REEL-C 4308

A.T.I 93805

UNCLASSIFIED

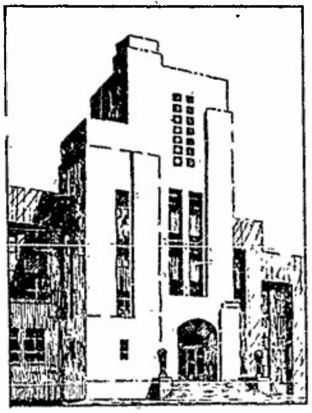
ATI No. 23985
CADO FILE COPY

THE DAVID W. TAYLOR MODEL BASIN

UNITED STATES NAVY

INSTRUMENTS AT THE DAVID TAYLOR MODEL BASIN FOR MEASURING VIBRATION AND SHOCK ON SHIP STRUCTURES AND MACHINERY

BY R. B. ALLNUTT AND F. MINTZ



JULY 1948

REPORT 563

TABLE OF CONTENTS

NOTATION

Symbol	Description	Units	Dimensions in Force-Length-Time System
k	Linear spring constant or torsional spring constant	Pounds per inch or inch-pounds per radian	fl^{-1} fl
v	Instantaneous velocity	Inches per second	lt^{-1}
a	Instantaneous acceleration	Inches per second^2	lt^{-2}
f	Frequency	Cycles per second	t^{-1}
f_n	Natural frequency with damping	Cycles per second	t^{-1}
ω	Circular frequency, 2π times the frequency in cycles per second	Radians per second	t^{-1}
ω_n	Natural circular frequency with damping	Radians per second	t^{-1}
$\omega_{\max}$	Circular frequency at which maximum amplitude occurs	Radians per second	t^{-1}
p	Natural circular frequency without damping, or the resonant circular frequency	Radians per second	t^{-1}
g	Acceleration of gravity	Inches per second^2	lt^{-2}
e	Base of natural logarithms, 2.718 (nondimensional)	Numeric	
δ	Logarithmic decrement (nondimensional)	Numeric	
w	Weight	Pounds	f
l	Length	Inches	l
t	Time	Seconds	t
m	Mass in ips units*	Pound-second^2 per inch	$fl^{-1}t^2$
x	Instantaneous value of displacement	Inches	l
X	Maximum value, i.e., amplitude, of a sinusoidal displacement	Inches	l
c	Linear damping force per unit velocity or torsional damping torque per unit of angular velocity	Pound-seconds per inch or inch-pounds per radian per second	fl^{-1} flt

---

* The mass is determined by dividing the weight in pounds by the acceleration of gravity in inches per second^2 and is expressed as $\frac{W}{386}$, in pound-seconds^2 per inch. This is referred to as the inch-pound-second (ips) unit; it has no other accepted name.

NOTATION

Symbol	Description	Units	Dimensions in Force-Length-Time System
c_c	Critical linear damping constant or critical torsional damping constant	Pound-seconds per inch or Inch-pounds per radian per second	$fl^{-1}t$ flt
ϕ	Phase angle by which force leads displacement in forced vibration	Radians	
Z	Ratio of relative amplitude X_1 of the mass of a system of one degree of freedom to the amplitude of its supporting structure when the latter undergoes a motion $x = X \sin \omega t$	Numeric	

INSTRUMENTS AT THE DAVID TAYLOR MODEL BASIN FOR MEASURING VIBRATION AND SHOCK ON SHIP STRUCTURES AND MACHINERY

ABSTRACT

The theory of the simple vibration- or shock-measuring instrument and its use for the recording of steady-state and transient motions is discussed briefly. Also, the inherent errors in the use of these instruments is discussed. Tables are presented listing the important characteristics of all instruments used at the David Taylor Model Basin for the measurement of vibration and shock. Photographs or schematic drawings and a brief description of each instrument are also included.

INTRODUCTION

During about fifteen years of vibration research work, the David Taylor Model Basin and the U.S. Experimental Model Basin have assembled a rather large and representative collection of vibration- and shock-measuring instruments. Begun with the simple pallographs, Types A, B, and C, (1)*, which were originally developed at the U.S. Experimental Model Basin, this collection grew rapidly as new instruments were purchased or designed and built to suit the different requirements of various vibration problems that were undertaken by the Taylor Model Basin during World War II.

As a result of the wide variations in instrumentation requirements that had to be satisfied during the past five years, the vibration and shock instruments on hand or on order at the Taylor Model Basin cover a variety of possible applications. Among the instruments which are available, at least one can be found that will suit the requirements of almost any type of vibration investigation likely to occur in research for the United States Navy.

The very fact that so many combinations of characteristics are available, however, limits the number of instruments with the proper characteristics for any particular application. In general, only a few of the available instruments are satisfactory for a given test, and, of these, one will be best suited to the job. The problem therefore arises of choosing the one or ones with the most suitable characteristics for every test. This can rarely be done satisfactorily, even by an individual who has used and is familiar with most of the instruments on hand, without considerable reference to written and printed material which must be gathered from a number of sources. For most efficient use of the instruments, it becomes necessary to have available for ready reference in one source sufficient information about all the instruments to permit comparison of their characteristics and the determination of the most suitable one.

---

* Numbers in parentheses indicate references on page 99 of this report.

The present report is the outgrowth of an informal table that was prepared to serve this function for personnel of the Taylor Model Basin. The original table listed, for the vibration instruments on hand and a number of typical commercially available instruments, the more important characteristics, such as frequency range, amplitude range, recording method, and weight. The present report is of somewhat greater scope, containing additional information and photographs of the instruments listed, an introduction to the theory of vibration and shock instruments, and a discussion of the relative merits of certain general features of these instruments. This report does not contain a complete list of commercially available instruments, as the number of such instruments now available commercially is too great to allow inclusion of a complete list in a report such as this. However, some of the best of these have been acquired by the Taylor Model Basin since the original table was prepared, and are described herein.

The purpose of this report is to present in a systematic manner all pertinent information that is known about the vibration and shock instruments at the Taylor Model Basin. This information is arranged in tabular form for the reference of personnel of the Taylor Model Basin and of organizations for which this activity has performed or is likely to perform vibration measurements of any kind.

THEORY OF THE VIBRATION OR SHOCK INSTRUMENT

The term "vibration instrument" as used in this report covers a wide variety of devices, some of which are included only because they are intended to measure a quantity associated with vibration. Conventionally, however, a vibration instrument is a device containing a spring-supported weight with some means of indicating or recording the relative motion between the weight and the case. The theory is discussed rather thoroughly in a number of publications (2) (3) (4) and will be treated briefly here.

A typical vibration instrument is shown schematically in Figure 1. The weight, of mass m, is attached to the instrument case by a spring of stiffness k. The dashpot between the weight and the instrument case introduces a viscous damping constant c. The instrument is rigidly connected to the vibrating body and is therefore subjected to the motions of that body.

If the body is vibrating harmonically with an amplitude X* and a circular frequency $\omega = 2\pi f$, then its displacement from neutral position at time t is

$$x = X \sin \omega t \qquad [1]$$

---

* See notation for explanation of symbols.

If x_1 is the relative displacement between the weight and the instrument case, then the behavior of the system is described by the differential equation of motion

$$m(\ddot{x} + \ddot{x}_1) + c\dot{x}_1 + kx_1 = 0$$

or

$$m\ddot{x}_1 + c\dot{x}_1 + kx_1 = -m\ddot{x} \qquad [2]$$

Dividing both sides of the equation by m gives

$$\ddot{x}_1 + \frac{c}{m}\dot{x}_1 + p^2 x_1 = -\ddot{x} \qquad [3]$$

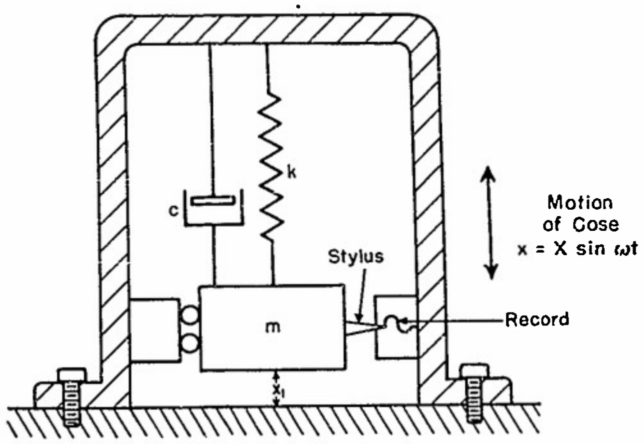


Figure 1 - Example of a Typical Vibration Instrument

where $p^2 = \frac{k}{m}$. Since $x = X \sin \omega t$, $\ddot{x} = -\omega^2 X \sin \omega t$, and Equation [3] becomes

$$\ddot{x}_1 + 2\frac{c}{c_c} p\dot{x}_1 + p^2 x_1 = +\omega^2 X \sin \omega t \qquad [4]$$

where c_c, the critical damping constant, is defined as $2\sqrt{km}$ or $2pm$.

A solution to Equation [4] is given by the expression

$$x_1 = e^{-\frac{c}{c_c}pt}[A \sin \omega_n t + B \cos \omega_n t] + \frac{X \cdot \frac{\omega^2}{p^2} \sin(\omega t - \phi)}{\sqrt{\left(1 - \frac{\omega^2}{p^2}\right)^2 + \left(2\frac{c}{c_c}\frac{\omega}{p}\right)^2}} \qquad [5]$$

where

$$\omega_n = p^2\sqrt{1 - \left(\frac{c}{c_c}\right)^2}$$

$$\phi = \arctan \frac{2\frac{c}{c_c}\frac{\omega}{p}}{1 - \frac{\omega^2}{p^2}}$$

and A and B are arbitrary constants depending on the initial conditions.

The first term on the right-hand side of Equation [5] gives the transient response of the instrument; this motion vanishes after a short time owing to the diminution with time of the term $e^{-\frac{c}{c_c}pt}$. The second term gives the steady-state response of the instrument and is a constant in a given instrument for a given applied amplitude and frequency.

STEADY-STATE VIBRATION

The maximum value of the relative sinusoidal displacement or the amplitude of the relative motion between the weight and the instrument case is seen to be

$$X_1 = \frac{X \cdot \frac{\omega^2}{p^2}}{\sqrt{\left(1 - \frac{\omega^2}{p^2}\right)^2 + \left(2\frac{c}{c_c}\frac{\omega}{p}\right)^2}} \qquad [6]$$

since $\sin(\omega t - \phi)$ in Equation [5] becomes unity; the phase angle between the relative motion and the applied motion is as before,

$$\phi = \arc\tan \frac{2\frac{c}{c_c}\frac{\omega}{p}}{1 - \frac{\omega^2}{p^2}} \qquad [7]$$

It is convenient to discuss the behavior of vibration instruments in terms of a nondimensional response which may be called Z, the dynamic magnification factor of the instrument. It is defined as

$$Z = \frac{X_1}{X} = \frac{\frac{\omega^2}{p^2}}{\sqrt{\left(1 - \frac{\omega^2}{p^2}\right)^2 + \left(2\frac{c}{c_c}\frac{\omega}{p}\right)^2}} \qquad [8]$$

The variations of Z and ϕ with the frequency ratio ω/p are plotted in Figures 2 and 3, respectively, for various values of c/c_c.

The determining characteristic of a vibration instrument is its natural frequency relative to the frequency of the vibration being measured. As seen from Equation [8] and Figure 2, an instrument with a natural frequency less than one-third the frequency of the vibration being measured records very nearly true amplitude for a large range of damping, whereas an instrument with a natural frequency higher than twice the frequency of the vibration being measured has a response proportional to the acceleration of the vibratory motions, i.e., the magnification factor fits a parabolic curve.

If damping is neglected, for simplicity of discussion, Equation [8] becomes

$$Z = \frac{X_1}{X} = \frac{\frac{\omega^2}{p^2}}{\sqrt{\left(1 - \frac{\omega^2}{p^2}\right)^2}} = \frac{\frac{\omega^2}{p^2}}{1 - \frac{\omega^2}{p^2}} \qquad [9]$$

For values of $\frac{\omega^2}{p^2}$ considerably greater than 1,

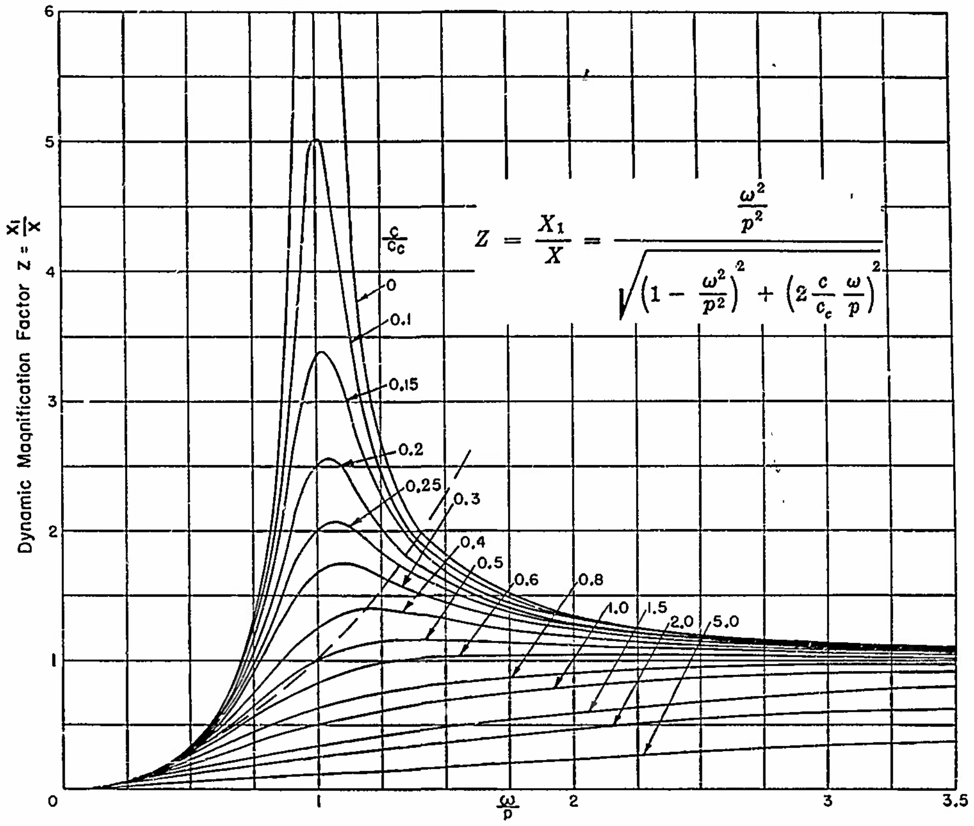


Figure 2 - Dynamic Magnification Factor for the Ideal Vibration Instrument Subjected to the Motion $x = X \sin \omega t$.

X_1 is the amplitude of the relative displacement between the mass and the instrument case. The parabolic curve, shown by the broken line, gives the ideal accelerometer response which has the equation $\frac{X_1}{X} = \frac{\omega^2}{p^2}$.

$$\frac{X_1}{X} \approx \frac{\frac{\omega^2}{p^2}}{-\frac{\omega^2}{p^2}} \approx -1$$

and the relative amplitude between the element and the instrument case is approximately equal to the applied amplitude of vibration and the two motions are approximately 180 degrees out of phase. As the instrument case is moving with the body under test, it is apparent that the element remains effectively motionless in space, acting as an absolute reference point or a seismic* weight.

---

* Instruments for recording the motion of the earth during earthquakes are called seismographs. The vibrometer is based on the same principle as the seismograph, i.e., it includes a spring-supported weight with a value of ω/p considerably greater than 1. The weight as employed in these instruments is often called a seismic weight (2).

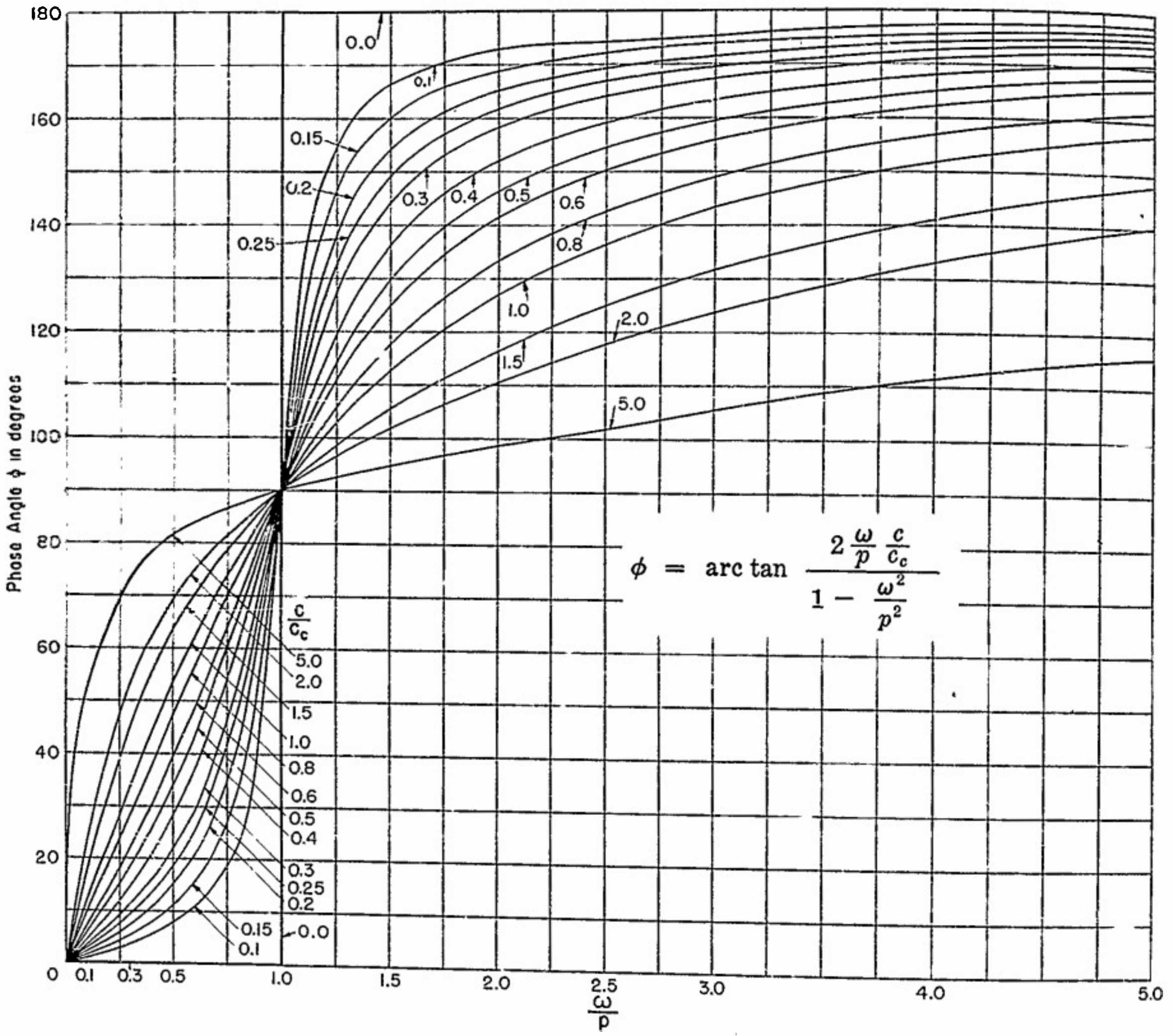


Figure 3 - Phase Angle for the Ideal Vibration Instrument Subjected to Motion $x = X \sin \omega t$

For ω/p = 3, the value of X_1/X in Equation [9] diverges from unity by about 12 per cent, which is the dynamic magnification error. As the value of ω/p increases, the dynamic magnification error decreases and X_1/X approaches unity. Any such instrument is therefore considered to be a seismometer, or vibrometer, when it is used, for measuring vibrations at frequencies more than 3 times its own natural frequency.

The effect of damping for $\frac{c}{c_c} \leq 1$, as shown in Figure 2, is to reduce the dynamic magnification error, permitting use of the instrument as a seismograph at frequencies below 3 times the natural frequency. A value of damping of 0.6 critical, $\frac{c}{c_c}$ = 0.6, permits use of a vibrometer with acceptable accuracy down to the frequency $\omega = p$.

If the frequency ratio ω/p is considerably smaller than 1, then from Equation [9], X_1/X is approximately equal to ω^2/p^2. As p^2 is a constant of the instrument, X_1 is therefore proportional to $\omega^2 X$, which is the acceleration amplitude of the structure vibrating with the motion $x = X \sin \omega t$.

The dotted curve in Figure 2 is the graph of $\frac{X_1}{X} = \frac{\omega^2}{p^2}$ plotted on a basis of ω/p which is the ideal accelerometer response. It is apparent that, for any value of c/c_c less than unity, X_1 is very nearly proportional to $\omega^2 X$, or to the acceleration amplitude, up to $\frac{\omega}{p} = \frac{1}{2}$; for values of c/c_c between 0.6 and 0.7, X_1 represents the acceleration amplitude with only a small error up to ω/p = 0.75.

It follows that the fundamental requirement for an accelerometer is a natural frequency at least twice as high as the highest frequency of the acceleration to be measured. If the applied motion is not a pure sine motion but contains higher-frequency harmonics, the components at frequencies close to the natural frequency of the instrument will be unduly magnified by resonance effects unless the damping is fairly high, and the components at frequencies considerably above the natural frequency of the instrument will be represented as displacement amplitudes rather than acceleration amplitudes.

High damping (about 0.6 c_c) in an accelerometer therefore serves a multiple purpose. Besides increasing the useful frequency range of the instrument, damping cuts down the resonant magnification of components with frequencies near the natural frequency of the instrument and in addition causes the rapid dying-away of free vibrations of the instrument excited by sharp transient pulses.

The presence of damping, however, does introduce an undesirable feature in the behavior of a vibration instrument, namely the phase-shift error. The steady-state term of Equation [5] contains the factor sin $(\omega t - \phi)$. As the applied motion is assumed to be $X \sin \omega t$, ϕ is the angle by which the phase of the recorded motion differs with respect to that of the applied motion. But $\phi = \text{arc tan} \frac{2\, c/c_c\ \omega/p}{1 - \omega^2/p^2}$, from Equation [7], and obviously depends on the frequency of the applied motion. If the motion of the structure contains components of different frequencies, the phase shift of all components will be different, and the resultant record will not have exactly the same shape as the original motion. If the damping is known, however, the proper correction factor may be applied by use of Figure 3. The phase-shift error is, in general, negligible in the vibrograph, for if the natural frequency of the instrument is low with respect to the fundamental frequency the phase shifts in all the harmonics will be practically the same.

TRANSIENT VIBRATION; SHOCK MOTION

Vibration instruments are often used in the measurement of shock. As shock is essentially a rapidly applied transient motion, not necessarily sinusoidal in nature, Equation [5] does not generally describe properly the response of an instrument to such excitation. Equation [3], the differential equation of motion, is still valid, however, since it describes the behavior of the instrument when acted upon by $\ddot{x}$, an acceleration varying in an unspecified manner with time.

The significance of the record obtained due to an applied transient, or shock, motion may be deduced from consideration of Equation [3],

$$\ddot{x}_1 + \frac{c}{m}\dot{x}_1 + p^2 x_1 = -\ddot{x} \qquad [3]$$

which may also be written

$$\ddot{x}_1 + 2\frac{c}{c_c}p\dot{x}_1 + p^2 x_1 = -\ddot{x}$$

If the acceleration $\ddot{x}$ is the required quantity, it may be found by performing the operations indicated in the expression on the left-hand side of the equation. The term p^2x_1 represents the actual record multiplied by the instrument constant; this term represents the acceleration $\ddot{x}$ exactly for steady-state vibration. If the frequency ω of a transient motion is low relative to the instrument frequency, then $\ddot{x}_1$ and $\dot{x}_1$, which depend on ω, are small and p^2x very nearly represents the true acceleration $\ddot{x}$.

Most accelerometer records are analyzed on the assumption, whether justified or not, that the condition just stated exists. If the assumption is not correct, the acceleration curve deduced from the record may be considerably in error. It is nearly hopeless to attempt to apply the necessary corrections, however, owing to the extreme difficulty of accurate double differentiation by graphical or mechanical means. Accelerometers used for recording shock or transient accelerations should therefore have as high a natural frequency as practicable.

It is often desired to deduce the velocity-time relation, or displacement-time relation, of a transient motion from the record obtained with a vibration instrument. The significance of the record in terms of these quantities may be seen by successive integrations of Equation [3].

$$\int_0^t \ddot{x}_1\,dt + 2\frac{c}{c_c}p\int_0^t \dot{x}_1\,dt + p^2\int_0^t x_1\,dt = -\int_0^t \ddot{x}\,dt \qquad [10]$$

or

$$\dot{x}_1 + 2\frac{c}{c_c}px_1 + p^2\int_0^t x_1\,dt = -\dot{x} \qquad [11]$$

and

$$x_1 + 2\frac{c}{c_c}p\int_0^t x_1\,dt + p^2\int_0^t\int_0^t x_1\,dt\,dt = -x \qquad [12]$$

where the constants of integration vanish if $x = 0$, $x_1 = 0$, $\dot{x} = 0$, and $\dot{x}_1 = 0$ at time $t = 0$, that is, if the instrument and the structure are initially at rest and at zero, or datum, position.

It is apparent from Equation [11] that the velocity-time relation of a transient motion may theoretically be deduced from the record of any vibration instrument by addition of the record, its differential curve, and its integral curve, all multiplied by appropriate factors. The inherent errors and the laborious procedures involved in such a process, however, ordinarily preclude its use. A velocity meter is generally used if velocities are required.

In the previous discussion, the term x_1 has been treated as though it were equivalent to the recorded displacement. Actually, however, x_1 represents the relative displacement between the inertia element and the case of the instrument and has merely been assumed to be equivalent to the recorded displacement. Such an assumption is correct for displacement meters and acceleration meters, but is not correct for velocity meters. The voltage generated by a velocity meter is proportional to the velocity of the element relative to the case. In a discussion of the record of a velocity meter, it is therefore convenient to introduce a new ordinate u which represents the actual record and is therefore identical with $\dot{x}_1$. Then

$$x_1 = \int_0^t \dot{x}_1\,dt = \int_0^t u\,dt$$

and

$$\int_0^t x_1\,dt = \int_0^t\int_0^t \dot{x}_1\,dt\,dt = \int_0^t\int_0^t u\,dt\,dt$$

and Equation [11] becomes

$$u + 2\frac{c}{c_c}p\int_0^t u\,dt + p^2\int_0^t\int_0^t u\,dt\,dt = -\dot{x} \qquad [13]$$

The record u therefore represents the applied velocity $\dot{x}_1$ only if the two integrated terms on the left-hand side are negligible relative to u. This condition holds whenever the time interval from 0 to t is very short relative to the natural period of the inertia element and if the damping is low. To give reliable results, therefore, a velocity meter should have low damping and the ratio of the natural period of the inertia element to the period of the applied motion should be large.

Equation [12] applies in the determination of displacement from the record of a transient motion. As Equation [12] and [13] are completely analogous, the consideration discussed in connection with Equation [13] applies equally well to Equation [12]. For the record to indicate the true transient displacement, both the damping and the natural frequency of the element should be as low as possible; a sample check for the size of the correction factors should be made when in doubt.

It may not always be feasible to obtain a sufficiently low frequency and at the same time retain other satisfactory characteristics in a displacement meter. When it is not feasible, the simplest method of obtaining shock displacement may be to use an accelerometer with low damping and a relatively high natural frequency. Then the third term on the left-hand side in Equation [12], i.e., $p^2 \iint x_1\, dt\, dt$, is practically equal to the shock displacement. The second integral curve of the record may be obtained rather simply by use of an integraph, and this curve multiplied by the scale factor p^2 represents the variation in time of the actual shock displacement. It should be noted that the sensitivity of an accelerometer varies inversely as the square of the natural frequency of its inertia element. Hence there is a practical upper limit for the frequency.

The superimposed high-frequency vibrations, or "hash," that appear almost inevitably in accelerometer records are generally irrelevant as regards displacement and may be faired through without appreciably increasing the errors involved in the integration process provided they are recorded clearly.

It should be kept in mind that the foregoing discussion is based on simple single-degree-of-freedom theory and on the assumption that where electrical recording is used no distortion is introduced by the recording system. While these assumptions are fairly safe for steady-state measurements they require careful investigation in the case of transient measurements.

METHODS OF DETECTING, INDICATING, AND RECORDING VIBRATION OR SHOCK

In addition to a weight, or sensitive element, flexibly attached to a case, the vibration instrument embodies some means of making apparent to the observer the relative motion between the element and the case that constitutes the response of the instrument to the applied motion. This is accomplished by a detecting or transmitting device which is activated by the relative motion, producing a signal which is recorded or indicated by a suitable recording or indicating device.

A considerable number of detecting and recording schemes are currently in use, each of which has its own particular merits and fields of application. These methods fall into three general categories, i.e., mechanical, optical, and electrical (5). Although the electrical methods in general are capable of the greatest sensitivity and versatility, they are often rather unwieldy in application when used for field work. The mechanical methods are popular for certain applications by virtue of the small amount of total equipment required, the immediate availability of the record for inspection, and general ruggedness of parts. The optical methods combine the freedom from accessory equipment that is characteristic of the mechanical methods with high amplification, but the equipment is generally less rugged.

MECHANICAL METHODS

Detection in the mechanical methods generally consists merely in transmitting the motion of the element to the appropriate indicating or recording device by a lever or suitable linkage. The sensitivity obtainable with such methods depends on the amplification in the lever system, which ranges from about unity, in direct recording schemes as in the TMB shock-displacement gage, Figure 4a, to about 50, which is the effective amplification of a dial gage, as used in the Karelitz vibrometer, Figure 5a.

Indication in the mechanical methods is generally given by dial gages; the band swept out by the dial-gage pointer swinging back and forth indicates the double amplitude of the vibration being measured. Another useful method is that used in the Cordero vibrometer, in which the amplitude is indicated on a radial scale by the apparent point of intersection of the opposite sides of a tapered pointer which is vibrating; see Figure 5b.

Mechanical recording is generally obtained by a scriber scratching on a prepared surface. Such devices as a stylus scratching on waxed paper, chemically sensitized paper, or strip celluloid, a pen writing on paper, or a steel scriber scratching on plated brass are among the most commonly used ones. Several actual applications of mechanical transmission and recording or indicating are illustrated schematically in Figure 4.

OPTICAL METHODS

Optical methods of detection usually embody mechanical transformation of the linear motion of the element to rotational motion of a member supporting a mirror. A light beam is reflected from the rotating mirror to a screen for viewing or to a photographic film for recording. This scheme permits the attainment of high magnification and resultant high sensitivity.

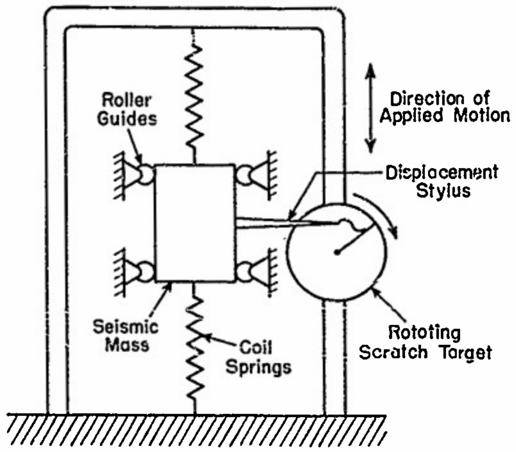


Figure 4a - TMB Shock-Displacement Gage

The shock-displacement gage employs direct scratch recording on a circular chromium-plated brass disk.

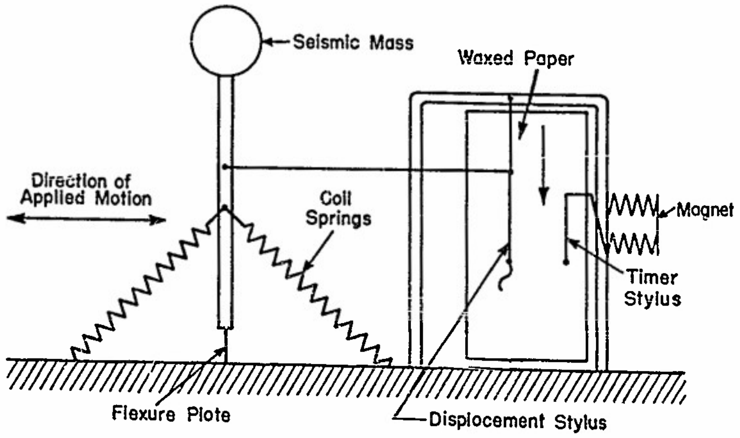


Figure 4b - TMB Type-C Pallograph

The Type-C pallograph employs a system of mechanical linkages to obtain the desired magnification, and records on waxed paper.

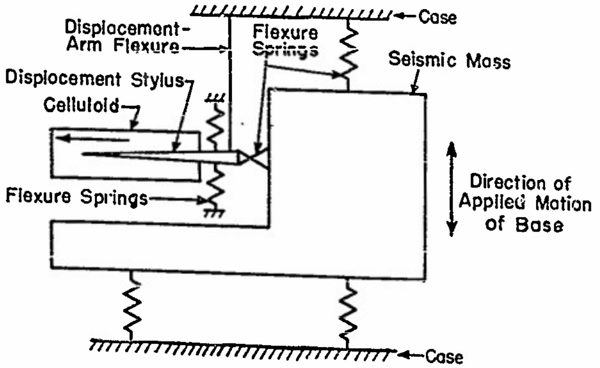


Figure 4c - Westinghouse LE Vibrograph

The Westinghouse LE Vibrograph uses a mechanical lever with flexure pivots and records on celluloid. The LE may be used as a hand instrument by locking the mass into the case, detaching the displacement-arm flexure from the case, and attaching a probe to the end of this arm.

Figure 4 - Schematic Arrangements of Various Methods of Mechanical Transmission and Recording

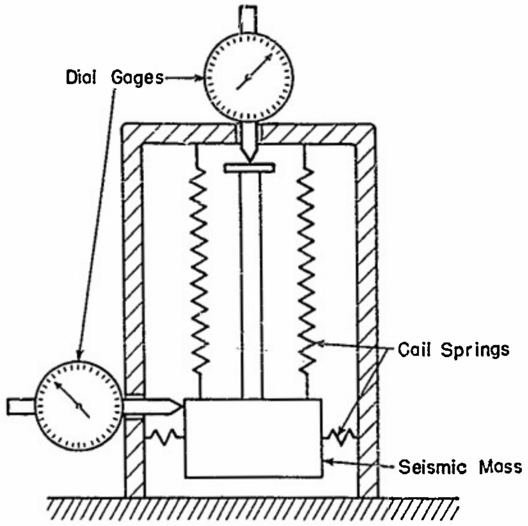


Figure 5a - Karelitz Vibrometer

The Karelitz vibrometer employs a dial gage for indicating: by a gear train the magnification is obtained within the gage.

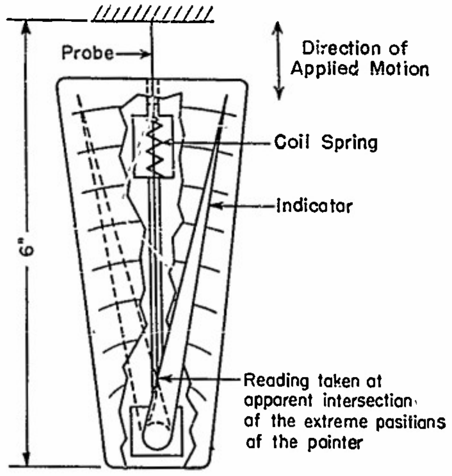


Figure 5b - Cordero Vibrometer

The Cordero vibrometer indicates amplitudes from the radial graduations at the point of apparent intersection of the extreme positions of the pointer image. Magnification is obtained by a simple mechanical linkage.

Figure 5 - Schematic Arrangements Showing Two Methods of Indication Involving Mechanical Transmission

The optical lever used in certain instruments developed at the Taylor Model Basin utilizes a Tuckerman optical strain gage and a recording autocollimator. This system yields a magnification of about 76. Another method, applicable to fairly low-frequency work and used successfully in the Shrader tri-dimensional vibrograph, employs a mirror mounted on a spindle which is caused to rotate by the relative motion between the seismic weight and the instrument case. A schematic arrangement of the two methods described is shown in Figure 6.

The photographic recording that is a usual characteristic of the optical methods may be a decided liability in field measurements since the records are not available for immediate inspection. Faulty records, which sometimes occur owing to defective operation of the instrument or accidental exposure of the emulsion during handling or processing, are often not discovered until it is too late to repeat the test run. If an optical system of recording is used in an accelerometer for recording transient motions, it should be noted that the light intensity should be sufficient to record clearly at the high "writing" speeds occasioned by superimposed high-frequency vibrations or "hash."

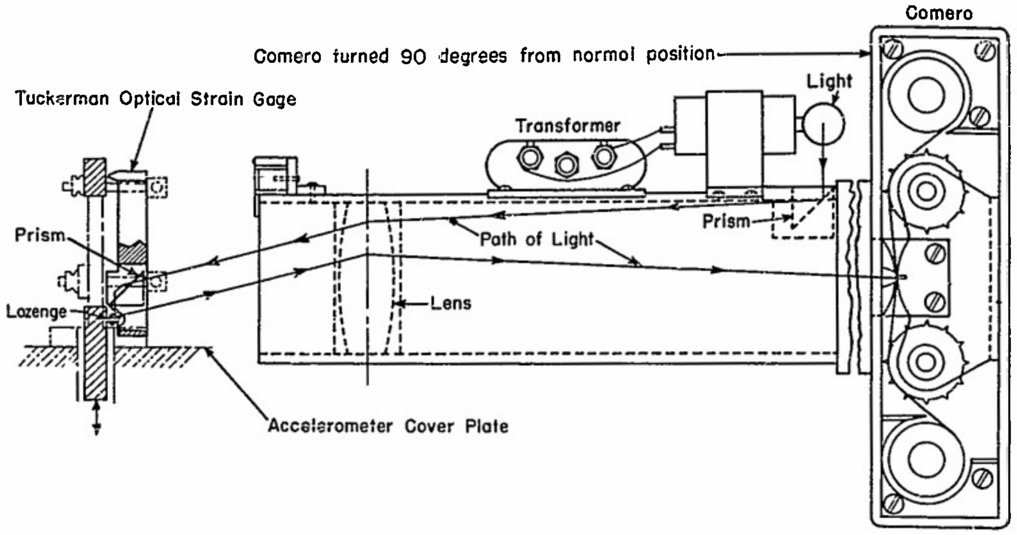


Figure 6a - Tuckerman Optical Strain Gage and Recorder

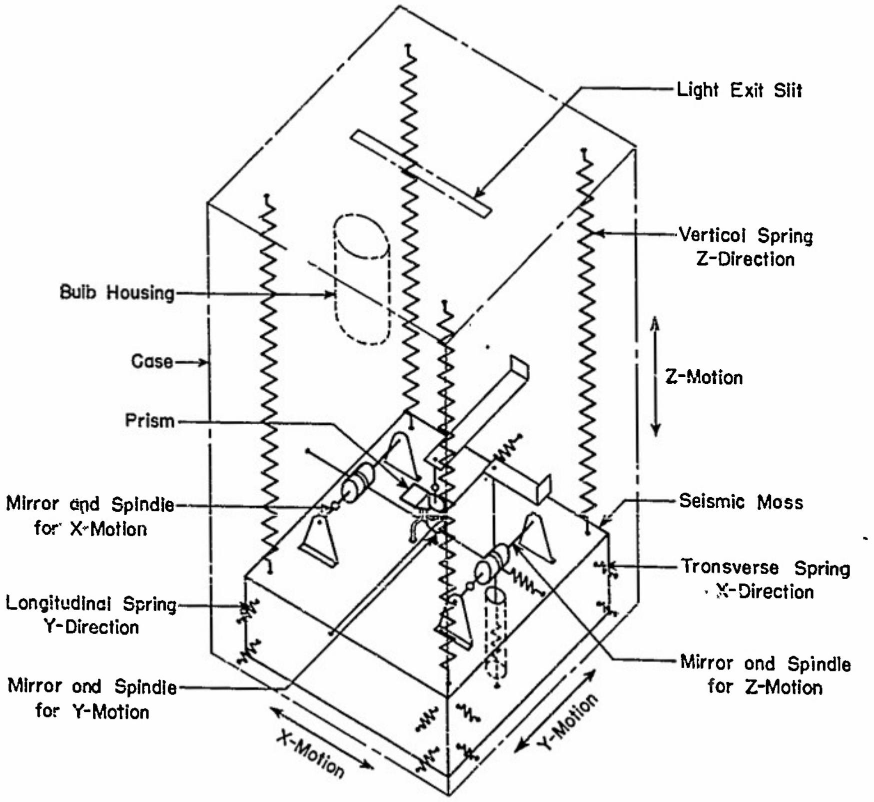


Figure 6b - Shrader Tri-Dimensional Vibrograph

Figure 6 - Schematic Arrangements Showing Two Methods of Indication Involving Optical Systems

ELECTRICAL METHODS

The many electrical methods of detection, each with its particular faults and merits and its own special field of application, have a number of noteworthy features in common. In general they permit the attainment of high sensitivity, measurement with good precision over a wide range of sensitivity, compactness of the pickup devices, and location of recording instruments at a considerable distance from the pickup (6).

However, electrical pickups generally necessitate the use of considerable accessory equipment that is both bulky and delicate, and their effective operation is dependent upon a steady, reliable source of electric power. The presence of specialized personnel for setup, maintenance, and repair is also required. These characteristics are distinctly disadvantageous. In addition, the photographic recording usually employed introduces the liabilities previously mentioned under optical recording.

The versatility of electrical instruments is such that, for many applications, they are greatly superior to mechanical instruments in spite of the disadvantages listed and are used instead of the latter because of the rigorous test requirements.

The principal electrical methods of detection employed in instruments at the Taylor Model Basin are the following:

a. Use of wire-resistance strain gages, in which the strains arising from motion of the sensitive element are detected and recorded by electronic apparatus (7) (8);

b. Application of the generator principle, utilizing a coil moving in a magnetic field, the signal being proportional to the velocity of relative motion between the coil and the magnet (9);

c. Utilization of piezoelectric effect, in which the pressure on a piezoelectric crystal generates a charge proportional to the pressure or to the displacement between the ends of the crystal (10);

d. Frequency-deviation methods (11), which use an oscillating circuit with a coil (or capacitor) whose inductance (or capacitance) is changed by the displacement of the sensitive element, causing a corresponding change in the frequency of the oscillating circuit;

e. The photoelectric method, which employs a photocell to determine the variation in light intensity caused by relative motion between a fixed and a moving member;

f. Reluctance-variation methods, in which the displacement of a metal spacer varies the reluctance of the core of a coil, producing a corresponding change in inductance which is detected by a bridge circuit;

g. Application of the Gayhart telemeter principle (12), which uses two oppositely wound coils connected in series which are attached to the moving element and which act as the secondary of a transformer, the primary coil of which is attached to the instrument case.

Although the individual requirements for accessory equipment vary with the particular method used, there is a certain amount of equipment that is practically a necessity for successful use of electrical, or electronic, methods with oscillographic recording. This equipment consists of a voltage regulator and variable transformer, or Variac, to assure a reasonably high and steady voltage supply; an amplifier, generally with accompanying power supply; an audio oscillator and microvolter for calibration purposes; and finally, either a string oscillograph or a cathode-ray oscillograph with a camera, and for transient work, a sweep generator. A saving feature of all this is that many of the items suffice for the operation of two to four or more instruments and channels simultaneously, so that the amount of equipment per pickup or channel generally decreases as the number of pickups or channels used increases. Recently designed equipment such as the TMB strain indicator (7) has greatly simplified certain instrument requirements.

CLASSIFICATION OF INSTRUMENTS

In order to conform more closely with the stated purpose of this report, the data on the instruments are presented primarily in tabular form. All available information that is considered pertinent in determining the suitability of the instruments for any given application is given in the tables. Photographs or schematic diagrams of every instrument are also included with such additional descriptive material as may be required for a better understanding of the operation of the instruments.

TABLES OF CHARACTERISTICS OF INSTRUMENTS

For ease of reference, all instruments are classified into groups based on the different types of measurements for which they have been used or are intended to be used at the Taylor Model Basin.

The classification used, and the corresponding table numbers under which the instruments are listed, are as follows:

I. Instruments for Steady-State Vibration
  A. Accelerometers for Measurement of Steady-State Vibration — Table 1
  B. Vibrometers and Vibrographs
    1. Indicating Instruments
      (a) Instruments for Indicating the Amplitude of Steady-State Vibration — Table 2
      (b) Instruments for Indicating the Frequency of Steady-State Vibration — Table 3
    2. Recording Instruments
      (a) Instruments for Displacement-Time Recording of Linear Vibrations — Table 4
      (b) Instruments for Recording Torsional Vibrations (13) — Table 5

II. Instruments for Transient Motions
  A. Displacement and Velocity Meters for Measurement of Transient Motions — Table 6
  B. Indicating "Accelerometers" for Measurement of Transient Motions — Table 7
  C. Recording Accelerometers for Measurement of Transient Motions — Table 8

The groups described in the previous paragraph are somewhat arbitrary in nature, being based on experience at the Taylor Model Basin, and are by no means mutually exclusive. A number of the instruments on hand may properly be listed in more than one category, and duplicate listings are given for these instruments. Any instrument, therefore, that is considered suitable for use in a given type of measurement is listed in the appropriate table for that type.

TABLE 1

Accelerometers for Measurement of Steady-State Vibration

Name	Practical Frequency Range CPS	Practical Single Amplitude Range g	Sensitivity	Direction of Vibration	Method of Detection	Method of Recording	Method of Damping
BuOrd torpedo accelerometer	0 to 30	0.25 to 25	0.04 in. per g on record	Any one	Spring-mounted mass, mechanical lever	Stylus on waxed paper	Oil, not adjustable
Brush VP-5 acceleration pickup	10 to 500	0.001 to 10	About 80 mv RMS per g	Any one	Piezoelectric crystal	Oscillo-graphic	None
Single damped-cantilever accelerometer	0 to 50	0.1 to 18	22.5 µv per g per 45 volts	Any one	Metalectric strain gage	Oscillo-graphic	Oil film between parallel plates, adjustable
Double cantilever accelerometer, Types A to E	10 to 800	1 to 2000, estimated	Varies, about 45 µv per g per 45 volts	Any one	Metalectric strain gage	Oscillo-graphic	Very little, internal damping of plastic material
DVL-type accelerometer	0 to 35	0.02 to 5	0.15 in. per g on record	Any one	Optical lever, Tuckerman strain gage	Photo-graphic	Oil, not adjustable
Jacklin 3-component linear accelerometer							
Low-frequency A elements	0 to 60	0.01 to 1.5	1.25 in. per g on record	Two horizontal and one vertical simultaneously	Optical lever	Photo-graphic	Oil film between stationary and moving surfaces
Low-frequency B elements		0.02 to 2.3	0.80 in. per g on record				
High-frequency A elements High-frequency B elements	0 to 150	0.06 to 12.5	About 0.15 in. per g				
Jacklin 3-component angular accelerometer	0 to 25	0.1 to 15 rad/sec^2	About 0.1 in. per rad/sec^2	Angular about 3 perpendicular axes	Optical lever	Photo-graphic	Oil film between stationary and moving surfaces
Jacklin 6-component accelerometer	Combines in one recorder 3 linear elements and 3 angular elements with the same characteristics as those above						

TABLE 1 (continued)

Natural Frequency of Element CPS	Weight pounds	Overall Dimensions (LxWxH) or (DxH) inches	Power Required	Accessory Equipment Required	Method of Mounting on Vibrating Structure	Figure Number	Remarks
35	7 3/4	5 x 10	6-v dry cell	Timer, if desired	Bolted or clamped to structure	7	Holds maximum of 40 inches of paper which permits 30 seconds of record
1500	0.4	3 x 2	110-v a.c.	Usual electronic equipment*	Held against or clamped to structure	8	
215	4.2	4 1/2 x 2 x 6	110-v a.c.	Usual electronic equipment*	Bolted or clamped to structure	9	Development inactive.
200 1400 1800 2400 3500	Type D 1.0	Type D 8 x 2 1/2 x 2	110-v a.c.	Battery box and usual electronic equipment*	Bolted or clamped to structure	10	Not currently in use, requires filter. Of Historic interest only. Statham accelerometer employs similar principle more effectively.
67	98 (with recorder)	17 x 12 x 14	110-v a.c.	Tuckerman recorder and timer	Bolted or clamped to structure	11	Not currently in use.
About 100	Recorder, 30; control unit, 30	Recorder, 7 x 11 x 14; control unit, 12 x 5 3/8 x 10	35-amp, 12-v d.c.	None	Bolted or clamped to structure	12	Each recorder is capable of holding 6 elements. All elements are interchangeable.
About 250							
About 50	Recorder, 30; control unit, 30	Recorder, 7 x 11 x 14; control unit, 12 x 5 3/8 x 10	35-amp, 12-v d.c.	None	Bolted or clamped to structure	12	On order.
						12	On order.

* Usual electronic equipment consists of amplifier and power supply; Variac transformer and regulator; oscillator and microvolter; cathode-ray oscillograph and camera, or string oscillograph.

TABLE 1 (continued)

Accelerometers for Measurement of Steady-State Vibration

Name	Practical Frequency Range CPS	Practical Single Amplitude Range g	Sensitivity	Direction of Vibration	Method of Detection	Method of Recording	Method of Damping
TMB pallograph-type accelerometer Group I**	0 to 1 0 to 1 0 to 1.5 0 to 2 0 to 2.5 0 to 3	0.001 to 0.08 0.002 to 0.16 0.004 to 0.34 0.007 to 0.63 0.013 to 1.0 0.016 to 1.0	On record, inches per g 5.76 2.65 1.33 0.71 0.35 0.28	Vertical only	Spring-mounted weight, mechanical lever	Stylus on waxed paper	Air dashpot, adjustable
Group II**	0 to 2 0 to 3 0 to 4 0 to 5 0 to 6	0.03 to 1.2 0.05 to 2.0 0.10 to 4.3 0.15 to 6.8 0.20 to 9.0	0.66 0.4 0.2 0.14 0.1	Any one normal to base			
Consolidated accelerometer	0 to 35	0.02 to 15	25 mv per g with 15-v carrier	Any one	Seismic inductance, variable reluctance	Oscillographic	Magnetic
Shrader 3-component accelerometer	0 to 50	0.05 to 5	About 0.3 in. per g	Two horizontal and one vertical simultaneously	Optical lever	Photographic	Air dashpot
Wimperie accelerometer	0 to 0.25	0.1 to 8.0 ft/sec^2	1/4 in. per ft/sec^2 on scale	Horizontal	Mechanical lever	Pointer on scale	Permanent magnet
Statham accelerometer R-500-700	0 to 850	1 to 500	About 0.22 μ amp per g for 15-ohm impedence; about 0.1 mv RMS per g (max) for high impedance load	Any one normal to base	Strain wires forming bridge circuit support inertia mass	Oscillographic	Organo-silicone fluid
Statham accelerometer Ar-12V-250	0 to 150	0.1 to 12	About 13 μ amp per g for 15-ohm impedence; about 2.3 mv RMS per g (max) for high impedence load	Any one normal to base	Strain wires forming bridge circuit support inertia mass	Oscillographic	Organo-silicone fluid
Statham accelerometer S-1.5-120	0 to 60	0.05 to 1.5	About 34 μ amp per g for 15-ohm impedance; about 3.5 mv RMS per g (max) for high impedance load	Any one parallel to base	Strain wires forming bridge circuit support inertia mass	Oscillographic	Organo-silicone fluid
Statham accelerometer R-5-120	0 to 90	0.1 to 5	About 17 μ amp per g for 15-ohm impedance; about 1.8 mv RMS per g (max) for high impedance load	Any one normal to base	Strain wires forming bridge circuit support inertia mass	Oscillographic	Organo-silicone fluid

** The springs listed in Group I replace the pallograph displacement spring. The springs listed in Group II are used with a special weight and two-spring suspension as shown in Figure 13.

TABLE 1 (continued)

Natural Frequency of Element CPS	Weight pounds	Overall Dimensions (LxWxH) or (DxH) inches	Power Required	Accessory Equipment Required	Method of Mounting on Vibrating structure	Figure Number	Remarks
2.16 2.76 3.83 5.35 6.79 7.48	40	20 x 8 x 14	110-v a.c.	Synchronous timer	Bolted or clamped to structure	13	Adapted from Type B pallograph.
5.42 7.00 9.9 12.1 14.0							Uses special weight and two-spring suspension.
	0.8	2 3/4 x 2 1/2 x 2 3/4	110-v a.c.	1000-CPS bridge, usual electronic equipment*	Bolted or clamped to structure	14	
About 100	15	6 x 5 1/2 x 9 1/2	6-v d.c.	None	Bolted or clamped to structure	15	
About 1.0	2	4 x 2 1/2	None	None	Placed on horizontal plane	16	May be photographed for recording.
1670	0.5	2 x 1 1/4 x 2 1/2	20-v d.c. (max)	5-KC carrier, power supply, oscillograph	Bolted to structure (5-40 screws)	17	Resistance: Input, 686.3 ohms Output, 686.3 ohms Input current: 30 ma (max) Input voltage: 20 v (max)
300	0.5	2 x 1 1/4 x 2 1/2	12.5-v d.c. (max)	Modified TMB 1-A strain amplifier	Bolted to structure (5-40 screws)	17	Resistance: Input, 236.4 ohms Output, 236.4 ohms Input current: 60 ma (max) Input voltage: 12.5 v (max)
115	0.8	2 3/8 x 1 3/4 x 2 3/8	5-v d.c. (max)	Usual electronic equipment* or modified TMB 1-A strain amplifier	Bolted to structure (5-40 screws)	17	Resistance: Input, 126.3 ohms Output, 126.3 ohms Input current: 40 ma (max) Input voltage: 5 v (max)
185	0.5	2 x 1 1/4 x 2 1/2	5-v d.c. (max)	Usual electronic equipment* or modified TMB 1-A strain amplifier	Bolted to structure (5-40 screws)	17	Resistance: Input, 136.2 ohms Output, 136.2 ohms Input current: 40 ma (max) Input voltage: 5 v (max)

* Usual electronic equipment consists of amplifier and power supply; Variac transformer and regulator: oscillator and microvolter: cathode-ray oscillograph and camera, or string oscillograph.

TABLE 2

Instruments for Indicating the Amplitude of Steady-State Vibration

Name	Practical Frequency Range* CPM	Practical Single Amplitude Range* mils	Direction of Vibration	Method of Detection	Method of Indication	Natural Frequency of Element CPM	Weight pounds
Cordero vibrometer	500 to 2000	0.5 to 15	Any one	Mechanical lever	Vibrating arm on scale	300	2
Modified Cordero vibrometer	500 to 2000	1 to 35	Any one	Mechanical lever	Vibrating arm on scale	About 300	2 1/2
GR vibration meter and Shure crystal pickup	120 to 30,000	0.05 to 30,000	Any one	Piezoelectric crystal pickup and integrating circuits	Meter reading of amplitude	90,000	Pickup, 0.8; meter, 23
Karelitz vibrometer	400 to 2000	0.5 to 25	Vertical and horizontal	Direct measurement of motion relative to seismic weight	Dial gage	200	35
Westinghouse hand vibrometer	600 to 6000	1 to 50	Any one	Direct measurement of motion relative to seismic weight	Dial gage	About 400	4

* The ranges of frequencies and amplitudes given are not necessarily concurrent. i.e., the minimum amplitude cannot always be measured at the lowest frequency since enough force must be produced to overcome the inherent friction of the particular instrument; conversely, the maximum amplitude listed cannot always be measured at the maximum frequency.

TABLE 2 (continued)

Overall Dimensions (LxWxH) or (DxH) inches	Power Required	Method of Mounting on Vibrating Structure	Figure Number	Remarks
6 x 2 1/2 x 1	None	Held against structure	18a	Good for qualitative check of amplitude.
6 x 2 1/2 x 1 1/2	None	Held against structure	18b	Good for qualitative check of amplitude.
Pickup, 2 1/2 x 2 1/2 x 2; meter, 13 x 9 x 13	Self-contained batteries	Held or clamped against structure	19	Pickup is accelerometer. Meter reads acceleration or integrates to give velocities and displacements. May be used with GR vibration analyzer which weighs 32 pounds and is 16 1/2 x 9 1/2 x 10 1/4 inches.
11 1/2 x 4 1/2 x 10	None	Set or clamped on structure	20	
4 x 3	None	Held against or set on structure	21	Hand-held operation preferable.

TABLE 3

Instruments for Indicating the Frequency of Steady-State Vibration

Name	Practical Frequency Range CPM	Method of Detection	Method of Indication	Weight pounds	Overall Dimensions (LxWxH) or (DxH) inches	Power Required	Method of Mounting on Vibrating Structure	Figure Number	Remarks.
Frahm's reeds	Single-row unit 1400 to 2000	Resonant vibration of a reed at its natural frequency	Reed with largest amplitude indicates correct frequency	1 1/2	5 3/4 x 1 3/4 x 4	None	Set on or near structure	22	Other units up to 12,500 CPM on order.
	Double-row units 800 to 1400 1500 to 3000 2500 to 5000 4500 to 9000			2	5 3/4 x 2 3/4 x 4				
Westinghouse reed vibrometer	500 to 20,000	Adjustment of length of reed to give proper frequency	Resonant vibration of reed at proper frequency indicated on scale	0.5	9 1/4 x 1 3/4 x 1 1/4	None	Held against structure	23	0.35-inch to 0.5-inch (depending on instrument) motion of reed equals approximately one mil amplitude.
Strobomeca (Rotoscope)	500 to 8000	Rotational speed of slotted disk is varied to "stop" motion	Frequency corresponding to correct speed indicated on scale	0.6	2 3/4 x 2 5/8	None	Held in hand; structure viewed through rotating slotted disk	24	Strong light is required for effective use. Use upper 85 per cent of scale, lower 15 per cent unreliable
Strobotac	600 to 14,500	Variable frequency flashing light; stroboscopic principle	Flashing Frequency indicated on scale	9	7 1/2 x 8 1/2 x 9 1/2	110-v a.c.	Held in hand or set on convenient base	25	Dim surroundings required for effective use.
Strobolux	600 to 6000	Variable frequency flashing light; stroboscopic principle	Flashing frequency indicated on scale	32	12 x 11 x 12	110-v a.c.	Held in hand or set on convenient base	26	Gives much stronger light than Strobotac; Strobotac used for frequency control.
Communications Measurement Laboratories Stroboscope	600 to 600,000	Variable frequency flashing light; stroboscopic principle	Flashing frequency indicated on scale	Probe 1; cabinet, 50	Probe, 5 3/4 x 2 x 2; cabinet, 16 1/8 x 9 3/4 x 8 3/4	110-v a.c.	Held in hand or set on convenient base	27	Dim surroundings required for effective use. Use d-c illuminator only when necessary.

TABLE 3 (continued)

TABLE 4 - Instruments for Displacement-Time Recording of Linear Vibrations

Name	Practical Frequency Range* CPM	Practical Single Amplitude Range* mils	Sensitivity or Magnification	Direction of Vibration	Method of Detection	Method of Recording	Method of Damping
Brush DP-1 vibration pickup	600 to 6000	0.01 to about 25	0.28 v RMS per mil	Any one	Piezoelectric crystal seismically mounted	Oscillographic	None
Cox vibration recorder	400 to 3000	2 to 350	Adjustable 1, 2, 4, or 8	Vertical or horizontal (separate adaptors required)	Seismic weight, mechanical transmission of motion	Stylus on waxed paper, 6 paper speeds	Friction of stylus on wax
TMB electrical vibration pickup (pendulum-type)	200 to 2000	0.1 to 250	Up to 1000	Horizontal	Seismic pendulum, variable transformer coupling	Oscillographic	Inherent friction
TMB Type A pallograph	60 to 700 vertical, 120 to 700 horizontal	5 to 500	1.75	Vertical but may be adapted for horizontal	Seismic pendulum, mechanical lever	Stylus on waxed paper	Inherent friction
TMB Type B pallograph	50 to 1000 vertical, 170 to 1000 horizontal	3 to 225	2.0	Vertical but may be adapted for horizontal	Seismic pendulum, mechanical lever	Stylus on waxed paper	Air dashpot, adjustable
TMB Type C pallograph	150 to 1000	2 to 150	3.0	Horizontal	Seismic pendulum, mechanical lever	Stylus on waxed paper	Air dashpot, adjustable
TMB Type H pallograph	120 to 1800	1 to 250	Adjustable 2, 4, or 6	Horizontal	Seismic pendulum, mechanical lever	Stylus on waxed paper	Air dashpot, adjustable
TMB Type V pallograph	60 to 1800	1 to 250	Adjustable 2, 4, or 6	Vertical	Seismic pendulum, mechanical lever	Stylus on waxed paper	Air dashpot, adjustable
Photoelectric vibration pickup	300 to 3000	0.5 to 125	4 mv RMS per mil single	Vertical	Seismic pendulum, photoelectric cell	Oscillographic	
Shrader tridimensional vibrograph	450 to 3000	About 0.5 to 25	About 50	Vertical and two horizontal simultaneously	Seismic weight, optical lever	Photographic	
Shrader tridimensional vibrograph	450 to 3000	About 0.5 to 25	About 50	Vertical and two horizontal simultaneously	Seismic weight, optical lever	Photographic	Felt in coil springs
Sperry-MIT - Consolidated large linear-vibration pickup	300 to 18,000	1 to 750	75 mv per in./sec	Vertical or horizontal (separate units)	Seismic magnet moving along a coil	Oscillographic	Oil, adjustable
Sperry-MIT - Consolidated small linear-vibration pickup	900 to 60,000	0.1 to 250 (varies with frequency)	78 mv per in./sec	Vertical or horizontal (separate units)	Seismic magnet moving along a coil	Oscillographic	Oil
Consolidated Type 4-102 velocity pickup	500 to 42,000	0.05 to 700 vertical, 0.05 to 1000 horizontal	110 mv per in./sec	Any one	Seismic magnet moving along a coil	Oscillographic	Oil
Type LE Westinghouse vibrograph	600 to 15,000	0.1 to 25	8 1/2 mechanical, 40 microscope	Any one	Seismic weight, mechanical lever	Stylus on celluloid film	Friction of stylus on celluloid
Askania vibrograph	450 to 6000	1 to 200	6 times, with attachment reduces to 2 times or 1 time	Any one	Spring-loaded pickup, probe attached to mechanical lever	Stylus on waxed paper	Friction of stylus on waxed paper

* The ranges of frequencies and amplitudes given are not necessarily concurrent, i.e., the minimum amplitude cannot always be measured at the lowest frequency since enough force must be produced to overcome the inherent friction of the particular instrument; conversely, the maximum amplitude listed cannot always be measured at the maximum frequency.

TABLE 4 (continued)

Natural Frequency of Element CPM	Weight pounds	Overall Dimensions (LxWxH) or (DxH) inches	Power Required	Accessory Equipment Required	Method of Mounting on Vibrating Structure	Figure Number	Remarks
About 720 when suspended by probe	0.6	3 1/2 x 2 3/4	110-v a.c.	Usual electronic equipment**	Hand-held with probe against structure	28	
270 horizontal, 285 vertical	29	12 x 9 1/4 x 9 1/2	110-v a.c. and 6-v d.c.	None	Set on, bolted, or clamped to structure	29	Adapter added to Cox torsiograph to convert for linear vibrations.
60	30	7 1/2 x 10 x 16	110-v a.c.	Usual electronic equipment**	Set on, bolted, or clamped to structure	30	
20 vertical, 40 horizontal	110	32 x 9 1/2 x 23 3/4	110-v a.c.	Synchronous timer	Set on, bolted, or clamped to structure	31	May be adapted for recording horizontal vibrations.
15 vertical, 60 horizontal	40	20 x 8 x 14	110-v a.c.	Synchronous timer	Set on, bolted, or clamped to structure	32	May be adapted for recording horizontal vibrations.
60	25	15 x 7 1/2 x 11	110-v a.c.	Synchronous timer	Set on, bolted, or clamped to structure	33	
40	60	18 x 9 x 11 1/2	110-v a.c.	Synchronous timer	Set on, bolted, or clamped to structure	34	
20	75	18 1/2 x 9 1/2 x 14 1/2	110-v a.c.	Synchronous timer	Set on, bolted, or clamped to structure	35	May be adapted for recording horizontal motions.
215	14	12 x 6 x 7	110-v a.c.	Usual electronic equipment**	Set on, bolted, or clamped to structure	36	In process of development.
300	20	6 x 8 x 11	6-v d.c. or 110-v a.c. with rectifier	None	Set on, bolted, or clamped to structure	37	Instrument has been modified to give magnification listed.
240	6.8	6 1/2 x 4 1/2 x 4	110-v a.c.	Usual electronic equipment**	Set on, bolted, or clamped to structure	38	Pickup generates a voltage proportional to velocity. An integrating circuit is used to obtain displacement.
300	0.33	2 x 3	110-v a.c.	Usual electronic equipment**	Set on, bolted, or clamped to structure	39	Pickup generates a voltage proportional to velocity. An integrating circuit is used to obtain displacement.
540 (damped)	0.6	2 x 2 3/4	None, self-generating	Usual electronic equipment**	Set on, bolted, or clamped to structure	40	900-ohm noninductive-wound d-c coil resistance. Pickup generates a voltage proportional to velocity. An integrating circuit is used to obtain displacement. Sensitivity gradually decreases with increasing single amplitudes above 300 mils. Frequency response flat plus or minus 5 per cent over entire range up to 25 mils.
400	10	7 1/2 x 5 x 4 3/4	None	None	Set on, bolted, or clamped to structure	41	May be used hand-held with a probe adapter. At 25 mils single amplitude the maximum frequency is 3000 CPM using probe, may be used to record deflection up to 25 mils as long as the accelerator does not exceed 6.25 g
300	3.2	7 x 5 x 3	Flashlight battery for timer	None	Hand-held with probe against structure	42	Capable of recording deflections up to 1 inch as long as the acceleration is less than 20 g.

** Usual electronic equipment consists of amplifier and power supply; variac transformer and voltage regulator; oscillator and microvolter; cathode-ray oscillograph and camera, or string oscillograph.

TABLE 5

Instruments for Recording Torsional Vibrations

Name	Practical Frequency Range* CPM	Practical Single Amplitude Range* degrees	Sensitivity or Magnification	Method of Detection	Method of Recording	Method of Damping
Cox torsiograph	600 to 5000	0.03 to 3.5	About 0.4 in./deg (max)	Inertia element, bell crank transmission	Stylus on waxed paper	Friction of stylus on waxed paper
Phase-shift torsiograph	500 to 50,000**	Depends on pickup gear, about 0.03 to 5	Depends on pickup gear, about 1/2 in. per degree	Phase-shift in gear-tooth carrier wave due to vibration	Oscillo-graphic	None
TMB photoelectric torsional vibration pickup	500 to 50,000**	About 0.01 to 5	Varies with light intensity	Inertia element with slotted cylinder, photoelectric detection	Oscillo-graphic	Dry friction
Consolidated torsional vibration pickup	900 to 60,000**	0.075 to 5 (varies with frequency)	1.2 mv per deg/sec	Inertia element, magnet moving about coil	Oscillo-graphic	Dry friction
General Motors mechanical torsiograph	1000 to 20,000**	0.05 to 2.5	About 0.2 in. per degree	Inertia element, mechanical lever	Stylus on sensitized paper	Dry friction
TMB-Sperry torsional vibration pickup	900 to 60,000**	0.075 to 5	About 1.2 mv per deg/sec	Inertia element, magnet moving about coil	Oscillo-graphic	Dry friction

* The ranges of frequencies and amplitudes given are not necessarily concurrent, i.e., the minimum amplitude cannot always be measured at the lowest frequency since enough force must be produced to overcome the inherent friction of the particular instrument, conversely, the maximum amplitude listed cannot always be measured at the maximum frequency.

TABLE 5 (continued)

Natural Frequency of Element CPM	Weight pounds	Overall Dimensions (LxWxH) or (DxH) inches	Power Required	Accessory Equipment Required	Method of Attaching to Shaft	Figure Number	Remarks
About 300	28 1/2	12 x 9 1/4 x 9 1/2	110-v a.c. and 6-v d.c.	None	Attached by belt on a pulley	43	Amplitude range may be increased by using small pulley or engine shaft.
	Power supply 24 1/2 Detector unit 12 1/2 Pickup gears 3, 60 teeth 6, 120 teeth 11, 120 teeth	14 3/4 x 6 x 10 1/4 14 1/8 x 8 x 9 3 5/8 x 5 1/2 5 3/4 x 6 1/2 9 3/4 x 4 3/8	110-v a.c.	Cathode-ray oscillograph and camera	Pickups fastened to end of shaft. Pickup gear (split) may be welded anywhere along shaft	44	Principal component of torsiograph is the phase-shift detector gear; must be devised for each new job.
About 400	8	3 1/2 x 5 3/4	110-v a.c. and 6-v d.c.	Light-ring unit and cathode-ray oscillograph and camera.	Fastened to end of shaft with 1-inch diameter collet	45	May be calibrated by inserting plug and rotating case relative to inertia element.
600	3 1/2	3 x 5	110-v a.c.	Sperry calibrator, amplifier, and string oscillograph	Fastened to end of shaft with 1-inch diameter collet	46	Velocity meter principle, integrating circuit used.
480	9 1/2	6 1/4 x 10	None	None	Fastened to end of shaft with 1-inch diameter collet	47	Celluloid chart provided for analyzing polar diagram obtained.
About 600	5 1/2	3 1/2 x 5 1/2	110-v a.c.	Sperry calibrator, amplifier, and string oscillograph	Fastened to end of shaft with 1-inch diameter collet	48	

** The upper frequency limit is approximate; it is based on manufacturers' data or on consideration of the mechanical construction of the pickup. Present TMB facilities permit calibration only up to 10,000 CPM.

TABLE 6

Displacement and Velocity Meters for Measurement of Transient Motions

Name	Practical Frequency Range* CPM	Practical Single Amplitude Range* inches	Sensitivity or Magnification	Direction of Vibration	Method of Detection	Method of Recording	Method of Damping	Natural Frequency of Element CPM	Weight pounds	Overall Dimensions (LxWxH) or (DxH) inches	Power Required	Accessory Equipment Required	Method of Mounting on Vibrating Structure	Figure Number	Remarks
British-type velocity meter	400 to 5000	0.001 to 1.0	About 30 mv per in./sec	Any one	Seismic weight, electromagnet moves relative to coil	Oscillographic	Inherent friction, low	About 180 vertical, 240 horizontal	47	8 x 9 1/2	110-v a.c. and 6-v d.c.	Usual electronic equipment**	Base bolted to structure	49	Effective weight, 37 pounds; weight of seismic magnet, 10 pounds.
Modified British-type velocity meter	400 to 5000	0.001 to 1.0	About 30 mv per in./sec	Any one	Seismic weight, electromagnet moves relative to coil	Oscillographic	Inherent friction, low	About 180 vertical, 240 horizontal	30	8 x 10 1/2	110-v a.c. and 6-v d.c	Usual electronic equipment**	Screwed to expendable base which is welded to structure	50	Currently being modified to decrease the weight, strengthen the case, and eliminate pitting between roller bearings and seismic magnet of original meter.
Consolidated large linear vibration pickup	300 to 18,000	0.001 to 0.750	75 mv per in./sec	Vertical or horizontal (separate units)	Seismic weight, electromagnet moves relative to coil	Oscillographic	Oil, adjustable	240	6.8	6 1/2 x 4 1/2 x 4	110-v a.c.	Usual electronic equipment**	Base bolted to structure	38	Used without integrating circuit for velocity recording
THB shock displacement gage	800 to 10,000	0.01 to 1.0	1.0 inch per inch	Any one	Seismic weight, direct recording	Scriber on polished metal disk	Friction of scriber on disk	520	89	25 x 12 x 15	110-v a.c.	None	Base bolted to structure	51	

* The ranges of frequencies and amplitudes given are not necessarily concurrent, i.e., the minimum amplitude cannot always be measured at the lowest frequency since enough force must be produced to overcome the inherent friction of the particular instrument; conversely, the maximum amplitude listed cannot always be measured at the maximum frequency.

** Usual electronic equipment consists of amplifier and power supply; Variac transformer and regulator; oscillator and microvolter; cathode-ray oscillograph and camera, or string oscillograph.

TABLE 7

Indicating Accelerometers for Measurement of Transient Motions

Name	Practical Single Amplitude Range g	Method of Indication	Meaning of Indication	Method of Damping	Natural Frequency of Element CPS	Weight pounds
Copper-ball accelerometer	10 to 3200	Flattening of small copper ball by large steel ball	Amount of flattening of target is presumed to be a measure of the peak acceleration	None		1.5
Mass-plug accelerometer	100 to 4500	Fracture of bakelite plug	Fracture of plug presumed to indicate that a definite value of acceleration has been attained	None	500 to 2600	1.25
Multifrequency reed gage Type I	5 to 20,000	Total displacement of each of 10 interchangeable reeds of different frequency scribed on waxed paper	Useful in comparing shock severities, variation of peak displacement with natural frequency of reed is compared with theoretical response to certain arbitrary shocks.	Friction of scriber on wax	25 to 2000	19 1/2
NRL contact accelerometer	5 to 500	Electrical indication of breaking or making of contact of preloaded spring-mass unit	Break-contact is presumed to indicate attainment of a definite value of acceleration. Use of a number of cells permits bracketing the peak value. Make-contact may be considered to indicate impulsive velocity as well as acceleration	None		0.1
Putty gage	25 to 2000	Indentation of conical rod in putty cylinder, 8 mass-spring units per gage	Amount of indentation in putty is supposed to indicate peak acceleration. May be interprated in terms of effective impulsive velocity	Inherent friction plus putty resistance	35 to 200	6.2
TMB 7-reed contact accelerometer	50 to 10,000	Electrical indication of breaking or making of contact of preloaded cantilever reeds	Break-contact is presumed to indicate attainment of a definite value of acceleration. Use of a number of cells permits bracketing the peak value. Make-contact may be considered to indicate impulsive velocity as well as acceleration	None	90 to 3900	3 1/4

TABLE 7 (continued)

Overall Dimensions (LxWxH) or (DxH) inches	Power Required	Method of Mounting on Vibrating Structure	Figure Number	Remarks
2 1/2 x 2 1/2 x 2 1/2	None	Bolted to structure	52	
1 1/2 x 2 3/4	None	Screwed to 1/2-inch stud which is welded to structure	53	Several plugs are used in an attempt to bracket the actual peak acceleration.
9 5/8 x 3 5/8 x 9	None	Bolted to structure	54	A more detailed analysis of the meaning of the indication made by this instrument is possible. This analysis does not presuppose that the motion is characterized by an impulsive velocity. A Type II instrument is under development and is described on page 91 Figure 54. See TMB Report 613, in preparation.
7-cell holder, 6 x 4 x 4 1/2	110-v a.c.	Clamped in 7-cell holder which is bolted to structure	55	Utilized TMB neon make-or-break indicator; see Figure 58.
3 x 5 1/2	None	Bolted to structure	56	
3 3/4 x 3 1/2	110-v a.c.	Screwed to 1/2-inch stud which is welded to structure	57	Utilizes TMB neon make-or-break indicator; see Figure 58.

TABLE 8

Recording Accelerometers for Measurement of Transient Motions

Name	Practical Frequency Range CPS	Practical Single Amplitude Range g	Sensitivity	Direction of Vibration	Method of Detection	Method of Recording	Method of Damping
Brush VP-5 crystal acceleration pickup	10 to 500	0.001 to 10	About 80 mv RMS per g	Any one	Piezoelectric crystal	Oscillographic	None
BuOrd torpedo accelerometer	0 to 30	0.25 to 25	0.04 in. per g on record	Any one	Spring-mounted mass, mechanical lever	Stylus on waxed paper	Oil, not adjustable
Single damped-cantilever accelerometer	0 to 50	0.1 to 18	22.5 µv per g per 45 volts applied	Any one	Metalectric strain gage	Oscillographic	Oil film between parallel plates, adjustable
Double cantilever accelerometer, Types A to E	10 to 800	1 to 2000, estimated	About 45 µv per g per 45 volts applied	Any one	Metalectric strain gages	Oscillographic	Very little, internal damping of plastic material
Metalectric accelerometer	10 to 5000	10 to 5000, estimated	0.185 µv per g per volt applied	Any one	Weighted cylinder, metalectric strain gages.	Oscillographic	None
Consolidated accelerometer	0 to 35	0.02 to 15	25 mv per g with 15-volt carrier	Any one	Seismic inductance, variable reluctance	Oscillographic	Magnetic
TMB Pallograph type accelerometer			On record, inches per g		Spring-mounted weight, mechanical lever	Stylus on waxed paper	Air dashpot, adjustable
Group I*	0 to 1 0 to 1 0 to 1.5 0 to 2 0 to 2.5 0 to 3	0.001 to 0.08 0.002 to 0.16 0.004 to 0.34 0.007 to 0.63 0.013 to 1.0 0.016 to 1.0	5.76 2.63 1.33 0.71 0.35 0.28	Vertical only			
Group II*	0 to 2 0 to 3 0 to 4 0 to 5 0 to 6	0.03 to 1.2 0.05 to 2.0 0.10 to 4.3 0.15 to 6.8 0.20 to 9.0	0.66 0.4 0.2 0.14 0.1	Any one			

* The springs listed in Group I replace the pallograph displacement spring. The springs listed in Group II are used with a special weight and two-spring suspension; see Figure 13.

TABLE 8 (continued)

Natural Frequency of Element CPS	Weight pounds	Overall Dimensions (LxWxH) or (DxH) inches	Power Required	Accessory Equipment Required	Method of Mounting on Vibrating Structure	Figure Number	Remarks
1500	0.4	3 x 2	110-v a.c.	Usual electronic equipment**	Held against or clamped to structure	8	
35	7 3/4	5 x 10	6-v dry cell	Timer, if desired	Bolted or clamped to structure	7	Holds maximum of 40 inches of paper which permits 30 seconds of record.
215	4.2	4 1/2 x 2 x 6	110-v a.c.	Usual electronic equipment**	Bolted or clamped to structure	9	Development inactive.
200 1400 1800 2400 3500	Type D, 1.0	Type D 8 x 2 1/2 x 2	110-v a.c.	Battery box and usual electronic equipment**	Bolted or clamped to structure	10	
15,000	1/2	1 1/2 x 1 1/2 x 2	100-v a.c.	Battery box and usual electronic equipment**	Screwed to 5/8-inch stud which is welded to structure	59	
	0.8	2 3/4 x 2 1/2 x 2 3/4	110-v a.c.	1000-CPS bridge, usual electronic equipment**	Bolted or clamped to structure	14	
2.16 2.76 3.83 5.35 6.79 7.48	40	20 x 8 x 14	110-v a.c.	Synchronous timer	Bolted or clamped to structure	13	Adapted from Type B pallograph.
5.42 7.00 9.9 12.1 14.0							Uses special weight and two-spring suspension.

** Usual electronic equipment consists of amplifier and power supply; Variac transformer and regulator; oscillator and microvolter; cathode-ray oscillograph and camera, or string oscillograph.

TABLE 8 (continued)

Name	Practical Frequency Range CPS	Practical Single Amplitude Range g	Sensitivity	Direction of Vibration	Method of Detection	Method of Recording	Method of Damping
Statham accelerometer R-500-700	0 to 850	1 to 500	About 0.22 μ amp per g for 15-ohm impedance; about 0.1 mv RMS per g (max) for high impedance load	Any one normal to base	Strain wires forming bridge circuit support inertia mass	Oscillographic	Organo-silicon fluid
Statham accelerometer Ar-12V-250	0 to 150	0.1 to 12	About 13 μ amp per g for 15-ohm impedance; about 2.3 mv RMS per g (max) for high impedance load	Any one normal to base	Strain wires forming bridge circuit support inertia mass	Oscillographic	Organo-silicon fluid
Statham accelerometer R-5-120	0 to 90	0.1 to 5	About 17 μ amp per g for 15-ohm impedance; about 1.8 mv RMS per g (max) for high impedance load	Any one normal to base	Strain wires forming bridge circuit support inertia mass	Oscillographic	Organo-silicon fluid
Statham accelerometer S-1.5-120	0 to 60	0.05 to 1.5	About 34 μ amp per g for 15-ohm impedance; about 3.5 mv RMS per g (max) for high impedance load	Any one parallel to base	Strain wires forming bridge circuit support inertia mass	Oscillographic	Organo-silicon fluid
Westinghouse crystal accelerometer	10 to 5000	10 to 5000	0.62×10^{-12} coulombs per g	Any one	Piezoelectric crystal	Oscillographic	None
TMB crystal accelerometer, single-faced	10 to 5000	10 to 5000	0.77×10^{-12} coulombs per g	Any one	Piezoelectric crystal	Oscillographic	None
TMB crystal accelerometer, push-pull	10 to 5000	10 to 5000	0.77×10^{-12} coulombs per g	Any one	Piezoelectric crystal	Oscillographic	None

** Usual electronic equipment consists of amplifier and power supply; Variac transformer and regulator; oscillator and microvolter; cathode-ray oscillograph and camera, or string oscillograph.

TABLE 8 (continued)

Natural Frequency of Element CPS	Weight pounds	Overall Dimensions (LxWxH) or (DxH) inches	Power Required	Accessory Equipment Required	Method of Mounting on Vibrating Structure	Figure Number	Remarks
1670	0.5	2 x 1 1/4 x 2 1/2	20-v d.c. (max)	5-KC carrier, power supply, oscillograph	Bolted to structure (5-40 screws)	17	Resistance: Input, 686.3 ohms Output, 686.3 ohms Input current: 30 ma (max) Input current: 20 v (max)
300	0.5	2 x 1 1/4 x 2 1/2	12.5-v d.c. (max)	Modified TMB 1-A strain amplifier	Bolted to structure (5-40 screws)	17	Resistance: Input, 236.4 ohms Output, 236.4 ohms Input current: 60 ma (max) Input voltage: 12.5 v (max)
185	0.5	2 x 1 1/4 x 2 1/2	5-v d.c. (max)	Usual electronic equipment** or modified TMB 1-A strain amplifier	Bolted to structure (5-40 screws)	17*	Resistance: Input, 136.2 ohms Output, 136.2 ohms Input current: 40 ma (max) Input voltage: 5 v (max)
115	0.8	2 3/8 x 1 3/4 x 2 3/8	5-v d.c. (max)	Usual electronic equipment** or modified TMB 1-A strain amplifier	Bolted to structure (5-40 screws)	17	Resistance: Input, 126.3 ohms Output, 126.3 ohms Input current: 40 ma (max) Input voltage: 5 v (max)
15,000	0.6	1 x 2	110-v a.c.	Usual electronic filter	Screwed to 1/2"-13 stud	60	
15,000	0.6	1 x 2	110-v a.c.	Usual electronic filter	Screwed to 1/2"-13 stud	60	
15,000	0.6	1 x 2	110-v a.c.	Usual electronic filter	Screwed to 1/2"-13 stud	60	

* The springs listed in Group I replace the pallograph displacement spring. The springs listed in Group II are used with a special weight and two-spring suspension; see Figure 13.

DESCRIPTION OF INSTRUMENTS

To familiarize the reader with the physical appearance and the principles of operation of the various shock and vibration instruments currently available at the Taylor Model Basin, photographs, schematic diagrams, and a brief verbal description of each instrument are given in this section.

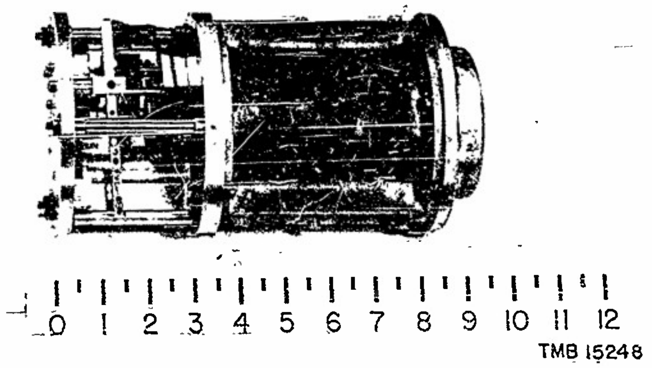


Figure 7a

Figure 7 - BuOrd Torpedo Accelerometer

This accelerometer was originally designed for recording the accelerations to which a torpedo is subjected when it strikes the water after being launched from an aircraft. An extremely high natural frequency was not considered to be of prime importance for the type of work for which it was to be employed. The instrument requires no external source of power, except small dry cells, and is small enough to be mounted in a torpedo or in other installations where only limited space is available. It consists of a cylindrical case in which a mass is supported by flexure springs. The case is sealed and is filled with oil for damping; an arm attached to the mass projects through a sylphon bellows, transmitting the motion to a mechanical lever which scribes on waxed paper. It has a paper capacity of 40 inches which makes obtainable a maximum time record of approximately 30 seconds. The paper is driven by a 6-volt d-c midget motor. As calibrated at the Taylor Model Basin the instrument has a linear response up to a frequency of 2000 CPM. The instrument has proved useful for measurement of low-frequency accelerations.

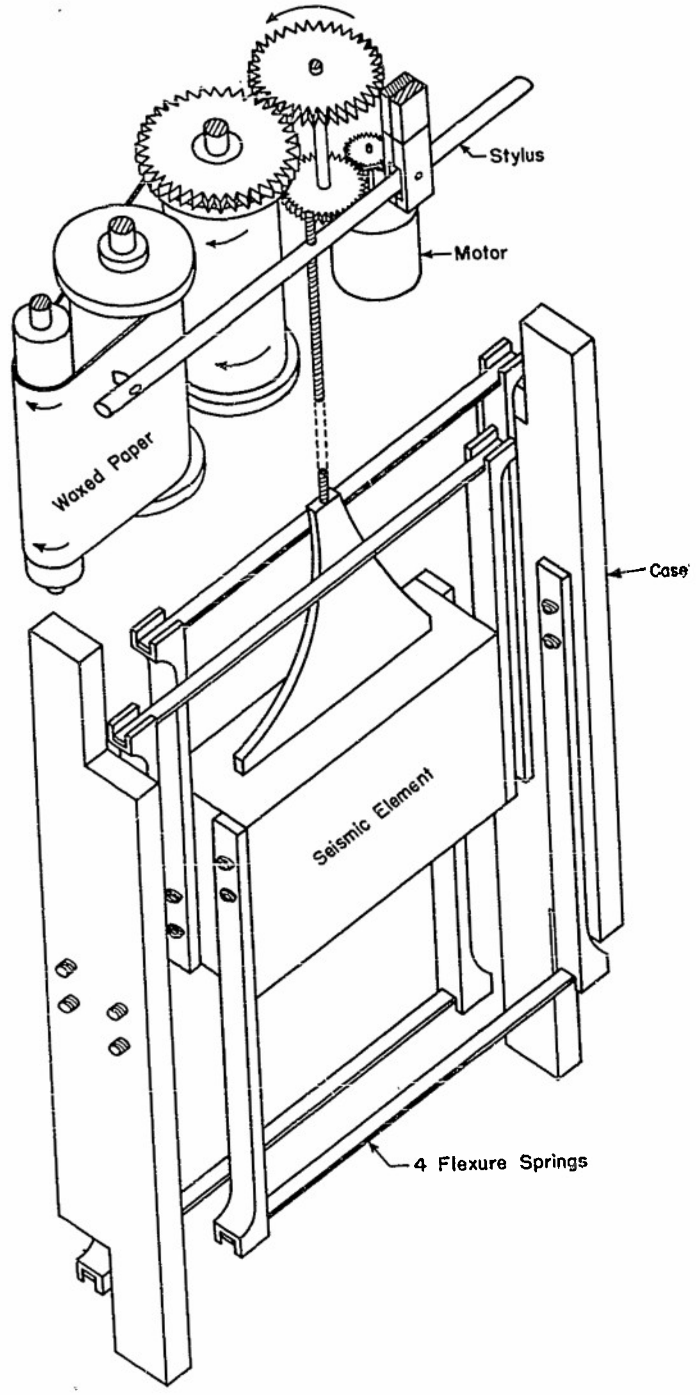


Figure 7b

TMB 15252

Figure 8a

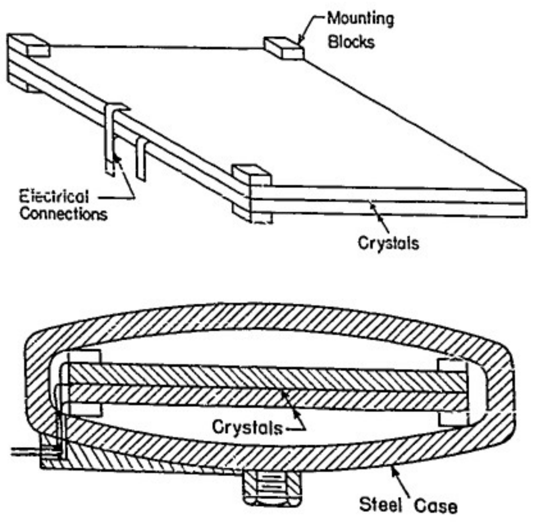
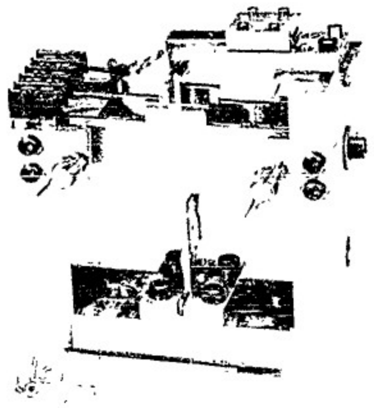


Figure 8b

Figure 8 - Brush VP-5 Acceleration Pickup

This pickup is of the inertia-type with a piezoelectric crystal as the sensitive element. The upper sketch in Figure 8b shows the arrangement of the crystals. The crystal is mounted in the case so that it bends because of its inertia when the case is subjected to vibration. 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. The resultant voltage produced is proportional to the applied acceleration. It may be used for frequencies up to 1500 CPS, but should not be subjected to accelerations greater than 10 g. The pickup should not be subjected to temperatures above 120 degrees fahrenheit.

This type of instrument may be used with an indicating meter for steady-state vibration, or with a cathode-ray oscillograph for recording purposes. The input impedance of the amplifying devices should be about 5 megohms.



TMB 16588

Figure 9a

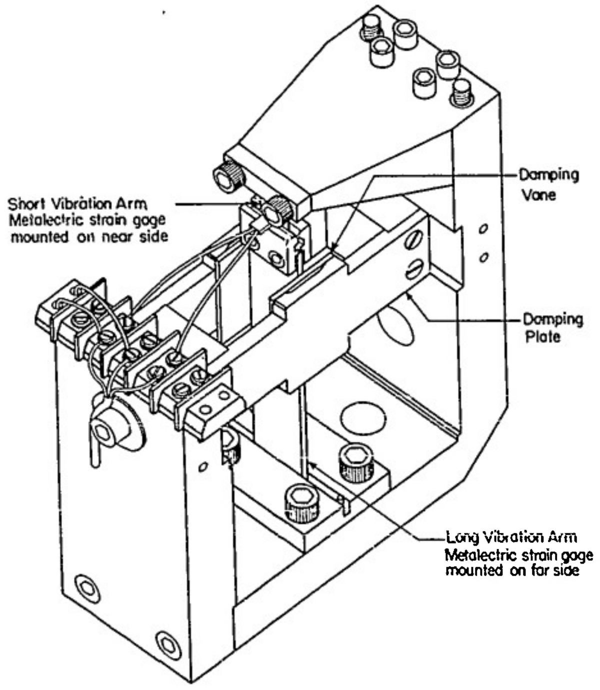


Figure 9b

Figure 9 - Single Damped-Cantilever Accelerometer

The inertia element is a steel cantilever reed of uniform thickness (0.1 inch) with a metalectric strain gage mounted at the base. Damping is obtained by two flat plates (damping vanes) attached to the reed, which move between two fixed parallel damping plates. The space between the vanes and the plates is of the order of 0.003 inch and is filled with oil which remains in place by capillary attraction. The damping may be varied by changing the oil or the clearance. With the strain-detecting equipment currently available at the Taylor Model Basin, accelerations as small as 0.1 g may be measured. Development of this instrument has been suspended.

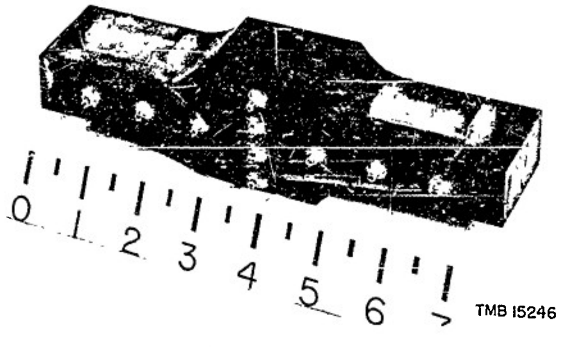


Figure 10a

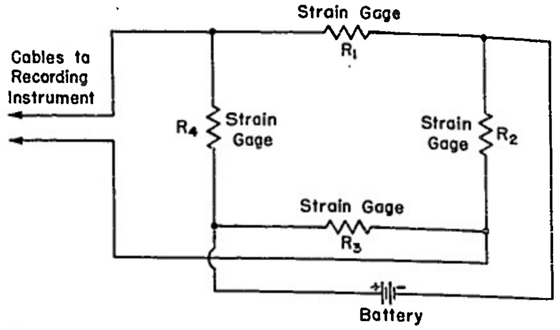
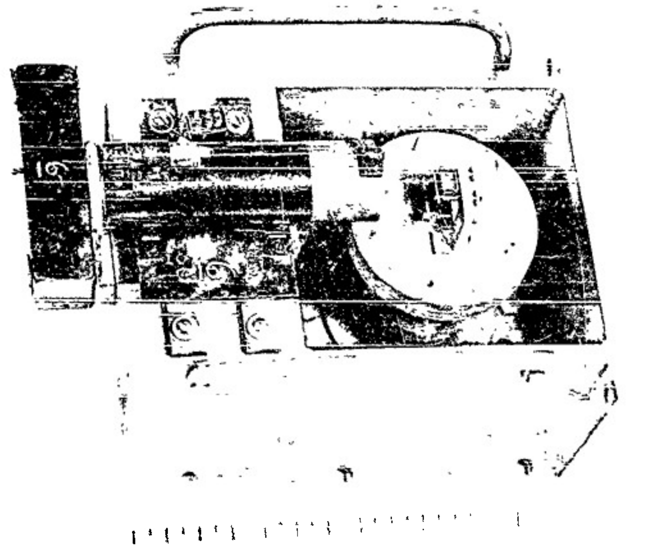


Figure 10b - Wheatstone-Bridge Hookup of Metalectric Strain Gages

Figure 10 - Double Cantilever Accelerometer

This instrument is made of a fabric plastic material in the form of a double cantilever. Metalectric strain gages mounted on each side of both cantilevers comprise a bridge circuit which yields optimum sensitivity. It should be used with a low-pass filter in measuring steady-state vibration. The only damping present is the internal damping of the plastic material, which is approximately 2 per cent of critical damping. A series of these instruments, Types A to E, each with a different sensitivity, is available. These instruments were the first electrical accelerometers developed and used at the Taylor Model Basin. Although they are not in current use, the metalectric strain-gage principle is employed in more recent designs.



TMB 14569

Figure 11a - DVL-Type Accelerometer with Tuckerman Optical Strain Gage and Recorder

Figure 11 - DVL-Type Accelerometer

The DVL accelerometer was built at the Taylor Model Basin on the basis of a previous German design.
It is similar in mechanical construction to the subsequently designed BuOrd torpedo accelerometer ex-
cept that the spring-mass system has a higher natural frequency and lower sensitivity. It employs a
Tuckerman strain gage with photographic recorder for obtaining the large magnification required and
for recording the motion. The sensitive element is a mass supported on flexure springs and surrounded
by oil for damping.

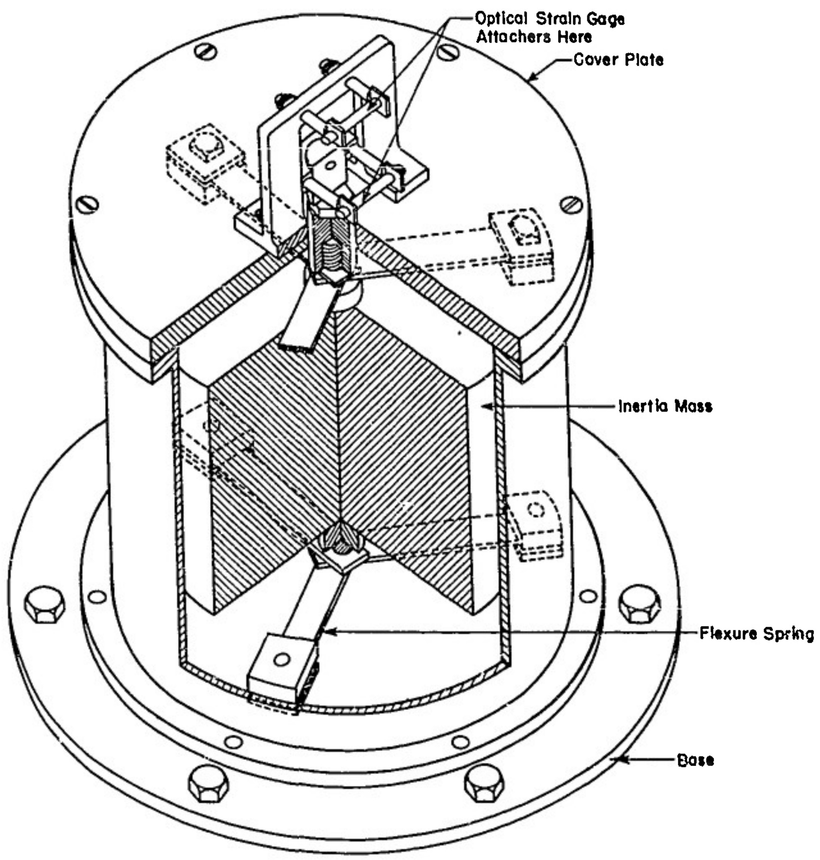


Figure 11b - DVL-Type Accelerometer

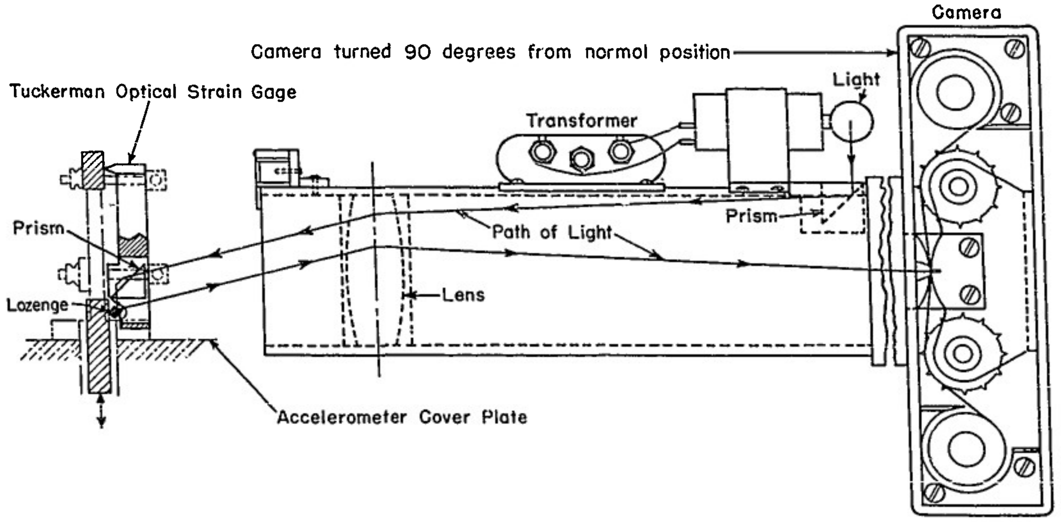


Figure 11c - Tuckerman Optical Strain Gage and Recorder

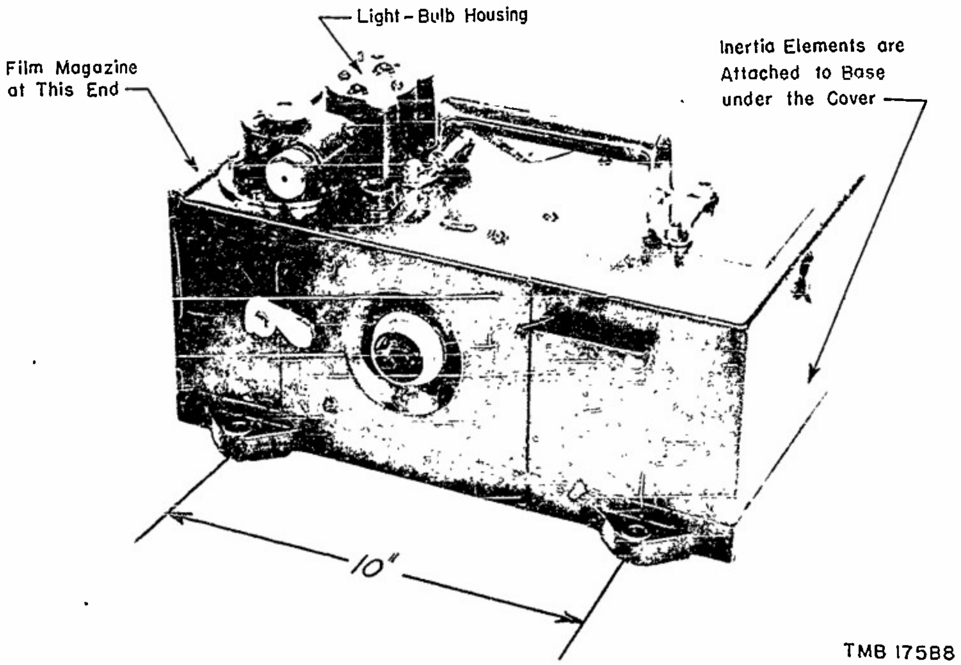


Figure 12a - Recording Unit of Jacklin Accelerometer

Figure 12 - Jacklin Three-Component Linear Accelerometer

This accelerometer records optically three orthogonal components of linear accelerations. The inertia elements consist of hollow cylinders mounted on flexure springs. When subjected to acceleration, the element moves relative to a stationary core which is separated from the element by an oil film providing the required damping. A novel optical lever reflects a light trace to a moving film, magnifying the motion of the element approximately 1250 times. The instrument operates entirely on storage batteries and consists of two units, one containing the inertia elements, optical system, and film magazine, and the other containing the drive motor and spring-wound Cambridge timer.

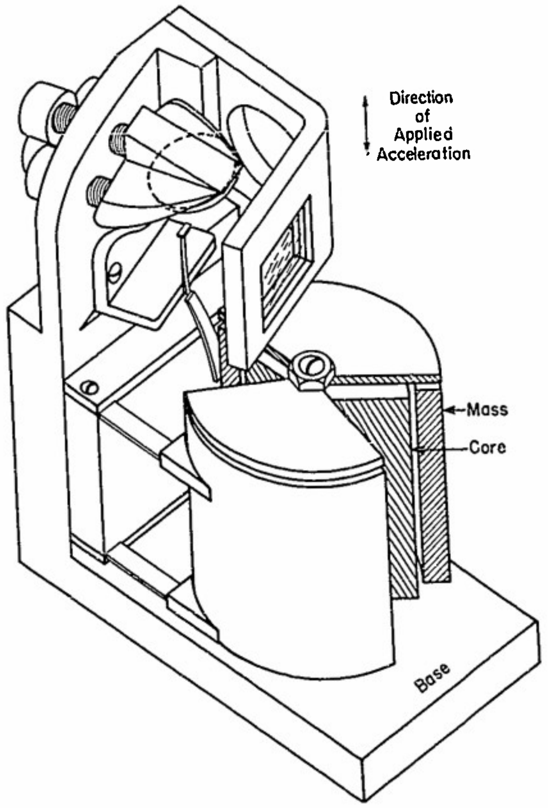


Figure 12b - Isometric View of Vertical Linear Element

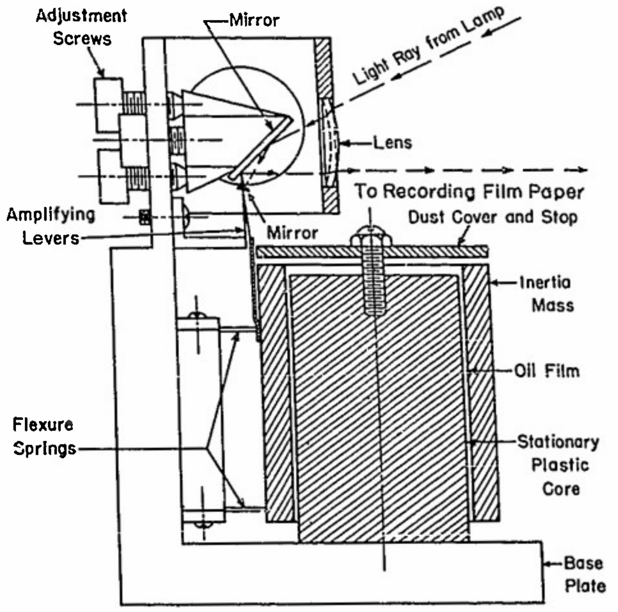


Figure 12c - Cross Section of Vertical Linear Element

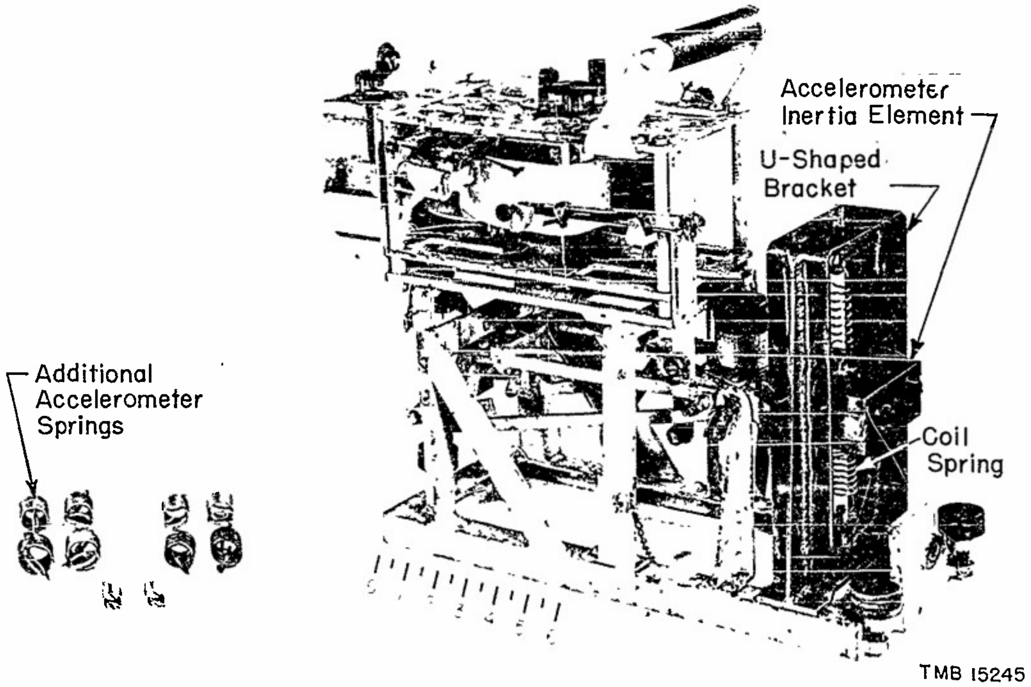


Figure 13 - TMB Pallograph-Type Accelerometer

This instrument is the Type B pallograph modified for recording low-frequency accelerations. The modification for recording acceleration less than g consists of a stiff spring replacing the regular low-frequency spring for the pallograph. Thus all the mechanical features of the pallograph are retained in the accelerometer. For recording acceleration up to about 10 g, the pallograph spring is removed and the seismic weight is replaced by a lighter weight. A U-shaped bracket which bridges the weight is bolted to the frame of the pallograph, and the mass is supported from above and below by two springs attached to the bridge as shown. As in the pallograph, a dashpot which produces adjustable air damping can be used if required.

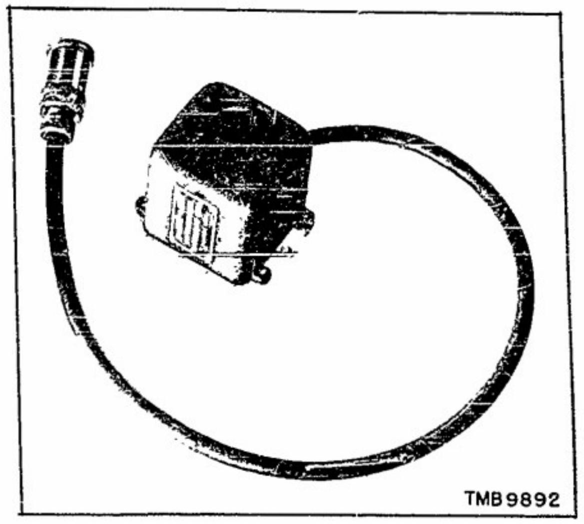


Figure 14a

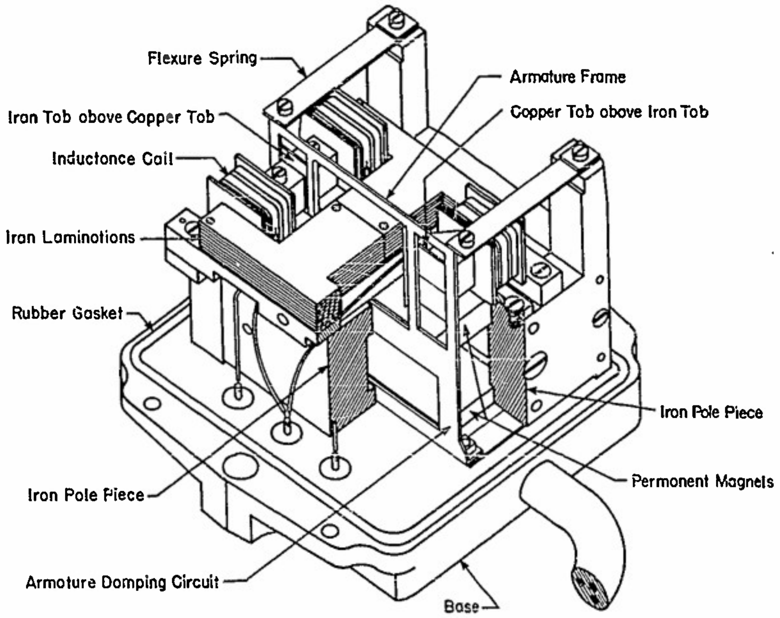
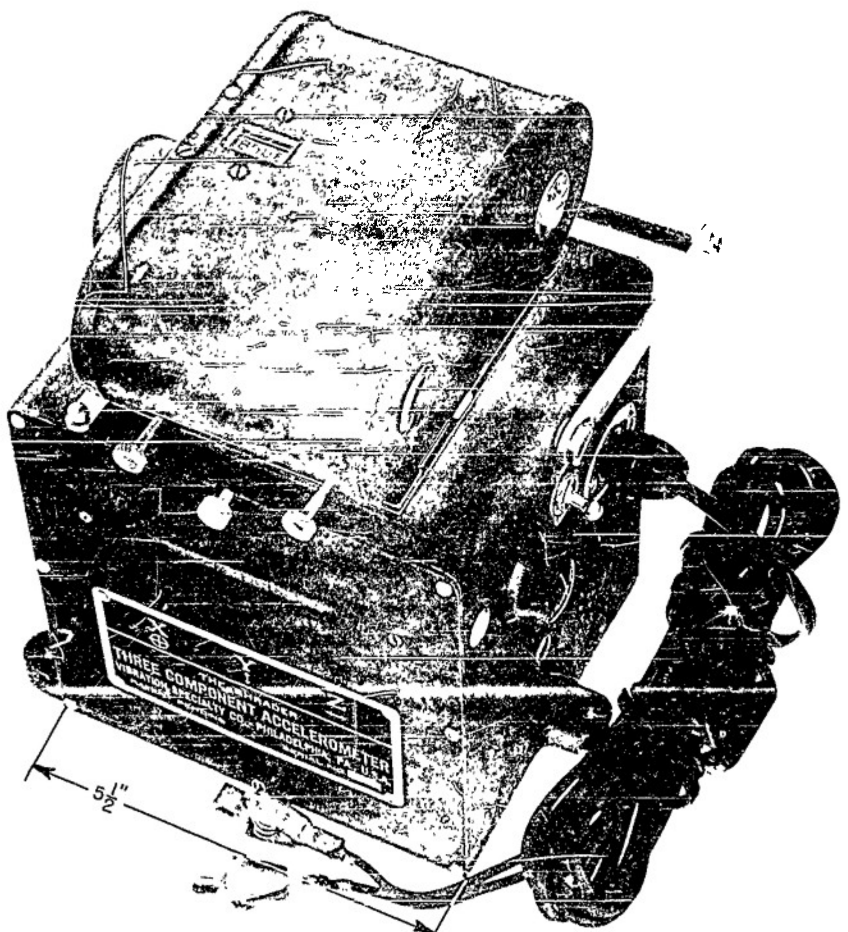


Figure 14b

Figure 14 - Consolidated Accelerometer

This pickup is an accelerometer of the variable-reluctance type with magnetic damping. It is designed to operate in a bridge circuit using 1000- to 1200-cycle carrier current. The pickup contains two inductances which are connected in series to form two arms of the bridge. Acceleration of the entire pickup causes the armature carrying the iron and copper tabs to move in the air gaps. This motion produces opposite changes in the impedances of the two inductances with respect to one another, and thus the bridge balance is altered to give a modulated carrier output whose envelope varies in proportion to the impressed acceleration. The natural frequency and damping of the seismic system are so chosen as to give the pickup a uniform response to accelerations over a frequency range from 0 to 30 cycles per second. Above 30 cycles the response drops off rapidly. The magnetic damping which is used is relatively little affected by temperature variations, and a uniform frequency response over a wide range of temperatures is obtainable.



TMB 9880

Figure 15a - Shrader Accelerometer with Film Magazine Attached

Figure 15 - Shrader Three-Component Accelerometer

The inertia elements of this instrument are three steel cantilever reeds mounted at angles of 90 degrees to each other. Relative motion between the case and the end of any one of the reeds rotates a spindle and small mirror. Each mirror reflects a beam of light onto a moving film. Visual readings may be obtained by measuring the width of each light trace on a ground glass plate in the front of the instrument. It has been impossible to obtain an accurate calibration of this instrument owing to high-frequency harmonics which obscure the actual motion. Originally a thin metal diaphragm was attached to the end of each cantilever to provide air damping. The damping principle used has merit but the free fibrations of the metal diaphragm introduce undesirable effects. Air damping with dashpots is under development at the Taylor Model Basin for this instrument.

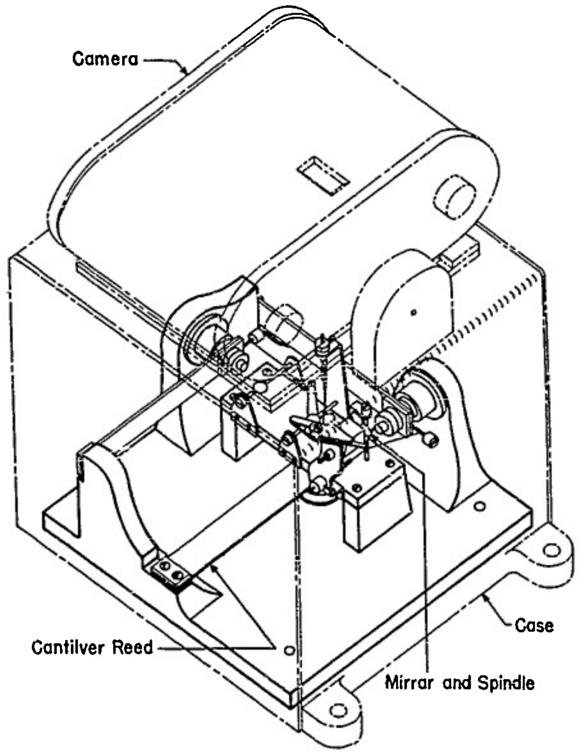


Figure 15b - Internal Construction of the Shrader Accelerometer

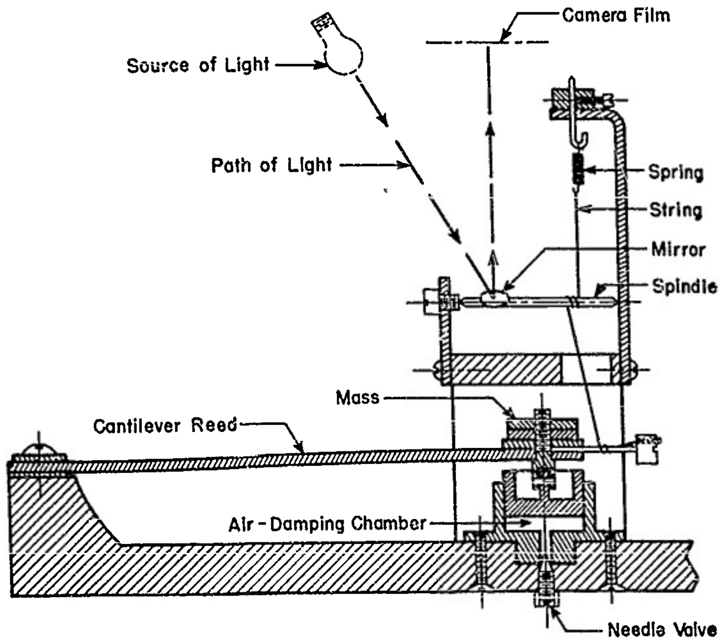


Figure 15c - Cross Section of Vertical Element as Modified at the Taylor Model Basin

TMB 14571

Figure 16a

Figure 16 - Wimperis Accelerometer

This is a dial-indicating accelerometer for recording small, relatively steady, unidirectional accelerations up to 8 feet per second^2 (about 1/4 g).

The instrument will measure accelerations only in a horizontal plane. An adjustment is provided for leveling the instrument before taking measurements. The indicating lever is pivoted and has a small weight attached to it which acts against a coil spring at the pivot; it is magnetically damped by a copper plate passing through a permanent magnetic field.

If desired, a record of the accelerations may be obtained by photographing the movement of the indicating lever.

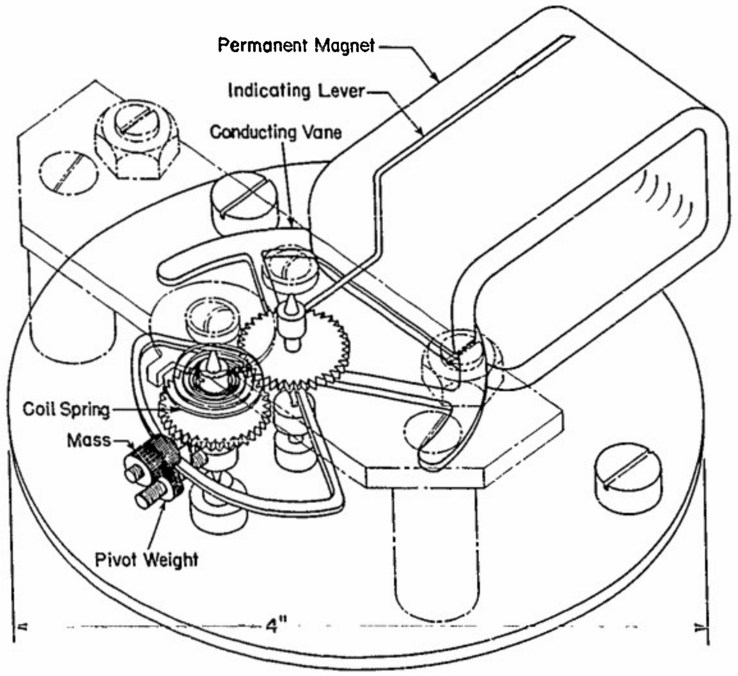


Figure 16b

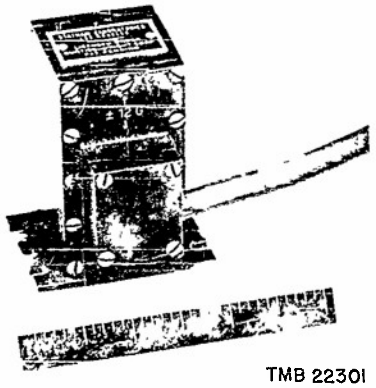
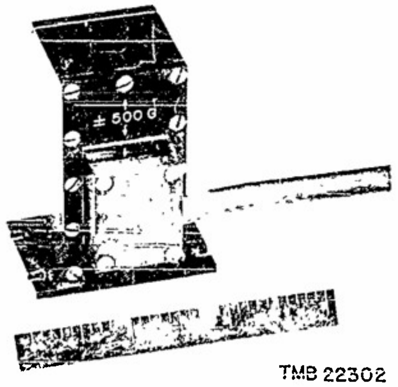

TMB 22301

Figure 17a - Photograph of 12-g Statham Accelerometer



TMB 22302

Figure 17b - Photograph of 500-g Statham Accelerometer

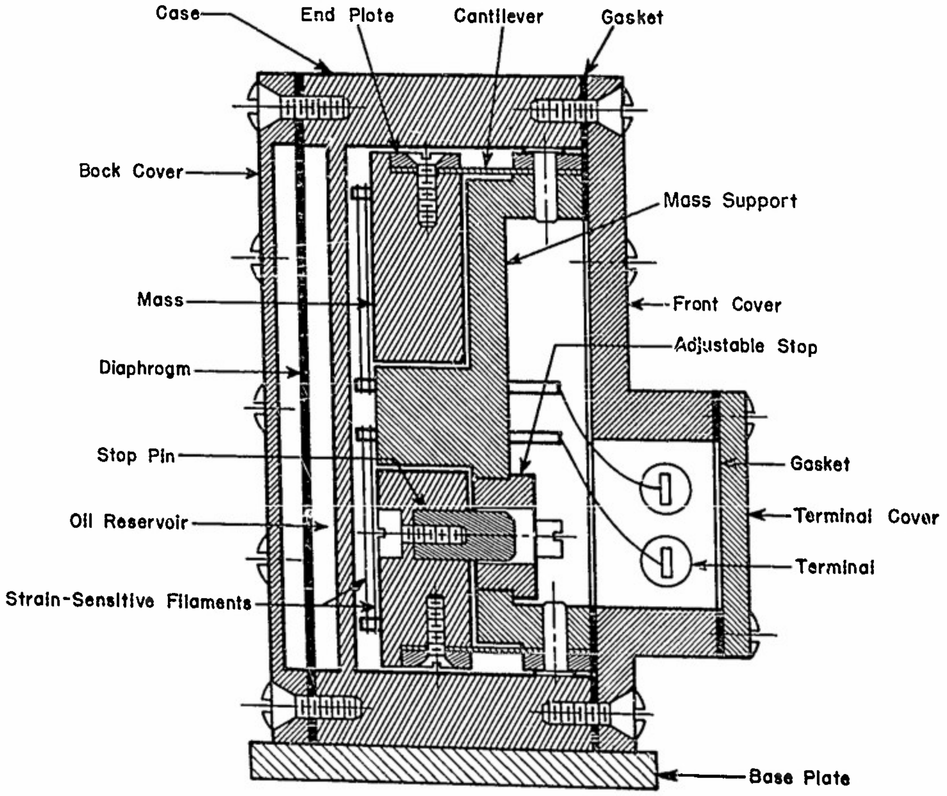


Figure 17c - Cross-Sectional View of Statham Accelerometer

Figure 17 - Statham Accelerometer

The Statham accelerometer utilizes the strain-sensitive wire principle. In order to obtain high sensitivity the strain-sensitive wires serve as supporting springs for the mass or inertia element. In this manner a high ratio of strain to imposed acceleration is obtained. When the mass is subjected to acceleration, the strain wires which comprise a bridge circuit are changed in length thereby unbalancing the bridge circuit. The output signal is amplified and recorded by electronic equipment. The instrument is entirely enclosed, and the case is filled with a silicone fluid which provides the required damping.


TMB 9895

Figure 18a - Cordero Vibrometer

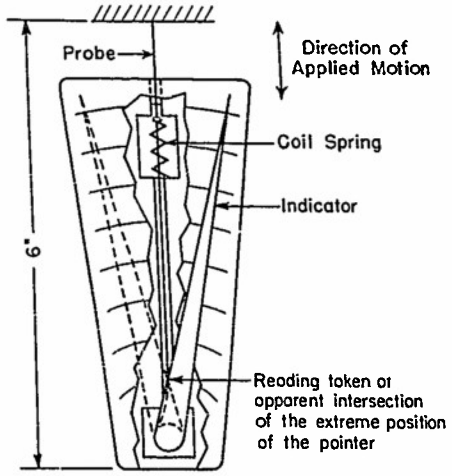


Figure 18c - Schematic Arrangement of Cordero Vibrometer

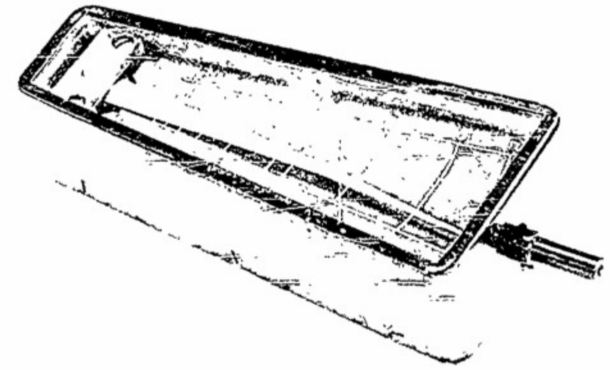

TMB 15249

Figure 18b - Modified Cordero Vibrometer

Figure 18 - Cordero Vibrometers

The Cordero vibrometer is a hand-held amplitude-indicating instrument. The weight of the case in the hand acts as a seismic mass which remains motionless while the probe follows the motion of the vibrating body. The probe acts against a compression spring and is connected to the indicating pointer by a simple mechanical linkage which magnifies the motion. The tapered indicator moves back and forth across the radially graduated face which, when read at the intersection of the two extreme indicator positions, indicates the double amplitude in mils. The modified or increased-range Cordero has a stiffer spring to ensure continuous contact at the higher accelerations produced at larger amplitudes; the weight of the case is heavier in order to maintain its seismic effect against a stiffer spring, and the magnification at the linkage is approximately one-half that of the original instrument, thus permitting indication of twice the amplitude for the same motion of the indicating pointer. A schematic arrangement of the Cordero vibrometer is shown in Figure 18c. This instrument is particularly useful for exploring the vibration of large structures and for obtaining comparative amplitudes.

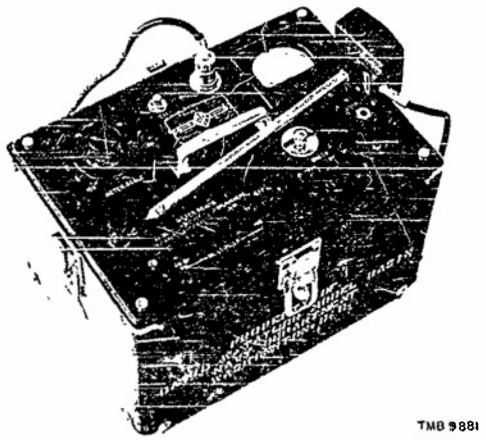


Figure 19a - GR Vibration Meter and Pickup

The GR vibration meter indicates RMS values of displacement, velocity, and acceleration when used to measure steady-state motion. It is convenient to carry, needs no external source of power, and results are indicated for immediate information. The pickup used with this meter is a Shure piezoelectric crystal accelerometer similar to the Brush VP-5 pickup described in Figure 7. An amplifying circuit and two integrating circuits enable the a-c meter to indicate accelerations, velocities, or amplitudes of steady-state vibration over a wide range. The a-c meter is calibrated to give readings in RMS values of microinches, microinches per second, or microinches per second². When used for measuring small vibration amplitudes, the vibration meter itself should not be in a location which is very noisy or subject to vibration. Because of the large R-C components (time constants) in this instrument, transient currents initiated by throwing a switch should be allowed 5 or 10 seconds to stabilize before reading the meter. The pickup should not be subjected to acceleration greater than 10 g RMS, or to temperature higher than 120 degrees fahrenheit.

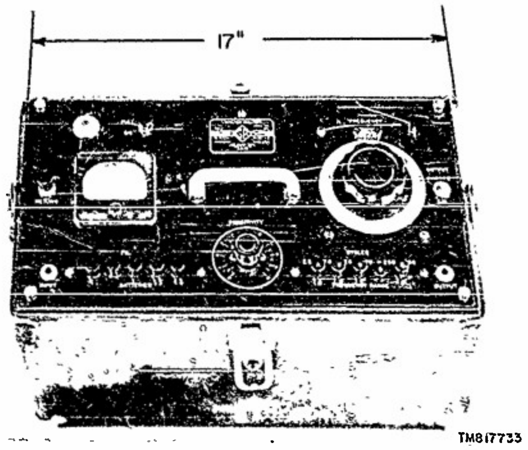


Figure 19b - GR Vibration Analyzer

The GR vibration analyzer is a self-contained instrument used with the GR vibration meter in separating and determining the relative amplitudes of the various harmonics of a complex steady-state vibration. The analyzer input connects to the output of the vibration meter, and the frequency range is scanned on the analyzer in order to obtain the ratio of the amplitude of each harmonic component to the amplitude of the fundamental component. Absolute readings may also be made with the analyzer, but for most purposes relative-amplitude data are sufficient. Complete information for the operation and check of the instrument is found in the instructions mounted in the cover of the instrument.

Figure 19 - General Radio Vibration Meter and Analyzer

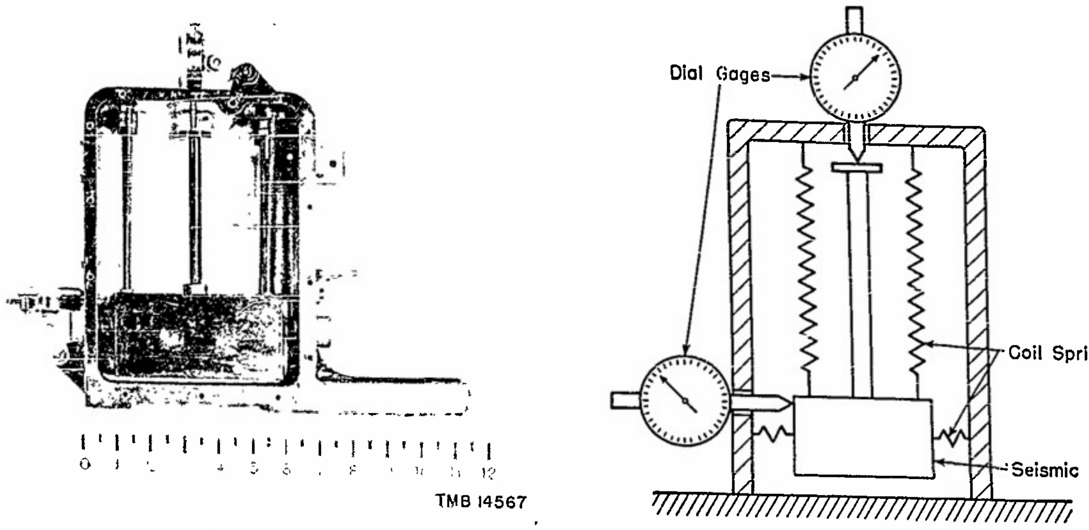


Figure 20a

Figure 20b

Figure 20 - Karelitz Vibrometer

The Karelitz vibrometer has a spring-mounted weight with freedom of motion in two directions. The weight acts as a seismic element, and the relative motions between it and the case in the vertical and in one horizontal direction are indicated by dial gages. This instrument was one of the earlier vibration-indicating instruments available at the Taylor Model Basin. It has been largely superseded by other indicating vibrometers and recording instruments.

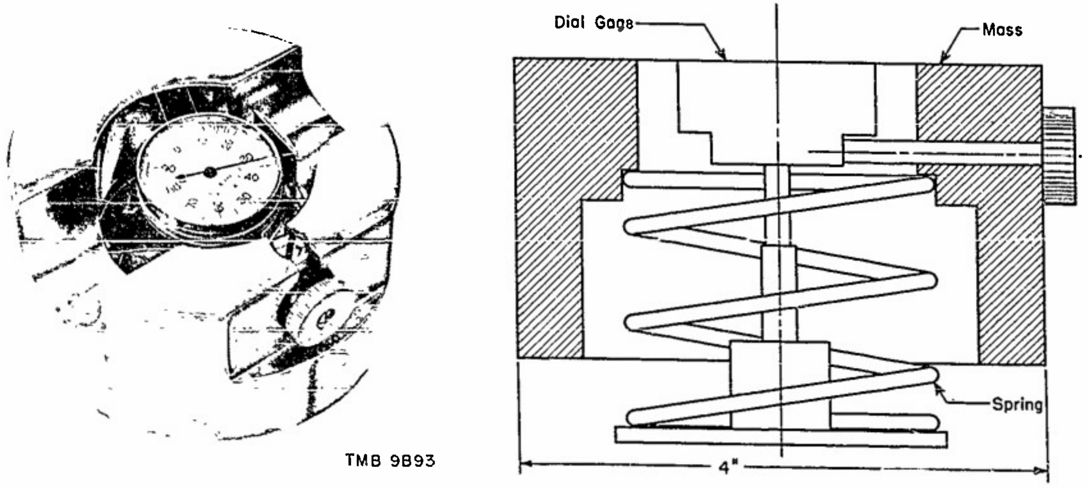


Figure 21a

Figure 21b

Figure 21 - Westinghouse Hand Vibrometer

This amplitude-indicating instrument is similar in principle to the Karelitz vibrometer described in Figure 20, except that it is much smaller and lends itself readily to hand use. It can be used by allowing it to rest on the vibrating body and reading the dial indication, but it has been found that hand-held operation is more satisfactory. It has a greater frequency and amplitude range than the Karelitz vibrometer.

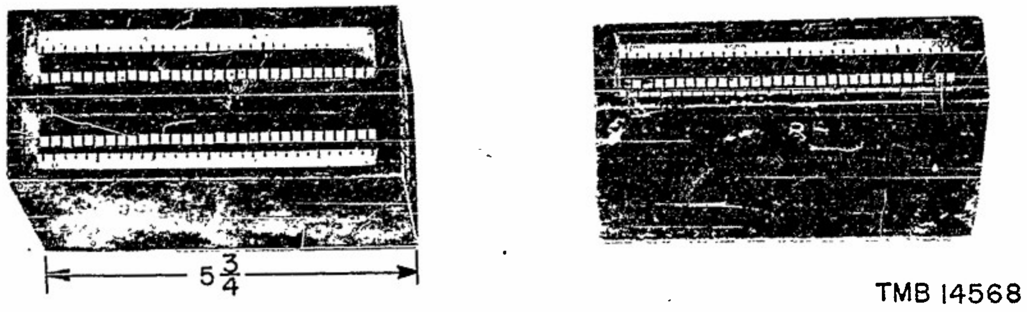


Figure 22a

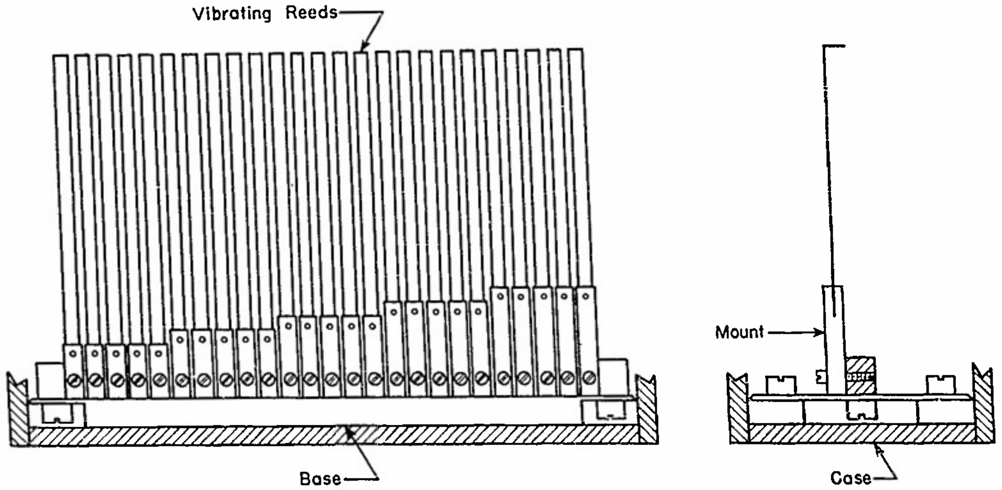


Figure 22b

Figure 22 - Frahm's Reeds

Each instrument has a set of reeds, all of different natural frequencies, designed to give continuous frequency indications through a given range of frequencies. Indication of the frequency is given by resonant vibration of the reed at, or closest, to the frequency of the vibrating body. The white enameled ends of the reeds aid in determining which reed is in resonance. In order not to produce excessive stresses in the reeds, care should be observed in the use of the instrument to see that the reeds do not vibrate continuously with double amplitude greater than 3/4 inch for frequencies up to about 3600 CPM, and correspondingly less for higher frequencies. Where vibrations are excessive, this can be accomplished by cushioning the instrument with the hand rather than applying it directly to the vibrating body.

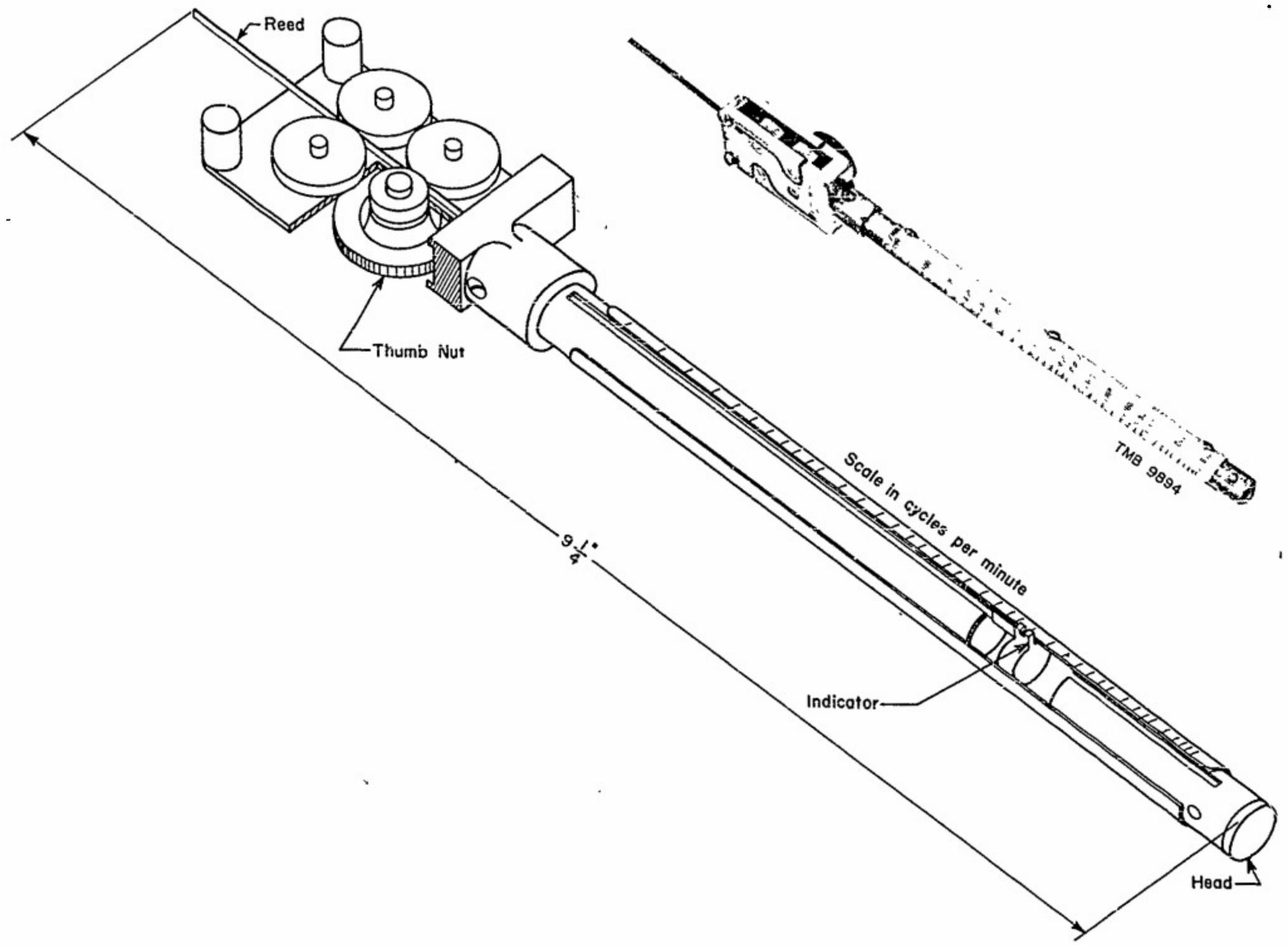


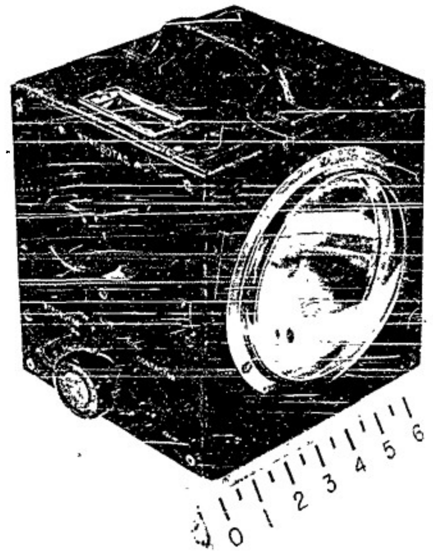
Figure 23 - Westinghouse Reed Vibrometer

This frequency meter consists of a thin steel reed clamped between rollers and extending from them as a cantilever. Rotation of one of the rollers, by means of a thumb nut, increases or decreases the free length of the reed with a corresponding change in the natural frequency of the reed. This frequency is indicated by the position of a pointer on the fixed end of the reed along a calibrated frequency scale on the frame. To measure vibration frequency the head of the instrument is held against the vibrating body and the reed is slowly extended by turning the thumb nut until the reed vibrates at a maximum amplitude. If the reed is not tuned exactly to the vibration frequency, beating will occur which disappears when the reed is tuned exactly. The meter may be used to estimate small amplitudes of vibration, as 0.001-inch amplitude of vibration applied at the head of the instrument produces approximately 1/2-inch motion at the end of the reed, that is, the amplitude is magnified about 500 times by the reed.

TMB 16589

Figure 24 - Strobomeca (Rotoscope)

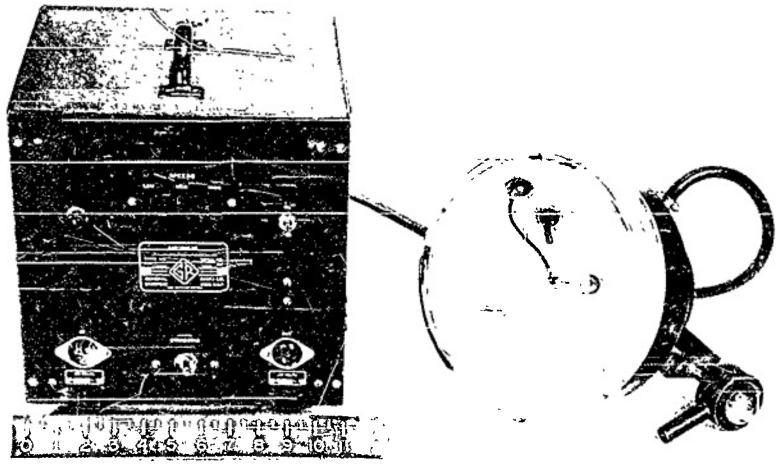
This is a mechanical stroboscope for determining the frequency of vibration or the speed of a rotating body. A slotted disk is rotated by a spring-wound motor at variable speeds from 500 to 2000 RPM. The speed of rotation is indicated by the scale and pointer on the periphery of the instrument. Observations are made by viewing the vibrating body through the eyepiece and varying the speed until the body appears to be stationary. Frequencies above 2000 CPM can be determined by substituting for the single-slot disk a disk with a greater number of equally spaced radial slots. Frequencies above or below the range of the instrument may be found by measuring submultiples and multiples, respectively, of the actual frequency. Readings should be taken using the upper 85 per cent of the scale only, since the lower 15 per cent is not reliable. Fairly strong lighting is required for effective use of the Strobomeca.



TMB 15250

Figure 25 - Strobotac

The Strobotac employs stroboscopic light pulses to determine the frequency of moving objects and to study their behavior while in motion. The frequency of the "stopped" motion is read on a lighted scale at the top of the instrument which indicates the flashing frequency required to "stop" the motion. In contrast to the Strobomeca, described under Figure 24, the Strobotac is most effective in dim light.

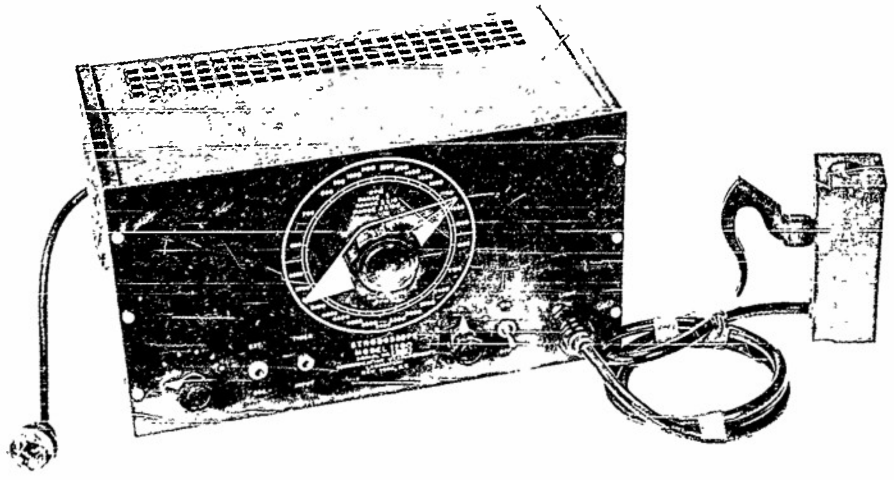


TMB 16590

Figure 26 - Strobolux

The Strobolux is, in effect, a modification of the Strobotac intended to give an increased output of light. A Strobotac or other pulse-generating device is connected to the Strobolux to control the frequency of the light flashes. The Strobolux is particularly applicable where the motion under study covers a large area or requires fairly intense light flashes for the study of fine details.

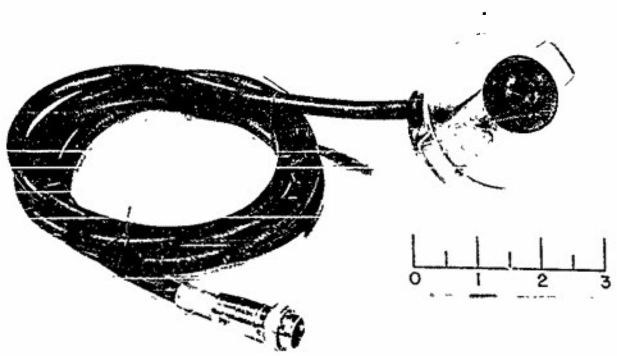
In the photograph the light has been removed from the case.



TMB 16591

Figure 27 - Communications Measurement Laboratories Stroboscope

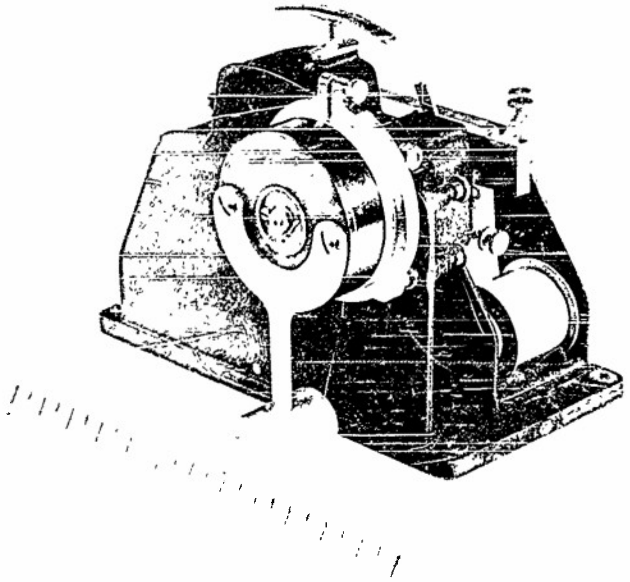
This stroboscope is of fairly recent design and employs the same principle of stroboscopic light as does the Strobotac described in Figure 25. However, it has a maximum frequency range which is much higher than that of the Strobotac. Another feature of this instrument is that the glow tube is encased in a small probe at the end of a flexible cable, making it possible to examine small inaccessible objects which are sometimes difficult to observe when the light is mounted in the cabinet. On the other hand, the weight of the total assembly, including cabinet, is greater than that of the Strobotac, so that for most applications it is not as convenient for use in field work.



TMB 15251

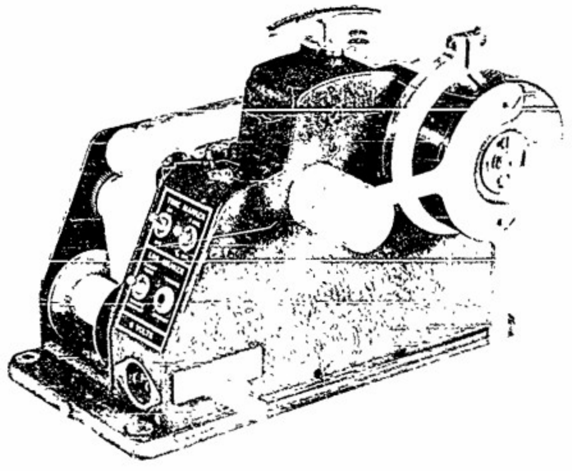
Figure 28 - Brush DP-1 Vibration Pickup

This vibration pickup is similar to the Brush VP-5 pickup described in Figure 8 in that it employs the piezoelectric crystal principle. When applied to a body having vibratory motion, the pickup converts the motion into an electrical potential of similar characteristics, permitting determination of mechanical vibration amplitude, frequency, and harmonic content. This, however, is a displacement-type pickup, delivering a voltage which is directly proportional to the amplitude of motion and independent of frequency within its linear range. To achieve this response, the crystal element is actuated directly by a drive pin which bears against the vibrating body. A fixed stop is provided to protect the element.



TMB 14556

Figure 29a - Cox Vibration Recorder with TMB Horizontal Adapter



TMB 14557

Figure 29b - Cox Vibration Recorder with TMB Vertical Adapter

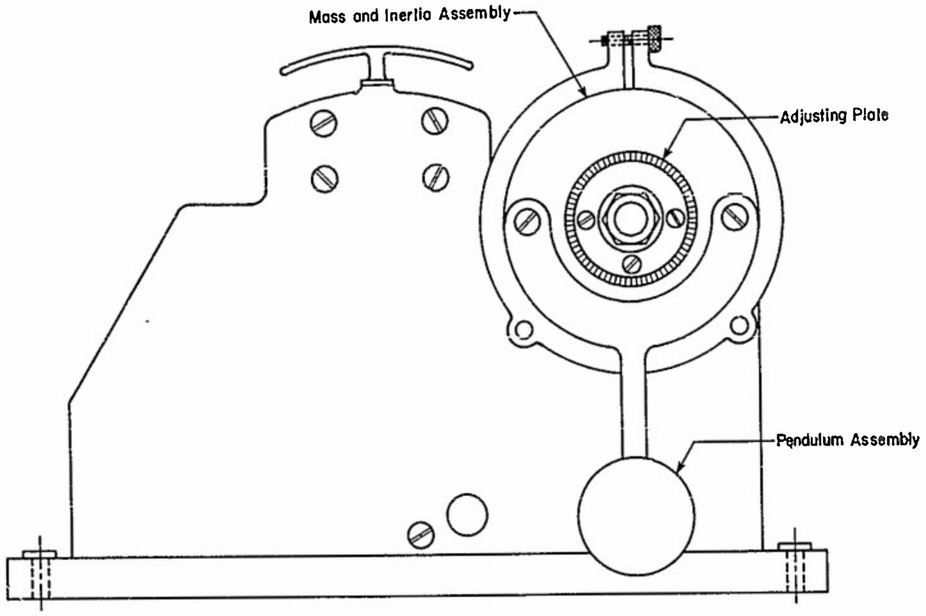


Figure 29c - View Showing Adapter for Horizontal Vibration

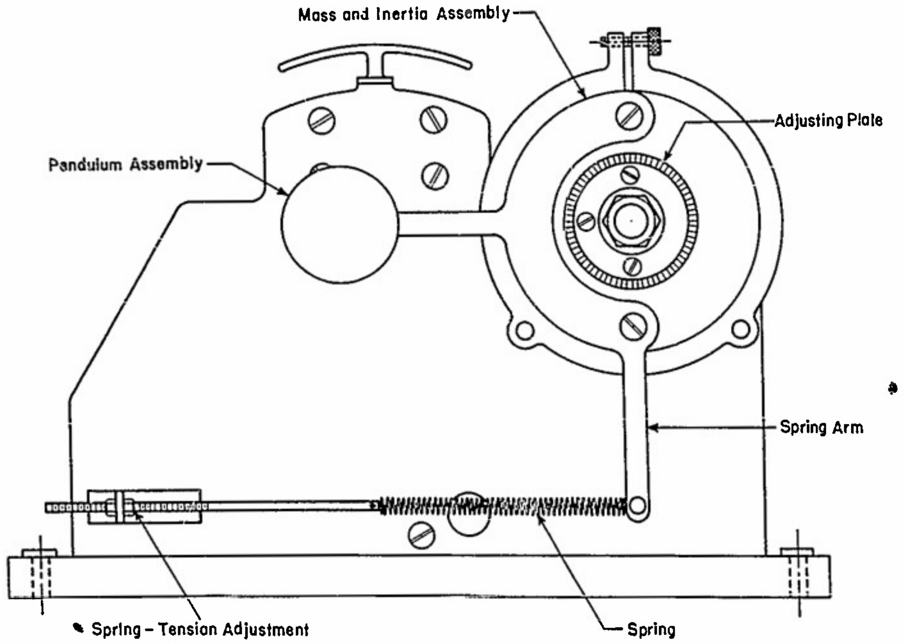


Figure 29d - View Showing Adapter for Vertical Vibration

Figure 29 - Cox Vibration Recorder

This instrument is primarily a mechanical torsiograph which has been adapted to record vertical and horizontal linear vibrations. It records with a stylus on waxed paper and has six paper speeds. Two timing styluses are provided, one for 1-second or 1/5-second timing, and another for an external timing such as a shaft contactor. To record horizontal vibrations, the revolving pulley is locked in place by a clamping ring and a seismic pendulum is attached to the torsional seismic element as shown in Figure 29a. In adapting the instrument for recording vertical vibrations a similar attachment is made except that the pendulum is held in a horizontal position by a flexible spring which is attached to the side of the case as shown in Figure 29b. A commercial linear adapter is now available for use with this instrument.

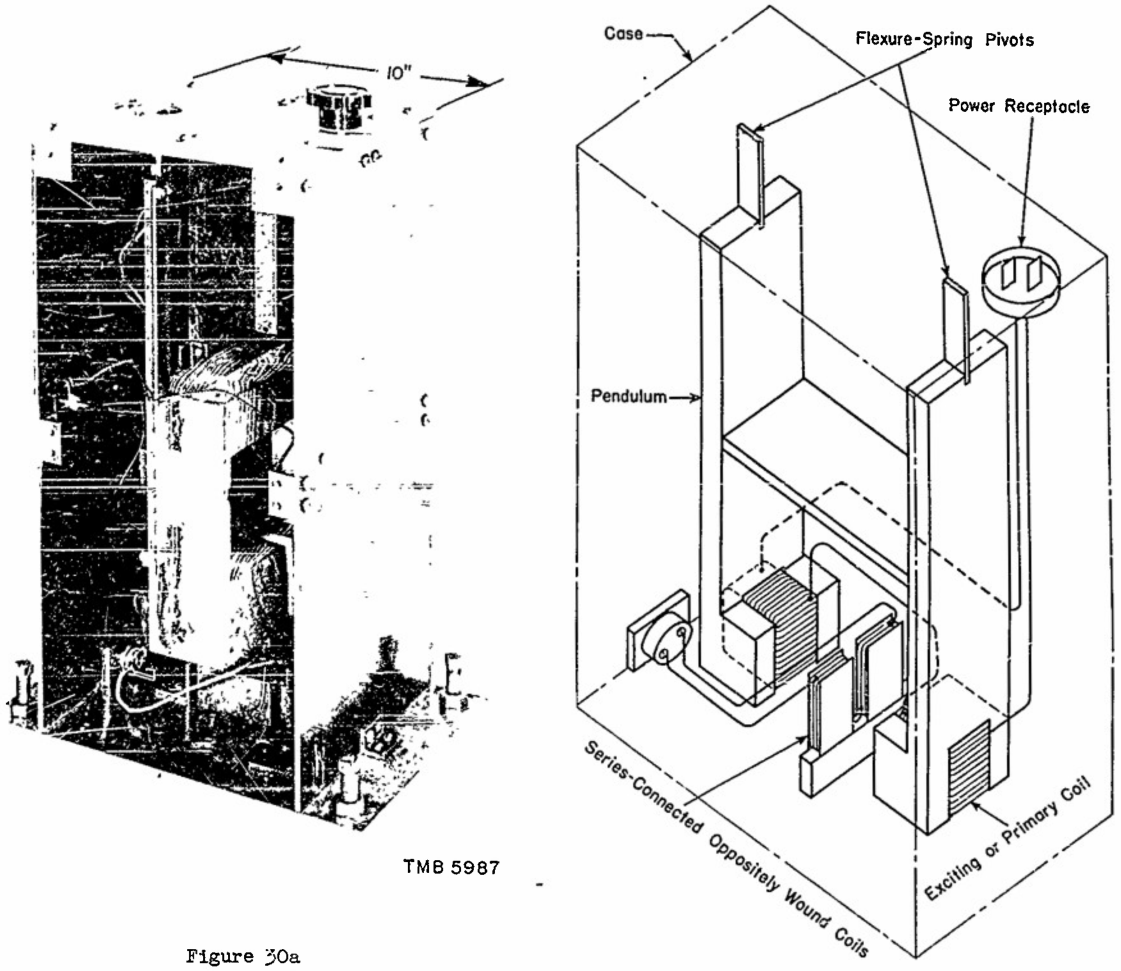


Figure 30a

Figure 30b

Figure 30 - TMB Electrical Vibration Pickup (Pendulum-Type)

This instrument was one of the earlier electric vibration pickups used at the Taylor Model Basin. Although used successfully on several tests, the experimental model was never improved in mechanical design. It consists of an exciting or primary coil carrying alternating current, causing an alternating flux to pass through an air gap. A pair of series-connected, oppositely wound coils are attached to the case; the primary coil fastened to the end of a pendulum comprises the seismic element. When an equal area of both fixed coils is in the flux field, the resultant voltage is zero. Any displacement from zero position produces a resultant voltage proportional to this displacement. Thus the signal coming from the fixed coils is characterized by amplitude modulation, the modulating frequency being the same as the frequency of the vibration. The upper frequency limit of the instrument is determined by the carrier frequency. A control providing for a static calibration of the instrument consists of a micrometer-screw adjustment which shifts the oppositely wound coils from zero position a known amount.

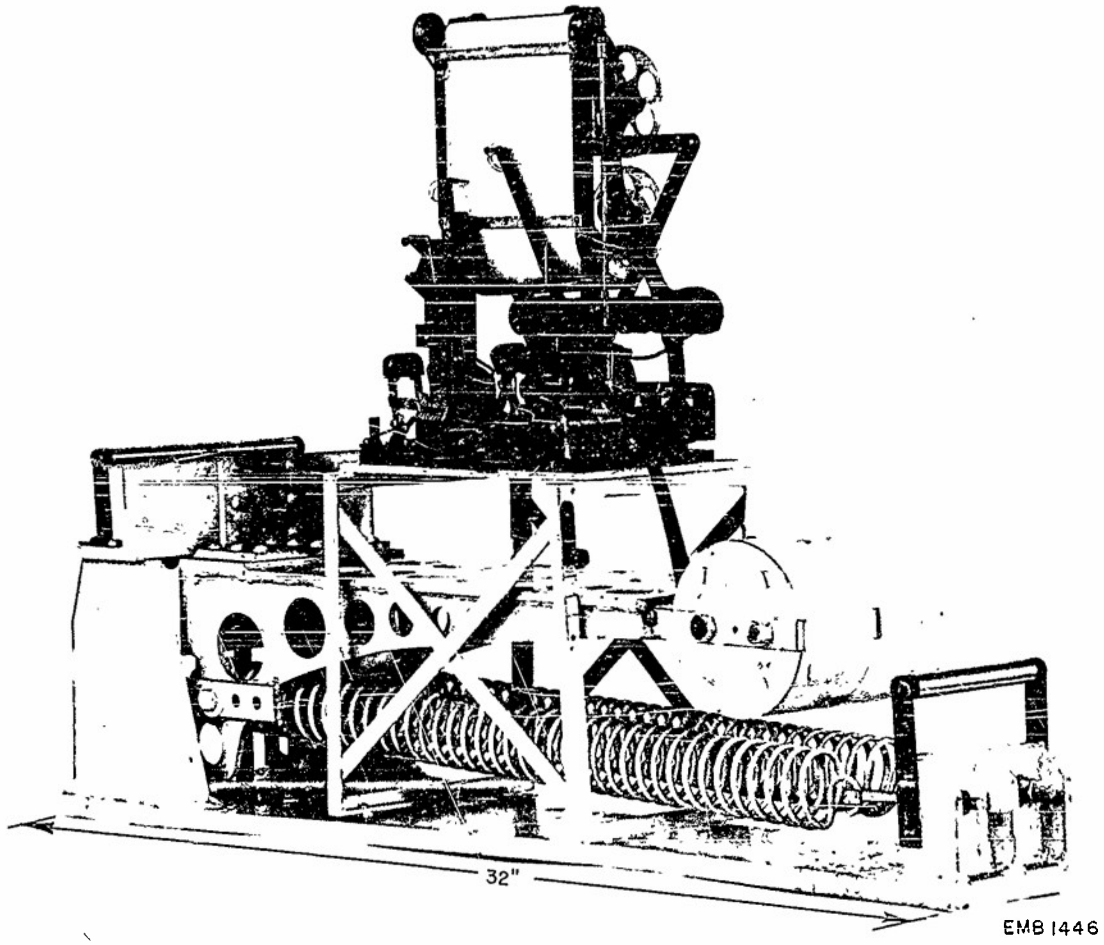


Figure 31 - TMB Type A Pallograph

The initial development of the pallograph at the Experimental Model Basin in 1933 originated from the need for a portable instrument which would permit accurate recording of the large amplitudes and very low frequencies of vibration encountered during shipboard vibration tests with vibration generators. The fundamental principle of the pallographs is similar to that of the typical vibration instrument shown in the schematic diagram, Figure 1.

The Type A pallograph is designed for recording vertical vibrations and consists of a seismic mass suspended pendulum-fashion by an arm which is supported by flexure springs attached to the frame. The required low frequency is obtained by employing the instability principle for suspending the seismic mass. The basic idea of the instability principle is that the restoring spring is attached in such a way that its lever arm decreases as the spring is extended and vice versa. In this manner the product of the change of lever arm and the change in restoring force, which determines the restoring torque, for a change in angular position can be made to approach zero resulting in a period of vibration which approaches infinity. The magnification is obtained through a simple mechanical linkage, and the motion is recorded on waxed paper. The Type A pallograph may also be adapted for measuring horizontal vibrations by mounting the instrument in a vertical plane and removing the springs to allow the long arm with the siesmic weight attached to hang as a pendulum. The natural frequency of this system is higher than that for vertical measurement.

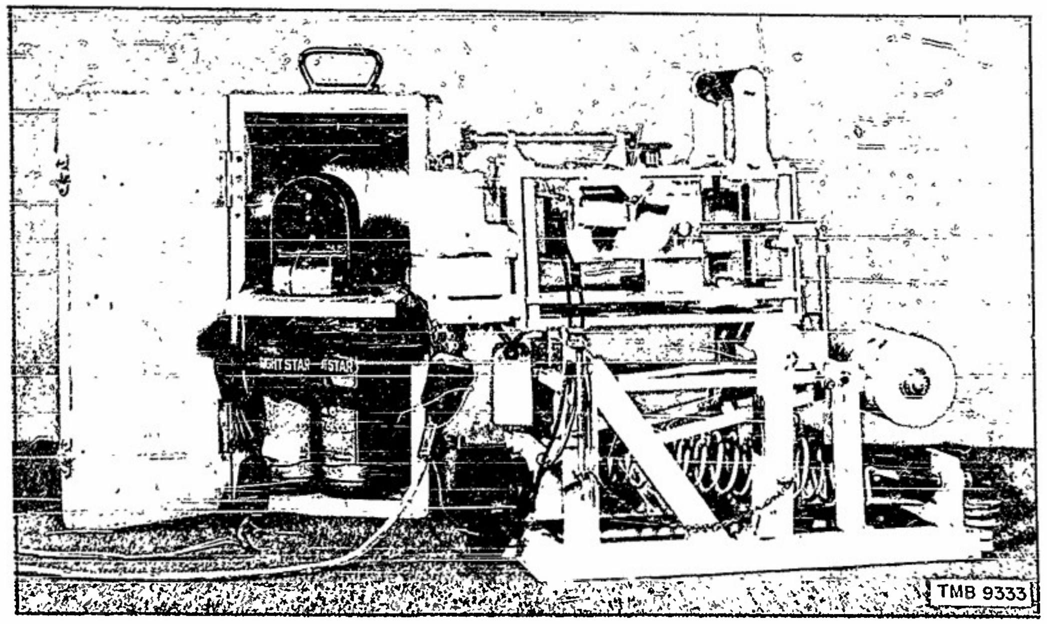


Figure 32a

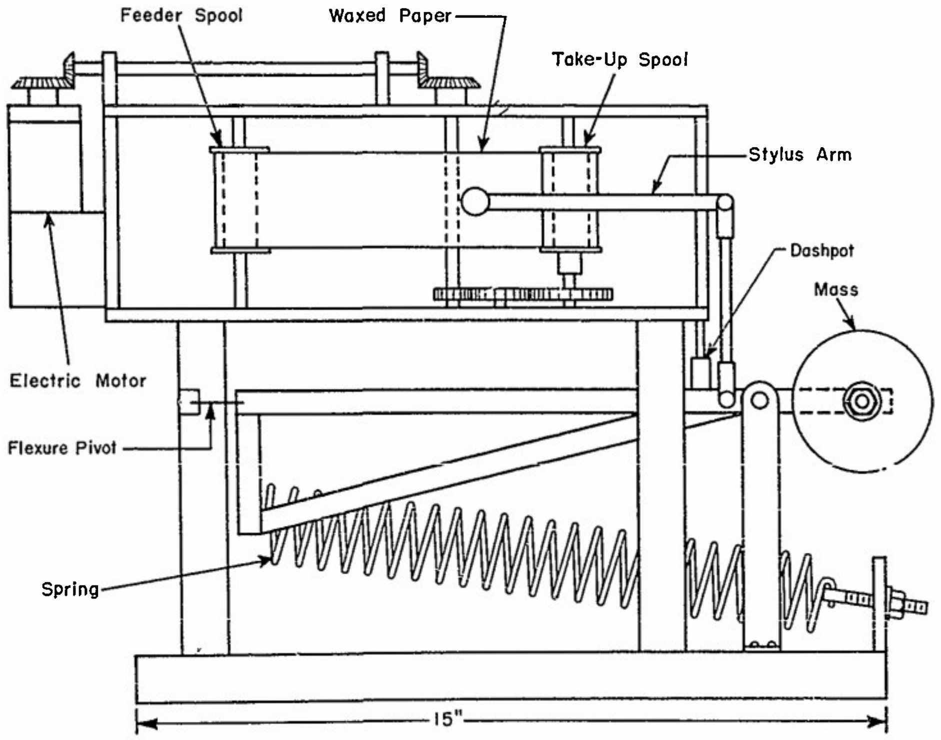


Figure 32b

Figure 32 - TMB Type B Pallograph

The Type B pallograph is a smaller and lighter version of the Type A. It has a slightly lower natural frequency, is suitable for higher frequencies, and weighs one-third as much as Type A. It also has a dashpot with adjustable air damping which is particularly useful in shipboard work when the ship is pitching or rolling. The maximum amplitude obtainable, however, is one-half that of Type A. Type B may also be adapted for recording horizontal vibrations in the same manner as described in Figure 31, its natural frequency being considerably increased.

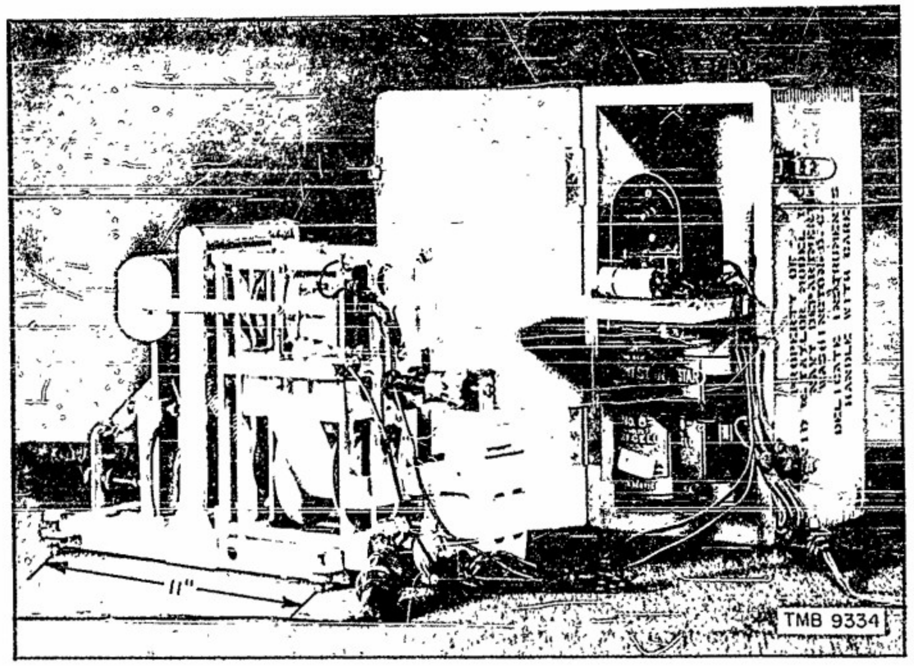


Figure 33a

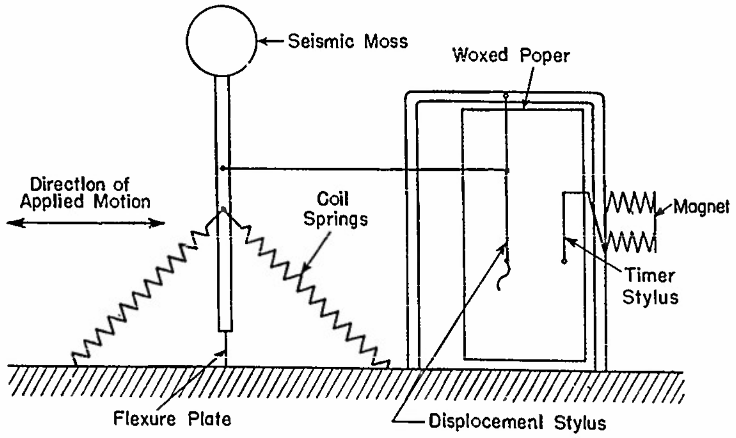


Figure 33b

Figure 33 - TMB Type C Pallograph

The Type C pallograph was developed specifically to record vibration of ship superstructures. It is a horizontal vibrograph and weighs only 25 pounds. It has the same type of magnification, recording, and timing as the Type B, but its natural frequency is slightly higher. The seismic mass is supported as an inverted pendulum with two springs, one on each side, used to restore it to its vertical position.

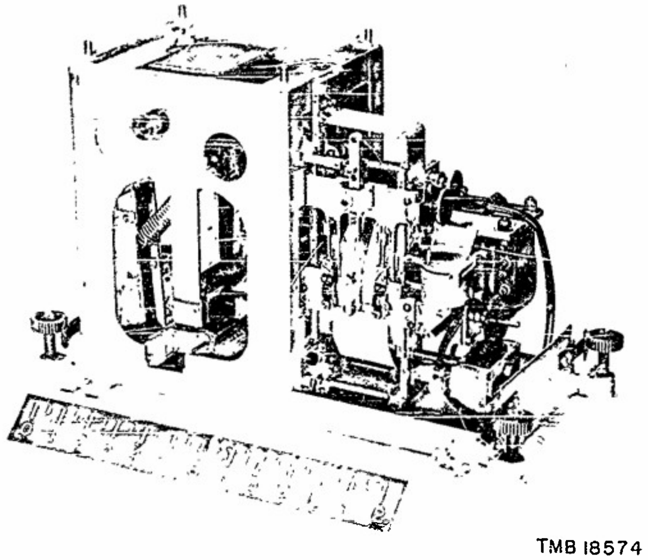


Figure 34a - Covers Removed

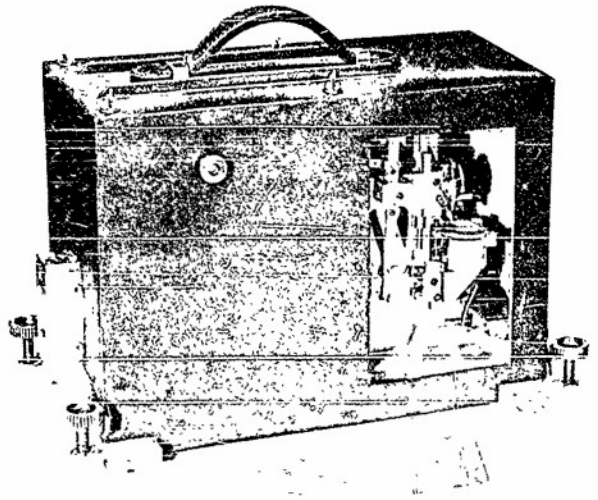


Figure 34b - Covers in Place

Figure 34 - TMB Type H Pallograph

The Type H pallograph for horizontal recording incorporates the improved features of the Type V pallograph (see Figure 35) while essentially corresponding to the old Type C pallograph

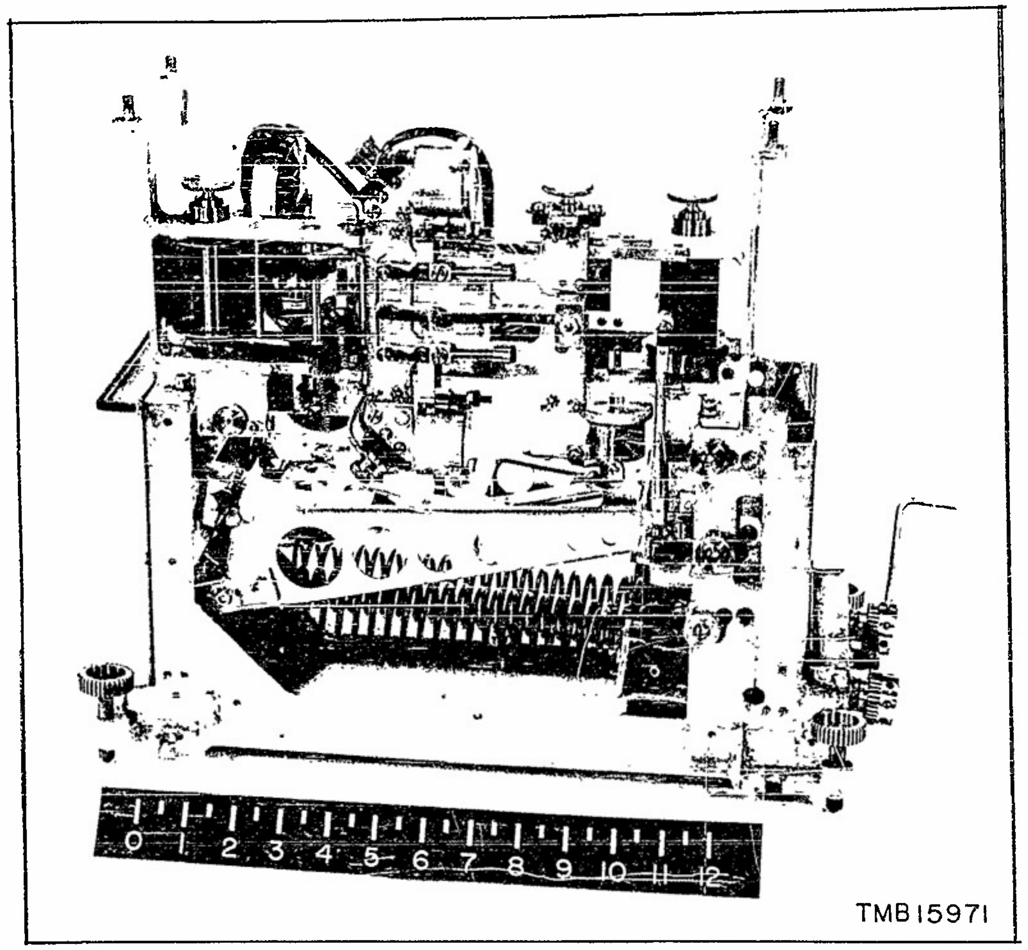


Figure 35 - TMB Type V Pallograph with Covers Removed

This is a new type of vertical pallograph recently completed. Essentially it corresponds to the Type B pallograph, but it incorporates many new features which aid in vibration measurement. Adjustable linkage ratios of 6:1, 4:1, and 2:1 are available so that magnifications may be varied to suit the amplitude being measured. The instrument is provided with two timers, one for indicating shaft revolutions (for ship measurements) or some other indication of relative time, and the other for indicating time in seconds. Two paper speeds are provided of approximately 2 inches per second and 1 inch per second, and an adjustment is provided for using either a constant paper speed or a variable speed. Improvement in the design of the mechanical linkages has been made by replacing pin joints with flexure pivots where possible.

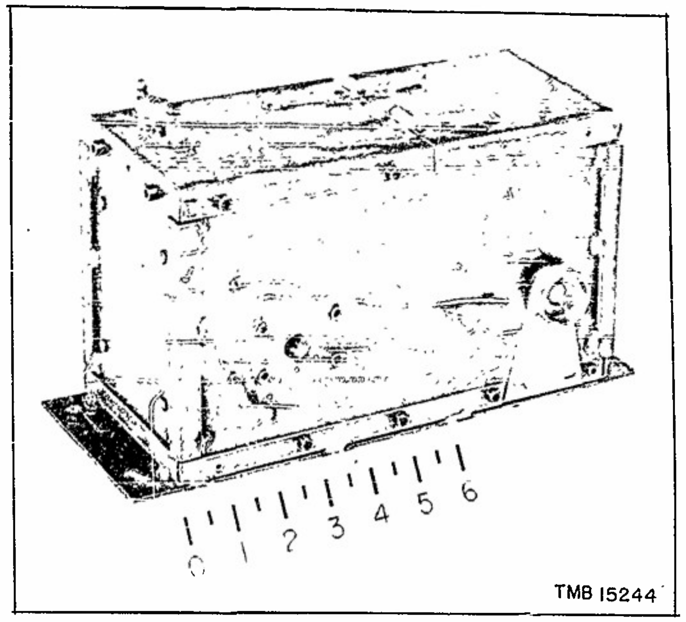


Figure 36a

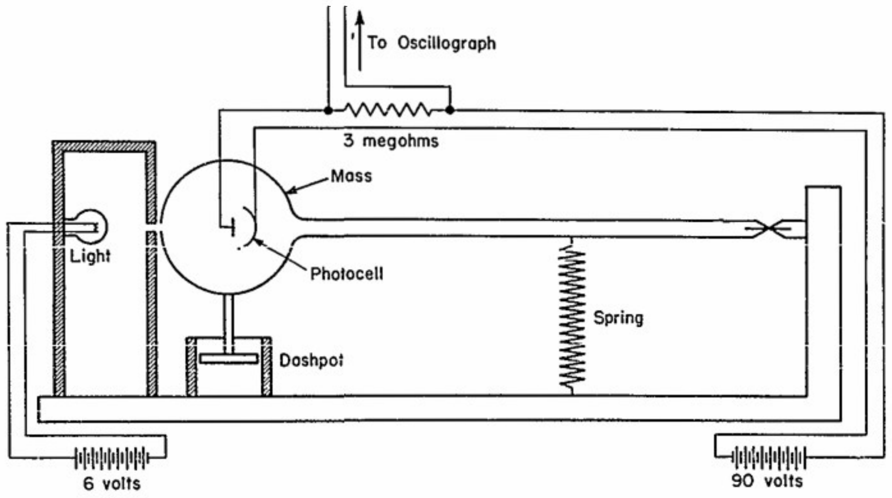
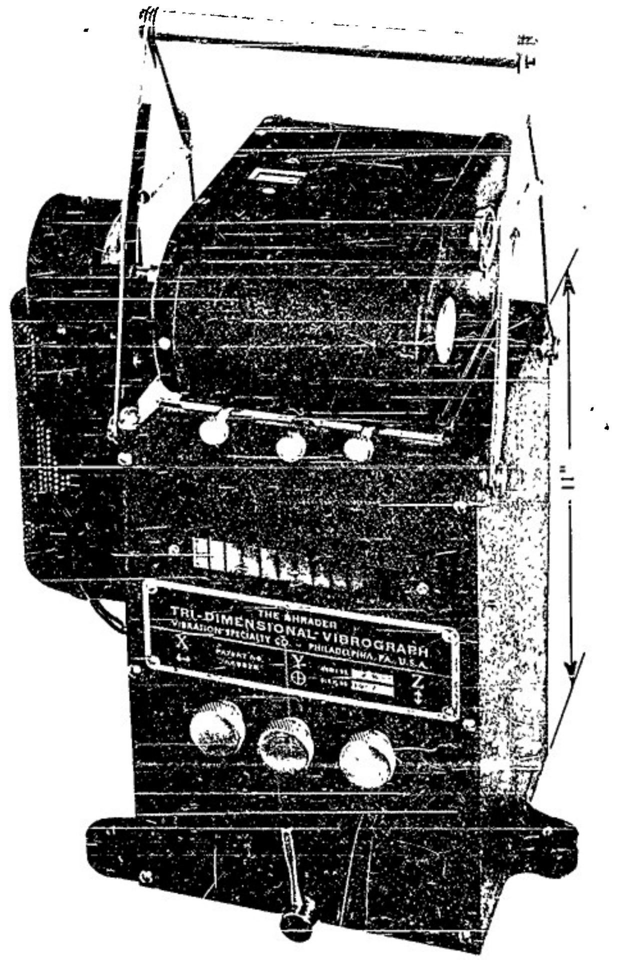


Figure 36b

Figure 36 - Photoelectric Vibration Pickup

This pickup is currently in development at the Taylor Model Basin. It is essentially a seismic-pendulum instrument similar to the pallographs. It has, however, a higher natural frequency and a lower amplitude range, and is smaller and lighter than the pallographs. The relative motion between a slot in the seismic element and a slot in the case produces variations in the intensity of a light source which are detected by a photoelectric cell. The use of electronic equipment is required for recording the signal obtained.



TMB 9878

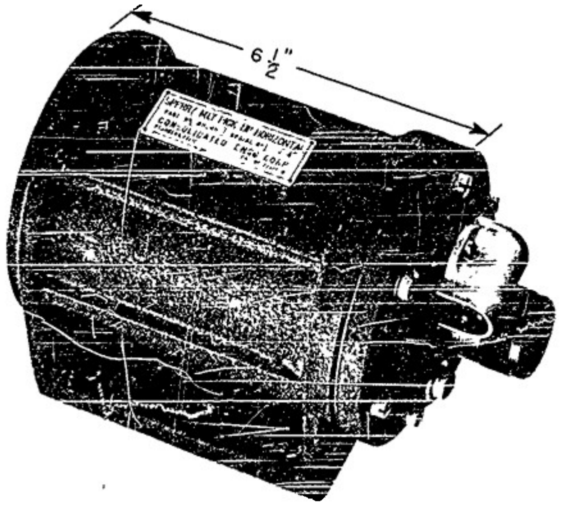
Figure 37 - Shrader Tri-Dimensional Vibrograph

The Shrader vibrograph has a spring-mounted seismic mass with three degrees of freedom in translation. The motion of the instrument case relative to the seismic mass rotates a spindle to which a small mirror is attached for each direction of motion. Each mirror reflects a light trace which is recorded on moving film.

Visual readings may be made by measuring the width of the light trace on the ground-glass view plate at the front of the instrument. In making visual measurements, the camera magazine may be replaced by a rotating mirror and the wave form studied.

As originally received, the instrument had a magnification factor of about 300 times but it was subsequently modified to reduce the magnification to 50 times, thereby increasing the range by a factor of 6.

A schematic arrangement of this instrument is shown in Figure 6b.



TMB 9877

Figure 38a

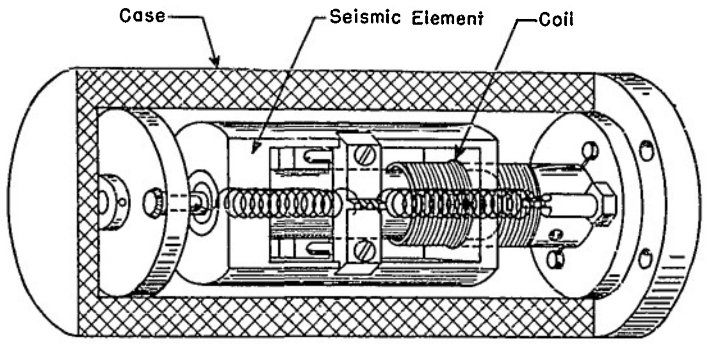


Figure 38b

Figure 38 - Sperry-MIT-Consolidated Large Linear-Vibration Pickup

The seismic element of this pickup is a guided magnet suspended on coil springs. The output voltage is generated by the relative motion between this magnet, which produces a radial magnetic field, and a coil fixed to the base. The signal is therefore proportional to the applied velocity. Over the useful range of the instrument the output voltage is proportional to the product of the amplitude and frequency of the motion applied to the case. The pickup has externally adjustable oil damping. It is available in two types, one for vertical measurement and one for horizontal measurement. An integrating amplifier is used for measuring displacements.

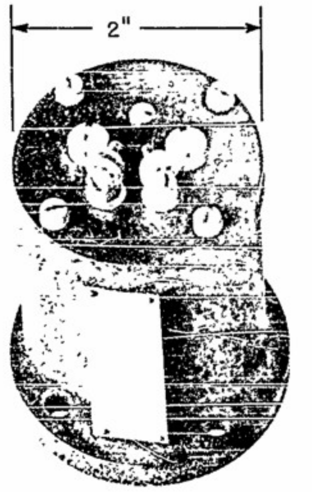


Figure 39 - Sperry-MIT-Consolidated Small Linear-Vibration Pickup

This instrument is identical in principle with the large Sperry pickup described in Figure 38. It is, however, considerably smaller and lighter than the large pickup, and may therefore be used in applications for which the large pickup is either too bulky or too heavy. Owing to its small size, it has a higher natural frequency and smaller travel than the large unit, and consequently is not suitable for as low frequencies and as large amplitudes. The oil damping of this pickup is not adjustable.

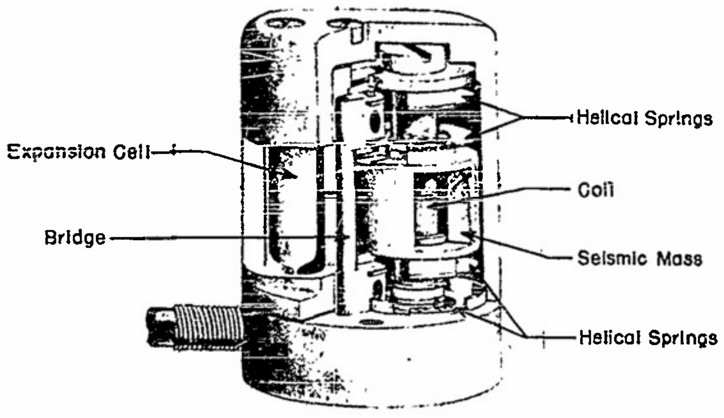


Figure 40a

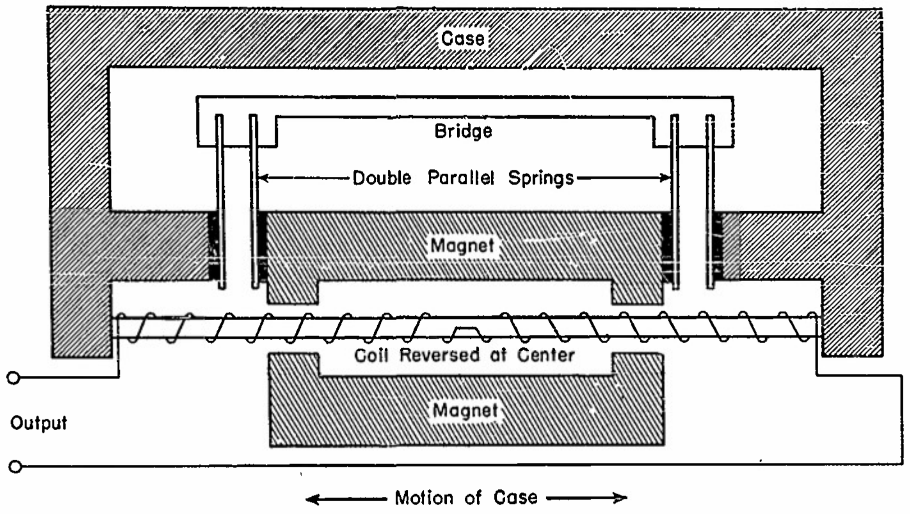
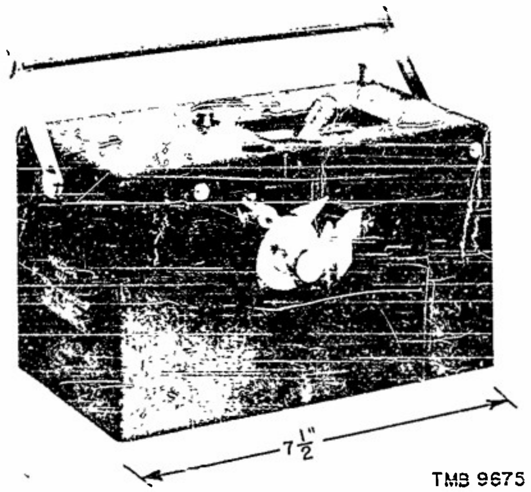


Figure 40b

Figure 40 - Consolidated Type 4-102 Velocity Pickup

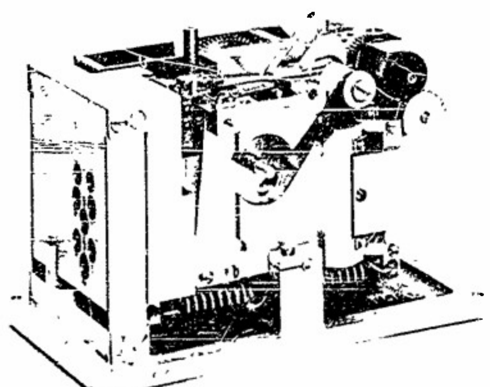
This pickup is similar in principle to the Consolidated pickup shown in Figure 38. However, the Type 4-102 pickup has the inertia mass supported on double, flat, helical springs which respond to acceleration in one direction only, thus eliminating bearing surfaces and accompanying friction.

High sensitivity and output are obtained by the use of a double-ended coil in a push-pull circuit (the two parts being in fields of opposite polarity). This coil is oppositely wound from the center out and is mounted securely to the case and surrounded by the seismic magnet. Voltage output is proportional to the velocity of the case.



TMB 9675

Figure 41a - Covers in Place



TMB 9673

Figure 41b - Covers Removed

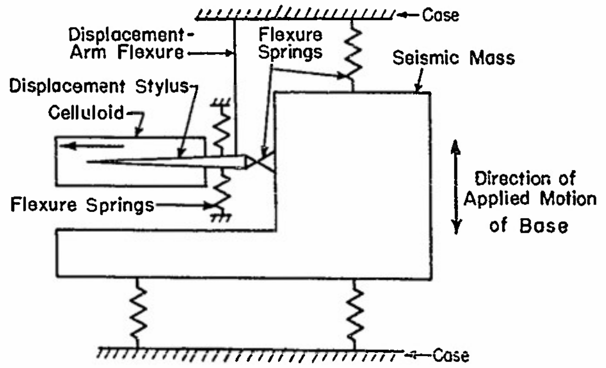


Figure 41c - Schematic Diagram

Figure 41 - Type LE Westinghouse Vibrograph

The Type LE Westinghouse vibrograph is a small mechanical seismograph consisting of a spring-mounted seismic mass and a system of mechanical levers for recording and magnification. A schematic arrangement of the instrument is shown in Figure 41c. The recording stylus scribes on a moving celluloid strip, which is driven by a spring-wound motor. A record of time is obtained from an intermittently excited, tuned, timing stylus which also scribes on the moving celluloid. The instrument may either be mounted on the vibrating structure or held in the hand and used with a probe for exploration of the structure. A simple adjustment converts the instrument from one condition to the other.

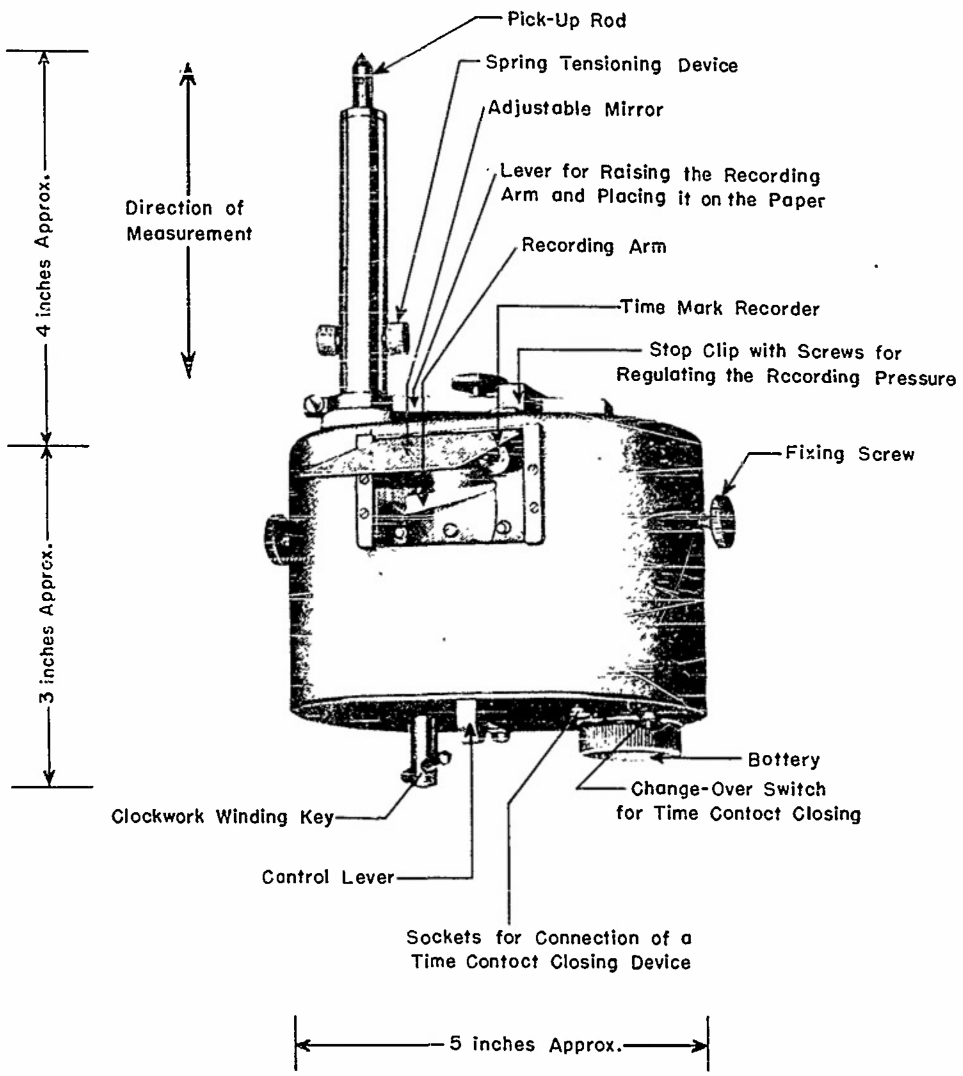
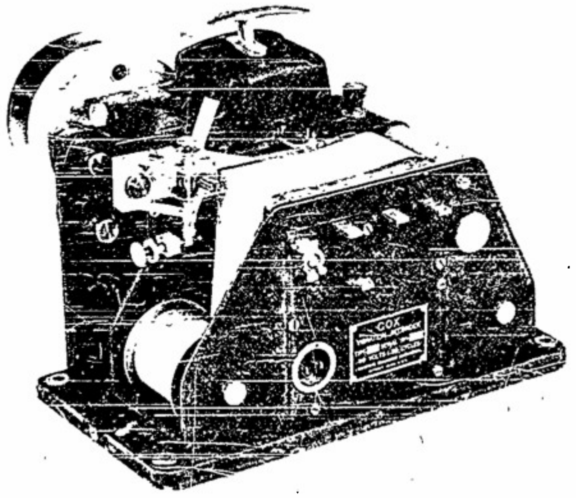


Figure 42 - Askania Vibrograph

The Askania hand vibrograph measures vibration in the direction of the pickup rod. It consists of a case containing a spring-wound chart-feeding mechanism and a pickup rod guided in bearings and supported relative to the case by a helical spring. The tension in the spring is adjustable; when set for maximum tension, the pickup rod will theoretically follow vibrations with accelerations up to 20 g. The motion of the pickup rod is magnified six times by a mechanical lever which scribes on waxed paper. By means of an additional lever arrangement (attenuator) which can be attached to the case, the total recording magnification can be reduced from six to two times or to one time.

The time-mark recorder is normally actuated by a seconds contact controlled by the clockwork drive. Provision is also made for operating the timer from external contacts.

The entire instrument hand-held comprises the inertia mass. An additional weight is sometimes attached to the case of this instrument to increase the inertia mass which effectively lowers its natural frequency.



TMB14558

Figure 43a

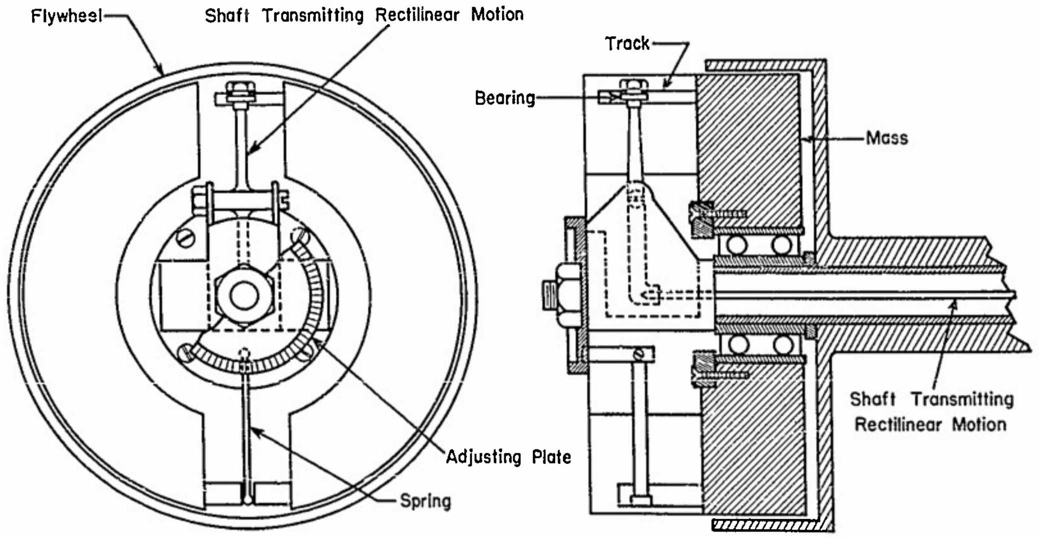
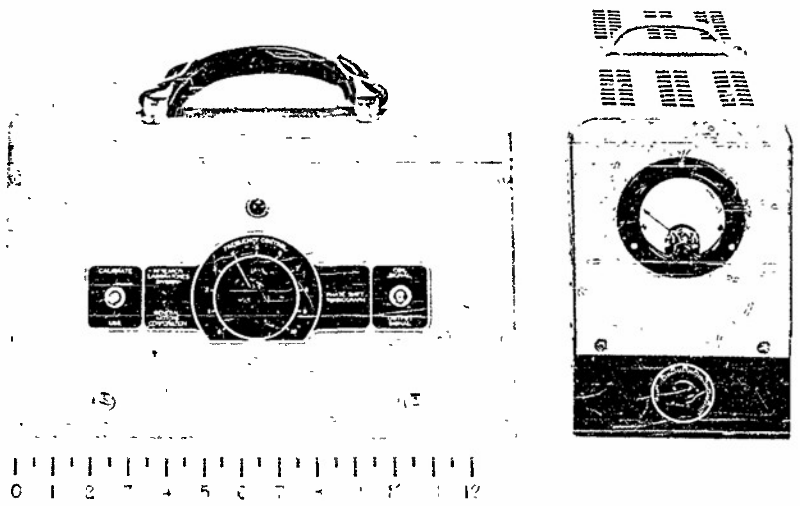


Figure 43b - Torsional Pickup Unit

Figure 43 - Cox Torsiograph

The Cox torsiograph is a mechanical instrument for recording the amplitudes and frequencies of torsional vibration. It may also be adapted to record linear vibrations as shown and described in Figure 29. The basic member of the instrument is a light aluminum pulley 100 millimeters in diameter, which is driven from the test shaft by a short, stiff belt. Within the pulley is a flywheel or inertia mass elastically connected to the pulley; this mass tends to revolve uniformly owing to its inertia. The fluctuations of rotation cause relative motions between the pulley and the flywheel, which are transmitted by a rocker arm and connecting rod through a hollow spindle to the recording stylus. The stylus records on waxed paper which may be driven at six different speeds by a synchronous motor or may be driven directly by the pulley. Magnifications of 3:1, 6:1, 12:1, or 24:1 may be obtained by proper adjustment of the stylus and support arm.



TMB 14559

Figure 44a - Detector Unit and Power Supply

Figure 44 - Phase-Shift Torsiograph

The phase-shift torsiograph was originally developed by General Motors Research Laboratories for measuring torsional vibrations on a shaft inside a crankcase. The basic members of the instrument are a steel gear attached to the shaft, two iron-core coils, and the detector unit with power supply. The gear may be mounted almost anywhere on the shaft, and the two coils are mounted, generally, on a bracket attached to the crankcase in such a way that they are 180 degrees apart and close to the gear teeth. Several pickups have been prepared at the Taylor Model Basin in which the gear is fixed to a shaft which is in turn fastened to the end of the crank shaft; the coils are attached to a disk which rides on a bearing on the pickup shaft. This disk is snubbed, providing a fixed reference point for the coils.

Motion of the gear teeth past the coils produces a periodic voltage signal whose phase angle, relative to a signal having a frequency equal to the mean tooth frequency, varies in step with the torsional vibration. The detector unit combines these signals for observation on a cathode-ray oscillograph. The number of gear teeth used depends on the expected torsional amplitude and the rotation speed of the shaft.

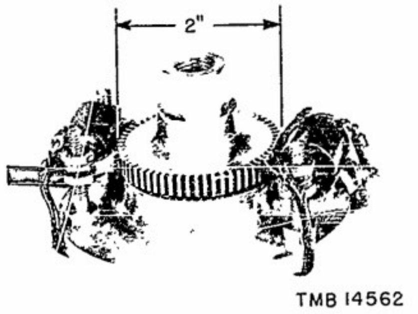


Figure 44b - Two-Inch Pickup Gear

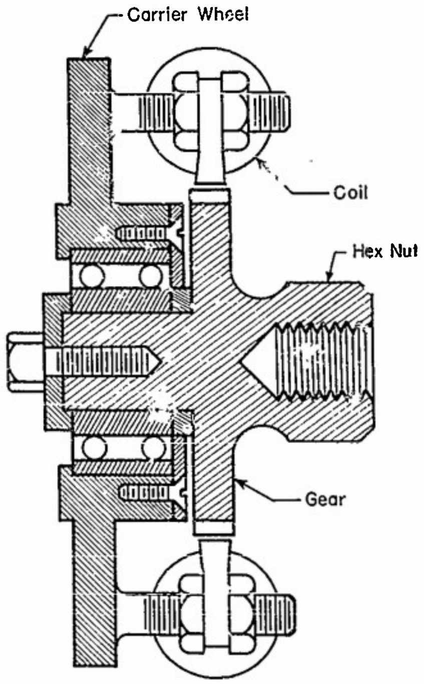


Figure 44c - Cross-Sectional View of Pickup Gear

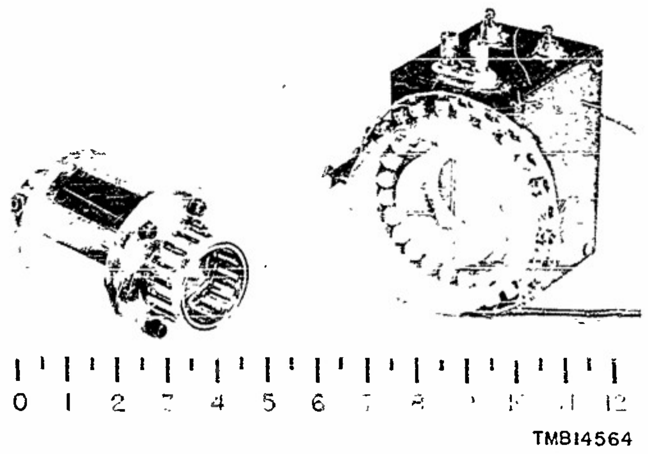


Figure 45a - Experimental Model

Figure 45 - Photoelectric Torsional Vibration Pickup

The photoelectric torsional vibration pickup contains an inertia flywheel driven through an elastic connection by a rotating shaft. Any relative motion between a series of slots attached to the seismic mass and a series of corresponding slots attached to the rotating shaft varies the amount of light which passes through the slots. This light is then reflected to a photoelectric cell. These variations are proportional to the amplitude of torsional vibration. In this model the light ring and photocell are in a unit separate from the pickup; however, an improved pickup has been built in which the light ring and photocell ride on the pickup shaft. A cross-sectional view of the latter model is shown in Figure 45b.

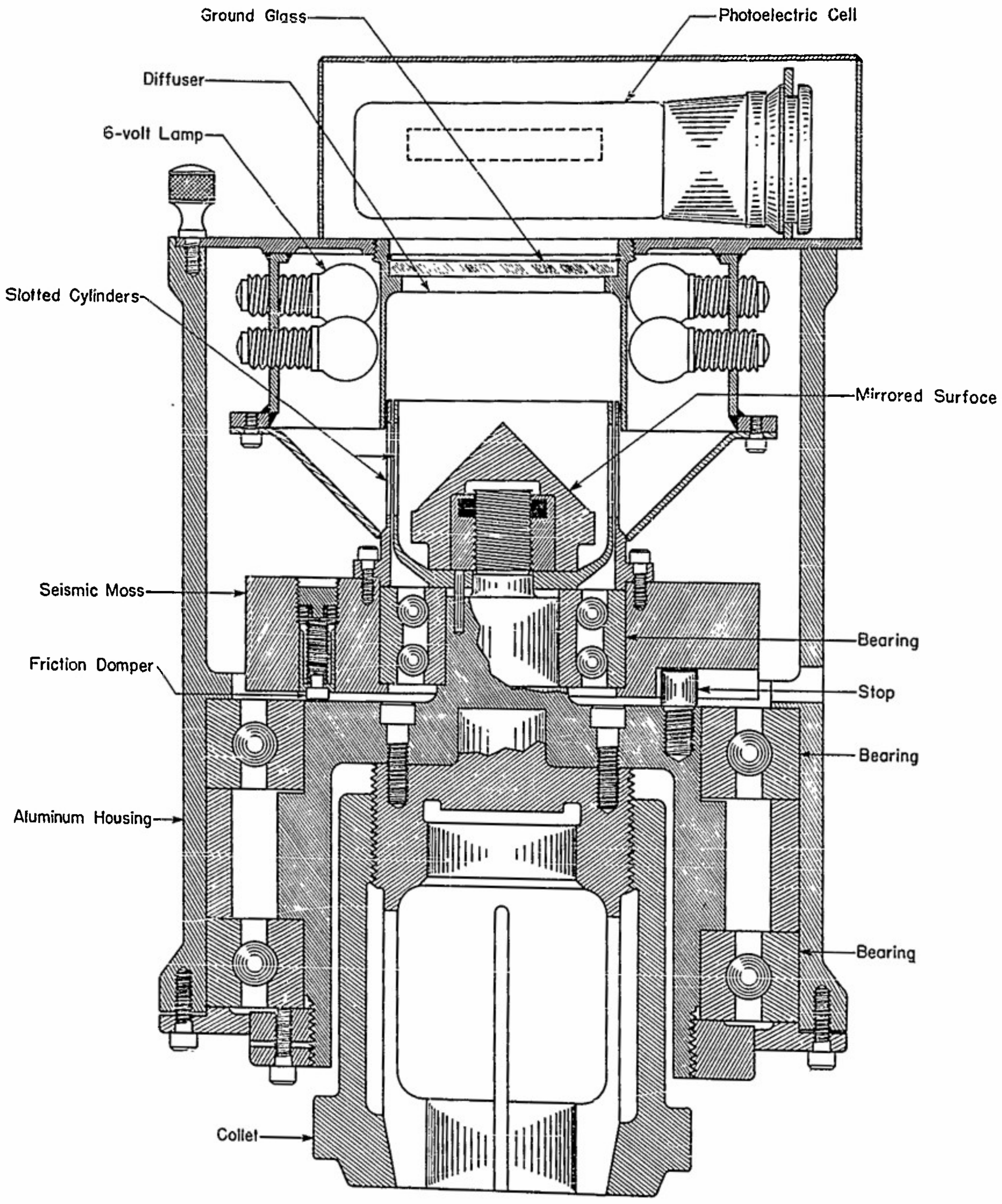


Figure 45b - Cross-Sectional View of Improved Torsiograph

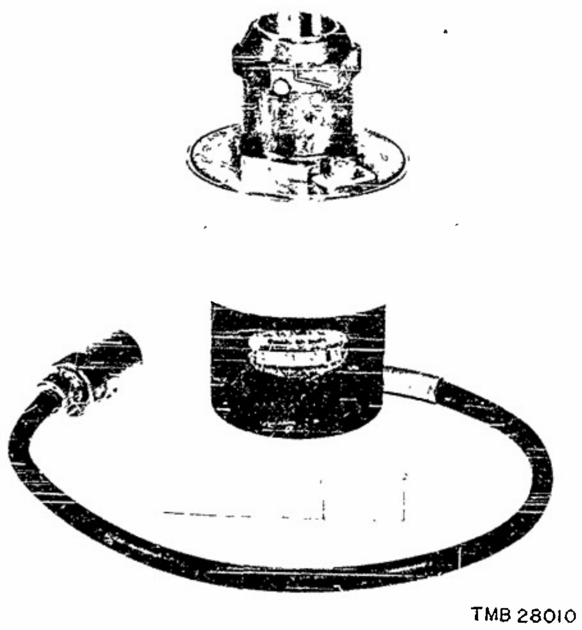


Figure 46a - Photograph of Torsional Pickup

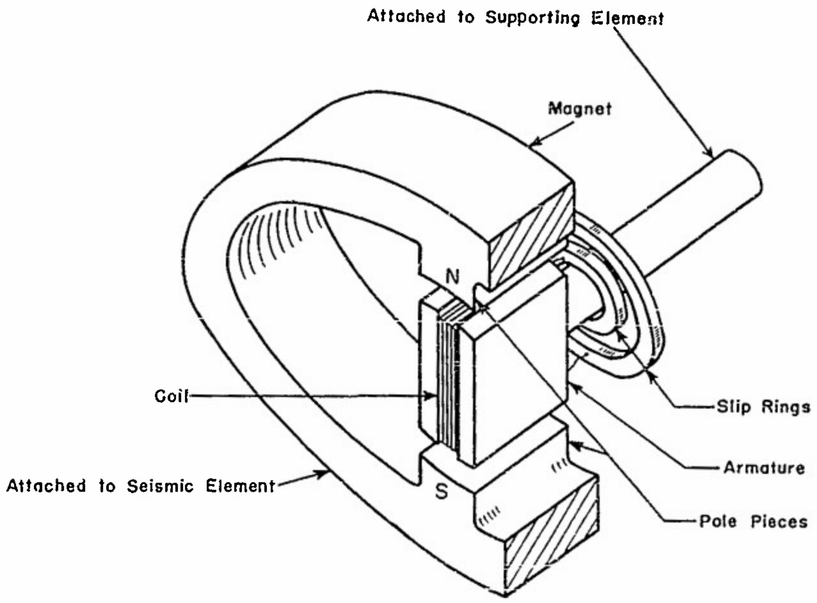


Figure 46b - Schematic Arrangement of Magnet and Coil

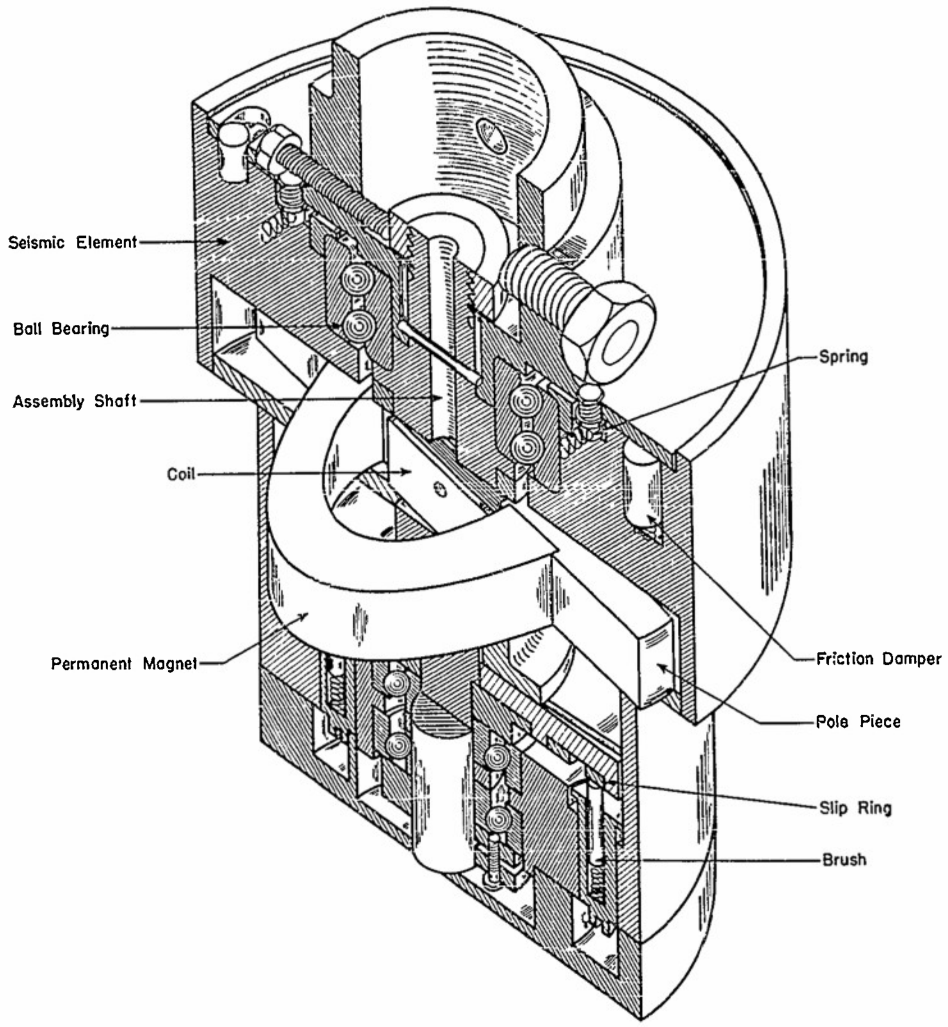


Figure 46c - Cross-Sectional Isometric View of Torsional Pickup

Figure 46 - Consolidated Torsional Vibration Pickup with Collet Adapter

The Consolidated torsional vibration pickup contains an inertia flywheel driven through an elastic connection by the rotating shaft of the pickup. An output voltage is generated by the relative motion between a coil fixed to the shaft and a magnetic field moving with the inertia flywheel, and is therefore proportional to the angular velocity of torsional vibration. Over the useful range of the instrument this output voltage is proportional to the velocity or to the product of the amplitude and frequency of the motion applied to the pickup shaft. The output signal is generally fed through an integrating amplifier, as with the Sperry linear pickups, for recording amplitude.

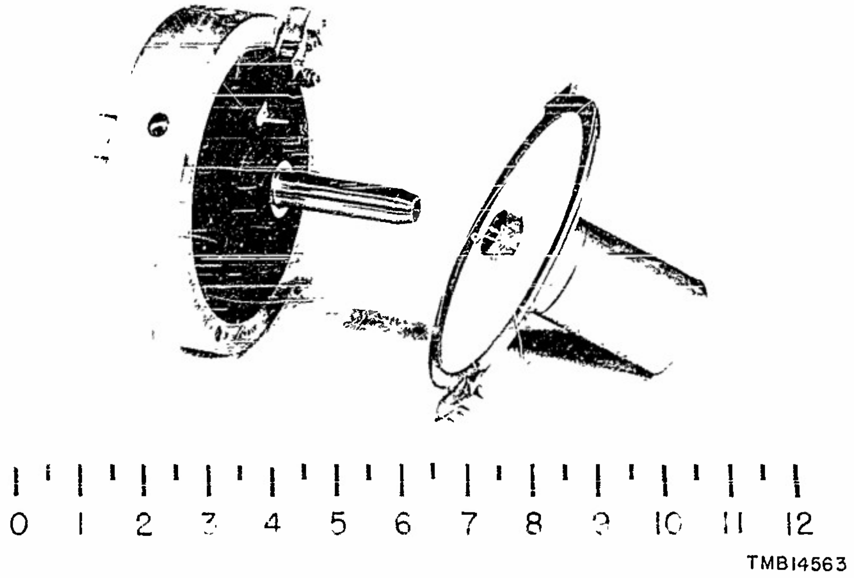


Figure 47a

Figure 47 - General Motors Mechanical Torsiograph

The General Motors mechanical torsiograph is a displacement type of vibration pickup consisting of an inertia flywheel driven through an elastic connection with the shaft under test. An indicating finger is connected to the seismic mass and to the shaft through a mechanical-linkage system. Any angular displacement between the seismic mass and rotating shaft actuates the stylus finger which records the motion on chemically sensitized paper attached to a hand held member which is momentarily held against the stylus. The indicator should always revolve in a direction that causes the stylus finger to drag (not push) around the surface of the sensitized paper disk. An extra arm is provided for scribing torsiograms of shafts rotating counterclockwise. In operation the sensitized paper disk, mounted on a supporting metal disk, is brought in contact with the indicating finger for about one shaft revolution. Thus a polar diagram of the torsional vibration is obtained. A transparent scale is provided for measuring the amplitude of the record.

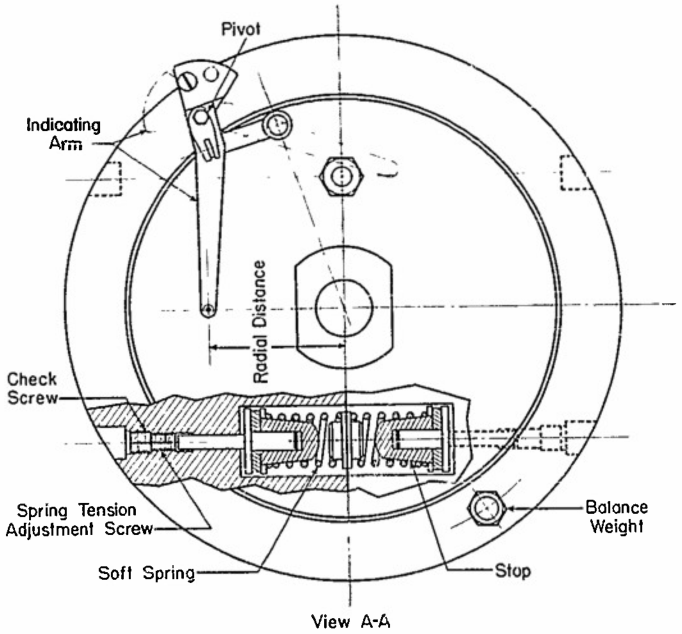


Figure 47b

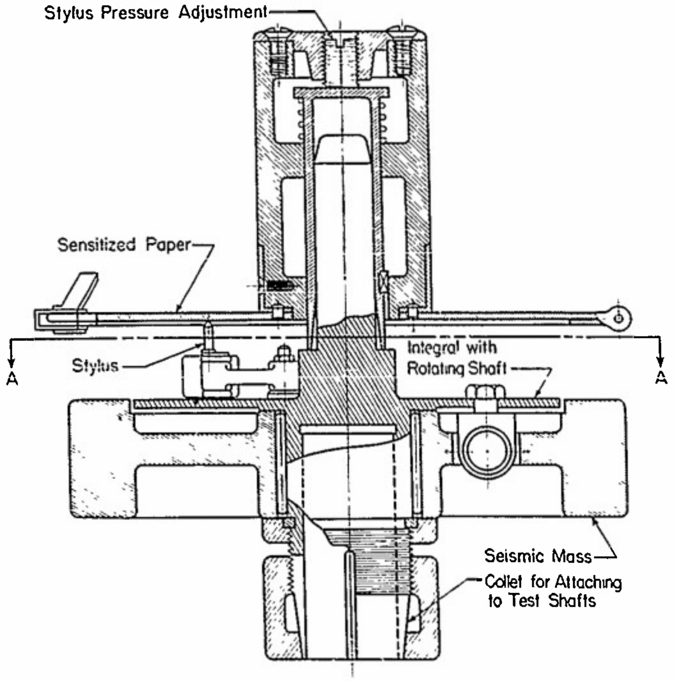
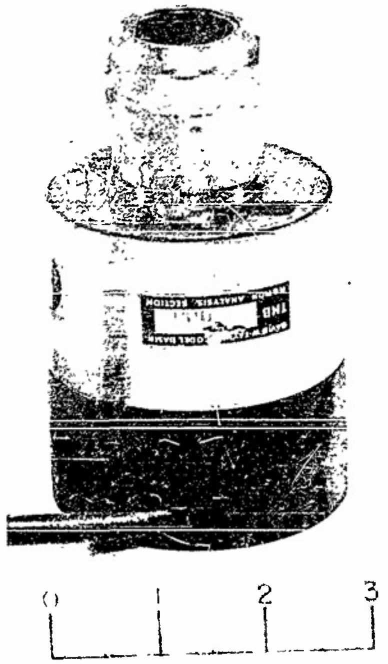


Figure 47c

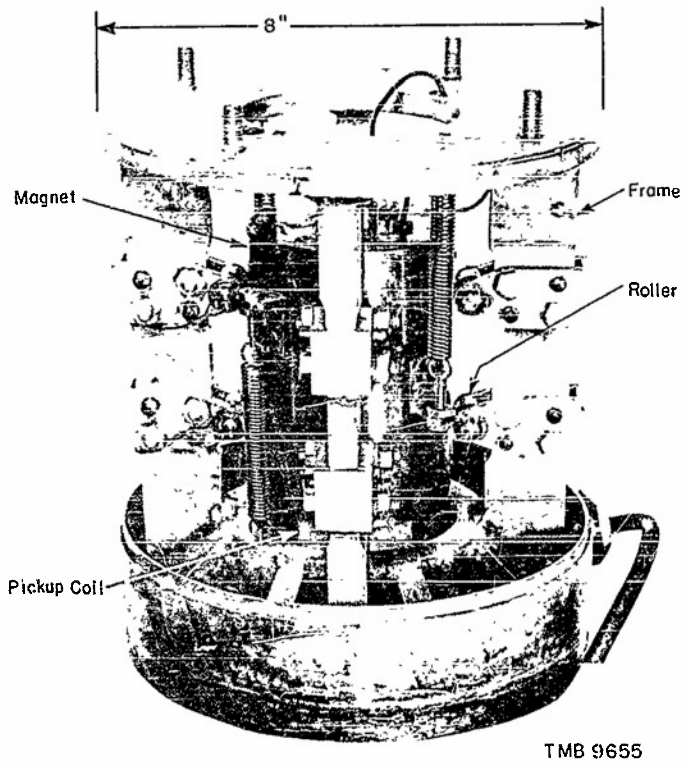


TMB 28007

Figure 48 - TMB-Sperry Torsional Vibration Pickup

This pickup was designed and built at the Taylor Model Basin and is identical in principle to the Consolidated pickup shown in Figure 46. However, in designing the TMB pickup, considerable attention was given to its mechanical strength. In several endurance tests made by the Taylor Model Basin on diesel-engine crankshafts, delay was caused by the repeated failure of certain parts of the Consolidated pickups. Parts that had failed in engine-endurance tests were redesigned with a view toward increasing the durability of the pickup for such tests.

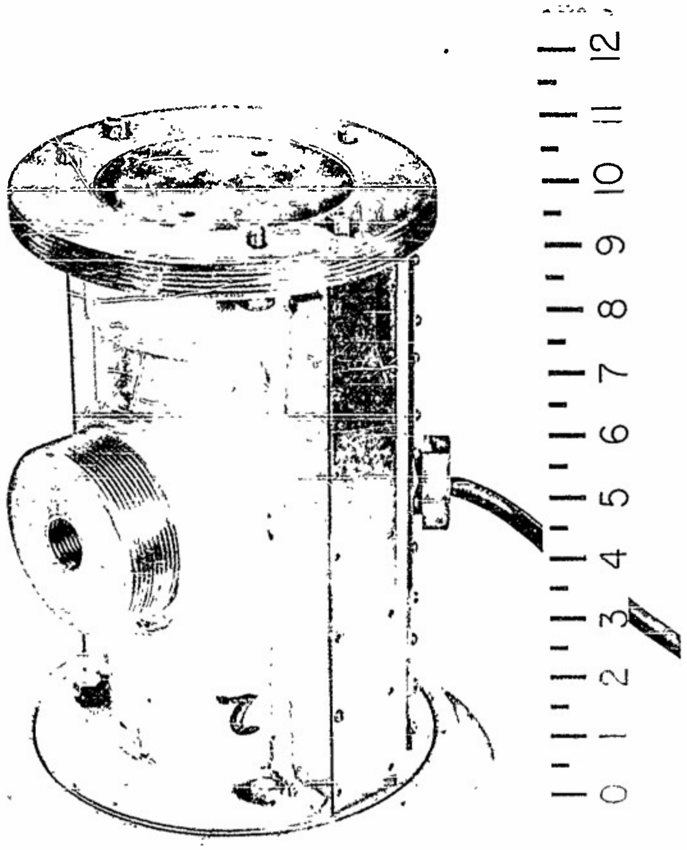
Initial tests indicate that the new pickup is durable and has greater sensitivity.



TMB 9655

Figure 49 - British-Type Velocity Meter

This velocity meter consists of a pickup coil, which is attached rigidly to the instrument case, and a seismically supported d-c electromagnet which produces a uniform radial magnetic field. The seismic magnet is guided by steel rollers so that it has freedom of motion only in a direction perpendicular to the base of the instrument. The output voltage, which is proportional to the velocity of the imposed motion under the conditions discussed on Page 9, is generated by the relative motion between the coil and the radial magnetic field. This instrument, although identical in principle with the large Sperry-MIT pickup shown in Figure 38, is considerably sturdier in construction to withstand the severe shocks it is intended to measure.



TMB15247

Figure 50 - Modified British-Type Velocity Meter

This instrument is a modification of the velocity meter described in Figure 49. No changes have been made in the basic principles of operation. However, an attempt has been made to improve several of the mechanical features of the instrument which have proved undesirable on field tests. In the modified version the seismic magnet and pickup coil are entirely enclosed by the case and the seismic magnet is guided by the walls of the case. The case is provided with threads so that the instrument, when mounted either vertically or horizontally, can be screwed to an expendable base which is welded to the test structure.

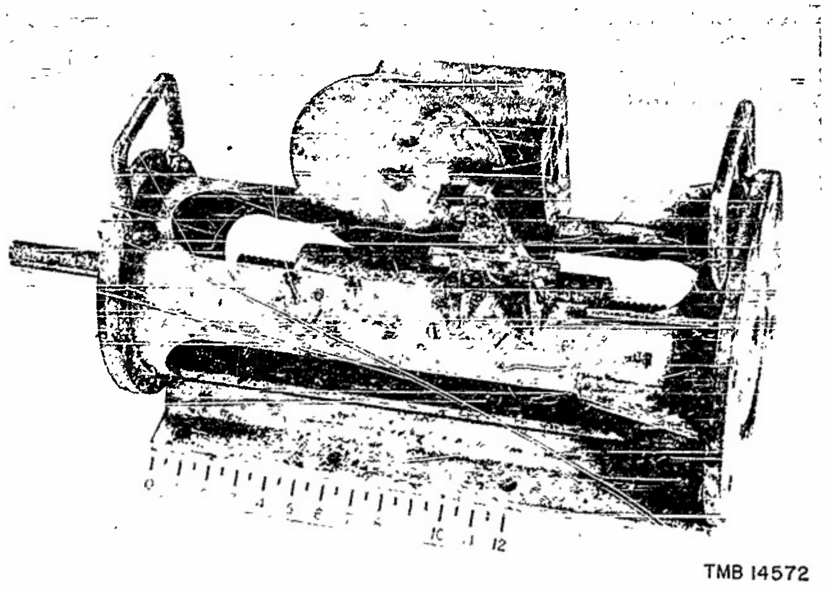


Figure 51a

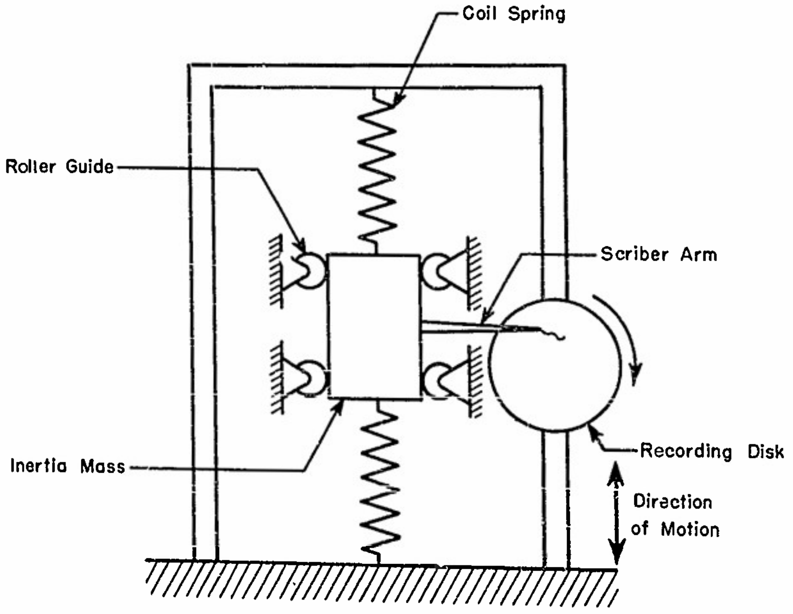


Figure 51b

Figure 51 - TMB Shock Displacement Gage

This instrument employs as the inertia element a spring-mounted seismic weight restrained by rollers to one degree of freedom. It is similar to the pallographs in principle but was designed primarily for the purpose of obtaining time-displacement records of large-amplitude shock displacements. No magnification of the actual motion is required, and the instrument records on a rotating chrome-plated disk by a steel scriber attached directly to the seismic element.

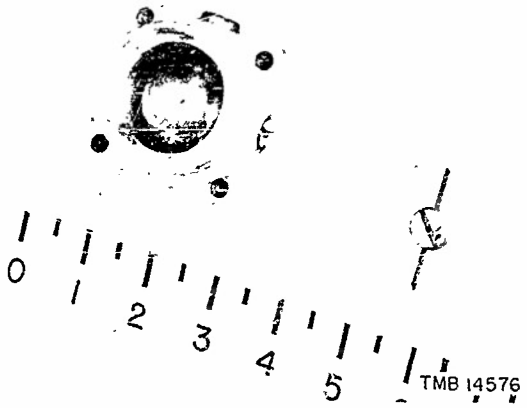


Figure 52a

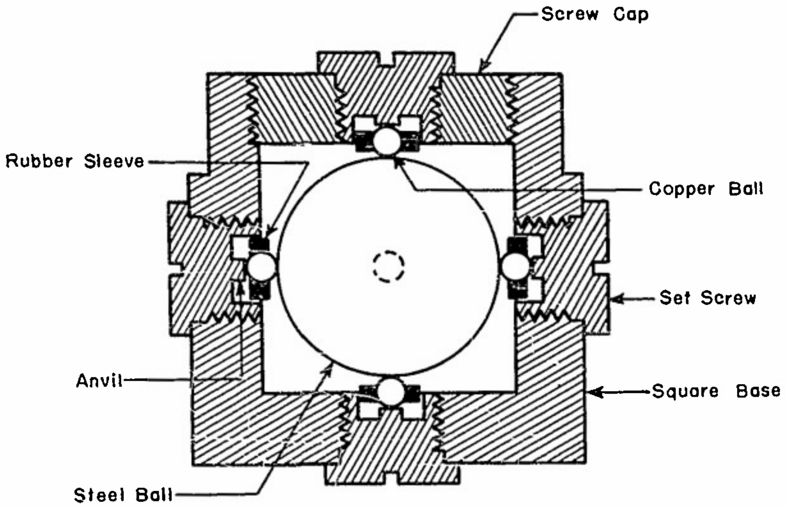


Figure 52b

Figure 52 - Copper-Ball Accelerometer

The copper-ball accelerometer is designed to indicate accelerations in three directions. It consists of a steel ball held in a case by point contact with six annealed copper balls, two in each direction of motion, which are held in place by set screws in the instrument case. When the pickup is accelerated, the copper balls are deformed by the steel ball. The deformation of the copper balls depends on the magnitude and duration of the acceleration. This instrument is not recommended for motions involving successive accelerations since, after the initial acceleration, a space is created between the steel and copper balls and a hammering effect is produced by successive accelerations. A later design of the instrument employs a spring-loaded wedge between the copper balls and the instrument case for the purpose of keeping the steel and copper balls in contact throughout the motion being measured.

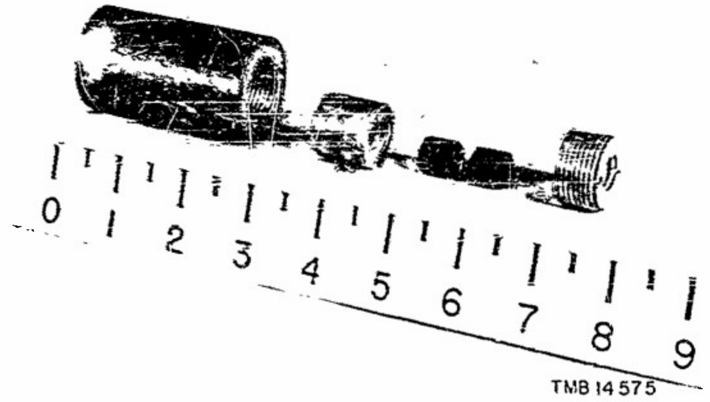


Figure 53a - Photograph of Component Parts

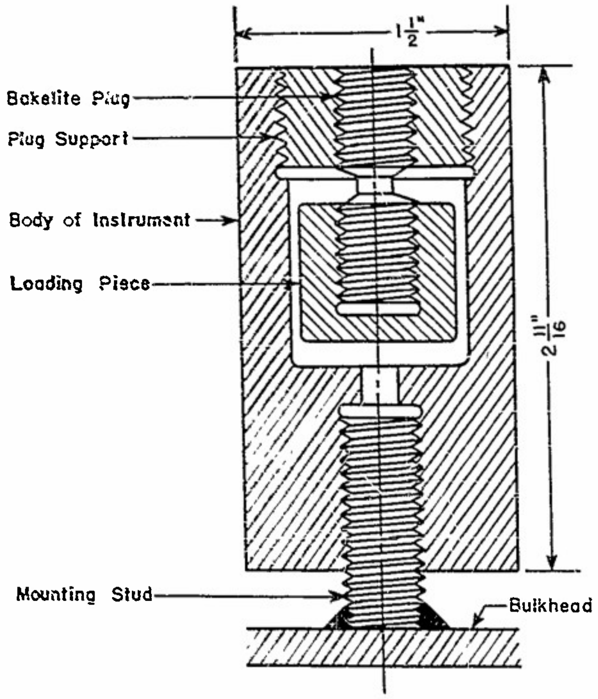
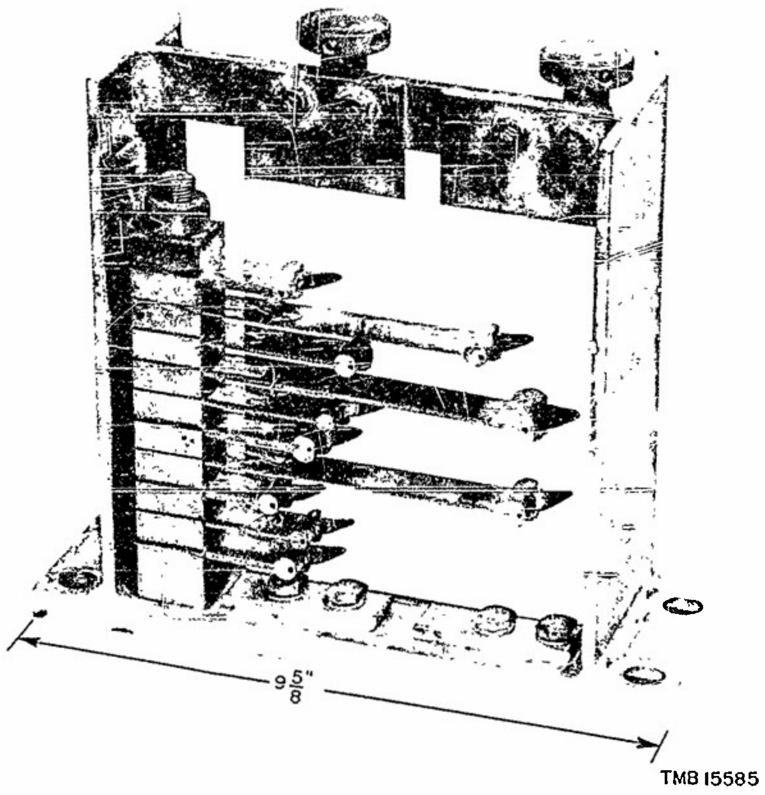


Figure 53b - Cross-Sectional View

Figure 53 - Mass-Plug Accelerometer

The mass-plug accelerometer (14) consists of a loading piece of known weight which screws onto one end of a bakelite plug which has a reduced section at mid-length. The other end of the plug screws into the plug support which screws into the body of the instrument. The accelerometer may be attached to the test body by screwing it onto a 1/2-inch mounting stud which is welded to the latter. In this type of gage it cannot be arbitrarily assumed that the tensile force on the turned down part of the plug is the same as the equivalent force acting on the seismic element when the case is accelerated. Dynamic factors due to the oscillatory motion of the system and involving the duration of the applied acceleration must be taken into account as shown in TMB Report 481, (15).



Figures 54a - Type I Gage

Figure 54 - Multifrequency Reed Gages

Type I gage was designed at the Taylor Model Basin to measure shock caused by explosions (16). As shown here it consists of ten reeds of different frequencies with small masses attached at the ends. It has been found preferable to reduce the number of reeds to eight in order to prevent one from coming in contact with another. The relative motion of the reeds and the instrument case is recorded on waxed paper. For impulsive shock motions the total displacement of the reeds is considered to indicate the velocity associated with the shock. At present a theoretical study of this instrument is being made to determine the exact significance of its records. It appears from preliminary studies that a good approximation to the nature of the applied shock motion may be obtained in the following manner: The "frequency spectrum" of the record, i.e., the variation of peak displacement with the natural frequency of the reed, is compared with the frequency spectra theoretically computed for a number of standard arbitrary shocks. The instrument is considered particularly useful in comparing shock severities.

Type II gage was designed to give more information about the actual motions of the individual reeds than can be obtained from a peak-indicating instrument. The main advantage of Type II over Type I is that it shows whether multiple shocks occur which mask out the reed deflections due to the initial shock. For single shocks it is believed that Type I is adequate for analysis of the motion. The target on which the styluses record is attached to a sliding plate and hence the oscillatory movement of the reeds is revealed. It was considered of primary importance that no external power be required for the operation of this instrument. The plate is free to move about two inches in a direction parallel to the lengths of the reeds. The shock motion which is being recorded actuates an inertia element which releases a mechanism, allowing the plate holding the paper to respond to a spring force. A dashpot is provided and the speed with which the paper holder moves when released can be varied by changing the damping. No time record is provided but certain time relations of the impressed motion can be related to the resonance frequencies of the reeds.

A recently proposed analysis of the reed-gage record consists chiefly of comparing the amplitudes and motions of the reeds with previously calculated amplitudes and motions of a similar single-degree-of-freedom system under several different types of impressed motion, such as step velocity, step acceleration, and simple harmonic motion.

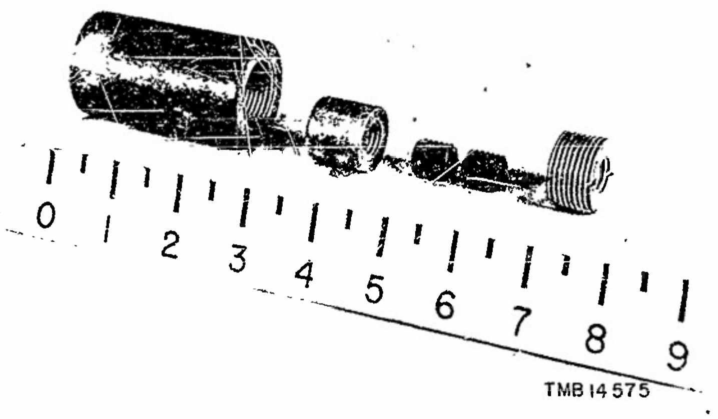


Figure 53a - Photograph of Component Parts

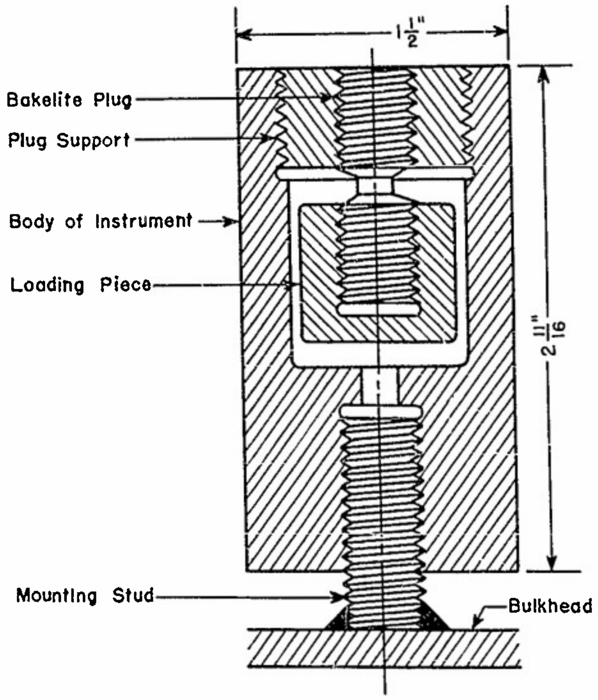
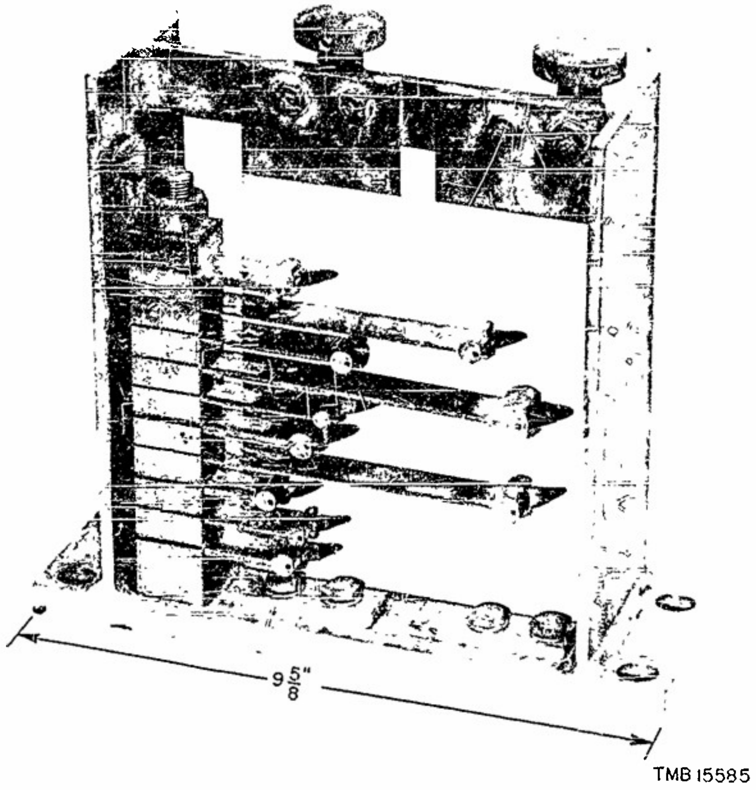


Figure 53b - Cross-Sectional View

Figure 53 - Mass-Plug Accelerometer

The mass-plug accelerometer (14) consists of a loading piece of known weight which screws onto one end of a bakelite plug which has a reduced section at mid-length. The other end of the plug screws into the plug support which screws into the body of the instrument. The accelerometer may be attached to the test body by screwing it onto a 1/2-inch mounting stud which is welded to the latter. In this type of gage it cannot be arbitrarilly assumed that the tensile force on the turned down part of the plug is the same as the equivalent force acting on the seismic element when the case is accelerated. Dynamic factors due to the oscillatory motion of the system and involving the duration of the applied acceleration must be taken into account as shown in TMB Report 481, (15).



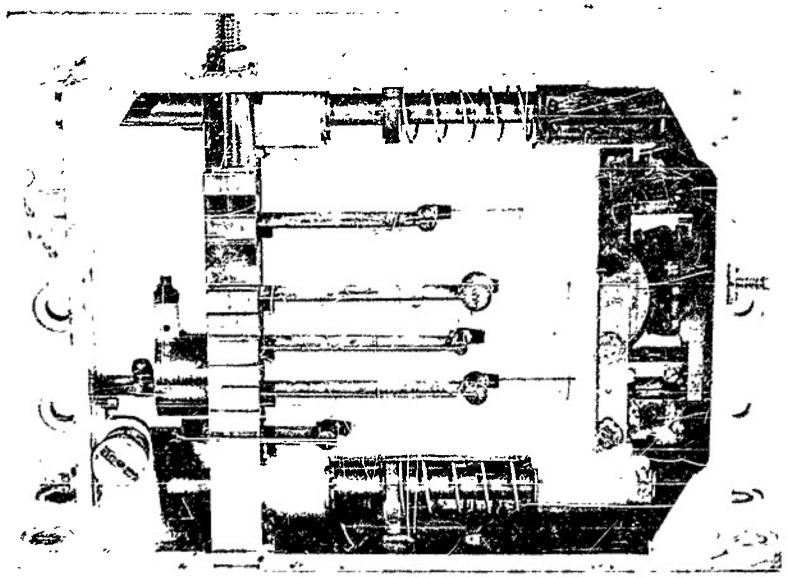
Figures 54a - Type I Gage

Figure 54 - Multifrequency Reed Gages

Type I gage was designed at the Taylor Model Basin to measure shock caused by explosions (16). As shown here it consists of ten reeds of different frequencies with small masses attached at the ends. It has been found preferable to reduce the number of reeds to eight in order to prevent one from coming in contact with another. The relative motion of the reeds and the instrument case is recorded on waxed paper. For impulsive shock motions the total displacement of the reeds is considered to indicate the velocity associated with the shock. At present a theoretical study of this instrument is being made to determine the exact significance of its records. It appears from preliminary studies that a good approximation to the nature of the applied shock motion may be obtained in the following manner: The "frequency spectrum" of the record, i.e., the variation of peak displacement with the natural frequency of the reed, is compared with the frequency spectra theoretically computed for a number of standard arbitrary shocks. The instrument is considered particularly useful in comparing shock severities.

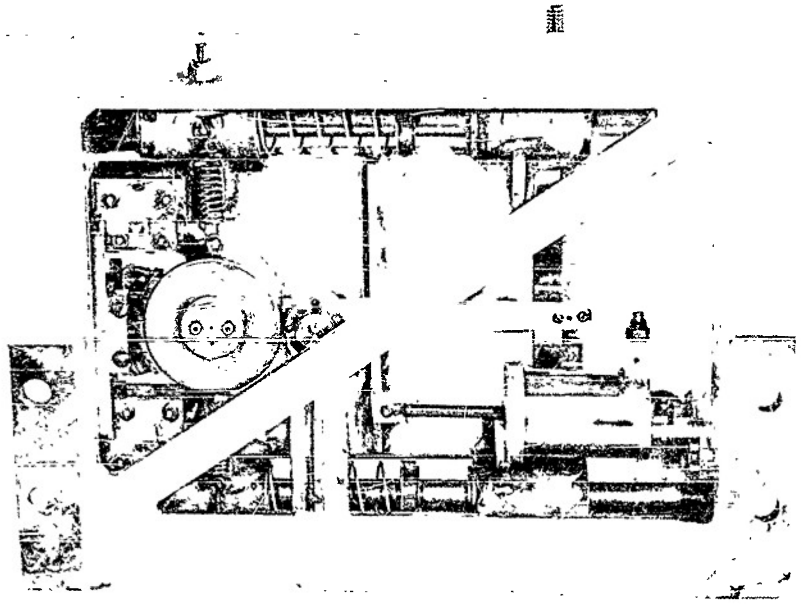
Type II gage was designed to give more information about the actual motions of the individual reeds than can be obtained from a peak-indicating instrument. The main advantage of Type II over Type I is that it shows whether multiple shocks occur which mask out the reed deflections due to the initial shock. For single shocks it is believed that Type I is adequate for analysis of the motion. The target on which the styluses record is attached to a sliding plate and hence the oscillatory movement of the reeds is revealed. It was considered of primary importance that no external power be required for the operation of this instrument. The plate is free to move about two inches in a direction parallel to the lengths of the reeds. The shock motion which is being recorded actuates an inertia element which releases a mechanism, allowing the plate holding the paper to respond to a spring force. A dashpot is provided and the speed with which the paper holder moves when released can be varied by changing the damping. No time record is provided but certain time relations of the impressed motion can be related to the resonance frequencies of the reeds.

A recently proposed analysis of the reed-gage record consists chiefly of comparing the amplitudes and motions of the reeds with previously calculated amplitudes and motions of a similar single-degree-of-freedom system under several different types of impressed motion, such as step velocity, step acceleration, and simple harmonic motion.



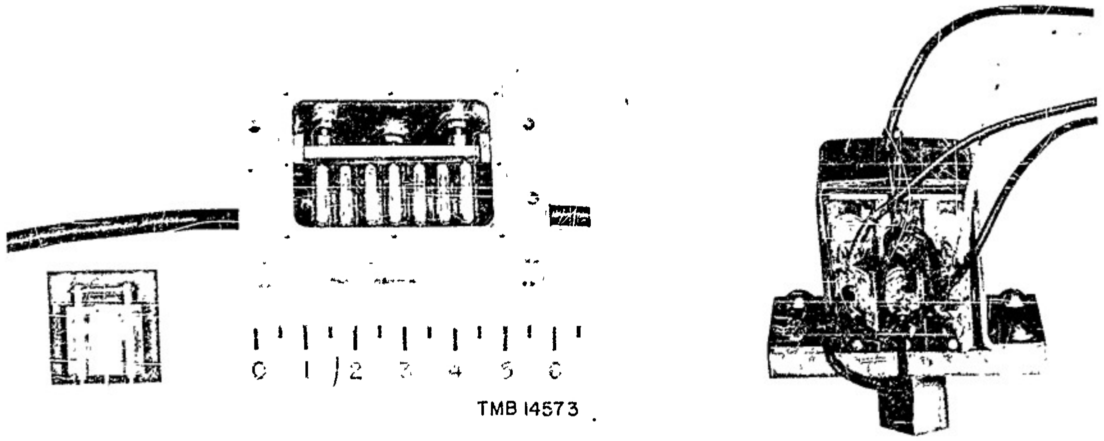
TMB 26652

Figure 54b - Type II Gage, Front View



TMB26653

Figure 54c - Type II Gage, Rear View



TMB 14573

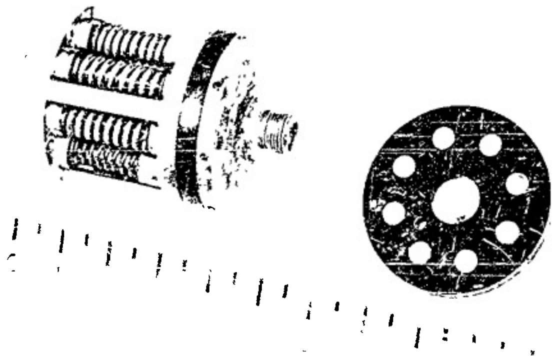
Figure 55a - Seven-Cell Unit

TMB 9176

Figure 55b - Three-Cell Unit

Figure 55 - NRL Contact Accelerometer

This instrument has an inertia element consisting of a small steel cantilever reed with a small weight attached to the end. The proper adjustment of either of two set screws on each side of the mass produces a pre-load on the cantilever. The bent reed thus exerts a force which keeps the mass in contact with the screw. When a given value of acceleration is reached, the mass remains momentarily behind, owing to its inertia, and the contact is broken. This is indicated by the lighting of a neon bulb on the TMB contact indicator shown in Figure 58. Two types of loaded holders are shown in the above photographs, one holding seven cells and the other three. A single cell is also shown in Figure 55a. Because no indication is obtained of the duration of the acceleration, the usefulness of such instruments in studying shock motions is limited.



TMB 14574

Figure 56a

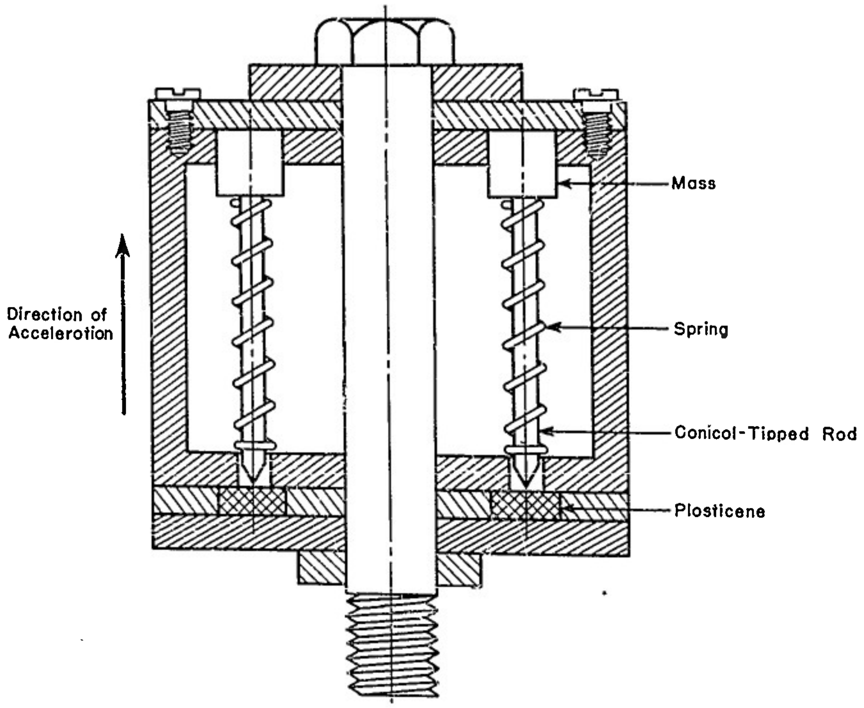
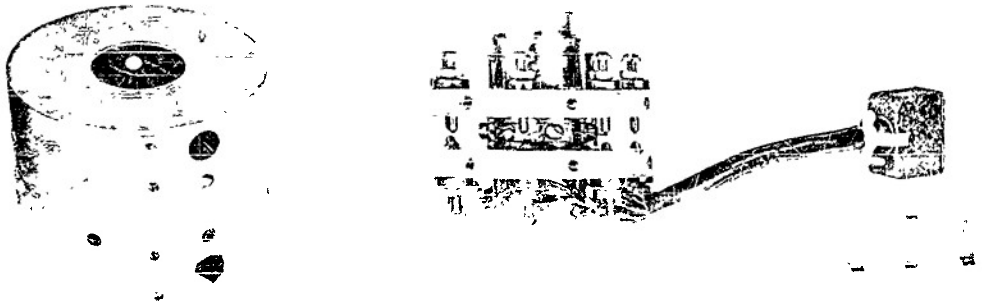


Figure 56b

Figure 56 - Putty Gage

This gage consists of eight spring-loaded masses of different frequencies ranging from 35 to 200 CPS. Each mass has a cylindrical rod with a conical tip, which runs axially through the spring. When the instrument is subjected to an acceleration, the motion of the rod against the spring force produces an indentation in the plasticine cylinder which is considered to indicate peak acceleration. Plasticine has been found superior to putty because it retains its properties over a longer period of time. The condition of the plasticine is a critical factor in the amount of indentation produced and is the chief source of uncertainty.

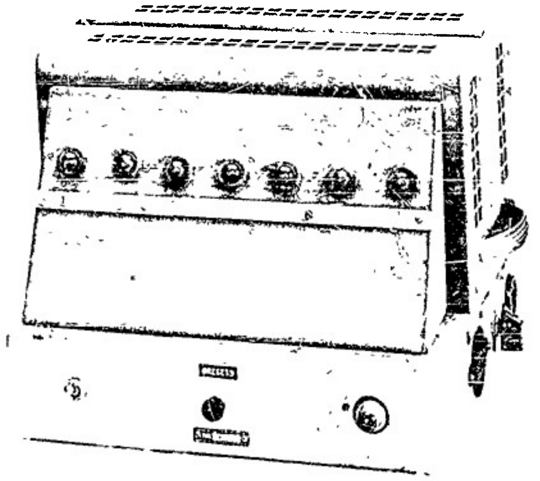
A paper recently presented at a shock and vibration symposium discusses the results of studies concerning the characteristics of this instrument (17)



TMB 18576

Figure 57 - TMB Seven-Reed Contact Accelerometer

The TMB seven-reed contact accelerometer is similar in principle to the NRL contact accelerometer described in Figure 55. The reeds of the TMB unit are of uniform thickness and thus act as a uniform cantilever when subjected to acceleration. The reeds are interchangeable, and by choosing reeds of proper thickness a desired range of acceleration may be indicated. The limitations mentioned under Figure 55 apply here also.



TMB 9181

Figure 58a - TMB Seven-Channel Electronic Contact Indicator

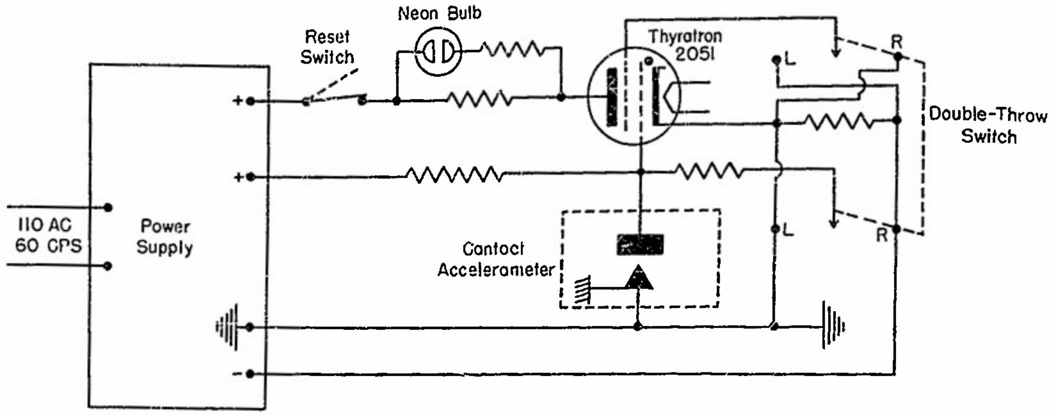
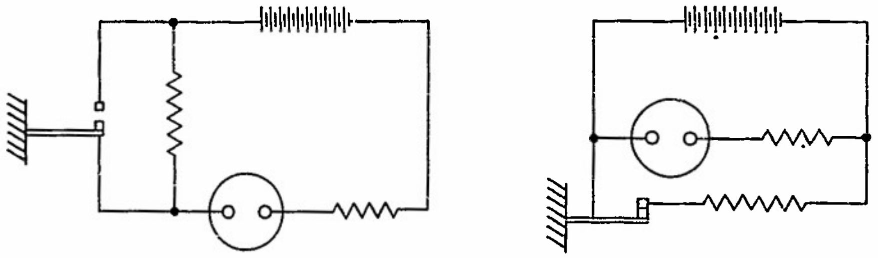


Figure 58b - Wiring Diagram for Single-Channel Electronic Contact Indicator



Make Circuit

Break Circuit

Figure 58c - Wiring Diagram of Simple Electrical Make-and-Break Circuit

Figure 58 - TMB Contact Indicator

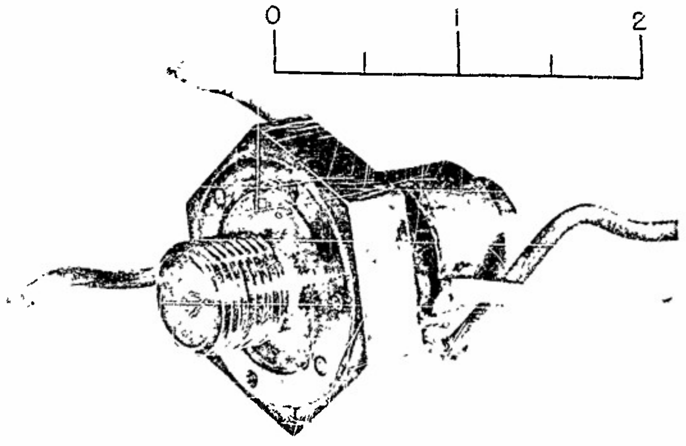
This electronic device, operated on 110-volt alternating current, or on a storage and B-battery, indicates the momentary opening of a circuit by the lighting of a neon bulb which remains lit until the circuit is reset. It is used with the NRL contact accelerometer, Figure 55, or with the TMB seven-reed contact accelerometer, Figure 57, to indicate a contact break. It can be used either with two 3-channel units or with one 7-channel unit.

With switch at R and the contact normally open, the grid closest to the cathode has a negative voltage while the other grid is at ground level. The grid closest to the cathode prevents the thyratron tube from firing. However, when the contact closes, this grid voltage rises to ground potential and the tube fires, lighting the neon bulb.

With switch at L and the contact normally closed, the grid closest to the cathode is at ground potential. The second grid has a negative voltage which prevents the tube from firing. However, when the contact opens, the grid closest to the cathode acquires a positive voltage sufficient to fire the tube.

When the thyratron tube is fired, the neon bulb will continue to glow until the reset switch is opened which takes the positive charge from the plate or anode.

Figure 58c shows a simple electrical circuit for indicating make-and-break contact. Compared to the electronic device, it has the serious disadvantage that arcing may occur across the contact points, thus indicating a false make or a delayed break.



TMB 15253

Figure 59 - Metalectric Accelerometer

This instrument consists of a weighted steel cylinder used as the high-frequency inertia element with metalectric strain gages attached to it. Strains are produced in the steel cylinder when it is subjected to acceleration; these strains are proportional to the acceleration and are recorded with standard electronic equipment. No damping is provided.

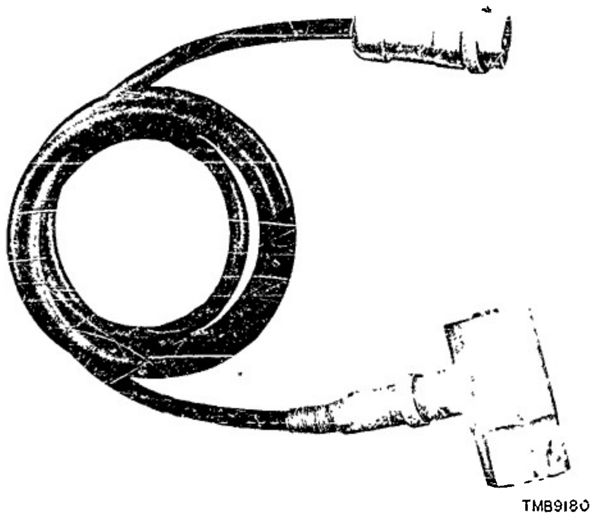


Figure 60a

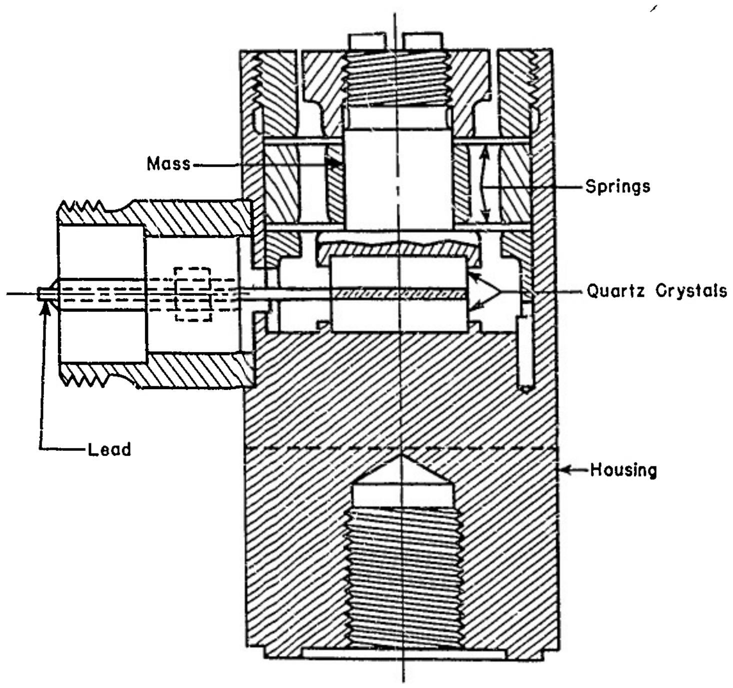


Figure 60b

Figure 60 - Westinghouse Crystal Accelerometer

This accelerometer has two small piezoelectric crystals mounted within the case. These crystals are loaded by a mass which is held against them by two annular flexure springs. When acceleration is applied to the instrument in the proper direction, the load upon the crystals is changed owing to the inertia of the spring held mass, and a piezoelectric signal proportional to the applied acceleration is produced.

The TMB crystal accelerometer, single faced, and the TMB crystal accelerometer, push-pull, are similar in appearance and construction to the Westinghouse crystal accelerometer shown above.

CONCLUSION

The data presented in this report show that a wide selection of equipment is now available for the study of vibration and shock. However, it is not felt at the Taylor Model Basin that the problem of developing adequate instruments for this purpose has been entirely solved, and further efforts are still being exerted in this direction, for the following reasons:

1. The frequency range over which instruments may be used should be extended.

2. Instruments are needed to satisfy more adequately the contradictory dual objectives, maximum sensitivity and wide frequency range.

3. Instruments for many applications need redesign so that their performance will be more reliable.

4. Instruments of increased flexibility, with consequent reduction of the number of types, can simplify the instrumentation requirements for a particular investigation.

5. Improvement of the method of recording reduces considerably the time necessary for the analysis of records.

Development and improvement of instruments is a slow process, with many set-backs. However, it has been the experience of the Taylor Model Basin that, as a result of the progress made here and elsewhere in this field to date, successful investigations which previously were impossible or at best extremely difficult to make can now be made readily.

ACKNOWLEDGMENTS

The information presented in this report was compiled by the authors with the cooperation and assistance of the other members of the Vibration Branch of the Structural Mechanics Department. Manufacturers' operating manuals and instruction books were freely used in compiling this information as well as information published by other naval establishments. Many helpful suggestions and criticism were made by R.T. McGoldrick, head of the Vibration Branch, and Capt. J. Ormondroyd, USNR, formerly of the David Taylor Model Basin staff.

REFERENCES

(1) "A Study of Ship Hull Vibration," by R.T. McGoldrick, EMB Report 395, February 1935.

(2) "Mechanical Vibrations," by J.P. Den Hartog, McGraw-Hill Book Company, New York, N.Y., Second Edition, 1940.

(3) "A Vibration Manual for Engineers," by R.T. McGoldrick, TMB Report R-189, March 1944.

(4) "Vibration Problems in Engineering," by S. Timoshenko, D. Van Nostrand Co., New York, N.Y., 1928.

(5) "Messung mechanischer Schwingungen" (Measurement of Mechanical Oscillations), by H. Steuding, Berlin, 1928.

(6) "Mechanical Measurements by Electrical Methods," by H.C. Roberts, Instruments Publishing Co., Pittsburgh, 1946.

(7) "A Carrier-Type Strain Indicator," by G.W. Cook, TMB Report 565, November 1946.

(8) "Applications of Unbonded-Type Resistance Gages," Richard D. Meyer, Instruments, Vol. 19, No. 3, March 1946.

(9) "The MIT-Sperry Apparatus for Measuring Vibration," by C.S. Draper, G.C. Bentley, and H.H. Willis, Journal of Aeronautical Sciences, Vol. 4, 1936-37, p. 695.

(10) "Quartz-Crystal Accelerometer," by R.O. Fehr, General Electric Review, Vol. 45, 1942, pp. 269-272.

(11) "Electronic Methods of Observation at the David W. Taylor Model Basin. Part 6 - The Application of Frequency-Deviation Methods to Measurements of Mechanical Changes," by E. Plesset, Ph.D., TMB Report R-79, February 1943.

(12) Patent No. 2,269,453, January 13, 1942, "Device for Detecting Displacements," Everett L. Gayhart, USN.

(13) "The Development of Improved Means for Evaluating Effects of Torsional Vibration on Internal Combustion Engine Installations," SAE War Engineering Board of the Society of Automotive Engineers, Inc., 1945.

(14) "Experimental and Theoretical Investigations of the Mass-Plug Accelerometer," by D.M. Smith, TMB Report R-267, March 1946.

(15) "Effects of Impact on Simple Elastic Structures" by Dr. J.M. Frankland, TMB Report 481, April 1942.

(16) "Theoretical Study of the Multifrequency Reed Gage for Measuring Shock Motion," by Samuel Davidson and Emily J. Adams, TMB Report 613, in preparation.

(17) "Peak-Reading Accelerometers," by R.E. Blake, NRL Report S-3276, Shock and Vibration Bulletin No. 8, March 1948.