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Methods for the Calibration of Shock and Vibration Pickups

Secretariat

**Acoustical Society of America
American Society of Mechanical Engineers**

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American National Standard

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Foreword

(This Foreword is not a part of American Standard¹ Methods for the Calibration of Shock and Vibration Pickups, S2.2-1959.)

This American Standard¹ 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 17

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¹ All American Standards are now designated USA Standards.

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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 Standard¹ Method for Specifying the Characteristics of Pickups for Shock and Vibration Measurement, Z24.21-1957;

American Standard¹ Method for Specifying the Characteristics of Auxiliary Equipment for Shock and Vibration Measurements, S2.4-1960;² and

American Standard¹ Shock and Vibration Terminology, S1.1-1960.²

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

¹ All American Standards are now designated USA Standards.

2. Definitions

The letter symbols and technical terms used in the standard comply as far as possible with those given in American Standard¹ Letter Symbols for Acoustics, Y10.11-1953 and American Standard¹ 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

¹ All American Standards are now designated USA Standards.

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-

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:

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

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

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

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

The *displacement sensitivity* is:

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

where $\phi_1 - \phi_2$ is the phase lag.

The *velocity sensitivity* is:

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

where $\phi_1 + \pi/2 - \phi_2$ is the phase lag;

and the *acceleration sensitivity* is:

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

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

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 Standard¹ 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

¹All American Standards are now designated USA Standards.

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,

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

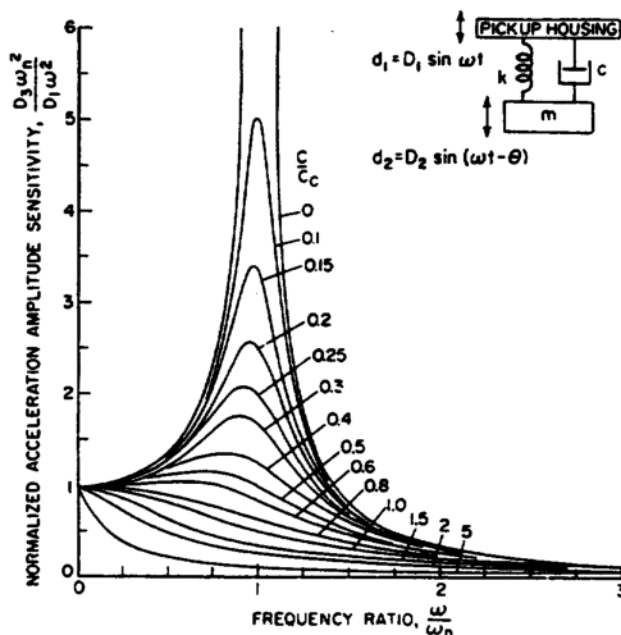


Fig. 1
Response of
Idealized Linear Acceleration Pickup

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

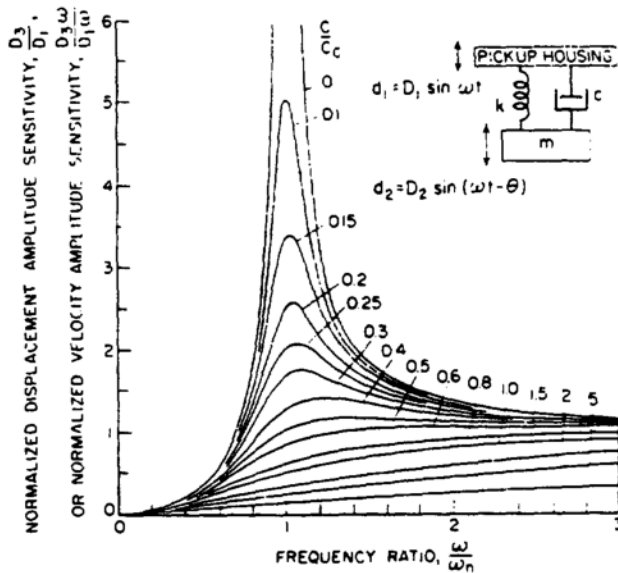


Fig. 2

Response of Idealized Linear Displacement or Velocity Pickup

is proportional to the ratio,

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

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

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

This occurs at the resonant circular frequency, ω_r ,

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

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_2 . The displacement or velocity amplitude sensitivity of the pickup is proportional to the ratio,

$$\frac{D_2}{D_1} = \frac{(\omega/\omega_n)^2}{\sqrt{(1 - \omega^2/\omega_n^2)^2 + 4(c/c_c)^2(\omega/\omega_n)^2}} \quad (\text{Eq 13})$$

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

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

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

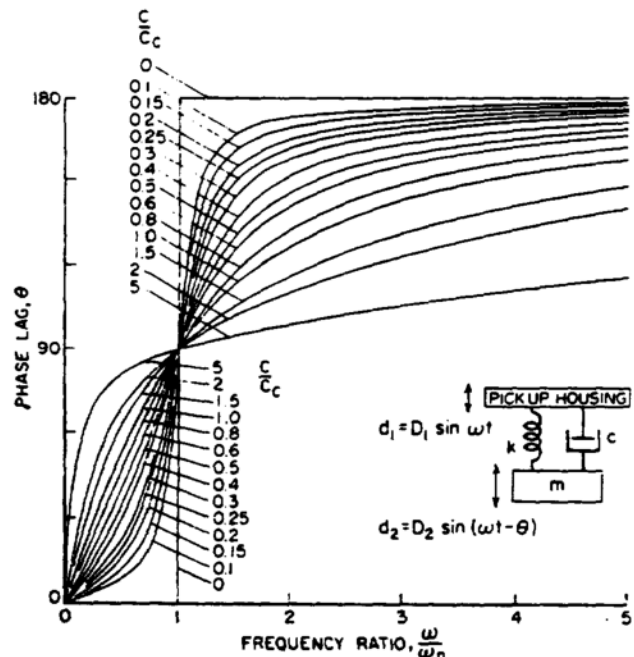


Fig. 3

Phase Lag of Idealized Linear Pickup

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

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

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

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

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

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

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.

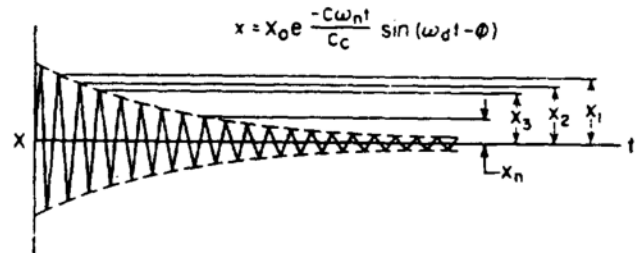
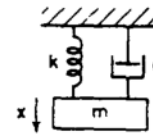


Fig. 4

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