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American Standard Methods for the

Calibration of Shock and Vibration Pickups

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Acoustical Society of America

American Society of Mechanical Engineers

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Approved November 27, 1959

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Foreword

(This Foreword is not a part of American Standard† Methods for the Calibration of Shock and Vibration Pickups, S2.2-1959.)

This American Standard† comprises a part of a group of definitions, standards, and specifications for use in work concerning acoustics, vibration, and mechanical shock. It has been developed under the Sectional Committee Method of ASA procedure, under the co-sponsorship of the Acoustical Society of America and the American Society of Mechanical Engineers.

The S2 Committee under whose jurisdiction this standard was developed has the following scope:

Standards, specifications, methods of measurement and test, and terminology in the fields of mechanical shock and vibration, but excluding those aspects that pertain to biological safety, tolerance, and comfort.

Various subcommittees have been organized to take care of the committee's program and this standard was developed by Subcommittee S2-W-27, whose personnel is shown below.

Suggestions for improvement gained in the use of this standard will be welcomed. They should be sent to the United States of America Standards Institute, 10 East 40th Street, New York, N.Y. York 1(

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Contents

Section		Page
Introduction		6
1. Purpose and Scope		6
	1.1 Purpose	6
	1.2 Scope	6
	1.3 Present and Future Choices of Methods	6
	1.4 Related Standards	6
2. Definitions		7
	2.1 Letter Symbols	7
	2.2 Pickup	7
	2.3 Input	8
	2.4 Output	8
	2.5 Sensitivity, Amplitude Sensitivity, Phase Lag	8
	2.6 Amplitude Distortion, Frequency Distortion, Proportional Phase Lag, Phase Distortion	8
	2.7 Calibration Factor	9
	2.8 Transverse Sensitivity Ratio	9
	2.9 Exciter	9
	2.10 Damping Ratio	9
	2.11 Undamped Natural Frequency	9
	2.12 Damped Natural Frequency	9
	2.13 Resonant Frequency	9
3. Characteristics to be Measured		9
	3.1 General	9
	3.2 Direct Response	9
	3.3 Response to Motion in Other Directions and About Other Axes	10
	3.4 Damping Ratio and Undamped Natural Frequency	10
	3.5 Nonlinearity	12
4. Standard Calibration Methods		12
	4.1 Tabulation of Standard Methods	13
	4.2 Tilting Support Calibrator	13
	4.3 Centrifuge Calibrator	14
	4.4 Rectilinear Electrodynamic Vibration Pickup Calibrator	15
	4.4.1 Sensitivity of Electrodynamic Calibrator Determined by Reciprocity Method	16
	4.4.2 Calibration of Vibration Pickups on Calibrator, General Method	17
	4.5 Physical Pendulum Calibrator	18
	4.6 Ballistic Pendulum Calibrator	20
5. Calibration by Comparison with Calibrated Pickup		22
Appendix		
A1. Survey of Other Calibration Methods		23
	A1.1 Static Calibration Methods	23
	A1.1.1 Static Load Method	23
	A1.2 Dynamic Calibration by Sinusoidal Excitation	23
	A1.2.1 Rectilinear Vibration Exciter	24
	A1.2.2 Angular Vibration Exciter	25
	A1.2.3 Tilted Centrifuge	26
	A1.2.4 Dual Centrifuge	26
	A1.2.5 Resonant Beam Vibrator	26
	A1.2.6 Acoustical Cavity Method	27
	A1.2.7 Condenser Microphone Method	27

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A1.3 Dynamic Calibration by Transient Excitation 28
A1.3.1 Free-Fall Test 28
A1.3.2 Pulse Calibrator 29
A1.3.3 Air Gun 29
A1.3.4 Shock Test Applying Measured Impact Acceleration 29
A1.3.5 Hydraulic Shock Test 30
A1.3.6 Impact Drop Test 30
A1.3.7 Elastic Pulses in Long Bars 30
A2. Theory of Reciprocity Method for Linear Electromechanical Pickups 30
A3. Reciprocity Method for Electrodynamic Calibrators 32
A3.1 Theory 32
A3.2 Measurements 34
A3.2.1 Transfer Admittance Measurements 35
A3.2.2 Voltage Ratio Measurements 35

Table 1 Estimated Ranges and Errors of Standard Methods 13

Figures
Fig. 1 Response of Idealized Linear Acceleration Pickup 10
Fig. 2 Response of Idealized Linear Displacement or Velocity Pickup 11
Fig. 3 Phase Lag of Idealized Linear Pickup 11
Fig. 4 Response of Idealized Linear Pickup to a Sudden Impulse 12
Fig. 5 Tilting Support for Static Calibration of Acceleration Pickups 14
Fig. 6 Schematic Cross-sectional View of Rectilinear Electrodynamic Vibration Pickup Calibrator 15
Fig. 7 Circuit for Calibration by Method A 18
Fig. 8 Pendulum Calibrator 19
Fig. 9 Recorded Output of Pickup on Physical Pendulum Calibrator 20
Fig. 10 Calibration of Pickup A on Ballistic Pendulum Calibrator 20
Fig. 11 Simple RC Network for Integrating Pickup Output 21
Fig. 12 Comparison Method for Calibrating Pickup 2 Against Calibrated Pickup 1 21
Fig. A1 Vibrating Wedge 23
Fig. A2 Rectilinear Vibration Pickup Calibrator with Piezoelectric Drive 25
Fig. A3 Dual Centrifuge 26
Fig. A4 Resonant Beam Vibrator 27
Fig. A5 Impact Load Acting on Mass and Displacement of Mass of Linear Mass-Spring System, with Natural Period T 28
Fig. A6 Typical Oscillograph Record from Free-Fall Test of Velocity Pickup 29
Fig. A7 Shock Test Applying Measured Impact Acceleration 29
Fig. A8 Circuits and Polygons for Making Transfer Admittance Measurements on Electrodynamic Calibrator and Pickups 34
Fig. A9 Circuits and Polygons for Making Voltage Ratio Measurements on Electrodynamic Calibrator 36

References 37

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USA Standard Methods for the Calibration of Shock and Vibration Pickups

Introduction

The calibration of shock and vibration pickups has become increasingly important as the need has grown for accurate measurements of the shocks and vibrations to which aircraft, missiles, and other high performance equipment are subjected in service. Numerous methods have been used or proposed for these calibrations. These are briefly described in Section 4 of this standard and in the Appendix. Section 4 contains a tabulation and detailed description of five "standard methods" which have proven themselves to be reliable means for the calibration of shock and vibration pickups. A tabulation (see 4.1) lists approximate ranges of application of each standard method and estimates of attainable accuracy. The description, which follows the tabulation, gives details of performing calibrations by each of the standard methods. Section A1 contains a brief survey of other methods which have been used to calibrate vibration pickups, but which have not found sufficient acceptance as yet to be included among the standard methods. The methods described range from precision techniques suitable for laboratory use only to procedures appropriate to field use.

It is anticipated that the standard will undergo frequent revision to keep pace with the advancement of the art in this new and growing field. Section 4 will grow as methods in Section A1 prove their adequacy as standards. Section A1 will expand as new methods make their appearance.

Calibration methods for both shock and vibration pickups are included in the same standard because it is impracticable to draw a line of demarcation between pickups used in measurements of shocks and vibrations. Using Fourier analysis [1][1] any shock can be described by the superposition of a sufficient number of sinusoidal vibrations of proper frequency, amplitude, and phase angle.

The standard is limited to the calibration of acceleration, velocity, and displacement pickups. It is not concerned with pickups used for measurements of force, pressure, or strain even though some of these may be calibrated by similar methods.

[1] Numbers in brackets denote references at the end of the standard.

1. Purpose and Scope

1.1 Purpose. This standard is designed to acquaint the user with the general principles of calibration of shock and vibration pickups and to describe concisely several standard methods which have proven to give reliable and reproducible results. Further details concerning these methods are given in the Appendix. Also, other methods that have not as yet reached the stage of development of the standard methods are described briefly in the Appendix.

1.2 Scope. Five methods have been selected as standard methods for the calibration of acceleration, velocity, and displacement pickups. They are described in Section 4 of this standard.

It is impracticable to calibrate all pickups by one standard method over the entire frequency and amplitude range of vibrations and shocks to be measured by the pickups. Several methods are accordingly described. Each method is limited to a range of frequency and amplitude, and to the weight of pickup that can be calibrated. The limitations may include, in addition, other variables such as volume of the pickup and temperature of operation.

1.3 Present and Future Choices of Methods. A pickup should be calibrated by the standard method or methods corresponding to its range of frequency, amplitude, and mass. The choice of method is facilitated by the tabulation of standard methods with estimated ranges and accuracies given in 4.1.

Other methods of calibration, of the types referred to in the Appendix, may be used in the future as these methods attain the degree of reliability characteristic of a standard method.

1.4 Related Standards. This standard is coordinated with the following standards which are closely related to the calibration of pickups:

American Standard† Method for Specifying the Characteristics of Pickups for Shock and Vibration Measurement, Z24.21-1957;

American Standard† Method for Specifying the Characteristics of Auxiliary Equipment for Shock and Vibration Measurements, S2.4-1960;[2] and

American Standard† Shock and Vibration Terminology, S1.1-1960.[2]

[2] These standards will become available in the latter part of 1960.

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2. Definitions

The letter symbols and technical terms used in the standard comply as far as possible with those given in American Standard† Letter Symbols for Acoustics, Y10.11-1953 and American Standard† Shock and Vibration Terminology, S1.1-1960. However, boldface italic type is used to indicate complex quantities. In addition the following quantities requiring definition are used repeatedly in the standard.

2.1 Letter Symbols

a — instantaneous acceleration
A — peak amplitude of sinusoidal acceleration, or area
c — damping constant
c_c — critical damping constant
C — capacity
d — instantaneous displacement, or mass deflection
D — peak amplitude of sinusoidal displacement
e — base of natural system of logarithms, or instantaneous voltage
E — peak amplitude of sinusoidal voltage
f — frequency, or instantaneous force
F — peak amplitude of sinusoidal force
g — acceleration of gravity
I — peak amplitude of sinusoidal current
j — unit imaginary vector
J — ordinate intercept
k — spring constant
l — length
m — mass
q — instantaneous electrostatic charge
Q — slope
r — radius
R — resistance
S — sensitivity, output/input
t — time
T — period
u — instantaneous velocity
U — peak amplitude of sinusoidal velocity
W — weight
x — instantaneous output of pickup
X — peak amplitude of sinusoidal output of pickup
Y_e — electrical admittance
Y_m — mechanical admittance
Z_m — mechanical impedance
δ — logarithmic decrement
θ — phase lag
ϕ — angle, or phase angle
ω — angular velocity, or circular frequency
ω_d — damped natural circular frequency
ω_n — undamped natural circular frequency
ω_r — resonant circular frequency

NOTE: When a symbol is printed in boldface italic type it indicates a complex quantity.

2.2 Pickup. A *pickup* is considered in this standard as a device for converting the motion to be measured, e.g., acceleration in a given direction, into a quantity which may be conveniently measured or recorded. Pickups are classified as *displacement pickups*, *velocity pickups*, or *acceleration pickups* depending on whether the converted quantity is proportional to the displacement, velocity, or acceleration.

A *continuous-reading pickup* is one which indicates the mechanical excitation as a function of time. A pickup is termed a *peak-reading pickup* if it indicates only the maximum of the mechanical quantity to be measured.[2] An example is the copper-ball accelerometer [3] in which the deformation of a soft copper ball is used to indicate the maximum acceleration which has been experienced by the accelerometer. Most of the calibration methods discussed are applicable only to continuous-reading pickups.

A *rectilinear pickup* is a pickup designed to measure some characteristic of translational motion. Most rectilinear pickups are designed to respond to the component of translational acceleration, velocity, or displacement in some specified direction relative to the pickup. This direction is the *axis of sensitivity* of the pickup. An *angular pickup* is designed to measure some characteristic of rotational motion, e.g., angular acceleration about a specified axis of sensitivity.

A continuous-reading pickup is termed a *linear pickup* if a sinusoidal input (see 2.3 and 2.4 for definitions of input and output) produces a sinusoidal output of the same frequency and if under these conditions the ratio of the amplitudes of the input and output, and the difference in their phases, are constants as the amplitude is varied at a particular frequency. Over a particular range of frequency and amplitude within which the pickup is linear, its behavior can be described by linear differential equations, and the principle of superposition applies. A pickup which does not satisfy these requirements is termed a *nonlinear pickup*.

A continuous-reading linear pickup is termed a *distortionless pickup* if the output is a faithful reproduction to scale of the input for any shock or vibration falling within the frequency range of the pickup. It should be remembered in this connection that true lack of distortion is an ideal which is never achieved in a pickup. The sinusoidal components of a vibra-

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tion can be faithfully reproduced in their proper phase relations over a limited range of frequencies and amplitudes only. This frequency range can be regarded as the *operating range* of the pickup.

A pickup is termed an *electromechanical pickup* if it converts a mechanical quantity, such as acceleration, into an electrical quantity, such as voltage. A continuous-reading electromechanical pickup is *bilateral* if it can be used either to produce an electrical signal as a result of a mechanical excitation, or to produce a motion as the result of an electrical excitation. The bilateral electromechanical pickup is *reciprocal* if the ratio of the applied current to produced force (when the pickup is restrained so the velocity is zero) equals the ratio of the applied velocity to the produced voltage (when the pickup is open-circuited so the current is zero). Familiar examples of such pickups are electrodynamic and piezoelectric pickups. A pickup employing strain gages as sensing elements is *unilateral* because an electrical excitation does not cause a perceptible mechanical effect in the pickup.

NOTE: The pickup will frequently include auxiliary equipment for amplifying, indicating or recording its output.

2.3 Input. The *input* is the quantity to be measured, e.g., the impressed acceleration for an acceleration pickup.

2.4 Output. The *output* is the quantity generated by the pickup in response to a given input.

2.5 Sensitivity, Amplitude Sensitivity, Phase Lag. The *sensitivity* of a continuous-reading linear pickup is the ratio of output to input during sinusoidal excitation parallel to a specified axis of sensitivity. In general, the sensitivity includes both amplitude and phase information and, consequently, is a complex quantity which varies with frequency.

If the input motion is a sinusoidal function of time, the output of a linear pickup is also a sinusoid of the same frequency. The input motion (displacement, d; velocity, u; and acceleration, a) and the output, x, may be written in complex notation as:

$$\boldsymbol{d} = \boldsymbol{D}e^{j\omega t} = De^{j(\omega t+\phi_1)}$$
$$= D[\cos(\omega t + \phi_1) + j\sin(\omega t + \phi_1)] \qquad \text{(Eq 1)}$$

$$\boldsymbol{u} = j\omega\boldsymbol{D}e^{j\omega t} = \boldsymbol{U}e^{j\omega t} = Ue^{j(\omega t+\phi_1+\pi/2)}$$
$$= U[\cos(\omega t + \phi_1 + \pi/2) + j\sin(\omega t + \phi_1 + \pi/2)] \qquad \text{(Eq 2)}$$

$$\boldsymbol{a} = j\omega\boldsymbol{U}e^{j\omega t} = \boldsymbol{A}e^{j\omega t} = Ae^{j(\omega t+\phi_1+\pi)}$$
$$= A[\cos(\omega t + \phi_1 + \pi) + j\sin(\omega t + \phi_1 + \pi)] \qquad \text{(Eq 3)}$$

$$\boldsymbol{x} = \boldsymbol{X}e^{j\omega t} = Xe^{j(\omega t+\phi_2)}$$
$$= X[\cos(\omega t + \phi_2) + j\sin(\omega t + \phi_2)] \qquad \text{(Eq 4)}$$

The *displacement sensitivity* is:

$$S_d = \frac{\boldsymbol{x}}{\boldsymbol{d}} = S_d\, e^{-j(\phi_1-\phi_2)}, \qquad \text{(Eq 5)}$$

where $\phi_1 - \phi_2$ is the phase lag.
The *velocity sensitivity* is:

$$S_u = \frac{\boldsymbol{x}}{\boldsymbol{u}} = S_u\, e^{-j(\phi_1+\pi/2-\phi_2)}, \qquad \text{(Eq 6)}$$

where $\phi_1 + \pi/2 - \phi_2$ is the phase lag;
and the *acceleration sensitivity* is:

$$S_a = \frac{\boldsymbol{x}}{\boldsymbol{a}} = S_a\, e^{-j(\phi_1+\pi-\phi_2)}, \qquad \text{(Eq 7)}$$

where $\phi_1 + \pi - \phi_2$ is the phase lag.
The *displacement amplitude sensitivity* is $S_d = X/D$, the *velocity amplitude sensitivity* is $S_u = X/U$, the *acceleration amplitude sensitivity* is $S_a = X/A$. Usually, the displacement sensitivity is determined for a displacement pickup, the velocity sensitivity for a velocity pickup, and the acceleration sensitivity for an acceleration pickup. In general, the amplitude sensitivities and the phase angles are functions of frequency, $f = \omega/2\pi$.

A displacement, velocity, or acceleration pickup in which the corresponding sensitivity does not vanish as the frequency approaches zero is said to have a *zero-frequency response* (direct-current response). Examples of pickups with zero-frequency response are acceleration pickups employing wire-resistance strain gages, potentiometers, differential transformers, or variable reluctance circuits as sensing elements. Seismic self-generating pickups, such as piezoelectric and electrodynamic pickups, are examples of pickups without zero-frequency response.

Sensitivity under constant acceleration corresponds to $\omega = 0$ and the phase lag is zero. Acceleration sensitivity is frequently expressed in units of output per g; this is obtained by multiplying S_a by the acceleration of gravity, g.

2.6 Amplitude Distortion, Frequency Distortion, Proportional Phase Lag, Phase Distortion. A pickup is said to have *amplitude distortion* if the ratio of the output to the input at a given frequency varies with the input amplitude. Although a linear pickup is always free of amplitude distortion, it usually has other types of distortion. A linear (displacement, velocity, or acceleration) pickup which possesses a constant (displacement, velocity, or acceleration, respectively) amplitude sensitivity over a

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specified range of frequency is said to be free from *frequency distortion* within that range; conversely, a variation of amplitude sensitivity with frequency is said to indicate frequency distortion within that range of frequencies (see Note below).

If over a specified range of frequencies, the ratio of the phase lag of a linear (displacement, velocity, or acceleration) pickup to the exciting frequency is substantially a constant, independent of frequency, the pickup is said to possess *proportional phase lag* (or *phase shift*) over that range of frequencies. A pickup which possesses proportional phase lag over a specified range of frequencies is free from *phase distortion* within that range. The output, as a whole, is delayed a constant time relative to the input. Conversely, a nonproportional phase shift will result in phase distortion within that range (see Note below).

If a linear pickup is distortionless over a specified frequency range, it is free of frequency and phase distortion over that frequency range.

NOTE: The foregoing definitions allow the presence or absence of frequency distortion within a given linear pickup to be specified irrespective of the presence or absence of phase distortion within the same pickup, and vice versa. However, it should not be inferred that the amplitude sensitivity and phase lag of a linear pickup are independently assignable functions of frequency. In fact, these characteristics cannot be designed independently, as is illustrated by generally applicable theorems which give relations between these characteristics. [4]

2.7 Calibration Factor. If the amplitude sensitivity of a linear pickup is substantially independent of frequency over a specified range of frequencies, the amplitude sensitivity is called the *calibration factor* for that range.

2.8 Transverse Sensitivity Ratio. The *transverse sensitivity ratio* is the ratio of the output of a pickup when oriented with its axis of sensitivity transverse to the direction of the input to the output when the axis of sensitivity is aligned in the direction of the same input. In certain pickups, particularly those involving piezoelectric crystals, the output due to a given transverse excitation will vary considerably as the pickup is rotated about its axis of sensitivity.

2.9 Exciter. An *exciter* is any device for applying a controlled motion to the mounting surface of a pickup. A *sinusoidal exciter* is one which applies a sinusoidal motion of controllable frequency and amplitude to the mounting surface of the pickup.

2.10 Damping ratio. The *damping ratio*, c/c_c, of a linear, viscously damped mass-spring system is the ratio of the damping constant, c, of the system to the damping constant, c_c, for which the system would be critically damped (see 3.4).

2.11 Undamped Natural Frequency. Regardless of the damping present, the *undamped natural frequency* of a linear pickup having a single degree of freedom is the frequency of sinusoidal excitation at which the motion of the mass element lags behind the motion of the housing of the pickup by a phase angle of 90 degrees. In the case of a more complicated pickup having several degrees of freedom, there may be as many frequencies at which the motion of the mass and the motion of the housing differ by a phase angle of 90 degrees as there are degrees of freedom. The lowest of these frequencies is taken as the undamped natural frequency.

2.12 Damped Natural Frequency. The *damped natural frequency* of a linear pickup is the frequency of its damped free vibration when the pickup housing is held fixed. In pickups having several degrees of freedom, there may be as many damped natural frequencies as there are degrees of freedom.

2.13 Resonant Frequency. The *resonant frequency* is defined only for linear pickups with a damping ratio less than $1/\sqrt{2}$. The resonant frequency is the frequency at which the sensitivity of the pickup is a maximum. Additional resonances corresponding to modes in which the principal displacements occur locally in the spring, housing, or attachment fittings are sometimes excited, particularly by shock motions.

3. Characteristics to be Measured

3.1 General. The primary object of the calibration of a pickup is to determine its calibration factor over the amplitude and frequency range for the degree of freedom for which the pickup is to be used. In addition, it is frequently important to know its response to motions in the other five degrees of freedom, e.g., for a rectilinear acceleration pickup, its response should be known to motions at right angles to the sensitive direction and to rotations. Other important factors include damping, phase shift, nonlinearity or variation of response with amplitude of motion, effect of temperature and pressure changes, and other extraneous conditions such as motion of the connecting cable.

Methods for specifying the characteristics of pickups for shock and vibration measurement are outlined in American Standard† Method for Specifying the Characteristics of Pickups for Shock and Vibration Measurement, Z24.21-1957.

3.2 Direct Response. The calibration factor of a pickup may be obtained by placing the pickup with its sensitive axis parallel to the direction of the

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motion of the exciter, measuring the motion or input applied by the exciter, and measuring the output of the pickup. Both continuous-reading and peak-reading pickups can be calibrated with a controlled transient excitation whose amplitude and frequency components are within the working range of the pickup. If the input and output of a continuous-reading pickup are very similar, the calibration factor may be taken as an average value of the ratio of corresponding pronounced features of the output and input. In the most common type of calibration, the pickup is mounted on a sinusoidal exciter, is vibrated at a measured frequency and amplitude, and the output signal is measured. The measurement is repeated over a sufficient range of frequencies to cover the operating range of the pickup. To detect any resonances, the output of the pickup should be observed while varying the exciter frequency slowly and continuously over the frequency range. In addition to the amplitude sensitivity, it is necessary to know the phase response for a complete specification of a linear pickup. This can be determined by measuring the phase difference between the output signal and the mechanical excitation over the frequency range of interest.

3.3 Response to Motion in Other Directions and About Other Axes. The transverse response of a pickup is determined by mounting it with its axis of sensitivity normal to the motion of an exciter and measuring the output. It is important that the motion of the exciter be rectilinear. The transverse response may vary with the direction of the excitation in the plane transverse to the nominal axis of sensitivity [5]. It is advisable, therefore, to repeat the determination of transverse response with the pickup rotated about its axis of sensitivity to several positions within an arc of 180 degrees.

3.4 Damping Ratio and Undamped Natural Frequency. The damping ratio and undamped natural frequency of a continuous-reading linear pickup can be determined by several methods if the pickup can be regarded as a single-degree-of-freedom system (see Fig. 1), consisting of a massless spring of spring constant k and a massless dashpot of damping constant c attached to a rigid mass element, m, which is restricted to movement in a fixed direction relative to a rigid support simulating the housing of the pickup.

The following equations [6] apply if such an idealized pickup is supported on a vibrating body executing a sinusoidal motion,

$$d_1 = D_1 \sin \omega t \, .$$

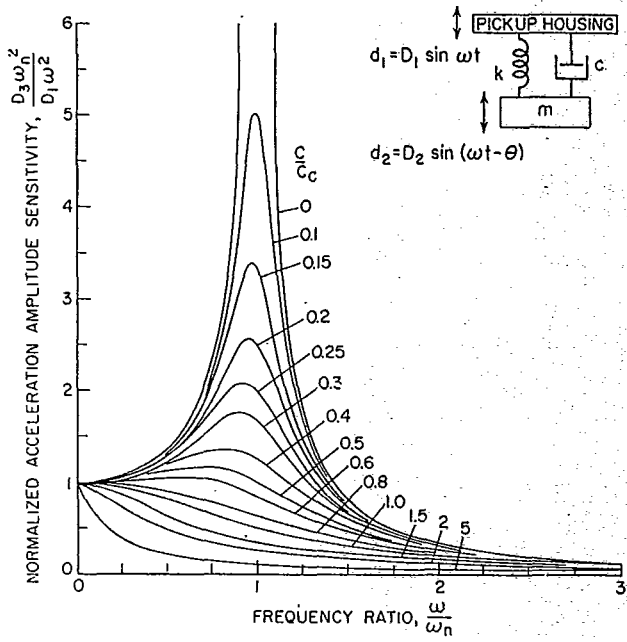


Fig. 1
Response of
Idealized Linear Acceleration Pickup

The motion d_2 of the mass, m, will be sinusoidal of the same frequency, but generally displaced in phase relative to the exciting motion:

$$d_2 = D_2 \sin (\omega t - \theta) \, .$$

The amplitude of motion of the pickup mass element relative to its housing, D_3, which is equal to the amplitude of $(d_2 - d_1)$, is given by [6]

$$D_3 = \frac{D_1 (\omega/\omega_n)^2}{\sqrt{(1 - \omega^2/\omega_n^2)^2 + 4(c/c_c)^2(\omega/\omega_n)^2}} \, , \quad \text{(Eq 8)}$$

where $\omega_n = \sqrt{k/m}$ is the undamped natural circular frequency of the pickup, and $c_c = 2\sqrt{mk}$ is the critical damping constant for the pickup, marking the boundary between oscillatory and nonoscillatory response after a sudden displacement of the mass element, m. The phase lag, θ, of the motion of the mass of the pickup relative to its housing is [6]

$$\theta = \tan^{-1} \frac{2(c/c_c)(\omega/\omega_n)}{1 - (\omega/\omega_n)^2} \, . \quad \text{(Eq 9)}$$

The idealized pickup may be regarded as measuring acceleration at frequencies below its natural frequency, ω_n, provided its instantaneous output is proportional to D_3. The constant of proportionality will depend upon the construction of the pickup. The acceleration amplitude sensitivity of the pickup

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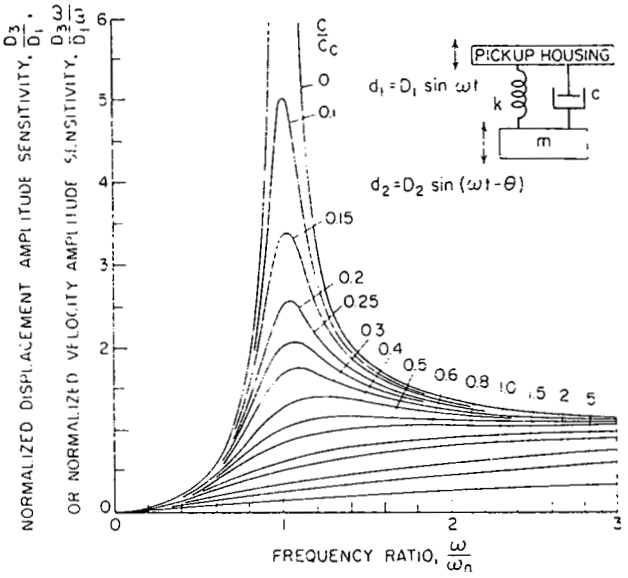


Fig. 2
Response of Idealized Linear Displacement or Velocity Pickup

is proportional to the ratio,

$$\frac{D_3\,\omega_n^2}{D_1\,\omega^2} = \frac{1}{\sqrt{(1-\omega^2/\omega_n^2)^2 + 4(c/c_c)^2(\omega/\omega_n)^2}}. \qquad \text{(Eq 10)}$$

Figure 1 is a plot of the response as given by this quantity for various damping ratios, c/c_c. When the damping ratio is less than $1/\sqrt{2}$, the maximum value of the response curve is

$$\left.\frac{D_3\,\omega_n^2}{D_1\,\omega^2}\right|_{\max} = \frac{1}{2\left(\frac{c}{c_c}\right)\sqrt{1-\left(\frac{c}{c_c}\right)^2}}. \qquad \text{(Eq 11)}$$

This occurs at the resonant circular frequency, ω_r,

$$\omega_r = \omega_n\sqrt{1-2\left(\frac{c}{c_c}\right)^2}. \qquad \text{(Eq 12)}$$

At frequencies above ω_n, the idealized pickup may be regarded as measuring displacement if its output is proportional to D_3, or velocity if its output is proportional to the velocity between the pickup mass element and its housing, ωD_3. The displacement or velocity amplitude sensitivity of the pickup is proportional to the ratio,

$$\frac{D_3}{D_1} = \frac{(\omega/\omega_n)^2}{\sqrt{(1-\omega^2/\omega_n^2)^2 + 4(c/c_c)^2(\omega/\omega_n)^2}}, \qquad \text{(Eq 13)}$$

and is plotted in Fig. 2. The maximum value of the corresponding response curve is identical to the right side of Equation 11. However, for a displacement or velocity pickup the resonant frequency, ω_r, is

$$\omega_r = \frac{\omega_n}{\sqrt{1-2\left(\frac{c}{c_c}\right)^2}}. \qquad \text{(Eq 14)}$$

Equation 9 gives the displacement, velocity, or acceleration phase lag for the corresponding type of pickup. Fig. 3 shows the variation of phase lag with frequency.

The damping ratio and natural frequency of a pickup can be measured by subjecting the pickup to sinusoidal motion or to a sudden impulse.

In the first method, the pickup is mounted on a sinusoidal vibration exciter and its sensitivity is determined at several frequencies. The results are compared with theoretical response curves [7, 8] like Fig. 1 or 2 to obtain the damping ratio. If phase measurements are included, it is best to use the 90-degree phase lag, Fig. 3, to establish the undamped natural frequency. The determination of the damping ratio can then be checked from Equations 11, 12, or 14 if the maximum sensitivity or resonant frequency of the pickup is measured.

In the second method, the response of the pickup to a sudden impulse is measured. The impulse may be applied in several ways, e.g., by tapping with a light hammer, by a drop tester, or, for pickups with a low natural frequency, by holding the pickup by a

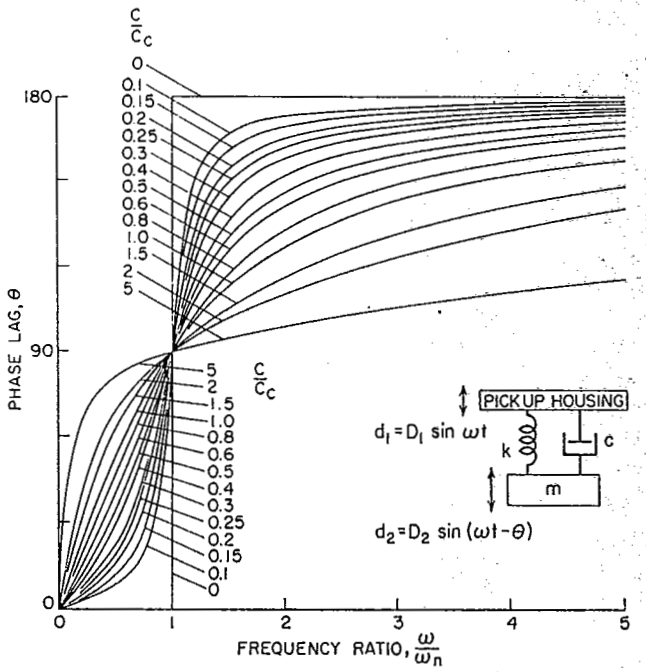


Fig. 3
Phase Lag of Idealized Linear Pickup

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string and then quickly cutting the string [9], or by suddenly releasing the mass element, m, from a deflected position. If the mass element of the pickup has a weight that is appreciable compared to the pickup, the pickup should be mounted on a small rigid metal block that is heavy in comparison to the mass element. If the damping ratio is less than unity, the resulting instantaneous output is a damped oscillation which may be described by

$$x = X_0 e^{\frac{-c\omega_n t}{c_c}} \sin(\omega_d t - \phi) , \qquad \text{(Eq 15)}$$

where X_0 and ϕ depend upon the internal construction of the pickup and upon the manner in which the impulse is applied, and where

$$\omega_d = \omega_n \sqrt{1 - \left(\frac{c}{c_c}\right)^2} \qquad \text{(Eq 16)}$$

is called the damped natural circular frequency even though the motion is not exactly periodic. The damped natural frequency, $f_d = \omega_d/2\pi$, can be determined from a record of the type shown in Fig. 4 as the reciprocal of the period. For the idealized pickup considered here, the ratio of successive maximum upward (or downward) deflections of mass, m, of the pickup will be constant. A good value of this ratio can be obtained from a record of the damped vibration, provided that c/c_c is small enough, preferably less than 0.3. The natural logarithm of that ratio, called the logarithmic decrement, δ, is

$$\delta = ln\left(\frac{x_1 - x_n}{n}\right) = \frac{2\pi \frac{c}{c_c}}{\sqrt{1 - \left(\frac{c}{c_c}\right)^2}} . \qquad \text{(Eq 17)}$$

Thus the damping ratio can be computed from Equation 17 and then the undamped natural circular frequency, ω_n, can be computed from Equation 16.

It must be kept in mind that most pickups behave like the system of Fig. 1 over a limited range of frequencies only. If the damping is by liquid, the liquid will add mass and elasticity to the vibrating system of the pickup.[10] The system of Fig. 1 remains a good approximation as long as the effect of the distributed mass, elasticity, and damping residing in the liquid are small enough. In such a case, a useful equivalent damping constant can sometimes be obtained from the preceding equations by treating the pickup as an idealized linear pickup with lumped mass and spring. If Coulomb damping is present, the response of the pickup will be nonlinear and may differ appreciably [11] from that shown in Fig. 1 or 2.

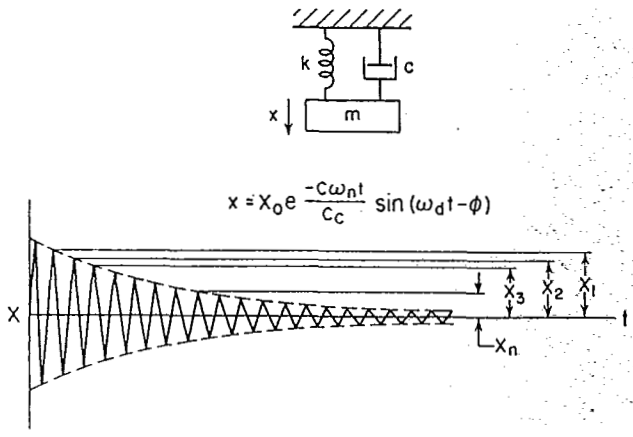


Fig. 4

Response of

Idealized Linear Pickup to a Sudden Impulse

3.5 Nonlinearity. Deviations of the output of a pickup from linearity (amplitude distortions) are determined by measuring its response as the amplitude of the input is increased from a small value to the largest value for which the pickup is designed. When a sinusoidal exciter is used, the measurement should be repeated for several frequencies.

The nonlinearity may take several forms. The sensitivity of the pickup may change progressively with increasing amplitude, there may be permanent set leading to a zero shift after subjecting the pickup to vibration or impact, or there may be stops that limit the range of motion suddenly.

The type and magnitude of the nonlinearity of a pickup may be indicated by its amplitude distortion and by comparing its resonance curve, its phase lag, and its decrement with the corresponding characteristics for the idealized linear pickup given in Equations 9, 10, 13 and 17 above and in Figs. 1, 2, 3, and 4.

The permissible deviations from linearity will depend on the measurements to be made with the pickup.

4. Standard Calibration Methods

In order to perform a direct calibration of a pickup, it is necessary to use an exciter which applies a controllable and measurable input to the pickup and to provide a means for recording or measuring the output of the pickup. The pickup is attached to the exciter (or is placed near it in the case of pickups whose output depends on the relative motion between the pickup and the vibrating object). If a fixture is

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Table 1
Estimated Ranges and Errors of Standard Methods

Method:	Tilting support	Centrifuge	Rectilinear electrodynamic calibrator	Physical pendulum	Ballistic pendulum
Input	constant acceleration	constant acceleration	sinusoidal acceleration, velocity, or displacement	transient acceleration, velocity, or displacement	transient velocity or acceleration
Amplitude	$-g$ to $+g$	0–60,000g	0–25g 0–50 in./sec 0–0.5 inch	0–10g 0–100 in./sec	2500g
Frequency	0	0	8–2000 cps	0.5 to 5 cps	—
Duration of pulse	—	—	—	—	0.00035–0.001 sec
Maximum weight of pickup	10 lb	100 lb at 100g to 1 lb at 60,000g	2 lb	2 lb	1 lb
Estimated errors of input	±0.0003g	±1%	±1% (8–900 cps) ±2% (900–2000 cps)	±2%	±5%

NOTE: This table is confined to pickups which measure rectilinear motion.

used in attaching the pickup for making vibration measurements, it is desirable to use the same fixture during calibration. The attachment must be sufficiently rigid to transmit the motion of the exciter to the pickup over the frequency range of the pickup. This requires that the natural frequency of the system, consisting of the pickup regarded as the mass and the attachment as the spring of a single degree of freedom system, be high compared to the highest frequency component of the motion of the exciter. The exciter may be a support for tilting the pickup relative to the pull of gravity, a centrifuge, an electrodynamic exciter, a physical pendulum, or the anvil of a ballistic pendulum (see 4.2 to 4.6). The tilting support and centrifuge are used for calibration at zero frequency. The electrodynamic exciter is used for steady-state sinusoidal calibrations. Physical or ballistic pendulums, which apply transient excitation, may be used as a complementary method to the electrodynamic exciter, to bring out natural frequency response and to permit calibration at high accelerations and velocities. Also, transient excitation may be used to check that auxiliary instrumentation connected to the pickup functions properly under transient conditions.

The requirements for the exciter are less severe for calibration of the pickup by the comparison method (see Section 5). For this method the output of the pickup is compared with that of a previously calibrated pickup while both pickups are subjected to the same input. The exciter need only subject both pickups to the same input over the desired range of frequencies and amplitudes.

4.1 Tabulation of Standard Methods. Table 1 gives estimated ranges and errors for the standard methods described below. The errors were deemed representative for calibrators of good construction and calibrations with good laboratory practice at the time of writing of the standard. Extensions in ranges are to be expected with improvements in the design and construction of the calibrators. Smaller errors than those given in the table are possible in most cases if extreme care is taken to reduce systematic and accidental errors affecting the calibration.

4.2 Tilting Support Calibrator. The tilting support calibrator utilizes the earth's gravitational field for the calibration of rectilinear acceleration pickups with zero-frequency response and with negligible transverse sensitivity. It is useful over the range from $-g$ to $+g$. The pickup to be calibrated is fastened at A, Fig. 5, to a platform at the end of an arm, B, to indicate the component of acceleration along the arm. The arm may be set at an angle, ϕ, relative to the vertical between 0 and 180 degrees. It is furnished with a pointer to read off the angle, ϕ, from a divided circle. Care should be taken to level the base to which the pickup is attached in the position $\phi = 0$. Positioning of the arm, B, to ±0.1 degree or better is possible with an accurately divided circle.

The component of acceleration along the arm, B, is given by

$$a = g \cos \phi . \qquad \text{(Eq 18)}$$

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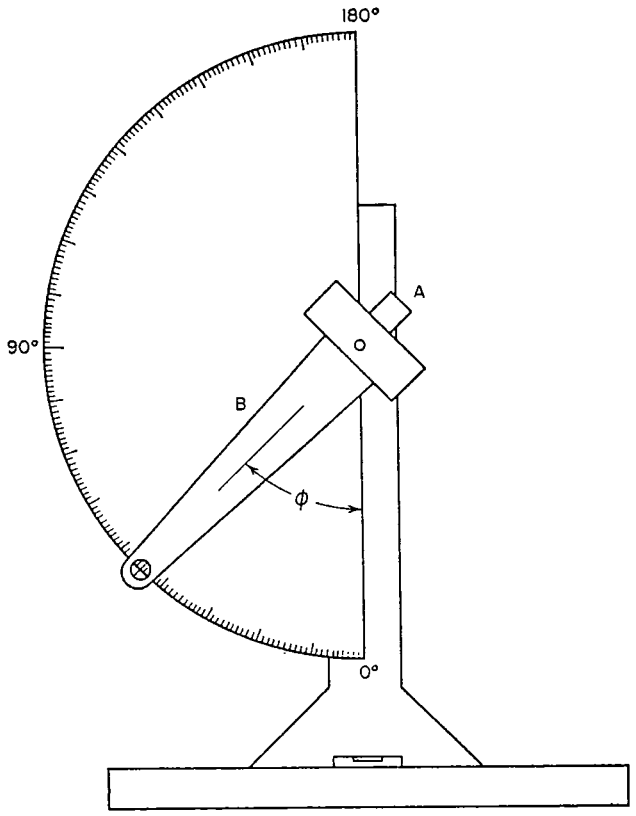


Fig. 5
Tilting Support for
Static Calibration of Acceleration Pickups

The change in acceleration, Δa, corresponding to an angular displacement, $\Delta\phi$, is, therefore,

$$\Delta a = -g \sin\phi\Delta\phi \,. \qquad \text{(Eq 19)}$$

The calibration factor is the change in output of the pickup divided by the corresponding Δa. Substituting $\Delta\phi = \pm 0.2$ degree $= \pm 0.004$ radian shows that the acceleration can be set within $|\Delta a| \leqq 0.004g$ where $|\Delta a|$ is the absolute value of Δa. In the neighborhood of $\phi = 0$ and 180 degrees for which $a = \pm g$, $|\Delta a|$ is much smaller; in fact, there is no difficulty in setting $\pm g$ within $\pm 0.0003g$.

The acceleration pickup is subjected to a component of acceleration at right angles to its sensitive direction equal to

$$a_t = g \sin\phi \,. \qquad \text{(Eq 20)}$$

Usually this does not affect the results of the calibration of pickups with negligible transverse sensitivity.

4.3 Centrifuge Calibrator. A centrifuge consists of a balanced table or arm which can be made to rotate about a vertical axis with uniform angular velocity. With this device an accurately known constant acceleration can be applied to an acceleration pickup for as long a time as desired. Centrifuges capable of subjecting pickups up to one pound in weight to accelerations up to 60,000g have been built [12] and centrifuges rated at lower accelerations are commercially available.

Only rectilinear acceleration pickups having zero-frequency response can be calibrated on a centrifuge.

To make a calibration, the acceleration pickup is mounted on the table or arm of the centrifuge with its axis of sensitivity carefully aligned on a radius of the circle of rotation. The acceleration acting on the pickup is

$$a = \omega^2 r \,, \qquad \text{(Eq 21)}$$

where ω is the angular velocity of the centrifuge in radians/sec and r is the distance from the axis of rotation to the center of gravity of the mass element of the pickup. Care is taken to mount the pickup at such a distance from the axis of rotation that the deflection of the mass element of the pickup can be neglected in the determination of r.

Most pickups are so constructed that it is not practical to measure r directly. The value of r may be determined from readings taken while the pickup, mounted at two positions separated by a known distance, Δr, is rotated on the centrifuge. It is good practice to adjust the speed so that approximately the same value of acceleration is applied to the pickup in both positions. The value of r in the second position, designated as r_2, is:

$$r_2 = \frac{\Delta r}{1 - \dfrac{\omega_2^2}{\omega_1^2}\dfrac{x_1}{x_2}} \,, \qquad \text{(Eq 22)}$$

where

ω_1 = the speed in the first position, for which $r = r_1 = r_2 - \Delta r$
ω_2 = the speed in the second position, for which $r = r_2$
x_1 = pickup output due to rotation speed ω_1
x_2 = pickup output due to rotation speed ω_2.

With this value of r_2 and the rotational speed ω_2, the acceleration can be determined from Equation 21.

The determination of r may be eliminated if the pickup has a linear range which extends down to $1g$. If this is the case, the pickup is first calibrated at $\pm g$ by the tilting support method. Then the pickup is placed on the centrifuge and the angular speed ω_1 is determined at which the output is that correspond-

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ing to 1g. The applied acceleration at another speed, ω, is then

$$a = \omega^2/\omega_1^2 . \qquad \text{(Eq 23)}$$

The angular velocity, ω, must be determined more accurately than the radial distance, r, because the applied acceleration varies as the square of this quantity. Most centrifuges which are designed for calibrating purposes are equipped with a tachometer which gives a direct indication of the speed of rotation within about 2 percent. A much more accurate determination of speed of rotation is possible either by stroboscopic means or by any one of several devices (e.g., one using a photoelectric cell or a magnet) which produces a pulse at a rate proportional to the speed. The pulse rate may be determined with an electronic counter.

In the calibration of electromechanical pickups on a centrifuge, leads are brought out through slip rings and brushes. Since acceleration pickups with zero-frequency response are relatively low-impedance devices, shielding from external fields and cable noise present no particular problem. The electrical noise from a worn-in slip-ring assembly of good design is negligible under normal circumstances. However, certain acceleration pickups using strain gages as the sensing element contain only one or two active elements, the other resistances of the Wheatstone bridge circuit being added externally. With such a pickup, the entire bridge should be mounted on the rotating table to avoid false signals which would otherwise occur as a result of small changes in resistance of the slip-ring assembly. Alternatively, a Kelvin bridge circuit may be used. [13]

In the calibration of pickups at small accelerations, gravity may have a significant effect if the pickup is sensitive to transverse accelerations. If possible, the pickup should be placed on the centrifuge with the axis of maximum transverse sensitivity of the pickup in a horizontal plane.

The sensitivity of an acceleration pickup at zero frequency can be determined with one percent accuracy or better on a good centrifuge. Calibration on a centrifuge will, of course, give no indication of the usable frequency range of the pickup.

4.4 Rectilinear Electrodynamic Vibration Pickup Calibrator. The rectilinear electrodynamic vibration pickup calibrator is a carefully designed and constructed rectilinear vibration exciter of the electrodynamic type equipped with a velocity-sensing coil to measure the vibration imposed on the pickup. This type of calibrator has gained a leading position among the calibration equipment in general use because it provides a means for applying sinusoidal excitations over a wide range of displacement amplitudes (10^{-6} to 1 inch), and over a wide range of frequencies (1 to 10,000 cps) with a relatively undistorted wave form. Sinusoidal acceleration amplitudes up to about 25g may be applied.

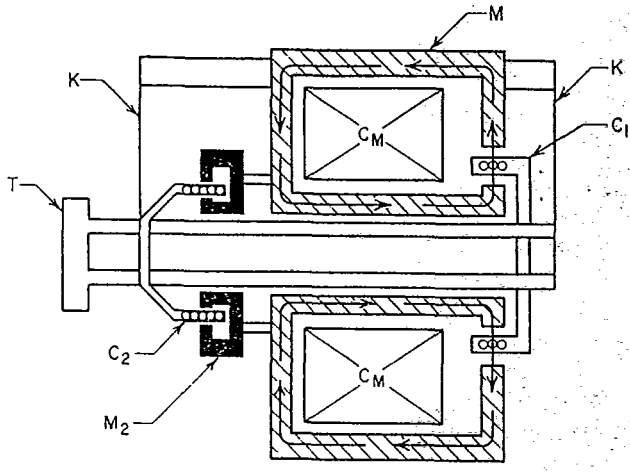


Fig. 6

Schematic Cross-sectional View of Rectilinear Electrodynamic Vibration Pickup Calibrator

The construction of a typical electrodynamic vibration pickup calibrator is illustrated schematically in Fig. 6. The pickup to be calibrated is rigidly attached to a table, T, which, together with the other moving parts, is supported on the main magnet, M, of the calibrator by springs, K, designed to constrain the motion of the moving parts to an axial direction. The table is set in motion by passing alternating current through the driving coil, C_1, which is connected to the table, T, and which is positioned in an annular air gap in the main magnet, M. The main magnet is excited by passing direct current through the field coil, C_M. The resulting axial motion of the table, T, is measured with the velocity-sensing coil, C_2. Coil C_2 is connected concentrically to the table and extends into an annular air gap in the small permanent magnet, M_2. Magnet M_2 of some calibrators is flexibly mounted relative to the calibrator frame in order that the structure and air gap magnetic field will remain stationary in a fixed reference system, allowing the generated voltage to be proportional to the absolute velocity of the table motion.

Some vibration pickup calibrators are mounted on trunnions, allowing the unit to be used with the axial table motion in a vertical as well as a horizontal direction.

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Careful attention must be given to many details in the design and construction of a calibrator of this type. Care must be taken to shield adequately the magnets, M and M_2, and the driving coil so that the magnetic field at the mounting table will be small. This is important if the calibrator is to be used to calibrate pickups sensitive to magnetic fields, e.g., electrodynamic velocity pickups. Care should also be taken to make the weight of the table and coil assembly small enough to attain the desired maximum amplitude with the exciting force supplied by the driving coil. At the same time, the assembly must be made stiff enough to make it free from resonant response throughout the operating range. This requires a minimum of structural weight distributed throughout the assembly. The moving parts must be suspended by flexible attachments between them and the calibrator body which will properly locate the force-generating coil in the gap in magnet M and support the added weight of the mounted pickup when the calibrator is used in the vertical direction. The suspension should be compliant enough to minimize its elastic restraint in an axial direction and to lead to a sufficiently low natural frequency of the moving parts acting as a rigid body, but it should be stiff enough to keep the deflection of the moving parts, due to their weight, within tolerable limits when the calibrator is used in the vertical direction. The elastic elements in the suspension should tend to prevent rotational motion of the mounting table during its vibration. Unfortunately, it is not always possible to satisfy all these requirements without resonant responses in the springs, K, and moving parts that cause motion in a plane transverse to the axial direction. In many cases the frequencies where these resonances occur can be changed by adding weights to the resonant parts. The transverse motion caused by these resonances may be reduced by providing adequate damping.

The calibrator is operated, usually, at frequencies well above the natural frequency of the moving parts acting as a rigid body. At these frequencies, the acceleration wave form of the table, T, is similar to the wave form of the driver current in C_1; the wave forms for velocity of table motion and displacement of table motion have less distortion than those for acceleration, since velocity and displacement are single and double integrals, respectively, of the acceleration. Obviously, it is important that the calibrator apply pure sinusoidal motion. A suitable wave analyzer can be used to determine if the distortion in the wave form of the motion is negligible.

Since the electrodynamic vibration calibrator contains two linear electrodynamic transducers, a driving coil, C_1, and a velocity-sensing coil, C_2, its sensitivity as a function of frequency can be determined by the reciprocity method. The general theory of the reciprocity method and its application to certain vibration pickups are described in A1.2 and A2 of the Appendix. A3.1 describes a modified reciprocity method and theory which are applicable to electrodynamic calibrators. This modified reciprocity method is briefly outlined in 4.4.1.

A calibrator, the sensitivity of which is determined by this absolute method described in 4.4.1, serves as a primary standard. An absolute determination of the sensitivity of the calibrator can also be made by the comparison method (see Section 5) at frequencies where the sensititivy of the comparing pickup has been determined by an absolute method. The calibrator then would be secondary standard. Optical methods can also be used at certain frequencies (see A1.2) to determine the amplitude sensitivity of a calibrator. The value of amplitude sensitivity obtained should agree with that obtained by the method described in 4.4.1. In the subsequent subsection, 4.4.2, three methods are outlined for calibrating vibration pickups on such a calibrator.

4.4.1 ***Sensitivity of Electrodynamic Calibrator Determined by Reciprocity Method.***[3] When the calibrator is energized with current in the driving coil at any particular frequency, the sensitivity, S_{uc}, is defined as the ratio of the voltage, E_{13}, in volts in the velocity-sensing coil to the velocity, U, in inches per second at the surface of the mounting table, i.e.,

$$S_{uc} = \frac{E_{13}}{U} . \qquad \text{(Eq 24)}$$

The object of the reciprocity method is to determine the sensitivity S_{uc} so that when the voltage E_{13} is measured, the velocity U may be computed by use of Equation 24. S_{uc} is determined from the following equation which is developed in the Appendix, Section A3:

$$S_{uc} = S_o + s_z Z_m , \qquad \text{(Eq 25)}$$

where Z_m is the pickup mechanical impedance (lb-sec/in.) and the quantities S_o and s_z are de-

[3] It is assumed throughout the remainder of 4.4 that the usual engineering system of electrical and mechanical units is employed (inch, pound, second, ampere, volt). All boldface italic symbols represent complex numbers in the manner commonly used for alternating-current electrical theory. If the same symbol appears in ordinary italic type, it indicates the magnitude of the complex number is used without regard to its phase angle. The number subscripts on the voltage symbols are used to facilitate identifying the terminals of Figs. A8 and A9.

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termined by the following two experiments and computational procedure.

Experiment 1: Several weights are attached to the mounting table. For each weight and for no weight attached, the transfer admittance Y_e in amperes per volt is measured between the driving and sensing coils:

$$Y_e = \frac{I}{E_{13}}, \qquad \text{(Eq 26)}$$

where

I = current in driving coil

E_{13} = voltage generated in open-circuited sensing coil.

A suggested procedure for measuring Y_e is given in the Appendix, A3.2.1.

Experiment 2: The moving parts of the calibrator are set into sinusoidal vibration by connecting the mounting table of the calibrator to a vibration exciter and then energizing the exciter. The ratio, E_{13}/E_{15}, of the open circuit voltage, E_{13}, generated in the velocity-sensing coil to the open circuit voltage, E_{15}, generated in the driving coil is measured. A suggested procedure for measuring this ratio is given in the Appendix, A3.2.2.

At frequencies above axial resonances in the moving parts (above 1000 cps for most calibrators), the above two experiments are conducted with the field coil at the same temperature.

Computational procedure: Determine the ordinate intercept, J, and the slope, Q, of the function $W/(Y_{ew} - Y_{eo})$ when plotted against the weight, W, attached to the mounting table in Experiment 1, where Y_{ew} is the value of Y_e with weight W attached and Y_{eo} the value for $W = 0$. This plot is made by separating $W/(Y_{ew} - Y_{eo})$ into its real and imaginary parts from which the real and imaginary parts of J and Q are determined, (see the Appendix, A3.1). The quantities S_o and s_z in Equation 25 are then given by

$$S_o = 0.01711\sqrt{j\omega J E_{13}/E_{15}}, \qquad \text{(Eq 27)}$$

$$s_z = 6.601Q\sqrt{(E_{13}/E_{15})/(j\omega J)}, \qquad \text{(Eq 28)}$$

where ω is the frequency in radians per second, and j is the unit imaginary vector.

4.4.2 ***Calibration of Vibration Pickups on Calibrator, General Method.*** Before a pickup can be calibrated, its mechanical impedance, Z_m, must be known so that it can be used in Equation 25 to determine the sensitivity of the calibrator for use with the particular pickup being calibrated. For many vibration pickups, sufficient accuracy is achieved if Z_m is computed from the formula $Z_m = j\omega W/g$ where W is the total weight of the pickup and the fixtures used to attach it to the mounting table. However, this formula cannot be used if the weight of the seismic mass element of the pickup is not small compared to W. This is particularly true if the pickup is used near or above its natural frequency as in certain velocity pickups in which the seismic mass element is a permanent magnet. If Z_m of the pickup is not known, it can be measured on the calibrator by the following procedure. The transfer admittance Y_{ep} given by Equation 26 is measured with the pickup attached to the mounting table. Also, the transfer admittance Y_{eo} is measured with nothing attached to the table. A suggested procedure for making these measurements is given in A3.2.1. These values are substituted into the following equation, which is derived in A3.1:

$$Z_m = j\left(\frac{\omega}{386}\right)\frac{J(Y_{ep} - Y_{eo})}{1 - Q(Y_{ep} - Y_{eo})}. \qquad \text{(Eq 29)}$$

The measurements of Y_{ep} and Y_{eo} should be made at the same field-coil temperature that was used when J and Q were determined in Experiment 1, (see 4.4.1).

The calibration of the pickup is then performed by measuring two transfer admittances, with the pickup attached, connected, or placed near to the mounting table in the same manner that the pickup is normally used to measure vibrations. In order to calibrate the pickup, it is only necessary to measure the ratio of the voltage from the pickup to that from the velocity-sensing coil of the calibrator. This can conveniently be done by the following procedure. First the transfer admittance Y_{ep}, i.e., the ratio of the current, I, in the driving coil to the voltage E_{13} in the velocity-sensing coil, is measured. Then the transfer admittance $Y_{ep'}$, i.e., the ratio of the current, I, in the driving coil to the voltage $E_{13'}$ in the pickup, is measured. These measurements are repeated at each frequency at which a calibration is desired. The procedure outlined in A3.2.1 may be used for these measurements. The displacement, velocity, and acceleration sensitivities of a pickup are, respectively,

$$S_d = \frac{Y_{ep}}{Y_{ep'}} j\omega S_{uc}, \qquad \text{(Eq 30)}$$

$$S_u = \frac{Y_{ep}}{Y_{ep'}} S_{uc}, \qquad \text{(Eq 31)}$$

$$S_a = \frac{Y_{ep}}{Y_{ep'}} \frac{S_{uc}}{j\omega}. \qquad \text{(Eq 32)}$$

The acceleration sensitivity of pickups is usually given in units of output per g (g = approximately

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386 in./sec^2), in which case the right side of Equation 32 must be multiplied by g. Since the phase angle measurements are made, it is very easy to determine the undamped natural frequency of the pickup by noting at what frequency the phase lag of the sensitivity is 90 degrees.

The calibration may be performed at frequencies other than those for which S_o and s_z are known by interpolating to determine these values at the calibration frequency. At frequencies where there is no relative motion between the mounting table and velocity-sensing coil, S_o will be a constant, independent of frequency, and the term $s_z Z_m$ will be negligible compared to S_o. Usually this term is negligible at frequencies up to 900 cps for pickups which weigh less than 2 pounds. This simplifies the computation greatly since it is not necessary to measure the mechanical impedance, Z_m, of the pickup. The calibration can be further simplified if only the amplitude sensitivity (S_d, S_u, or S_a) of the pickup is desired. In this case, Y_{ep} and $Y_{ep'}$ are measured directly without regard to phase angle and S_{uc} instead of S_{uc} is used in Equations 30, 31, and 32.

4.4.2.1 *Alternate Calibration Method A.* The above method, described in 4.4.2, is general in so far as it can be used throughout the usable frequency range of the calibrator whether or not the mechanical impedance, Z_m, of the pickup is known. The following somewhat simpler method is applicable if the mechanical impedance of the pickup is known or if the term $s_z Z_m$ is negligible compared to S_o. A voltage-dividing circuit is put across the velocity-sensing coil, C_2, as shown in Fig. 7, with R_1 large in comparison with the coil impedance. The variable resistance, R, is adjusted until E_R is equal to $E_{13'}$ as indicated by a high-impedance voltmeter. Then the displacement, velocity, and acceleration amplitude sensitivities of a pickup are, respectively,

$$S_d = \frac{R}{R + R_1}\,\omega S_{uc}\,, \qquad \text{(Eq 33)}.$$

$$S_u = \frac{R}{R + R_1}\,S_{uc}\,, \qquad \text{(Eq 34)}$$

$$S_a = \frac{R}{R + R_1}\,\frac{S_{uc}}{\omega}\,. \qquad \text{(Eq 35)}$$

As in Equation 32, the right side of Equation 35 must be multiplied by g if it is desired to give S_a in output/g. If the phase lag of the pickup is desired, a suitable method for measuring the phase angle between the output of the pickup and the velocity-sensing coil should be used and the above equations should be modified to make them identical to Equations 30, 31, and 32 except that $E_{13'}/E_{13}$ replaces $Y_{ep}/Y_{ep'}$. If the voltage $E_{13'}$ is greater than E_{13}, the voltage-dividing circuit should be connected across the pickup output instead of across the velocity-sensing coil, C_2, and Equations 33, 34, and 35 should be changed correspondingly.

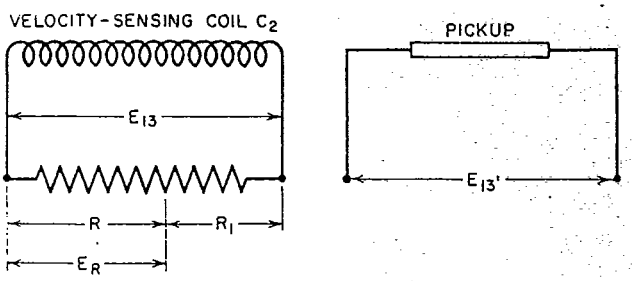


Fig. 7
Circuit for Calibration by Method A

4.4.2.2 *Alternate Calibration Method B.* This alternate method is similar to alternate method A except that it does not require the output of the pickup to be measured with a voltmeter, e.g., the output may be taken from an oscillographic record. With the pickup attached to the mounting table, the output voltage, E_{13}, of the velocity-sensing coil, C_2, is measured with a voltmeter or other suitable instrument and, at the same time, the output of the pickup is measured. The displacement, velocity, and acceleration amplitude sensitivities of a pickup are, respectively,

$$S_d = \frac{\text{pickup output}}{E_{13}}\,\omega S_{uc}\,, \qquad \text{(Eq 36)}$$

$$S_u = \frac{\text{pickup output}}{E_{13}}\,S_{uc}\,, \qquad \text{(Eq 37)}$$

$$S_a = \frac{\text{pickup output}}{E_{13}}\,\frac{S_{uc}}{\omega}\,. \qquad \text{(Eq 38)}$$

As in Equation 32, the right side of Equation 38, must be multiplied by g if it is desired to give S_a in output/g. If the phase lag is desired, a suitable method for measuring the phase angle between the pickup output and the velocity-sensing coil should be devised. It is difficult to obtain an accuracy of 1 percent by this method since the accuracy depends not only on S_u but also on the accuracy with which E_{13} and the pickup output are measured.

4.5 Physical-Pendulum Calibrator. The physical-pendulum calibrator is a simple device for subjecting a rectilinear acceleration pickup with negligible transverse sensitivity to a nearly sinusoidal

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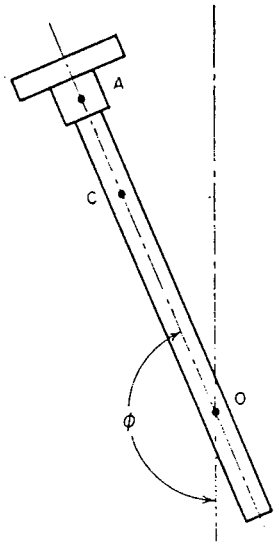


Fig. 8

Pendulum Calibrator

transient pulse of acceleration up to several times g for a duration of the order of one second.

The physical-pendulum calibrator consists of a physical pendulum, Fig. 8, with center of gravity at C. The pendulum is free to swing about a horizontal axis through O and is provided with a platform to which the pickup to be calibrated is attached. If this platform is deflected by an angle, ϕ_1, from the vertical and is released, it will swing to its lowest position with an acceleration having radial and tangential components which vary nearly sinusoidally with time. The variation will be exactly sinusoidal only if the amplitude ϕ_1 is very small and if friction is negligible. However, regardless of the amplitude ϕ_1, the radial component of acceleration will vary from $g \cos \phi_1$ at the instant of release to $g + u_1^2/l_p$ at the lowest point of the swing where u_1 is the tangential velocity of the platform at a distance l_p from the axis of rotation; this velocity may be computed directly from the conversion of the change in potential energy from dropping the center of gravity of the pendulum into the kinetic energy of rotation of the pendulum. The tangential component of acceleration will vary from $g \sin \phi_1$ at the point of release to zero at the lowest point of the swing. For large angles of swing such as indicated in Fig. 8, the change in the radial component of acceleration imposed on the platform during the swing is much greater than the change in the tangential component. Hence it is preferable to place the pickup to be calibrated on the platform with its axis of sensitivity in a radial direction.

For calibration, the pickup is attached with its axis of sensitivity along a radius, l_p = **OA** of the pendulum and with its mass element at A. The pendulum is deflected from the vertical downward direction, is allowed to swing through one or more complete cycles and the output of the pickup is recorded as a function of time, as indicated in Fig. 9. Both the maximum angle, ϕ_1, from which the pendulum starts at the beginning of a cycle and the angle, ϕ_1', to which it returns at the end of that cycle are measured carefully and their average is taken as the average amplitude of deflection, ϕ, for the cycle:

$$\phi = \frac{\phi_1 + \phi_1'}{2}. \qquad \text{(Eq 39)}$$

The acceleration input, Δa, is defined as the difference in the acceleration at $\phi = 0$ minus the acceleration at $\phi = \phi_1$. It is obtained by substituting ϕ in the following equation:

$$\Delta a = g\left(1 + 2\,\frac{l_p l_0}{\kappa^2}\right)(1 - \cos \phi), \qquad \text{(Eq 40)}$$

where

g = acceleration of gravity

l_p = **AO** = distance of center of gravity of the mass element of the pickup from axis of rotation

l_o = **CO** = distance of center of gravity of physical pendulum, including pickup, from axis of rotation

κ = radius of gyration of physical pendulum about axis of rotation.

The quantity l_o/κ^2 in this equation may be determined from the period, T, of the pendulum when it is allowed to oscillate with a small amplitude. This is given by [15]

$$T = 2\pi \sqrt{\frac{\kappa^2}{l_o g}}. \qquad \text{(Eq 41)}$$

Substitution of Equation 41 in 40 leads to

$$\Delta a = g\left(1 + \frac{8\pi^2 l_p}{T^2 g}\right)(1 - \cos \phi). \qquad \text{(Eq 42)}$$

The output, E, of the pickup corresponding to the acceleration input may be read from a record such as that of Fig. 9 as follows:

$$E = \frac{(E_1 - E_o) + (E_1' - E_o')}{2}, \qquad \text{(Eq 43)}$$

where E_o and E_o' are the outputs from the pickup at the instant the pendulum passes through the bottom on successive swings. E_1 and E_1' are the outputs from the pickup corresponding respectively to ϕ_1 and ϕ_1'

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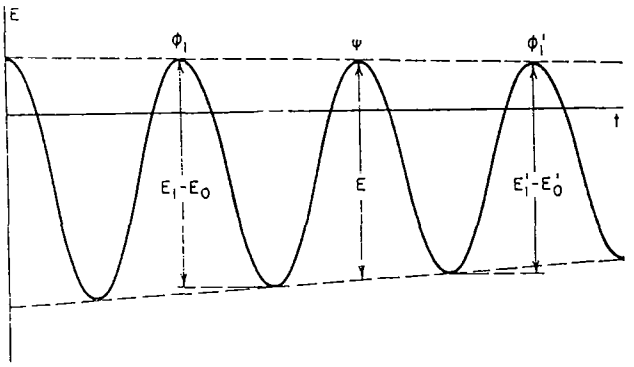


Fig. 9
Recorded Output of Pickup on Physical Pendulum Calibrator

when the pendulum reaches the highest point in its swings at the beginning and at the end of the complete cycle. The amplitude sensitivity of the pickup is the ratio of this output to the acceleration input, Δa.

Equation 41 requires that the pickup be rigidly attached to the pendulum and that its mass element be negligible compared to the mass of the pendulum. The period, T, should be measured with ϕ less than 15 degrees and with the pickup or a mass equal to that of the pickup attached at A, Fig. 8. The decay in amplitude of the pendulum

$$2(\phi_1 - \phi_1')/(\phi_1 + \phi_1'),$$

should be small, probably less than 2 percent per cycle, in order that the approximation in Equation 39, would cause little error in the Δa of Equation 40.

Accelerations up to $10g$ have been applied to light acceleration pickups with pendulum calibrators consisting of a solid bar of constant section [16]. There is no difficulty in measuring the imposed acceleration within 2 percent.

4.6 Ballistic Pendulum Calibrator. The ballistic pendulum calibrator provides a convenient means for applying a sudden change in velocity to rectilinear velocity or acceleration pickups which are designed to measure shocks or high frequency vibrations. It is particularly useful because it is applicable to pickups without zero-frequency response as well as to those with zero-frequency response.

The ballistic pendulum calibrator consists of two masses m_1, m_2 which are suspended by wires, or metal ribbons, as indicated in Fig. 10. The supports permit the masses to swing freely in a common vertical plane and offer a firm constraint against lateral motions. They maintain a fixed horizontal alignment of the principal axes of the masses in a direction parallel to the direction of motion at impact and cause the impact to take place on the principal axes. The mass m_1, used as the hammer, strikes the anvil mass m_2 when the latter is at rest at its lowest position.

The velocity attained by the anvil mass as the result of the impact must be determined. This can be done by several methods, one of which merely requires a determination of the period and the amplitude of swing of the anvil pendulum. The drag imposed by attached elements must be negligible. The pendulum method illustrated is but one of many arrangements possible for obtaining a reproducible velocity change in a controlled time and direction. The general principles given below apply to all such impact methods of calibration.

The velocity or acceleration pickup to be calibrated (A, Fig. 10) should have a mass which is small compared with the anvil mass to which it is attached and should have its sensitive direction carefully aligned with the direction of the impact force during collision. The impact should be controlled so that the velocity change is not so rapid, or so slow, as to excite important frequency components outside of the response range of the instruments.

The velocity change resulting from the impact is

$$\Delta u = \int_{t_1}^{t_2} a\, dt, \qquad \text{(Eq 44)}$$

where a is acceleration, t is time, and t_1, t_2 denote the beginning and the end of the impact.

Equation 44 makes possible the calibration of a linear acceleration pickup from its recorded output during the ballistic impact.

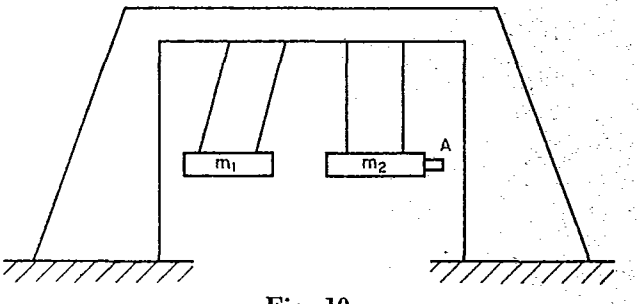


Fig. 10
Calibration of Pickup A on Ballistic Pendulum Calibrator

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The calibration factor of the pickup may be written as:

$$S_a = \frac{e}{a}, \qquad \text{(Eq 45)}$$

where e is the voltage output of the pickup corresponding to the acceleration, a.

In the case of piezoelectric pickups, $e = q/C$ where q is the charge in coulombs developed by the pickup and C is the capacitance in farads of the pickup plus all parallel capacitances charged by the voltage, e.

Either one of two techniques may be used to obtain the calibration factor. Technique 1 requires a graphical determination of the area under the curve of recorded output, proportional to acceleration, as a function of time. Technique 2 eliminates this by electrically integrating the signal from the pickup so as to obtain a "velocity" output. They are described, respectively, in References 17 and 18 and are given briefly as follows:

Technique 1: Obtain an oscillographic record of the impact, giving the output of the acceleration pickup as a function of time. Determine the time and voltage scales of the record by superimposing a calibrated voltage signal, e_c, and a calibrated time signal, t_c, on the record. If the resultant deflections on the record are y_c and x_c, respectively, the voltage and time scale factors are given by

$$\begin{aligned} K_1 &= e_c/y_c, \\ K_2 &= t_c/x_c. \end{aligned} \qquad \text{(Eq 46)}$$

Define the area under the record of accelerometer output vs time by

$$A = \int_{x_1}^{x_2} y\,dx, \qquad \text{(Eq 47)}$$

where x_1, x_2 denote the beginning and the end of the impact. Substitution of these quantities in Equation 45 results in

$$S_a = \frac{K_1 K_2 A}{\Delta u}. \qquad \text{(Eq 48)}$$

If S_a is desired in units of output/g, the right side of Equation 48 must be multiplied by g. The area, A, can be obtained by graphical integration. If the impact is against a linear spring, it will have the shape of a half-sine pulse of area $A = 0.637\ hb$ where h and b are the height and width of the pulse, respectively.

Technique 2: If a simple RC_1 network consisting of a series resistance, R, followed by a parallel capacitance, C_1, Fig. 11, is used to integrate the output of the acceleration pickup, the integrated output voltage is

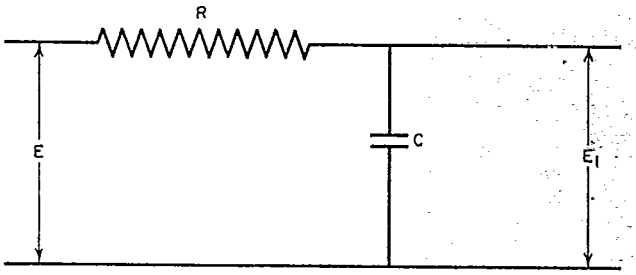


Fig. 11

Simple RC Network for Integrating Pickup Output

$$e_1 = \frac{1}{RC_1}\int_{t_1}^{t_2} e\,dt, \qquad \text{(Eq 49)}$$

from which

$$e_1 = \frac{S_a}{RC_1}\int_{t_1}^{t_2} a\,dt = \frac{S_a \Delta u}{RC_1} \qquad \text{(Eq 50)}$$

or

$$S_a = \frac{RC_1 e_1}{\Delta u}. \qquad \text{(Eq 51)}$$

If S_a is desired in units of output/g, the right side of Equation 51 must be multiplied by g.

Nonlinearity in the pickup should be suspected if different calibration factors result from impacts of different intensities.

Ballistic-pendulum calibrators make possible the calibration of linear shock and vibration pickups with an error of less than 5 per cent.

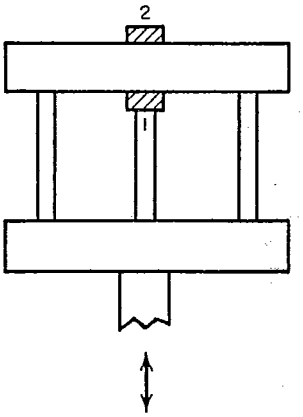


Fig. 12

Comparison Method for Calibrating Pickup 2 Against Calibrated Pickup 1

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5. Calibration by Comparison with Calibrated Pickup

A pickup calibrated by any one of the above standard methods may be used as a secondary standard for the calibration of other pickups.

In making such a calibration, both the calibrated pickup 1 and pickup 2 to be calibrated are subjected to the same input motion by mounting the pickups back to back (see Fig. 12), and their outputs, x_1 and x_2, measured. If both pickups 1 and 2 are linear, the amplitude sensitivity, S_2, of pickup 2 is related to the corresponding amplitude sensitivity, S_1, of the calibrated pickup by

$$S_2 = \frac{x_2}{x_1} S_1 . \qquad \text{(Eq 52)}$$

Calibration by this comparison method is limited to the range of frequencies, time duration of pulses, and amplitudes for which pickup 1 has been calibrated. The sensitivity S_2 may also be determined if the phase response of pickup 1 is known and if the phase relation between x_2 and x_1 is measured.

Care must be taken to insure that pickups 1 and 2 experience the same motion. If both pickups are rectilinear and are placed on the table of a vibration exciter, the rocking motion of the table must be negligible. This may be checked by moving one of the pickups farther away from the center of the table. The error due to rocking motion may be reduced by attaching pickups 1 and 2 firmly on opposite faces of the table near the center of the table, (see Fig. 12).

One may check that the relative translational motion between the points of attachment for 1 and 2 is negligible by exchanging pickups 1 and 2 and noting whether or not x_2/x_1 is the same for both positions.

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Appendix

(This Appendix is not a part of American Standard† Methods for the Calibration of Shock and Vibration Pickups, S2.2-1959, but is included to facilitate its use.)

A1. Survey of Other Calibration Methods

A1.1 Static Calibration Methods. This heading includes calibration methods in which the pickup is subjected to a constant acceleration. Two static calibration methods, the tilting support calibrator and the centrifuge calibrator are included with the standard methods and are described in 4.2 and 4.3. These two methods are applicable only to the calibration of acceleration pickups having zero-frequency response, while the static load method described below can be used also for the calibration of acceleration pickups having no zero-frequency response.

A1.1.1 ***Static Load Method.*** Acceleration pickups consisting of an exposed mass element riding on a spring as a single-degree-of-freedom system can be calibrated at accelerations greater than $\pm g$ by placing the sensitive axis of the acceleration pickup in a vertical direction, adding a constant vertical force, f, to the weight $W = mg$ which acts at the center of gravity of the mass element, and measuring the resulting change in output of the acceleration pickup. Usually the force can be applied by weights [19]. The total equivalent acceleration is then given by

$$a = \frac{f + W}{m}, \qquad \text{(Eq 53)}$$

where f is taken as positive if acting in a downward direction.

A modification of this technique is sometimes used to calibrate piezoelectric acceleration pickups, which have no zero-frequency response. The output of the pickup is connected to a microcoulombmeter [20]. The static load is slowly applied to the acceleration pickup, is maintained at a prescribed value until equilibrium is reached, and is then suddenly released. The accompaning release of charge by the piezoelectric element is measured with the microcoulombmeter. The impedance of the microcoulombmeter must be sufficiently high so that the meter which indicates the charge output of the acceleration pickup can be read before significant leakage takes place.

A1.2 Dynamic Calibration by Sinusoidal Excitation. Dynamic calibrations of shock and vibration pickups are generally made by subjecting them to sinusoidal excitation over the working range of frequencies for which the pickup is designed. This method is generally used for continuous reading pickups. The sinusoidal motion applied by the exciter should be along a well defined straight line; lateral motion should be negligible.

Many dynamic calibration methods depend on the accurate measurement of the amplitude of the vibration to which the pickup is subjected.

Several optical methods are available. Relatively large amplitudes may be measured by observing the image of a sharp wedge or of two intersecting lines placed on the vibrating body with the base line PA at right angles to the vibration. For this purpose one may attach to the body a card having one straight line, PA, [see Fig. A1(A)] perpendicular to the expected motion and another, PB, intersecting the first at P and forming a small angle with it. When vibrating [see Fig. A1(B)], the apparent intercept, C, is displaced from P′ by an amount proportional to the peak-to-peak amplitude, PP′, of the vibratory motion. If a scale is marked along PA at each tenth of its length, as shown in Fig. A1(A), it is possible to read directly the double amplitude to tenths of the distance **AB** and estimate to hundredths. If in the example, Fig. A1(B), **AB** equals 0.1 inch, and the intercept is at **P′C** = 0.75 PA, the double amplitude **PP′** equals 0.075 inch. The use of this method with the triangular area APB filled in to form a wedge should be avoided since this may introduce an error due to the penumbra.

Vibration amplitudes of the order of 0.5 inch can be measured with an accuracy of the order of ±0.01

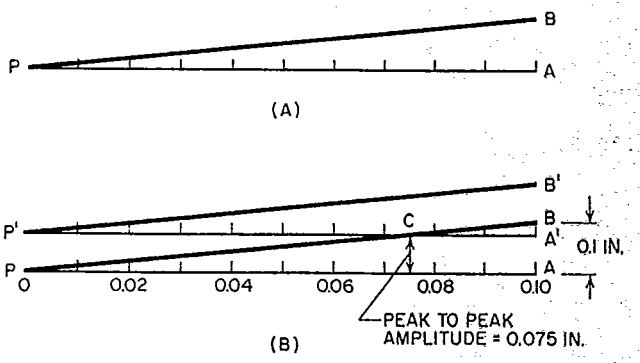


Fig. A1

Vibrating Wedge

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inch by observing the amplitude of a brightly illuminated point on the vibrating body through a telescope fitted with a reticule on which a sheet of cross section paper has been photographed [21]. With modern telescopes equipped with optical micrometers, amplitudes may be read in thousandths of an inch.

Vibrations of small amplitude are commonly determined by direct viewing with a microscope, with errors of about 0.0005 inch. Care should be taken to isolate the microscope from the vibration exciter. A hairline moved by a micrometer screw in the eyepiece improves the ease and accuracy of the measurement. The use of stroboscopic light [22] to give the illusion of slowing or stopping the motion is also an aid. With the use of specially designed equipment, this method has been used to measure amplitudes of displacements from 6×10^{-4} cm at 3500 cps to 0.2 cm at 30 cps [23].

Extremely small amplitudes of vibration can be determined under laboratory conditions by using the phenomenon of disappearance of the interference bands at discrete amplitudes. This method has been applied over the frequency range from 50 cps to 11,000 cps [23, 24]. According to Reference 25 it is possible to use this method up to 20,000 cps.

The measured displacements can be used to indicate velocities and accelerations by the equations $U = 2\pi fD$ and $A = (2\pi f)^2 D$ which are derived by single and double differentiation respectively for the sinusoidal displacement, D, and frequency, f. These formulas assume that the harmonic and noise content of the motion remains negligible even after the differentiation. They emphasize the need for minimizing the distortion due to the electrical power supply or due to other causes such as bearing noise. The harmonics are objectionable also since they may excite resonant response in a pickup.

Acceleration amplitudes of $1g$ in a vertical direction can be measured by the Bragg chatter method [26], which utilizes the fact that a solid body resting on a vibrating support will start to bounce or "chatter" on the support as this support is vibrated vertically with an acceleration amplitude exceeding $1g$. In a refinement by Kissinger [27], chatter is detected with a piezoelectric pickup; with this method acceleration amplitudes from about $1.01g$ to $1.04g$ may be set with an accuracy of approximately ± 0.5 percent at frequencies up to 60 cps, and with less accuracy to about 150 cps.

Linear electromechanical pickups can be calibrated indirectly without measurements of motion by a reciprocity method [28, 29, 30]. The theory of the reciprocity method is outlined in Section A2. In the method most frequently used, two different tests are performed to calibrate two pickups simultaneously. At least one of the pickups, identified below as the first pickup, must be reciprocal. In the first test the two pickups are driven mechanically by a common sinusoidal excitation, and the ratio of their open-circuit output voltages is measured. In the second test the first pickup is used to drive the second pickup. For this purpose, the second pickup is connected mechanically to the first pickup with a known mass at their junction. The first pickup is driven electrically with a measured current and the open-circuit output voltage is measured for the second pickup. The ratio between the current of the first and the voltage of the second pickup is measured at least twice, using first one, and then another mass attached to the common junction. With the velocity sensitivity, S_u, defined as the ratio of the open-circuit output voltage to the velocity of the pickup housing, the first test yields the ratio S_{u1}/S_{u2} and the second test yields the product $S_{u1}S_{u2}$. The individual velocity sensitivities are then obtained by simple multiplication. If it is desired to determine the acceleration or displacement sensitivity, S_u should be, respectively, divided or multiplied by $j\omega$. In making reciprocity calibrations, it is necessary to determine the weights of the masses, which are usually metallic cylinders. At the higher frequencies, it is also necessary to take into consideration the compliance of the masses [30].

A1.2.1 ***Rectilinear Vibration Exciter.*** A rectilinear vibration exciter applies rectilinear sinusoidal motion of controllable amplitude over a limited frequency range to a pickup attached to it. The frequency range is limited principally by the need for avoiding resonant response in the components of the exciter which may cause undesirable vibration in a lateral as well as in the axial direction. A vibration exciter may be used as a vibration pickup calibrator if it is equipped with a means for measuring the sinusoidal motion applied to the pickup. The motion can be measured by using a previously calibrated pickup or by one of the optical methods described above.

Rectilinear vibration exciters may be actuated by any one of a number of drives. Sinusoidal motion over a wide range of frequencies (1 to 10,000 cps) may be obtained with an electrodynamic drive [31, 32]. This drive is utilized in the rectilinear electrodynamic vibration pickup calibrator described in detail in 4.4 as one of the standard methods. Rectilinear vibration calibrators employing other types of drive are listed below.

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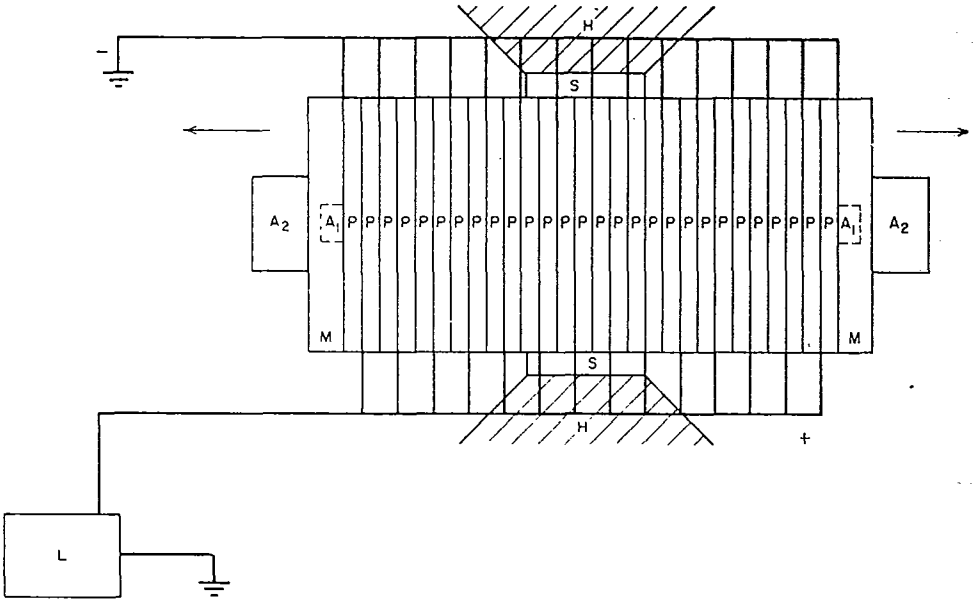


Fig. A2

Rectilinear Vibration Pickup Calibrator with Piezoelectric Drive

A_1 Built-in calibrated acceleration pickups
A_2 Acceleration pickups under calibration
M End plates for mounting acceleration pickups
P Individual crystals
S Compliant material
L Power generator
H Mount

A1.2.1.1 *Rectilinear Vibration Exciter with Positive Mechanical Drive.* Sinusoidal motion at relatively low frequencies (less than 100 cps) may be produced by a mechanical drive consisting of an electric motor turning a cam [33] or any other mechanism converting continuous rotation into sinusoidal displacement.

A1.2.1.2 *Rectilinear Vibration Exciter with Rotating Eccentric Weights.* Sinusoidal vibrations over a limited frequency range can be applied to a pickup mounting table by supporting the table on leaf springs which limit its motion to one direction and setting the table into vibration by the rotation of eccentric weights at a rate in rpm well above the fundamental frequency of the table on its supports [34, 35, 36].

A1.2.1.3 *Rectilinear Vibration Pickup Calibrator with Piezoelectric Drive.* Sinusoidal motions of small amplitudes of displacement at frequencies from 500 to 30,000 cps and with amplitudes of acceleration up to 1000*g* can be applied with a piezoelectric vibration exciter [37]. This consists of a stack of discs (Fig. A2) of piezoelectric material, such as barium titanate, which expand and contract when a sinusoidally alternating voltage is applied to the faces of the discs. The acceleration pickups A_2 are placed so that there are identical loads at each end of the crystal stack. The exciter is supported at its center with a compliant material to isolate it from the supporting structure. By means of interferometer techniques [24], the built-in crystal acceleration pickups A_1 are calibrated. Then the crystal acceleration pickups A_2 are calibrated by comparing the outputs of A_2 and A_1. Calibrations have been performed with accuracies of better than 5 percent up to frequencies of 10,000 cps and better than 10 percent up to 16,000 cps.

A1.2.2 ***Angular Vibration Exciter.*** An angular vibration exciter applies angular sinusoidal motion of controllable amplitude over a limited frequency range to a pickup attached to it. The driver setting the table into motion may be of the positive mechanical, the electrodynamic, or the rotating eccentric type, as outlined for the rectilinear vibration exciter in the previous section.

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Angular vibration exciters are available commercially to apply torsional oscillations at frequencies up to 1500 cps to pickups with moments of inertia up to 0.1 slug ft^2.

A1.2.3 ***Tilted Centrifuge.*** The acceleration applied in a centrifuge will have a gravitational component, $g \sin \phi \sin \omega t$, added to the centripetal acceleration, $r\omega^2$, if the axis of the centrifuge is inclined at an angle ϕ to the vertical. The effect of the gravitational component on a pickup approximated by a spring-mass system is discussed in Reference 38 for the case in which the centrifuge is spun about a horizontal axis ($\sin \phi = 1$).

A1.2.4 ***Dual Centrifuge.*** The dual centrifuge consists essentially of a small centrifuge eccentrically mounted on a large centrifuge, (see Fig. A3). The vibration pickup, A, attached to the small centrifuge may be driven independently or may be connected by a belt drive to a pulley fixed in space but concentric with the large centrifuge. When the two centrifuges are driven at constant angular velocities, the sensitive axis of the pickup is alternately changing its direction relative to the center of the large centrifuge at a frequency in cps equal to the angular velocity of the small centrifuge relative to the large centrifuge expressed in revolutions per second. The component of acceleration applied along the sensitive axis of the pickup at any time t is

$$a = r_c\omega^2 \cos \omega_p t + r\,(\omega \pm \omega_p)^2, \qquad \text{(Eq 54)}$$

where

ω = angular velocity of large centrifuge, rad/sec
ω_p = angular velocity of small centrifuge relative to the large centrifuge, rad/sec
r_c = distance between centers of both centrifuges
r = distance from center of gravity of mass element of pickup to center of the small centrifuge.

The sign is plus in the last term of Equation 54 when ω and ω_p are either both clockwise or both counterclockwise, and minus when they are in opposite directions.

When the term $r(\omega \pm \omega_p)^2$ can be neglected, the applied acceleration along the sensitive axis of the pickup reduces to the sinusoidal term

$$a = r_c\omega^2 \cos \omega_p t\,. \qquad \text{(Eq 55)}$$

Thus the component of acceleration applied along the sensitive axis of the pickup is sinusoidal. There is also a component of acceleration applied transverse to the sensitive axis, which renders this method inapplicable to pickups affected by transverse accelerations. The term $r(\omega \pm \omega_p)^2$ is zero if ω and ω_p are equal but in opposite directions. A dual centrifuge of this type can be built in the following manner. A pulley is fixed in space with its center coincident with the center of the large centrifuge [39]. A pulley of the same size is fixed concentrically to the small centrifuge and connected to the other pulley by a belt. The large centrifuge is driven by a motor and the angular velocities of both centrifuges about their respective centers will be always equal and opposite in direction. In this case Equation 55 is exact and the component of acceleration along the sensitive axis of the pickup should be purely sinusoidal.

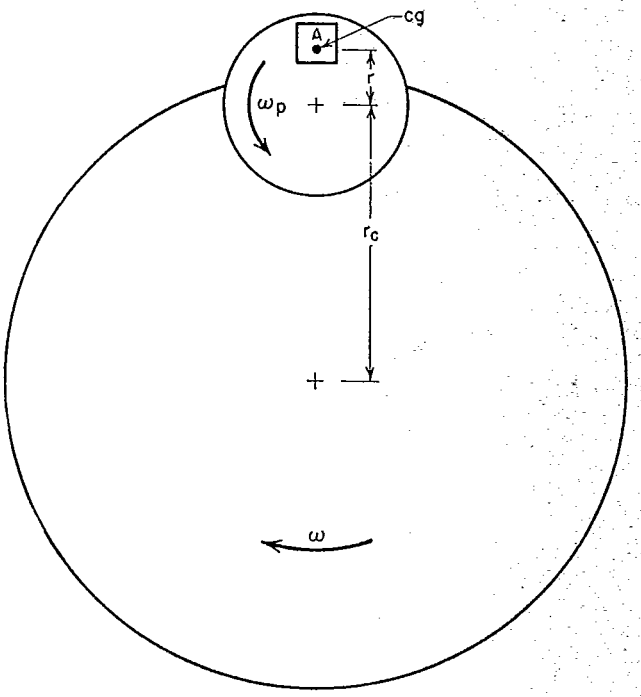


Fig. A3

Dual Centrifuge

The dual centrifuge is useful for applying sinusoidal accelerations up to 50g in the frequency range from 0.7 to 10 cps.

A1.2.5 ***Resonant Beam Vibrator.*** The resonant beam vibrator is a common representative of a class of vibration generators consisting of an elastic body which is maintained in resonant motion in one of its natural modes of vibration by being excited at the frequency of that mode. The vibrating body should be mounted at or near one of its nodal regions for the desired mode of vibration in order to reduce motion of the support to a negligible amount. The excitation may be applied near an antinode of the vibration, or by vibrating the supports through a small amplitude. Under these conditions, it is possible to obtain large

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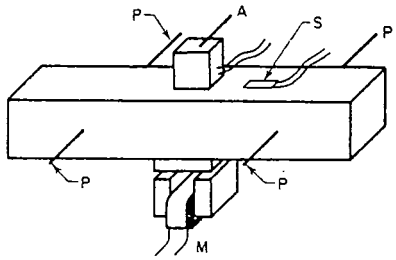


Fig. A4

Resonant Beam Vibrator

amplitudes of vibration with good sinusoidal wave forms with little expenditure of power.

The resonant beam vibrator is mounted to vibrate in one of its flexural modes, such as its fundamental mode, as a free-free beam [40] or as a cantilever beam [41] built into a heavy rigid mass at its "fixed end." The pickup is attached to the center of the free-free beam or to the end of the cantilever. Calibration with a free-free beam is preferable in most cases because a pickup attached to the free end of a cantilever beam will be subjected to rotation as well as to translation, while it is subjected to translation only at the center of the free-free beam.

Figure A4 shows a typical mounting arrangement. The pins, P, are attached at or near the nodal points of the beam and serve for its mounting. An electromagnet, M, is the source of excitation. A magnet armature is attached to the bar. The magnet armature and the magnet consist of transformer laminations. The pickup, A, is mounted at the center of the beam. The magnet can be energized by means of an oscillator and power amplifier. The beam can be self-excited by feeding the output of a suitable pickup, placed near the beam, into the amplifier. A polarizing direct current should be applied to the electromagnet.

The amplitude of the resonant motion may be measured indirectly by means of strain gages, S, Fig. A4, attached to positions away from the magnet where the beam is undergoing considerable stress. The strain gages may be calibrated in terms of displacement at the location of the pickup. The displacement at the point of attachment of the pickup can be measured by optical means (see A1.2). Care should be taken to ascertain that the mode shape under these conditions is the same with the pickup attached to the beam as without the pickup attached. This requires that the calibration be made either with the pickup in place or with a mass equal to that of the pickup substituted for it. In any case it is advisable that the mass of the pickup be kept small compared to the mass of the beam (e.g., pickup mass less than one-fourth of beam mass).

Beams having a thickness of about 2 inches, and lengths varying from about 31 to 14 inches, will vibrate at discrete frequencies in the region between 400 and 2,000 cps for their first flexural mode. Amplitudes corresponding to several hundred g can be obtained easily. With much smaller beams, calibrations are possible [42] up to several thousand g.

A1.2.6 ***Acoustical Cavity Method.*** Calibration with extremely small vibration amplitudes in the audio-frequency range is possible by an acoustical method which utilizes a calibrated condenser microphone as a reference [43]. In this method, the raised center portion of a circular piston, driven by an exciter undergoing sinusoidal motion, projects upward into one end of a gas filled cavity, the shelf of the piston being located outside of the enclosure. A condenser microphone, which has been calibrated by the reciprocity method [44], is coupled to the other end of the cavity to respond to the sound pressure generated by the piston. The measured sound pressure is related theoretically to the vibrational amplitude of the piston by an equation involving the cavity volume, the piston area, the static pressure and the ratio of specific heats for the gas. The motion of the piston thus determined is monitored at the piston shelf by an annular capacitance pickup whose output is proportional to the piston motion. The calibration of other pickups is made by placing them on or near the vibrating piston and comparing their output to that of the annular capacitance pickup. This method is particularly adapted to the calibration of electrostatic pickups, such as the one described in Reference 43.

Using a cavity similar to the typical cavity for reciprocity calibration of type-L laboratory standard microphones illustrated in Fig. 4 of Reference 45, the frequency range of 50 to 10,000 cps can be covered.

A1.2.7 ***Condenser Microphone Method.*** The absolute calibration of electrostatic pickups of special construction [46] can be performed by using the diaphragm of a condenser microphone as a vibrating surface. The pickup is calibrated by placing it near the diaphragm of the microphone to detect the variation in capacitance between the diaphragm and the pickup when the diaphram is driven by applying an electrical signal to the microphone terminals. The variation in capacitance is proportional to the motion of the diaphragm averaged over its surface.

Computation of the sensitivity of the capacitance pickup may be based upon a set of two linear equa-

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tions describing the microphone as a reversible transducer, or upon a measurement made in the process of determining the microphone pressure response by the acoustical reciprocity method [44]. The sensitivity of the electrostatic pickup can be determined at small amplitudes in the frequency range of 10 to 40,000 cps.

A1.3 Dynamic Calibration by Transient Excitation. In several calibration methods the pickup is subjected directly to a transient motion. The adequacy of such a method for calibrating shock pickups depends on the degree to which the imposed transient approaches the transients or shocks to be measured with the pickup. The Fourier components of the calibrating transient should include the Fourier components of transients to be measured with the pickup.

Calibration of the pickup with a transient which rises rapidly to a constant value provides a particularly severe test of the pickup's freedom from natural frequency response [47] since such a transient will contain appreciable Fourier components over a wide frequency range and will bring out the natural frequency response of the pickup. To illustrate, Fig. A5 shows the computed displacement, $d(t)$, of two idealized undamped pickups when a transient force, $f(t)$, is applied to the mass of the pickup. The natural period, T, of one pickup is 1.5 times the rise time, t_0, of the force, while T for the other pickup is only 0.3 t_0. A good approximation to the transient

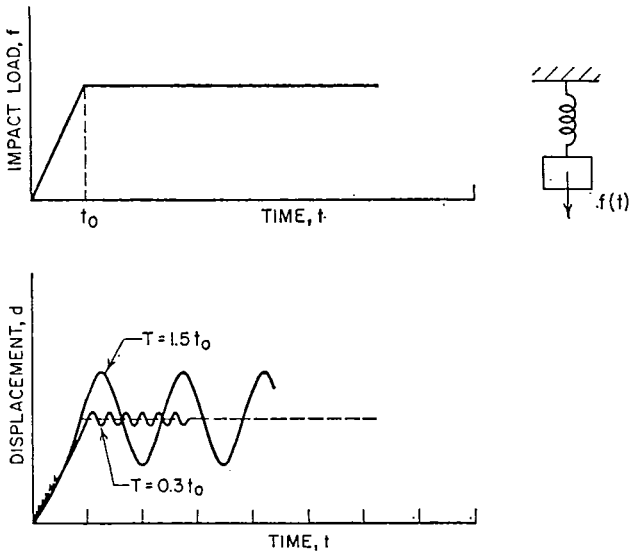


Fig. A5

Impact Load Acting on Mass and Displacement of Mass of Linear Mass-Spring System, with Natural Period T

force is obtained from the record of the higher frequency pickup by fairing a curve through the midpoints of the oscillations. This is much more difficult in the case of the lower frequency pickup. The effect of damping is not included in Fig. A5. Damping with a given logarithmic decrement would dissipate the superimposed oscillations of the pickup much more quickly in the high-frequency pickup than it would in the low-frequency pickup. The theoretical responses of acceleration pickups with various amounts of damping to half-sine wave, triangular, and square pulses are described in Reference 48.

Two calibration methods involving transient excitation, namely the physical-pendulum calibrator and the ballistic-pendulum calibrator are included in the standard methods and are described in 4.5 and 4.6, respectively. Seven other methods are described below.

A1.3.1 ***Free-Fall Test.*** The amplitude sensitivity of an undamped rectilinear velocity pickup may be determined by means of a free-fall test.

In this test the mass element of the pickup is released from rest to drop freely with a velocity which increases nearly linearly with time. The output voltage generated by the pickup is nearly proportional to the velocity. This output voltage is measured as a function of time until it hits a stop a given distance below the point of release. The imposed velocity is calculated from the time required to drop this distance.

For this test, the support springs of the mass element of the velocity pickup are removed and the base of the pickup is set on a horizontal surface. The mass element is then raised to the top of its stroke and is carefully released so that it falls freely. The output voltage of the pickup is recorded as a function of time on an oscillograph. A typical record is shown in Fig. A6. The record shows, in addition to the output for the initial drop, outputs corresponding to the drops after successive rebounds from the bottom. These rebound records are not suitable for calibration. The test is usually repeated with the instrument inverted in order to increase the accuracy of the measurement at the ends of the travel.

The maximum velocity and the time of free fall are calculated from the maximum travel of the mass element. The measured time of fall on the oscillograph record should agree closely with the calculated time of fall if the damping is negligible as assumed in the calculation. The amplitude sensitivity at any position along the travel is the ratio of the output voltage to the velocity at that position. The velocity can be determined from the oscillograph record corresponding to the position.

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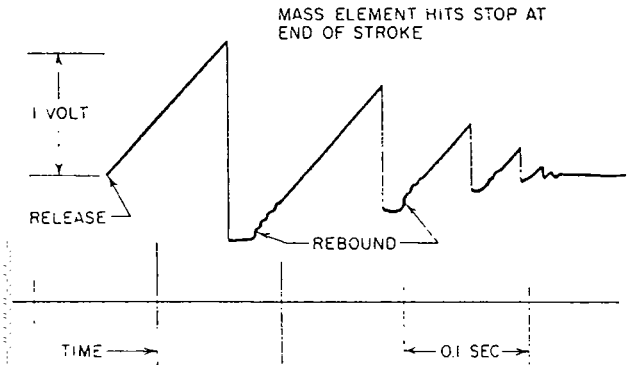


Fig. A6

Typical Oscillograph Record from Free-Fall Test of Velocity Pickup

As a quick but rough check, the calibration factor may be found from the deflection on a cathode ray oscillograph and the computed maximum velocity of free fall.

The velocity applied to a pickup may be measured within ±2 percent by this method.

A1.3.2 ***Pulse Calibrator.*** Transients of relatively low dominant frequencies can be applied by deforming an elastic system and then releasing it suddenly from the deformed state.

In its simplest form, the elastic system consists of a single spring-mounted mass to which the pickup is fastened. The mass is released from a deflected position to execute a damped sinusoidal vibration whose amplitude may be measured as a function of time [49].

In a more complex form, the system may consist of several spring-connected masses. The pickup is attached to one of these and the system is set into vibration by releasing any one of the remaining masses. This has the advantage of removing the pickup from the local chatter which is likely to be associated with the sudden release of the deflected mass. An example is the portable calibrator described in Reference 35, which consists of a compound-cantilever beam with two masses attached, one at the free end, and one at an intermediate point. The pickup is attached to the intermediate mass; it executes a smooth transient motion with dominant frequencies of 12 and 30 cps when the end mass is suddenly released from a deflected position.

A1.3.3 ***Air Gun.*** An air gun consists of a long, straight tube at one end of which a piston is initially locked in place. After the desired pressure is built up in an air chamber behind the piston, the piston is released and is accelerated down the tube. The acceleration of the piston can be calculated from the mass and cross-sectional area of the piston, and from the pressure. The calculated acceleration may then be used to calibrate a rectilinear acceleration pickup rigidly attached to the piston. Accelerations of the order of 6,000g have been applied thus to pickups weighing up to 2 pounds [50].

Impact accelerations of the order of 50,000g have been applied with an air gun [51] by firing a projectile with a velocity up to 310 ft/sec at an "intermediate target" consisting of the pickup and its mount, which is accelerated to a measured, nearly uniform velocity before it is caught in a cushioned fixed back stop.

A1.3.4 ***Shock Test Applying Measured Impact Acceleration.*** Accelerations of high intensity and short duration may be applied to an acceleration pickup of rigid mass m (see Fig. A7), by mounting this pickup rigidly on a much larger rigid mass, M, which is subjected to a measured central horizontal impact force, $f(t)$, through an elastic link of small mass, m_l, rigidly attached to M. The suspension of mass M restrains its motion to a horizontal direction. The impact force, $f(t)$, acting on $M + m$ may be measured with a pair of wire strain gages attached to the link if m_l is negligible compared to $M + m$ and as long as the resonant response excited by the impact is confined to the fundamental period of the elastic system. The elastic system consists of the mass applying the impact force $f(t)$, the elastic

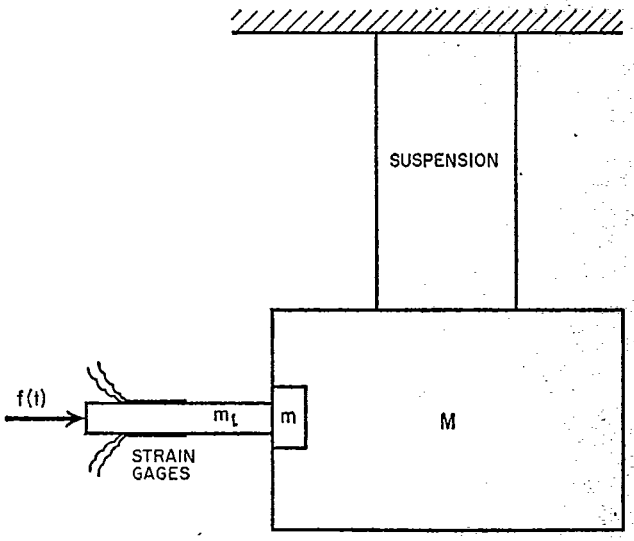


Fig. A7

Shock Test Applying Measured Impact Acceleration

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link, and the mass $M + m$. The acceleration applied to the pickup of mass m is then given by

$$a(t) = \frac{f(t)}{M + m} . \qquad \text{(Eq 56)}$$

If the mass, m_l, of the elastic link is small compared to $M + m$ but not negligible, it may be taken into account by increasing $M + m$ by an amount equal to the portion of m_l between the section at which the strain is measured and the mass M.

According to Brennan and Nisbet [52] acceleration pickups may be calibrated under shock conditions by this means with errors ranging from 1 percent to 10 percent, depending on the conditions of the test.

A1.3.5 ***Hydraulic Shock Test.*** A hydraulic shock test [53] can be applied to a pickup by attaching it to a column which is attached to the top side of a piston. A hydraulic pressure of some low value is maintained on the top side of the piston. The bottom side of the piston has a sealing ring, covering an area smaller than the cross-sectional area of the piston, which rests around a circular hole in an orifice plate. As the pressure in the orifice opening is increased to some high value, the piston moves, losing contact with the seal, and suddenly the high pressure is released against the entire cross-sectional area of the piston. The acceleration of the piston can be determined from the mass of the piston, column, and pickup, the area of the piston, and the difference in pressure between the top and bottom sides of the piston.

A1.3.6 ***Impact Drop Test.*** A known sudden change in velocity and, consequently, high acceleration can be applied to a rectilinear pickup by attaching it to the moving head of a drop tester and dropping it to rest from a given height [17]. The acceleration acting on the pickup during the impact can be varied by cushioning the drop. The cushioning may be done by plastic material or by elastic springs. Springs will produce a half-sine acceleration pulse with superimposed higher frequencies. With soft cushions impact times as long as a few tenths of a second and accelerations as low as a few g are possible. By using impact surfaces of steel on steel, accelerations in excess of 10,000g can be obtained with impact times considerably less than a millisecond. A nearly square pulse may be obtained by attaching a cylindrical spike to the platform with the pickup and dropping this on a cushioning material such as lead. The formulas given in 4.6 apply to any impact test involving impulsive velocity changes.

A1.3.7 ***Elastic Pulses in Long Bars.*** A displacement pulse of extremely short duration, measured in microseconds, can be applied to pickups which do not require attachment to the moving body such as pickups of the variable capacitance type, and to pickups of negligible mass, by connecting the pickup to one end of a long "Hopkinson bar" and then applying an impact to the other end of the bar by firing a projectile or carefully controlled explosive charge against it [54]. The displacement at the pickup end of the bar and the lateral expansion of the bar may be measured with pickups of the variable capacitance type [55].

Displacement pulses of short duration may be produced also by causing two long bars of constant cross section, but with rounded ends, to collide axially [56], or by dropping a bar vertically on an anvil and catching it after its rebound.

Closely controlled elastic pulses of lateral expansion and contraction may be produced in a long bar of paramagnetic material with a magnetostriction-distributed amplifier [57]. This subjects the bar to pulses of magnetostrictive force by sending current pulses through coils placed around the bar at several stations, the pulses being timed with delays between them equal to the travel time of the elastic pulse between stations.

A2. Theory of Reciprocity Method for Linear Electromechanical Pickups

A linear bilateral electromechanical pickup which is to be calibrated by the reciprocity method must possess a well defined mechanical terminal moving in a single degree of freedom. The following pair of equations relate, at any particular frequency, the associated complex force, $\boldsymbol{F}$, and velocity, $\boldsymbol{U}$, to the voltage, $\boldsymbol{E}$, and current, $\boldsymbol{I}$, which are associated with the electrical terminals:

$$\boldsymbol{I} = K_3\boldsymbol{E} + K_4\boldsymbol{U},$$

$$\boldsymbol{F} = \pm K_4\boldsymbol{E} + K_5\boldsymbol{U}, \qquad \text{(Eq 57)}$$

where K_3, K_4, and K_5 are in general complex functions depending upon frequency, and where $\boldsymbol{I}$, $\boldsymbol{E}$, $\boldsymbol{F}$, and $\boldsymbol{U}$ are expressed in consistent units [e.g., in mks (meter-kilogram-second) units, using amperes, volts, newtons, meters/sec, respectively] so that the product of current and voltage gives power in the same units as the product of force and velocity. If $\boldsymbol{F}$ is defined as the externally applied force, taken as positive in the direction in which $\boldsymbol{U}$ is assumed positive, and $\boldsymbol{I}$ is defined as the externally applied current, taken as positive when entering the electrical terminal which is assumed positive, then Equations 57

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apply for pickups which are reciprocal. Many pickups which have no internal sources of energy and which are constructed of linear and bilateral elements are reciprocal. Electrodynamic pickups which employ purely electromagnetic coupling (in which case the ambiguous sign in the second equation is plus), and condenser or crystal pickups which employ electrostatic or piezoelectric coupling, respectively (in which case the sign is minus), satisfy these requirements. Unilateral pickups such as those employing variable reluctances or strain gages as sensing elements never do.

Calibration by reciprocity methods depends upon a universal relationship—between suitably defined driving and receiving sensitivities S_i and S_u, respectively—which is independent of the design of the pickup. Defining S_i as the externally applied force which is necessary to block the mechanical terminal when the pickup is being driven with unit current:

$$S_i = \left.\frac{F}{I}\right|_{U=0}, \qquad \text{(Eq 58)}$$

and defining S_u as the open circuit voltage which is caused by unit velocity:

$$S_u = \left.\frac{E}{U}\right|_{I=0}, \qquad \text{(Eq 59)}$$

it is easily shown [28] that:

$$S_i/S_u = \mp 1, \qquad \text{(Eq 60)}$$

the negative sign applying to electromagnetic coupling, and the positive to electrostatic or piezoelectric coupling.

Several different sequences of calibrating experiments which exploit this relationship have been suggested [58], but attention will be restricted here to the original sequence [28], inasmuch as it is the one most easily applicable to direct calibration of field-type pickups. This sequence requires two electromechanical pickups, one of which (denoted in the following as the reciprocal pickup) satisfies the foregoing relationship between S_i and S_u. It is irrelevant whether or not the second pickup satisfies the same relationship; it must, however, be linear and must possess its own well defined mechanical terminal moving in a single degree of freedom.

One experiment in the sequence determines the ratio of the receiving sensitivities of these pickups. For this experiment, a sinusoidal exciter capable of driving the pickups at the desired frequency of calibration is required. The exciter is arranged to drive the mechanical terminals of the two pickups simultaneously with velocities which are equal in magnitude but opposite in phase. The ratio E_r/E_l of the open circuit voltages of the pickups is measured in both magnitude and phase. The subscript r refers to the reciprocal pickup, and l to the second, linear, pickup. Inasmuch as it is easily shown [28] that:

$$\frac{S_{ur}}{S_{ul}} = \frac{-E_r}{E_l}, \qquad \text{(Eq 61)}$$

the measured value of E_r/E_l is the negative of the desired ratio of sensitivities.

The remainder of the sequence of experiments involves the two pickups, some means for aligning their mechanical terminals, and a number of objects serving the role of mechanical standards. Usually the latter have been [29, 30] metallic right circular cylinders whose masses are determined by weighing. If one of these of mass m is inserted between the mechanical terminals of the pickups, and the reciprocal pickup is excited with a current, I_r', from an external electrical source, there may be observed an open-circuit voltage, E_l', at the terminals of the second linear pickup and the ratio of these may be denoted the electrical transfer admittance, Y_e:

$$Y_e = \left.\frac{I_r'}{E_l'}\right|_{I_l'=0}, \qquad \text{(Eq 62)}$$

which is to be measured in both amplitude and phase. At frequencies well removed from resonances of the pickups, it is usually possible in exploratory work to estimate the phase angle of Y_e (and of E_r/E_l in the preceding experiment). However, for greatest accuracy these must be measured; a phase meter [29] and a simple resistance and capacitance circuit [14] have both been employed. It may be shown [28, 29, 30] that in the arrangement of pickups under consideration:

$$Y_e = \pm\frac{j\omega m + Y_m}{S_{ur}S_{ul}} \qquad \text{(Eq 63)}$$

where the negative sign corresponds to electromagnetic coupling in the reciprocal pickup, the positive sign to electrostatic or piezoelectric coupling, ω is 2π times the calibrating frequency, and Y_m is a mechanical admittance whose value depends upon the design of the pickups and upon the frequency, but which may be regarded as a constant for present purposes.

The sequence of calibration experiments may be completed in principle by measuring the electrical transfer admittance, Y_{eo} and Y_{em}, which correspond to the mechanical admittances with no mass attached and with mass m attached, respectively. Upon applying the foregoing equation to each of these

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cases and eliminating Y_m, we have

$$S_{ur}S_{ul} = \mp\frac{j\omega m}{Y_{em} - Y_{eo}}, \qquad \text{(Eq 64)}$$

whence, using the result of the first experiment,

$$S_{ur}^2 = \pm\frac{j\omega m}{Y_{em} - Y_{eo}}\frac{E_r}{E_l}, \qquad \text{(Eq 65)}$$

the positive sign in Equation 65 corresponding to electromagnetic coupling in the reciprocal pickup and the negative sign to electrostatic or piezoelectric coupling. Inasmuch as all of the quantities on the right-hand side are measurable, S_{ur} can be determined completely, in principle, as regards its magnitude, and as regards its phase except for the possibility of a phase reversal.

In practice a more accurate determination of $S_{ur}S_{ul}$ results if a sequence of masses, m_1, m_2, $\cdots$, is used in conjunction with a corresponding sequence of electrical admittance measurements, Y_{e1}, Y_{e2}, $\cdots$. Using R to mean "the real part of" and I, "the imaginary part of," we may rewrite Equation 63 as the equations:

$$\mathrm{R}[Y_e] = \pm\,\omega m\mathrm{I}[S_{ur}S_{ul}]^{-1} \mp \mathrm{R}[Y_m(S_{ur}S_{ul})^{-1}],$$
$$\mathrm{I}[Y_e] = \mp\,\omega m\mathrm{R}[S_{ur}S_{ul}]^{-1} \mp \mathrm{I}[Y_m(S_{ur}S_{ul})^{-1}], \qquad \text{(Eq 66)}$$

where the upper sign corresponds to electromagnetic coupling in the reciprocal pickup and the lower sign to elastostatic or piezoelectric coupling. Plots of $\mathrm{R}[Y_e]$ and $\mathrm{I}[Y_e]$ versus m should fit straight lines, and if such is actually the case, $S_{ur}S_{ul}$ can be determined in both magnitude and phase from the slopes of these lines. If such is not the case, one is warned that some assumed condition has not been met; therefore the use, in the foregoing manner, of a sequence of masses provides a simple check on the calibration procedure. The linearity of the pickups should also be checked; this is easily done by checking the constancy of Y_e while varying the amplitude of the driving current of the reciprocal transducer.

At sufficiently high frequencies, it is necessary that the compliance of the mechanical standards be taken into account. Methods for doing so are known [30, 58]. Experiments have shown [27, 28, 58] that at low frequencies the effect of this compliance is usually inconsequential.

The foregoing equations presuppose that a consistent system of units, e.g., mks or cgs (centimeter-gram-second), has been employed. For other systems multipliers must be introduced. In particular, if it is desired to employ volts and amperes, but to measure forces in pounds and velocities in inches per second, and to regard mass m as a weight, W, in pounds, one must replace Equation 60 by

$$S_i/S_u = \mp\,8.85, \qquad \text{(Eq 67)}$$

and Equation 65 by

$$S_{ur}^2 = \pm\,2.93 \times 10^{-4}\frac{j\omega W}{Y_{em} - Y_{eo}}\frac{E_r}{E_l}. \qquad \text{(Eq 68)}$$

A3. Reciprocity Method for Electrodynamic Calibrators

A3.1 Theory. The reciprocity theory has been extended [14] to electrodynamic vibration-pickup calibrators (see Fig. 6), in which case the mechanical terminals of the coils, C_1 and C_2, and the point on the mounting table, T, where pickups are attached are separated by a mechanical structure which may not act as a rigid body throughout the useful frequency range of the calibrator. The extension in the theory allows for the possibility of relative motion between the coils or between the coils and the mounting table. This extended theory is the basis of the standard calibration method described in 4.4.

The equations which relate the mechanical and electrical quantities of the calibrator when operating within its linear amplitude range* are

$$U = K_6F + K_7L_1E, \qquad \text{(Eq 69)}$$

$$I = -K_7L_2F + K_8L_1E, \qquad \text{(Eq 70)}$$

$$E_{13} = K_9F + K_{10}L_1E, \qquad \text{(Eq 71)}$$

where U and F are, respectively, the velocity and force at the mounting table, I and E are, respectively, the current and voltage in the driving coil, and E_{13} is the voltage in the velocity-sensing coil. The constants L_1 and L_2 are conversion factors determined by the system of units used. If the mks system (see Section A2) is used, L_1 and L_2 have the value of unity. If the usual engineering system of units (inch pound, second, ampere, and volt) is used for all quantities, the values are $L_1 = 2.249 \times 10^{-7}$ lb-sec^2/gm-cm and $L_2 = 2.540 \times 10^{-8}$ cm-volts/in.-abvolt. The characteristic quantities K_6, K_7, K_8, K_9 and K_{10} depend on the construction of the calibrator and vary with frequency. All the above symbols except L_1 and L_2 represent complex numbers in the manner commonly used in alternating-current electrical theory.

* The linear amplitude range is the range within which the motion of any part is proportional to the applied force, the voltage generated in a coil is proportional to velocity, etc.

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The reciprocity relation which exists for the calibrator is

$$\left.\frac{F}{L_1 I}\right|_{U=0} = \left.\frac{-E}{L_2 U}\right|_{I=0}.$$

This relationship is determined by evaluating Equation 69 when $U = 0$ and Equation 70 when $I = 0$.

The sensitivity, S_{uc}, of the calibrator is defined as $S_{uc} = E_{13}/U$, the ratio of the voltage in the velocity-sensing coil to the velocity at the mounting table. If an object with mechanical impedance, Z_m, is attached to the table in such a way that F is its only reaction,

$$F = -UZ_m. \qquad \text{(Eq 72)}$$

Substituting Equation 72 into 69 and 71 and combining the results by eliminating E, one obtains

$$S_{uc} = S_o + s_z Z_m, \qquad \text{(Eq 73)}$$

where S_o and s_z are combinations of the above mentioned characteristic quantities.

The relationship for the transfer admittance, $Y_e = I/E_{13}$, between the coils is obtained by substituting Equation 72 into 69 and the result into Equations 70 and 71,

$$Y_e = \frac{I}{E_{13}} = \frac{K_8 + (K_8 K_6 + K_7^2 L_2) Z_m}{K_{10} + (K_{10} K_6 - K_7 K_9) Z_m} \qquad \text{(Eq 74)}$$

Now consider attaching on the mounting table weights of known mechanical impedance $Z_m = j\omega W/g$ where W is the weight in pounds, ω is the circular frequency in radians per second, j is the unit imaginary vector, and g is the acceleration of gravity (386 in./sec^2). From Equation 74 one can form the relationship

$$\frac{W}{Y_{ew} - Y_{eo}} = J + QW, \qquad \text{(Eq 75)}$$

where Y_{ew} and Y_{eo} are the values, respectively, of the transfer admittance at a given frequency with a weight weighing W pounds attached to the mounting table, and with no weight attached. J and Q are combinations of j, ω, g, and the above mentioned characteristic quantities. Note that if we measure the transfer admittance with at least two known weights attached to the table and with no weight attached, we can determine the intercept, J, and slope Q, of Equation 75.

An expression for the voltage ratio

$$\left.\frac{E_{13}}{E}\right|_{I=0},$$

which is called E_{13}/E_{15} in 4.4.1, is obtained by letting $I = 0$ in Equation 70 and substituting the result into Equation 71,

$$\frac{E_{13}}{E_{15}} = \frac{K_9 K_8 L_1 + K_7 K_{10} L_1 L_2}{K_7 L_2}. \qquad \text{(Eq 76)}$$

Having formed these relationships, the following equations are formed simply by algebraic manipulation of the above mentioned characteristic quantities:

$$S_o = 0.01711 \sqrt{j\omega J \frac{E_{13}}{E_{15}}}, \qquad \text{(Eq 77)}$$

$$s_z = 6.601 Q \sqrt{E_{13}/(E_{15} j\omega J)}, \qquad \text{(Eq 78)}$$

when the values $L_1 = 2.249 \times 10^{-7}$, $L_2 = 2.540 \times 10^{-8}$, and $g = 386$ in./sec^2 are used and the dimensions of ω are in rad/sec, E_{13}/E_{15} in volts/volt, J in pounds/mho, and Q in ohms. Thus the sensitivity of the electrodynamic calibrator can be determined at each of the desired frequencies from measurements of transfer admittance between coils C_1 and C_2 with a series of weights on the mounting table and with no weight on the table, and of the ratio of the voltage generated in coils C_1 and C_2 when both are open-circuited.

As mentioned above, it is only necessary to measure the transfer admittance, Y_e, with two weights, W, and with no weight attached to the mounting table in order to determine J and Q. However, better accuracy will be obtained [13] if it is measured with a series of weights, W, on the table. In that case it is convenient to separate the quantity on the left side of Equation 75 into its real and imaginary parts and plot them against W. The real and imaginary parts of this plot should be straight lines if the assumption of linear amplitude response is satisfied. The data in these plots are best fitted by a weighted least squares procedure for a straight line. The weighting as determined by a consideration of the expected error in the real and imaginary part of $1/(Y_{ew} - Y_{eo})$ is 1, 2, 3, $\cdots$, 10 for $W = 0.1, 0.2, 0.3, \cdots, 1.0$ lb.

In order to measure the open-circuit voltage ratio, E_{13}/E_{15}, the calibrator must be driven at the desired amplitude by an external vibration exciter mechanically connected to the calibrator table. The voltage ratio can be measured with a given electrical load on the velocity-sensing coil if this same load is used in the transfer admittance measurements and if it is kept on the coil permanently.

This theory applies regardless of the presence of resonant response, except when there is transverse motion present. However if, for example, the driving coil is in axial resonance with respect to the velocity sensing coil, E_{13}/E_{15} will approach zero, making accurate measurements difficult, and the amplitude of

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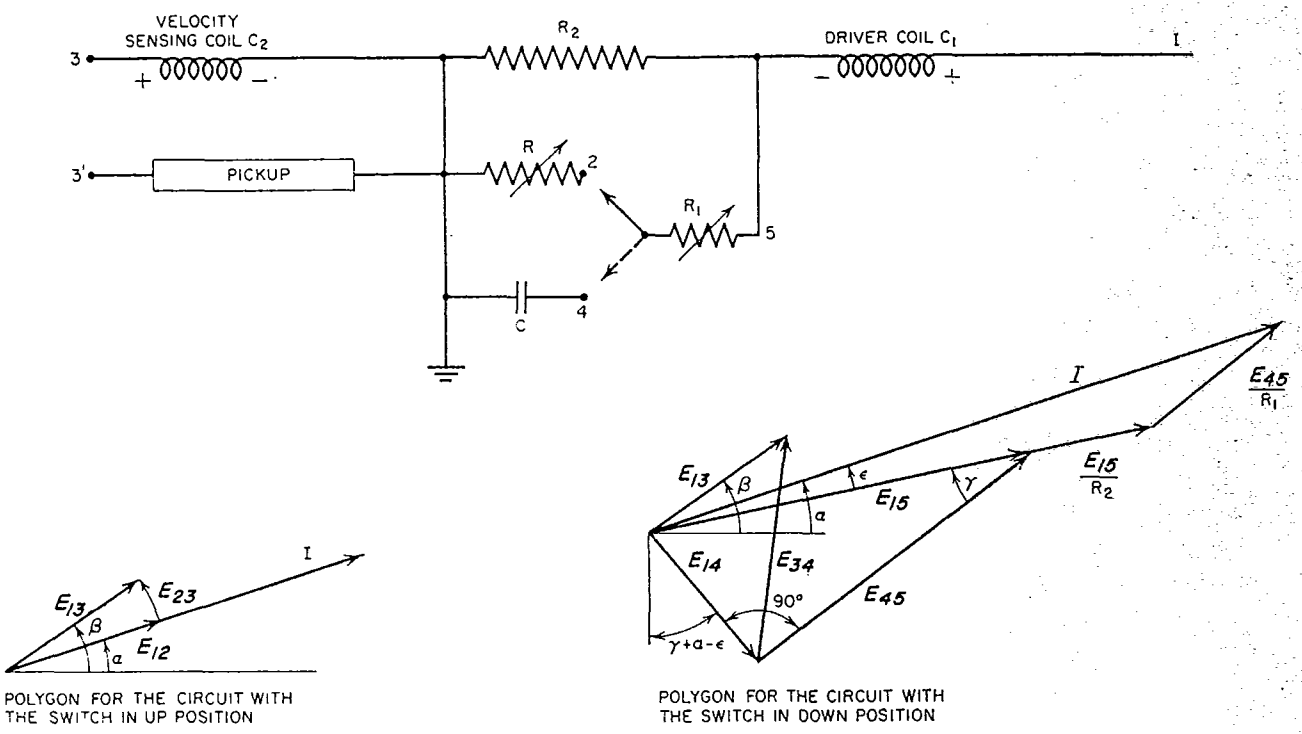


Fig. A8

Circuits and Polygons for Making Transfer Admittance Measurements on Electrodynamic Calibrator and Pickups

the driving coil may be sufficient to exceed its linear amplitude range. Therefore it is practical to determine the sensitivity below and above axial resonance but not at axial resonance.

Once the above measurements are made on a calibrator, it can be used to measure the mechanical impedance, Z_m, of any object that is attached to the mounting table. The equation which related Z_m to the constants of the calibrator is

$$Z_m = \frac{\frac{j\omega J}{g}(Y_{ep} - Y_{eo})}{1 - Q(Y_{ep} - Y_{eo})}, \qquad \text{(Eq 79)}$$

where Y_{ep} is the transfer admittance expressed in mhos between the driving and velocity-sensing coils with the object attached to the mounting table. This equation is obtained by solving Equation 74 for Z_m and by manipulating the quantities represented by J and Q.

A3.2 Measurement. The procedures that follow are suggested methods for making the transfer admittance and voltage ratio measurements. These measurements are used to determine the sensitivity of electrodynamic calibrators and to calibrate vibration pickups on the calibrators. The methods, used to determine both the magnitude and phase angle of these complex ratios, are particularly useful because they make use of relatively simple components and yet yield accurate results. The accuracy of the magnitude of the quantities measured depends only on the accuracy of the components and on the repeatability of the voltmeter readings, but not on the accuracy of the voltmeter. The accuracy of the phase angles does depend on the accuracy of the voltmeter. However, phase angle errors less than 2 degrees usually are easily achieved.

The circuits used for these measurements are shown in Figs. A8 and A9. High quality resistors with negligible internal inductance should be used for R, R_1, and R_2. Capacitors with a small dissipation factor should be used for C. A switch box which makes the various connections described below conveniently and rapidly is very helpful.

Before proceeding with the measurements, it is necessary to identify the positive terminals of the velocity-sensing and driving coils. The positive terminals are defined as those having positive voltages when the mounting table of the calibrator is moving inward. Conversely, current flowing from the positive to the negative terminals of the coils produces outward velocity at the mounting table.

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The positive terminals can be determined by pushing the mounting table inward quickly while observing which terminal of each coil has a positive voltage as indicated on a dc voltmeter. While determining the positive terminals of the coils, they should be open-circuited. It is immaterial which terminal of the vibration pickup is used as positive. However, if one terminal is connected to the housing of the pickup or is otherwise grounded, it should be connected to the ground terminal in Fig. A8 when the transfer admittance between the pickup and driving coil is measured.

A3.2.1 ***Transfer Admittance Measurements.*** The transfer admittance, $\boldsymbol{Y}_e$, i.e., the ratio of the current, $\boldsymbol{I}$, in the driving coil to the voltage, $\boldsymbol{E}_{13}$, in the velocity-sensing coil, can be measured by using the circuit shown in Fig. A8. The series-parallel combination consisting of R, R_1, R_2, and C is connected in series with the driving coil so that the total current will be identical to $\boldsymbol{I}$. It is usually convenient to insert this combination in the output network of the power amplifier which supplies current to the driving coil. If there is feedback in the output network, it is good practice to connect one terminal of the resistance circuit to ground. The negative terminal of the velocity-sensing coil should be connected to the terminal of the resistance circuit that is grounded.

The magnitude and phase angle of the transfer admittance are determined from the following procedure.

Step 1: After the calibrator is vibrating at the desired amplitude and with the switch in Fig. A8 in the up position, R and R_1 are adjusted until the magnitude of the voltage between terminals 1 and 2, hereafter designated as E_{12}, is equal to the magnitude of the voltage between terminals 1 and 3, E_{13}. Then the voltage between terminals 2 and 3, E_{23}, is measured.

Step 2: The switch in Fig. A8 is put in the down position and R_1 is adjusted until the voltage between terminals 1 and 4, E_{14}, is equal to E_{13}. E_{34} is then measured.

The magnitude of the transfer admittance, $\boldsymbol{Y}_e$, is determined from the values of R, R_1 and R_2 of Step 1 by use of the following equation:

$$Y_e = \frac{R + R_1 + R_2}{RR_2}. \qquad \text{(Eq 80)}$$

The phase angle, ϕ_y, of the transfer admittance, $\boldsymbol{Y}_e$, is determined from the voltage measurements made in both Steps 1 and 2. The polygons of voltages, Fig. A8, for the circuits indicate that $\phi_y = \alpha - \beta$. From the polygon of voltages for the circuit with the switch in the up position, the equation which applies to the voltages measured in Step 1 is:

$$\phi_y = \pm\cos^{-1}\left(1 - \frac{1}{2}\frac{E_{23}^2}{E_{13}^2}\right). \qquad \text{(Eq 81)}$$

The polygon for the circuit with the switch in the down position is used to derive the equation which applies to the voltages measured in Step 2,

$$\phi_y = 90° \pm \cos^{-1}\left(1 - \frac{1}{2}\frac{E_{34}^2}{E_{13}^2}\right) - \gamma + \epsilon, \qquad \text{(Eq 82)}$$

where $\gamma = \sin^{-1}(1/\omega C\sqrt{R_1^2 + 1/\omega^2C^2})$, $\epsilon = \sin^{-1}(1/Y_e\sqrt{R_1^2 + 1/\omega^2C^2})$, and the value of R_1 is that of Step 2. If ϕ_y is not near 0 or 180 degrees, Equation 81 is used to determine the value of ϕ_y and Equation 82 is used only to determine the sign of ϕ_y in Equation 81. For this purpose, γ can be ignored if R_2 in Step 2 is chosen so that $R_1\omega C > 5$. If ϕ_y is near 0 or 180 degrees, it is usually preferable to use Equation 82 to determine the values of ϕ_y and Equation 81 to determine the sign of the second term in Equation 82. In this case γ can be ignored if R_2 in Step 2 is chosen so that $R_1\omega C > 50$. The value of ϵ is so small that it is usually ignored regardless of the value of ϕ_y.

The above procedure can also be used to measure the transfer admittance $\boldsymbol{Y}_{ep'}$, i.e., the ratio of the current $\boldsymbol{I}$ in the driving coil to the voltage $\boldsymbol{E}_{13'}$ in a vibration pickup attached to the mounting table of the calibrator. One terminal of the pickup is connected to the circuit as shown in Fig. A8. The only change in the procedure is that the subscript 3′ replaces the subscript 3 wherever it appears. The values of R, R_1, R_2, $E_{13'}$, $E_{23'}$, and $E_{34'}$ obtained are used in Equations 80, 81 and 82 to compute the magnitude and phase angle of $\boldsymbol{Y}_{ep'}$.

A3.2.2 ***Voltage Ratio Measurements.*** The voltage ratio, $\boldsymbol{E}_{13}/\boldsymbol{E}_{15}$, i.e., the ratio of the open circuit voltage, $\boldsymbol{E}_{13}$, generated in the velocity-sensing coil to the open circuit voltage, $\boldsymbol{E}_{15}$, generated in the driving coil, can be measured by using the circuit shown in Fig. A9. The driving coil is disconnected from the power amplifier, and the series-parallel combination consisting of R, R_1, R_2, and C is connected in parallel with the driving coil. Also the negative terminal of the velocity-sensing coil is connected to the negative terminal of the driving coil.

The magnitude and phase angle of the voltage ratio are determined by the following procedure.

Step 1. The calibrator is set into sinusoidal motion by an external vibration exciter. With the switch in Fig. A9 in the up position and with R_1 very large compared to the impedance of the driving coil

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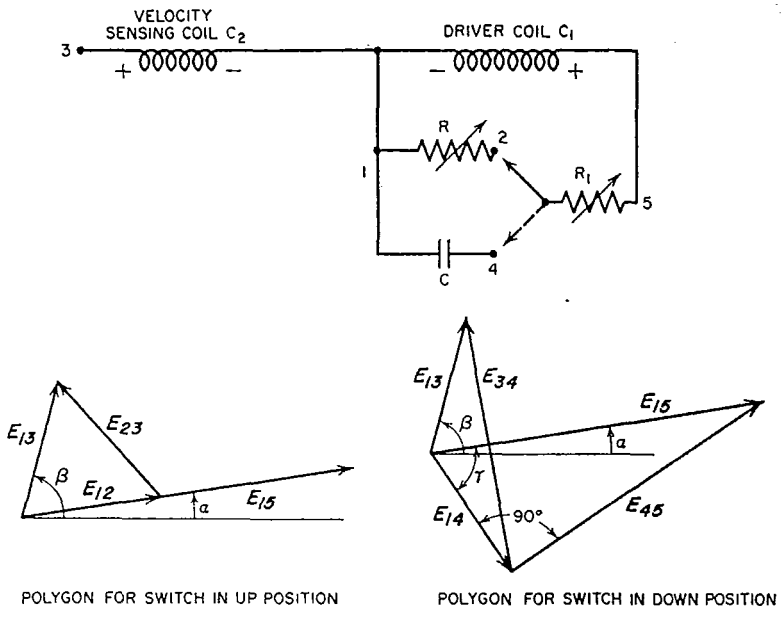


Fig. A9

Circuits and Polygons for Making Voltage Ratio Measurements on Electrodynamic Calibrator

(usually 10,000 ohms is sufficient), R is adjusted until the magnitude of the voltage between terminals 1 and 2, E_{12}, is equal to the magnitude of the voltage between terminals 1 and 3, E_{13}. Then the voltage between terminals 2 and 3, E_{23}, is measured.

Step 2. The switch in Fig. A9 is put in the down position and R_1 is adjusted until the voltage between terminals 1 and 4, E_{14}, is equal to E_{13}. E_{34} is then measured.

The magnitude of the voltage ratio $\boldsymbol{E}_{13}/\boldsymbol{E}_{15}$ is determined from the values of R, R_1, and R_2 used in Step 1 from the following equation:

$$E_{13}/E_{15} = R/(R_1 + R). \qquad \text{(Eq 83)}$$

The phase angle, ϕ_E, of the voltage ratio, $\boldsymbol{E}_{13}/\boldsymbol{E}_{15}$, is determined from the voltage measurements made in Steps 1 and 2. The polygons of voltages, Fig. A9, for the circuits indicate that $\phi_E = \beta - \alpha$. From the polygon of voltages for the circuit with the switch in the up position, the equation which applies to the voltages measured in Step 1 is:

$$\phi_E = \pm\cos^{-1}\left(1 - \frac{1}{2}\frac{E_{23}^2}{E_{13}^2}\right). \qquad \text{(Eq 84)}$$

The polygon for the circuit with the switch in the down position is used to derive the equation which applies to the voltages measured in Step 2,

$$\phi_E = \pm\cos^{-1}\left(1 - \frac{1}{2}\frac{E_{34}^2}{E_{13}^2}\right) - \cos^{-1}(E_{13}/E_{15}). \qquad \text{(Eq 85)}$$

Usually ϕ_E is near either 0 or 180 degrees. Equation 84 is insensitive for these angles, either because E_{23} is very small for ϕ_E near 0 degrees or because the cosine is insensitive to small changes in E_{23} near 180 degrees. Therefore, Equation 85 is used to determine the value of ϕ_E and Equation 84 to determine the sign of the first term in Equation 85.

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