 126 913

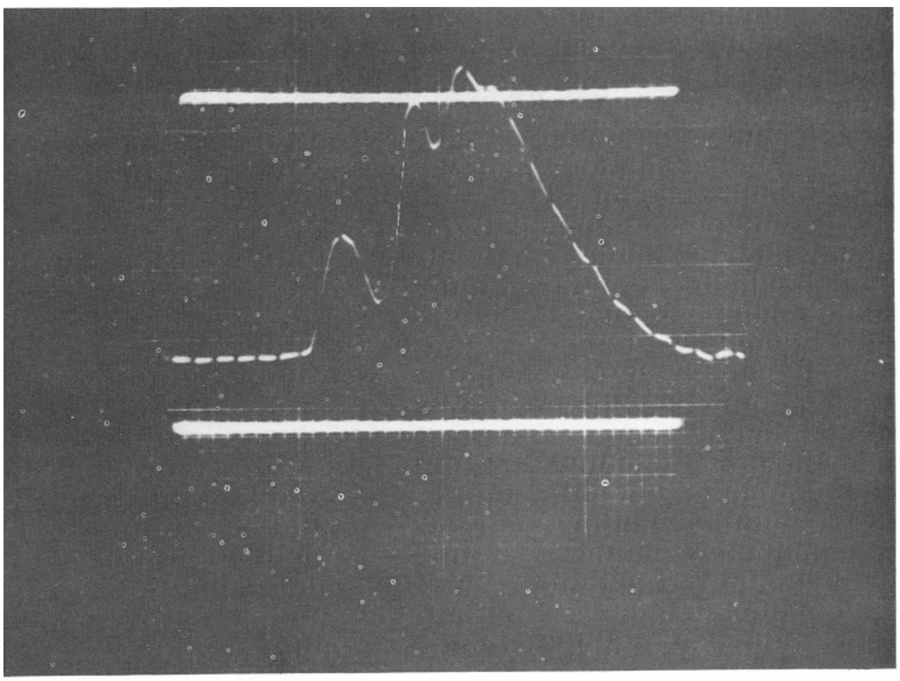

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Figure 3.--A record of acceleration and time for an impact test of bound hair showing the shock wave effect on the leading (left) side of the pulse with respect to time.

The facings of the 12– by 15– by 2–inch impact panel are 0.020–inch aluminum and those of the side panels are of 0.012–inch aluminum. The edges of the impact panel are reinforced with balsa wood inserts, and an aluminum mounting block for the accelerometer 2–3/4 inches by 1 inch by 1/4 inch in size is glued to the rear face of the impact panel. Loading is accomplished by attaching weights to the rear face of the impact panel with T–nuts glued to the panel.

The wood pendulum (fig. 2, right) weighs 13.0 pounds, and it is used for all testing at this weight or above. The arms of the pendulum are made of hard maple, and the 8– by 8– by 3–inch impact panel is made of laminated birch veneer with 1/8–inch steel facings glued to each side. Loading is accomplished by attaching steel plates to the arms.

The fundamental natural frequency of the impact panel of the wooden head is about 1,300 cycles per second, and that of the aluminurn head is about 1,000 cycles per second.

Loading head design is one of the most important and difficult aspects of the development of suitable dynamic compression testing equipment. Ideally, a loading head should be quite rigid, yet lightweight. Adequate rigidity will prevent data bias caused by cushioning action of the loading head, and provide a shock–excited high–frequency characteristic that can be separated rather easily from the principal pulse.[2] Light weight, together with loading capacity over a wide range, is desirable in order to achieve a high degree of loading capability. Adequate robustness, especially in the impact panel, is essential to prevent compression failure of the panel under loading.

No single or combination of materials has yet been tried that will provide optimum performance in all the listed requirements. However, sandwich construction as described appeared to afford the best compromise between the divergent requirements.

Effects of shock waves.––During the development of a suitable pendulum design, certain irregularities of the acceleration–time pulses were recorded. This effect is demonstrated in figure 3, which is an acceleration–time pulse (time is plotted along the x-axis) obtained by dropping a 5.83–pound pendulum on a 2.5–inch rubberized hair specimen with a density of 2.59 pounds per cubic foot. The irregularities occurred on the leading edge of the pulses, and the

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[2] The high–frequency component is customarily disregarded in data analysis because it cannot be considered as a part of generally applicable data.

number of humps varied inversely with specimen thickness. After investigating several possible causes for the distortion, Smiley[3] theorized that it was caused by shock wave propagation in the materials. To prove this thesis, he derived mathematical expressions based upon shock wave theory and then found that theoretically expected results agreed closely with actual test results, Generally, this effect occurs to some extent in all dynamic compression tests of cushioning materials, but it is most pronounced when a lightweight loading head is used to test a relatively stiff cushion.

Supporting wires.--For testing, the pendulum is supported from the ceiling by four adjustable, divergent, 10-foot, stranded, steel cables that are 1/32 inch in diameter. The wires are attached to the pendulum by clevises, which simplify changing of pendulums. The upper ends of the wires are attached to reels, which are a part of a ratchet gear assembly. The minimum length adjustment of a wire is about 1/20 inch.

Abutment.--The abutment consists essentially of a cubic yard of concrete with a steel plate 23-3/4 by 26 by 2 inches in size embedded in the side that is used for testing. The barrier is mounted on two steel I-beams that are anchored to a massive concrete slab. The test specimen is attached to the steel face of the abutment with pressure-sensitive tape having adhesive on both sides.

Release mechanism—The principal component of the release mechanism is a solenoid-activated pair of jaws, remotely controlled by the operator of the recording equipment, that are held in a mount which is adjustable vertically along a steel upright frame. The frame is movable along the ways of a horizontal framework that is anchored to the concrete floor. The vertical motion of the release mechanism is parallel to the face of the abutment, and the horizontal motion of the upright framework is perpendicular to the face of the abutment. Front and side views of the release mechanismand mount are shown in figure 4.

Ideally, to simulate loading of a cushioned item, the pendulum should strike the cushioning material squarely and compress it in a direction perpendicular to the face of the abutment. The extent of divergence of the actual loading path from the ideal was reduced to a negligible amount by the use of the long wires and the placement of the specimen so that its loading occurs at the bottom of the swing. The use of the four-wire suspension system eliminated rotation of the pendulum during the loading of the specimen.

Generally, it is desirable to test materials at predetermined rates of loading. The final velocity attained by the pendulum just before impact with the specimen

[3] Smiley, V. N. Investigation of shock waves developed during dynamic tests of cushioning materials. WADC Technical Report No. 56-547, U.S, Air Force, Wright Air Development Center, Dayton, Ohio. 1957.

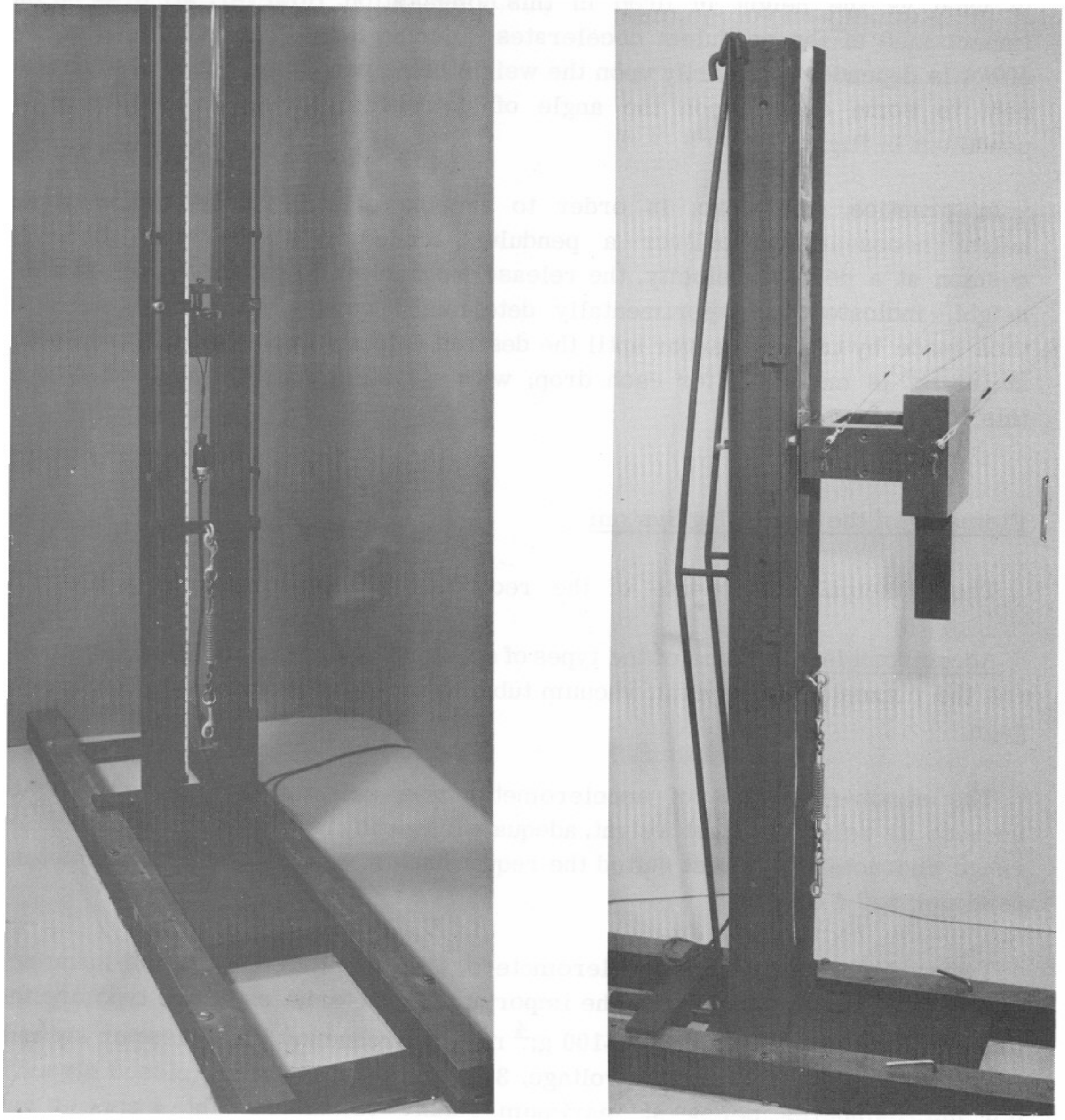

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Figure 4.--Adjustable mount for release mechanism: A, front view; B, side view, showing pendulum engaged.

can be calculated approximately with the use of equations for uniformly accelerated motion. The vertical distance between the position of a reference point on the pendulum before release and the position of the same point at impact is used as the height of drop in this computation. However, air drag on the impact face of the pendulum decelerates it during flight. The magnitude of this effect is dependent primarily upon the weight of the pendulum, but is also dependent to some extent upon the angle of incidence of the air on the face of the pendulum in flight.

In practice, therefore, in order to set the point of release to the proper height necessary to deliver a pendulum loaded to a specific weight to the cushion at a desired velocity, the release mechanism is set at the approximate height, indicated by experimentally determined curves. Finer adjustment is then made by trial and error until the desired velocity is obtained. The velocity at impact is measured for each drop, with a system that is described later in this report.

Elements of the Recording System

The principal components of the recording system are shown in figure 5.

Accelerometers.--Some of the types of accelerometers commercially available are the piezoelectric crystal, vacuum tube, differential transformer, and strain gage.

The strain-gage type of accelerometer was selected for use in this work because its relatively light weight, adequate frequency response, and acceleration range characteristics best suited the requirements. Each of the accelerometers used weighed 4 ounces.

Two types of strain-gage accelerometers, both supplied by the same manufacturer, were used in this work. The important characteristics of one type are the following: Acceleration range ±100 g;[4] natural frequency 725 cycles per second, 2,500 ohms; maximum supply voltage, 34 volts; output current (closed circuit), 8.6 microamperes per g at maximum supply voltage; weight, 4 ounces: and response to transverse acceleration, not more than 2.0 percent.

[4] "g" is herein used to symbolize the dimensionless ratio of a value of acceleration (positive or negative in direction) to the constant rate of acceleration of a freely falling body due to the earth's gravitational force (32.2 feet per second per second).

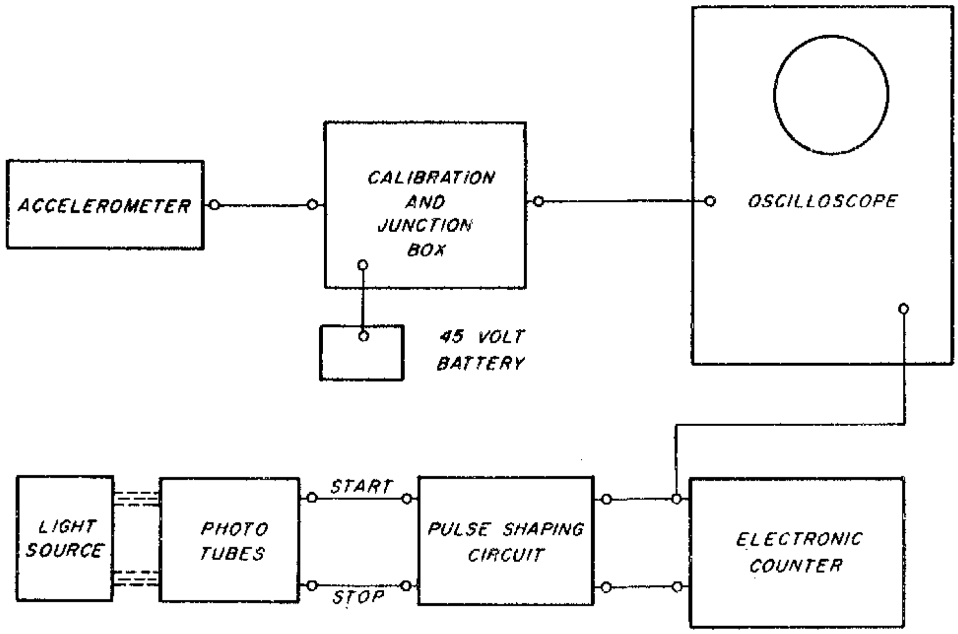

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Figure 5.--Block diagram of principal components of the recording system

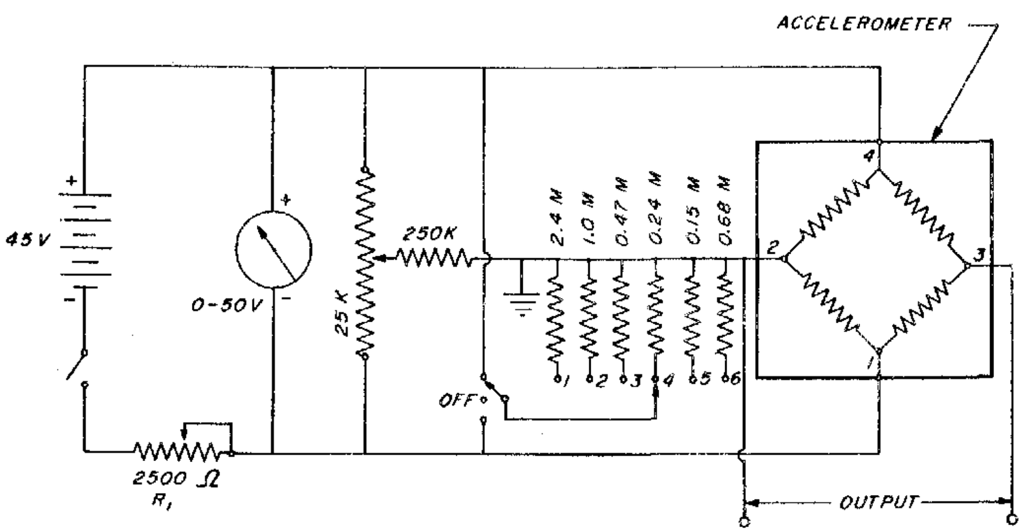

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Figure 6.--Schematic diagram of junction box.

The characteristics of the second type of accelerometer are the following: Acceleration range, ±500 g; natural frequency, 1,550 cycles per second; sensitivity (open circuit), 0.36 millivolts per g at maximum supply voltage; bridge resistance, 2,500 ohms; maximum supply voltage, 38 volts; output current (closed circuit), 0.14 microamperes per g; weight 4 ounces; and response to transverse acceleration, not over 2.0 percent.

Frequency Response

Basically, an accelerometer is a damped mass-spring system that will act as an accelerometer well below its natural frequency and is known generally to be usable only over a certain range of frequencies. The band width of this range is determined by the physical parameters of the system and the quantity being measured, namely, displacement, velocity, or acceleration.

In the past, some testing engineers have assumed that an accelerometer will accurately reproduce an applied acceleration. if the frequency of the applied acceleration is no greater than one-third the natural frequency of the accelerometer and the accelerometer is damped to 0.6 or 0.7 of critical damping.[5] In this regard, White[6] showed that an accelerometer having a response that can be described by a second-order differential equation will reproduce steady state oscillatory accelerations with good accuracy if the damping is 0.7 critical. and the applied frequency is less than about 0.3 of the natural frequency of the accelerometer.

However, in impact testing such as the dynamic loading of cushioning material, the acceleration occurs as a single pulse or transient, which generally resembles a half cycle of a sine wave rather than as a steady state oscillation.

As shown by Levy and Kroll,[7] the transient response of an accelerometer to a transient shock is not what one might expect from the steady oscillatory response.

In this work they developed the expected response of accelerometers that varied in degree of damping to transient half sinusoid, triangular, and square

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[5] "Critical damping" is defined as the minimum coefficient of damping C_c that will just prevent a damped transient oscillation of a damped seismic system in response to displacement. Numerically, $C_c = 2\sqrt{km}$, where k is the spring constant and m is the mass.

[6] White, G. Response characteristics of a simple instrument. Instrument Notes No. 2, 1948. Statham Laboratories, Los Angeles, Calif.

[7] Levy, S., and Kroll, W. D. Response of accelerometers to transient accelerations, Research Paper 2138, Journal of Resources, National Bureau of Standards, Vol. 45. No. 4. 1950.

acceleration pulses of variable duration. From this work they concluded that in order to obtain an accuracy of better than 5 percent in measuring peak accelerations of transient phenomena, which are nearly half sine waves or triangular pulses, the accelerometer must have a natural period of about one–third the acceleration pulse duration or smaller and a value for the damping constant of 0.4 to 0.7 critical. Expressed in terms of the natural frequency f_n of the accelerometer, $f_n \geqq \frac{3}{\tau}$ where f_n is the natural frequency of the accel– erometer and τ is the duration of the acceleration pulse. According to this rule, the f_n of an accelerometer required to reproduce accurately a specific pulse would have to be twice as high as the f_n indicated by the rule based upon oscillatory input.

Thus, the type 2 accelerometer, having a natural frequency of 1,550 cycles per second, is suitable for measuring, with anaccuracy of better than 5 percent, peak accelerations of transient acceleration having a duration between 1.9 milliseconds and infinity.

Calibration.––The calibration sensitivity values supplied by the manufacturer for the accelerometers have been checked at the Forest Products Laboratory by the use of a system described in detail by Godshall.[8]

Junction Box

The junction box serves as a common connection point for the accelerometer, the oscilloscope, and the accelerometer power supply and as a housing for precisian calibration resistors, switches for system calibration and power, a 0- to 50–volt voltmeter, and controls for voltage adjustment and accelerometer bridge balancing. A schematic diagram of the junction box and its component parts is shown in figure 6.

Precision calibrating resistors. ––The calibrating resistor bank consists of a group of six precision resistors of different values. If one of these resistors is connected across an arm of the accelerometer bridge, the output voltage of the accelerometer changes as if an acceleration had actually been applied. The magnitude of the simulated acceleration can be calculated since it depends only on the calibration resistance, the accelerometer resistances, and the calibration factor for the accelerometer. The method for calculating the simulated acceleration value is given in the appendix,

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[8] Godshall, W. D. The FPL linear deadweight accelerometer calibrator. Forest Products Lab. Rpt. 2239. 1962.

The calibration voltage is applied to the oscilloscope and appears as a horizontal line displaced from the zero or reference line. The vertical distance between the two lines represents the acceleration in g's simulated by the particular resistor connected. The six resistors used give different values of acceleration from about 6 to 100 g's for ±100 g accelerometers, and from about 22 to 355 g" for ±500 g accelerometers.

The advantages of such a system of calibration are ease of operation and freedom from errors, caused by voltage drift in the power supply and the sensitivity of the oscilloscope.

Control of supply voltage.--The supply voltage for the accelerometer is varied by means of potentiometer R_1 (fig. 6). The voltage is indicated by the voltmeter.

Cathode Ray Oscilloscope

The accelerometer is connected at the junction box to the vertical input of a single beam oscilloscope. The principal features of this instrument are given in the following paragraphs.

Amplifier characteristics.--The horizontal and vertical amplifiers are similar and provide high sensitivity of 1 millivolt per centimeter or 10 millivolts at full-scale deflection. The amplifiers have wide pass bands from d.c. to 300 kilocycles, and provide balanced input circuits on the six most sensitive ranges. The amplifiers also provide single ended input, and they can be either a.c. or d.c. coupled.

Time base.--The oscilloscope is equipped with a calibrated horizontal sweep which is linear and accurate within 5 percent. Twenty-one sweep rates, ranging from 1 microsecond per centimeter to 5 seconds per centimeter, are available.

Triggered sweep.--By the use of an externally applied pulse, a single sweep can be obtained.

A photoelectric method is employed to obtain the triggered sweep A small aluminum strip attached at the bottom of the rear of the face plate of the pendulum (fig. 1, No. 6) serves as an interrupter arm for breaking a light beam that is incident on a 0.012-inch slit behind which is it phototube (fig. 1, Nos. 5 and 7). Actually, there are two slits spaced 1 inch apart, The light and phototube system also serves as a velocity-measuring system. A report of the function and circuitry is presented in a subsequent section of this publication.

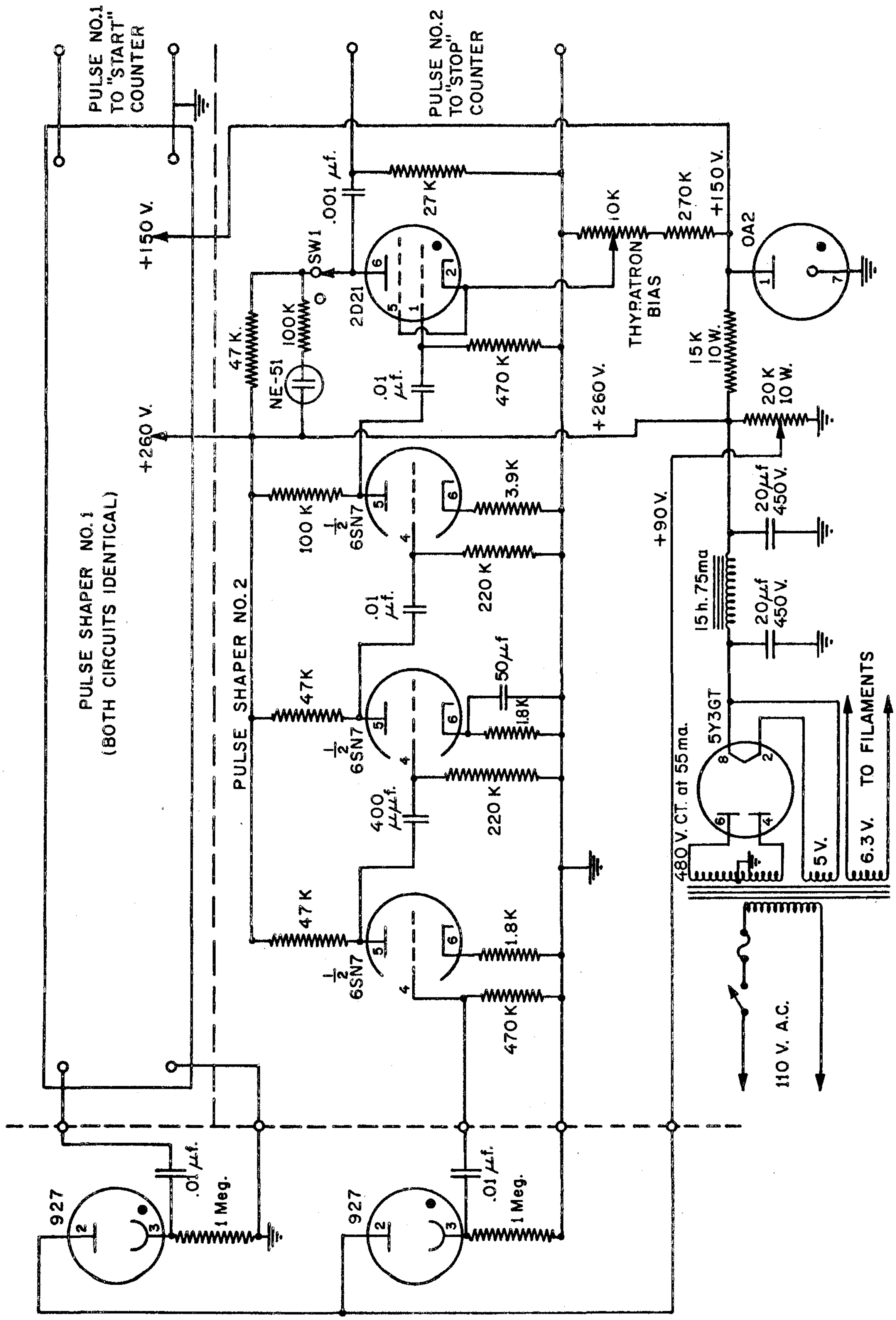

Figure 7.--Schematic diagram of pulse-shaping circuit.

When the pendulum arrives at the bottom of the swing, the interrupter arm breaks the first light beam, causing the first phototube to send a voltage pulse to a three-stage amplifier (figs. 1, 5, and 7); the amplified signal is then applied to the grid of a 2D21 thyratron, causing it to 'fire" and send a large negative voltage pulse to the external sync connection of the oscilloscope. If the sweep control is set to driven sweep, a single sweep will be produced when the pulse arrives. The use of the thyratron prevents a second sweep from being produced when the pendulum rebounds and swings back through the light beam. The thyratron must be reset with a pushbutton(fig. 7, SW1) before the next drop.

Photographic records.--The acceleration-time curves are recorded with a Land process camera that is mounted on the oscilloscope (fig. 1, No. 13). It is possible to observe the oscilloscope screen visually at the same time that a picture is being taken because a half-silvered mirror in the camera assembly reflects part of the light from the screen vertically to the camera and allows part of the light to be transmitted directly to the observer's eye. The pictures are developed in approximately 10 seconds in the camera. Some examples of typical acceleration time records are shown in figure 8. Both pulses were obtained from impact tests involving a 13.0-pound pendulum and the equivalent of a 24-inch drop height. A represents 1.7 pounds per cubic foot wood-fiber felt and B represents 5.2 pounds per cubic foot fibrous glass.

The two calibration lines are photographed with recurrent sweep just before the drop. The acceleration pulse is photographed during the impact. The beam intensity is set at the optimum rate for the sweep frequency and the amplitudes and frequencies contained in the acceleration waveform. Trial drops are helpful in determining this setting.

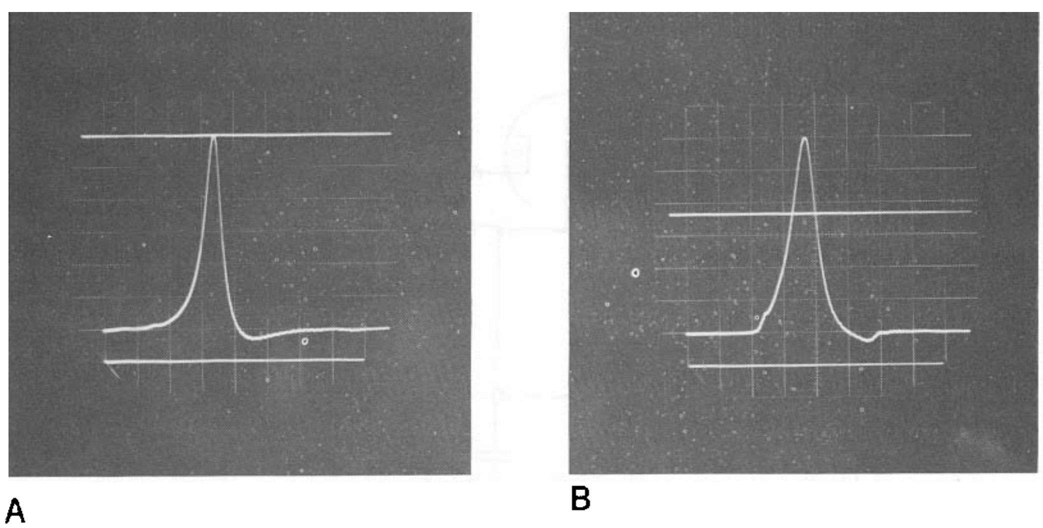

Figure 8.--Typical acceleration-time records from dynamic compression tests of cushioning materials: A, wood-fiber felt; B, fibrous glass.

Calculation of acceleration--To calculate the peak value of acceleration from the oscilloscope records, the number of divisions between the horizontal calibration lines is measured. From this the sensitivity S of the entire recording system can be determined from

$$S = \frac{A_c}{D_c} \text{ g's per division} \tag{1}$$

where A_c is the number of g's represented by the particular calibration traces, and D_c is the number of divisions betweencalibrations lines. The peak acceleration in g's is then

$$a = DS \tag{2}$$

where a is the peak acceleration in g's and D is the maximum vertical deflection of the trace in divisions.

The fidelity of the recording system is limited primarily by the accelerometer. Therefore, if a type 2 accelerometer, which has a natural frequency of 1,550 cycles per second, is used, the system described is capable of recording within 5 percent the peak amplitude of acceleration-time wave forms having a maximum amplitude of 500 g and a duration of 1.9 milliseconds to infinity.

Velocity-Measuring System

The velocity of the loading head at the moment of impact with the cushion is an important parameter which must be closely controlled. Since the pendulums have a large bearing area and must swing through a relatively long arc, air resistance decelerates the pendulum considerably during flight. Air drag varies with the velocity of the pendulum, and the rate of deceleration varies with the loaded weight of the pendulum. To overcome air drag, the pendulum is released from a greater height so that the desired impact velocity is obtained. Curves of height correction were developed by calculations and empirical tests to facilitate rapid determination of release heights, but it was still necessary to check the accuracy of the release height settings by measuring the impact velocity. To accomplish this, the system described in the following text was devised It is noteworthy that the system actually measures tho time required by the pendulum to travel a relatively small known distance near the bottom of its swing. With this information, the impact velocity can be computed. Thus, the system is based upon the assumption that the velocity is constant during the measured time interval. This approximation is valid because the velocity of a pendulum is nearly constant near the bottom of its swing.

Components

Light-phototube system--As reported previously, the light-phototube system consists of two beams of light that are incident on two slits. Each slit is 0.012 Inch wide and is located in front of a phototube. The slits are spaced 1.008 inches apart. In figure 1. the light source is shown as No. 7 and the phototube housing is shown as No. 5.

Pulse-shaping circuit.--In order to utilize the output from the phototubes, it was necessary to amplify and reshape the pulses with the circuit shown in figure 7. Each pulse goes through three stages of amplification. A 120-cycle wave is superimposed upon the pulse because of the fluctuations in light intensity as the temperature of the filament changed with 60-cycle alternating current. The amplitude of the undesired signal was reduced by adding a 400-micromicro-farad capacity and a 220,008-ohm resistor after the first stage of amplification, thus decreasing the low frequency response of the amplifier.

The amplified pulse from each channel was applied to the grid of a 2D21 thyratron tube which provided voltage discriminator action. The thyratron tube could be set to fire at a specific voltage by means of bias controls. When the thyratrons fire, they produce pulses of very short duration, and the time between pulses can be measured accurately. To obtain good accuracy the amplitude of pulses that are applied to the thyratron tubes must be large so that any drift or change in the thyratron firing voltage will cause only a negligible change in the firing time. Therefore, the thyratron tubes are set to fire on the leading edges of the pulses at a voltage somewhat higher than the noise voltage present.

The thyratron tubes receive pulses when the pendulum rebounds through the beams, but they will not fire again until they are reset. Two neon lights, which indicate when the thyratron tubes are fired, are used for adjusting the firing voltage of the thyratron tubes.

Electronic counter.--An electronic counter (fig. 1, No. 8) is used to measure the time between the pulses. The output of the first channel starts the counter; that of the second stops it. The time in milliseconds, required by the interrupter arm to travel the distance between the slits, is indicated in digital form by the counter.

Check of the System

The accuracy of the velocity-measuring circuit was checked by dropping a 20-pound steel plate edgewise through the Bight beams from a height of 30 inches. The leading edge of the plate was ground to a knife edge, and a solenoid-activated release mechanism was used to drop the plate. Because of the large ratio of weight to area of the plate when falling edgewise through air, the air resistance to the motion of the plate was negligible. The recorded time for the plate to pass between the slits agreed to within 1 percent of the calculated value and the accuracy of the velocity-measurement system was rated to be within ±1 percent.

Design Data Derived With the Equipment

Fundamental Considerations

Certain considerations must be made by the packaging engineer who wishes to select efficient. thicknesses and kinds of cushioning material for protecting specific item during shipment. The more fundamental of these are summarized in the following paragraphs.

Fragility of the item--Some system for rating the degree of fragility of specific items is a prerequisite for "exact cushion design." The common rating system being used by packaging engineers involves the maximum acceleration that specific items can withstand, expressed in multiples of g, the constant acceleration exerted by gravity upon a body that is falling freely.

The relationship between maximum acceleration, g_m, and maximum force, F_m, is obtained with Newton's law

$$F_m = W\ g_m \tag{3}$$

where F_m is maximum force in pounds, and W is the loading weight in pounds.

The record of the deceleration of a loading device during tests of cushioning materials as a function of time has several principal characteristics, namely, maximum or peak acceleration, rise time, and period. That the use of peak acceleration alone as an index of fragility might be an oversimplification can be illustrated by considering an item having one or more fragile elements. In addition to magnitude of acceleration, the resistance of the element or elements to breakage is related to such factors as their resonant frequency, the fatigue resistance of their component material or materials, the period of the transient acceleration pulse (or the frequency of the pulses, if repetitive), and the rise time of the pulse. Consideration of all of these factors is possible by testing individual items under the conditions expected during service, and then correlating damage of the item with the characteristics of the acceleration-time pulses obtained from the tests. Such a testing program is ideal, but expensive. Thus, until more complete knowledge is gained regarding the relative importance of effects of rise time, period, and other factors upon specific items, the problem of rating fragility has been simplified by the assumption that peak acceleration is a satisfactory comprehensive index of fragility. Nevertheless, the apparatus described in this report could be used for investigating the effects of rise time and period of transient pulses upon items, if desirable.

Severity of shock to which container will be subjected.--Frequently this factor is expressed in terms of the maximum expected height of drop in inches. A 38-inch drop is often used because of its relation to the height of an average man’s hands from the floor when he is standing erect. However, the design method presented in this report enables one to use any height of drop desired.

Energy-absorption characteristics of cushioning material. --Cushioning materials differ widely in their mechanical properties, such as stiffness, efficiency, and versatility. Generally, no single material is optimum for all cushioning applications, and the user must decide which of the different materials is especially suited to his need. The energy-absorption characteristic of a specific cushioning material. can be expressed by various curves derived from compression test data for the material, such as force-displacement, stress-strain, and static stress-acceleration curves. The dynamic compression testing apparatus described in this report was built to facilitate evaluation of this characteristic of cushioning materials.

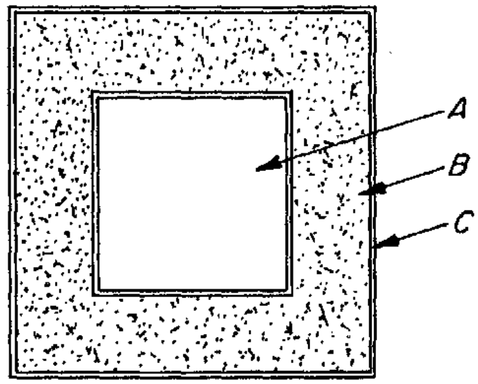

Figure 9.--A cushioned pack consists essentially of A, an article; B, a cushion: and C, an outer container.

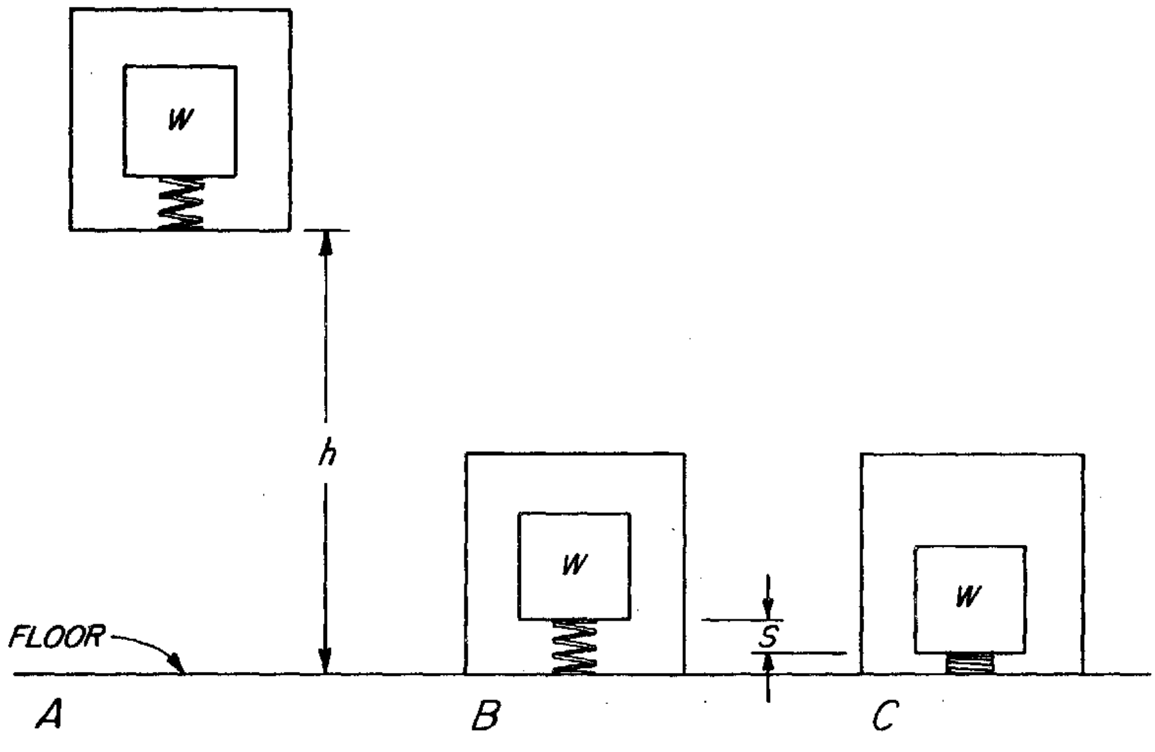

Figure 10.--An idealized representation of a package during a drop.

Idealized Cushioned Package

A cushioned package is represented in figure 9 wherein A represents the item, B the cushioning material, and C the outer container. In order to analyze the action of this package when it is dropped, it is necessary to represent the package as an idealized mechanical system wherein the cushioning material is represented by a spring.

Effects of Dropping

When the package is dropped from a height h (fig. 10, A), it is given a constant acceleration of 1 g by gravity. In general, at the moment of impact with the dropping surface (fig. 10, B), the outer container ceases motion, but the item compresses the cushion through a distance S (fig. 10, C). During compression, the cushion absorbs all of the kinetic energy which the item possessed at the moment of impact, and at the instant of maximum compression, the maximum force is exerted upon the item. Thus, the item also is subjected to maximum deceleration at this instant. Ideally, the cushioning would absorb the kinetic energy at a uniform rate over a relatively large displacement, thus cushioning the item gradually without exerting high stress or causing rapid deceleration.

Peak Acceleration-Static Stress Curves

It is desirable, of course, to utilize the most efficient materials for specific applications, and peak acceleration-static stress curves are helpful in making this selection.

Several peak acceleration-static stress curves for wood-fiber felt material varying only in thickness are shown in figure 11. The material was about 2, 3, 4, and 5 inches in thickness, as indicated, and 2.4 pounds per cubic foot in density. The curves indicate the maximum deceleration which articles that differ in load per unit area (static stress) would receive, if they were dropped from a height of 30 inches upon the materials represented. The curves were derived with the dynamic compression testing system described in this report.

To derive a single curve, a particular specimen was tested with the pendulum loaded to several successive increments of weight. The pendulum simulated the loading action of a fragile item. The maximum deceleration recorded for each drop was plotted against a value obtained by dividing the corresponding weight

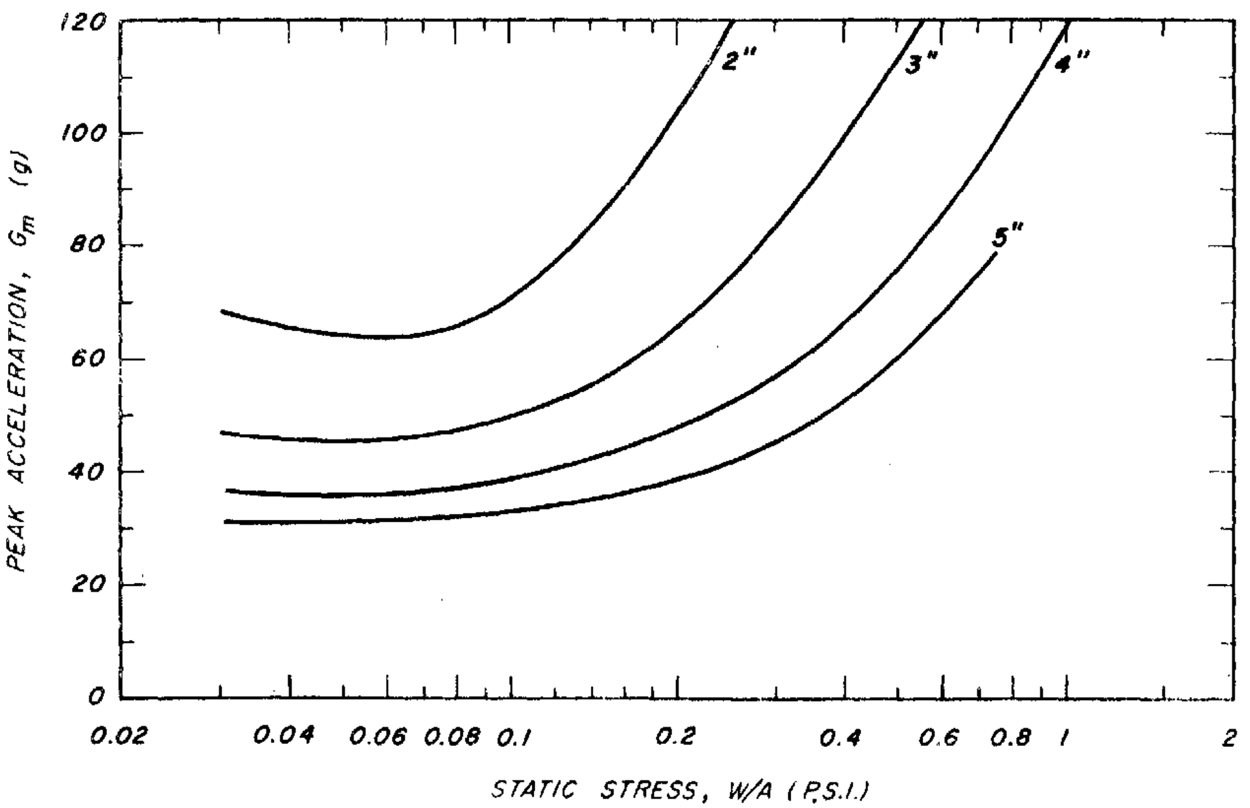

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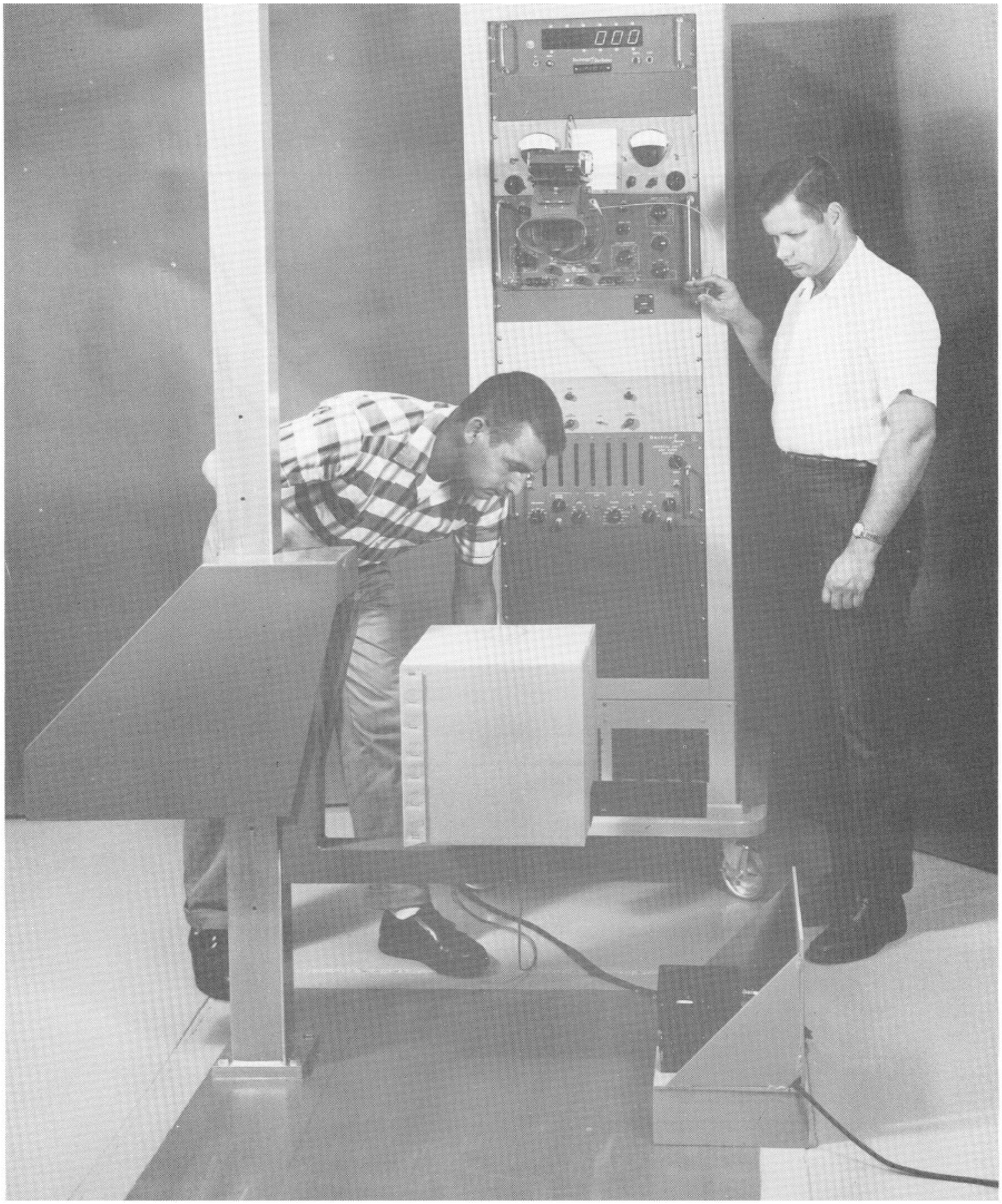
Figure 11.--Peak acceleration static-stress curves for wood fiber felt.



M 126 910

Figure 12.--Making an instrumented drop test of a complete cushioned package.

of the pendulum by its bearing area on the specimen. Thus a static stress-acceleration curve was derived for that material. Similar curves must be derived for different thicknesses of material and heights of drop.

The packaging engineer, having available curves of this type and knowing the weight, bearing area, and fragility of an item, can determine the approximate amount of material needed to protect the item. In order to utilize the most economical material for the job, he would check curves for all likely materials and then select the one that is most satisfactory with respect to costs, amount required, availability, tare weight, and related factors.

Tests of Complete Cushioned Packages

Precise data representing the performance of the various cushioning materials can be obtained by the use of the equipment described in the preceding text, and these data would be especially useful for classifying cushioning materials according to their efficiency in specifications. However, exploratory tests of cushioned items inside containers have shown that vibration of container members resulting from impact (especially "flat drops") frequently will increase the stress exerted upon the item by the cushion. The most severe condition exists when the item is approaching maximum displacement as it compresses the cushion, while the container member on which the cushion is resting is oscillating in a direction opposite to that of the item. In this situation, the cushion is compressed simultaneously from both sides and a higher stress, and deceleration, is produced. In contrast, crushing of container members during impact will often aid the action of the cushioning material. The net container effects are determined by such factors as the type and orientation of the container at impact, the stiffness of members, moisture content (if the material is cellulosic), nature of the dropping surface, and height of drop. Obviously, the cushioning protection for a specific item might be inadequate under certain conditions, if container effects are ignored in the selection process.

The transducer-recording system is adaptable for tests of complete cushioned packages, as shown in figure 12. For this type of test, the accelerometer is mounted on a loading plate, which simulates a fragile item The plate is placed on the cushioning material inside the container and the package is dropped. An electric hoist and solenoid-activated release mechanism can be used to suspend and release the package, and turnbuckles can be used to produce the desired container orientation. By testing the various cushioning materials in representative types of containers, static stress-acceleration curves that include container effects can be derived. Generally, this approach would be most feasible where the number of combinations of material and container is limited.

Other Container Tests

The electronic recording equipment has been used for various other container tests not involving cushioning materials.

One test series involved determination of the dynamic tensile loads applied during rough handling tests of various tapes being used to suspend aircraft members in crates. Modified bonded wire strain gages were used as the sensing elements.

Other work was conducted with large crates to determine the dynamic compressive and tensile stress in certain members in order to accomplish more efficient design. Bonded wire strain gages or piezoelectric accelerometers were used as the sensors in these tests.

Summary

A dynamic compression testing system consisting essentially of a pendulum, abutment, and electronic recording equipment was built by the Laboratory for testing package Cushioning materials. The pendulum test simulates the cushioning action of an item in a cushioned package when the package is impacted. The equipment can simulate heights of drop up to 52 inches.

The recording equipment is capable of measuring within ±5 percent accuracy peak accelerations up to ±500 g that occur during transient accelerations that vary in duration from 1.9 milliseconds to a value limited only by the lowest sweep speed of the oscilloscope. The velocity–measuring portion of the system is capable of measuring impact velocities of from 0 to at least 20 feet per second within ±1 percent.

In addition to dynamic compression tests of cushioning materials alone, the recording equipment can be used for evaluation of the combined performance of cushioning materials and the containers in which they are shipped and for measurement of dynamic loads and strains in other types of tests.

Acknowledgment

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APPENDIX

Derivation of Simulated Accelerations from Precision Calibrating Resistors

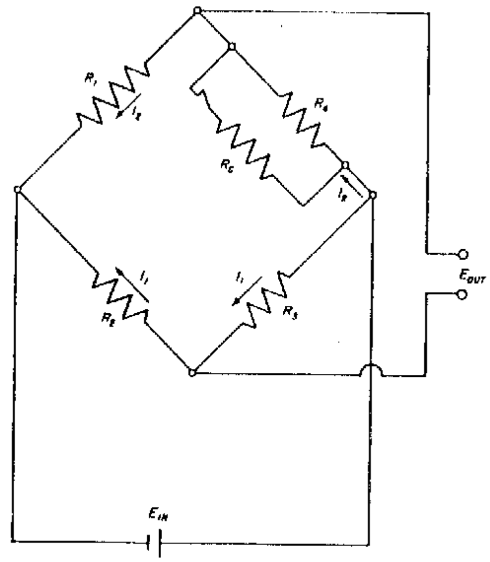

Figure 13.--Schematic diagram of strain-gage accelerometer bridge circuit.

Figure 13 shows a diagram of the Wheatstone bridge circuit formed by the strain gage wires. R_c is one of the precision calibrating resistors which is connected in parallel with R_4 when calibrating.

Currents in the two branches are indicated by I_1 and I_2. It is desirable to find E_{out} in terms of the bridge resistances, the calibrator resistor, and calibration factor for the accelerometer.

From figure 13:

$$E_{out} = I_2 R_1 - I_1 R_2 \tag{1}$$

or

$$E_{out} = -I_2 \frac{R_c R_4}{R_c + R_4} + I_1 R_3 \tag{2}$$

Adding (1) and (2),

$$2 E_{out} = I_2 \left(R_1 - \frac{R_c R_4}{R_c + R_4} \right) + I_1 \left(R_3 - R_2 \right) \tag{3}$$

The currents are $I_2 = \dfrac{E_{in}}{\dfrac{R_c R_4}{R_c + R_4} + R_1}$ and $I_1 = \dfrac{E_{in}}{R_2 + R_3}$

Substituting in (3), we have

$$2\,E_{out} = \frac{E_{in}\left(R_1 - \dfrac{R_c R_4}{R_c + R_4}\right)}{\dfrac{R_c R_4}{R_c + R_4} + R_1} + \frac{E_{in}\left(R_3 - R_2\right)}{R_2 + R_3}$$

The resistances of each arm of the bridge are specified as being equivalent; therefore,

$$R_1 = R_2 = R_3 = R_4$$

so

$$2\,E_{out} = E_{in}\left[\frac{R_1 - \dfrac{R_1 R_c}{R_1 + R_c}}{\dfrac{R_1 R_c}{R_1 + R_c} + R_1}\right]$$

$$E_{out} = \frac{E_{in}}{2}\left[\frac{R_1^2}{R_1^2 + 2R_1 R_c}\right]$$

$$E_{out} = \frac{E_{in}}{2}\left[\frac{R_1}{R_1 + 2R_c}\right] \qquad (4)$$

The manufacturer of the strain gage accelerometers specifies a calibration factor, F, for each accelerometer which is expressed as the open circuit output voltage in microvolts due to a unit input of acceleration with 1 volt applied to the input terminals.

$\underline{E_{out}}$ could then be expressed by $\underline{E_{out}} = F\ N\ \underline{E_{in}} \times 10^{-6}$ volts where $\underline{N}$ is the number of g's of acceleration.

Then

$$F\ N\ E_{in} \times 10^{-6} = \frac{E_{in}}{2} \left[\frac{R_1}{R_1 + 2R_c}\right]$$

Solving for R_c, we have

$$R_c = \frac{R}{4}\left(\frac{10^6}{FN} - 2\right) \tag{5}$$

The subscripts on $\underline{R}$ are dropped as the value applies to the input and output resistance of the bridge as well as to the individual arms.

For voltage calibration of the recording equipment, convenient values are chosen for $\underline{R_c}$ from (5) to give convenient values of $\underline{N}$. The values of the calibrating resistors used in the junction box are 2.40, 1.00, 0.680, 0.470, .0.240, and 0.158 megohms.

As an example of what acceleration is simulated by these resistors, we will consider the 2.4 M resistor used with a 100 g accelerometer. The value of $\underline{F}$ given by the manufacturer for the accelerometer is 43.00 microvolts per g per volt input and $\underline{R}$ is 2,586 ohms. Solving 28 for $\underline{N}$, the number of g of simulated acceleration, we have

$$N = \frac{R \times 10^6}{2F\left(R + 2R_c\right)} \tag{6}$$

$$N = \frac{2.586 \times 10^9}{2 \times 43.00\left(2.586 \times 10^3 + 2 \times 2.4 \times 10^6\right)}$$

$$N = 6.27\ g$$

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