INTERNATIONAL STANDARD ISO 5347-0:1987
TECHNICAL CORRIGENDUM 2

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Methods for the calibration of vibration and shock pick-ups —

Part 0:
Basic concepts

TECHNICAL CORRIGENDUM 2

Méthodes pour l'étalonnage des capteurs de vibrations et de chocs —
Partie 0: Concepts de base

RECTIFICATIF TECHNIQUE 2

Technical corrigendum 2 to International Standard ISO 5347-0:1987 was prepared by Technical Committee ISO/TC 108, *Mechanical vibration and shock*, Sub-Committee SC 3, *Use and calibration of vibration and shock measuring instruments.*

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In the formula in the left-hand column, delete the two pairs of brackets { }.

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Descriptors: vibration, mechanical shock, measuring instruments, vibration meters, transducers, calibration.

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TECHNICAL CORRIGENDUM 1

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RECTIFICATIF TECHNIQUE 1

Technical corrigendum 1 to International Standard ISO 5347-0 : 1987 was prepared by Technical Committee ISO/TC 108, *Mechanical vibration and shock,* Sub-Committee SC 3, *Use and calibration of vibration and shock measuring instruments.*

Page 7

Subclause 6.2.2

Second paragraph, lines 3 and 4, delete "in the velocity-sensing coil" and insert "generated by the accelerometer".

Second paragraph, line 5, delete "surface of the mounting table" and insert "mounting surface".

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Subclause 6.2.2

Third paragraph, line 7, delete "per metre".

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Subclause 6.2.3.2

Line 9, delete "$\phi = 0$" and insert "$\phi = 90°$".

Subclause 6.2.3.3

First paragraph, lines 2 to 6, delete "fixture attached to the wall (see figure 3). The vibration pick-up, 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." and insert "centrifuge made to rotate about its vertical axis in accordance with 6.2.3.1 (see figure 3). The vibration pick-up, A, is attached to the small centrifuge, which is driven independently."

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Reference number
ISO 5347-0 : 1987 (E)

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work.

Draft International Standards adopted by the technical committees are circulated to the member bodies for approval before their acceptance as International Standards by the ISO Council. They are approved in accordance with ISO procedures requiring at least 75 % approval by the member bodies voting.

International Standard ISO 5347-0 was prepared by Technical Committee ISO/TC 108, *Mechanical vibration and shock.*

Users should note that all International Standards undergo revision from time to time and that any reference made herein to any other International Standard implies its latest edition, unless otherwise stated.

Printed in Switzerland

Methods for the calibration of vibration and shock pick-ups —

Part 0 :
Basic concepts

0 Introduction

The calibration of vibration and shock pick-ups has become increasingly important as the need has grown for accurate measurements of the shocks and vibrations to which man and a wide variety of equipment are subjected in service. Several methods have been used or proposed for these calibrations and some of them are described in this part of ISO 5347. Clause 6 describes methods which have proved to be reliable means for the absolute calibration of vibration and shock pick-ups.

Methods of calibration for both vibration and shock pick-ups are included in this International Standard because it has proved to be impracticable to make a distinction between pick-ups used in measurements of vibrations and those used in measurements of shocks.

This International Standard is limited to the calibration of acceleration, velocity and displacement pick-ups. It does not deal with pick-ups used for measurements of force, pressure or strain, even though some of these may be calibrated using similar methods. Furthermore, pick-ups used to measure rotational vibratory motion are also excluded because, at present, they are few in number and the calibration hardware and methods are somewhat different from those for the rectilinear pick-ups covered by this International Standard.

This part of ISO 5347 contains definitions and describes basic absolute calibration. In addition, it describes, in general terms, various methods for the calibration of vibration and shock pick-ups as well as methods for measuring characteristics other than sensitivity. In order to be able to carry out a calibration with known accuracy, detailed specifications for instruments and procedures have to be laid down. Information of this kind for each method of calibration is specified in the following subsequent parts of ISO 5347.

Part 1 : Primary vibration calibration by laser interferometry.

Part 2: Primary shock calibration by light cutting.

Part 3: Secondary vibration calibration.

Part 4: Secondary shock calibration.

Part 5: Calibration by Earth's gravitation.

Part 6: Primary vibration calibration at low frequencies.

Part 7: Primary calibration by centrifuge.

Part 8: Primary calibration by dual centrifuge.

Part 9: Primary vibration calibration by comparison of phase angles.

Part 10: Primary calibration by high impact shocks.

Part 11: Testing of transverse vibration sensitivity.

Part 12: Testing of transverse shock sensitivity.

Part 13: Testing of base strain sensitivity.

Part 14: Resonance frequency testing of undamped accelerometers on a steel block.

Part 15: Testing of acoustic sensitivity.

Part 16: Testing of mounting torque sensitivity.

Part 17: Testing of fixed temperature sensitivity.

Part 18: Testing of transient temperature sensitivity.

Part 19: Testing of magnetic field sensitivity.

NOTE — Further parts are under study.

The pick-up may be calibrated as a unit by itself; it may include a cable connection and/or a conditioning device. The calibration system shall always be properly described.

A bibliography is included and is referred to by numbers in square brackets.

1 Scope

This International Standard describes methods of calibration of vibration and shock pick-ups. It also includes methods for the measurement of characteristics in addition to the sensitivity.

One absolute calibration method has been selected as the preferred method (see 6.2.1). Comparison calibration methods for vibration and shock are also described (see 6.3). More detailed descriptions are given in the other parts of this International Standard.

2 Field of application

This International Standard is applicable to continuous-reading rectilinear acceleration, velocity and displacement pick-ups and recommends a preferred method which has proved to give reliable and reproducible results.

It is not applicable to methods for the calibration of rotational pick-ups.

3 References

ISO 1101, *Technical drawings — Geometrical tolerancing — Tolerances of form, orientation, location and run-out — Generalities, definitions, symbols, indications on drawings.*

ISO 2041, *Vibration and shock — Vocabulary.*

ISO 2954, *Mechanical vibration of rotating and reciprocating machinery — Requirements for instruments for measuring vibration severity.*

4 Definitions

For the purpose of this part of ISO 5347, the definitions given in ISO 2041, together with the following, apply.

4.1 pick-up: Device for converting the mechanical motion to be measured, for example acceleration in a given direction, into a quantity which may be conveniently measured or recorded.

NOTE — A pick-up may include auxiliary equipment for amplifying, supplying necessary operating power, providing necessary circuit elements, indicating or recording its output, etc.

4.1.1 operating range: That range in frequency and amplitude for which the pick-up behaves as a linear pick-up within specified limits of tolerance.

4.1.2 reciprocal pick-up: Bilateral electromechanical pick-up for which the ratio of the applied current to force produced (when the pick-up is restrained so the velocity is zero) equals the ratio of the applied velocity to the voltage produced (when the pick-up is open-circuited so the current is zero). Examples of such pick-ups are electromagnetic and piezo-electric pick-ups.

4.1.3 unilateral pick-up: Pick-up employing strain gauges as sensing elements for which an electrical excitation does not cause a perceptible mechanical effect in the pick-up.

4.2 input signal: Signal applied to the input of the pick-up, for example the attenuation applied to the mounting surface.

4.3 output signal: Signal generated by the pick-up in response to a given input signal.

4.4 sensitivity: For a linear pick-up, the ratio of the output to input during sinusoidal excitation parallel to a specified axis of sensitivity at the mounting surface. In general, the sensitivity includes both amplitude and phase information and is, consequently, a complex quantity which varies with frequency. The sinusoidal input motion may be represented by the following equations:

$$\begin{aligned} d &= \hat{d}\ \exp[j\,(\omega t + \varphi_1)] \\ &= \hat{d}\,[\cos(\omega t + \varphi_1) + j\sin(\omega t + \varphi_1)] \end{aligned} \qquad \ldots (1)$$

$$\begin{aligned} u &= j\omega d = \hat{u}\ \exp[j\,(\omega t + \varphi_1 + \pi/2)] \\ &= \hat{u}\,[\cos(\omega t + \varphi_1 + \pi/2) + j\sin(\omega t + \varphi_1 + \pi/2)] \end{aligned} \qquad \ldots (2)$$

$$\begin{aligned} a &= j\omega u = \hat{a}\ \exp[j\,(\omega t + \varphi_1 + \pi)] \\ &= \hat{a}\,[\cos(\omega t + \varphi_1 + \pi) + j\sin(\omega t + \varphi_1 + \pi)] \end{aligned} \qquad \ldots (3)$$

$$\begin{aligned} x &= \hat{x}\ \exp[j\,(\omega t + \varphi_2)] \\ &= \hat{x}\,[\cos(\omega t + \varphi_2) + j\sin(\omega t + \varphi_2)] \end{aligned} \qquad \ldots (4)$$

where

d is the complex quantity of the displacement;

u is the complex quantity of the velocity;

a is the complex quantity of the acceleration;

x is the complex quantity of the output;

$\hat{d}$ is the peak amplitude of sinusoidal displacement;

$\hat{u}$ is the peak amplitude of sinusoidal velocity;

$\hat{a}$ is the peak amplitude of sinusoidal acceleration;

ω is the angular frequency;

φ_1 and φ_2 are the phase angles;

t is the time;

j is the imaginary unit.

The displacement sensitivity, S_d, expressed in the units of the output signal per metre, is

$$S_d = \frac{x}{d} = \hat{S}_d\ \exp\,[-j\,(\varphi_1 - \varphi_2)] \qquad \ldots (5)$$

where

$\hat{S}_d = \dfrac{\hat{x}}{\hat{d}}$ is the magnitude of the displacement sensitivity;

$(\varphi_1 - \varphi_2)$ is the phase lag.

The velocity sensitivity, S_u, expressed in the units of the output signal per metre per second, is

$$S_u = \frac{x}{u} = \hat{S}_u \exp\left[-j\left(\varphi_1 + \pi/2 - \varphi_2\right)\right] \qquad \ldots (6)$$

where

$\hat{S}_u = \frac{\hat{x}}{\hat{u}}$ is the magnitude of the velocity sensitivity;

$(\varphi_1 + \pi/2 - \varphi_2)$ is the phase lag.

The acceleration sensitivity, S_a, expressed in the units of the output signal per metre per second squared, is

$$S_a = \frac{x}{a} = \hat{S}_a \exp\left[-j\left(\varphi_1 + \pi - \varphi_2\right)\right] \qquad \ldots (7)$$

where

$\hat{S}_a = \frac{\hat{x}}{\hat{a}}$ is the magnitude of the acceleration sensitivity;

$(\varphi_1 + \pi - \varphi_2)$ is the phase lag.

Usually, the displacement sensitivity is determined for a displacement pick-up, the velocity sensitivity for a velocity pick-up, and the acceleration sensitivity for an acceleration pick-up. In general, the sensitivity magnitudes and the phase angles are functions of the frequency, $f = \omega/2\pi$.

NOTE — A displacement, velocity or acceleration pick-up in which the corresponding sensitivity does not become zero as the frequency approches zero is said to have a zero-frequency response (direct-current response). Sensitivity under constant acceleration corresponds to $\omega = 0$ and the phase lag is zero. Examples of pick-ups with zero-frequency response are acceleration pick-ups employing strain gauges, potentiometers, differential transformers, force-balance (servo) or variable reluctance circuits as sensing elements. Seismic self-generating pick-ups, such as piezo-electric and electrodynamic pick-ups, are examples of pick-ups without zero-frequency response.

4.5 transverse sensitivity ratio (TSR): The ratio of the output of a pick-up, 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.

4.6 vibration generator: Any device for applying a controlled motion to the mounting surface of a pick-up.

NOTE — Vibration generators are sometimes referred to as exciters or shakers.

5 Characteristics to be measured

5.1 General

The primary object of the calibration of a pick-up is to determine its calibration factor over the amplitude and frequency range for the degree of freedom for which the pick-up is to be used. In addition, it may be important to know its response to motions in the other five degrees of freedom; for example, for a rectilinear acceleration pick-up, its response should be known to motions at right angles to the sensitive direction and to rotations. Other important factors include damping, phase lag, non-linearity or variation in response with amplitude of motion, effect of temperature and pressure changes, and other extraneous conditions such as motion of the connection cable.

5.2 Direct response

5.2.1 Frequency response and phase response

The sensitivity of a pick-up is obtained by placing the pick-up with its sensitivity axis parallel to the direction of motion of the vibration generator, measuring the motion or input applied by the vibration generator and measuring the output of the pick-up. Both continuous-reading and peak-reading pick-ups can also be calibrated with a controlled transient excitation whose amplitude and frequency components are within the working range of the pick-up. To detect any resonances, the output of the pick-up should be observed while varying the vibration generator frequency slowly and continuously over the frequency range. In general, only information concerning magnitude sensitivity calibration is given as a function of frequency. However, for the use of a vibration pick-up close to its upper or lower frequency limits, or for special applications, the phase response may be required. This is determined by measuring the phase lag between the output signal and the mechanical excitation over the frequency range of interest.

5.2.2 Non-linearity

Deviations from linearity of the output of a pick-up (amplitude distortions) are determined by measuring its output magnitude as the magnitude of the input is increased from the smallest value to the largest value for which the pick-up is designed. When a sinusoidal vibration generator is used, the measurement should be repeated for several frequencies.

Non-linearity may take several forms. The sensitivity of the pick-up may change progressively with increasing amplitude, there may be a permanent change leading to a displacement of the zero after subjecting the pick-up to vibration or shock, or there may be stops that limit the range of motion suddenly.

The type and magnitude of the non-linearity of a pick-up 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 pick-up. The permissible deviations from linearity will depend on the measurements to be made. Non-linearity should be expected at the upper limit of the useful dynamic range of the pick-up.

5.3 Spurious response

5.3.1 Temperature dependency

The sensitivity, damping ratio and resonance frequency of many pick-ups change as a function of temperature. Temperature response calibrations are usually performed using a comparison method. The standard pick-up is mounted axially in line with the test pick-up, the test pick-up is placed inside a temperature chamber and the standard pick-up is located outside the chamber or otherwise protected from changes in temperature in such a way that its sensitivity remains constant to within 2 % for the ambient temperatures present during the entire calibration. The vibration generator is used only at frequencies where it is known that the transverse motion is less than 25 % of the axial motion. The vibration generator is selected and a fixture designed so that there is negligible relative motion between the test and standard pick-ups at frequencies at which the calibration is to be performed.

An alternative procedure for performing temperature response calibrations is to mount the standard and test pick-ups on a suitable fixture inside the temperature chamber. This method is limited to temperature ranges in which the response of the standard pick-up is known.

For pick-ups which respond to static acceleration, the zero unbalance is measured at the maximum and minimum temperatures.

Pick-ups with internal damping greater than 10 % of the critical damping should be calibrated at a minimum of four frequencies at a single vibration amplitude and at each of four temperatures in addition to room temperature. This method is equally applicable to pick-ups, such as the electrodynamic types, which utilize a coil of wire in their operation. The frequencies are selected throughout the frequency range of intended use.

The internal capacitance and resistance of piezo-electric pick-ups shall be measured after stabilization at the maximum calibration temperature.

If the measured resistance of a piezo-electric accelerometer at the maximum calibration temperature is so low that it affects the low-frequency response of the type of amplifier to be used, a low-frequency response calibration should be performed at that temperature. A number of frequencies shall be selected to describe adequately the frequency response. The calibration should be performed on the complete system, using the amplifier that is used with the accelerometer.

NOTE — High temperature may affect the low-frequency response of the accelerometer as well as the noise and stability of the accelerometer-amplifier combination. Temperature response deviations are computed as the change in calibration factor determined at the test temperature referred to the room temperature (20 °C) calibration factor (measured at a frequency in the range of frequencies in which the pick-up response is uniform). This change is expressed as a percentage of the room temperature calibration factor. It is usually desirable to select pick-ups which have temperature response deviations not exceeding ± 15 % throughout the temperature range of intended use.

5.3.2 Transient temperature sensitivity in piezo-electric pick-ups

Pyroelectric outputs are generated in all piezo-electric pick-ups subjected to transient temperatures. This is especially true for ferroelectric materials. The magnitude of the pyroelectric outputs depends upon the material constituting the crystal and the design of the pick-up. Usually, the predominant frequency of the pyroelectric output is considerably less than 1 Hz. Also, most of the pyroelectric output from the pick-up is filtered owing to the low-frequency characteristics of most amplifiers. Accordingly, the pyroelectric output is dependent on the rate of change in temperature and on the characteristics of the amplifier together with the characteristics of the pick-up.

The pyroelectric test is performed using the type of amplifier normally used with the pick-up. The pick-up is attached to an aluminium block by the usual means of attachment. Both are quickly immersed in an iced water bath or a bath of other suitable liquid at a temperature which differs by approximately 20 °C from room temperature. The liquid in the bath should be described. The mass of the block should be approximately 10 times the mass of the pick-up. Precautions are required to ensure that the liquid does not penetrate the pick-up or that electrical leakage resistance is not lowered by the liquid at the connector, etc. The maximum amplifier output and the time from the start of the transient at which this maximum output is reached are measured on a direct-current oscilloscope or recorder. If the output reverses within the first 2 s and reaches a peak of opposite polarity, the magnitude and time of this peak are also recorded. For an accelerometer, the transient temperature sensitivity is expressed in equivalent metres per second squared per degree Celsius [$(\mathrm{m/s^2})/^\circ\mathrm{C}$] by dividing the maximum pick-up output by the product of the difference between the bath temperature and room temperature and the accelerometer sensitivity.

For special applications using amplifiers having significantly different low-frequency characteristics, the pyroelectric test is performed with the specific amplifier to be used. Also, for applications in which the transient temperature rate differs greatly from that described by the above conditions, the test may be performed by simulating the particular temperature environment.

5.3.3 Transverse sensitivity ratio

The transverse sensitivity ratio (TSR) is usually determined at a single frequency below 500 Hz. The frequency used shall be reported. Sinusoidal motion is applied at a frequency at which it is known that the motion in a plane perpendicular to the sensing axis is at least 100 times the motion in the direction of the sensing axis. For transverse sensitivity ratios less than 1 %, the requirements for motion are more severe and extreme care and skill are required to obtain the value of the transverse sensitivity ratio.

The pick-up is mounted and rotated about its sensing axis through 360°, in increments of 45° or less, to determine the maximum transverse response.

NOTE — Experimental transverse sensitivity measurements on accelerometers indicate no detectable frequency dependence up to about 2 000 Hz. Only limited data are presently available regarding the transverse response within the frequency range from 2 000 to 10 000 Hz. Several experimenters have stated that their measurement results usually indicate the high-frequency transverse response (that is, 2 000 to 10 000 Hz) to be of the same order of magnitude as in a low-frequency determination (that is, less than 500 Hz). Generally, it is considered that for accelerometers whose axial resonance frequency is greater than 30 kHz, major transverse resonances will be greater than 10 kHz and, thus, beyond a pick-up's normal operating range. For vibration pick-ups of other types, even less information is currently available. If possible, the lowest frequency of transverse resonance should be determined.

5.3.4 Sensitivity to rotational motion

Certain rectilinear vibration pick-ups are susceptible to rotational inputs. Examples of these include flexion-type piezoelectric and piezoresistive accelerometers, and pendulum force-balance (servo) accelerometers. No specific requirements nor test methods can be given at this time owing to lack of knowledge regarding suitable tests. Attention is drawn, however, to the existence of rotational sensitivity, and precautions may have to be taken in other tests to preclude a measurement error due to this effect.

5.3.5 Strain sensitivity

The technique described below is the preferred method to determine the error produced in a pick-up output due to bending of its base.

The pick-up is mounted on a simple cantilever beam which produces a radius of curvature of 2 500 cm and a strain of 250×10^{-6}.

A steel cantilever beam is clamped to a rigid support. The beam is 76 mm wide and 12,5 mm thick with a free length of 1 450 mm.

The natural frequency is very close to 5 Hz. The strain is measured by strain gauges bonded to the beam near the pick-up mounting location about 40 mm from the clamped end. The motion at the mounting location can be checked by means of a pick-up attached using extra isolation against base bending. A pick-up with a calibration factor more than 10 times higher than the units under test is normally adequate. The outputs from the strain gauges and the pick-up under test are recorded.

The system is excited by manually deflecting the free end of the beam. The output of the pick-up is recorded at a point where the strain in the surface of the beam is 250×10^{-6}. (This is equivalent to a radius of curvature of 25 m.) The error is the difference between the motion of the beam at the mounting location and the motion indicated by the pick-up. The strain sensitivity, for a strain of 10^{-6}, is determined by dividing the above difference by 250.

The strain sensitivity should be tested at various strain amplitudes, in various directions. The maximum strain sensitivity of some pick-ups can produce significant errors in certain applications and mounting conditions. For example, some piezo-electric accelerometers produce error signals of several per cent at certain frequencies where strains are produced in vibration generators used for calibration purposes.

5.3.6 Magnetic sensitivity

The pick-up is placed in a known magnetic field at 50 or 60 Hz, and rotation of the pick-up is started. The maximum electrical output of the pick-up is recorded. For accelerometers, metres per second squared per tesla is recorded as the equivalent based on the sensitivity. For velocity pick-ups, metres per second per tesla over the useful frequency range is recorded as the equivalent. Induced mechanical vibrations and spurious electrical noise shall be eliminated from the test assembly.

5.3.7 Mounting torque sensitivity

The change in calibration factor due to pick-up mounting torque is determined by applying torques of one-half specified, specified, and twice the maximum specified mounting torque. This test applies only to pick-ups that are mounted by screws, bolts, or other threaded fasteners. If more than one fastener is used in the normal mounting, the torques should be applied to each fastener.

Care should be taken to ensure that the pick-up mounting surface is free from burrs or other surface defects which would prevent a flat mounting. The test surface to which the pick-up is to be mounted should be flat and smooth and made from steel. The recommended values of flatness and roughness are a curvature greater than 5 µm and an r.m.s. ground finish of 2 µm or better.

The test surface on which the pick-up is to be mounted should be drilled and tapped square to the mounting surface with a perpendicularity of 0,05 mm or better (see ISO 1101). The interface lubrication normally recommended should be used and stated. The torque should always be applied from an unmounted condition, that is from zero torque for each of the three test torques. The torque sensitivity is recorded as the change in pick-up calibration factor for one-half and twice the specified torque in relation to the specified torque. The uncertainty in the applied torque should not exceed ± 15 %.

5.3.8 Special environments

The operation of some pick-ups may be adversely affected in certain special environments, such as strong electrostatic, variable magnetic or radio-frequency fields, acoustic fields, in the case of cable effects, and nuclear irradiation. At present, there are no generally accepted techniques for measuring the effect of such special environments on a pick-up, although special tests have been developed in instances where adverse effects could be expected. (See ISO 2954.)

6 Calibration methods

6.1 General

In order to perform a direct calibration of a pick-up, it is necessary to use a vibration generator which applies a controllable and measurable input to the pick-up and to provide a means for recording or measuring the output of the pick-up. The pick-up shall be attached to the vibration generator (or placed near it in the case of pick-ups whose output depends on the relative motion between the pick-up and the vibrating object).

The attachment shall be sufficiently rigid to transmit the motion of the vibration generator to the pick-up over the frequency range of the pick-up. This requires that the natural frequency of the system, consisting of the pick-up regarded as the mass and the attachment as the spring of a single-degree-of-freedom system, be high compared with the highest frequency component of the motion of the vibration generator. The vibration generator may be a support for tilting the pick-up relative to the pull of gravity, a centrifuge, an electrodynamic vibration generator, or the anvil of a ballistic pendulum. The tilting support and centrifuge are used for calibration at zero frequency. Rotational calibration is used for low-frequency calibration for the Earth's gravitational field. The electrodynamic vibration generator is generally used for steady-state sinusoidal calibrations. Ballistic pendulums, which apply transient excitation, may be used as a complementary method to the electrodynamic vibration generator, to bring out natural frequency response and to permit calibration at high accelerations and velocities. In addition, shock excitation may be used to verify pick-up performance for high accelerations and velocity changes and to check that auxiliary instrumentation connected to the pick-up functions properly under transient conditions.

A number of calibration methods are described in this International Standard and they may be used for special purposes. However, the use of a laser interferometer is recommended for absolute calibration. Whenever possible, it is recommended that standard pick-ups be calibrated by this method, and if only one frequency is used, this should preferably be 160, 80 or 16 Hz depending on the application. Frequency response may be obtained by calibration at discrete frequencies over the frequency range of interest or as the frequency response relative to the sensitivity at the reference frequency with less accuracy. Most other calibration needs can be covered by comparison against a standard pick-up with absolute calibration. The calibration is always referred to the moving base of the pick-up and, for "back-to-back" calibration standards, to the mounting base for the unknown pick-up.

6.2 Absolute calibration methods

6.2.1 Calibration by measuring displacement amplitude and frequency

6.2.1.1 General

Many dynamic calibration methods depend on the accurate measurement of the displacement amplitude of the vibration to which the pick-up is subjected. This method is generally used for continuous-reading pick-ups. The sinusoidal motion applied by the vibration generator should be along a well-defined straight line; lateral motions should be negligible.

The measured displacements can be used to calculate velocities, u, and accelerations, a, using the formulae $u = 2\pi fd$ 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 formulae 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 sources or due to other causes such as mechanical resonance. Harmonics are also objectionable since they may excite resonant response in a pick-up.

Once the displacement amplitude is known, the pick-up sensitivity may be calculated as the ratio of the measured pick-up output to the velocity or the acceleration amplitude.

The displacement amplitude shall be measured by laser interferometry. The method is well described in [1], [2], [3], [4], [5] and [6].

The methods of calculation used in laser interferometry generally give good accuracy up to 600 Hz at 1 000 m/s² (corresponding to a displacement amplitude of 70 µm); 1 % uncertainty has been reported at 600 Hz, and 0,5 % has been reported in the range 80 to 160 Hz. Considerable errors in the measurement of displacement will occur if the reference mirror is perturbed at the frequency (or a harmonically related frequency) at which the accelerometer is vibrated. Error may also result from perturbation of the beam splitter. It is advisable to monitor for such perturbation using a very sensitive accelerometer.

6.2.1.2 Theory for the ideal interferometer

The principle of operation is shown in figure 1, where E_0, E_1 and E_2 represent the electric field vectors, and l_1 and l_2 represent the actual path lengths the beams have to travel after the beamsplitter. The displacement to be measured is represented by d (mirror 2).

The electric field vectors E_1 and E_2 can be represented by the formulae

$$E_1 = A_1 \exp\left[j\left(\omega t + \frac{4\pi}{\lambda} l_1\right)\right]$$

$$E_2 = A_2 \exp\left\{j\left[\omega t + \frac{4\pi}{\lambda}(l_2 + d)\right]\right\}$$

where λ is the wavelength of the laser light.

The intensity of the photodetector $I(t)$ is given by the formula

$$I(t) \approx |E_1 + E_2|^2 = A + B \cos\left[\frac{4\pi}{\lambda}(L + d)\right]$$

where

A and B are constants of the system;

$L = l_2 - l_1$

From the intensity expression, it can be seen that the maxima will occur when

$$\frac{4\pi}{\lambda}(l_2 - l_1 + d) = 2n\pi$$

and, therefore, the displacement corresponding to the distance between two intensity maxima is given by $d = \lambda/2$. The number of maxima, R_f, for one vibration cycle is then

$$R_f = 4\xi/(\lambda/2) = 8\xi/\lambda$$

which is commonly referred to as the "frequency ratio" because it can be calculated by dividing the number of fringes counted during 1 s by the vibration frequency.

The displacement amplitude, ξ, is thus given by the formula

$$\xi = R_f \cdot \lambda/8$$

If, in addition to the frequency ratio, the vibration frequency is measured, one can also compute the velocity and acceleration.

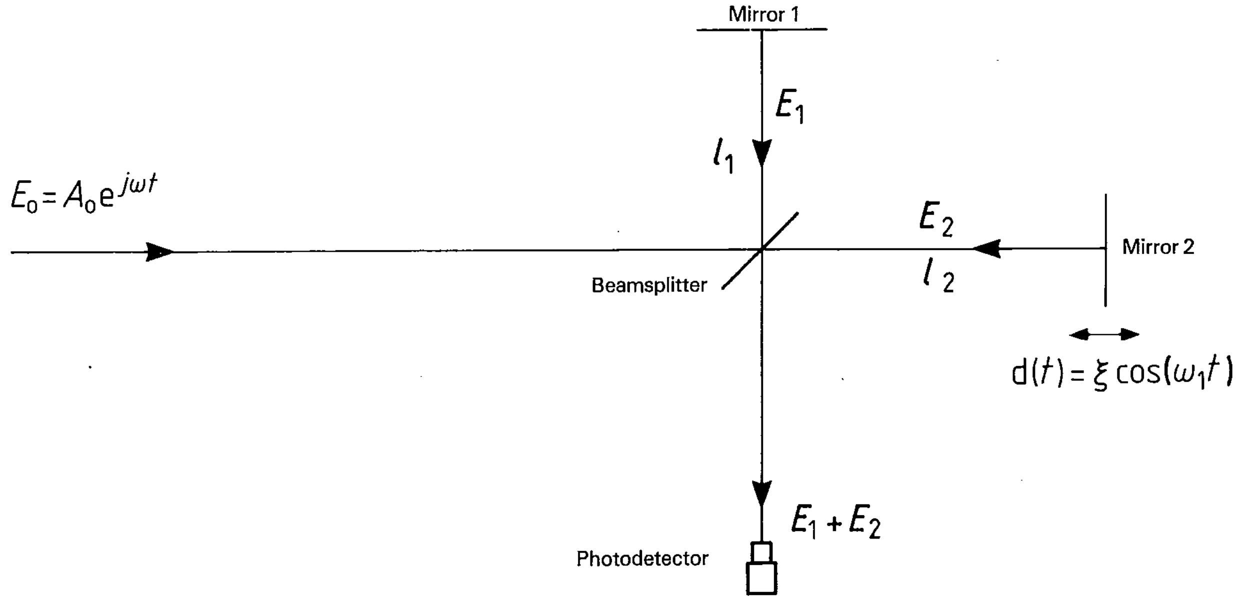

Figure 1 — Principle of the ideal interferometer

The same system can be used to measure displacement amplitude at frequencies outside the range recommended earlier for the fringe-counting method. Several other methods can be devised by considering the frequency spectrum of the intensity $I(t)$. As given in [1], the expansion gives

$$\begin{aligned} I(t) = A + B\cos\left\{\frac{4\pi L}{\lambda}\left[J_0\left(\frac{4\pi\xi}{\lambda}\right) - 2J_2\left(\frac{4\pi\xi}{\lambda}\right)\cos(2\omega_1 t) + \right.\right. \\ \left.\left. + 2J_4\left(\frac{4\pi\xi}{\lambda}\right)\cos(4\omega_1 t) - \ldots\right]\right\} - \\ - B\sin\left\{\frac{4\pi L}{\lambda}\left[2J_1\left(\frac{4\pi\xi}{\lambda}\right)\cos(\omega_1 t) - \right.\right. \\ \left.\left. - 2J_3\left(\frac{4\pi\xi}{\lambda}\right)\cos(3\omega_1 t) + \ldots\right]\right\} \end{aligned}$$

The following two examples adequately illustrate the type of signal processing that is required here.

a) Adjusting the vibration amplitude to a level which makes the n^{th} harmonic component zero, one can solve the equation $J_n\left(\frac{4\pi}{\lambda}\xi\right) = 0$, to obtain ξ.

b) In cases where it is not possible or practical to calibrate at amplitude levels required by the $J_n\left(\frac{4\pi}{\lambda}\xi\right) = 0$ method, one can extract the value of ξ from the ratio of two harmonic components, for example, by solving for ξ from

$$\frac{J_1\left(\frac{4\pi}{\lambda}\xi\right)}{J_3\left(\frac{4\pi}{\lambda}\xi\right)} = \frac{V_1}{V_3}$$

where V_1 and V_3 are the measured magnitudes of the first and third harmonics.

6.2.1.3 Measuring system

An example of a measuring system is shown in figure 2. The pick-up is a so-called reference pick-up and the sensitivity shall be determined for the upper surface (reference mounting surface). The laser has an output power of 1 mW, and the detector is a normal silicon phototransistor. The pulse generator is used to obtain a well-defined signal for the counter input instead of the internal crystal oscillator. The frequency analyser is used to select the appropriate frequency when the zero-point method is used. The laser and the interferometer system and the vibrator system should be mounted on independent heavy vibration isolation blocks (for example each of mass more than 400 kg) to avoid perturbation of the reference mirror or the beam splitter by the reaction of the vibrator support structure.

6.2.2 Calibration by reciprocity method (see [4], [6], [7] and [8])

Primary calibrations can also be carried out using the technique of reciprocity calibration. The reciprocity theory is applicable to the calibration of vibration standards in the amplitude range where the pick-up's electrical output is linearly proportional to the motion of the vibration generator on which it is calibrated. The theory shows a reciprocity relationship for the driver coil of the vibration generator and equates the ratios of force/current and potential difference/velocity.

When the calibrator is energized with current in the driving coil at a specified frequency, the sensitivity, S_{uc}, is defined as the ratio of the potential difference, E_{13}, in volts, in the velocity-sensing coil, to the acceleration, a, in metres per second squared, at the surface of the mounting table, that is

$$S_{\text{uc}} = \frac{E_{13}}{a} \qquad \ldots (8)$$

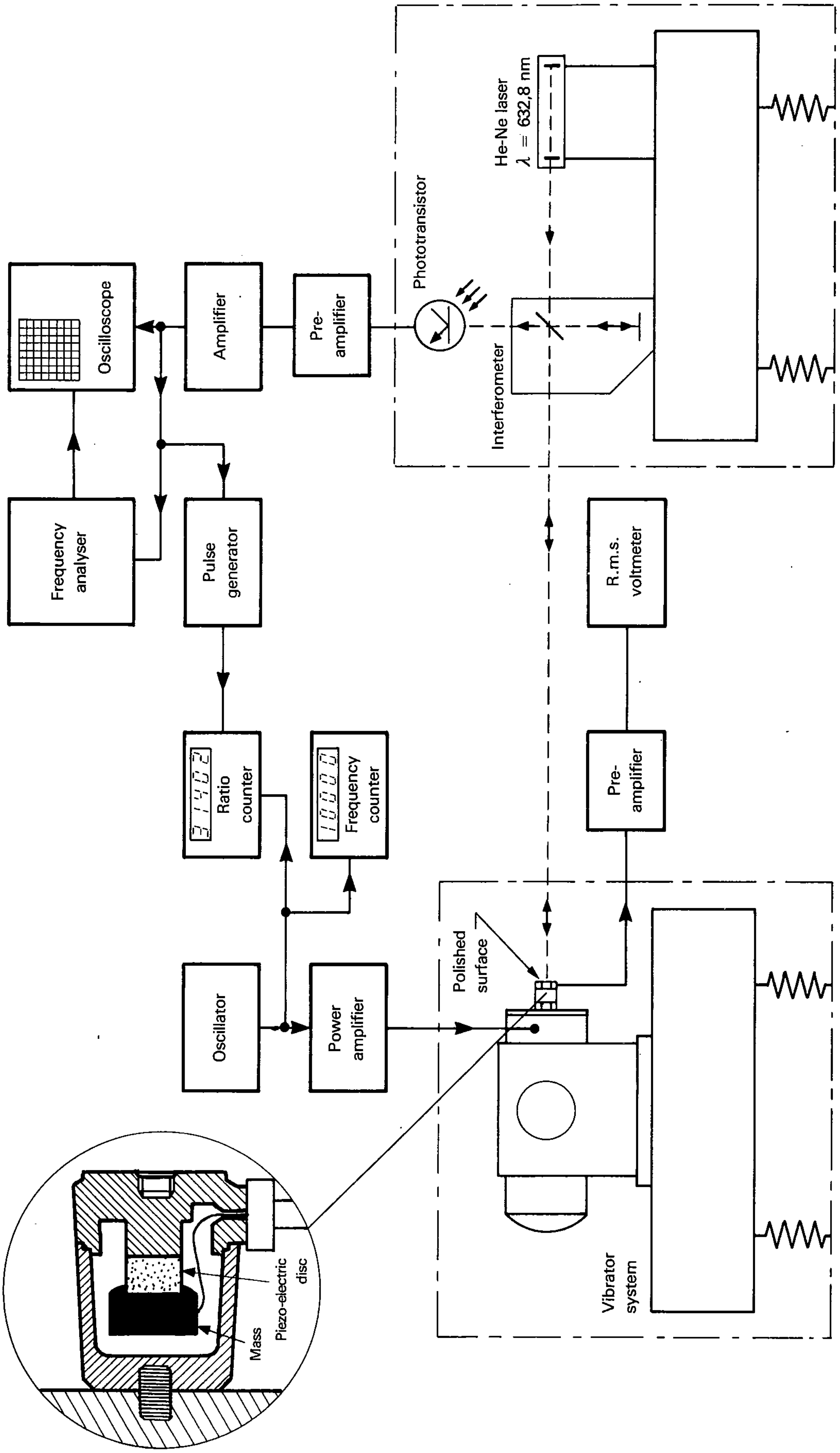

Figure 2 — Example of a measuring system using a interferometer

The object of the reciprocity method is to determine the sensitivity S_{uc} so that when the potential difference E_{13} is measured, the acceleration a may be computed by use of equation (8). S_{uc} is determined from the following equation:

$$S_{uc} = S_0 + s_z Z_m \qquad \ldots (9)$$

where Z_m is the mechanical impedance of the pick-up, in kilograms per second per metre.

The quantities S_0 and s_z are determined by the following two experiments and computational procedure.

Experiment 1

Several weights are attached to the mounting table. For each weight, and with no weight attached, the transfer admittance Y_e, in amperes per volt, is measured between the driving coil and the accelerometer, and is given by the formula

$$Y_e = \frac{I}{E_{13}} \qquad \ldots (10)$$

where

I is the current, in amperes, in the driving coil;

E_{13} is the potential difference, in volts, generated by the accelerometer.

Experiment 2

The moving parts of the calibrator are set into sinusoidal vibration by connecting the mounting table of the calibrator to a vibration generator and then energizing the vibration generator[1]. The ratio, E_{13}/E_{15}, of the potential, E_{13}, generated in the accelerometer to the open-circuit potential, E_{15}, generated in the driving coil is measured.

Computational procedure

Determine the ordinate intercept, J, and the slope, Q, of the function $W/(Y_{eW} - Y_{e0})$ when plotted against the mass W, of the weight attached to the mounting table in experiment 1, and where Y_{eW} is the value of Y_e with a weight of mass W attached and Y_{e0} is the value for $W = 0$. This plot is made by separating $W/(Y_{eW} - Y_{e0})$ into its real and imaginary parts from which the real and imaginary parts of J and Q are determined. The quantities S_0 and s_z in equation (9) are then given by

$$S_0 = \sqrt{j\omega J E_{13}/E_{15}} \qquad \ldots (11)$$

$$s_z = \sqrt{(E_{13}/E_{15})/j\omega J} \qquad \ldots (12)$$

where

ω is the angular frequency, in radians per second;

j is the imaginary unit.

6.2.3 Calibration by centrifuge

6.2.3.1 Single centrifuge

A centrifuge consists of a balanced table or arm which can be made to rotate about a vertical axis at a uniform angular velocity. With this device, an accurately known constant acceleration can be applied to an acceleration pick-up for as long a time as is desired. Centrifuges capable of subjecting pick-ups to masses of several kilograms and to accelerations up to 6×10^5 m/s^2 have been built and centrifuges rated at lower accelerations are commercially available.

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

To make a calibration, the acceleration pick-up shall be 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 pick-up is

$$a = \omega^2 r \qquad \ldots (13)$$

where

ω is the angular frequency, in radians per second, of the centrifuge;

r is the distance from the axis of rotation to the centre of gravity of the mass element of the pick-up.

It is necessary to mount the pick-up at such a distance from the axis of rotation that the deflection of the mass element of the pick-up can be neglected in the determination of r.

Most pick-ups are so constructed that it is not easy to measure r directly. The value of r may be determined from readings taken for the pick-up mounted at two positions separated by a known distance, Δr, while it 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 pick-up in both positions. The value of r in the second position, designated r_2, is

$$r_2 = \frac{\Delta r}{1 - \omega_2^2 x_1/\omega_1^2 x_2} \qquad \ldots (14)$$

where

ω_1 is the angular frequency in the first position, for which $r = r_1 = r_2 - \Delta r$;

ω_2 is the angular frequency in the second position, for which $r = r_2$;

x_1 is the pick-up output due to the angular frequency ω_1;

x_2 is the pick-up output due to the angular frequency ω_2.

With this value of r_2 and the angular frequency ω_2, the acceleration can be determined from equation (13).

---

1) Some electrodynamic vibration generators have been constructed having two drive coils mechanically connected to the vibration generator's armature and mounting table. In this instance, it is not necessary to use a separate vibration generator.

The determination of r may be eliminated if the pick-up has a linear range which extends down to the acceleration due to gravity, g. If this is the case, the pick-up is first calibrated at $\pm g$ by the tilting support method. The pick-up is then placed on the centrifuge and the angular frequency ω_1 at which the output is that corresponding to g is determined. The applied acceleration at another angular frequency, ω, is then

$$a = g \cdot \omega^2/\omega_1^2 \qquad \dots (15)$$

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

In the calibration of electromechanical pick-ups on a centrifuge, leads are brought through slip rings and brushes. Since acceleration pick-ups with zero-frequency response are relatively low-impedance devices, shielding from external fields and cable noise presents no particular problem. The electrical noise from a worn-in slip-ring assembly of good design is negligible under normal circumstances. However, certain acceleration pick-ups using strain gauges 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 pick-up, 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.

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

The sensitivity of an acceleration pick-up at zero frequency can be determined with an accuracy to 1 % or better on a good centrifuge. Calibration on a centrifuge will, of course, give no indication of the usable frequency range.

6.2.3.2 Tilted centrifuge

When the axis of rotation of a centrifuge is not parallel with the Earth's gravitational vector, the acceleration applied to a pick-up mounted on the centrifuge will have a gravitational component, $g \sin\phi \sin(\omega t)$, which will be added to the centripetal acceleration, $\omega^2 r$, where ϕ is the angle between the rotational axis and the vertical axis. The effect of the gravitational component on a pick-up approximated by a spring-mass system is discussed in [9]. Sinusoidal acceleration can be applied to the pick-up when $r = 0$ and $\phi = 0$. In this instance, the acceleration due to gravity can be determined with minimal uncertainty. The limit is, of course, $\pm g$ at whatever frequency is produced by the rotation. The maximum frequency is generally less than several hundred hertz as limited by the centrifuge and balancing ability.

6.2.3.3 Dual centrifuge (see [10])

The dual centrifuge consists essentially of a small centrifuge eccentrically mounted on a large fixture attached to the wall (see figure 3). The vibration pick-up, 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 frequencies, the sensitivity axis of the pick-up is alternatively changing its direction relative to the centre of the large centrifuge at a frequency, in hertz, equal to the angular frequency, in revolutions per second, of the small centrifuge relative to the large centrifuge. The component of acceleration, a, applied along the sensitive axis of the pick-up at any time t is

$$a = r_c \omega^2 \cos(\omega_p t) + r(\omega \pm \omega_p)^2 \qquad \dots (16)$$

where

ω is the angular frequency, in radians per second, of the large centrifuge;

ω_p is the angular frequency, in radians per second, of the small centrifuge relative to the large centrifuge;

r_c is the distance between the centres of the two centrifuges;

r is the distance from the centre of gravity of the mass element of the pick-up to the centre of the small centrifuge.

The sign in the last term of equation (16) is plus 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 pick-up reduces to the sinusoidal term

$$a = r_c \omega^2 \cos(\omega_p t) \qquad \dots (17)$$

Thus, the component of acceleration applied along the sensitive axis of the pick-up is sinusoidal. There is also a component of acceleration applied transverse to the sensitive axis, which renders this method non-applicable to pick-ups with high transverse sensitivity ratios. The term $r(\omega \pm \omega_p)^2$ is zero if ω and ω_p are equal but in opposite directions.

When a dual centrifuge of this type is built in the following manner, equation (17) is exact and the component of acceleration along the sensitive axis of the pick-up should be purely sinusoidal. A pulley is fixed in space with its centre coincident with the centre of the large centrifuge. 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 frequency of both centrifuges about their respective centres will always be equal and opposite in direction.

The dual centrifuge is useful for applying sinusoidal accelerations up to 500 m/s^2 in the approximate frequency range from 0,7 to 10 Hz.

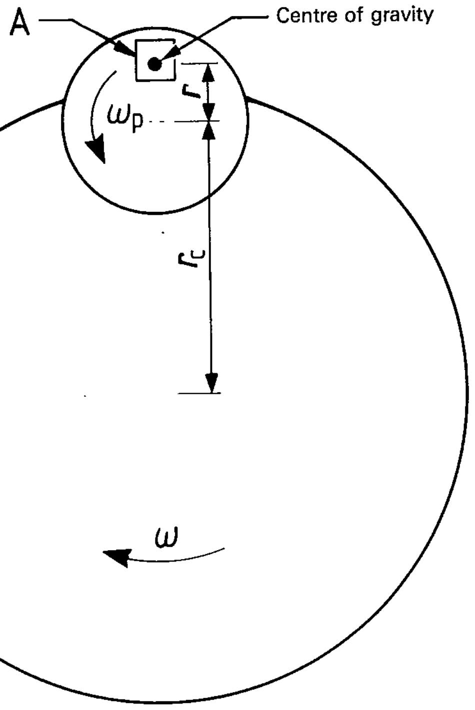

Figure 3 — Dual centrifuge

6.2.3.4 Tilting support calibrator

The tilting support calibrator utilizes the Earth's gravitational field for the calibration of rectilinear acceleration pick-ups with zero-frequency response and with negligible transverse sensitivity. It is useful over the range from $-g$ to $+g$. The pick-up to be calibrated is fastened to a platform at the end of an arm which indicates the component of acceleration along the arm. The arm may be set at an angle, ϕ, relative to the vertical between 0 and 180°. 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 pick-up is attached in the position $\phi = 0$. Positioning of the arm to ± 0,1° or better is possible with an accurately divided circle.

The component of acceleration along the arm is given by

$$a = g \cos \phi \qquad \ldots (18)$$

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

$$\Delta a = g \sin \phi \, \Delta \phi \qquad \ldots (19)$$

The acceleration pick-up is subjected to a component of acceleration at right angles, a_t, to its sensitive direction equal to

$$a_t = g \sin \phi \qquad \ldots (20)$$

Usually, this does not affect the results of the calibration of pick-ups with negligible transverse sensitivity.

NOTE — Vibration isolation of the test apparatus may be required to achieve satisfactory results. Electronic filtering and averaging in direct-current voltage-sensing instrumentation may help to reduce the effects of bench-top vibration etc.

6.2.4 Shock calibration method

Most absolute shock calibrations are based on the principle of change in velocity (see [6] and [11]). This is because velocity is a physical parameter which can be measured practically. The usual configuration is to mount the pick-up to be calibrated on an anvil suspended by some means in a resting position (see [12]). A hammer of some sort is then allowed to strike the anvil, thus generating a transient motion of the anvil. The impact shall 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 or acceleration pick-up to be calibrated shall have a mass which is small compared with the anvil mass to which it is attached and should have its sensitivity direction carefully aligned with the direction of the impact force during collision. During impact, the accelerometer output versus time is recorded. Immediately following impact, the anvil velocity, Δu, is measured.

The velocity may be measured by timing the anvil over a known distance. Photoelectric or magnetic pick-ups can be used to trigger an electronic timer. The velocity is a direct result of the acceleration applied during impact:

$$\Delta u = \int_{t_1}^{t_2} a(t) \, dt \qquad \ldots (21)$$

where

Δu is the velocity increment, in metres per second;

$a(t)$ is the time-varying acceleration, in metres per second squared.

The accelerometer output, $e_r(t)$, is then

$$e_r(t) = S_r a(t) \qquad \dots (22)$$

where S_r is the sensitivity of the reference standard, in units of the output signal per metre per second squared.

Combining equations (21) and (22), and solving for S_r, gives

$$S_r = \left[\int_{t_1}^{t_2} e_r(t)\,dt\right] \Big/ \Delta u \qquad \dots (23)$$

Equation (23) makes possible the calibration of a linear acceleration pick-up from its recorded output during the ballistic impact. 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 the width respectively of the pulse. The pulse shapes and durations are usually adjusted by varying mass, impacting mediums and some initial conditions such as drop height, air pressure, or other physical parameters depending on the nature of the shock generator.

Both techniques (impact against an anvil and impact against a linear spring) are practical to obtain the value of Δu as required *for equation (23). The output of the acceleration pick-up may* be recorded during impact as a function of time by a high-speed oscillograph or from a storage-type oscilloscope and photographed. Potential difference scales and times scales can be verified by superimposing a known potential difference signal, e_c, and a known time area, y_c and x_c, respectively. The potential difference, K_1, and time scale, K_2, factors are given by

$$\left.\begin{aligned} K_1 &= e_c/y_c \\ K_2 &= t_c/x_c \end{aligned}\right\} \qquad \dots (24)$$

The area under the record of accelerometer output versus time is defined by

$$A = \int_{x_1}^{x_2} y\,dx \qquad \dots (25)$$

where x_1 and x_2 denote the beginning and the end of the impact. Substitution of these quantities into equation (23) results in

$$S_r = \frac{K_1 K_2 K A}{\Delta u} \qquad \dots (26)$$

The area, A, can be obtained by graphic integration of the recorded acceleration time history. A planimeter is useful in measuring the area under the acceleration-time record. Care has to be taken in the determination of area with regard to zero offsets, overshoot and ringing.

The integral shown in equation (23) may also be determined by electronic integration or by digital recording and summation techniques. This accelerates the calibration process and reduces the subjective errors and operator fatigue.

Absolute shock calibrations of quality accelerometers can be performed with uncertainties of less than 5 % over most reasonable ranges of shock amplitudes and durations. An important assumption made is that the pick-up being calibrated has linear frequency response in the frequency range of interest. If it does not, errors will result which are very difficult to evaluate. Furthermore, a single value of sensitivity is determined and does not in any way yield any practical information regarding frequency or phase response. This is not a serious restriction except for the most demanding requirement for accuracy.

6.3 Comparison calibration methods

A vibration pick-up calibrated by one of the above methods may be used as a reference standard for the calibration of other pick-ups. The method described in 6.2.1 is the preferred method.

In making such a calibration, both the calibrated reference pick-up 1 and the pick-up 2 to be calibrated are subjected to the same input motion by suitably mounting the pick-ups, and their outputs, x_1 and x_2, or the ratio of the two outputs, are measured. If the two pick-ups sense the same vibration parameter, i.e. both sense velocity or both sense acceleration, and if the responses of both pick-ups 1 and 2 are linear, the amplitude sensitivity, S_2, of pick-up 2 is related to the corresponding amplitude sensitivity, S_1, of the calibrated pick-up 1 by

$$S_2 = \frac{x_2}{x_1} S_1 \qquad \dots (27)$$

Calibration by this comparison method is limited to the range of frequencies, time duration of pulses, and amplitudes for which pick-up 1 has been calibrated. The complex sensitivity S_2 may also be determined if the phase response of pick-up 1 is known and if the phase relation between x_2 and x_1 is measured. If the two pick-ups sense different vibration parameters, for example if a velocity pick-up is compared to an accelerometer, the sensitivity S_2 will be related by some power of $j\omega$. Best results are generally obtained when the two pick-ups are rigidly mounted in a back-to-back configuration with the sensing axes parallel with the direction of motion. Care has to be taken to ensure that pick-ups 1 and 2 experience the same motion. If both pick-ups are rectilinear and are placed on the table of a vibration generator, the rocking motion of the table has to be negligible. Wave-form distortion is generally not as critical for comparison calibrations as for absolute calibrations, especially if both pick-ups sense the same vibration parameter. However, the presence of harmonic components in the motion may increase the output voltages of the two pick-ups by different amounts, depending on the ratio of the sensitivities at the frequencies of the harmonics.

Practical calibration can be carried out using an electrodynamic vibration generator. A back-to-back reference accelerometer is mounted on the vibration generator with the calibrated surface opposite the table. The unknown accelerometer is placed on the back-to-back reference accelerometer. For comparison at high frequencies, the reference accelerometer shall be calibrated for a mass load of the same order of magnitude as that of the unknown accelerometer.

The electrical output of the reference accelerometer preamplifier may be conveniently and precisely compared against the output of the unknown accelerometer using a precision amplifier with attenuator and comparing the signals by adjusting to the zero indication using a balance comparator meter.

It shall be noted that the sensitivity of the reference pick-up may depend on the mass load at the surface where the unknown pick-up is mounted. Therefore the sensitivity values for the reference pick-up shall be known for the mass of the unknown pick-up [13].

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