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

Part 0 :
Basic concepts

Méthodes pour l'étalonnage des capteurs de vibrations et de chocs —

Partie 0 : Concepts de base

Reference number
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Foreword

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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.

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Part 0 :
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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 [$(m/s^2)/°C$] 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 $u = 2\pi f d$ 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/s^2 (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.

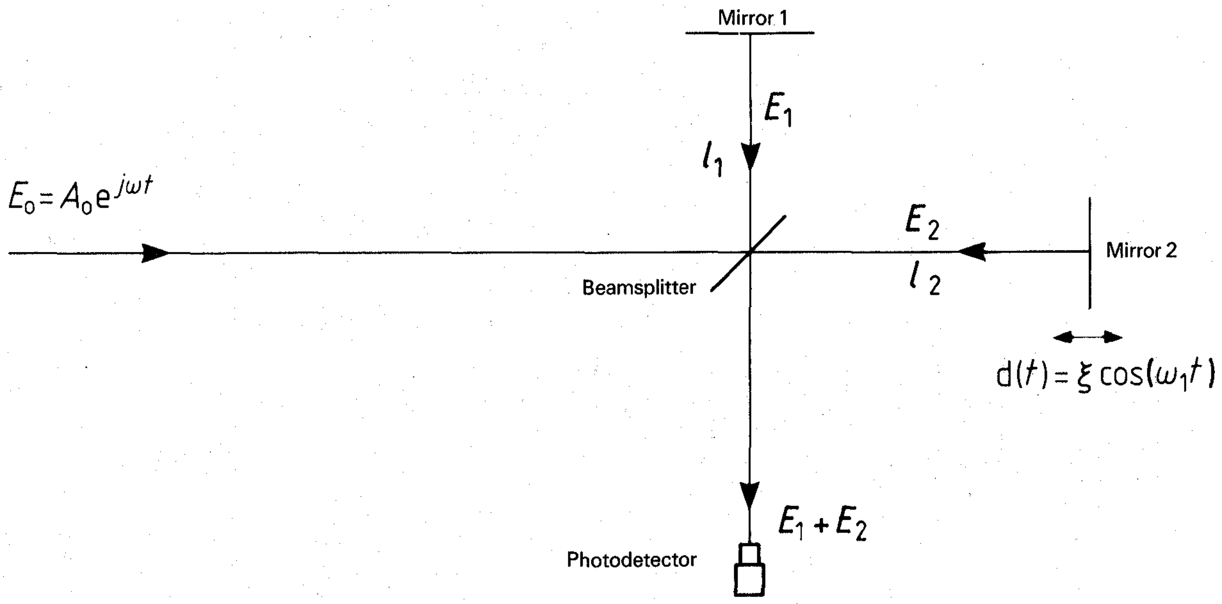

Figure 1 — Principle of the ideal interferometer

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

$$I(t) = A + B\cos\left\{\frac{4\pi L}{\lambda}\left[J_0\left(\frac{4\pi\xi}{\lambda}\right) - 2J_2\left(\frac{4\pi\xi}{\lambda}\right)\cos(2\omega_1 t) + \right.\right.$$

$$\left.\left. + 2J_4\left(\frac{4\pi\xi}{\lambda}\right)\cos(4\omega_1 t) - \ldots\right]\right\} -$$

$$- B\sin\left\{\frac{4\pi L}{\lambda}\left[2J_1\left(\frac{4\pi\xi}{\lambda}\right)\cos(\omega_1 t) - \right.\right.$$

$$\left.\left. - 2J_3\left(\frac{4\pi\xi}{\lambda}\right)\cos(3\omega_1 t) + \ldots\right]\right\}$$

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

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