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SHOCK AND VIBRATION INSTRUMENTATION AND MEASUREMENTS SECOND PARTIAL REPORT

By I. Vigness, E. W. Kammer, and S. G. Holt

FR-2645 - Report 0-2645

Unclassified

* * *

Approved by:

W. H. Sanders - Asst. Superintendent, Mechanics & Electricity Division

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Rear Adm. A. H. Van Keuren, USN (Ret.)
Director, Naval Research Laboratory

Numbered Pages 60
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NRL Problem 0-54

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ABSTRACT

Three general topics within the subject of mechanical shock instrumentation and measurements are considered. These are:

a. General Instrumentation. Instrumentation, suitable for vibration and mechanical shock measurements in ranges of most interest to the Navy, is discussed. These include accelerometers, velocity meters, displacement meters (including high speed moving picture methods), strain gages, and impact gages. The significance of the measurements made by various types of peak reading accelerometers and impact gages is considered in detail. The established methods of shock and vibration measurements used at the Naval Research Laboratory are given.

b. Shock and Vibration Characteristics from Field Measurements. Typical curves are presented that show shock characteristics for shipboard shocks of sufficient intensity to cause minor damage to the ship's structure. Amplitudes and frequencies of steady state vibrations that may exist aboard ships and aboard aircraft are briefly considered.

c. Characteristics of High Impact Type Navy Shock Machines and of Vibration Machines. Shock characteristics of the Navy Type High Impact Shock Machines are presented and compared with shipboard shocks of intensity sufficient to cause minor damage to the ship's structure. It is concluded that motions of the shock machine anvil plate simulate reasonably well the shipboard shocks that may occur for parts rigidly connected to the hull. However, the shocks delivered by the shock machine, as usually specified, are more severe than probable shipboard shocks at locations distant from the hull. It is suggested that shock specifications be written with more consideration given to the probable location of apparatus on board ship.

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INTRODUCTION

A. Authorization

1. This work was authorized under the Bureau of Ships Project Order No. 100/45 of 1 July 1944.

B. Statement of Problem

2. This report will replace NRL Report #0-1965 of 28 November 1942 entitled "High Impact Shock Instrumentation and Measurements, First Partial Report", which is now incomplete in many respects. The contents of this report are expanded over that of the last report. The contents include:

a. General classification and description of shock measuring instruments and a partial list of vibration measuring instruments.

b. General characteristics of shock and vibration as determined from field measurements. In order that this report may be limited to a restricted classification no details of field measurement conditions will be given.

c. General characteristics of High Impact Shock Machines and vibration machines.

3. In addition to shocks and vibrations that occur on waterborne ships, the Navy is much concerned about the shocks and vibrations that are encountered on aircraft and land vehicles. Some consideration will be given to shocks and vibrations on aircraft but conditions on land vehicles (see Appendix I), or those involved in handling and transportation of equipment, will not be considered at this time.

INSTRUMENTATION

A. Amplitude and Frequency Ranges Required for Shock and Vibration Measuring Instruments.

4. It is necessary to anticipate some of the characteristics of shock and vibration, which will be presented in more detail later, in order that the types and scale ranges of suitable instruments can be discussed. Shock characteristics are usually measured in terms of acceleration, velocity, or displacement as functions of time. Often measurements are made of several of these quantities in order that a greater range of frequencies and amplitudes can be covered. For example, displacement meters do not show the small displacements that are associated with the high frequency accelerations, and accelerometers do not show the small accelerations that are associated with low frequency displacements. A more complete picture of the shock at a given region would require additional information as to strains, deformations, and rotations as functions of time. This information is not usually obtained. Shocks are often initiated by high pressure regions in air or water. Measurements of these pressures give information of value for shock studies.

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5. No concise definition has been given to the general terms "Shock" and "High Impact Shock". The generally used meaning is that an object suffers shock when the major part of an applied impulse is delivered in a time that is short compared to fundamental natural periods of the object. A high impact shock, by Navy usage, is caused initially by an applied impulse of about a millisecond duration and of intensity sufficient to cause velocity changes greater than a few feet per second at its source. The complicated transient motions of a many-degree-of-freedom system, initiated by a high impact shock, for example, the motions of a mounting panel of a Navy H.I. shock machine are usually the motions of interest. High impact shock, loosely used, also refers to these transient motions. The characteristics of the shock are described from measurements of these motions. Generally objects that are mounted so that their points of mounting are forced to follow these motions are said to have been given a high impact type shock.

6. It is not generally desirable or possible to measure the entire range of amplitudes and frequencies encountered in these shock motions. It is preferable to include only the range considered most damaging to typical equipment. Shock characteristics reported are therefore dependent upon the choice of measuring instruments. This is particularly true with respect to the high frequency accelerations and the low frequency displacements. While special conditions may require shock instrumentation to extend beyond the amplitude and frequency ranges given, accelerometers, velocity meters, and displacement meters should usually cover the following ranges:

a. Accelerometers. For shipboard shock full scale accelerometer values should be adjustable from about 100 g (g = acceleration of gravity) to 5000 g and the accelerometer should be capable of measurements involving frequencies between 20 and 5000 cps. It is not necessary, although it is desirable, that one unit cover this entire range. For aircraft work accelerometers should have full scale values adjustable from about 2 g to 20 g and should have frequency coverage between 0 and 10 to 30 cps for landing, maneuvering, etc.

b. Velocity meters. Velocities encountered in shipboard shocks seldom exceed 50 ft/sec. Most measurements will encounter maximum values less than 20 ft/sec. Most velocity meters in use at the present time cover a frequency range between about 8 cps and an indefinite upper limit that is of the order of 2000 cps.

c. Displacement meters. Displacements involving frequencies higher than a few cycles per second seldom exceed a few inches for shipboard shocks. A frequency range between 8 cps and 500 cps should generally be covered. The instruments, for shipboard use, should be capable of measuring at least 1.5 inches displacement; for shock machines, 3 to 5 inch motions are sometimes necessary.

The intensities of shocks indicated by the above ranges are such that may occur on board ship without serious damage to the structural parts of the ship.

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7. Vibration measurements here refer to conditions of steady state vibrations. Most of the shock instruments can also serve as vibration measuring instruments. Shipboard vibration measuring instruments should cover a frequency range between 3 cps and 60 cps at maximum amplitudes (1/2 total excursion) up to 0.1 or 0.2 inches, or an amplitude corresponding to 10 g,whichever is greater. Many of the instruments used at this time do not extend to the low frequency end. Aircraft vibrations are generally of much less displacement amplitude than shipboard, but they extend to very high frequencies. However an instrument that covers from a few cycles per second to about 500 cps should suffice for most purposes. Attention is directed to reference (1) for a complete coverage of electrical gaging methods for strain, pressure, and vibrations.

B. Pickup Units for Acceleration-Time Recording.

8. General Types - Accelerometers, as considered in this report, are defined as instruments that give signals proportional to acceleration without requiring differentiation or integration. An accelerometer generally includes a mass that is sufficiently rigid, and sufficiently rigidly supported, so that the mass is subjected to essentially the same acceleration as the portion of the test object to which it is attached. Den Hartog (reference 2) states this by saying that an accelerometer is a seismic instrument with a natural frequency at least twice as high as the highest frequency of the acceleration to be recorded. Sensitive accelerometers, capable of recording high frequencies, must therefore be able to provide measurable signals for displacements of the seismic mass that are small compared with the displacements caused by the high frequency accelerations. Piezoelectric crystals and wire strain gages have, up to this date, been the best means of providing these signals. Sometimes electrical circuits are introduced so as to extend the frequency range of an accelerometer (reference 3) but usually such circuits are not practical as the accelerometers may contain several natural modes of vibration.

9. Accelerometers have been constructed using the following principles of operation:

a. Piezoelectric
   (1) Quartz or tourmaline.
   (2) Rochelle Salt
   (3) Ammonium dihydrogen phosphate, (A.D.P.).

b. Change of Resistance
   (1) Bonded wire strain gages
   (2) Carbon strips or piles

c. Change of Capacity

d. Change of Inductance
   (1) Unbalance of magnetic paths by varying air gaps in iron circuits.
   (2) Magnetostriction

e. Electronic

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f. Optical-mechanical

g. Stylus-mechanical

All of the above types are capable of giving signals proportional to acceleration as a function of time within limited frequency ranges. For high frequency work (over 1000 cps) the types that have been used with success, or show good promise of success are: a. Piezoelectric, (1), (2), and (3); b. Change of Resistance, (1); For low frequency work types d (1), e, f, and g are also of importance. Peak reading type accelerometers will be considered separately.

10. A brief description will be given of the above accelerometer types. A full description of most of these types can be found in the listed references.

11. a. Piezoelectric; (1) Quartz or Tourmaline. A mass is supported on a crystal. The pressure of the mass on the crystal, caused by acceleration of the mass, is measured by the piezoelectric charge developed. Quartz, rather than tourmaline, is used in almost all cases. Accelerometers of this type, made by Westinghouse (reference 4) the Naval Ordnance Laboratory (reference 5) and a British model (reference 6) are shown on Plates 1 and 2. General Electric makes an accelerometer (reference 7) that is very similar to the Westinghouse type. Most acceleration-time curves, requiring high frequency response, have been made with quartz crystal accelerometers.

12. a. Piezoelectric; (2) Rochelle Salt, (3) A.D.P. Rochelle Salt crystals (reference 8) are about 1000 times as sensitive as quartz, but they are mechanically weak and their sensitivity is a function of temperature. Their lack of strength makes them unsuitable for very large acceleration measurements, but for low accelerations they are of great value in spite of their chemical and electrical instability. The A.D.P. (Ammonium dihydrogen phosphate) crystal (reference 9 and 10) is about ten times as sensitive as quartz. It is not as sensitive to temperature as Rochelle Salt over the normal operating range. It is more stable and stronger than Rochelle Salt. Some methods of growing this crystal result in it having objectionably low electrical resistance. It shows fair promise of development for use in accelerometers.

13. b. Change of Resistance; (1) Bonded Wire Strain Gage. Wire strain gages, of the SR-4 type manufactured by Baldwin Southwark Company, are used to measure strain in the supports of a mass that is subjected to acceleration. The supports of the mass may constitute part of the mass. This method of developing a signal proportional to acceleration is generally not as sensitive as the quartz crystal method, for a given frequency range, but has the very great advantage of providing a low impedance source of signal. It also has the advantage of easily being able to have the acceleration modulate a fixed frequency carrier so that zero frequency response can be obtained with A.C. amplifiers (reference 11). A cantilever strain gage type accelerometer (reference 12) and a push-pull longitudinal strain gage type developed at this Laboratory are shown on Plate 3. The wire strain gage type accelerometer has given good results and shows excellent possibilities for development particularly

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for use in the medium and low frequencies (below 2000 cps). The Statham laboratories of Los Angeles make a series of instruments, including accelerometers, in which the seismic mass is supported entirely by fine strain gage type wires.

14. b. Change of Resistance, (2) Carbon Strips or Piles. Accelerometers employing pressure sensitive carbon piles, or pressure or strain sensitive carbon strips, are not sufficiently reliable for shock measurements. The advent of the less sensitive, but more reliable, bonded wire strain gage has largely made these methods obsolete although some laboratories can make reliable records with the carbon type gages.

15. c. Change of Capacity. The small relative motion of the accelerometer mass with respect to the accelerometer body can be measured by the change of capacity between suitably arranged parts. This type of instrument has not been successful for high impact shock work because parasitic capacity changes and electrical charges developed in the connecting cable have been large compared with the pick-up signal. This type of instrument does not show much promise for development.

16. d. Change of Inductance, (1) Unbalance of Magnetic Paths by Varying Air Gaps in Magnetic Circuits. This type instrument is satisfactory for accelerations of relatively low frequency. A Glenn L. Martin accelerometer (reference 13, 14) of this type is shown on Plate 4. The inductance coils are usually placed in an A.C. bridge circuit.

17. d. Change of Inductance, (2) Magnetostriction. Magnetostriction type accelerometers have been constructed, in particular, by Lt. Comdr. Dunbar at the Annapolis Engineering Experimental Station. These accelerometers give good signal output and have low impedence, but the non-linear properties of magnetostrictive phenomena make the interpretation of the signal very difficult.

18. e. Electronic. Electronic type accelerometers have had the least development. They operate on the principle that a small change of electrode spacings may cause appreciable changes of electrode currents. It is expected that they would be useful mainly for low frequency low amplitude accelerations (100 cps and 50 g). The advantage of this type accelerometer is that it is capable of supplying sufficient current so as to operate a microammeter or galvanometer with no auxiliary amplifier. This Laboratory has adopted the "Electrical Micrometer" (reference 15) as a sensitive accelerometer for very low frequency work on aircraft.

19. f. Optical-Mechanical. In the measurement field of low frequency low magnitude accelerations the types of measuring instruments, that may provide suitable records, become very numerous. The types mentioned here do not constitute a complete list.

20. A self contained mechanical-optical type accelerometer has been built by Shrader (reference 16). Its principle of operation is illustrated on Plate 5.

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Air damping and moving film recording are employed. This instrument has three units oriented perpendicularly to each other so as to measure acceleration in three directions. Its range probably extends to 60 cps and several g, the latter of which could be easily increased. It has been suggested (reference 17) that wire strain gages be attached to the cantilever springs so that this instrument can also be used with electrical recording. This would eliminate effects of back lash and slippage that may occur in the mechanical-optical system.

21. A unique type accelerometer that could be built with wide frequency and acceleration ranges is illustrated on Plate 5. It consists of a ribbon with a mirror at its center. The ribbon should be of suitable spring material and should be twisted in opposite directions on either side of the mirror. The ribbon is attached to the accelerometer body at one end and to a mass at the opposite end. The mass is held by a spring so that the ribbon is always in tension. Accelerations, that cause the mass to move small amounts along the axis of the ribbon, cause the mirror to rotate.

22. g. Stylus-Mechanical. For low frequency measurements (below several hundred cycles per second) small self contained accelerometers have been constructed that give recordings of accelerations as a function of time. An instrument constructed by the Naval Ordnance Laboratory (reference 18) records the motion of a seismic mass, along the direction of measured acceleration, by having a diamond stylus press a groove on a strip of celluloid tap. The tap is on a drum that is rotated by a spring drive, thus providing the time axis.

C. Peak Recording Accelerometers and Impact Gages.

23. General Types. There has been, and still exists, a need for simple rugged instruments that give an index of shock severity. Many types of these instruments have been developed and great confusion has resulted because the indications of these instruments have been expressed only in terms of peak acceleration. The frequencies of the measured accelerations usually extend beyond the frequency ranges of the measuring instruments, and as the effective frequency ranges of most of these types of instruments are different, the numerical values indicated by different instruments for a given shock, are not the same. It is not sufficient to express these numerical values in units of peak accelerations without indicating the time required for the instrument response. With most of the impact type gages the situation is still worse as the resulting numerical value indicated is not only a function of the magnitude of acceleration, but also of the number of acceleration oscillations. It is essential that the principles of operation of these types of instruments be understood so that their measurements can be properly interpreted. No attempt will be made to include all developed instruments of these types, however, it is believed that most principles of operation will be included. These types of instruments are classified as follows:

a. Mass-Spring types
   (1) Electrical
   (2) Self contained mechanical recording

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b. Fracture types

c. Crusher and Indentation types

d. Miscellaneous

24. A brief description, illustrating the principles of operation of these instrument types, will be given. This will be followed by a short discussion of the significance of their measurements.

25. a. Mass-Spring, (1) Electrical. This type is best illustrated by the Buchanan cell developed by the transmitter section of this laboratory. A diagram of this gage is shown on Plate 6. A mass is pressed against an electrode by a cantilever spring. When the force, caused by a suitably directed acceleration surpasses the force exerted by the spring, the electrical contact will be broken. If the acceleration persists in sufficient magnitude for a sufficient time the mass will make contact with the opposite electrode. These contact makes and breaks can be easily indicated electrically. Comparison of the break indication of these cells with peak accelerations determined with quartz accelerometers using 12000 cps and with 5000 cps low pass filteration, shows that the Buchanan cell indicates a greater acceleration. This may be taken to indicate that the cells, together with their electrical circuits, respond to frequencies of acceleration greater than about 12000 cps. Not much work has been devoted to analyzing the significance of the "make" electrical contact. It is essentially an instrument of low frequency response, when operating under make conditions, and deserves further attention.

26. a. Mass-Spring, (2) Self Contained Mechanical Recording. Many instruments of this type have been constructed. A model constructed at NRL is shown on Plate 2. It weighs slightly less than a pound. It has 12 cantilever springs radiating from a common center. At the end of each of these springs is attached a suitable mass and a prong. When a suitable directed acceleration exceeds a certain value the mass and prong will move toward the base of the accelerometer and impact against a paper ring. An adjacent carbon paper ring will cause the impression to be permanently recorded. By suitable choosing the springs and masses the range of the instrument can be made to bracket accelerations from 25 g to about 1500 g. The motion of the mass is usually limited to about 0.005 inches.

27. An instrument employing coiled springs, rather than the cantilever type has been built by the Electrical Section (660d) of the Bureau of Ships. This is shown on Plate 7 as the "Putty Gage" peak acceleration indicator. Although this instrument weighs 6 lbs. and is quite large it has performed very well for a variety of uses. It normally has 8 springs and masses that may be adjusted so as to cover accelerations varying from about 20 g to several thousand. Records are made by a conical tip of a shaft that is caused to press into an "artists clay" or "Plasteline" insert (shown on Plate 7) by a suitably directed acceleration. Records not only show that the acceleration has been bracketed between certain values, but by measurements of the diameter of the impression made by the conical tip, the distance of travel of the shaft against the force

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of the spring can be determined. The shaft has to travel several thousandths of an inch before making contact with the clay. Although the gage has sometimes been called the "Putty" gage, it has been found that putty will not provide a suitable substitute for the plasteline.

28. A mass-spring gage, in which the force exerted by a coiled spring on a mass is readily adjustable, is shown as the lower figure on Plate 6. This gage (reference 19) employs a mechanical means of indicating if the mass has been unseated by the acceleration. Electrical menas could as well be employed.

29. b. Fracture Types. Fracture type peak acceleration indicators have a mass supported by a brittle material. An acceleration of a given magnitude and direction will cause the brittle material to break and thus indicate that the acceleration has exceeded a certain minimum value. What this minimum value is can be determined from a knowledge of the tensile properties of the brittle material and the magnitude of the mass. An accelerometer (reference 17) of this type is shown on Plate 7 as the mass-plug acceleration indicator. Various sizes of plugs may be used to extend the range of the instrument. It is essential that the constricted length of this plug be short so as to keep the natural frequency of the unit high. The Naval Research Laboratory has constructed gages of this type containing up to 7 mass-plugs. The masses were small, 1/4 to 1/2 inches in diameter and 3/4 inches long. The plugs were of phenolic material and were molded as 8:32 screws. A constricted section was turned in the center of these molded screws. A unit containing 4 to 7 mass-plugs weighed less than a pound. The range of accelerations indicated was from about 25 g to 2000 g. It is to be noted that with short constricted areas in the plug it is possible to use metallic plugs without much elongation before fracture.

30. c. Crusher and Indentation Types. The crusher and indentation type peak acceleration indicator consists of a mass that is supported by a relatively soft inelastic material, such as annealed copper or lead. Accelerations cause the mass to exert a sufficient force so as to deform these supports. Generally the calibration consists of determining the deformation as a function of static load exerted by the mass on the supports. By consideration of the magnitude of the mass, the deformation can be expressed in terms of maximum acceleration.

31. There are three principal reasons why the values indicated by these instruments are not the true peak values. These are:

a. High impact types of shock are almost always oscillatory. Unless special construction or preloading is employed, the mass will be held loosely by its supports after the first deformation, and multiple impacts will cause too great a deformation.

b. The displacement associated with a short time duration acceleration pulse may be small compared with the displacement required by the gage element for that acceleration indication. This is equivalent to stating that the period of the acceleration pulse is too short compared with the effective natural period of the gage.

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c. the static calibration allows more "creep" to occur than occurs during normal use of the gage.

In spite of the inaccuracies of these types of gages they are widely used. Moreover, if used with full knowledge of their properties, they can provide valuable information. All of these types of instruments must be given an effective natural frequency which should be high compared with the frequencies associated with the peak accelerations considered. This point will be further discussed in paragraphs 37 through 39.

32. An impact gage in which a steel sphere is supported by 6 small annealed copper balls is shown on Plate 8. This is one of many types built by the Naval Ordnance Laboratory (reference 18). Others described in reference 18 include wedge type gages in which a wedge is forced by a spring to take up the slack caused by the deformation of the copper balls. This is in consideration of the first point mentioned in paragraph 31. A British (reference 20) unidirection type employing an annealed copper ball is also shown on Plate 8. Indenter type gages designed by General Electric and by N.D.R.C. (reference 21) are shown on Plate 9.

33. d. Miscellaneous. Many other types of gages have been constructed to operate as complete self recording units and to give various types of information concerning the intensity of shock. None of these types have been widely used. Perhaps the only one of these that involve different principles of operation than the preceeding types are the tuned reed instruments. This type of instrument consists of a series of springs of different stiffness. Each spring supports a given mass. Usually the springs are cantilever type of varying length. The maximum deflection suffered by each of the springs can be recorded by some scribing device and some indication of shock properties is thereby given. Because of the difficulty in interpreting the values indicated by this device it probably will not be greatly used, although it may indicate resonant frequencies and, for single impulse type shocks, it could indicate velocity changes and the time for the velocity change to take place.

D. Acceleration and Impact Gage Measurements - Their Significance.

34. Acceleration Measurements Stress High Frequency Components of Shock and Vibration. A rough rule of thumb for shipboard shocks of reasonably severe intensity states that the numerical value of the acceleration, expressed in units of gravity, may attain values about equal to the frequency, expressed in cycles per second, associated with the acceleration. It is obvious that unless great velocities are attained the time of duration of large magnitude accelerations (1000 g) must be small. In other words the frequency components of the large magnitude accelerations must be high. The displacements associated with the high frequency large magnitude accelerations are small. For example the displacement of a sinusoidal wave having an acceleration amplitude of 1000 g and a frequency of 3000 cps is only about 0.001 inch single amplitude.

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35. Consider a displacement vibration represented by

$$x = A (\sin \omega t + 0.01 \sin 100 \omega t)$$

which represents a wave composed of a fundamental and a harmonic of 1/100 the amplitude and 100 times the frequency of the fundamental. It would be hard to detect the harmonic on a usual displacement curve because of its small amplitude. If this equation is differentiated twice with respect to time an equation representing the acceleration is obtained. This is:

$$x = -A\omega^2 (\sin \omega t + 100 \sin 100 \omega t)$$

A picture of the acceleration curve will show the harmonic to have 100 times the amplitude of the fundamental and so for the acceleration curve the fundamental would be difficult to detect. Because of these facts acceleration curves are usually rich in high frequency components.

36. Accelerations Occuring During Measurement Generally Exceed the Frequency Range of the Accelerometer or Impact Gage. It is well known (reference 2) that accelerometers should have their lowest fundamental natural frequency about twice as high as the highest acceleration frequency to be measured. If suitable damping exists in the accelerometer the range may be extended to near the resonant frequency. As the frequency of high impact type accelerations appears to extend to indefinitely high values it is apparent that the values measured will be a function of the gage used. There is usually little difficulty in determining the natural frequency of a gage that gives acceleration as a function of time, and by suitable damping or filtration the upper frequency range of the instrument can be quite well determined. However, most of the peak reading acceleration indicating devices have no natural frequencies of significant values. Attempts that are made to compare peak acceleration values obtained by different gages lead to confusing results.

37. High Frequency Limits of Peak Reading Accelerometers and Impact Gages. It is realized that all accelerometers and impact gages fail to indicate true values of acceleration if the acceleration frequencies are above certain values. It is necessary to realize the frequency limitation of the gage in use so that when peak accelerations are expressed it will be known that they do not include frequencies above a certain value.

38. The types of acceleration measuring instruments may be idealized as the mechanical arrangements shown in Figure 1.

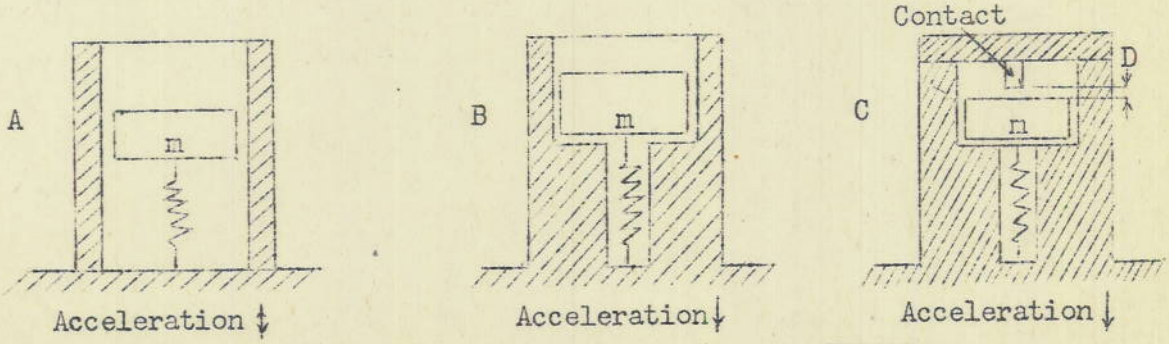

Figure 1 - Accelerometer and Impact Gage Types

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Part A can be taken to include, besides the acceleration-time recording instruments, the fracture, crusher, and indentation types classified in paragraph 23. Part B represents a contact break type. Part C represents a contact make type or a type that requires the mass to travel quite an appreciable distance before recording.

39. With some reservations, see paragraph 31, the fracture type instrument can, for this particular discussion, be included as an instrument with elastic springs. Crusher and indentation gages will be assumed to be of this type and will be given an "effective" natural frequency that should be about twice as high as the upper frequency range of the instrument. This effective natural frequency is simply taken as:

$$f = \frac{1}{2\pi}\sqrt{\frac{g}{\delta_{st}}} = 3.14\sqrt{\frac{1}{\delta_{st}}} \text{ cycles per second}$$

g = acceleration of gravity, inches/sec^2

δ_{st} = static deflection; inches = W/k

W = weigh of mass, pounds

k = spring constant, lbs/in.

For example, the N.O.L. Ball peak reading accelerometer (reference 18) has a static deflection of 5×10^{-5} inches for the 1-1/2" diameter steel sphere on the 5/32" copper balls. Its effective natural frequency is 444 cps. This instrument could not therefore be expected to give correct indications for accelerations having appreciable frequency components in excess of 220 cps.

40. The assigning of an upper frequency limit to an acceleration indicating gage by the above method is simply one way of being assured that the relative displacement of the mass and accelerometer body is small compared with the displacement resulting from the acceleration. For acceleration indicators Parts B and C of Figure 1 some trouble is experienced in determining the upper frequency limit. For the contact break, type B instruments, the amount of motion required is indefinite, but very small. The Buchanan cell, paragraph 25, for contact break indicators, has been compared with the crystal accelerometer with 12000 cps low pass filterations. The Buchanan cell indicated greater peak values for a given shock. It may be inferred from that that this gage with its recording circuit is capable of recording peak accelerations with frequency components in excess of 12000 cps.

41. For Part C the reaction of the mass to a simple square wave acceleration pulse will be considered. This pulse is shown on Figure 2.

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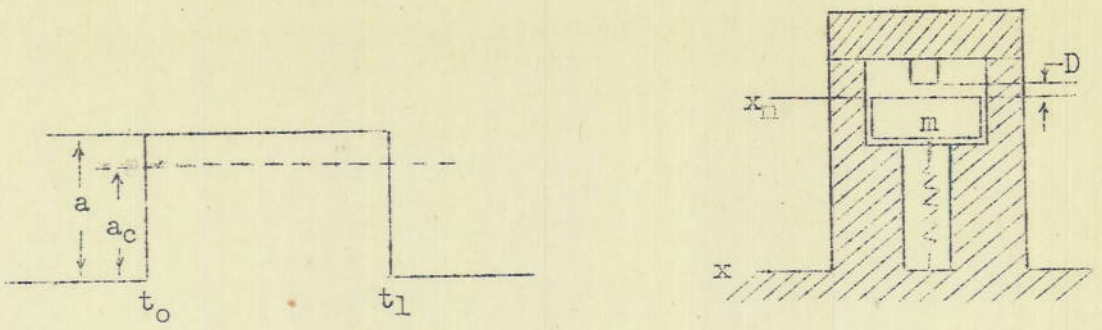

Figure 2 - Displacement of a mass to a square wave acceleration pulse.

Let F = force exerted on the mass by the spring. Assume that this force remains constant for the small spring deflections permitted.

m = mass
a_c = F/m = acceleration required to just raise the mass from its supports.
a = Acceleration amplitude of square wave pulse.
t_o = beginning of pulse = 0.
t_1 = end of pulse.
t = $-t_o + t_1$ = duration of pulse = t_1
x = displacement of gage
x_m = displacement of mass

For a greater than a_c the motion of the mass is defined by:

$$\frac{d^2 x_m}{dt^2} = a_c$$

and the motion of the gage body is

$$\frac{d^2 x}{dt^2} = a$$

If the initial velocities and displacements are taken as zero then the distance traveled by the mass and the gage are respectively

$$x_m = \frac{a_c t^2}{2} \quad \text{and} \quad x = \frac{at^2}{2} \quad \text{for} \quad t_o \leqq t \leqq t_1$$

42. It is required to determine the greatest relative displacement between the mass and the gage body. This is equal to $(x - x_m)_{max}$. It is apparent that this difference gets continually greater throughout the interval from $t = t_o$ to $t = t_1$, therefore, the interval $t > t_1$ must be considered. For $t > t_1$ there

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will be zero acceleration acting on the gage so

$$x = at_1 (t-t_1) + \frac{1}{2} at_1^2 = at_1 t - \frac{1}{2} at_1^2$$

However the acceleration ac will continue to act on the mass until collision with its support, so until $x_1 - x_m = 0$ we have

$$x_m = \frac{a_c t^2}{2}$$

$$x - x_m = at_1 t - \frac{1}{2} at_1^2 - \frac{a_c t^2}{2}$$

Determine the time at which the maximum difference occurs by differentiating and setting equal to zero

$$\frac{d(x-x_m)}{dt} = at_1 - a_c t = 0$$

$$\text{So } t = \frac{at_1}{a_c} \quad \text{and}$$

$$(x - x_m)_{max} = \left(\frac{a^2}{a_c} - a\right) \frac{t_1^2}{2}$$

43. Let D be the distance the mass has to travel, with respect to the gage body, before recording, and let a 10 percent error be permitted in the measurement of the acceleration, or $a = 1.1\, a_c$ then

$$D = (1.21 - 1.1) \frac{a_c t_1^2}{2} = .055\, a_c t_1^2$$

$$t_1 = 4.26 \sqrt{\frac{D}{a_c}}$$

where t_1 is the shortest duration square wave pulse that can be recorded within an accuracy of 10 percent.

44. As only an estimate of the upper frequency limit can be given, considering the unknown boundary conditions, it is reasonable to say that acceleration values will not be correctly indicated if the frequency exceeds $\frac{1}{2t_1}$.

As an example consider an instrument such as the NRL cantilever type, paragraph 26 and Plate 2. Let the distance of travel of the mass be D = 0.01 inches then for the following values of calibrated peak accelerations a_c we get the tabulated upper frequency range.

a_c	10g	30g	100g	300g	1000g	3000g
f(cps)	72.5	126	230	400	726	1260

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45. It is suggested that when peak accelerations are given that there also be included an indication of the upper frequency range of the recording apparatus.

46. Relation of Acceleration to Damaging Effects. The scope of this topic is of course much too large for a complete discussion here and only a few of the more widely considered factors will be discussed.

47. For many types of apparatus it is assumed that the probability of damage is proportional to the strain that occurs in, or a force that is exerted on, a part under consideration. This type of damage may exclude equipment involving relay contacts and a few others.

48. It is possible to calculate the strain that occurs in parts of equipment due to a given shock wave. In order to make the calculations reasonable simple it is generally assumed that equipment parts consist of rigid masses supported by flexible elements of negligible mass and fixed spring constants. Under such assumptions the force exerted on a mass and the strain in a flexible element is proportional to the total deflection of the flexible element. A force applied to one end of the flexible element is instantly transmitted to the other end. These assumptions are sufficiently good approximations in many cases. In particular they apply for a shock mounted equipment where the supported mass is both heavy and rigid compared with the mounts. These assumptions permit the application of "vibration isolation" principles, two of which are: (1) the detailed wave form of an applied shock motion is immaterial for periods of time short compared with natural periods of an equipment under test, and (2) An applied shock acceleration wave may be replaced by a static acceleration of magnitude equal to the maximum value of the shock wave if the period associated with the shock wave is long compared with the natural periods of an equipment under test. If these principles are used with full appreciation of the assumptions involved they can be of great value to design engineers.

49. As an example of the first of the above principles consider an equipment attached to a platform by means of flexible mounts. Let the platform acquire a given constant velocity in a time that is short compared with the period of the equipment on its mounts. Then the wave form and magnitude of the accelerations of the platform are not of great importance. The important factor is the change of velocity that takes place. From this change in velocity the force exerted by the mount on the equipment and the deflection of the mount can be calculated. Several papers (reference 22, 23, 24) have been written on the subject of damage caused by shock. Mr. Wagenseil (reference 24) states "If the time that an acceleration pulse lasts is less than $0.35/\omega$, (ω = radians/sec natural frequency of an equipment subjected to the acceleration pulse) the destructiveness of the shock can be expressed simply in terms of the amount of change in velocity of the supporting structure. Furthermore, this change may be considered to occur instantaneously."

50. If the assumptions involved in the above statements were generally valid it would not be necessary to make acceleration measurements involving frequencies higher than about 1000 cps as almost all equipment is supported so

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as to have natural frequencies less than a few hundred cycles per second. However, the assumptions are not valid for equipment in general. As an example suppose one end of a uniform rod is rigidly attached to a platform so that the rod is perpendicular to the platform surface. Let the platform and rod be initially at rest and then let the platform acquire in a certain time a given constant velocity in a direction perpendicular to the rod. In this case the wave form and magnitude of the acceleration of the platform is of importance even though the time for attainment of the final velocity is short compared with the lowest natural frequency of the rod. This case is illustrated in reference 23. At the present time there is little general knowledge concerning the propogation and strain magnitudes of transverse waves in beams and plates caused by transverse impacts (reference 25). A more complete knowledge of this subject would be of great value for the understanding of shock damage effects.

51. At the present time designers make little direct use of the high frequency large magnitude components of shock acceleration measurements. They realize that they can cause trouble for relay contacts, instrument needle bearings, and brittle materials. They justifiably disregard them for ductile materials. They do not usually understand the nature of transmission of transverse waves in plates and beams. It is to be expected that as designers gain knowledge on these matters that the higher frequency components of acceleration measurements will have more direct design value.

52. As our knowledge of the damaging effects of shock is limited and as the design applications are so involved it is always necessary to depend on a shock test to determine the ability of an apparatus to withstand shock. A most important use of acceleration measurements is the comparison of a shock machine's characteristics with other machines and with field results. It should be assured that those general components of shock that exist under field conditions also exist in shock testing machines.

E. Velocity Meters

53. General Types. A velocity pickup unit is here defined as an instrument that gives signals proportional in magnitude to a velocity being measured without integration or differentiation. The only types of velocity meters in general use involve the principle of changing magnetic flux linkages in a coil of wire. These require a relative velocity between a magnetic field and a coil of wire to be proportional to the velocity being measured. There is no difference in principle between a vibration-velocity meter and a velocity meter. The vibration-velocity meter usually will measure motions involving only small displacements, about 1/4 inch, while the velocity meter as used for high impact shock work encounters displacements up to several inches.

54. Shock measurements made in this country cover the desired frequency and amplitude ranges encountered by measuring both acceleration and displacement. The British, in an attempt to span this range with one type of instrument, developed and used predominately velocity measuring devices. In actual

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practice field measurements in both countries use displacement, velocity, and acceleration measuring instruments. Velocity measurements made by the Navy in this country have been made with the British type velocity meter.

55. Magnetic velocity meter types, see Plate 10, can be divided into four general classes:

a. Movable short coil in a long uniform radial magnetic field.
b. Long uniformly wound movable coil in a short radial magnetic field.
c. Long fixed uniform coil threaded by an axial differential magnetic field.
d. Differentially wound long uniform coil threaded by an axial magnetic field.

There is generally no fixed reference position during field shock measurements. Under these conditions the velocity meters are constructed as seismic type instruments with the flexibility supported mass having a natural period between 5 and 10 cps.

56. The British velocity meter is of type (a) with the magnetic sections seismically supported. Instruments have been constructed with permissible travel, of the coil with respect to the field, of slightly over an inch. It is difficult to obtain a long uniform magnetic field without requiring a considerable weight of material. The usual British velocity meter weighs about 35 lbs., and while some of this weight is seismically mounted, so as to not be very effective during a shock, the meter is too cumbersome for most works other than field measurements. It is regretable that no serious effort has been directed toward the development of a suitable velocity meter of the b, c, or d types as it appears that the requirements of up to several inches of travel without very great mass could be met for these types.

57. A velocity meter of type c has been described by reference 21. A velocity meter of type d has been constructed at the Naval Research Laboratory. This model has a movable iron rod 3/8" in diameter and 12 inches long (see Plate 10). The external dimensions of the magnetic field circuit are 6" in length and 1-1/4" in diameter. The gage was linear over a travel of slightly greater than 3 inches. The signal contained a small amplitude high frequency component, about 15000 cps, that is characteristic of the instrument.

58. It is interesting to note that all of the four types of velocity meters become displacement meters if an alternating magnetic field is used. There are considerable eddy current losses under the usual types of construction, but the signals generated can be made sufficiently large without undue heating of the parts.

59. Liquid Filled Seismic Type Velocity Meter. It is often a disadvantage, in the construction of a velocity meter or a displacement meter, to require that the relative displacements of a seismic mass and the gage body be large. A method of reducing this relative displacement has been described in references 26 and 27. The principle of operation will be briefly given.

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Assume a mass is suspended in a liquid by very weak springs. The mass and liquid are in a closed container with no included gas. If the container body is accelerated the mass will also be accelerated. If the density of the mass is less than the liquid the mass will suffer a greater acceleration than the container. If the densities of the mass and the liquid are the same the accelerations will be the same and there will be no relative motion. It has been shown (reference 27) that if the spring forces and damping forces are negligible that the relative motions of the mass and container will always be exactly proportional to the motion of the container, or:

$$\ddot{x} = (1 - \rho/\rho_m)\,\ddot{x}_o$$
$$\dot{x} = (1 - \rho/\rho_m)\,\dot{x}_o$$
$$x = (1 - \rho/\rho_m)\,x_o$$

Where x_o and x represent displacements of the container and mass respectively.

60. ρ and ρ_m represent densities of the liquid and of the mass respectively. The instruments of this type that are available at the present time have not proved satisfactory for shock work, but there does not seem to be any insurmountable difficulties involved in the design of a suitable instrument.

F. Displacement Gages.

61. General Types. The displacement devices considered will be those instruments that give signals proportional to displacement without differentiation or intergration. In addition some simple devices for determining maximum relative displacement will be discussed. A great variety of displacement measuring devices exist. The types and examples listed here are only those that have been used for shock measurements. The displacement-time measuring devices will be divided into 4 general classes:

a. Direct Photographic
   (1) Streak photography
   (2) Modified streak photography
   (3) High speed moving pictures

b. Electrical
   (1) Photoelectric
   (2) Change of inductance
   (3) Change of coil position in an alternating magnetic field
   (4) Change of resistance.

c. Mechanical

d. Miscellaneous

e. Peak relative displacement gages.

These classes will now be separately considered.

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62. a. Direct Photographic, (1) Streak Photography. Displacement measurements by streak photography have been extensively used by the Taylor Model Basin. The method is illustrated in Figure 3 below.

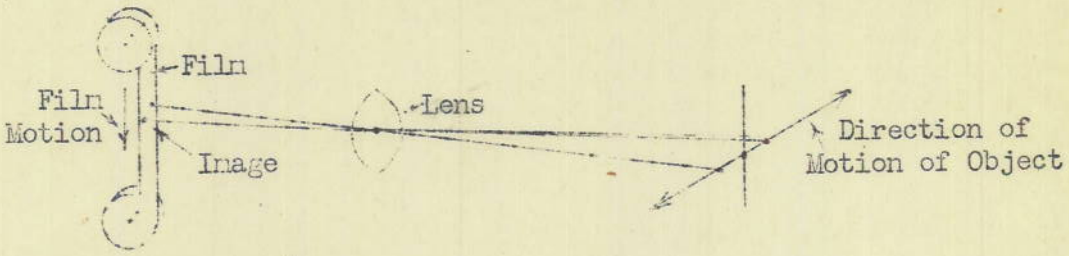

Figure 3 - Streak Photography

A moving film camera, such as the G. R. type 651A-E, is arranged so that the direction of shock motion is perpendicular to the cameraoptic axis and the direction of film motion. Suitable bright spots are then arranged against a dark background on the object whose motion is being studied. These bright spots may be illuminated small areas of white paint or they may be inset, illuminated, ball bearings. Several spots may be in the field of view and, consistant with depth of focus requirements, they can be spread over any distance from the camera. The method is exceedingly direct and simple. The chief source of error lies in the possibility of object motion in the direction of the film motion. This error can be reduced to small values by having the film velocity large compared with the image velocities. This is not always possible if the lens-object distance is small.

63. a. Direct Photographic, (2) Modified Streak Photography. In order that the effects of object motions parallel to the film motion may be in part eliminated a modified method of streak photography has been devised. The method is illustrated in Figure 4 below.

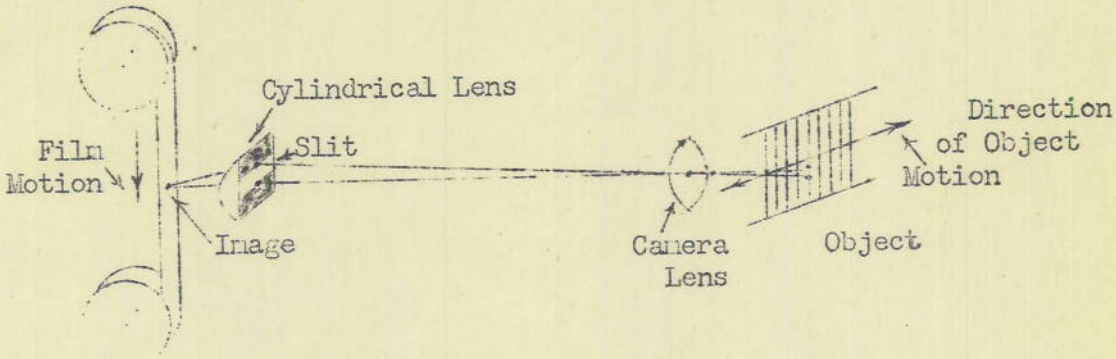

Figure 4 - Modified Streak Photography

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64. The object consists of a series of bright lines on a dark background. The lines are equispaced and run parallel to the direction of film motion. The direction of motion of the object, which is rigidly attached to the part whose shock motion is being studied, is perpendicular to the camera optic axis and to the direction of film motion. The camera lens will focus a line image on the film. A cylindrical lens, placed near the film focuses the line to an approximate point. Motions of the object in a direction parallel to the film motion will not result in any displacement of the image on the film. Rotations of the object about an axis parallel to the camera optic axis will cause a second order displacement of the image.

65. An arrangement used at the Naval Research Laboratory has an object that consists of a grid of piano wires, about 0.01" diameter, spaced 0.2" apart in narrow grooves milled in a black bakelite base. The object is varnished so as to cement the wire in position. A 2.0" focal length lens of f1.9 aperature is attached by means of an extension tube to the GR651A-E General Radio camera so as to be about 9" from the film. This arrangement causes the object to be enlarged about 4 times in linear dimensions and the image of sections of 2 object wires can be seen on the film if one image is near the edge of the film. This fixes the displacement scale of the object on the film. The cylindrical lens was made by sectioning and polishing a lucite rod, of about 5/8 in diameter, which was cemented to bakelite plate. This plate contained a slit about 1/16" wide as illustrated and replaced the ordinary film gate plate. Fair pictures may be had with a 1/32" wide slit and no cylindrical lens. Best results are obtained if the source of illumination is small, such as a laboratory arc with a focusing lens, the light must of course be in a plane containing the camera optic axis and perpendicular to the grid lines. Sufficient illumination is easily obtained for writing speeds of 100 ft/sec. A displacement curve of a part of the light weight high impact machine (reference 28) obtained by this method is shown on Plate 40.

66. a. Direct Photographic, (3) High Speed Moving Pictures. Motion picture cameras, that require intermittent film motion, normally do not take pictures at rates exceeding 128 frames per second although speeds up to 275 frames per second (reference 29) have been attained. For exposure rates greater than a few hundred frames per second it is necessary to have continuous film motion. This requires either, (a) that the picture image move with the film during the exposure time, or (b) that the film has not moved an appreciable distance during the exposure time interval. Some of the principal methods of accomplishing this are illustrated on Plates 11a and 11b.

67. The methods employed for moving the image along with the film are discussed in detail by Tuttle and Reid (reference 30). They group the methods as:

a. Moving lenses
b. rotating or moving plane parallel plates
c. refracting prisms
d. reflecting plane mirror
e. skewed image forming elements.

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68. Some of the specific models will be mentioned here. The Western Electric "Fastax" (reference 31) and the Eastman type III (reference 32) operate by having the image moved by a rotating plane-parallel plate or prism (see Plate 11a). The Western Electric takes up to 4000 or 8000 frames per second for 16 or 8 mm pictures respectively. The Eastman takes up to 3000 frames per second on 16 mm film. For both cameras film lengths up to 100 ft. can be used. The exposure time is about 1/5 of the time per frame. It should be mentioned that the large diameter sprocket wheel and the large distance of film contact on this sprocket wheel for the Fastax camera requires very accurately perforated film. Special film that has been very carefully stored must therefore be used. This requirement is much less severe for the Eastman type III camera which is generally much easier and more convenient to operate. A Zeiss-Ikon (reference 29 and 33) camera can take pictures up to 6000 frames per second. The image is moved by means of mirrors mounted on a drum. This type of camera is shown on Plate 11a. A Vinten (reference 29) 35 mm camera can take pictures up to 3000 frames per second. The image is moved by the rotation of a disc around the periphery of which is attached a battery of lenses. A Vinten (reference 29) or a Jenkins (reference 38) type camera is illustrated on Plate 11b. Prince and Rankin (reference 34) have developed a pin hole camera that can record 1000 frames at a rate up to 120,000 frames per second. This method is equivalent to a moving lens type but as the aperature is small it is only useful for very bright objects such as arcs explosions, etc.

69. The second method employs intermittent light sources in order to get exposure times completed during negligible film motions. Various stroboscopic light sources have been used, the most common of which consists of a gas discharge tube type developed largely by Edgerton (reference 35) and manufactured by General Radio. About 1500 frames per second are possible with these light sources. The 35 mm General Radio type 651 camera is usually synchronized with the stroboscopic light source and used for the recording camera. Often methods of spark illumination are used to take one to several dozen closely spaced pictures (reference 36 and 37). The method illustrated on Plate 11b,taken from reference 37, has 8 spark sources, f, a large diameter light gathering lens, L_c, camera lenses, L, and films F. The films are located back of the camera lenses in the proper position and the lens is focused on the object O. Good shadow pictures can be taken at rates of several hundred thousand frames per second.

70. Comparison of Direct Photographic Methods. The methods of streak photography and high speed moving pictures both have their fields of major usefulness. When the direction of motion of an object is known and is along a straight line and not much knowledge as to the overall action of the object is desired, then it is preferable to employ streak photography. The advantages of streak photography over moving pictures are two fold: (a) it provides a continuous record of displacement as function of time rather than the location at each exposure time, and (b) it provides a displacement curve completely plotted thus eliminating the tedious tabulation of data from moving picture records. To off-set these advantages the moving pictures not only provide information from which motions in several directions of all points visible in the field of view can be obtained, but they show an overall record

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of displacements, deformations, and events, that are of extreme value to the practical designers of the equipments under study.

71. Moving image type high speed moving picture equipment generally are more compact and convenient than the stroboscopic types. The former can obtain sufficient illumination with photofloods such as the R2 and R3 types and can be used up to about 1000 frames per second with only sunlight for illumination. The stroboscopic types must,of course, have little or no continuous illumination and require very specialized lighting equipment. They have the advantage of providing very sharp pictures and using any size film, although 35 mm is normally used.

72. b. Electrical, (1) Photoelectric. A photoelectric displacement meter has been developed by Cutler-Hammer (reference 39) and has been used for shock measurements on Navy Shock machines. The measurements should be accurate and may provide a means of checking acceleration measurements. It is probable that this method cannot compete with other less accurate methods because of the greater difficulty involved in its use.

73. b. Electrical, (2) Change of Inductance. A travel recorder has been constructed by General Electric (reference 40) that consists of an inductive wound coil the inductance of which is controlled by the position of a core of magnetic material that slides inside the coil. The core, an iron rod, is rigidly attached to the object whose motion is to be studied and the coil is fixed in space. The position of the core is then measured by determining the inductance of the coil. Travel of one (1) inch is possible directly, for larger displacements a lever system is used. It is not expected that this recorder will be suitable for displacements associated with frequencies greater than a few hundred cycles per second. A similar device has been successfully constructed. and used by the New York Navy Yard (reference 12). A slightly different travel recorder has been built by the Engineering Experimental Station (reference 41) at Annapolis. This consists of a primary exited by 18 KC wave.

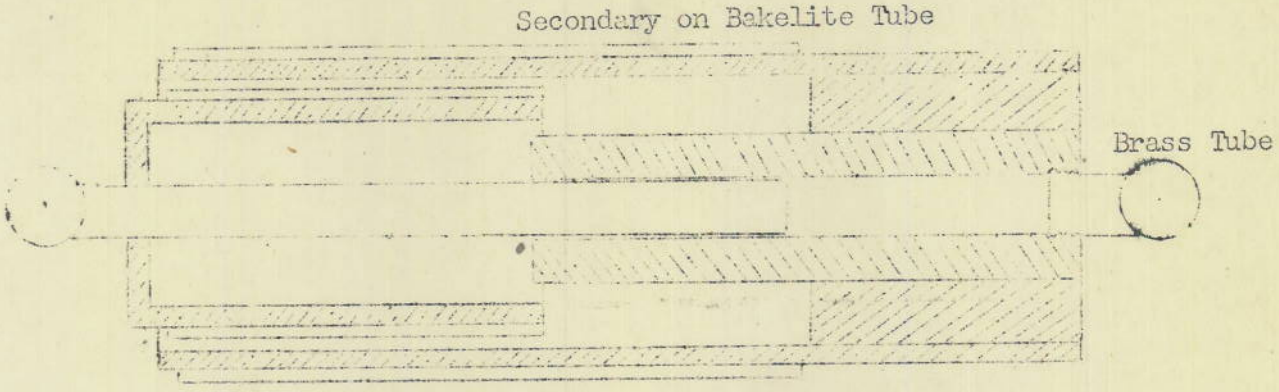

Figure 5 Engineering Experimental Station Moving Coil, Displacement pickup.

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The primary slides over a brass tube. Because of the losses introduced in this manner the secondary voltage is changed. This pickup is reasonably linear over several inches.

74. b. Electrical, (3) Change of Coil Position in an Alternating Magnetic Field. If an alternating magnetic field were applied to the velocity meter types, shown on Plate 10, then the voltage induced in the coils would be proportional to the location of the coil within its travel limitations. It is necessary that the alternating field period be short compared with displacement times considered. Instruments of this type are not extensively used.

75. b. Electrical, (4) Change of Resistance. It is surprising that this, the simplest of electrical displacement measuring methods, has not come into more general use. The essential difficulty that has prevented its extensive use is the problem of retaining good electrical connections across sliding contacts that are essential for this type of instrument. Two types that have performed satisfactorily under shock conditions are shown as (A) and (B) of Plate 12.

76. Type (A) has two wire wound resistance cards connected in parallel. Each of these have about 2500 ohms resistance. The spring contacts make four independent connections to the resistance. The spring contacts make four independent connections to the resistance. The unit is connected as a voltage divider so that the voltage between the sliding contact and one end of the resistance is proportional to the position of the contact. Some care is necessary to see that the voltage between the sliding contacts and either end of the resistance is not changed appreciably if any of the contacts are broken. It is possible to get several volts output pick-up voltage. The discontinuities caused by the contacts passing from one turn of resistance wire to another on the resistance card will limit the use of the instruments to displacement changes greater than about 0.01 inch.

77. A slide wire resistance pick-up unit developed by Westinghouse, is shown on B of Plate 12. This again is used as a voltage divider so that the voltage across the pickup unit is proportional to the position of the contact. By having two contact springs, as illustrated, the inertia effect of any acceleration along the long pickup axis will not tend to cause the contact to break. As the total resistance of the slide wire is small the voltage possible across its ends is small and the voltage output of the unit will be small. However, the output of the unit is sufficient to operate directly a sensitive magnetic galvanometer oscillograph unit. As the total resistance of this circuit is only in the order of 10 to 100 ohms small changes of contact resistance will be important. It may therefore be necessary to clean the slide wire at frequent intervals.

78. c. Mechanical. Mechanical displacement recorders considered, plot a direct record of the displacement as a function of time. Most types consist of rotating discs or cylinders moving at known speeds, the displacement is recorded by having a scriber travel perpendicularly to a direction of disc or cylinder motion. While it is possible to quickly improvise an instrument that will give fair results, it is not possible to get consistantly good

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results unless great care is taken in its design and construction. The principal factors to be considered in the design is rigidity of the instrument, especially the parts partaking the shock motion; and provision that the shock cause little change of scriber pressure. Probably the best instrument of this type has been designed by Mr. Hess, of the Bureau of Ships, and is shown as (c) of Plate 12. A rotating cylindrical drum, D, has a piece of carbon paper and graph paper placed face to face on its inside surface. A carefully guided scriber, A, can move freely only along the axis of the drum. A displacement record is plotted directly by the pressure of the scriber against the graph paper and carbon paper. A comparison of the displacement record obtained with this instrument and by the modified method of streak photography is shown on Plate 13.

79. d. Miscellaneous. Most of the displacement instruments considered require a fixed point of support and an attachment to the object whose motion is being studied. For field measurements there is usually no fixed point of reference available. In such cases seismic type instruments are used. These generally have natural periods up to about a second in length. These can measure displacements that take place in times short compared with the natural periods. The various pallographs used by the Taylor Model Basin are instruments of this type.

80. e. Peak Relative Displacement Gages. Reasonably accurate devices can usually be constructed by an ingenious individual that will indicate the maximum relative displacements between two parts. Artists clay, putty, chewing gum, and nails driven into a board, have all been used at various times with results of sufficient accuracy for the immediate purpose.

81. A device that has proved itself very convenient and useful

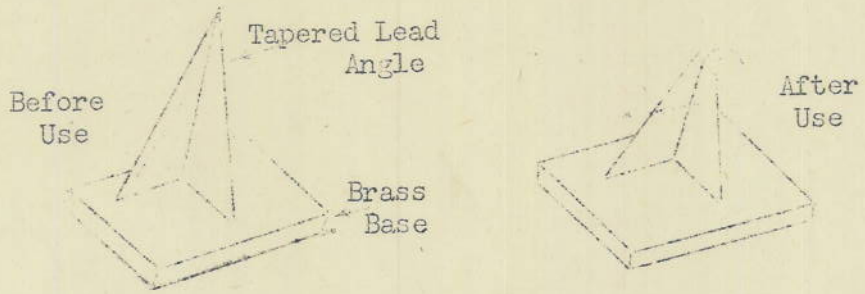

Figure 6 Tapered Lead Angle Maximum Displacement Gage

is shown in Figure 6. It consists of a tapered lead angle soldered to a base.

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The lead is about 1/32th inch thick with the sides of the angle about 1/2 inch wide at the base. Its length is trimmed to suit any particular use. The base is 1/8 inch thick brass and large enough to allow mounting holes or the attachment of clamps. To solder the angle to the base it is best to heat and tin the brass base with an excess of solder over the area of attachment. Then with the base still hot press the bottom of the lead angle into the liquid solder on the brass base and allow the assembly to cool. The gage is attached so that the relative motions of the two parts will crush a section of the lead angle and so allow the maximum relative motion to be determined. The device is reasonably accurate for velocity changes encountered in normal shipboard shock work.

G. Strain Gages

82. Bonded Wire Strain Gages. Because of the ease of application, convenience, and very small weight, the bonded wire type strain gages (reference 42) have shown themselves to be the most suitable strain gage for general use for shock measurements. This type of gage has been described in many papers (reference 43) in the last several years. It consists of a wire, about 0.001 inches in diameter

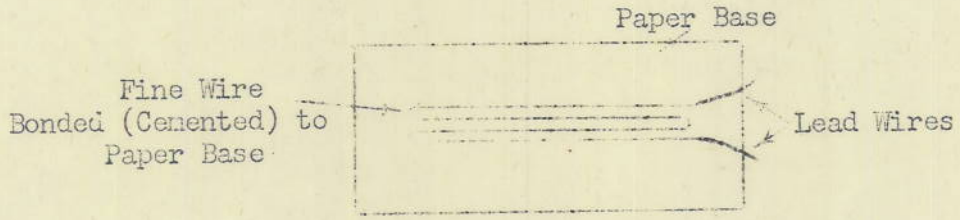

Figure 7 Wire Strain Gage

wound either on one side of a thin paper, as shown on Figure 7, or wound around a piece of paper. Usually one side of the gage is covered with felt to decrease temperature effects. The gage is attached to a surface for strain measurements by means of "duco" household cement, bakelite cement, or several other adhesives. Care should be taken that the cement is given full opportunity to dry before measurements are made. If no heat above normal room temperature is applied, and if the gages are open to the air, at least 24 hours should elapse for drying of duco cemented gages. If heat is applied and the gages are open to the air the drying time may be shortened to several hours. For dynamic measurements no unusual care need be taken to eliminate thermocouple effects, strains, and resistance changes caused by temperature effects. However for static measurements, in which the resistance changes take place over long periods of time, great care must be taken to eliminate all drifts. It must be remembered that the resistance changes involved may be only a few hundredths of a percent of the gage resistance. While strain records are rarely used in the description of shock they represent a very important measurement when obtained at critical points on apparatus being shock tested for

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development purposes. They are of great practical value to the design engineer.

83. Other strain gages that have been used for strain measurements during shock have been the magnetic strain gage (reference 44), a long base self recording gage (reference 45), and the use of brittle lacquer (reference 46). It is probable that the last mentioned method could give considerable information of value to the development engineer when used with shock tests performed for development purposes.

H. Vibration Measuring Equipment.

84. Ranges of Vibration. Many of the shock measuring instruments mentioned in the previous sections can also be used as vibration measuring instruments. Their differences do not involve different principles of operation, but only differences in range requirements. The displacements and accelerations involved are much less for the steady state vibrations considered. Shipboard vibrations rarely exceed 0.25 inch double amplitude, see Plate 32 and reference 47. For frequencies greater than several cycles per second the maximum amplitude of vibration encountered decreases as the frequency increases. Shipboard vibrations at frequencies greater than 30 cps occur infrequently and only at small amplitudes. Vibrations that occur on shock mounted shipboard equipment may be considerably amplified, as the resonant frequencies of the equipment on its mount is usually greater than the forcing frequencies. Vibration amplitudes and frequencies of most vibration machines, used for testing according to many Navy specifications, extend from about 6 cps to about 55 cps at amplitudes up to 1/2 inch or 10g, whichever is greater, although there are many exceptions. Aircraft usually suffer less vibration displacement amplitude, at locations within the plane body, but the vibrations extend to frequencies of many hundreds of cycles per second.

85. Vibration measuring instruments should therefore include a frequency range at least between several cycles per second and several hundred cycles per second if they are to cover the most important band. Some instruments should be available with frequency response, to several thousand cycles per second, for a few measurements on aircraft.

86. Vibration measuring instruments should be capable of measuring up to 1/2 inch double displacement amplitudes provided that the maximum acceleration encountered need not be greater than 10 g over the entire frequency range. It is probable that severe cases of resonance will occur that will require improvised measurement methods. Instruments that include only part of the above indicated ranges may be satisfactory for their particular uses. There are many kinds of vibration measuring equipments. A concise tabulation of 20 vibration pickups and recording systems together with the names and addresses of the manufacturing companies is given in reference 48. The vibration pickups considered in this report will include chiefly those that have been used at this Laboratory.

87. A vibration pickup may be constructed so as to give signals proportional to

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acceleration, velocity, or displacement. By electrical integration or differentiation the pickup signals, if electrical in nature, can be changed from one type of indication to another, although the integration or differentiation may impose additional limitations as to frequency ranges covered. The vibration measuring instruments considered here include the following general classes:

a. Crystal,
b. Wire Strain Gage,
c. Electro-magnetic velocity meter and variable inductance types,
d. Mechanical,
e. Miscellaneous.

Acceleration type pickups, i.e., those in which the natural frequency of the seismic mass is high compared with the frequency measured, have no lower frequency limitation except those associated with sensitivity and with the auxiliary amplifying equipment. Systems employing variable resistance and variable reluctance, classes b and c above, may have the variable unit in a bridge circuit. An A.C. carrier voltage of about 2000 cps is often used for the bridge voltage supply. The unbalanced output signal is then a 2000 cps carrier modulated by the variable unit. In this way a frequency range between 0 and about 300 cps can be obtained with usual A.C. amplifiers.

88. For steady state vibrations it is usually more convenient to read the amplitude on an ordinary pointer type electrical indicating instrument rather than to use oscillographic recording. If the steady state readings are to be interpreted as the amplitude of some definite frequency great care must be taken to be sure that the value given by the indicating instrument is for the frequency determined and not for some harmonic. This is especially true for acceleration measurements. The above classes will not be separately considered.

89. a. Crystal. Crystal type vibration pickups are accelerometers. The vibration pickups are normally constructed for much greater sensitivity than the accelerometers used for H. I. Measurements. The crystal pickup can be made to have a resonant frequency greater than 1000 cps and still provide good signal strength. The low frequency limit of measurement of this type of instrument is dependent on the electrical time constants of auxiliary apparatus and therefore possesses an advantage over seismic type velocity or displacement vibration meters which require that the instrument resonant point be below the lowest frequency to be measured. Of course it must be remembered, see paragraph 35, that the accelerations involved in the low frequencies are small so that the sensitivity of this type of pickup must be high if these measurements are to be properly made.

90. Although quartz crystals have been used for vibration pickups (reference 5) the crystal unit, of by far the greatest use, is the Rochelle salt pickup (reference 49) manufactured or distributed by Brush Development Company, Sure Brothers, and General Radio (reference 50). A sectional view of a Rochelle salt pickup is shown in Plate 14. Rochelle salt is used because of its extreme sensitivity in spite of its many known disadvantages. It is well to check the calibration of Rochelle Salt pickups frequently. Calibrations

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should be made within a few degrees of operating temperature. Temperatures above 130°F will permanently damage the crystal. Temperature changes below this value will not cause appreciable permanent change of sensitivity at a given temperature.

91. Unless wave analyzers or filters are used with this pickup unit there may be much high frequency acceleration present that is not truly representative of the actual vibration. Cunningham, of this Laboratory, has shown that this high frequency "hash" is mainly crystal resonant vibrations probably excited by minute irregularities of bearing surfaces. It is not recommended that the acceleration output of this pickup be used directly, but that the signal be integrated so that preferably the displacement amplitude is measured. For displacement measurements the amplitude determined for steady state vibration is very nearly the amplitude of the fundamental frequency even though no filters are used. However, if these measurements represent accelerations, then wave analyzers must be used if the values are to be associated with any particular frequency, see paragraph 35 and reference 51.

92. b. Bonded Wire Strain Gage. As yet there have been no extensive application of wire strain gage type pick-ups for vibration measurements. They could be easily applied to cantilever beams of a few hundred to a thousand cycles per second natural frequency in the same manner as illustrated on Plate 3, Figure A. Undoubtedly the reason for their lack of extensive use is that other types of pickups are as reliable and provide greater sensitivity. It is probable that their use will become more general.

93. c. Electromagnetic. The vibration-velocity meter pickup types are illustrated on Plate 10. Some units made by Sperry-MIT (reference 52); MIT-Draper, Consolidated Engineering Corporation, and Miller, are of this type. They are usually of a seismic type with a natural frequency between 5 and 10 cps. The pickup is often filled with a liquid so that viscous damping can be obtained. By adjusting the damping to about 0.7 of critical, it is possible to use the pickup unit at frequencies down to resonance although phase distortion must be expected. For steady state vibration measurements these instruments are small, generally dependable from about 10 cps to indefinitely high values of over 1000 cps, and for all amplitudes that reasonably occur within this frequency range.

94. Vibration pickup units of a variable inductance type usually consist of an iron core inductance coil with a small air gap in the magnetic circuit. The length of the air gap is dependent upon the acceleration acting upon a flexibly attached iron mass for frequencies below the resonant frequency of the mass. The resonant frequency is usually in the order of several hundred cycles per second. Damping is often incorporated so as to increase the frequency range to near resonance. Plate 4 illustrates a Martin pickup that has already, see paragraph 16, been described as an accelerometer.

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95. d. Mechanical. For low frequency vibration, up to about 60 cps, it is possible to measure the vibration excursion by the use of a suitable dial indicator. If the dial indicator is clamped to a stationary support the frequency range extends to zero. Usually the indicator is seismically mounted and under these conditions the low frequency limit is between 5 and 10 cps, (see plate 15a). Such an instrument is not usable if the displacement amplitude exceeds a few mils at the upper frequency range although they can be made to follow up to 50 mils at 10 cps. In general they are not suitable for measurements on vibration machines.

96. A light-beam type vibration indicator has been developed by General Electric (reference 53) for frequencies up to several hundred cycles per second at double displacements up to 30 mils. If the instrument is used seismically the low frequency limit is about 15 cps, (see Plate 15b).

97. The above two mechanical instruments indicate only the vibration amplitude. A convenient instrument that can be used to supplement the above is a reed vibrometer (reference 54). This indicates the frequency of vibration but not the amplitude (see plate 15c).

98. Vibrographs capable of giving oscillographic traces of the vibration wave form have been constructed. The Cambridge Instrument Company (reference 55) and Westinghouse (reference 56) have constructed similar instruments that record the vibration wave form on a moving celluloid tape. A periodically excited damped vibration of definite frequency is also put on the tape in order to provide a time scale. This type of instrument is compact and easy to use and is therefore very valuable for field measurements. However, the inconvenient form of the record makes its use undesirable when other oscillographic methods can conveniently be used. The Westinghouse instrument, when used seismically, has a frequency range from 13 to 250 cps with double amplitude limitations of 0.002 inches at 250 cps and 0.025 inches at 67 cps.

99. e. Miscellaneous. A commonly used gage consists of a piece of paper with a figure on one side similar to that shown on part A of Plate 14, and with mucilage on the other side. For vibrations perpendicular to the long axis of the figure the gage will appear as shown on part B of Plate 14. The amplitude of vibration is read from the beginning of the solid black area by markings printed on the gage. The device is very useful for rough measurements. For frequencies below about 15 cps the eye observes the motions of the gage rather than the envelope of motion. This makes the gage difficult to use at the lower frequencies.

100. Another quickly made method of estimating the vibration amplitude is to hold a pencil, or other stylus, firmly in hand and to quickly and lightly draw an approximately straight line along a smooth section of the vibrating part. The line should be perpendicular to the direction of vibration. As the pencil and hand will not follow the machine vibrations the line drawn will be a full scale trace of the vibration wave form. A paper attached to the vibrating part may be an added convenience.

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101. Peak vibration amplitudes can be read directly to about ± 0.0001 inch by means of a traveling microscope. It is advisable, but not necessary, to illuminate the part being studied by stroboscopic light of suitable frequency. This not only makes the displacement measurements more accurate but provides a frequency measurement. This method is too cumbersome to be of much use during routine vibration measurements, but it is of great value for the calibration check of vibration pickups.

SHOCK MEASUREMENT METHODS AT THE NAVAL RESEARCH LABORATORY

A. General Types of Measurements.

102. The first types of shock measurements made for the Navy during this war period consisted principally of recordings of accelerations and displacements. Velocity measurements were seldom made as suitable instruments of this type were not developed. The British, however, decided that in as much as it required only one integration or differentiation to obtain a displacement or acceleration record from a velocity record, that they would stress velocity measurements. They hoped to be able thereby to obtain most essential information with one type of instrument. As the weight and displacement limitations of velocity pickup units, about 35 lbs. and slightly over an inch respectively, did not allow it to be used for light structures, or for large displacements, the velocity records have been obtained chiefly for field measurements of motions of ships' structures.

103. Shock measurements normally made at the Naval Research Laboratory consist of:

a. acceleration records made with quartz crystal accelerometer,
b. displacement records determined from high speed moving pictures or streak photography,
c. strain measurements with bonded wire strain gages.

It is expected that a separate report will be issued by this Laboratory that will cover in more detail the shock measuring equipment and techniques used here. The following description will include only a brief discussion of the well standardized procedures at use at this time.

B. Amplifiers, Filters, and Oscillographic Recording Equipment.

104. Block Diagram. A block diagram of the equipment used for oscillographic measurements is shown on Figure 8. These components will now be separately considered.

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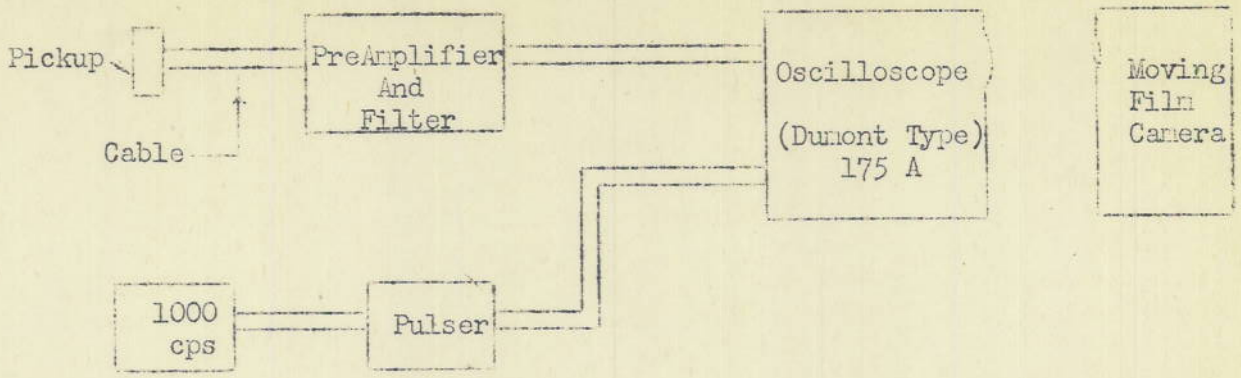

Figure 8 - General arrangement of apparatus for amplifying and recording signals from acceleration, strain, or other types of pickups.

105. Preamplifier and Filter. A preamplifier and filter is used with undamped acceleration type pickup units. A circuit diagram of a calibration circuit and one channel of a 3 channel amplifier and filter circuit is shown on Plate 16. The filter circuit with its transmission curve and square wave response is shown as circuit A of Plate 17. Plate 18 gives the phase shift as a function of frequency. A condition necessary for no distortion of a signal is that there be a linear relation between phase shift and frequency. In constructing a filter of this type it is usually necessary to adjust R_1 and R_2 about the given nominal value in order to get the best non-oscillatory square wave response.

106. The overall frequency response of the accelerometer and associated electrical equipment should be determined by the filter, although exception should be made for filters that are designed to balance the resonant amplification of a pickup unit.

107. It should always be remembered that the values of accelerations measured depend upon the frequency range of the measuring equipment. This is due to the fact that the acceleration frequency components present in H.I. measurements extend above the frequency range of the measuring equipment. It is obviously impossible to compare acceleration measurements, taken by different equipment, unless their frequency responses are known. Because of this fact it has been recommended (reference 57) that the overall response of the accelerometer and associated equipment used for H.I. measurements be determined by a filter having characteristics similar to the filter described. The particular cut-off value chosen for the filter was taken in order that the frequency range for acceleration measurements might overlap the frequency range of displacement measurements on the low side. The upper frequency range of acceleration measurements has been

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limited to values considerably below the resonant limitations of the pickup unit. Early measurements usually employed filters having a cut off value between 10000 and 12000 cps. It was found that the high frequencies present in the records made it very difficult to determine the low frequency (between 200 and 1000 cps) components. Experience and theory both indicate that the frequency components above 5000 cps are not damaging to most types of apparatus, because of the small strains and displacements involved. Therefore, a filter cut off value of 5000 cps was chosen so that the more important parts of the acceleration record would not be obscured by the less important part. However, considerable research work should be done to establish the damaging power of different components of shock motions. It is considered advisable that other low pass filters be standardized having nominal cutoff values of about 50 cps, 200 cps, 1000 cps, and perhaps 20000 cps. New accelerometers would have to be constructed for most of these ranges.

108. Timing Pulses. A 1000 cps tuning fork oscillator, GR type 813-A, provides a timing signal that is fed to a pulser, see Plate 19A. The pulser provides a sharp 1000 cps pulse that is fed to the accelerating grid of the cathode ray tube at such a polarity as to stop the beam for a short time every 0.001 second. A Dumont Type 175A oscilloscope is used as it provides convenient external connections for this "Z" axis modulation. A stage of amplification for this pulse is provided within the 175A scope case. These timing pulses are shown on Plate 19B. An alternative method of providing a time scale is shown in paragraph 111.

109. Oscilloscopes. Magnetic oscillographs are convenient to use if many channels are required such as is often the case for strain gage measurements. Cathode ray oscillographs are more suitable for acceleration measurements if frequencies up to 5000 cps are to be recorded. When one channel is required an unmodified Dumont type 175A oscilloscope is used. When more than one channel is required a modified 175A oscilloscope is used. This modification adds one cathode ray tube to the normal 175A oscilloscope in the following way. The upper part of the front panel of the'scope is cut off just below the cathode ray tube. Two cathode ray tubes are mounted in a new panel section that is made to replace the removed panel section. The vertical deflection plates of the tubes are not used except for centering the beam. The oscilloscope amplifier normally used for vertical deflection is used for horizontal deflection on the added tube. It is necessary to add a separate high voltage accelerating potential for the added tube. This can be fitted into the space within the back of the oscilloscope case.

110. A front view of a three channel arrangement in which one modified and one unmodified oscilloscope is used is shown on Figure 9. The unmodified'scope is placed upside down on the modified 'scope. The time zero of the two lower cathode ray tubes can be adjusted to the same point on the recording film. The time zero of the unmodified 'scope will be displaced from the others. The timing pulse is normally applied only to the unmodified 'scope. An oscillogram obtained from this arrangement is shown in Plate 19C.

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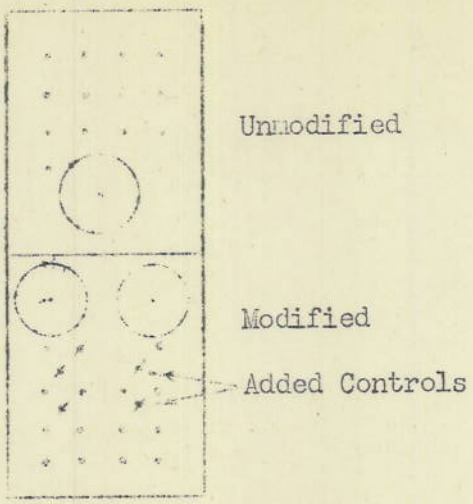

Figure 9 Modified and unmodified oscilloscopes in position for moving film photographic recording.

111. It is uncertain during some types of tests, whether or not the camera is fastened rigidly with respect to the oscilloscope and also whether the camera film tracks accurately. In order to eliminate these uncertainties, which would cause an axis shift of the film trace, a zero deflection light source is attached to the oscilloscope as shown in Figure 10. This consists simply as a pin-hole source of light the same optical distance from the camera as the cathode ray spot and aligned in the same vertical plane as the undeflected cathode ray spot and the camera lens. A rheostat should be placed in the light circuit so as to

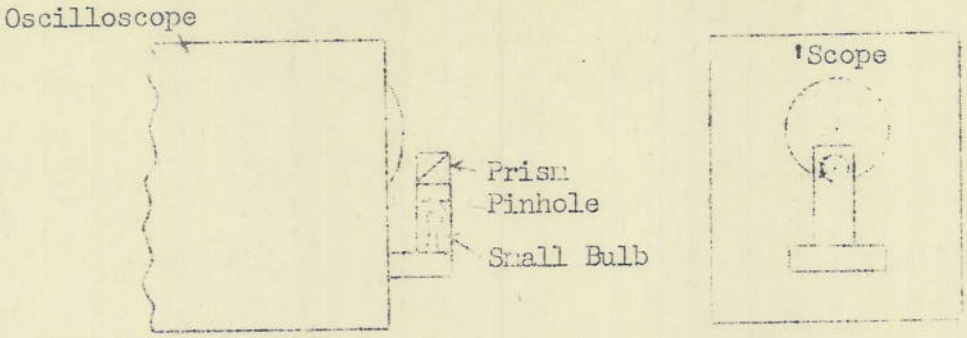

Figure 10 A device for adding a zero deflection trace.

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adjust its intensity to slightly less than the cathode spot intensity. It is helpful to add a blue filter in the light path so that the intensity can be compared more easily with the blue cathode ray spot. It should be noted that this device could easily be made to provide a timing scale by either mechanically interrupting the light beam at definite time intervals or by using a gas tube as a light source and periodically breaking the exciting voltage. The zero trace is shown on the blast pressure record on Plate 19B.

111b. A zero trace with time interval marks can conveniently be made by the arrangement shown on Figure 10b. Light from a line filament lamp is converged by the lens L on the mirror of a magnetic oscillograph galvanometer. The reflected light forms an image of the straight wire filament on a slit made in the form of a cross having perpendicular arms. With the galvanometer mirror at rest the image is adjusted until it illuminates the full length of one slit. This image and slit are arranged to be perpendicular to the direction of motion of the film in the camera. A total reflecting prism or mirror directs the light from the slit so as to enter the camera lens from nearly the same direction as the oscilloscope screen. If now a periodic current is applied to the galvanometer the image of the filament will traverse the cross slit. While the image is away from the center of the cross slit the camera sees a single point of light moving either in the same direction as the photographic film or the reverse. This will draw a single line the length of the film and serves as a reference line from which to observe deflections of the oscilloscope trace. When the lamp filament image falls on the center of the cross slit, light is permitted to pass to the camera from a considerable length of the image. This is recorded as a very brief broadening of the reference line and occurs twice for each cycle of the periodic current applied to the galvanometer. The time interval between every other one of these marks is accurately the time to complete one cycle of the periodic current but the time interval between two consecutive marks may not be exactly that for a half cycle unless the rest position of the galvanometer mirror places the filament image exactly on the slit center. This careful adjustment is not necessary if the observer takes the time interval from every other mark. A typical record using this device is presented in Plate 19D.

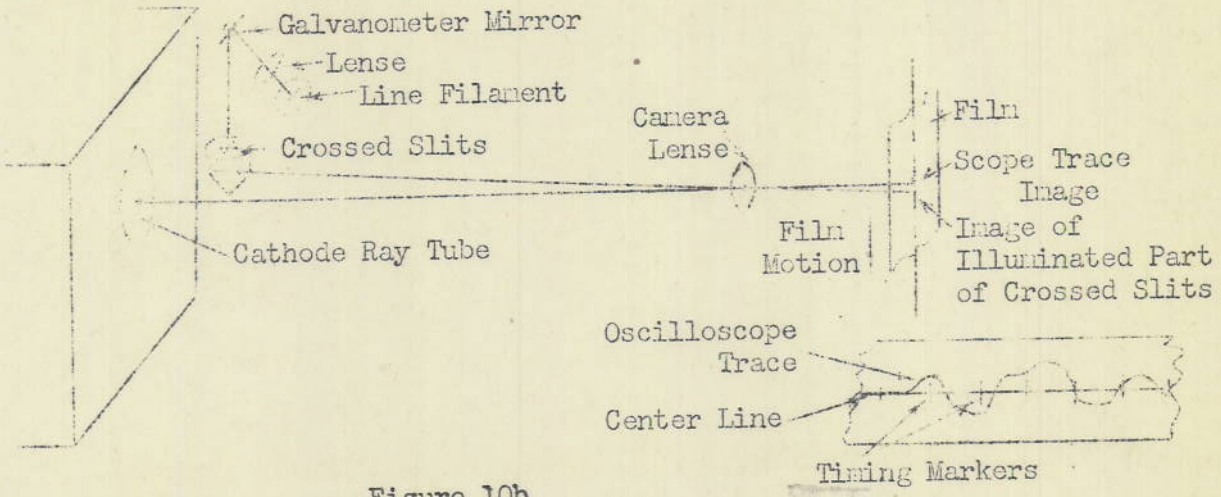

Figure 10b

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112. Moving Film Camera. Type 651-AE G.R. moving film cameras are used for oscillograph recordings. This provides a nearly uniform time scale at any desired speed. The long use of these cameras has resulted in several alterations. These include changes of the lens system, the focusing system and of the film drive sprocket.

113. Most records taken on 35mm film, which is used in this camera, are enlarged for detailed study. The enlargment may not consist of an actual reproduction, but merely of the viewing of the projected image. An excellent method is to use a "Recordax" such as is used in libraries for microfilm viewing. If enlargements are required then there are several reasons why the recorded image should be made as small as possible within the limitations of the camera optical system and the film grain size. These reasons are:

a. The effective writing speed of the camera is increased. This is true as long as the image, enlarged to full scale size, is a reasonably faithful reproduction of the oscilloscope pattern and cathode spot size. If the enlarged pictures are to retain the same amplitude-time scale ratio then the velocity of the moving film must be decreased in the same ratio as the image size. If this ratio is kept constant then the effective writing speed remains constant. There, of course, should be no decrease in amplitude of the deflection of the cathode beam.

b. There is great film economy. It is possible to decrease the length of film required and to put many rows of traces side by side. At this laboratory 7 traces are normally put on a film. Four of these traces are for film motions in one direction, i.e. unwinding from the original spool; and 3 traces are for film motions in the opposite direction, i.e. unwinding from the original take-up spool.

114. In order to reduce the film image size without encountering inconveniently large camera-oscilloscope distances it is necessary to use a short focal length lens. A 1-inch focal length 16 mm moving picture camera lens is generally satisfactory. The field covered is sufficient as only a small fraction of the width of the 35 mm film is exposed at a time.

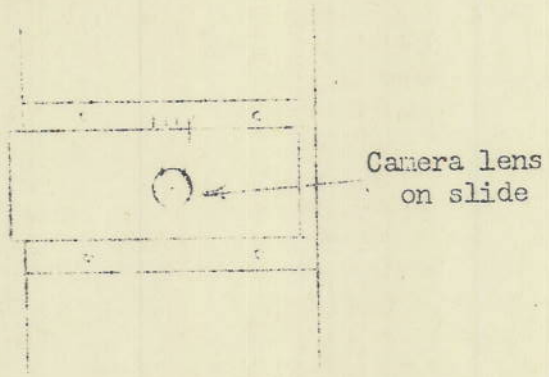

Figure 11 Section of the front view of modified GR type 651-AE camera showing adjustable lens arrangement.

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115. The lens is mounted so that it can be moved laterally across the front of the camera. In this way the image of the cathode ray can be shifted laterally on the film with no repositioning of the camera and oscilloscope.

116. The telescope, supplied with the camera for viewing the image in order to obtain a sharp focus, is not satisfactory. This has been replaced by a Gaertner type M-508 telescope that has a magnification of about 20 times at 14 cm object distance.

117. The third major alteration was to replace the film-drive sprocket wheel with a smooth surfaced wheel. Flanges on this wheel were used to guide the film. It was necessary to turn this wheel down while mounted on the camera bearing assembly, which was removed from the camera, in order to get good alignment of the wheel axis and the axis of rotation. There does not appear to be appreciable slippage for film speeds corresponding to applied motor voltages up to 115 volts A.C. There has been no noticeable lateral film motions. It is to be expected that a sprocket wheel would be necessary for very high film speeds. The principal advantage of the smooth wheel is that it allows film to be used that has inaccurately spaces perforations. Unperforated film can also be used.

C. Precautions Concerning Acceleration Measurements. Cable Effect.

118. In order to obtain successful acceleration records with frequency response up to at least 5000 cps, for measurements on Navy H.I. machines, extreme care must be taken on the following three points:

a. The accelerometer used must have natural frequencies high compared with the range of frequencies being measured.

b. The accelerometer, together with all brackets necessary for its attachment, must be rigidly and securely attached to the equipment under study. As an example, a fine thread 3/4 inch steel bolt, or its equivalent in strength, is about as weak an attachment as should be used to secure a 2 lb. weight, including the accelerometer pickup, to the H. I. machine. If attaching bolts loosen then the bolts are too weak or they have been insufficiently tightened. Lock washers should not be necessary.

c. A well designed and tested filter should be used, see paragraphs 105-107. A usual electrical filter causes distortion in the vicinity of the cut-off frequency. This often appears in the records as frequencies in the neighborhood of the cut-off frequency. Much of this can be eliminated by introducing losses into the filter circuit so that critical damping results for any electrical path.

d. A suitable accelerometer connecting cable must be used. It will be assumed that the cable from the pickup unit to the preamplifier is short, say less than 150 ft. so that traveling waves, impedance mismatches, and other effects common to long cables, will not be considered. Cable effect of chief concern for acceleration measurements

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consists of electrical potentials developed between the cable conductors and caused by mechanical deformations of the cable. The capacity change of the cable, caused by these deformations, is of secondary importance. The cable should be supported so as to be subjected to a minumum of shock motion.

119. Cable effect can be measured and compared with an accelerometer signal by using a dummy accelerometer under the same experimental conditions as the active accelerometer. All cable connectors used should be tested in this manner. This Laboratory has had little trouble obtaining cables in which cable signal is small compared with the maximum accelerometer signal. However, the cable signal will not permit the integration of the usual type crystal accelerometer signal over a period of time greater than a few hundredths of a second. Work is in progress with strain gage accelerometers and with more sensitive crystal accelerometers in order to minimize the cable effect.

120. Plates 20A and 20B show the comparative cable effect of a few cables tested at this laboratory. The good cables illustrated gave cable signals, under given shock conditions, less than about 5 percent of the maximum values provided by the Westinghouse quartz accelerometer. A cable consisting of a copper tube and an insulated central conductor gives less cable signal than any other cable tested. This is probably because the stiff tubing prevents severe mechanical deformations of the cable. The space between the tubing and the central conductor is filled with a suitable wax, usually a bees wax-ceresin mixture, by emersing the coiled cable in the hot liquid wax and applying a vacuum to one end of the tube. Project OD-03 of NDRC Division 2 states that "telconax" coaxial shielded cable, manufactured by Telegraph Construction and Maintenance Company, Ltd., Telcon Works, Greenwich, England, gives good results in spite of mechanical weakness. Cole (reference 58) discusses problems encountered in the use of electrical cables with piezoelectric gages and includes the cable effect signal.

121. In shock measurements there are always so many disturbances, such as cable effects, noise and microphonics, and other unanticipated disturbances, that measurements are often subject to reasonable doubt. One method of removing much of this doubt, at least down to the pickup unit, is to attach the cable in a position similar to the test position but with no pickup unit connected, and to make an oscillographic record with normal amplifier sensitivity. The signal then recorded will indicate spurious effects. If low impedance pickups are used a similar impedance should be placed across the cable during test. If both accelerometer leads were ungrounded a better test would be to reverse the accelerometer leads and see whether this caused a simple reversal of the sign of the signal output.

D. Accelerometer Calibrations

122. Accelerometers, of a type used for high impact measurements, may be calibrated by three usual methods. These are: (1) Vibrating Bar, (2) Plucked Bar, and (3) Spring Impact. Methods of determination of accelerometer calibrations, by means of displacement, velocity, or force measurements, have lacked success because of the great sensitivity and frequency range required of the comparison

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instruments. It is expected that these other methods will be developed so as to make possible a direct comparison of accelerometer measurements with acceleration determined from displacement, velocity, or force measurements. The three usual methods of calibration are subject to criticism as they cover neither the amplitude nor the frequency range necessary during normal acceleration measurements. These three methods will be described briefly.

123. Vibrating Bar. A bar is caused to vibrate at its natural frequency by a suitable driving force. An accelerometer is mounted on the bar. Measurements are made of the frequency and the displacement amplitude of the bar at the accelerometer location. By assuming that the bar motions are sinusoidal it is possible to determine the acceleration amplitude and to thereby calibrate the accelerometer.

124. A free-free vibrating bar calibrating arrangement used at this Laboratory is shown on Plate 21. The bar is usually vibrated electromagnetically as this method is more convenient. However, this method causes interference with some accelerometer units and in these cases the bar is caused to vibrate by compressed air excitation. The method of electromagnetic excitation is apparent from the block diagram included on Plate 21. A pickup signal, that is suitably shifted in phase, amplified, and fed to the bar exciting magnet, is induced by the vibrating bar. The exciting magnet is polarized by a direct current which is adjusted to a value at least as great as the peak exciting current. A choke coil keeps the exciting A.C. out of the battery circuit. (It is possible to eliminate the polarizing current by cutting the exciting frequency in two.) With the arrangement shown and with a 50 watt amplifier, it is possible to obtain peak sinusoidal accelerations greater than 500 g at a frequency of about 900 cps.

125. For compressed air excitation the open end of the illustrated cup, Plate 21, is clamped in position so as to be nearly in contact with the upper end of the bar. If the clamping arrangement is not too rigid the cup will align itself to a proper position after air pressure has been applied. With this arrangement, and with air pressures about 60 lbs/in^2, acceleration amplitudes up to 400 g at about 900 cps are possible.

126. The amplitude of displacement vibration can be measured by means of a traveling microscope preferably with stroboscope illumination. As the amplitudes are small, and the greatest probable error is in this measurement, an optical method was arranged, part D of Plate 21, that readily yielded sufficient accuracy with ease of reading. A microscope objective, of about 8 mm focal length, was attached to the bar adjacent to the accelerometer location. This objective forms an image of a distant small diameter light source. The image then displaces in the same manner as the bar at the objective location. Another similar microscope objective was arranged so as to project the image on a scale some distance away. The amplitude of vibration was thus amplified about 1000 times and read on an ordinary scale. A correction is necessary to determine the vibration amplitude at the actual accelerometer location. This was determined experimentally by two duplicate systems and was also determined theoretically. The two results were in agreement.

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127. Plucked Bar. If a simple cantilever beam has its free end displaced by a known force, and the force is suddenly released, it is possible to calculate the motion of the beam. It is generally sufficient to neglect the effects of higher modes of vibration, in these calculations, and to consider only the fundamental frequency of the recorded acceleration vibration. The fundamental recorded mode is then compared with the fundamental calculated mode.

128. Simple Impact. If the acceleration of one body, caused by an impact with another body, consists of a simple non-oscillatory pulse, then if the velocity

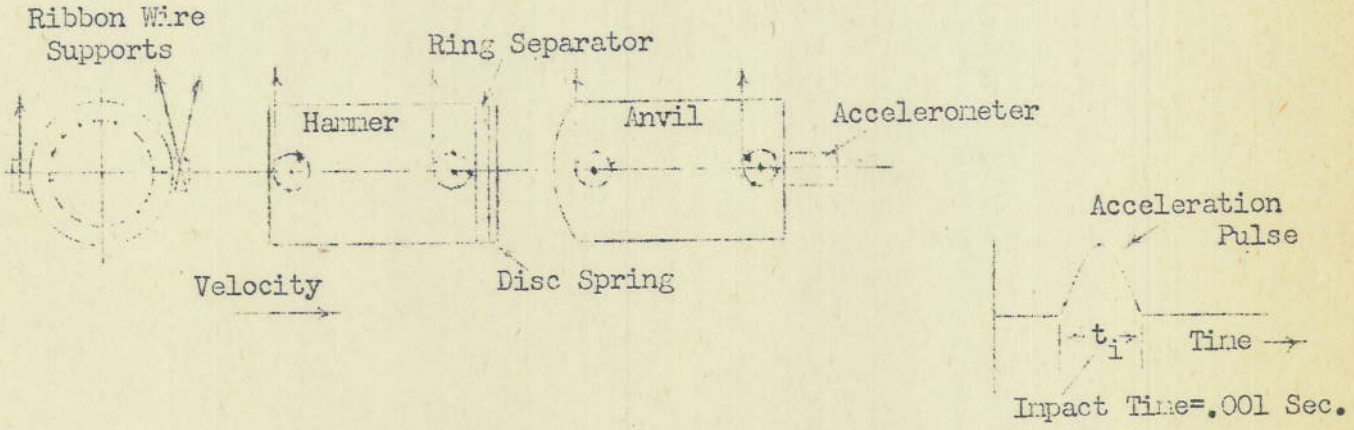

Figure 12 - Impact type Accelerometer Calibrator

change of the one body is known and if the time scale of the acceleration pulse is known, it is possible to determine the amplitude scale of the acceleration curve. This constitutes an accelerometer calibration.

129. An apparatus for calibrating an accelerometer in this manner is shown on Figure 12. The hammer and anvil are suspended as pendulums by light steel ribbons. The hammer and anvil are steel and are about 5 in. in diameter and 10 in. long. Impact is made by a 1/4 in. thick hardened steel disc spring attached to one end of the hammer and a spherical surface at one end of the anvil, the radius of curvature of which is 10 inches. The acceleration pulse given to the anvil is about one millisecond long and is sinusoidal in shape. The duration of impulse should not be much shorter than one millisecond if a 5000 cycle low pass filter is used in the accelerometer circuit.

130. It is believed that this method of accelerometer calibration will be of more value than the vibrating bar method as it is possible to determine the presence of spurious signals caused by shock excited natural frequencies of the accelerometer system. The calibration factor, of the Westinghouse type quartz accelerometers, as determined by vibration at 900 cps and by a simple impact of one millisecond time duration, agrees within 10 percent. The 5000 cps low pass filter, paragraph 105, was used in these tests.

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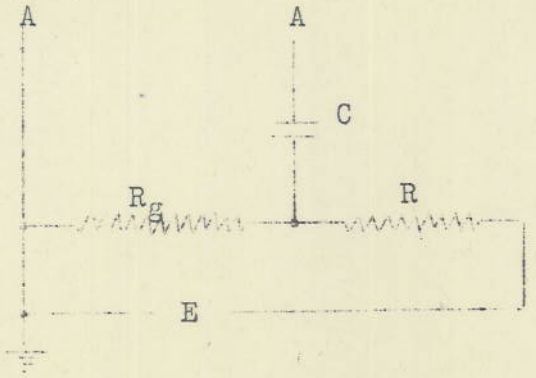
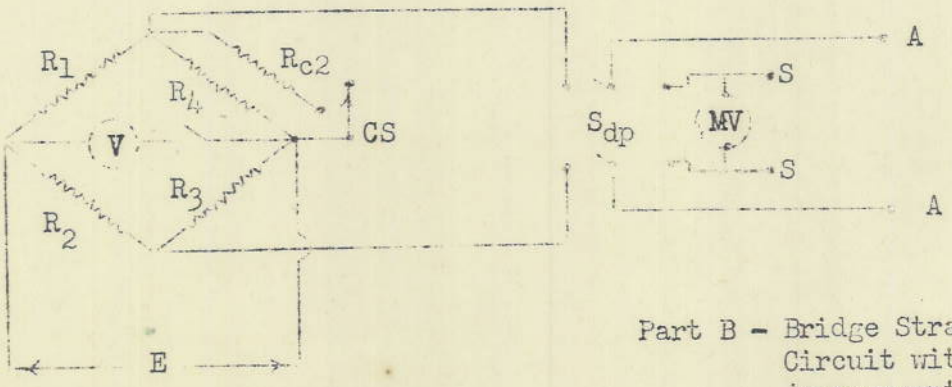
E. Strain Measurements

131. Strain measurements for shock work are made almost exclusively with bonded wire strain gages of the Baldwin Southwark SR-4 type. These have been previously discussed in paragraph 82.

132. Two methods of connecting the gages into electrical circuits are shown in Figure 13.



Part A - Voltage Divider Arrangement



Part B - Bridge Strain Gage Circuit with Calibrating Arrangements

S - to small A.C. voltage source for calibrating voltage

A - to suitable amplifier or galvanometer

CS - calibrating switch

E - bridge voltage

Figure 13 Strain Gage Arrangement

The bridge circuit, part b, is used at this laboratory because of its more general versatility. The sensitivity, gage locations in the bridge, calibration, and applied bridge voltage, will now be briefly considered.

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133. Sensitivity. For a gage in one bridge arm and with the assumptions: (a) that the bridge is approximately balanced, (b) that the change of gage resistance is very small compared with the gage resistance, and (c) that the resistance of the circuit, into which the unbalanced bridge voltage feeds, is large compared to bridge resistance values, then the change of unbalanced bridge voltage caused by a change of gage resistance, for a gage in one bridge arm, is:

$$\triangle e = \frac{E}{4} \frac{\triangle R_g}{R_g}$$

where

E = applied bridge voltage

$\triangle R_g$ = change of gage resistance

R_g = gage resistance

$\triangle l/l$ = strain

By definition the strain gage "gage" factor is $G = \frac{\triangle R_g}{R_g} \Big/ \frac{\triangle l}{l}$

so

$$\triangle e = \frac{E\,G}{4} \frac{\triangle l}{l}$$

The sensitivity, or output voltage, is directly proportional to the applied bridge voltage and the gage factor.

134. Gage Locations in Bridge. It is advantageous to have gages in more than one arm of the bridge, because: (a) greater sensitivity is possible, (b) undesirable temperature effects can be canceled and (c) either the difference or the sum of two strains can be directly determined. For example, consider identical gages, G_1, G_2, G_3, and G_4, cemented to a beam, see Figure 14, so that under bending the gages G_1 and G_3 are in tension and G_2 and G_4 are in compression.

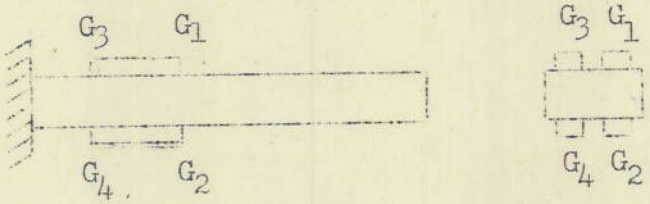

Figure 14

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The gages are at a common location along the bar axis so that the numerical values of tension and compression are the same. Gages G_1 and G_2 can be substituted for R_1 and R_2 of Figure 13b. With this arrangement resistance changes that occur in the same way in both gages will be canceled, and the sensitivity for bending will be double that of one gage. Gages G_1 and G_2 can be substituted for R_1 and R_3 of Figure 13b. With this arrangement the resistance changes caused by bending will be canceled and only the strains caused by tensile stresses will be measured. Similarly the sensitivity can be doubled again by using G_1, G_2, G_3 and G_4 in the respectively numbered bridge arms for bending strains, and for tensile strains by having G_1, G_2, G_3, and G_4 substituted for R_1, R_3, R_2 and R_4 respectively.

135. Calibration. It is essential that the strain measuring apparatus be calibrated just before use. The calibration refers to the determination of the amplifier and associated equipment response to a given change of unbalance bridge signal rather than a strain gage calibration. This is done by three methods: (1) A dummy strain gage is used for bridge arm. This dummy gage is mounted on a beam which can be subjected to a known strain. This known strain then provides the known bridge signal necessary for calibration. (2) The resistance of one bridge arm is changed to a small known amount usually by the addition of a parallel resistor. One such arrangement is shown on Figure 13b. The switch, CS, can put the resistance R_{c2} in parallel with R_4 and thus provide a known unbalance calibrating signal. R_{c2} is usually about 500 to 1000 times as large as R_4 so that contact resistance troubles are small. (3) A small known A.C. voltage is substituted for the bridge output voltage and the overall circuit response is determined, see Figure 13b, switch S_{dp}. This provides a voltage calibration of the overall equipment and the strain can be determined by applying the equation of paragraph 133 and noting paragraph 134.

F. A.C. Bridge Excitation Arrangements of Pickup Units (Modulated Carrier Current Circuits)

136. There are two principal advantages possessed by systems using A.C. bridge excitation or carrier type systems over those using D. C. bridge excitation. These are: (1) It is possible to use conventional A.C. amplifiers and still have the low frequency response to the measured signal extend to zero frequency. (2) By suitable arrangement of the circuits it is possible to cancel many spurious back-ground signals and to thereby make possible greater overall sensitivity. These two important advantages are off-set by one principal disadvantage, namely, the high frequency response of the carrier system is limited to less than 10 or 20 percent of the carrier frequency. Carrier frequencies above several thousand cycles per second become impractical because of the difficulties involved in obtaining balance of the bridge circuits. Thus, at the present time, most carrier type circuits used for strain or acceleration measurements have upper frequency response limits less than about 400 cps.

137. Various types of circuits used with carrier detection are shown on Plates 22A and 22B. It is to be noted that the phase of the bridge output signal changes by 180° as the unbalance of the bridge is changed from one side of

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balance to the other. The output of the bridge can be amplified and the degree of unbalance can be read directly either by using a suitable A.C. meter or by rectifying the signal and using a D. C. instrument. See circuits A and B of Plate 22A. With this arrangement and operating from an initially balanced bridge it is not possible to determine the direction of bridge unbalance, i.e., it would be impossible to determine whether a strain were a tension or a compression. This difficulty can be overcome by initially unbalancing the bridge by an amount as least as great as might be caused by the pickup element. The pickup element will then cause a change of a steady state reference signal and the "sign" of the pickup signal can be determined.

138. A considerable improvement in stability and consequently in sensitivity can be effected by various push-pull and phase sensitive circuit arrangements. Two methods of doing this are shown by parts C and D of Plates 22A and 22B. The circuit of part C has been described by Dinger (reference 59). Its action is similar to that of a full wave mechanical rectifier. The circuit of part D provides for mixing the amplified pickup signal and the carrier signal with proper respect to phase so as to make the unit sensitive to direction of pickup unbalance. The nature of the signal at various locations in the circuit are shown by the inset curves.

FIELD MEASUREMENTS OF SHOCK AND VIBRATION

A. Shocks on Waterborne Ships

139. Causes of shocks. Waterborne ships have structural parts capable of transmitting very large forces without themselves being destroyed. A knowledge of the nature of high intensity shocks sufficient to damage, but not to destroy, a ship is necessary before equipment can be properly designed to measure or to withstand these shocks.

140. The principal causes of shipboard shock are:

a. Underwater non-contact explosions.
b. Contact explosions and projectile impact.
c. Blast from gunfire.

The first two of the above causes are the result of external conditions. Only a small number of these shocks are expected. A reasonable amount of damage to equipment due to these shocks, may be permissible provided the equipment continues to perform its principal functions. Shock from firing of ones own ordnance is repeated many times and should cause no damage to equipment.

141. Shock Motions caused by Non-contact Underwater Explosions. Underwater non-contact explosions represent the principal shock problem. In this case the underwater pressure pulse is applied over a large part of the hull and the shock therefore is very general throughout the ship.

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142. A very extensive literature has developed on the subject of underwater explosions. It will suffice here to say that, although the underwater pressure pulse is complicated by numerous factors, the main damaging component consists of a pressure pulse that rises to a very high maximum value within a few microseconds and decays again to small values within a few milliseconds. The main impulse is delivered during a time in the order of a millisecond.

143. It is emphasized that there is no limit to the variety of shock motions that may occur on board ship. The curves shown represent salient features common to shocks of these types, but cannot be considered to be representative of all conditions. It is regretted that neither space, nor the security classification given to this report, permit a more detailed description of the experimental conditions involved in the obtainment of the field measurement curves. The shock curves are all obtained from the lighter types of fleet units. They have been collected from many different sources.

144. Plates 23 through 26 show ship motions caused by non-contact underwater explosions that were near enough to the ship to cause minor damage to the hull and structural parts of the ship. They represent shocks of approximately the maximum intensity that will occur without disabling or sinking the ship. It is desirable that Naval equipment withstand shocks of magnitudes corresponding to their locations on board ship. The acceleration curves, Plate 26, show values of acceleration up to 5000 g (12000 cps low pass filter) at locations near the hull. A position near the hull, but protected by flexible mounts of usual shipboard stiffness, has acceleration values of about 50 g maximum amplitude (1000 cps low pass filter).

145. Plates 24 through 26 show velocities and displacements of points near the hull, of machinery items that were usually fastened to frame members of the hull, and of bulkhead and deck positions. The displacement curves were derived from the measured velocity values. These records show: (a) that for locations near the hull velocities slightly greater than 20 ft/sec can be attained within one millisecond, (b) that for machinery items mounted to hull frame members, velocities between 15 and 20 ft/sec can be attained in less than 5 milliseconds, and (c) that for decks and bulkheads velocities between 5 and 10 ft/sec can be attained within 5 or 10 milliseconds. Displacements up to about an inch can take place for these locations in between 5 and 20 milliseconds.

146. Quite severe disturbances can be caused on a ship by depth charges dropped by the ship while underway. It is necessary that the ship go faster than a certain minimum speed in order that the explosion of the charge will not damage the ship. Plate 27 shows some velocity records taken at several locations on the ship and caused by the ship's own depth charges. These explosions were near enough to the ship to cause some misfunctioning of relays and other electrical equipment and can be considered fairly severe shocks of these types. As these types of shocks may be repeated many times no damage should result from their occurance. These shocks are of small magnitude compared with those illustrated on Plates 23 through 26.

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147. Shocks caused by Contact Explosions and Projectile Impact. Shocks caused by contact explosions and impacts are so severe in the vicinity of their occurance that protection against them is impossible. These shocks attenuate rapidly, in their transmission to other parts of a ship, so that there is only a small region in which the shocks are more severe than those caused by non-contact underwater explosions of severe, but not disabling, intensity. It is generally not desirable to build apparatus so that it will withstand much greater shock than is required for non-contact underwater explosions if much greater weight or expense is involved. It is therefore assumed that no additional shock precautions need be taken for shocks caused by contact explosions and projectile impact.

148. Shock Motions Caused by Blast from Gunfire. Shocks from gunfire blasts from a ship's own ordnance may be divided into two parts:

a. Direct gun blast
b. Indirect gun blast

Direct gun blast shocks are caused by the blast striking directly upon an equipment for which protection is desired. Indirect gun blast shocks are caused by the blast acting over decks or bulkhead surfaces. The resulting deck or bulkhead motions then provide the shock motions to equipment or other structures connected to them. Indirect gun blast shocks are generally severe only on the larger ships where both large guns and large surfaces tend to aggravate conditions. Direct gun blast shocks from smaller guns may be severe because equipment is mounted closer to them.

149. Acceleration curves for a point on an apparatus exposed to direct blast are shown on Plate 28. Peak accelerations occur during the first positive cycle and have values less than 500 g (5000 cps low pass filteration). The duration of the first positive impulse is about 3/4 millisecond. Maximum vibration velocities are estimated to be between 4 and 7 ft/sec. This type of shock can be especially severe as the use of flexible mounts for the exposed unit tends to aggravate rather than improve conditions. Flexible mounts internal to the unit may be used if necessary.

150. Some time-displacement and time-velocity curves, for locations on decks and bulkheads, are shown on Plates 29 through 31. The rule of thumb statement, that the numerical maximum value of acceleration, expressed in units of gravity, and the frequency in cps, associated with this acceleration value are numerically equal for shocks of reasonable severity, again applies reasonably well. The curves show double amplitudes of nearly an inch displacement and vibration velocities up to about 4 ft/sec. These vibrations may persist at considerable amplitudes for several tenths of a second. Deck and bulkhead vibrations of these amplitudes would not be expected on the smaller type ships, but only near the centers of unsupported exposed deck and bulkhead areas of the larger type vessels.

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151. Summary of Shock Characteristics on Waterborne Ships. No two shipboard shocks are alike, nevertheless, some characteristics common to shocks, of maximum severity for which protection need be provided, can be given. These are listed below:

a. If acceleration is expressed in units of gravity and the frequency is expressed in cycles per second then, roughly, the maximum acceleration expected on shipboard shock is numerically equal to the frequency associated with the acceleration. This approximation extends at least over the frequency range between 20 and 5000 cps.

b. In the vicinity of the hull, (1) accelerations up to 5000 g may exist between 0.0001 and 0.0002 seconds, (2) velocities between 20 and 30 ft/sec may be attained within 0.0005 seconds, and, (3) a maximum displacement of about an inch may occur within 0.005 seconds.

c. At locations removed from the hull, (1) accelerations of several thousand g may exist for about 0.0001 seconds, (2) velocities up to 20 ft/sec may be attained within 0.005 seconds (an average acceleration of 125 g for this time), and (3) maximum displacements of about an inch may occur in 0.01 to 0.02 seconds.

d. Shocks caused by direct gun blast may have accelerations up to 500 g (5000 cps low pass filteration) with velocity changes between 5 and 10 ft/sec occurring within 0.001 seconds. The displacements are functions of the mounting system, but should be less than a few tenths of an inch for the above velocities.

e. Indirect gun blast shock may be very severe on exposed decks and bulkheads. Vibrations involving double amplitudes of displacement up to one inch may occur in the lower end of the most common frequency range which extends between 20 and 100 cps. Accelerations involved follow the approximation stated in part (a) of this paragraph for frequencies up to several hundred cycles per second.

B. Vibrations on Waterborne Ships

152. Steady state shipboard vibrations of major concern are those caused by the ship's propellers. The frequency of the vibrations set up by a propeller is equal to the number of its blades times its revolutions per unit of time. Thus, a propeller with three blades revolving at 200 RPM will cause vibrations of 600 cycles per minute. At the present time maximum frequencies of vibration encountered on board ship set up by the propellers extend to about 1300 or 1400 cycles per minute. This limit may be revised upward. Maximum single amplitudes of deck or bulkhead vibrations are usually less than 0.030 inches, although field information is sketchy for extreme conditions of speed and maneuvering. Bad cases with considerably greater amplitudes are known to exist. Vibrations at frequencies below 300 or 400 cycles per minute are not usually severe enough to cause damage. Plate 32 illustrates a scatter arrangement of vibration amplitudes vs. frequency. It is probable that these

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measurements were taken, for the most part, at locations of bad vibration rather than for random locations.

153. Space on board ship is so limited that it is not practical to locate an apparatus at other than its assigned position. Hence, one cannot choose a nice quiet place for a particular piece of apparatus. Nor can one adjust the speed of a ship so that it will not linger where vibrations are bad. Moreover, shock mounts are not vibration isolators for propeller excited frequencies. Therefore, apparatus must be designed for extreme conditions of vibration.

C. Shock on Aircraft

154. Aircraft structural parts are not capable of transmitting severe shocks without themselves being destroyed. High Impact type shock on board aircraft is therefore not a major problem. For the smaller types of aircraft accelerations between 5 and 10 g may occur during landing, catapulting and maneuvering. These magnitudes may last for such a long period of time as to be general throughout the ship. General acceleration changes greater than $\pm$ 1 g rarely occur in large aircraft during flying. Accelerations, lasting several tenths of a second and with magnitudes between 5 and 10 g, may exist at some locations in large aircraft during landings and takeoffs (reference 60). Greater values may be expected on the smaller types. More information, of the type given in reference 60 is needed for smaller type aircraft particularly during carrier landings and catapult takeoffs.

D. Vibrations on Aircraft

155. Only a brief and incomplete summary will be given to the very large subject of vibrations on aircraft. Carter (reference 61) has given a good description of the causes of vibration in aircraft. Plate 33, taken from Critchlow (reference 48), illustrates frequency ranges. However, the most valuable information, to the designer of equipment that is to be mounted in the aircraft, is the approximate amplitudes and frequencies that can be expected at different locations on the aircraft.

156. Magnitudes and Frequencies of Vibrations on Aircraft Engines. Many aircraft power plant accessories are mounted directly to the power plant. These are subjected to very severe conditions of vibration. Tyler (reference 62) and Miller (reference 63) have made extensive vibration measurements on aircraft power plants. They show that these vibrations extend to many hundreds of vibrations per second at large amplitudes. A double amplitude of 0.005" can be expected at 200 cps and a double amplitude of over 0.05" can be expected at 100 cps. This latter value is near the maximum displacement amplitude measured at any frequency although it might be expected that very large amplitudes would be expected at low frequencies during idling and faulty engine operation.

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157. Vibrations at Aircraft Instrument Locations. Many measurements of aircraft vibrations are needed so that envelopes bounding amplitude-frequency vibration values can be determined for a large number of locations and conditions. Very little of this type of information is available and, as it is a type of information that can be very easily obtained, it is urged that more of this work be done.

158. Aircraft engine mountings are sufficiently flexible so that most of the high frequency vibrations present in the engine (paragraph 156) are not transmitted to the body of the plane. Some measurements taken within several planes are shown on Plates 34 and 35. Not enough information is available to state that these measurements represent typical conditions. It will be noticed that these aircraft vibrations extend to high frequencies, over 100 cps, at very appreciable amplitudes, 0.005" to 0.01" double amplitude. It has been noted by Crede (reference 64) that the most severe vibrations on an observed aircraft occured at the natural frequency of the part vibrating. There was usually sufficient excitation to cause this frequency of vibration regardless of engine speed. The amplitude of the vibration increased as engine vibration harmonics came into resonance with the part vibrating. It is to be noted that possible large amplitude low frequency displacements are not often measured because of the limited low frequency response of the pickup units.

SHOCK AND VIBRATION

A. Shock Machines and Some Shock Characteristics

158. Introductory. A summary of general characteristics of three Navy High Impact (H.I.) type shock machines will be given. These machines are called the "Medium Weight", the "Light Weight", and the "Shock Machine for Electronic Devices". The last is also sometimes referred to as the "Fly Weight" machine. The medium weight machine is described by Kirkpatric (reference 65) and in reference 28. Many reports have been written giving characteristics of the light weight machine, some of which are given in references 66 through 74. A description of the first model of the fly weight machine is given in reference 75. After the summarized characteristics of the above shock machines have been given there will follow a brief discussion of shock, and a comparison of shock as delivered by the shock machines and as determined by field measurements on board ships.

159. Medium Weight H.I. Machine. This machine consists of a hammer, weight 3000 lbs., that strikes an anvil table, weight about 4000 lbs. The anvil table is in a horizontal plane and is struck from underneath by the hammer. The table then moves vertically for slightly over an inch when it is stopped abruptly and allowed to rebound to a position somewhat below the initial location. The weight of equipment to be tested on this machine should be between about 400 lbs and 2500 lbs. Maximum accelerations (5000 cps low pass filtration) up to about 4000 g are obtainable for the higher hammer drops, although the value may be considerably less for heavy rigidly mounted loads. A typical acceleration curve is shown on Plate 36. The shock table attains its

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maximum velocity in about one millisecond. The average upward velocity of the table is between 10 and 15 ft/sec for a 5 ft. hammer drop.

160. Light Weight H.I. Machine. This machine consists of a hammer, weight 400 lbs., that strikes an anvil plate that weighs about 600 lbs. The weight of equipment to be tested should be limited to about 400 lbs. The anvil plate is aligned in a vertical plane and can be struck either a back blow, an end blow, or a top blow. Acceleration values (5000 cps low pass filtration) for 5 ft drop back blows of about 4000 g to 5000 g are obtained at the anvil bolt hole positions for auxiliary plate attachments. An acceleration curve for one such position is shown as curve A of Plate 36. The anvil plate attains a near maximum velocity in about 1 millisecond after the motion starts. The average velocity of the anvil is about 9 ft/sec for the first inch of travel. The anvil is stopped after about 1 1/2 inches travel for the back blow and after about 3 inches travel for the top blow. The stopping rate is slow compared with the starting rate. Typical displacement curves are shown on Plates 38 and 39

161. Fly Weight Machine. This machine consists of a hammer, weight 88 lbs. with attachment arms, that strikes the end of a horizontal anvil table. The table motion is in a horizontal plane. There has been no upper limit assigned to the weight of equipment to be tested on this machine, but it should be less than the weight of the anvil table, which is 68 lbs. The maximum hammer drop is about 3 ft. Accelerations, measured with 5000 cps low pass filtration, extend to about 1000 g. A typical acceleration curve for a location on the anvil table for a medium hammer drop is shown as Curve A of Plate 37. The anvil table attains its full velocity in about 3/4 milliseconds. It may be stopped gradually by shock abosrbers or abruptly by a back stop. The distance of travel is adjustable up to 4 inches. A velocity of the table up to about 10 ft/sec is attainable for light table loads.

162. Summary of Shock Machines Anvil Plate Characteristics. Shock motions of the anvil tables of the above three types of machines may be summarized as:

a. The anvil tables attain their maximum velocity within about one millisecond after the first detectable motion.

b. The velocities attained by the anvil plates extend to somewhat greater than 10 ft/sec.

c. High frequency accelerations, 1000 to 5000 cps, between 1000 and 5000 g amplitude may occur at anvil plate locations. The lower value given should apply to the fly weight machine.

d. Maximum displacements range from about 1.5 inches to about 4 inches.

163. Mounting Arrangements on Shock Machines. Apparatus to be shock tested is not mounted rigidly to the anvil table, except in the case of the fly weight machine. Reasonably flexible mounting panels or beams are attached to the anvil plate and the apparatus to be tested is attached to these panels or beams. The acceleration curve B of Plate 36 and curves B and C of Plate 37, are for locations on mounting plates for the machines indicated. A displacement curve

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showing the motions of a mounting panel of the light weight machine is shown on Plate 40.

164. Comparison of Shipboard Shock and Shocks Delivered by H.I. Shock Machines. Paragraph 151 gives a very brief resume of maximum shipboard shock characteristics that may occur without serious damage to structural parts of a ship. Table I summarizes some of these and other data concerning maximum shock characteristics on shipboard and on shock machines. For under water explosions and for locations on directly exposed hulls or hull stiffeners, it is shown that the shipboard shock characteristics have accelerations slightly greater, velocities considerable greater, and displacements slightly less, than the corresponding shock machine values for anvil plate locations. The velocities are attained in about the same time in the two cases. While the above criteria do not completely describe shock it may be stated that the intensity of shock delivered by shock machines anvil plates is somewhat less than can exist on hull structures without causing serious hull damage. A better simulation would be provided if the shock machine anvil displacement were less. Because of considerations, that will become apparent in the next paragraph, it is not advisable to increase the anvil velocity.

165. Shocks are attenuated and changed in nature as they are transmitted away from their source. It is in part the purpose of the shock machine mounting panels and other supports to provide flexibility so that the shocks delivered by the mounting panels will simulate the shocks that occur at some distance from the source of shock on a ship. However, there is one fundamental difference between the nature of shock attenuation and modification as performed by the mounting arrangements attached to the anvil plate and the shock attenuation and modification as performed by ship structural members attached to a hull. This is due to the fact that the energy given the anvil plate mounting arrangement assembly is not passed on to other structures as rapidly as is the energy of the shock motions on board ship. Thus on board ship the velocities, accelerations, and displacements all generally decrease in magnitude as they are transmitted away from the source of shock. On shock machines the accelerations decrease but generally the maximum velocities and displacements increase. Thus, although the severity of the shock at an anvil plate may be less than the shipboard hull shock, the maximum shock deliverable by a mounting plate (see Table 1) may be as severe as shocks on decks or bulkheads in the vicinity of a severely shocked hull. It is to be expected that the shocks that occur on the more remote decks and bulkheads are considerably less severe than shown in Table I. If the displacements involved in the shock machine shock motions were reduced to about an inch, then these shock motions would reasonably simulate the shock motions on board ship. It is to be remembered that all shocks on board ship are different and probably are as unlike each other as they are unlike the shocks delivered by the machines. It should also be noted that damage may be caused by some particular frequency and as such may cause failure in spite of successful shock machine tests.

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TABLE I - Some characteristics of maximum severity shipboard shocks that may occur without causing serious damage to structural parts of a ship, and maximum severity shock characteristics delivered by some Shock Machines.

General Location	Peak Accel. Values* (Units of Gravity)	Max. Velocity (ft/sec)	Time for attainment of max. velocity (Milliseconds)	Max. Displacement (inches)	Time for Attainment of Max. Displacement (Milliseconds)	Shock Machine		Peak Accel. Values* (Units of Gravity)	Max. Velocity (ft/sec)	Time for Attainment of Max. Velocity (milliseconds)	Max. Displacement*** Very approx.(inches)	Time for attainment of max. displacement (seconds)
On or very near Hull that is directly exposed to an underwater shock wave.	5000	20 to 40	0.4 to 1.0	1 1/4	5	Mounted on Anvil Table or Anvil Plate	Medium Weight**	4000	14	1	1 1/2	10
							Light Weight** Back Blow	5000	9	1	1 1/2	15
							End Blow	2500	9	1	2	20
							Top Blow	2000	7	1	2 1/2	30
							Fly Weight**	1000	10	3/4	4	
Bulkheads or Decks in the vicinity of a directly exposed hull.	2000	20	5	1	15	Light Weight** 4 A panel center back blow		2000	17	2	1 3/4	15

* Filtration was either 5000 or 12000 cps low pass.

** Light load conditions, 5 ft. hammer drop for light and medium weight machines, 2 ft. (90°) drop for the fly weight machine.

*** Max. displacement refers to displacement from equilibrium position, not to total excursion on either side of this position.

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166. It is concluded that shock machines can provide shocks that simulate satisfactorily most important aspects of shipboard shock conditions. It is questionable, however, if it is justifiable to require gear that is mounted in protected positions, i.e. positions remote from the hull, to withstand the most severe shock tests. The severity of the specification should depend on three factors: (a) the importance of the continuous function of the part considered, (b) the additional weight, size, cost and availability of a shock resistant part compared with one with reasonably less shock resistant properties, (c) the probable location of the part on board ship.

167. However,caution must be exercised in relaxing specifications. It is remembered that underwater non-contact explosions, that do not explode close to the water surface, provide the most severe general shock throughout a ship. It often appears, in operations, that a ship is subjected to very severe shock conditions whereas the very severe shocks are only of a very local nature. As much equipment that has not passed shock specifications continues to perform satisfactorily under these conditions it is often concluded that the specifications are too severe. Great care should be taken to be sure the ship is safe against any possible mode of attack, for it is along the most vulnerable mode that the next attacks will be planned.

B. Vibration Machine Characteristics

168. Machines Considered. Consideration will be given only to general characteristics of reaction and direct drive type machines.

169. Reaction type Machines. A reaction type machine is driven by one or more attached rotating unbalanced weights. It is simple to construct, operate and transmits negligible vibration reactions to the supporting structures. The operating principles are well described on page 9 of reference 76. The amplitude characteristics of this type machine are a very strong function of the load and frequency (reference 51). Because of this fact, this type of machine is seldom used for tests where vibration amplitudes are specified, although there are tests of these types, involving small rigidly attached loads, where the reaction type machine is suitable.

170. Direct Drive Type Machine. A direct drive type vibration machine is forced to vibrate at some fixed amplitude by mechanical linkages between the vibrating part and a heavy rigid base. This type of machine is difficult to construct and operate; (a) because of the very large bearing pressures possible, (reference 51), (b) because of the necessity of extreme rigidity in all parts of the machine and (c) because of the large reaction forces that are transmitted by the machine to its mounting structure which tend to vibrate the building in which it is located. Because it is possible to predict the amplitude of vibration of this type of machine with reasonable accuracy, this type of machine is used for most vibration specification tests.

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171. It is usually not possible to neglect the flexibility of the drive system of a direct drive machine. When it is realized that for a static deflection of only 0.001 inch a simple one degree of freedom system has a natural frequency of 100 cps., then the difficulties of the problems become more apparent. Plate 41 shows typical amplitude versus frequency curves for a given amplitude setting, for various typical vibration machines. A resonant amplification of motion up to about 600 percent of the amplitude at 10 cps has been observed for commercial machines. Typical curves are shown in reference 77. The "best" commercial machines of 100 lb. capacity or greater change their amplitude by about 30 percent over the designed frequency range. Often these machines are inconvenient to operate, as the factors that make for convenience in making adjustments and general versatility, usually make the mechanism more flexible.

172. Some direct drive machines are being equipped with a cam arrangement that will automatically change the amplitude setting, as a function of frequency, in some pre-determined manner. In this way the amplitude response can be made flat for any given kind of load. The variations caused by loads other than for a designed dead weight load are only in part compensated by the cam arrangement.

173. Most vibration machines used by the Navy have a frequency range between about 10 and 55 cps. It would be preferred if the low frequency end were reduced to about 5 cps. (reference 78). The upper frequency range, above about 40 cps, may not be needed for most shipboard work, but its inclusion makes the machine a much more versatile instrument. This type of machine can reasonably be used for aircraft vibration tests for apparatus that is mounted on vibration isolators. A higher frequency range would be required for unmounted equipment, see Plates 32, 34, 35. The amplitude of vibration specified for test (reference 78) is usually somewhat greater than encountered in service in order that defects that might show up in service may be made apparent in a reasonably short period of time.

SUMMARY

174. Instrumentation, suitable for vibration and mechanical shock measurements of ranges of most interest to the Navy, is discussed. The significance of the various types of peak reading accelerometers and impact gages is considered in detail. The better established methods of shock and vibration measurements used at the Naval Research Laboratory are given.

175. Typical curves are presented that show shock characteristics on board ships for shocks of sufficient intensity to cause minor damage to the ship's structure. Characteristics of shipboard shock, and shock as delivered by the H. I. shock machines, are compared. The displacements, as shown by shipboard shock measurements, are generally less than the displacements provided by the shock machine. However, it is concluded that the motions of the shock machine anvil plate simulate reasonably well the shipboard shocks that may occur for parts rigidly connected to the hull. The shipboard shocks for locations distant from the hull are of much less severity than shocks near to the hull. The shocks on the shock machine mounting panels, as usually specified, are more severe than probable shipboard shocks at locations distant from the hull. It is suggested that shock specifications give more consideration to the location of apparatus on board ship.

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APPENDIX I

Shock in Land Vehicles Caused by Driving over Rough Roads

A report(79) of work by Priebe, Mackas, Gallin, and others, of the Fort Monmouth Signal Laboratories has been issued since the writing of this paper. This concerns the vibrations in standard military motor vehicles. A series of reports will be issued by the Signal Laboratories on this subject. The following exerpts were taken directly from their report:

"Measurements were made of vibration frequencies, accelerations, and displacements, on the floors of a Weapons Carrier, a Jeep, a Half track M2A1, and an Armored Car M8, while traveling over selected sections of the Munson test roads at the Aberdeen Proving Grounds. The measuring equipment used was sensitive up to 60 and 100 cps."

" Frequencies and Accelerations. The vibration in any direction in the bodies of standard military motor vehicles traveling at any speeds over any kind of roads include three components. These are the natural frequencies determined by the springs, tires, and floors. There are also the frequencies of the irregularities in the road surface, but they are less noticeable. The three natural frequencies are predominate. They are 1 to 3 cps for the body-spring suspension, 10 to 15 cps for the tires, and 25 to 100 cps for the floors. The maximum accelerations of each component in the vertical direction are 5g at 1 to 3 cps, 2g at 10 to 15 cps, 2g at 25 to 60 cps, and 0.5g at 60 to 100 cps. In the horizontal transverse direction the maximum accelerations of each component are 2g at frequencies of the springs and tires and at the body frequencies of 25 to 60 cps. In the horizontal longitudinal direction they are 2g at the spring and tire frequencies, 1.5g at flow frequencies of 25 to 60 cps, and 1g at 60 to 100cps."

The above extracts indicate the frequencies and amplitudes of shock excited vibrations on board certain land vehicles. It is to be noted that the major vibrations are independent of engine or road speed. Some later work indicates that some major vibrations in tanks are functions of road speeds.

ACKNOWLEDGEMENTS

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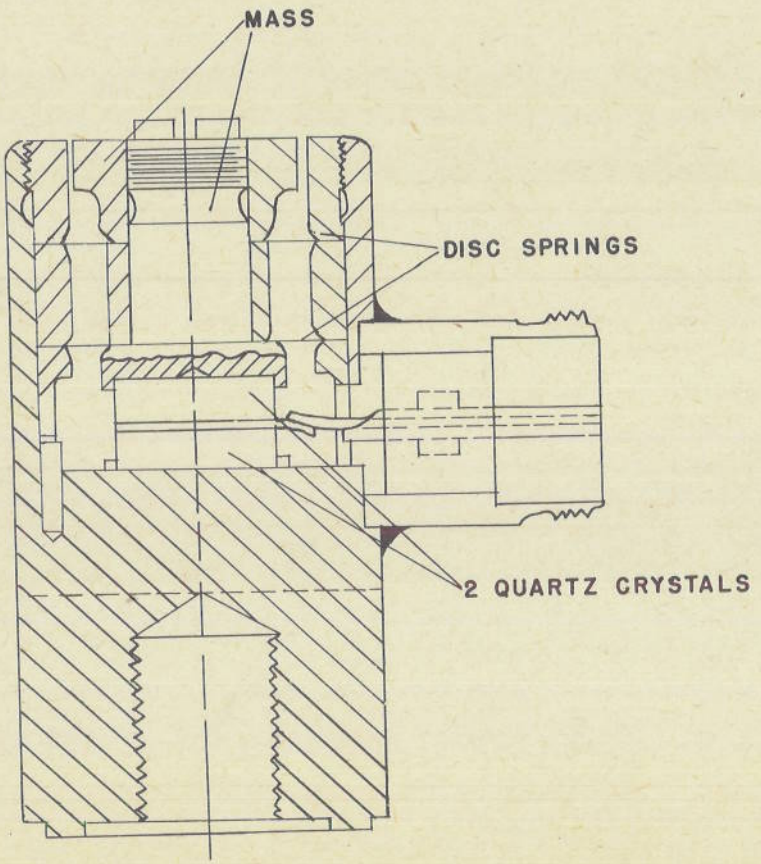
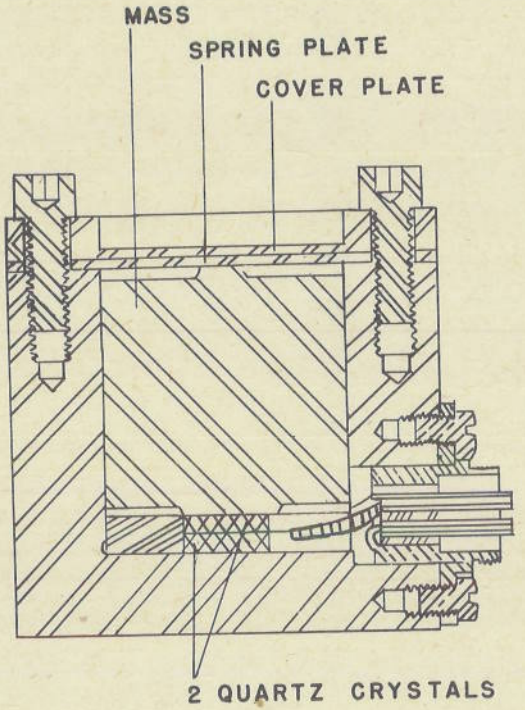
PLATE I



A. WESTINGHOUSE CRYSTAL ACCELEROMETER
(ABOUT 2X FULL SCALE)



B. N.O.L. CRYSTAL ACCELEROMETER
(FULL SCALE)

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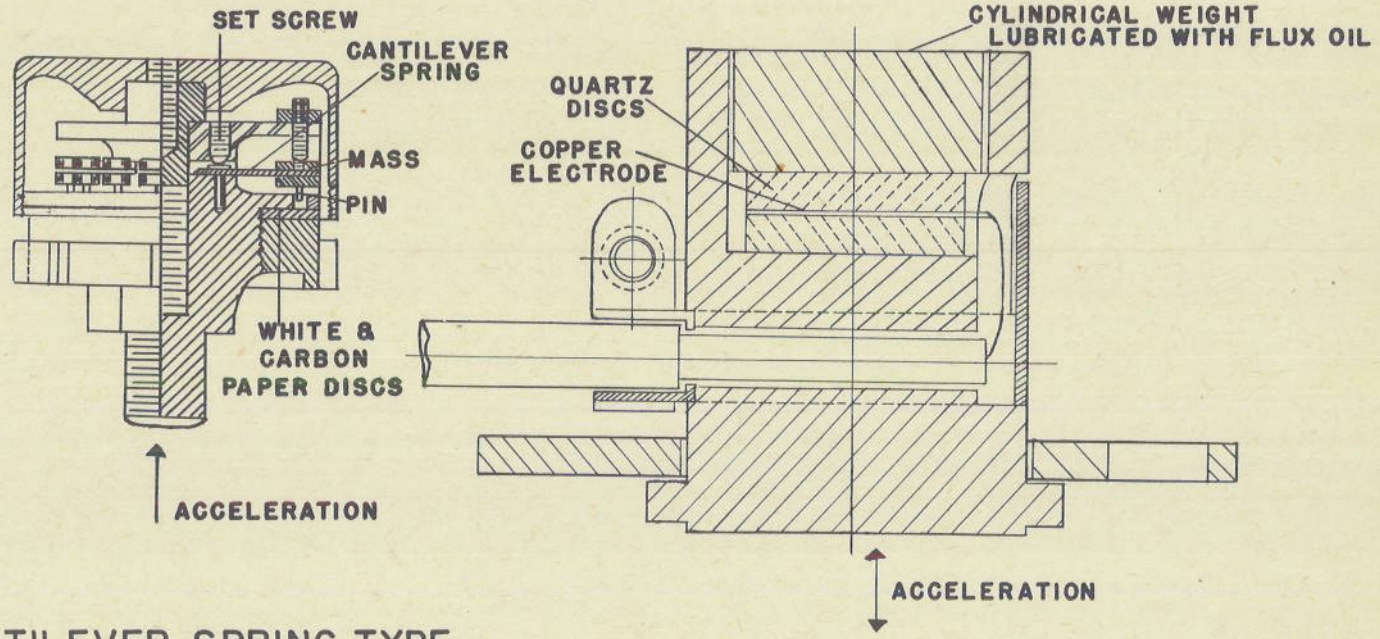

N.R.L. CANTILEVER SPRING TYPE ACCELEROMETER
(FULL SCALE)

BRITISH TYPE QUARTZ ACCELEROMETER
(2X FULL SCALE)

PLATE 2

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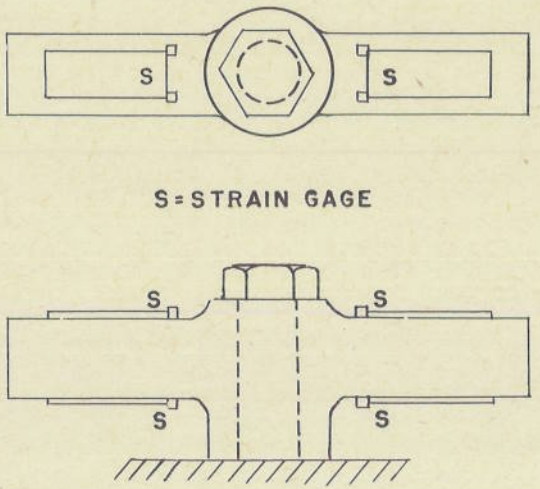
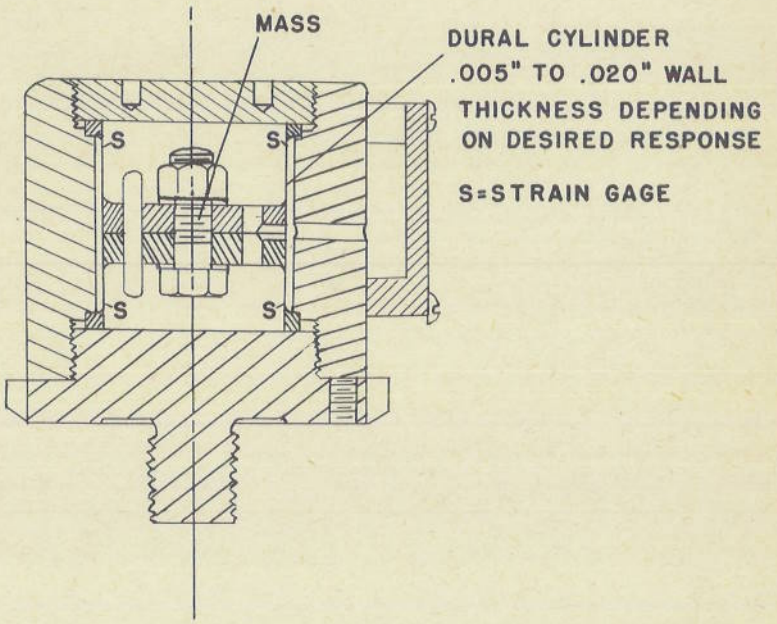


A. CANTILEVER STRAIN GAGE TYPE ACCELEROMETER



B. LONGITUDINAL STRAIN GAGE PUSH-PULL TYPE ACCELEROMETER

THE CENTRAL BOLT PUTS THE STRAIN GAGES IN TENSION, ABOUT .001"/INCH

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PLATE 3

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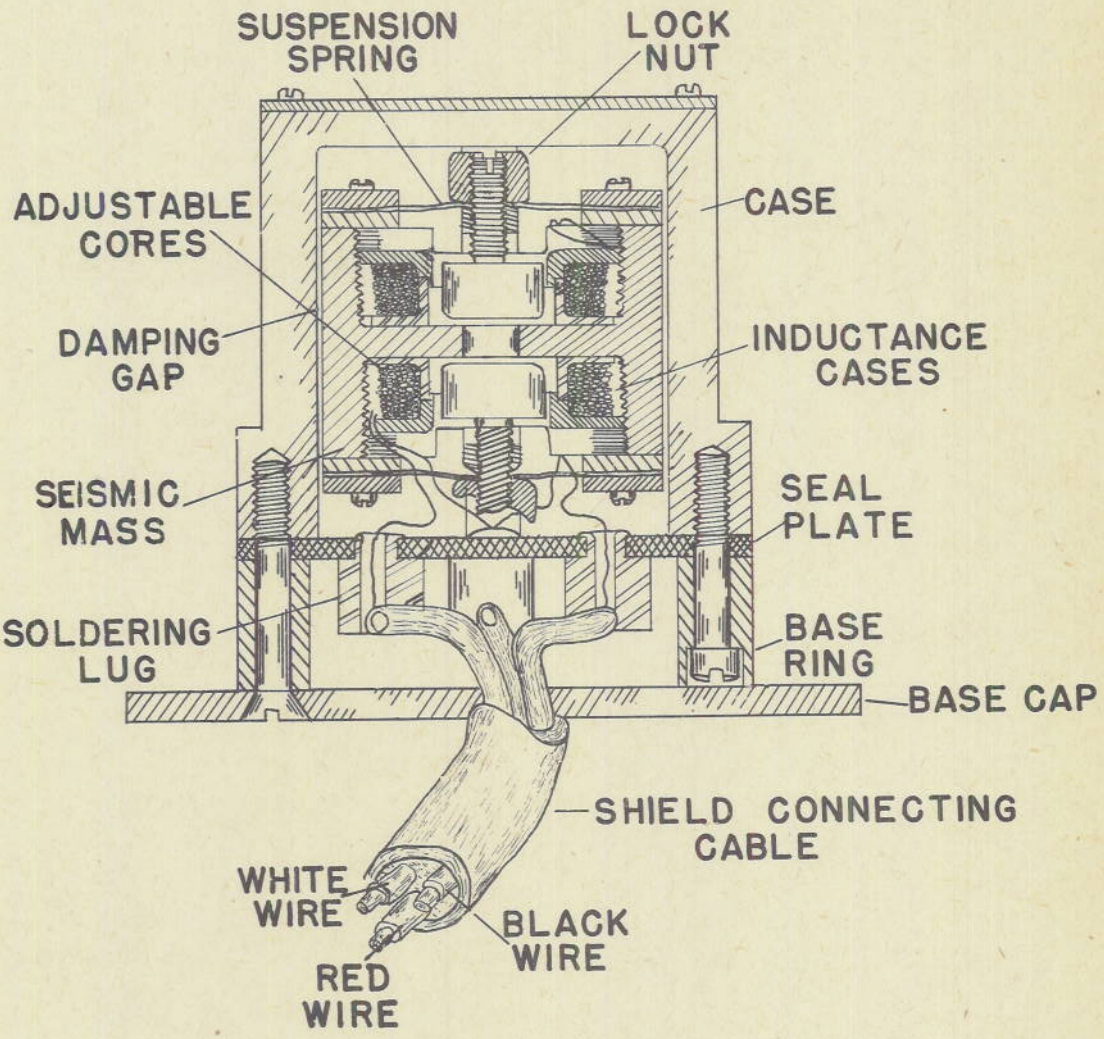

G.L.M. ACCELEROMETER

PLATE 4

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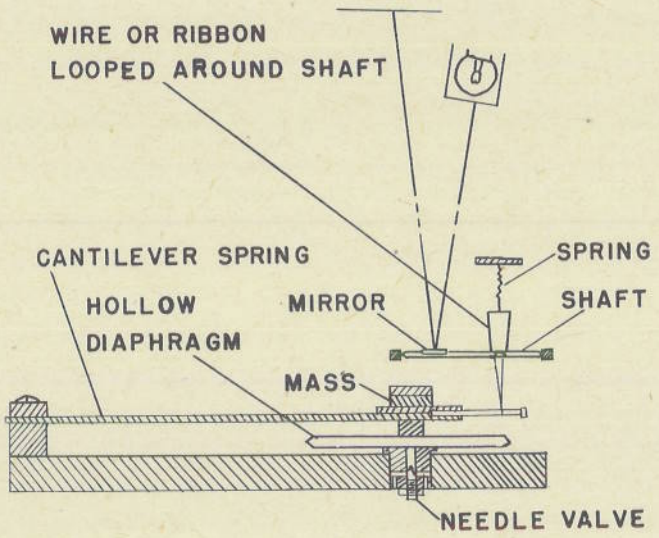
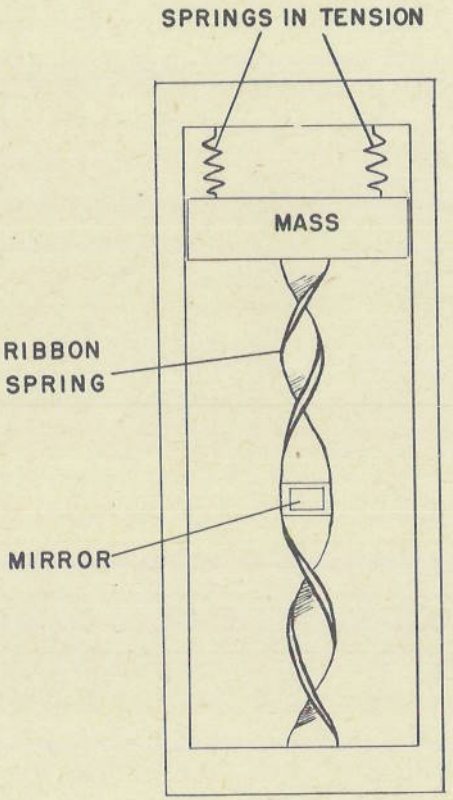


A. SHRADER ACCELEROMETER UNIT



B. RIBBON ACCELEROMETER

PLATE 5

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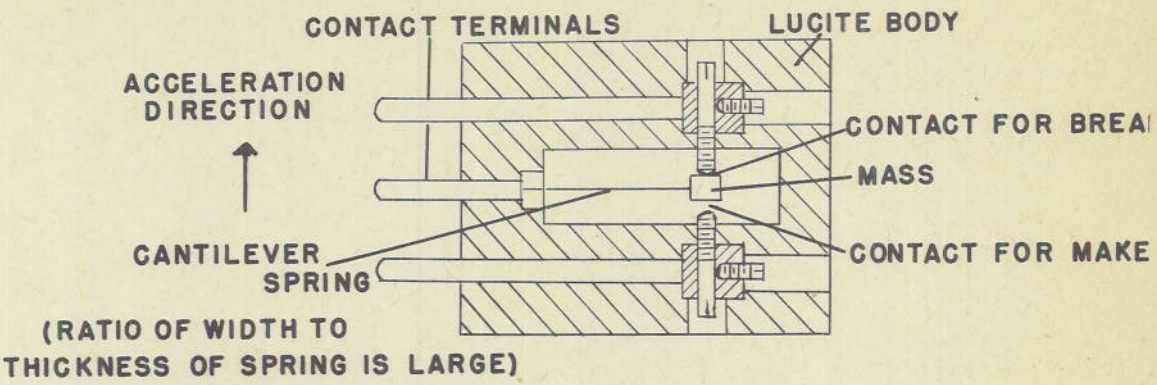
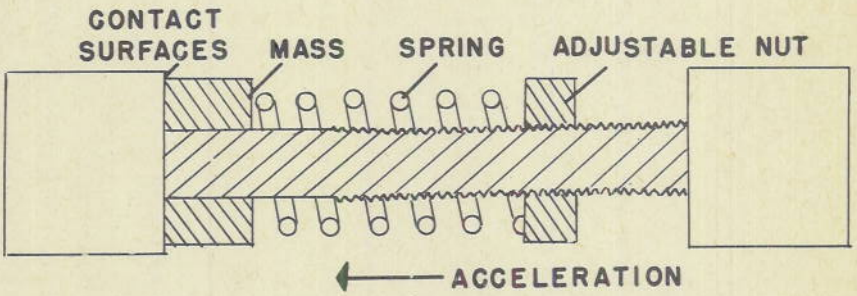


CANTILEVER TYPE PEAK ACCELERATION INDICATOR



PEAK ACCELERATION INDICATOR

(SEPARATION OF CONTACT SURFACES MAY BE INDICATED MECHANICALLY OR ELECTRICALLY)

PLATE 6

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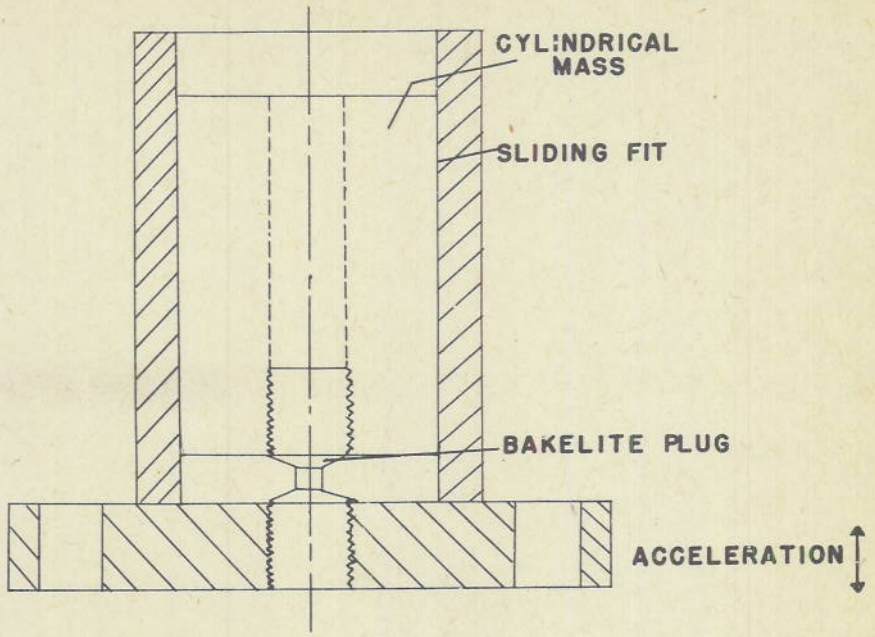
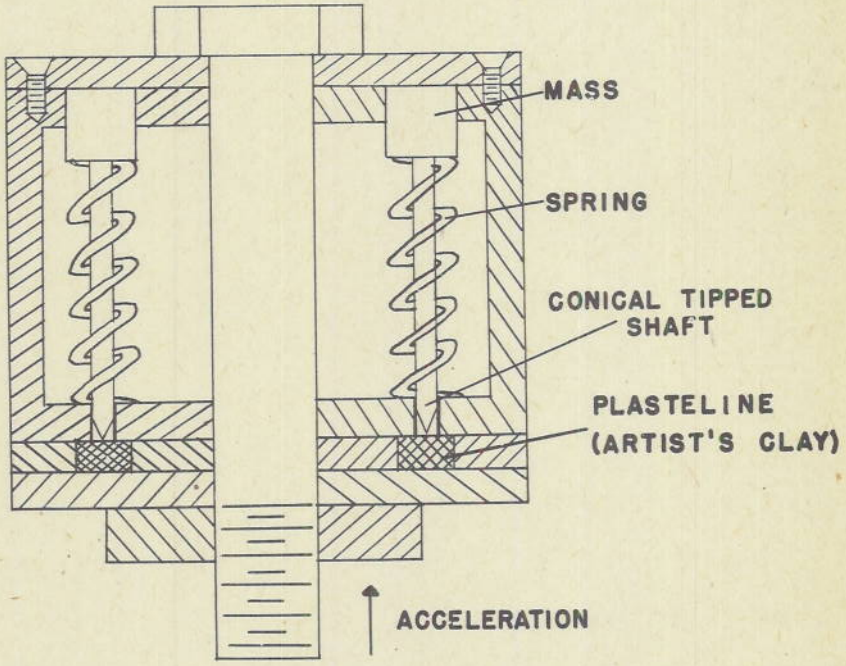


MASS PLUG ACCELERATION INDICATOR



"PUTTY GAGE" PEAK ACCELERATION INDICATOR

PLATE 7

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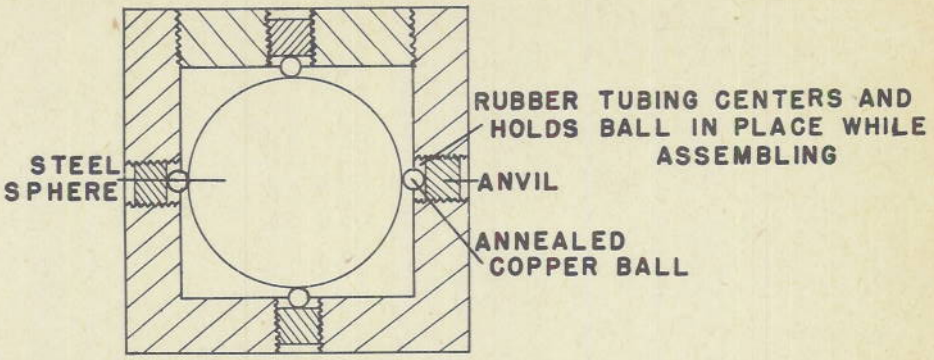
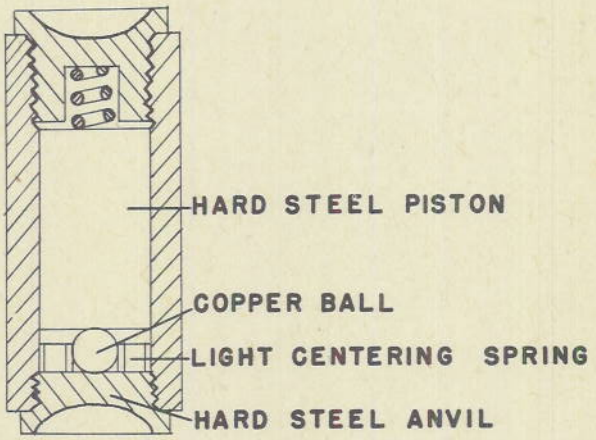


N.O.L. SIX DIRECTIONAL BALL ACCELEROMETER

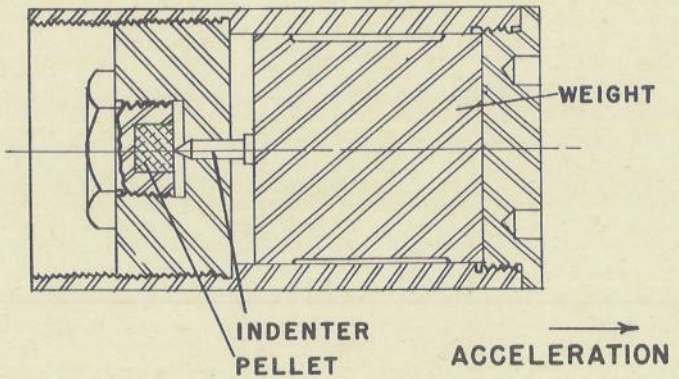


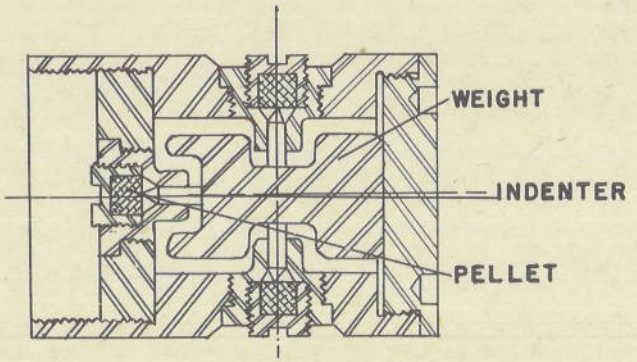
UNIDIRECTIONAL BALL ACCELEROMETER

(ABOUT 2X FULL SCALE)

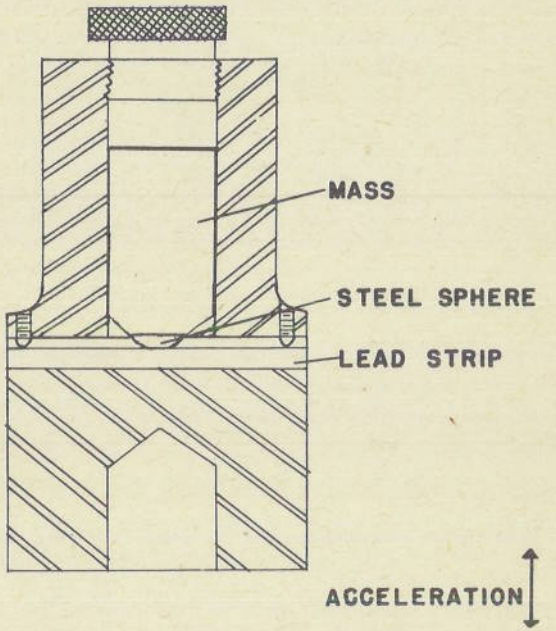
PLATE 8

DECLASSIFIED





ONE DIRECTIONAL & FIVE DIRECTIONAL
IMPACT GAGES
INDENTER TYPE



IMPACT GAGE
INDENTER (BRINELL-LIKE IMPRESSION)
TYPE - GENERAL ELECTRIC

PLATE 9

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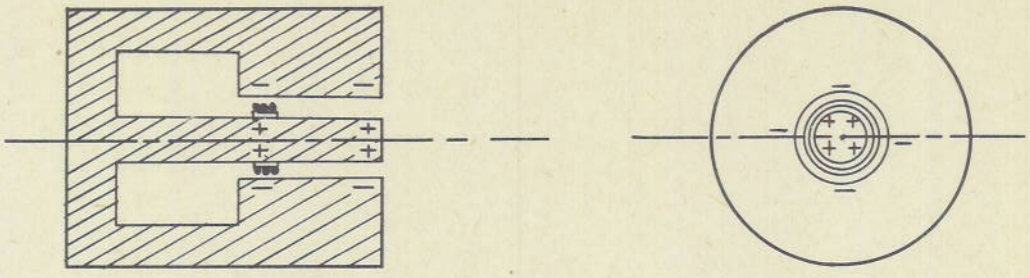
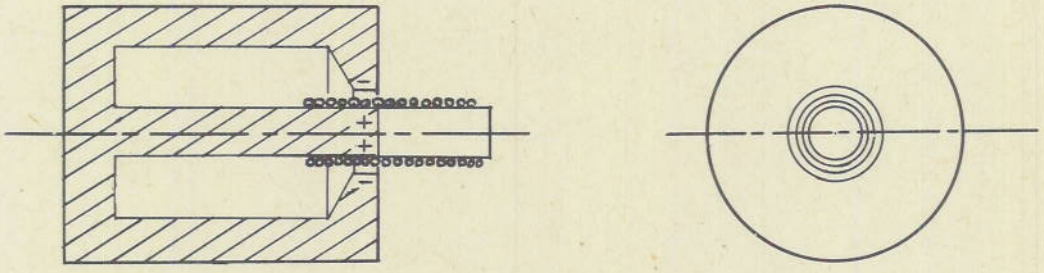
DECLASSIFIED

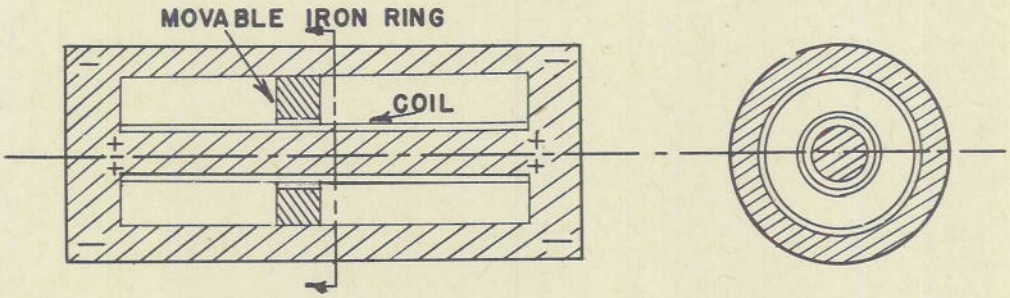
DECLASSIFIED



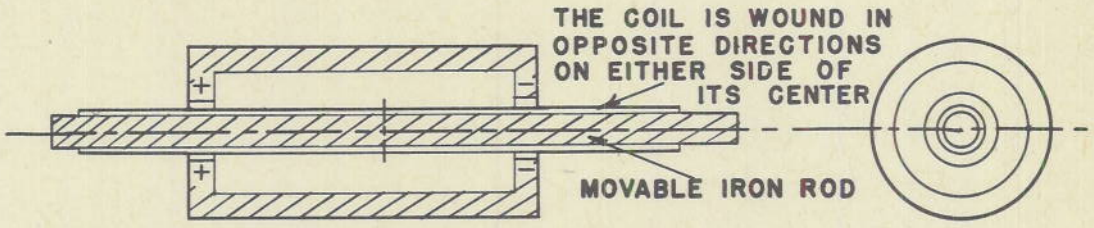
A. MOVABLE SHORT COIL IN A LONG UNIFORM RADIAL MAGNETIC FIELD



B. LONG MOVABLE COIL IN A SHORT RADIAL MAGNETIC FIELD



C. LONG FIXED COIL THREADED BY AXIAL DIFFERENTIAL MAGNETIC FIELDS

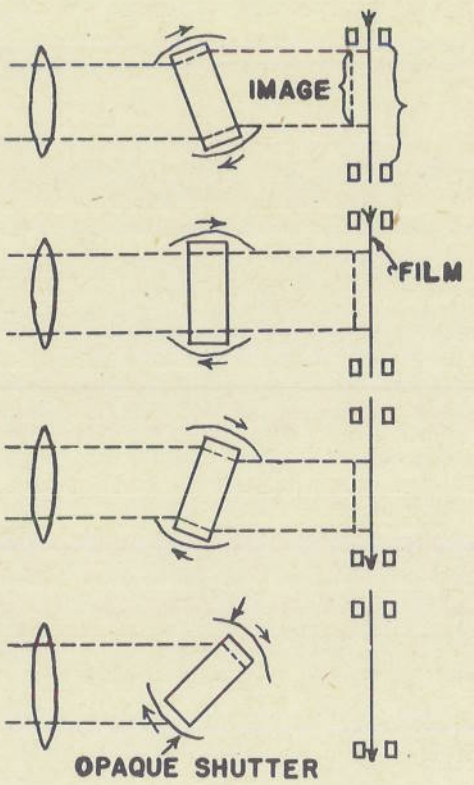


D. DIFFERENTIALLY WOUND COIL THREADED BY AN AXIAL MAGNETIC FIELD

PLATE 10

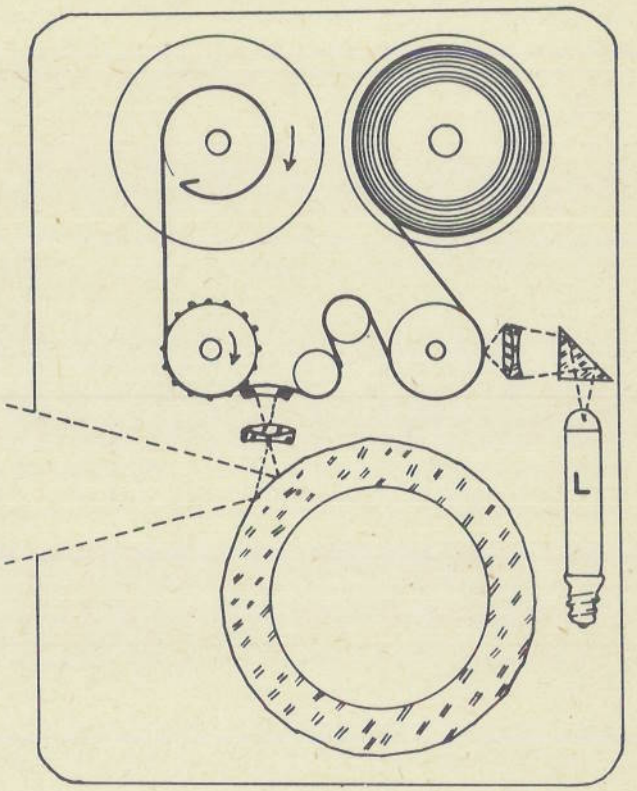
DECLASSIFIED

DECLASSIFIED



ROTATING PLANE PRISM OF
EASTMAN OR WESTERN ELECTRIC
HIGH SPEED CAMERA

THE FILM VELOCITY IS MADE THE SAME
AS THE IMAGE DISPLACEMENT VELOCITY



ZEISS-IKON MIRROR-RING
COMPENSATOR

L=STROBOSCOPIC TIMING
LIGHT

DECLASSIFIED

DECLASSIFIED

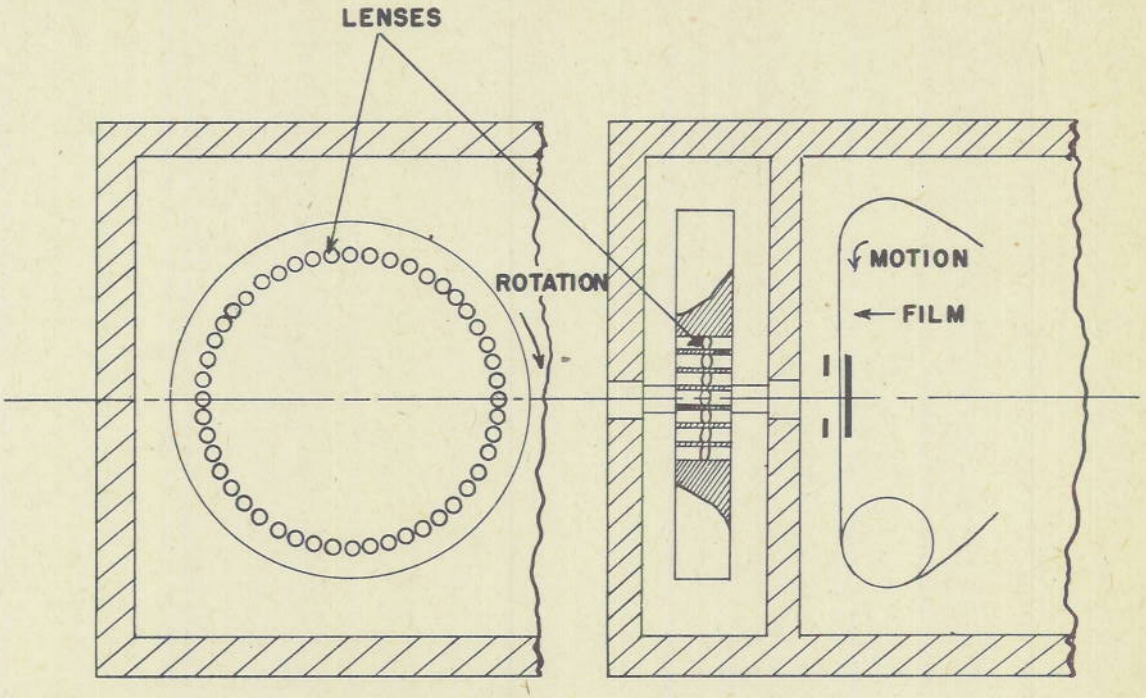
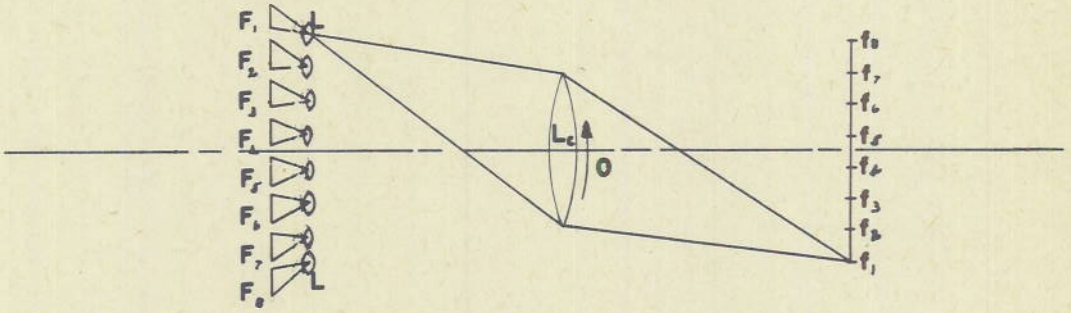


IMAGE MOTION PRODUCED BY A ROTATING CIRCLE OF MATCHED LENSES

THE FILM & LENS SPEED ARE THE SAME.

THIS IS THE PRINCIPLE OF THE VINTON & THE JENKINS CAMERA.



CRANZ METHOD OF MULTIPLE SPARK SOURCE HIGH SPEED PHOTOGRAPHY

f_1 TO f_8 ARE 8 SOURCES OF SHORT DURATION LIGHT PULSES, LIGHTED CONSECUTIVELY AT A FEW MILLIONTHS OF A SECOND INTERVAL

O = OBJECT THAT CASTS A SHADOW TO BE PHOTOGRAPHED.

L = LARGE DIAMETER LONG FOCAL LENGTH "LIGHT COLLECTING" LENS.

L_1 TO L_8 ARE LENSES FOR 8 CAMERAS.

FILMS F_1 TO F_8 ARE EXPOSED BY THE CORRESPONDINGLY NUMBERED LIGHT SOURCES.

PLATE IIB

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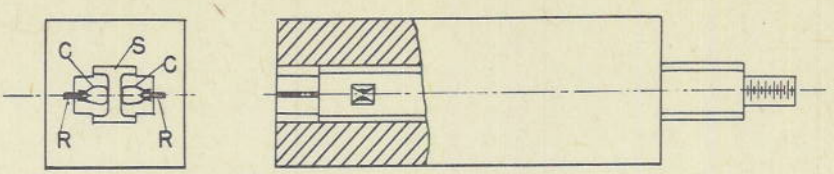
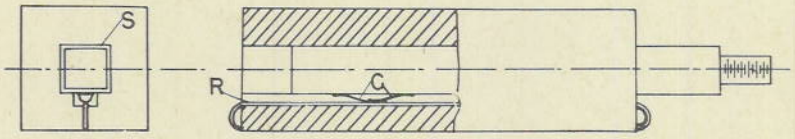
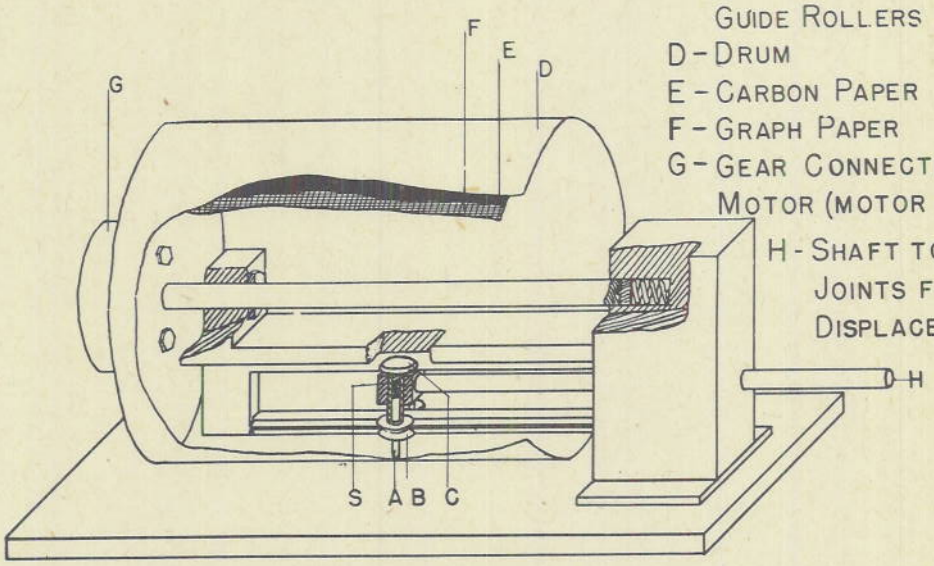
DECLASSIFIED



(A) NRL DISPLACEMENT PICKUP C - CONTACTS
R - RESISTANCE CARD S - DISPLACEMENT GUIDE ROD



(B) WESTINGHOUSE SLIDE WIRE DISPLACEMENT PICKUP
C - CONTACTS R - SLIDE WIRE RESISTANCE



(C) BUREAU OF SHIPS (SECTION 660D) ROTATING DRUM TYPE
PORTABLE TRAVEL RECORDER

PLATE 12

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DECLASSIFIED

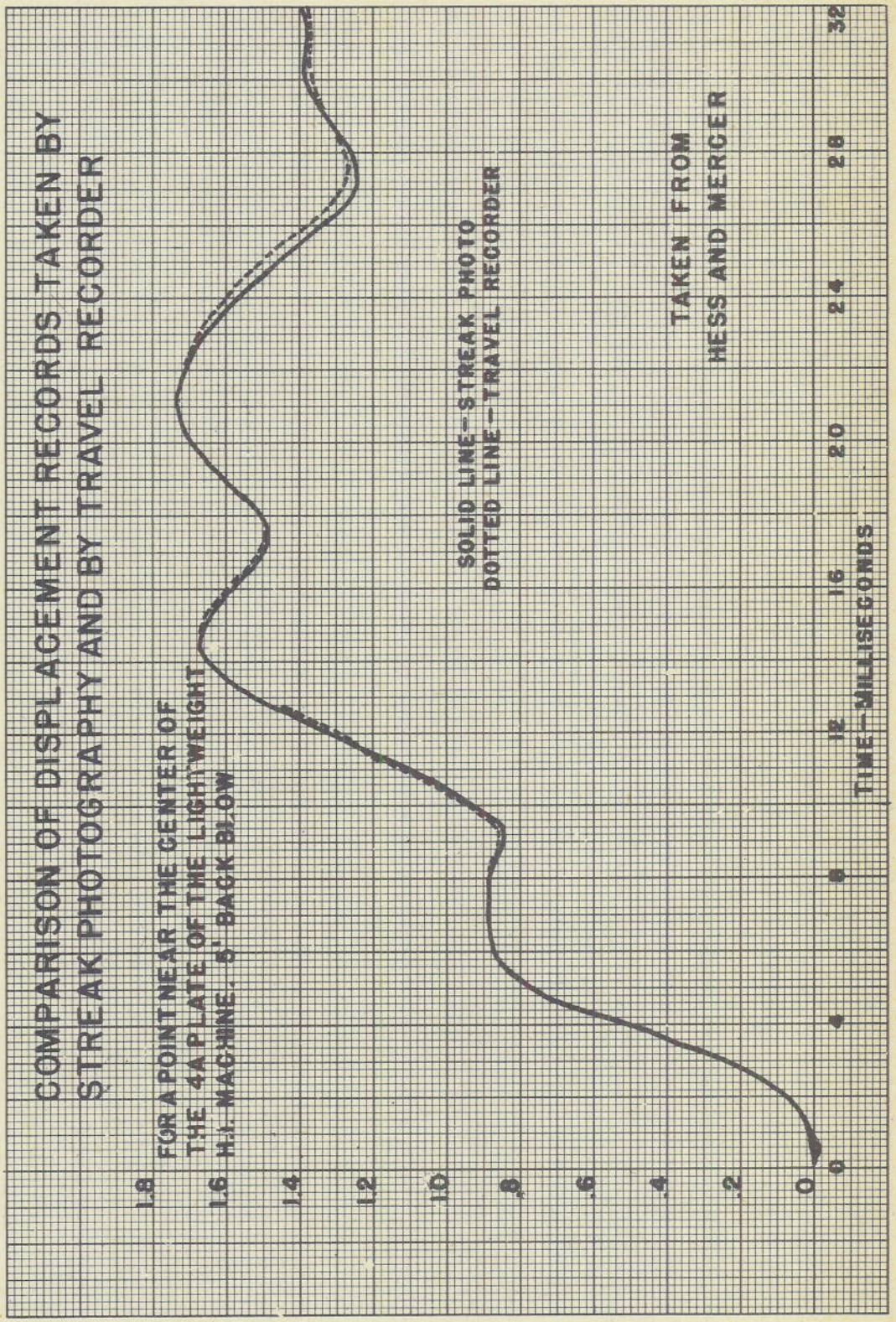
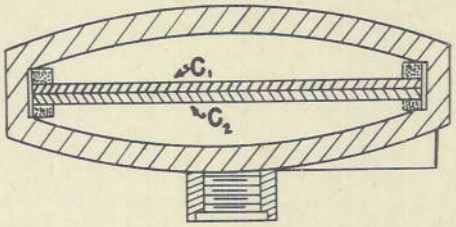


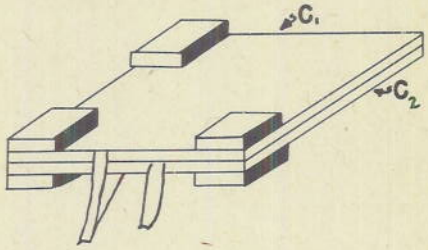
PLATE 13

DECLASSIFIED

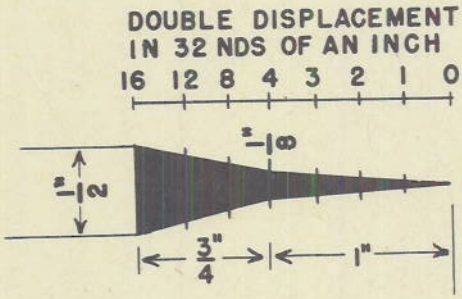
DECLASSIFIED

ROCHELLE SALT TYPE PIEZO ELECTRIC PICKUP USED FOR VIBRATION AND LOW MAGNITUDE ACCELERATIONS



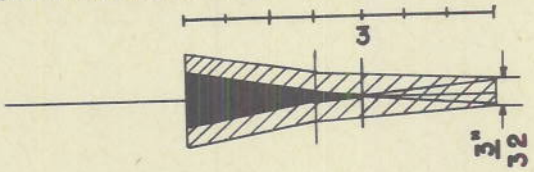


THE UNIT AT THE RIGHT SHOWS THE ARRANGEMENT OF THE CRYSTALS. CHARGES APPEAR ON THE LARGE FLAT SURFACES WHEN THE CRYSTAL IS BENT SO AS TO PUT ONE CRYSTAL IN TENSION AND THE OTHER CRYSTAL IN COMPRESSION.



3/32" DOUBLE AMPLITUDE

A GAGE APPEARANCE STATIONARY (DIMENSIONS NOT INCLUDED ON GAGE)

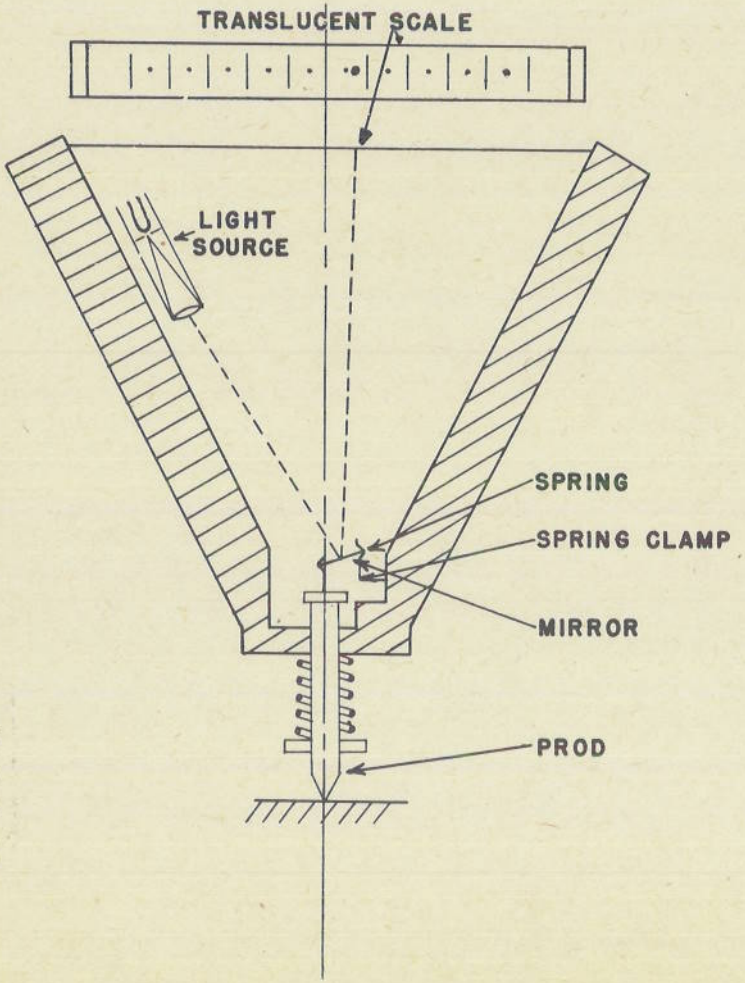


B GAGE APPEARANCE DURING 3/32" DOUBLE AMPLITUDE VIBRATION

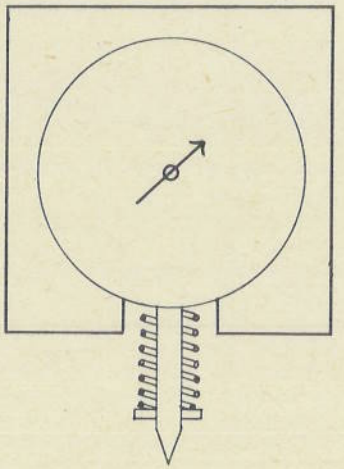
PAPER VIBRATION DISPLACEMENT GAGE

PLATE 14

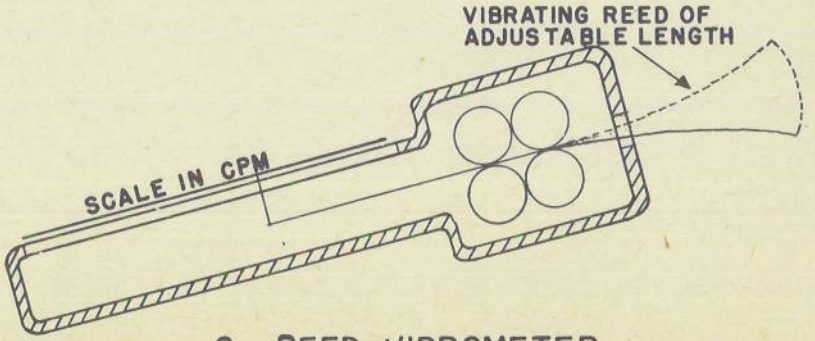
DECLASSIFIED



B. VIBRATION DISPLACEMENT INDICATOR



A. DIAL INDICATOR TYPE VIBRATION METER



C. REED VIBROMETER

PLATE 15

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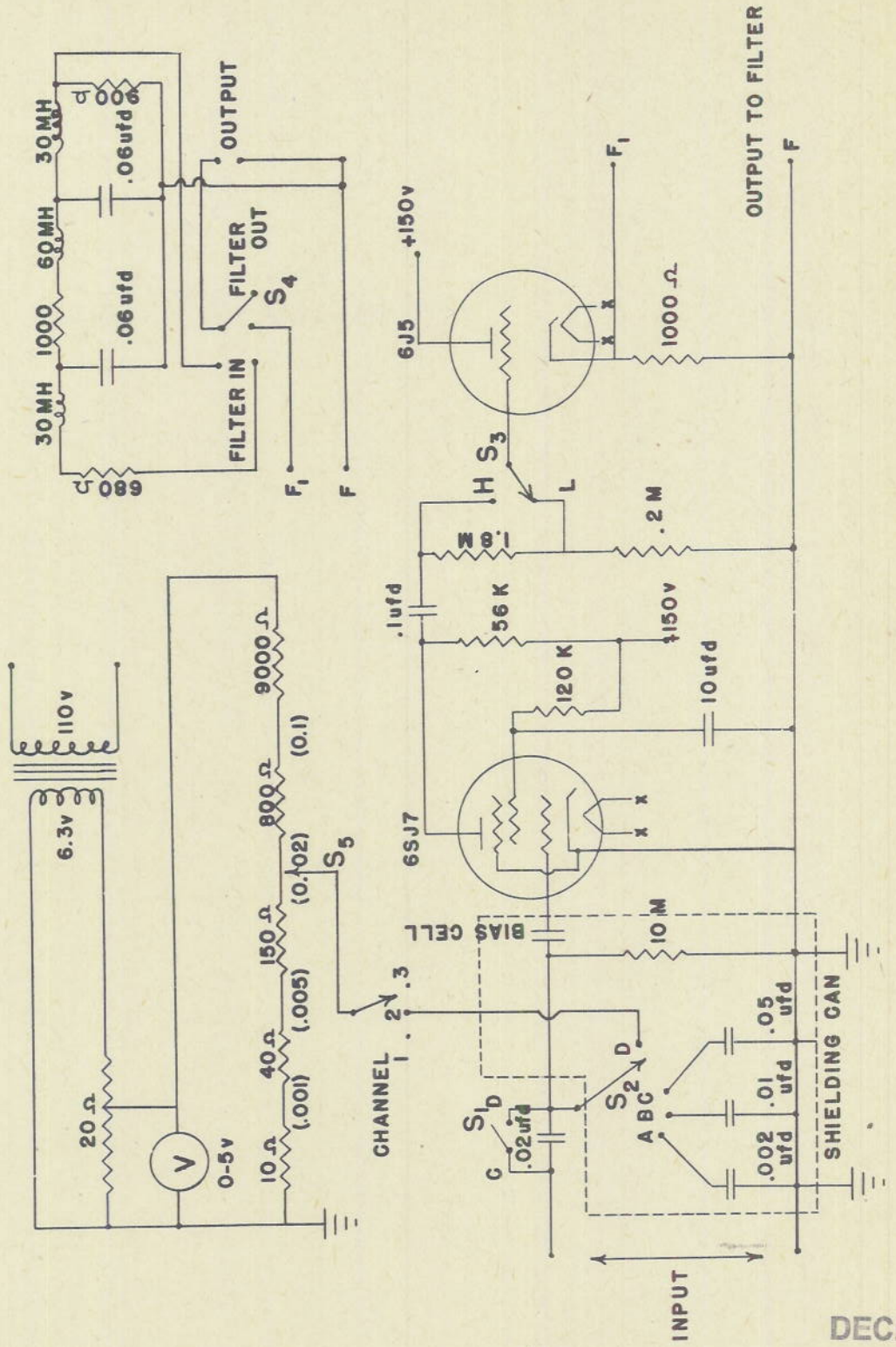
DECLASSIFIED

DECLASSIFIED



CALIBRATION CIRCUIT AND ONE CHANNEL OF THREE CHANNEL AMPLIFIER AND FILTER CIRCUIT

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PLATE 16

DECLASSIFIED

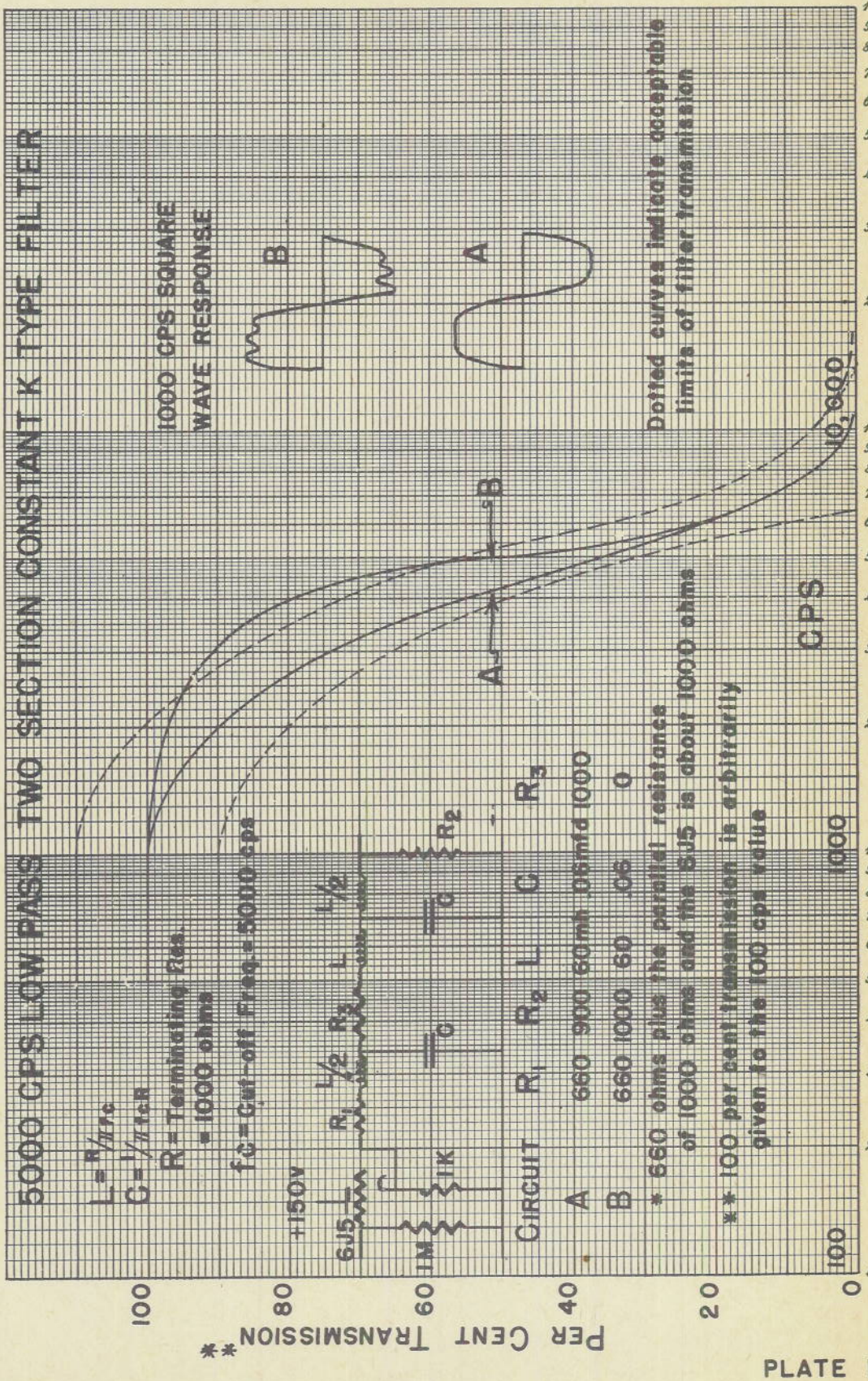


PLATE 17

DECLASSIFIED

DECLASSIFIED

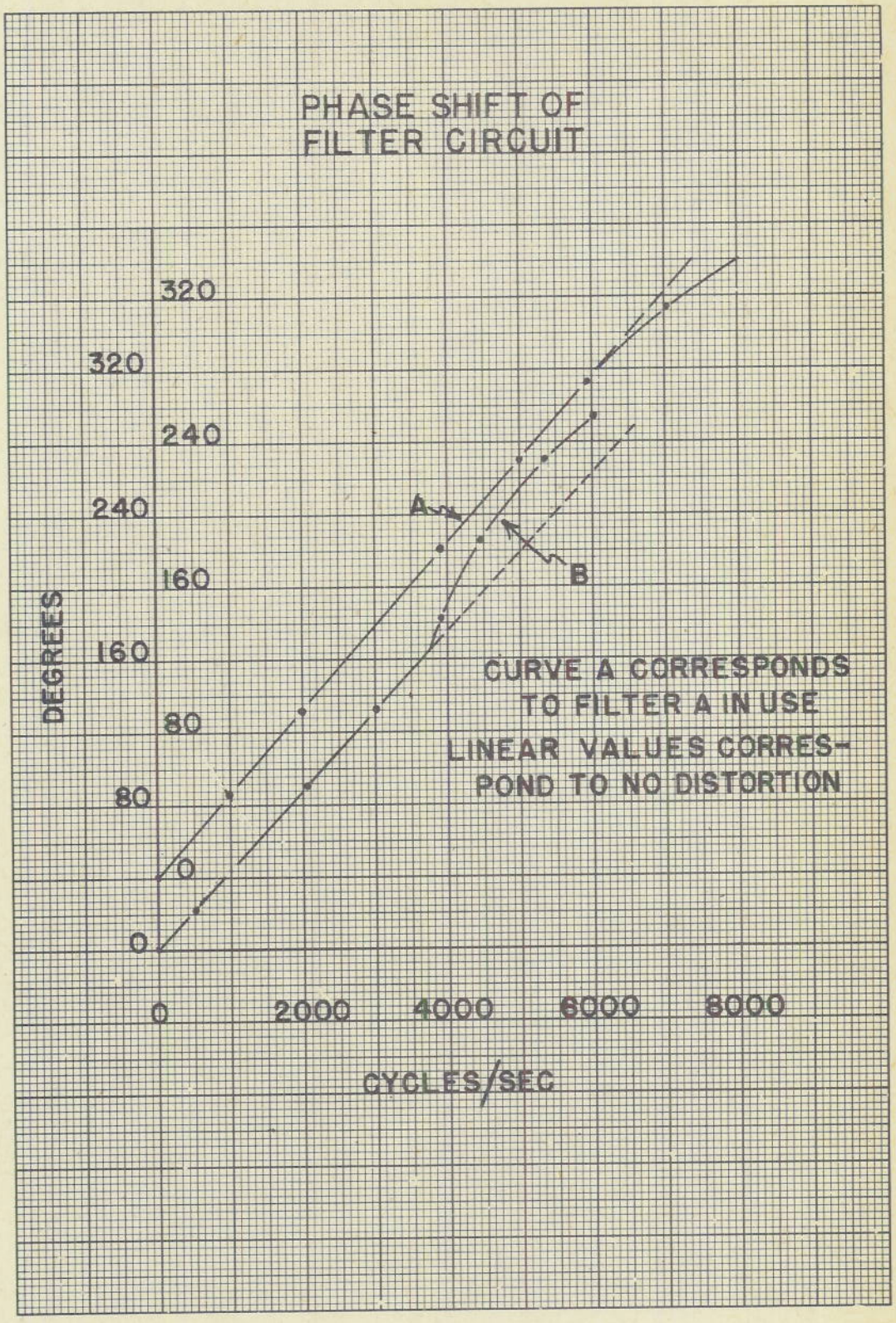
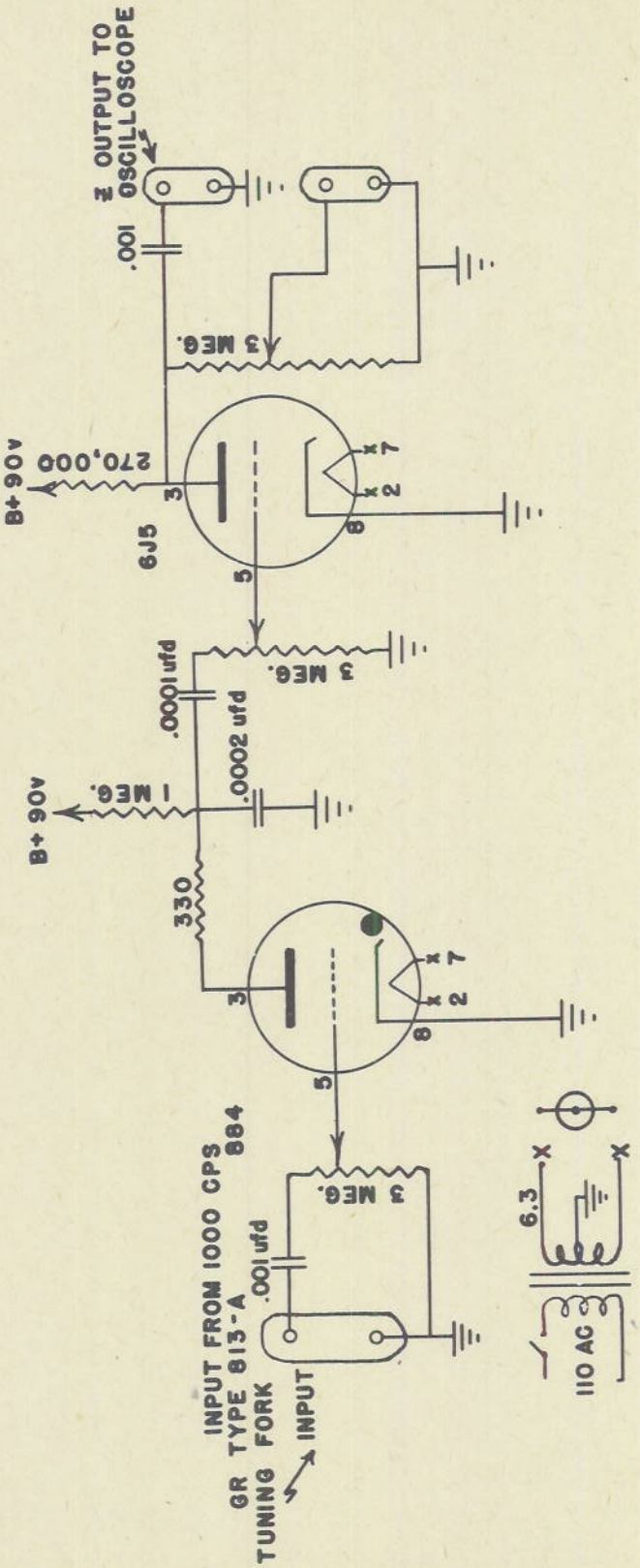


PLATE 18

DECLASSIFIED

DECLASSIFIED

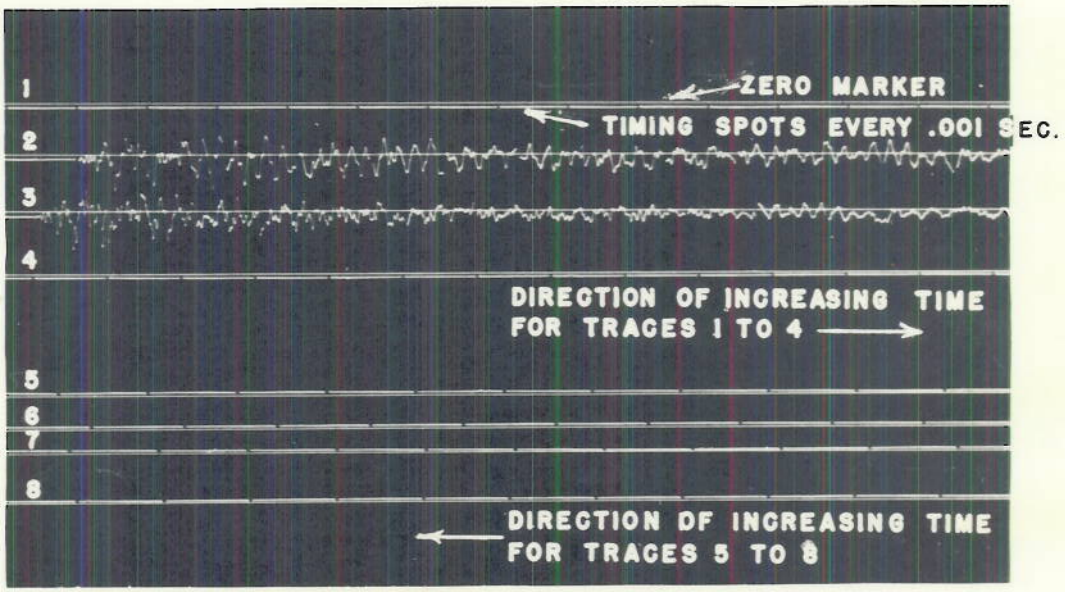
Z AXIS TIMING PULSER



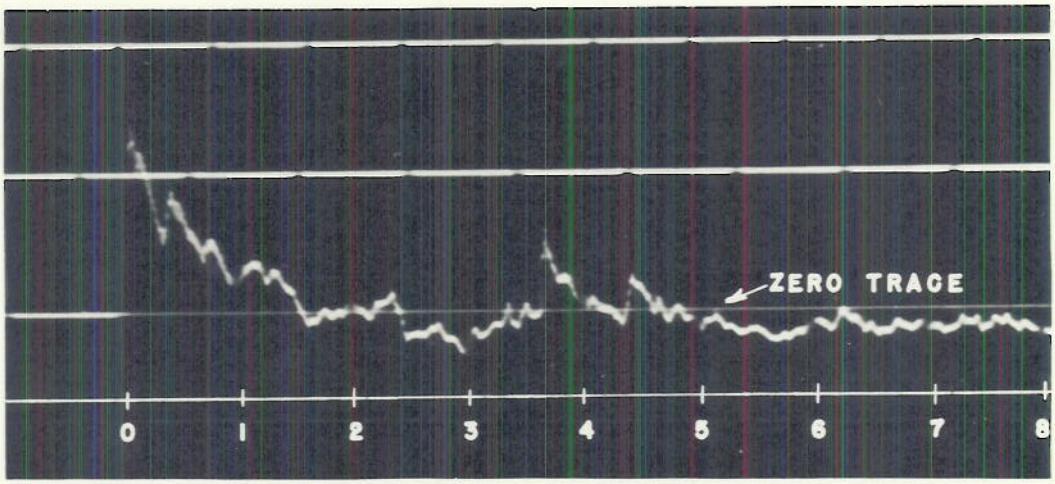
DECLASSIFIED

PLATE 19A

DECLASSIFIED

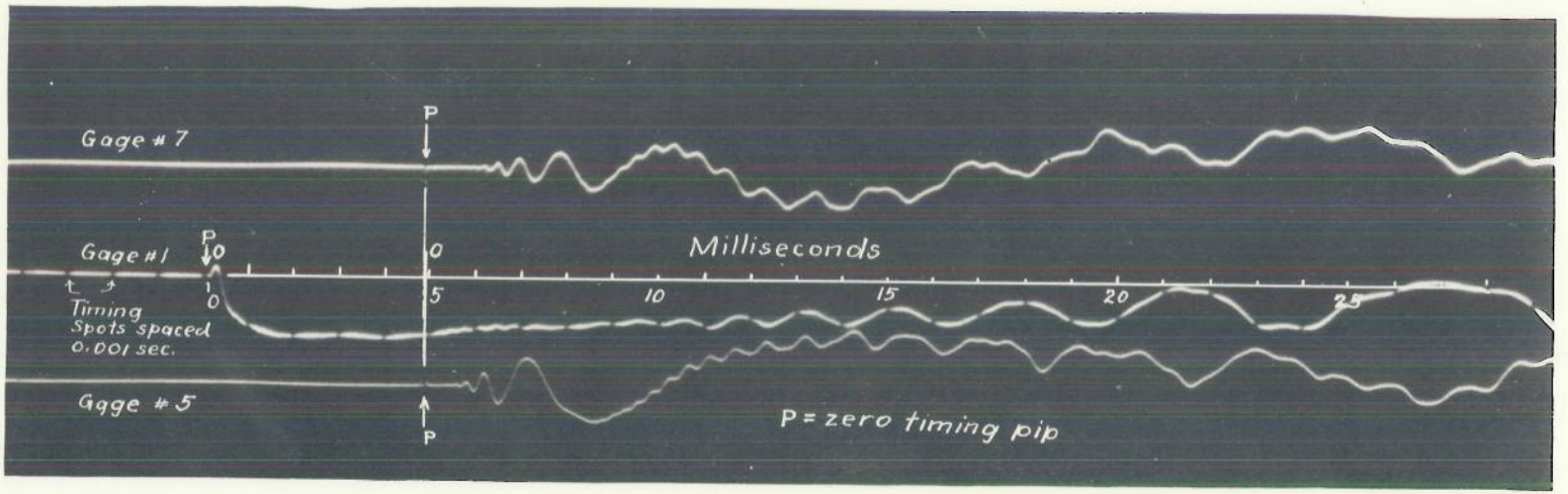


STRAIN IN AIRCRAFT ARMOR SUPPORT
CAUSED BY PROJECTILE IMPACT



TYPICAL GUN BLAST PRESSURE CURVE
(3" 50 CALIBRE A.D.P. CRYSTAL BLAST PRESSURE GAGE)

DECLASSIFIED



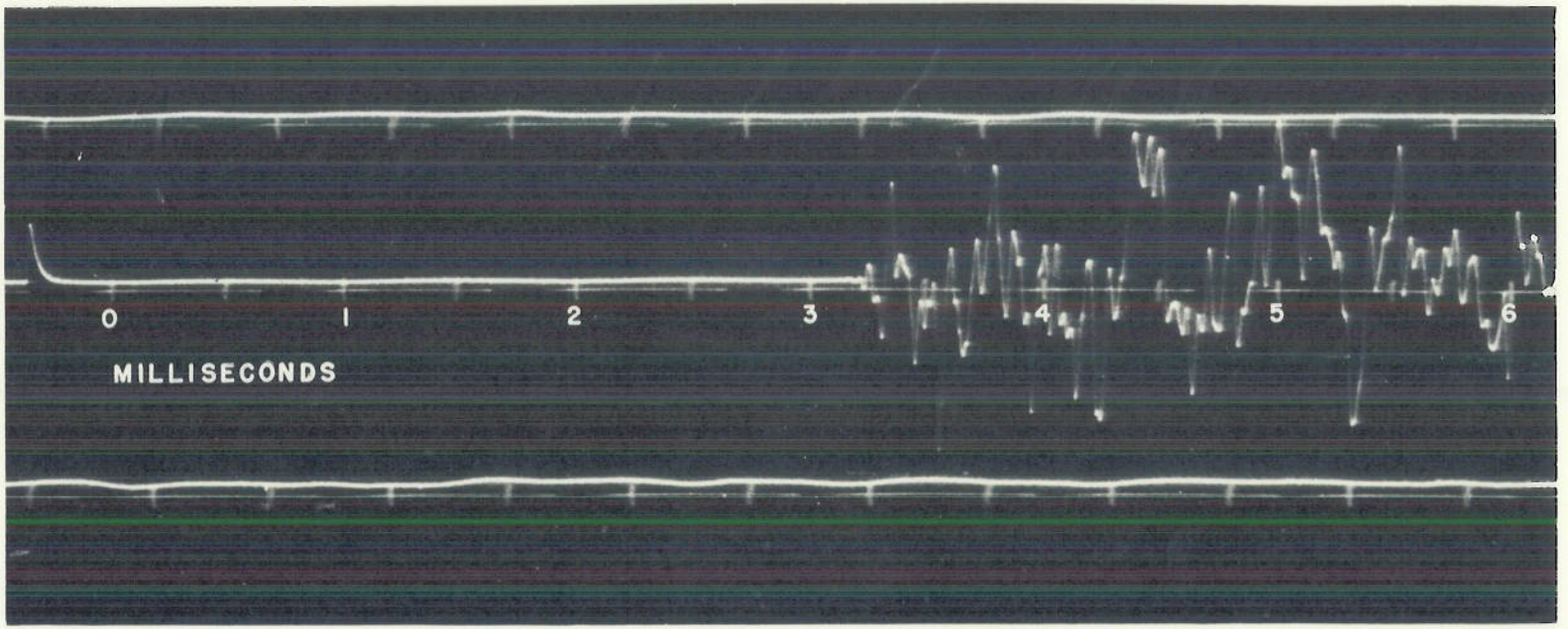
THREE CHANNEL CATHODE RAY OSCILLOGRAPH RECORD

A COMMON ZERO TIME IS INDICATED BY THE "PIPS" P.

STRAINS CAUSED BY BENDING MOMENTS IN A BAR THAT WAS STRUCK TRANSVERSELY.

DECLASSIFIED

DECLASSIFIED



STRAIN IN AIRCRAFT ARMOR SUPPORT

CAUSED BY PROJECTILE IMPACT

PLATE 19D

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DECLASSIFIED

CABLE EFFECTS

CABLE COMPONENTS ARE LISTED IN ORDER FROM THE OUTER SURFACE OF THE CABLE.

OUTSIDE DIAMETER OF CABLE IS GIVEN.

AMPLITUDE SCALE IS CONSTANT FOR ALL CURVES.

APPROXIMATE CAPACITY OF 0.003ufd IN PARALLEL WITH CABLE.
TIMING SPOTS ARE 0.001 SECONDS APART.

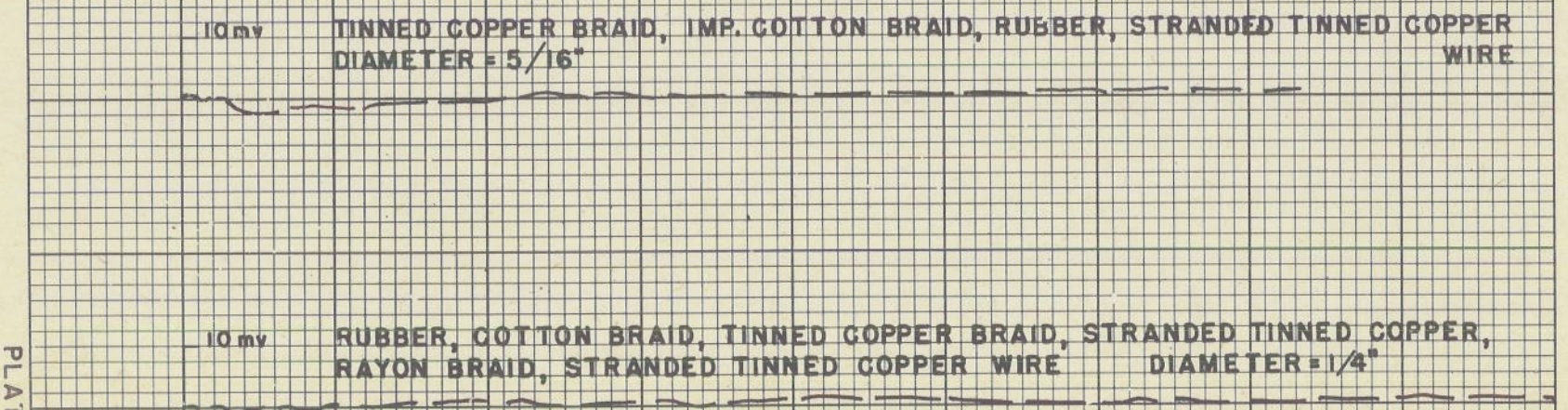


PLATE 20A

DECLASSIFIED

DECLASSIFIED

DECLASSIFIED

DECLASSIFIED

CABLE EFFECTS (con't)

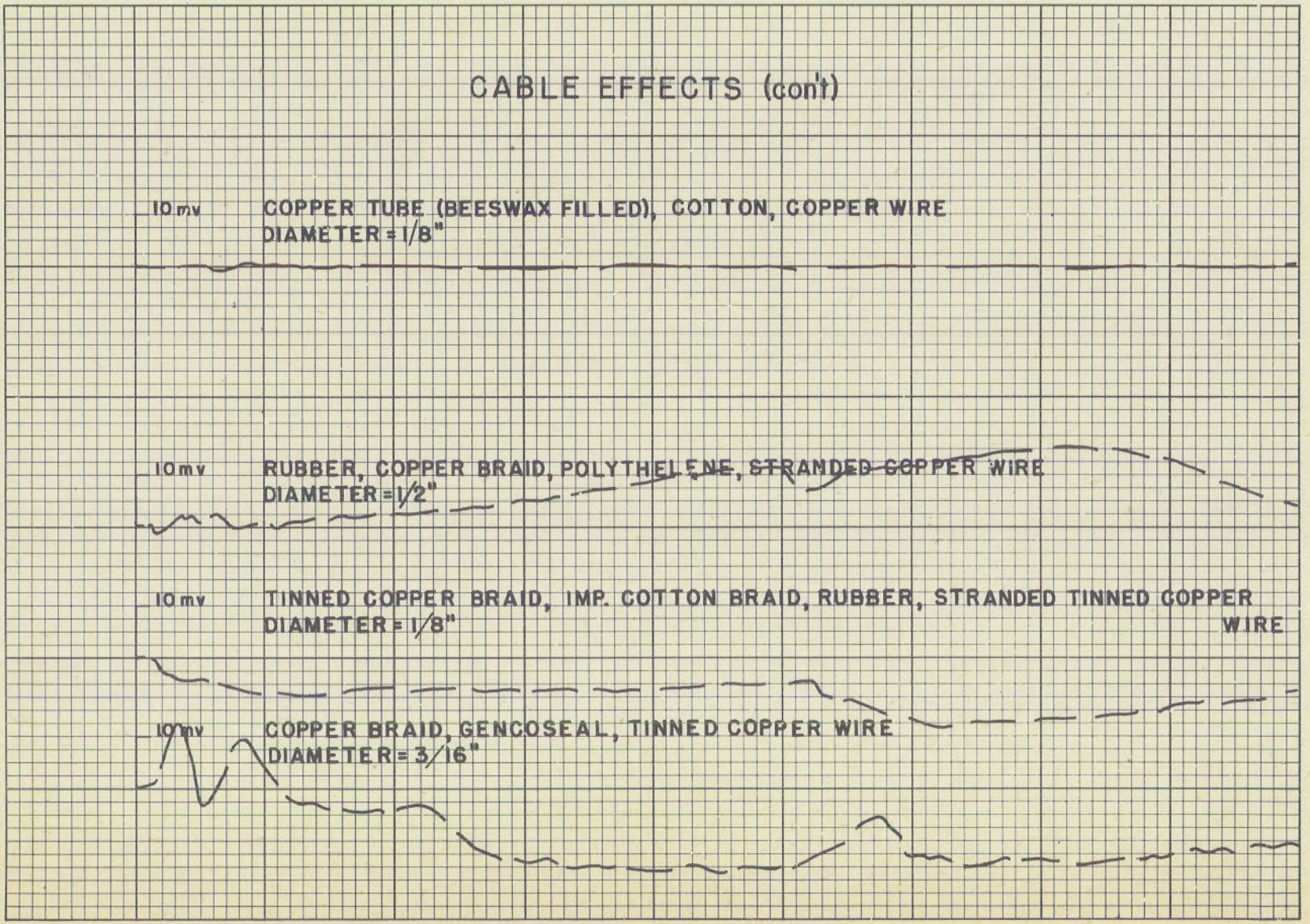
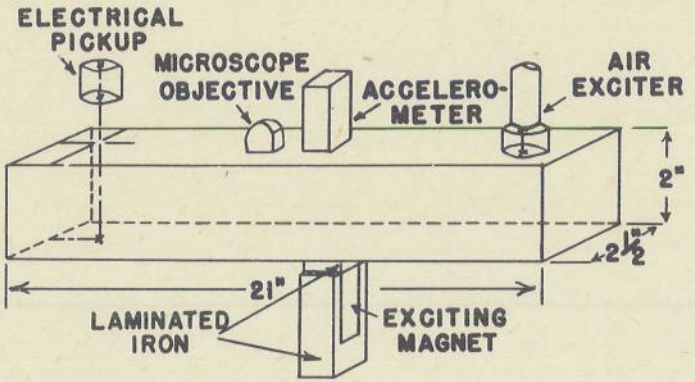
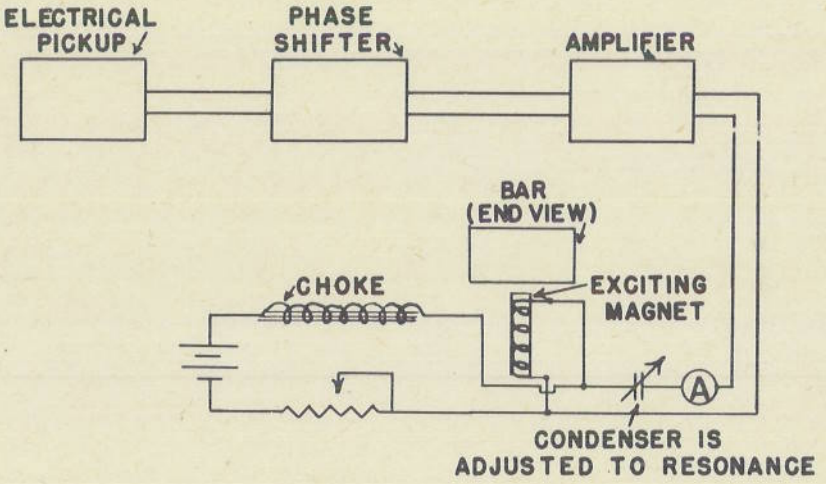


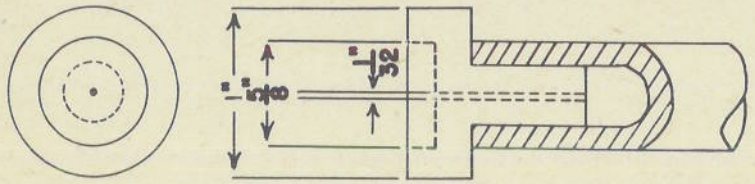
PLATE 20B



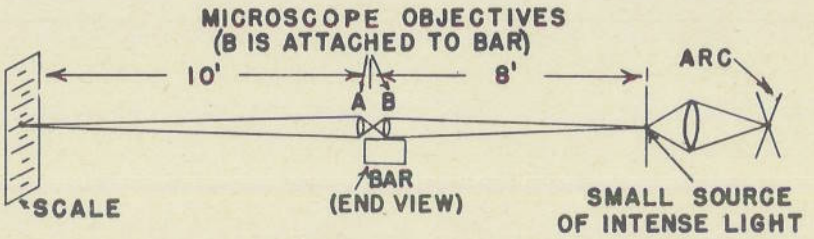
(A) FREE-FREE VIBRATION BAR FOR ACCELEROMETER CALIBRATION



(B) ELECTRICAL EXCITING CIRCUIT



(C) AIR EXCITER CUP



(D) OPTICAL DISPLACEMENT GAGE

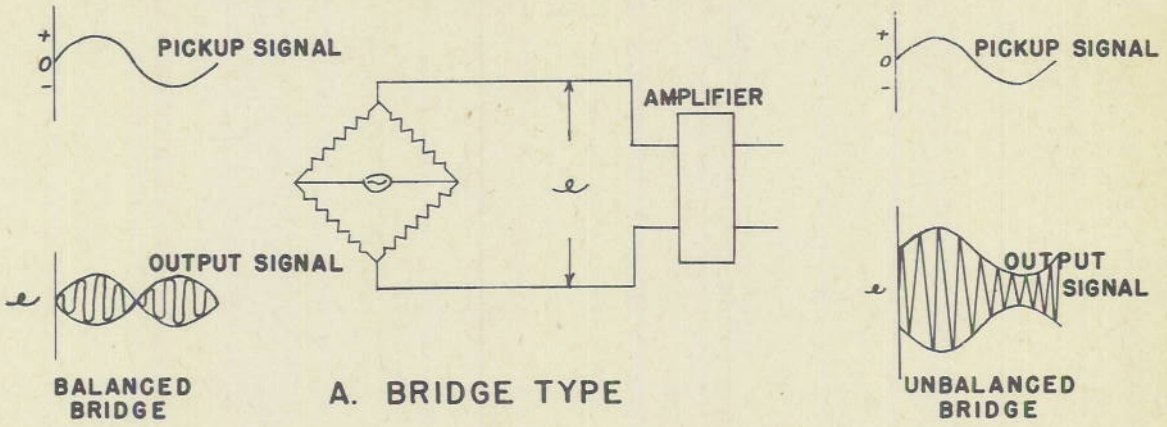
PLATE 21

DECLASSIFIED

DECLASSIFIED

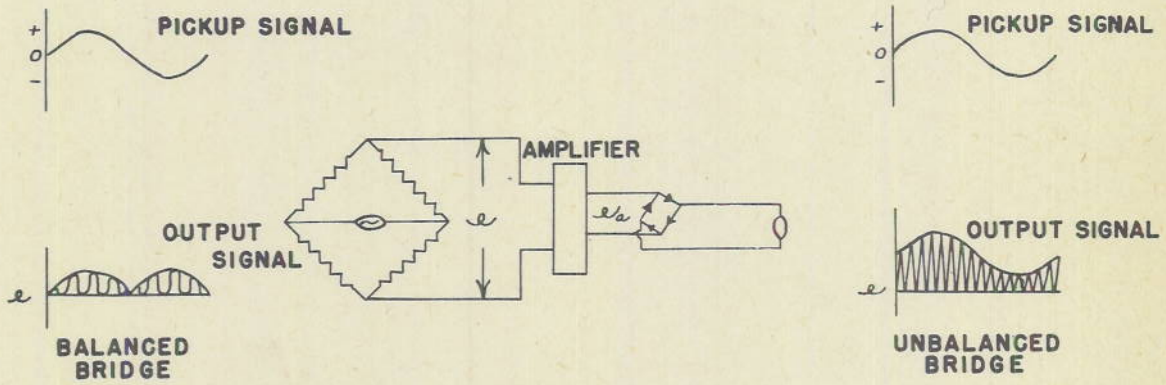
DECLASSIFIED

ELEMENTARY CARRIER TYPE CIRCUITS



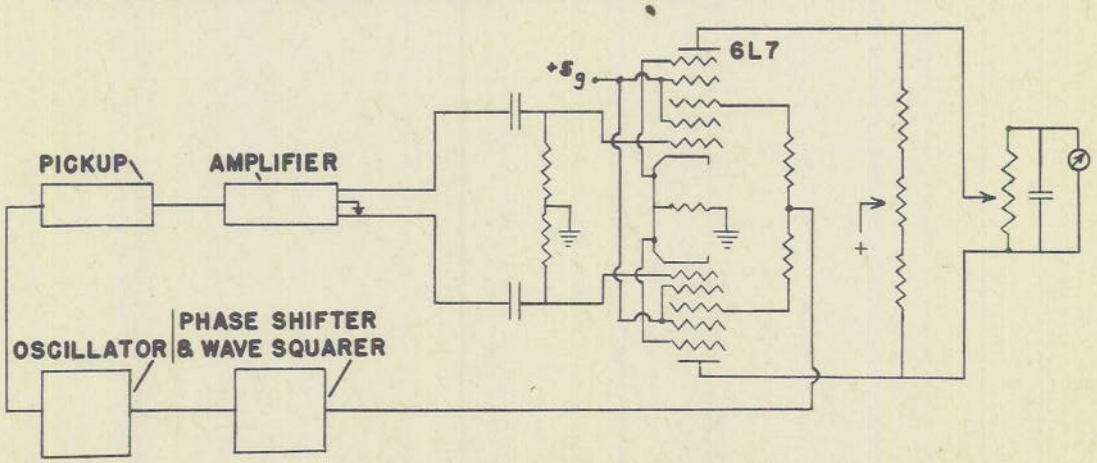
A. BRIDGE TYPE

OUTPUT SIGNAL DOES NOT DISTINGUISH BETWEEN PLUS & MINUS INPUT SIGNAL UNLESS INITIAL BRIDGE UNBALANCE IS PROVIDED



B. BRIDGE-RECTIFIER TYPE

OUTPUT SIGNAL DOES NOT DISTINGUISH BETWEEN PLUS & MINUS INPUT SIGNAL UNLESS INITIAL BRIDGE BALANCE IS PROVIDED



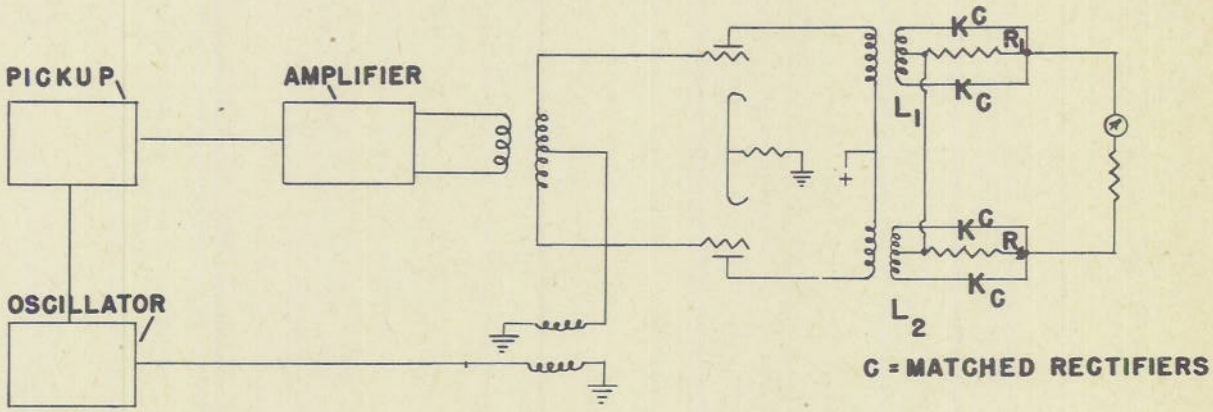
C. BRIDGE-"PHASE SENSITIVE RECTIFIER" TYPE

PLATE 22A

DECLASSIFIED

DECLASSIFIED

ELEMENTARY CARRIER TYPE CIRCUITS



D. BRIDGE - MIXER - RECTIFIER TYPE

BAND-PASS FILTERS, CARRIER FREQUENCY FILTERS, PHASE SHIFTING NETWORKS, AND OTHER REFINEMENTS MAY BE ADDED

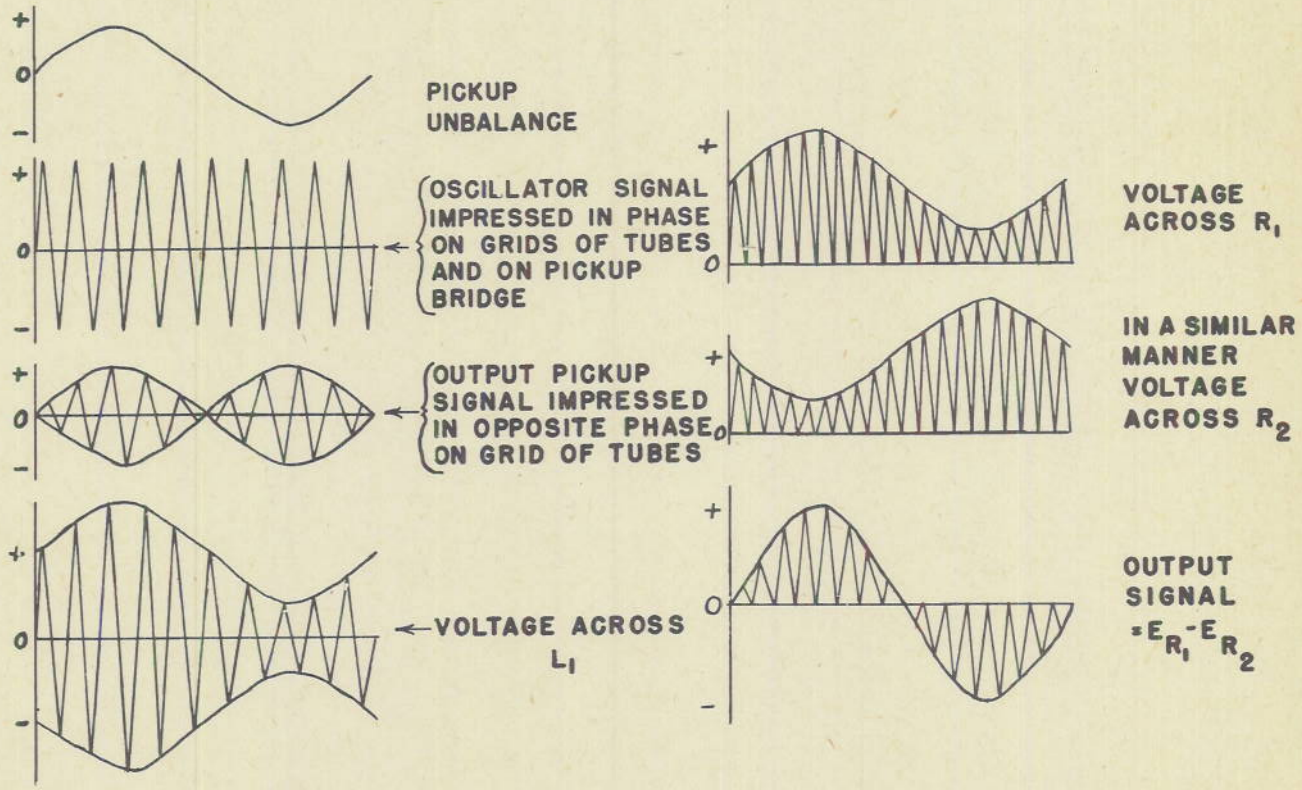
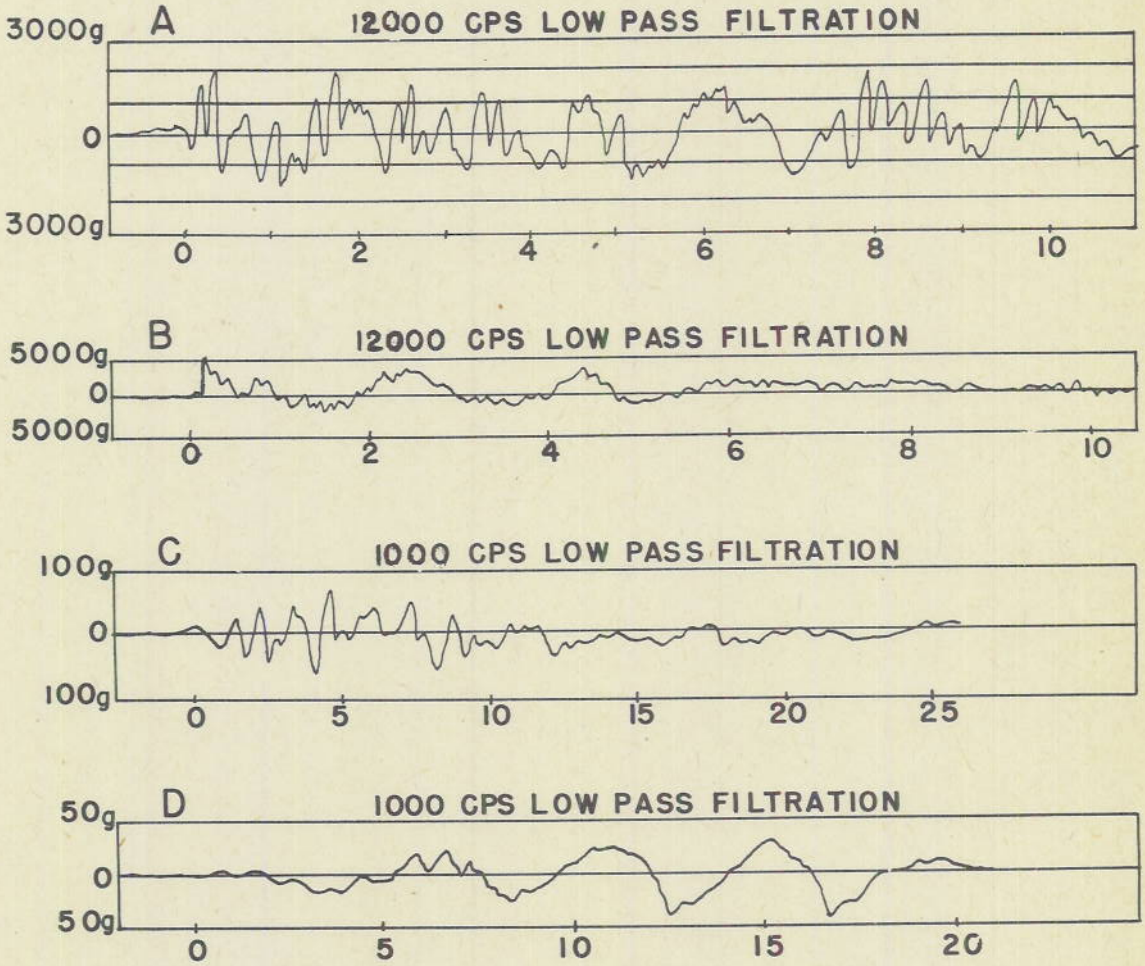


PLATE 22B

DECLASSIFIED

DECLASSIFIED

TYPICAL SHIPBOARD ACCELERATION CURVES CAUSED BY NON-CONTACT UNDERWATER EXPLOSIONS

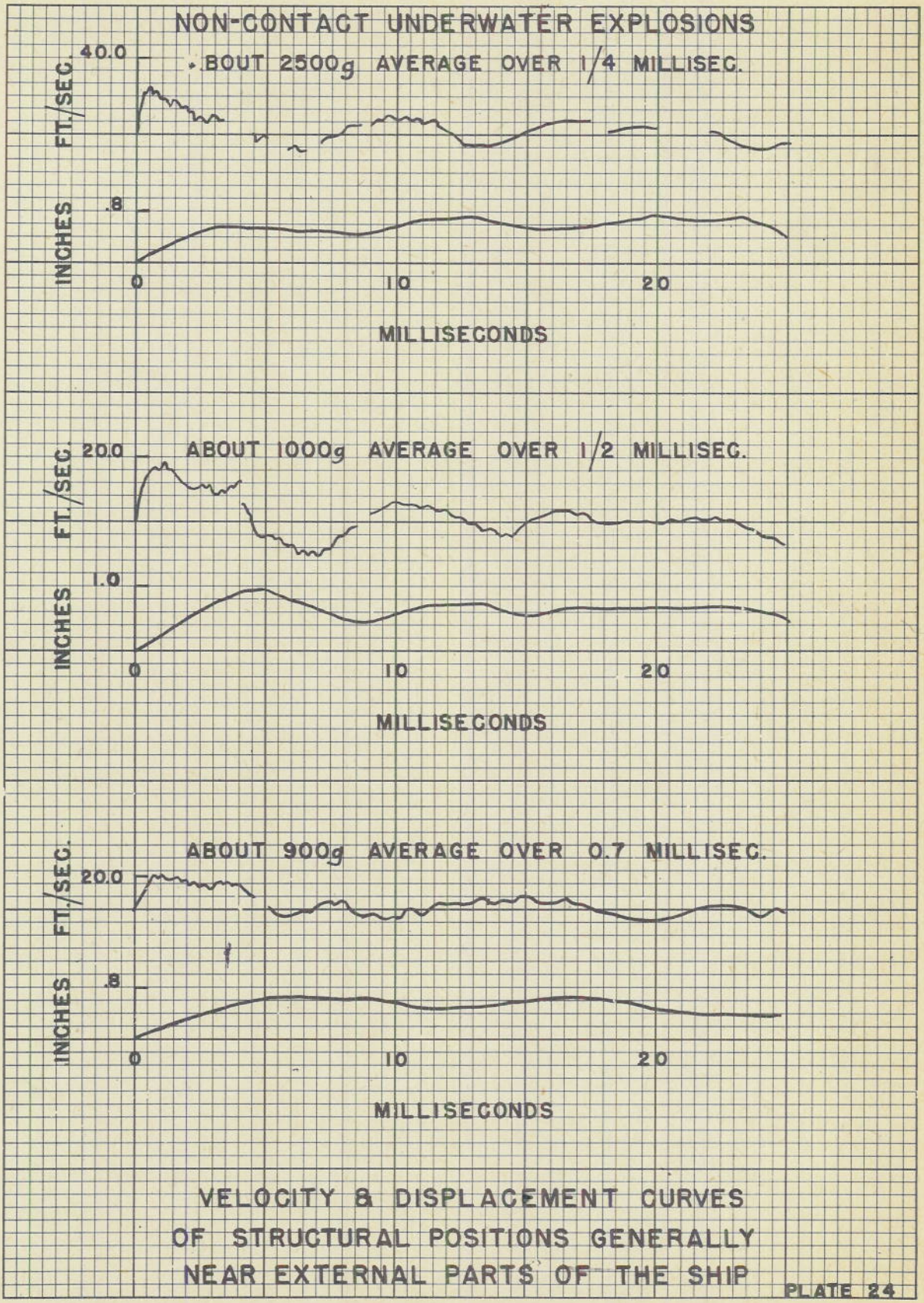


A & B ARE TYPICAL OF POSITION NEAR THE HULL, B IS TYPICAL OF A POSITION ON THE HULL ON THE SAME SIDE AS THE EXPLOSION

C & D ARE TYPICAL OF INTERIOR POSITIONS PROTECTED BY FLEXIBLE MOUNTS

DECLASSIFIED

DECLASSIFIED



VELOCITY & DISPLACEMENT CURVES
OF STRUCTURAL POSITIONS GENERALLY
NEAR EXTERNAL PARTS OF THE SHIP

PLATE 24

DECLASSIFIED

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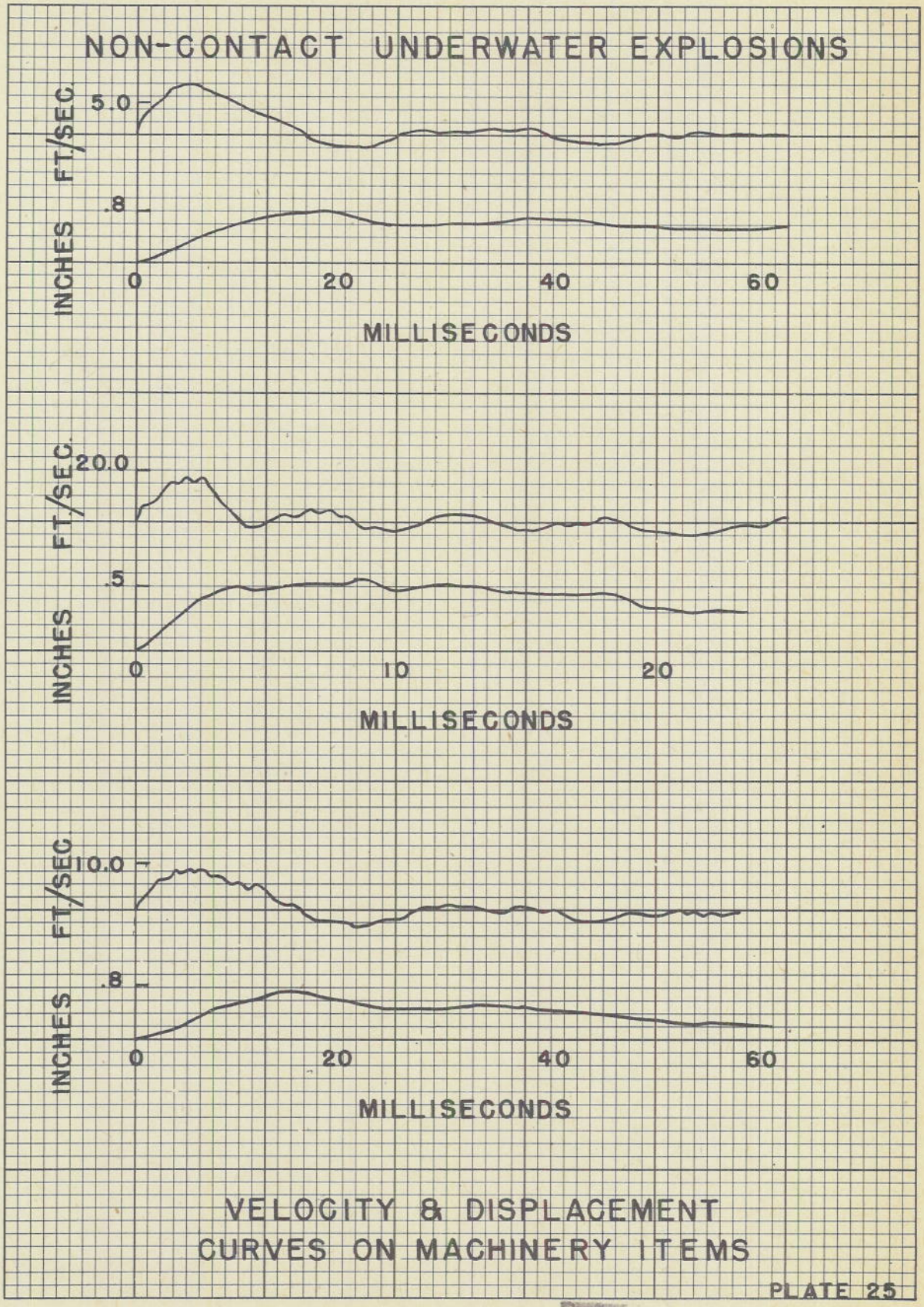

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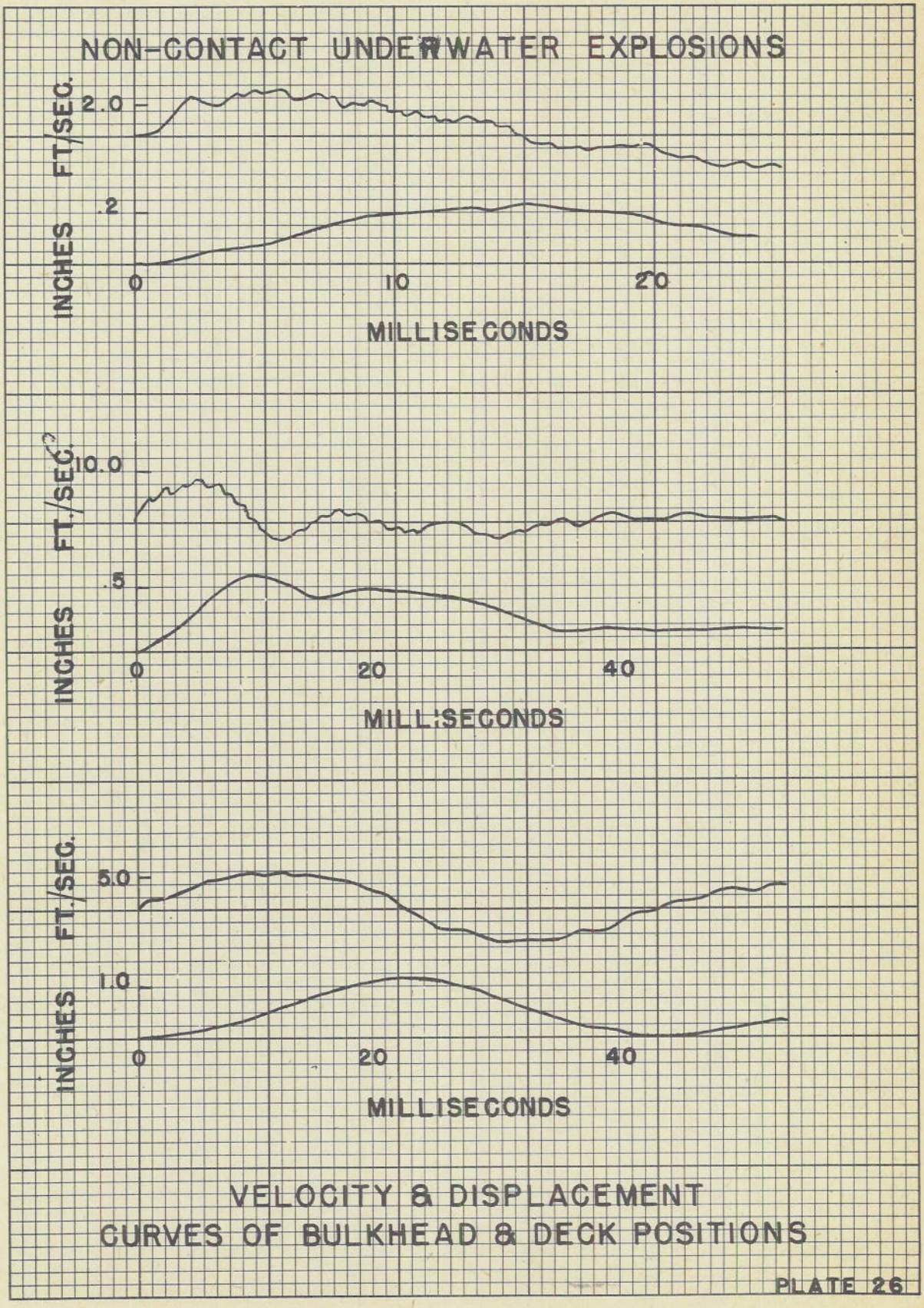

VELOCITY & DISPLACEMENT
CURVES OF BULKHEAD & DECK POSITIONS

PLATE 26

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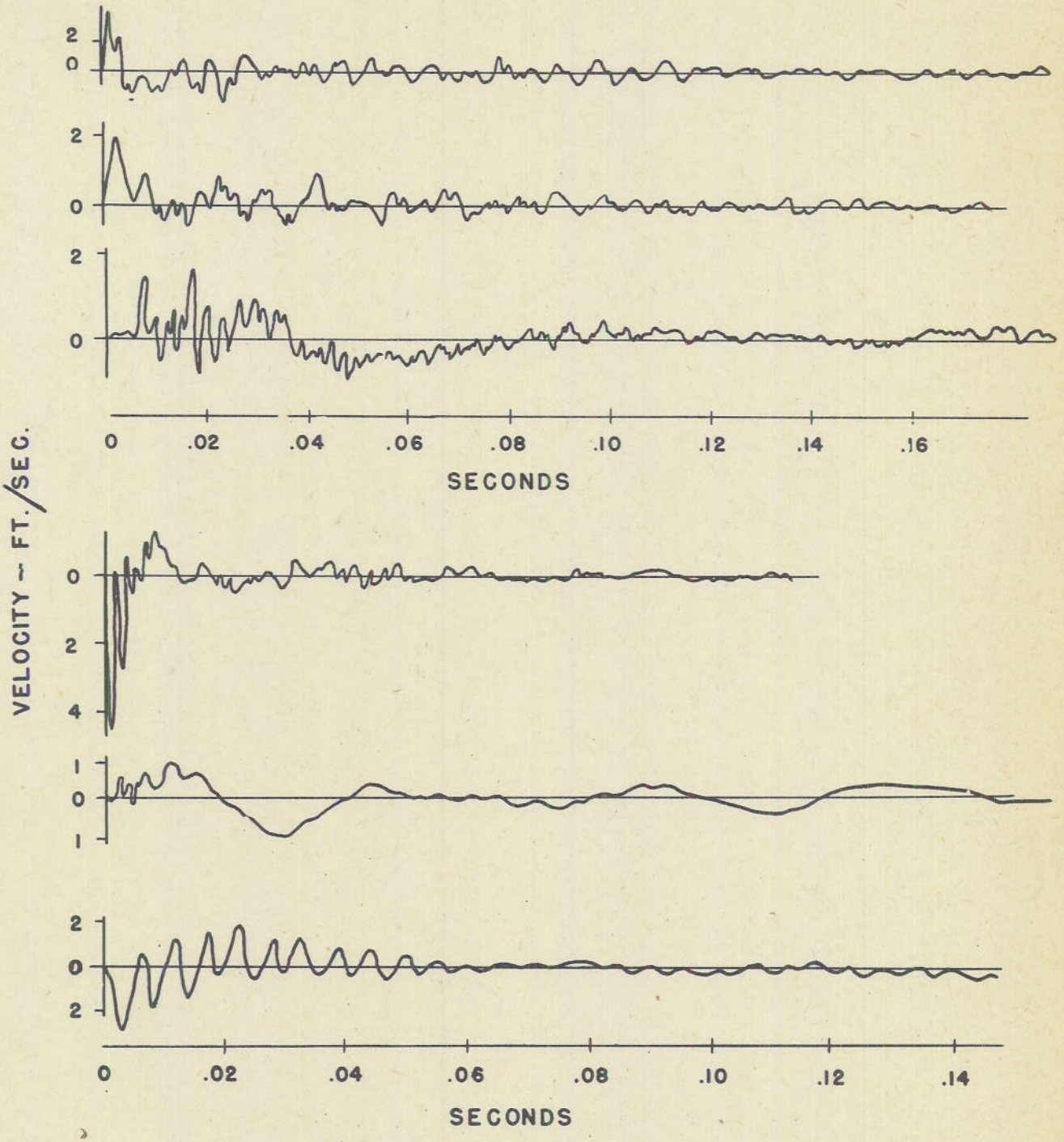

VELOCITY RECORDS OF SHIP VIBRATIONS CAUSED BY DEPTH CHARGES DROPPED BY THE SHIP WHILE UNDERWAY

PLATE 27

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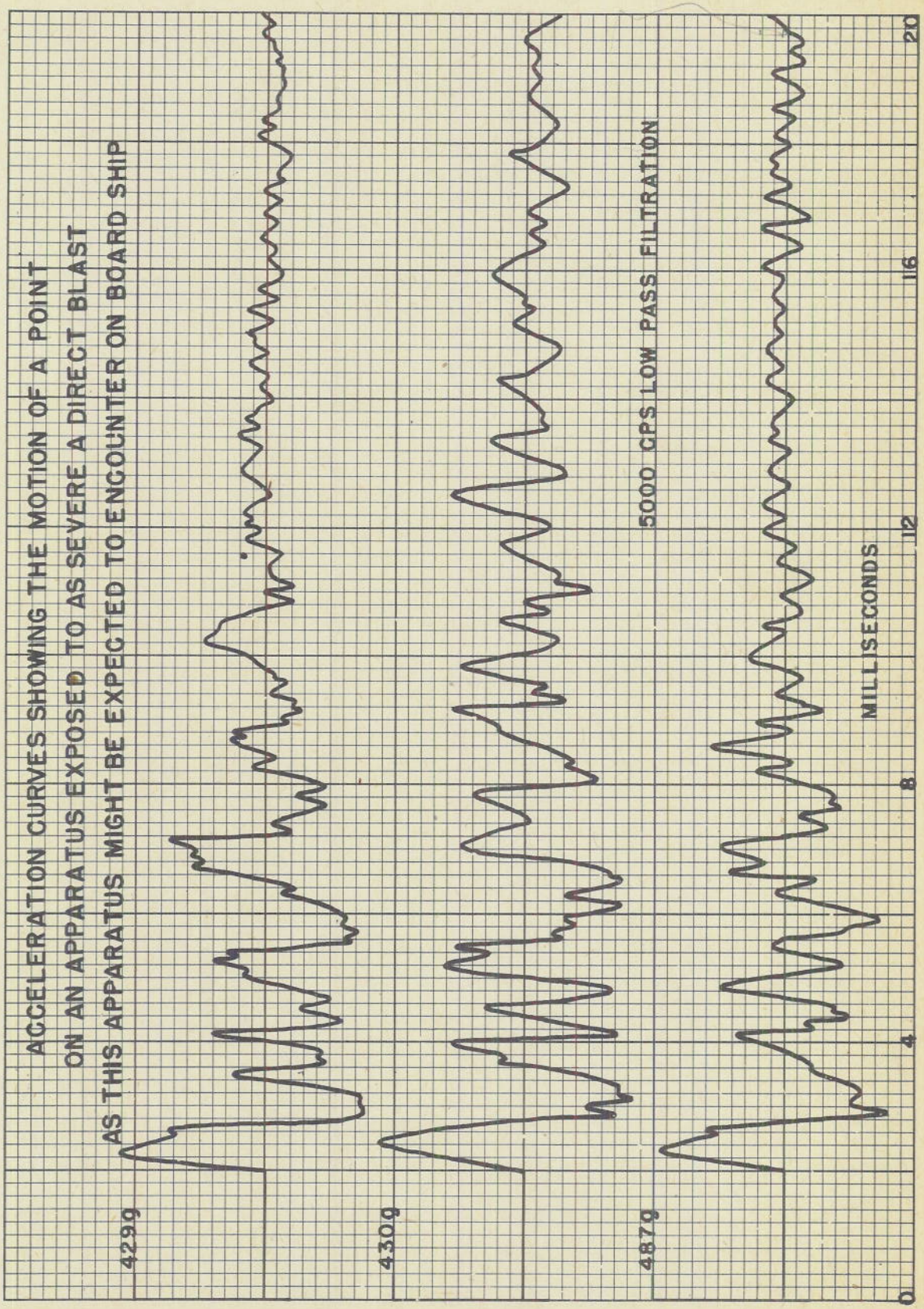

PLATE 28

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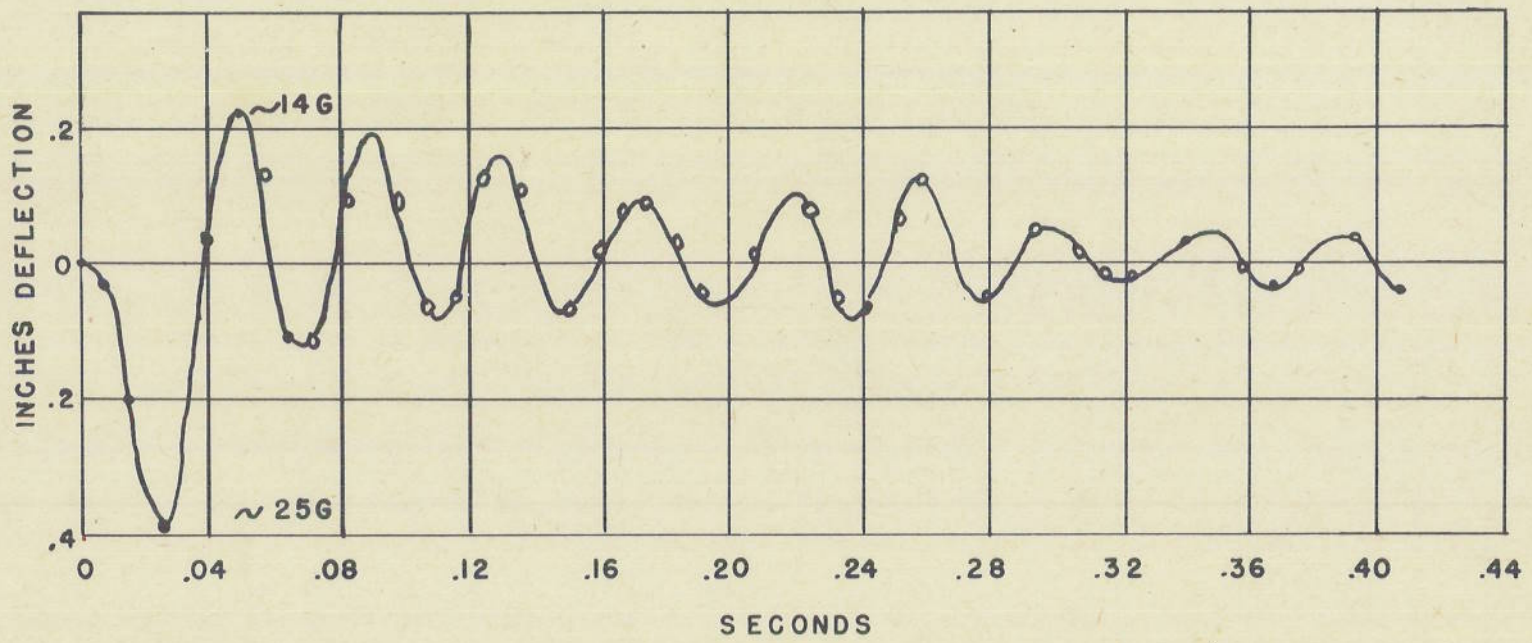

APPROXIMATELY 25 CPS

DECAYS TO ABOUT 1/4 ORIGINAL AMPLITUDE IN 3 CYCLES

DECK VIBRATIONS CAUSED BY GUN BLAST

PLATE 29

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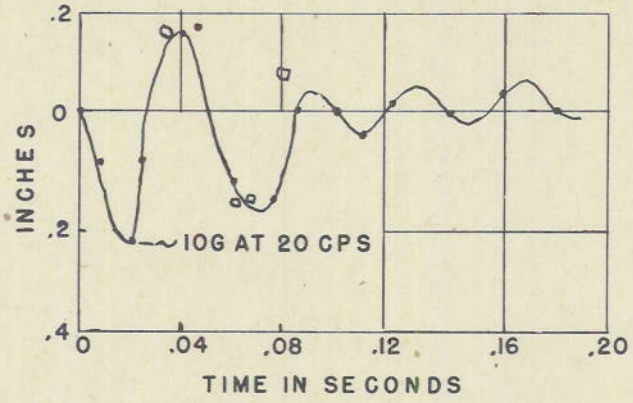
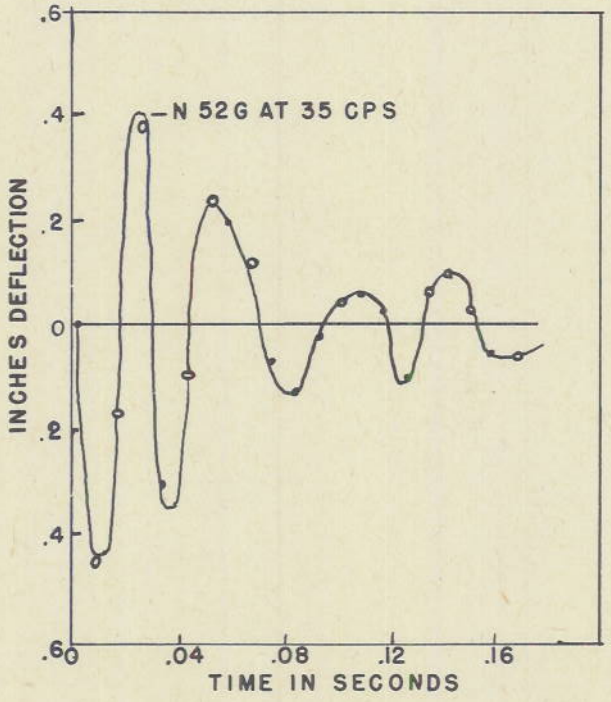
DECK VIBRATIONS CAUSED BY GUN BLAST



DECAYS TO ABOUT 1/6
AMPLITUDE IN 3 CYCLES



DECAYS TO ABOUT 1/5 ORIGINAL
AMPLITUDE IN 3 CYCLES

PLATE 30

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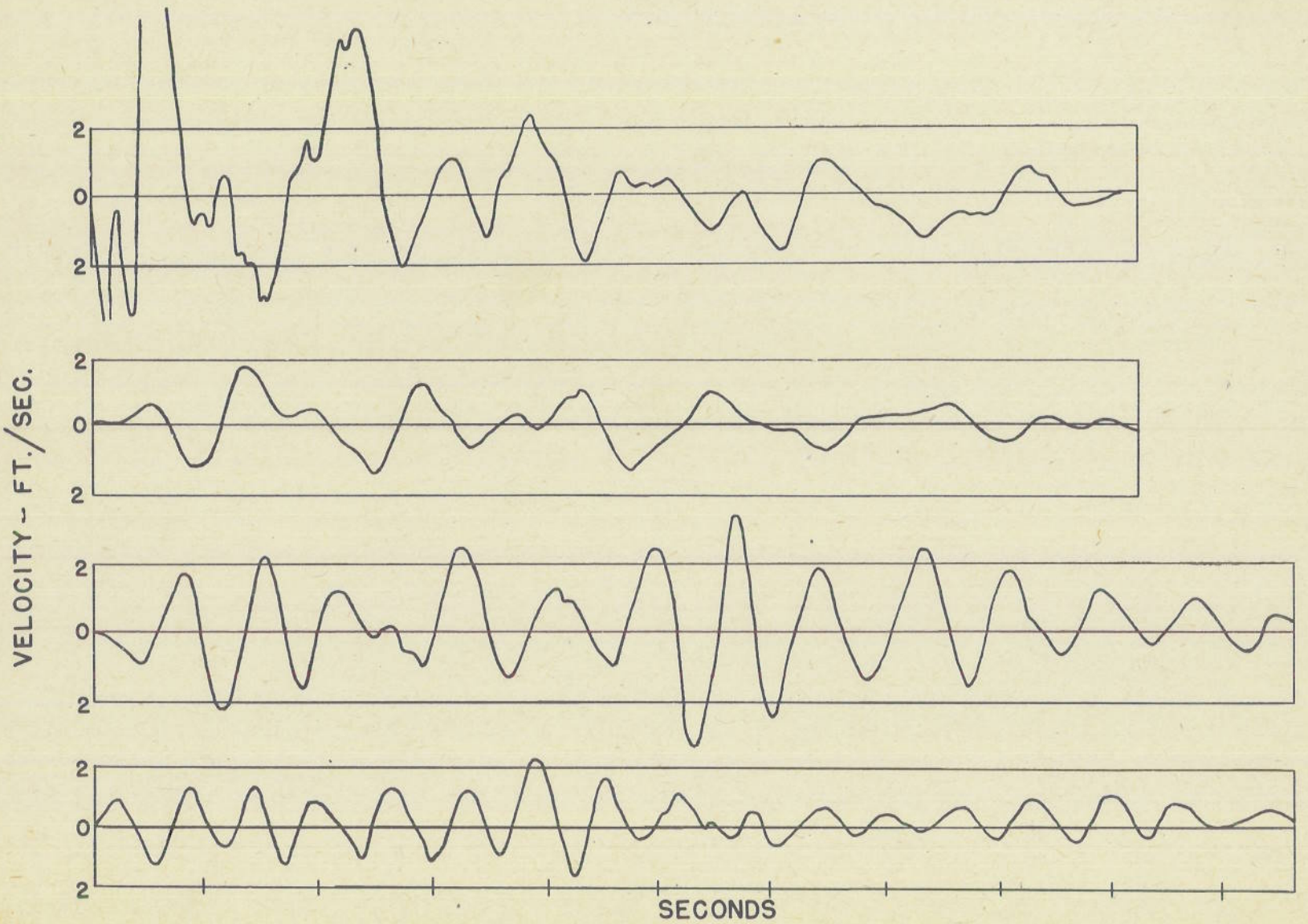

VELOCITY RECORDS OF DECKS & BULKHEADS
CAUSED BY GUN BLAST

PLATE 31

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124.

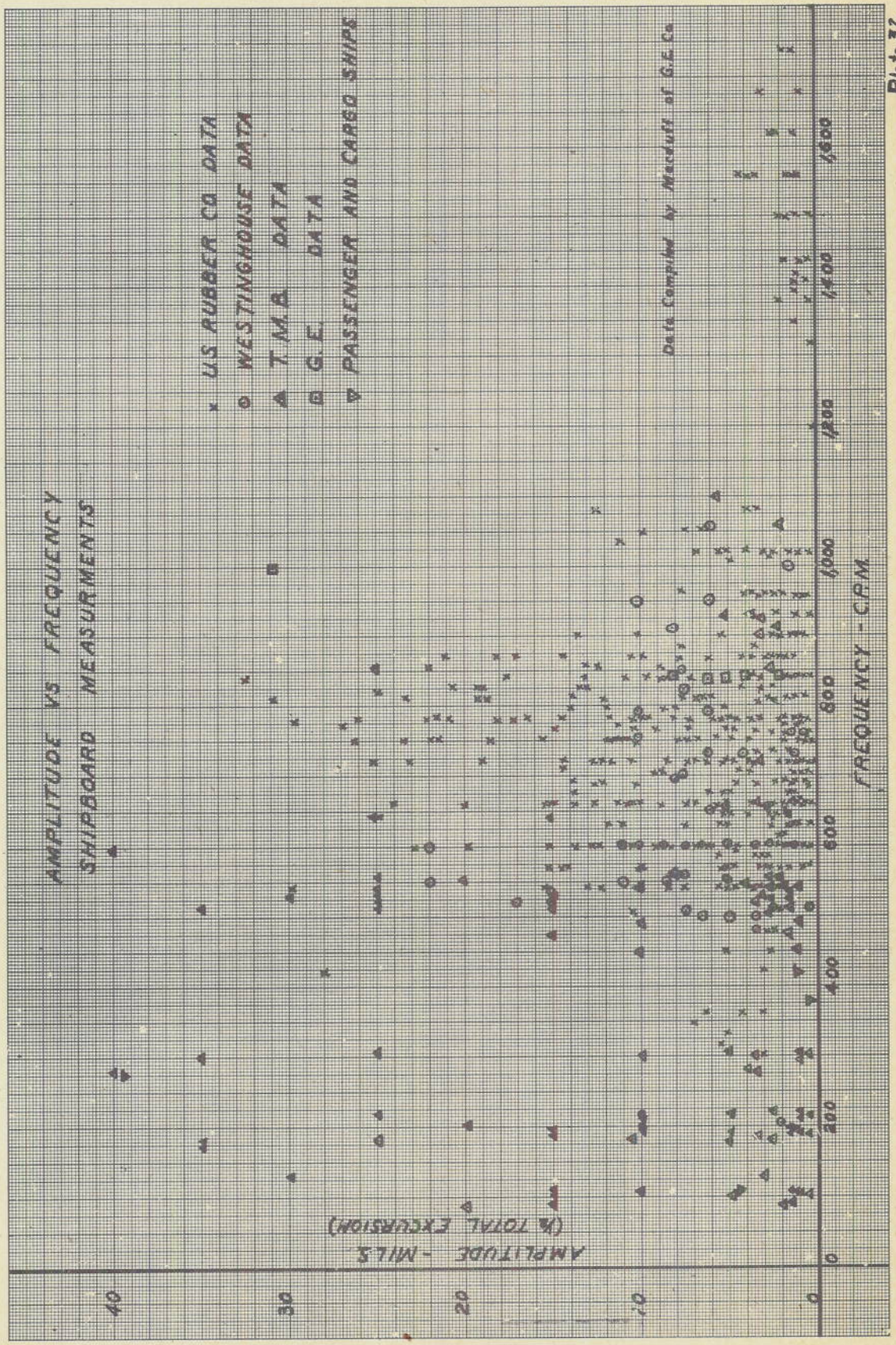

Plate 32

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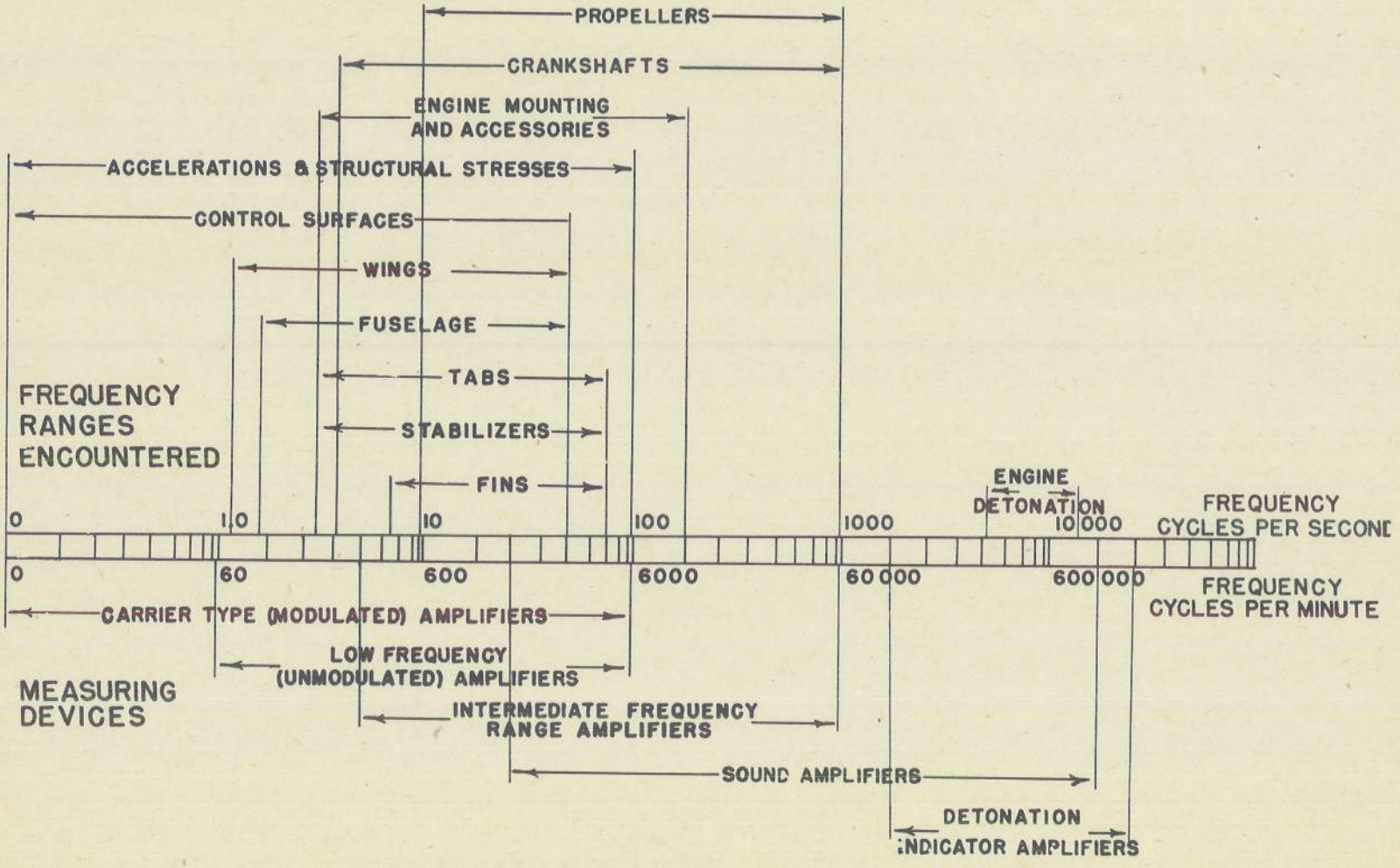

PLATE 33

SPECTRUM OF AIRCRAFT VIBRATION FREQUENCIES –
RANGES ENCOUNTERED AND FREQUENCY RANGE OF MEASURING DEVICES
BY CRITCHLOW, REF. NO 48

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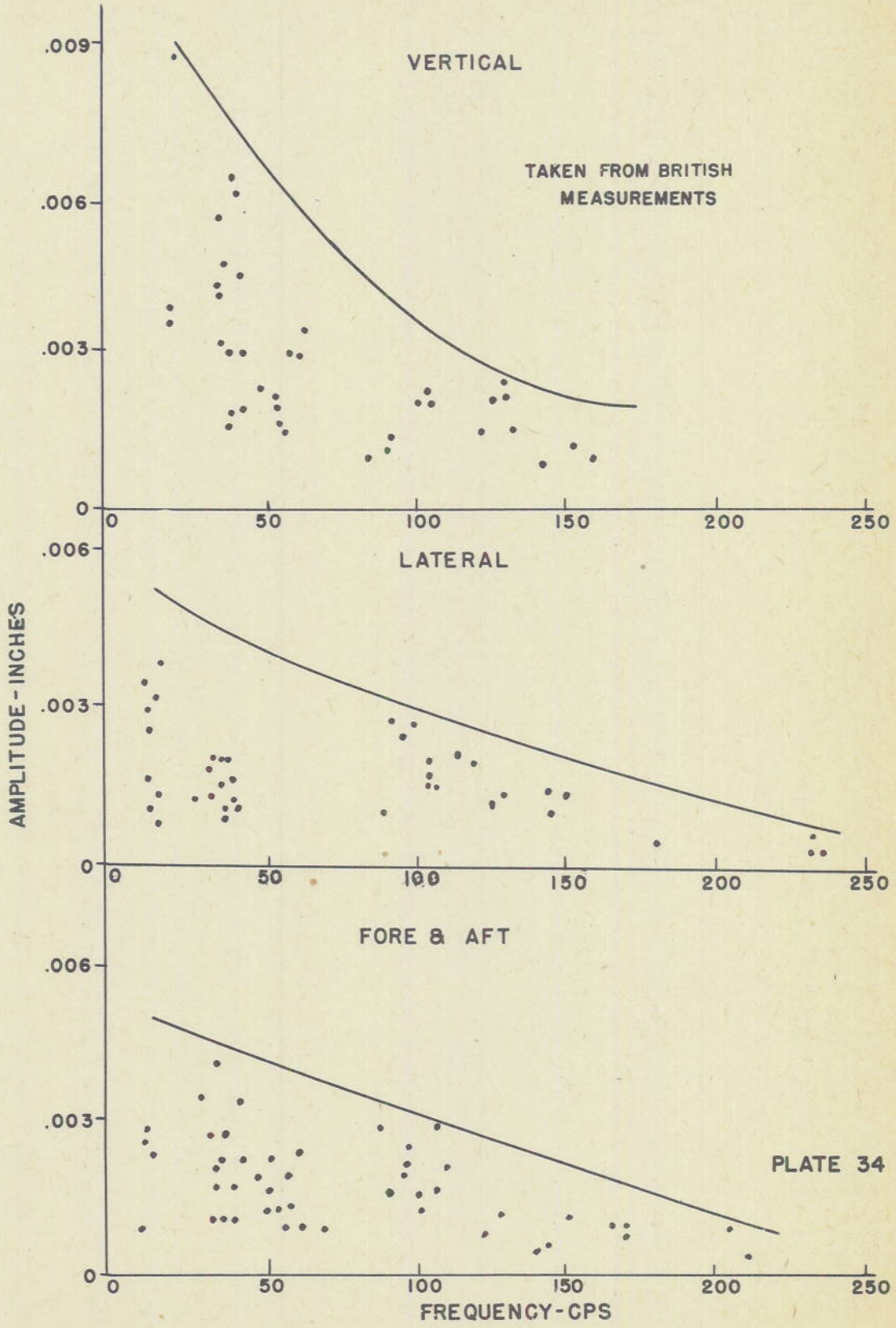

PLATE 34

MAXIMUM VIBRATIONS MEASURED IN PILOTS' COCKPITS

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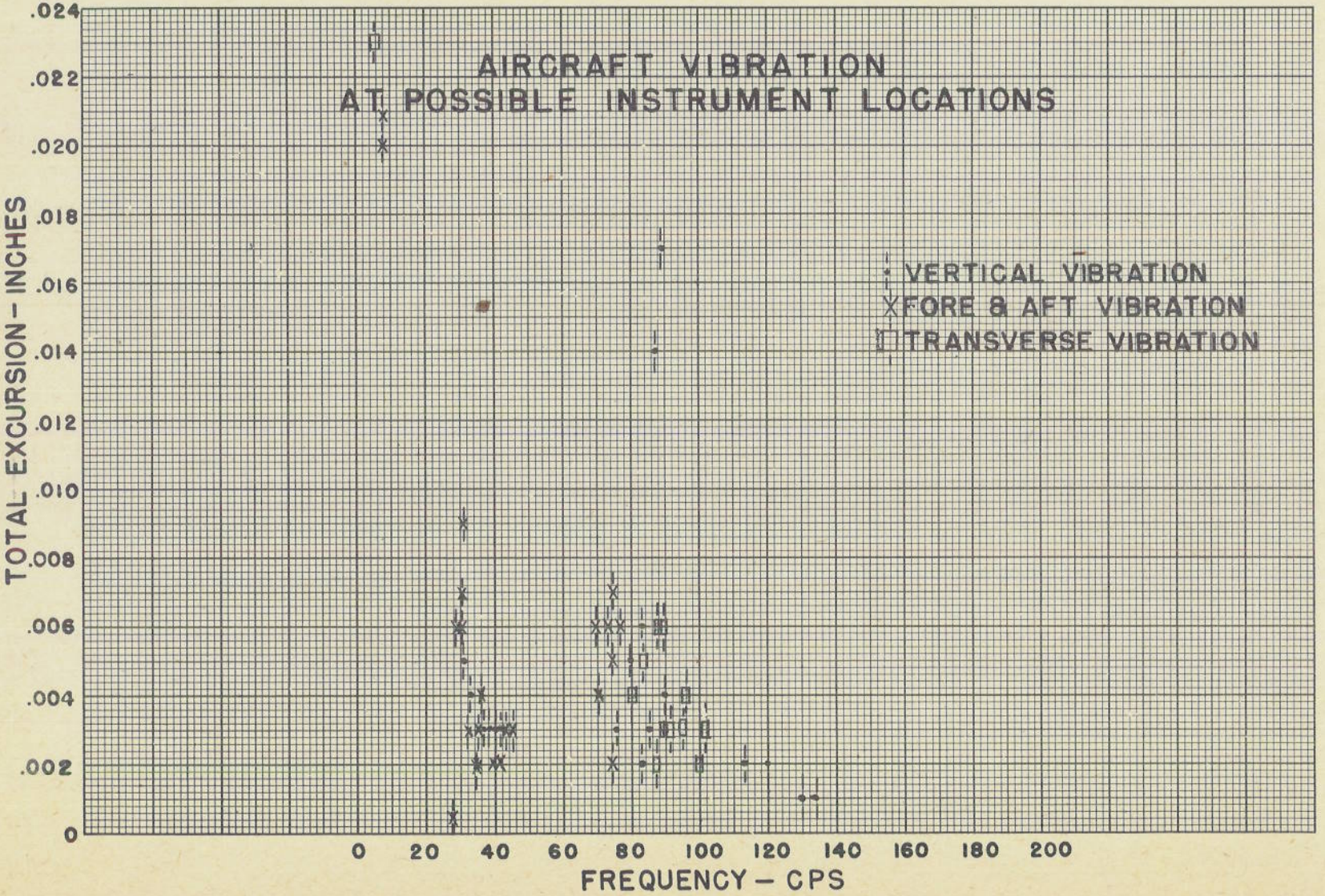

PLATE 35

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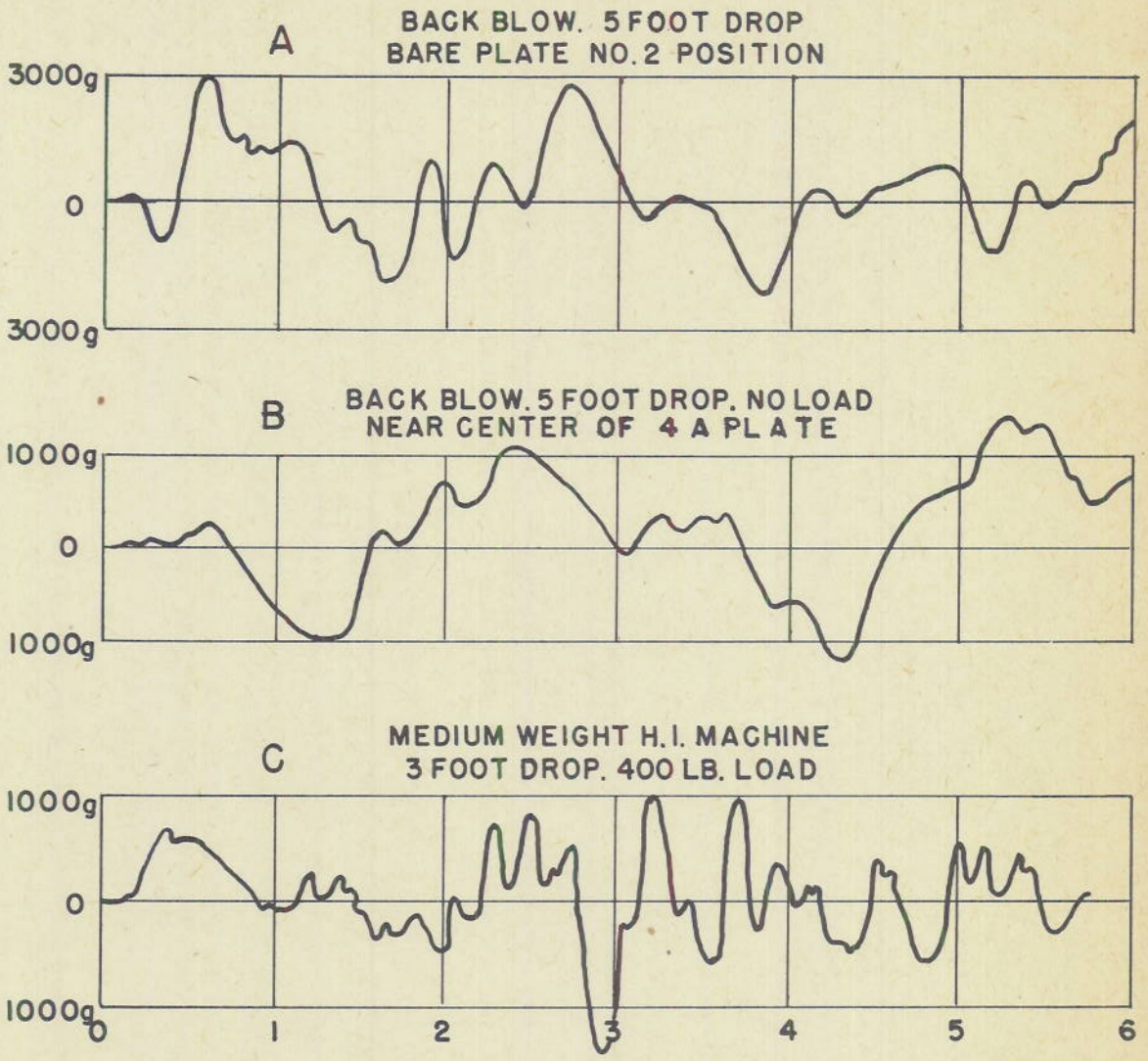

TYPICAL ACCELERATION CURVES
FOR HIGH IMPACT MACHINES.
5000 LOW PASS FILTRATION
CURVES A&B FOR LIGHT WEIGHT H.I. MACHINE
CURVE C FOR MEDIUM WEIGHT MACHINE

PLATE 36

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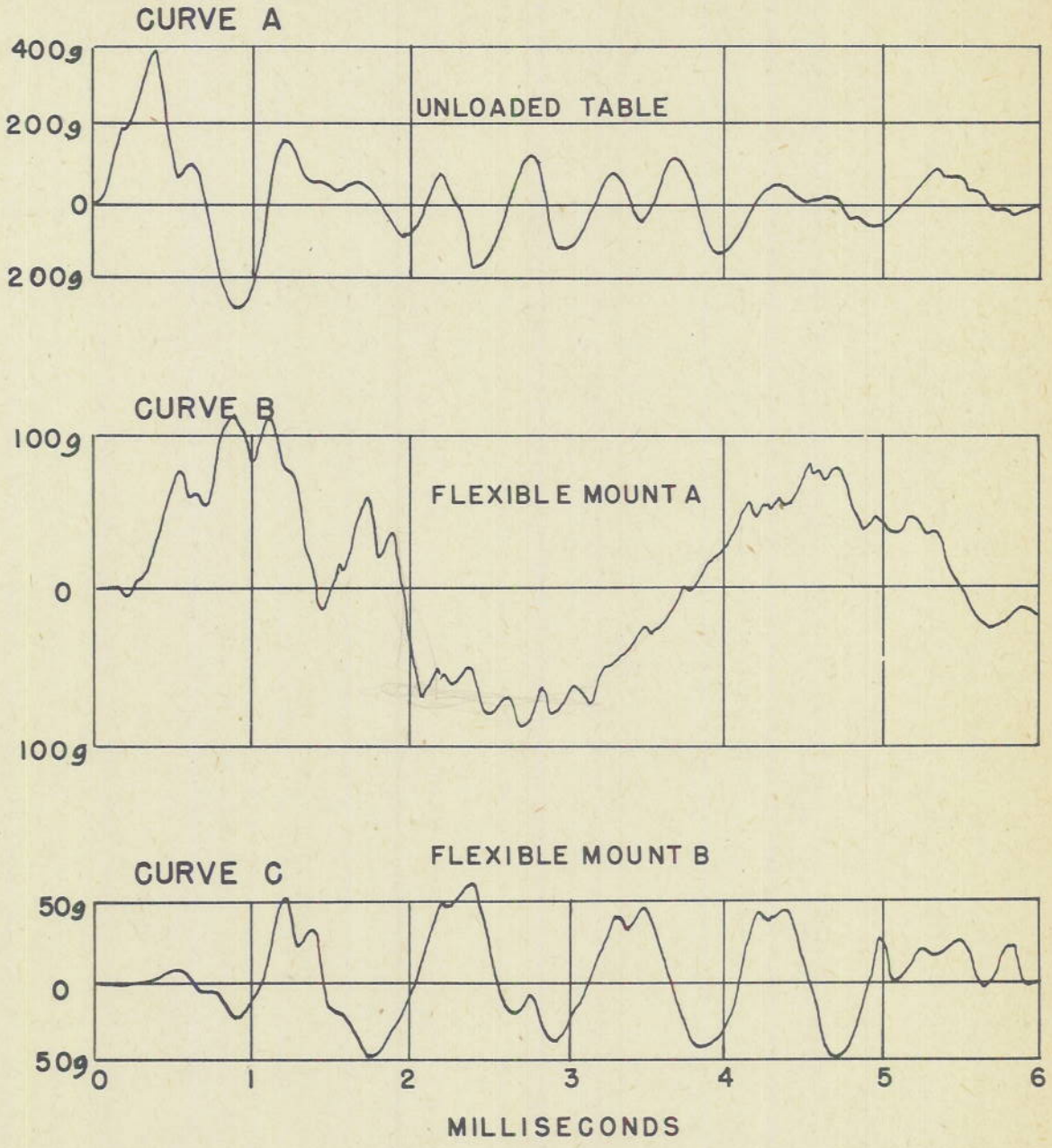

TYPICAL ACCELERATION CURVES OBTAINED FROM NAVY TYPE HIGH IMPACT MACHINES. H.I. MACHINE FOR ELECTRONIC DEVICES. 5000 LOW PASS FILTRATION

PLATE 37

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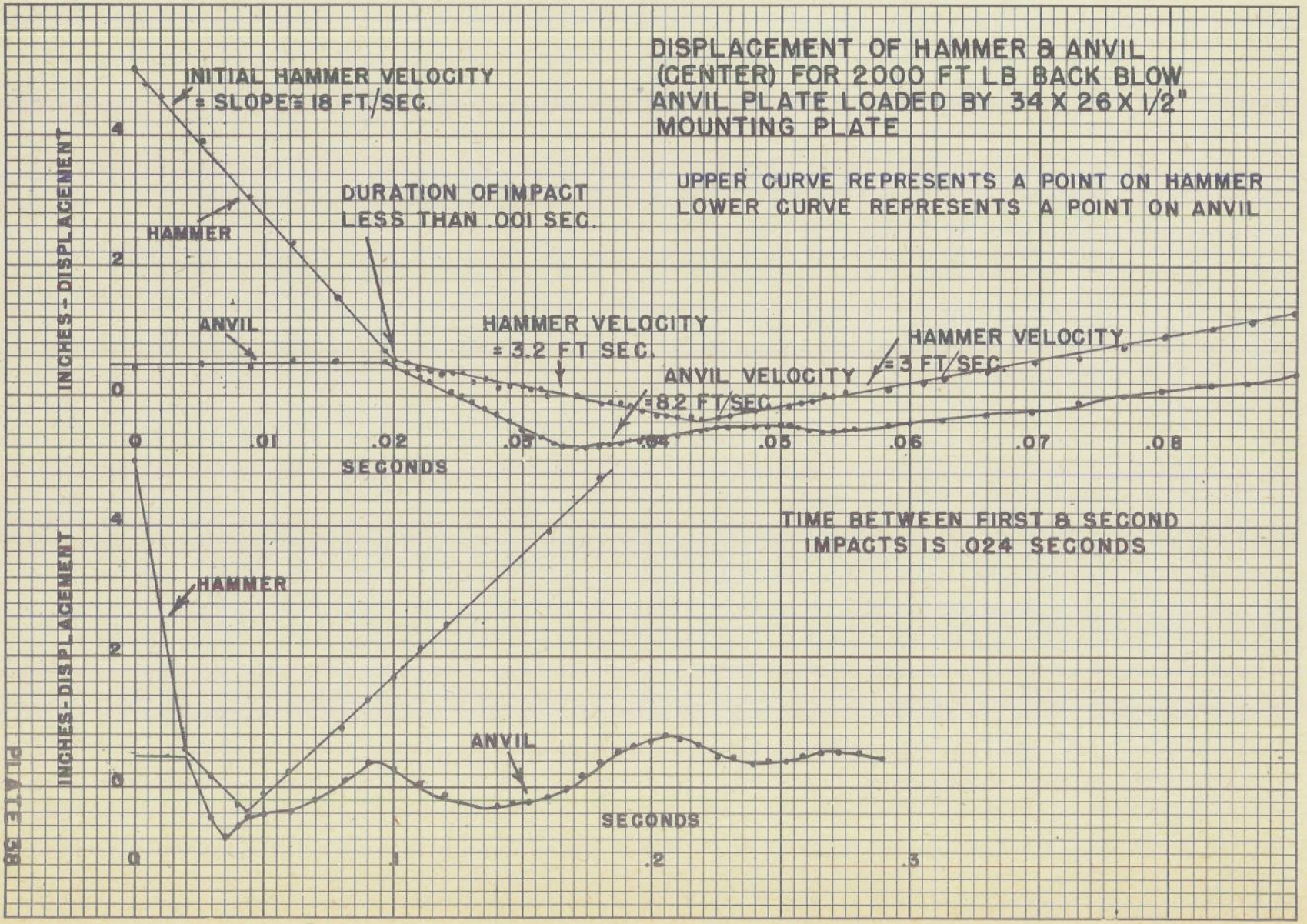

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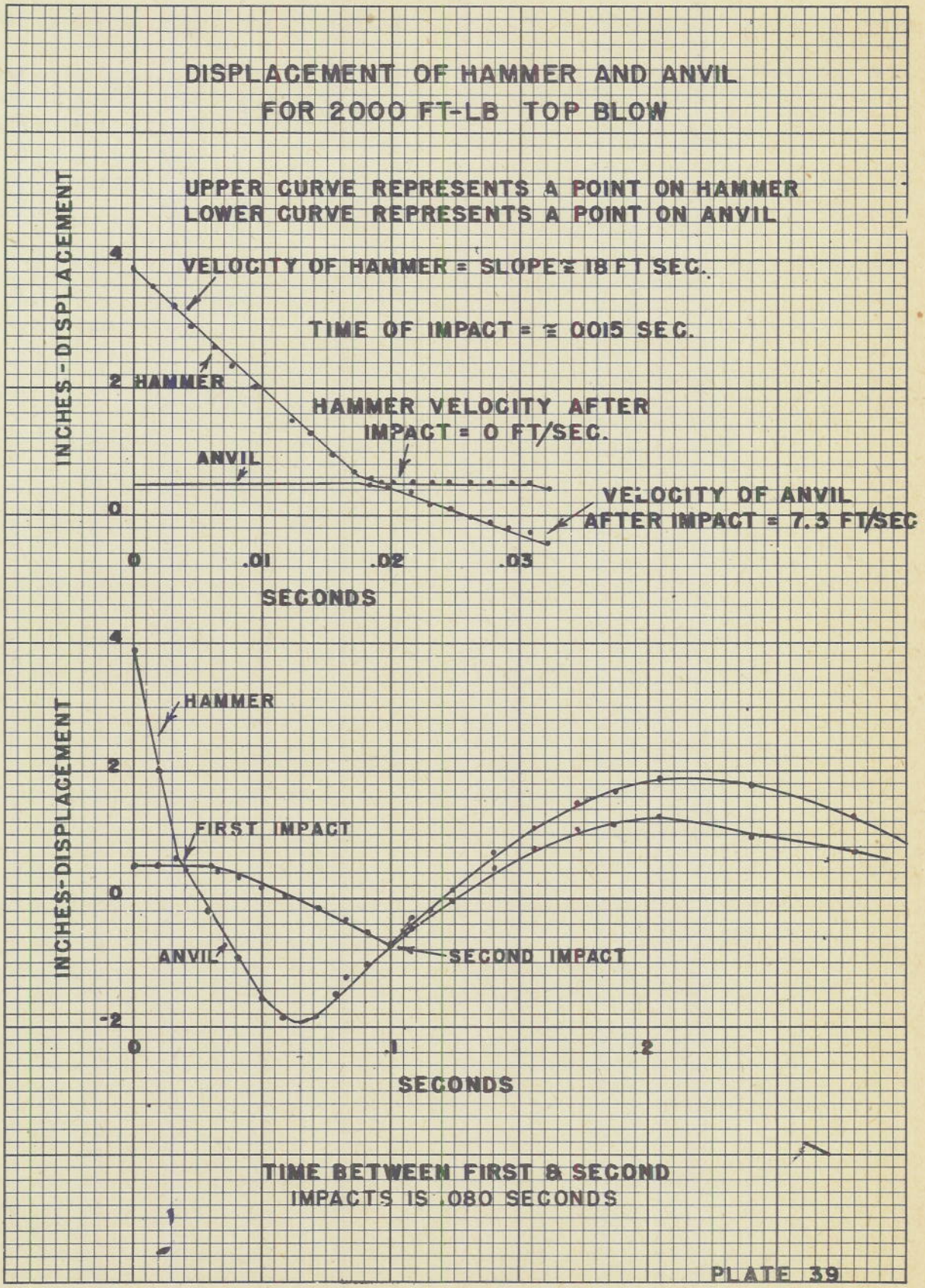

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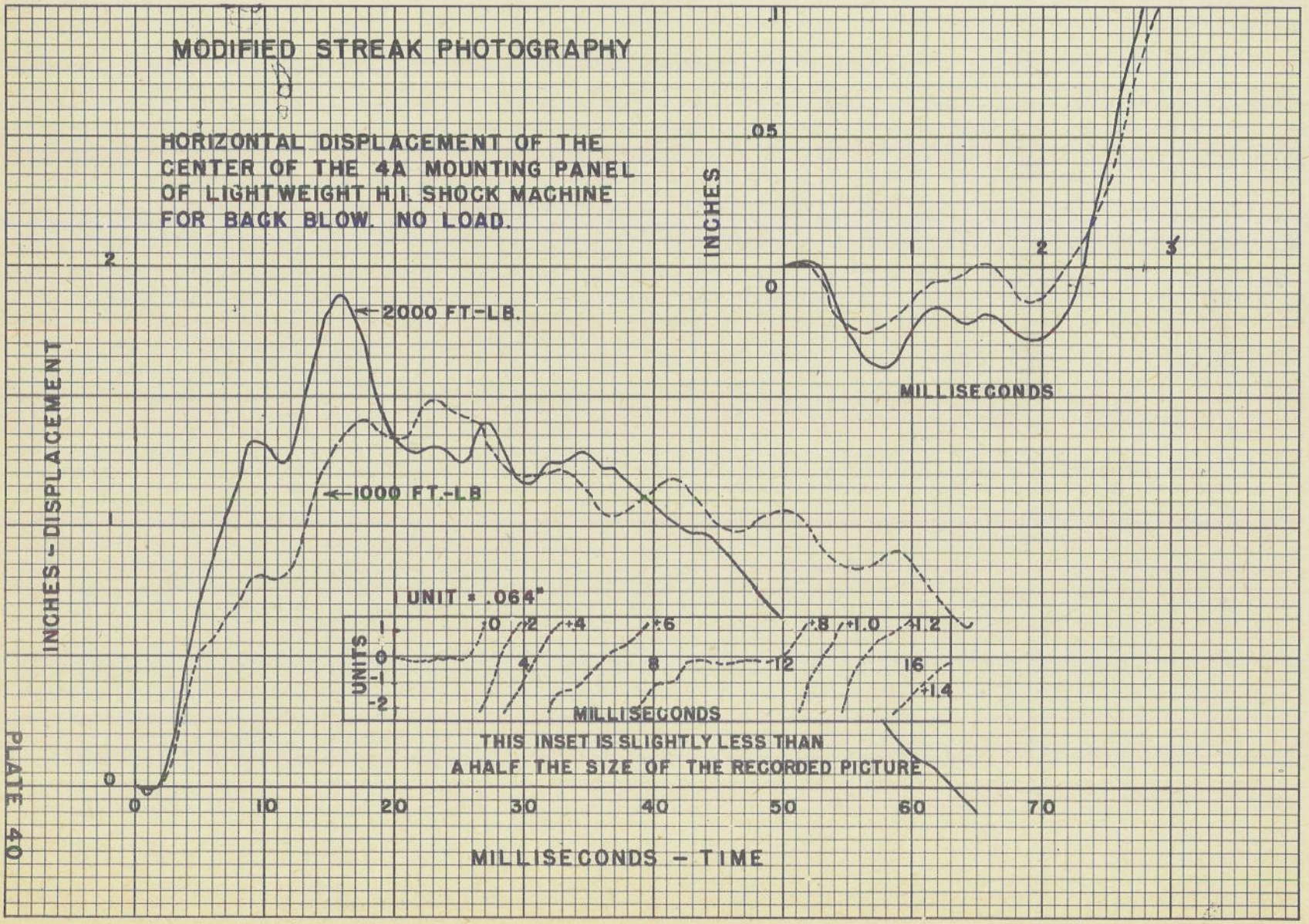

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AMPLITUDE—FREQUENCY RELATIONS FOR DIRECT DRIVE VIBRATION MACHINES

A—A TYPICALLY GOOD RESPONSE

B—NORMALLY ENCOUNTERED AMPLITUDE RESPONSE

C—VARIATIONS FOR FULL LOAD DEAD WEIGHT

D—MACHINE LOADED 270 PERCENT OF FULL LOAD DEAD WEIGHT

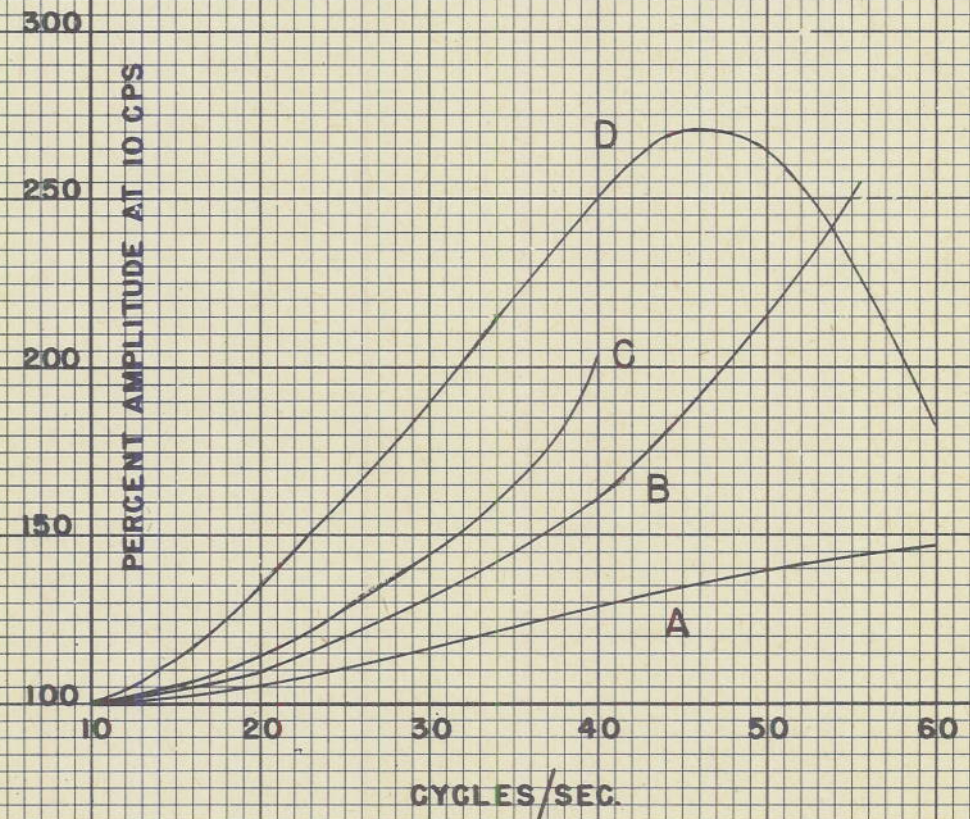

PLATE 41

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