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ISO 5347-1

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

Part 1:
Primary vibration calibration by laser interferometry

Méthodes pour l'étalonnage de capteurs de vibrations et de chocs —
Partie 1: Étalonnage primaire de vibrations avec interféromètre de laser

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Reference number
ISO 5347-1:1993(E)

Foreword

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Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

International Standard ISO 5347-1 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*.

ISO 5347 consists of the following parts, under the general title *Methods for the calibration of vibration and shock pick-ups*:

— *Part 0: Basic concepts*

— *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*

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- *Part 9: Secondary 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*
- *Part 20: Primary vibration calibration by the reciprocity method*

Annexes A and B form an integral part of this part of ISO 5347.

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

Part 1:
Primary vibration calibration by laser interferometry

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1 Scope

ISO 5347 comprises a series of documents dealing with methods for the calibration of vibration and shock pick-ups.

This part of ISO 5347 lays down detailed specifications for the instrumentation and procedure to be used for primary calibration of rectilinear accelerometers using laser interferometry for dynamic displacement measurements.

It is applicable for a frequency range from 20 Hz to 5 000 Hz and a dynamic range from 10 m/s^2 to 1 000 m/s^2 (frequency-dependent).

The limits of uncertainty applicable are as follows:

$\pm$ 0,5 % of reading at reference frequency (160 Hz or 80 Hz) and reference amplitude (100 m/s^2 or 10 m/s^2) and reference amplifier gain setting;

$\pm$ 1 % of reading for frequencies $\leqslant$ 1 000 Hz;

$\pm$ 2 % of reading for frequencies > 1 000 Hz.

2 Apparatus

2.1 Equipment capable of maintaining the ambient conditions, within the requirements specified in clause 3.

2.2 Frequency generator and indicator, having the following characteristics:

— uncertainty, for frequency: maximum $\pm$ 0,01 % of reading;

— frequency stability: better than $\pm$ 0,01 % of reading over the measurement period;

— amplitude stability: better than $\pm$ 0,01 % of reading over the measurement period.

2.3 Power amplifier/vibrator combination, having the following characteristics:

— total distortion: 2 % maximum;

— transverse, bending and rocking acceleration: kept to a minimum, maximum 10 % of the acceleration in the intended direction at frequencies used; above 1 000 Hz, a maximum of 20 % is permitted;

— hum and noise: 70 dB min. below full output;

— acceleration amplitude stability: better than 0,05 % of reading over the measurement period.

The attachment surface shall not introduce base strain to the accelerometer.

2.4 Seismic block for vibrator and laser interferometer (the same block), with a mass at least 2 000 times the mass of moving elements of vibrator, fixture and transducer.

The seismic block shall be suspended by low damped springs. If floor vibrations influence, the suspension resonance frequency vertically and horizontally shall be < 2 Hz.

2.5 Laser, of helium-neon type; in laboratory conditions of air pressure 100 kPa, temperature 23 °C and relative humidity 50 % the wavelength is 0,632 8 µm, which value is used in this part of ISO 5347.

If the laser has manual or automatic atmospheric compensation, this shall be set to zero or switched off.

2.6 Interferometer, of Michelson type, with light detector for sensing the interferometer bands and having a frequency response from d.c. to 15 MHz.

2.7 Counting instrumentation, (for Method 1, frequency range from 20 Hz to 800 Hz), having the following characteristics:

— frequency range: 10 Hz to 20 MHz;

— uncertainty, maximum: ± 0,01 % of reading.

The counter can be substituted by a ratio counter having the same uncertainty.

2.8 Tunable band-pass filter or spectrum analyser, (for Method 2, frequency range from 1 000 Hz to 5 000 Hz), having the following characteristics:

— frequency range: 100 Hz to 10 000 Hz;

— bandwidth: < 12 % of centre frequency;

— filter slopes: better than 24 dB/octave;

— signal-to-noise ratio: better than 70 dB below maximum signal;

— dynamic range: better than 60 dB.

2.9 Instrumentation for zero detection, (for Method 2 — not needed with spectrum analyser), with a frequency range from 30 Hz to 5 000 Hz. The range shall be sufficient for detection of output noise from the bandpass filter.

2.10 Voltage instrumentation, measuring true r.m.s. accelerometer output, having the following characteristics:

— frequency range: 20 Hz to 5 000 Hz;

— uncertainty, maximum: ± 0,01 % of reading; below 40 Hz: 0,1 %.

The r.m.s. value shall be multiplied by a factor of $\sqrt{2}$ to obtain the (single) amplitude used in the formulae.

2.11 Distortion-measuring instrumentation, capable of measuring total distortion of 0 to 5 % and having the following characteristics:

— frequency range: 5 Hz to 10 kHz;

— uncertainty, maximum: ± 10 % of reading.

2.12 Oscilloscope (optional), for checking the waveform of the accelerometer signal, with a frequency range from 5 Hz to 5 000 Hz.

2.13 Other apparatus requirements.

In order to achieve the required 0,5 % accuracy, the accelerometer and accelerometer amplifier shall be considered as one unit and calibrated together.

The accelerometer shall be structurally rigid. The base strain sensitivity shall be $< 0{,}2 \times 10^{-8}$ m/s^2 at a base strain of $2{,}5 \times 10^{-4}$ m/s^2, the transverse sensitivity shall be < 1 % and the stability of the accelerometer/amplifier combination shall be better than 0,2 % of the reading per year.

3 Ambient conditions

Calibration shall be carried out in the following ambient conditions:

— room temperature: (23 ± 3) °C;

— air pressure: (100 ± 5) kPa;

— relative humidity: (50 ± 25) %.

4 Preferred amplitudes and frequencies

Six amplitudes and six frequencies equally covering the accelerometer range shall be chosen from the following series:

a) **Acceleration** (Method 1 only), in metres per square second:

10, 20, 50, 100, 500;

reference acceleration 100 m/s^2 (second choice: 10 m/s^2).

b) **Frequency**, in hertz:

20, 40, 80, 160, 315, 630, 1 250, 2 500, 5 000;

reference frequency 160 Hz (second choice: 80 Hz).

5 Method 1, for frequency range from 20 Hz to 800 Hz

5.1 Test procedure

After optimizing the interferometer (2.6) settings, determine the reference calibration factor at preferably 160 Hz (second choice: 80 Hz), 100 m/s^2 (second choice: 10 m/s^2) and the standard position of amplifier range switch by measuring either the fringe frequency with the counter (2.7) — the fringe-counting method

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in accordance with figure 1 shall be used — or the ratio between the vibration frequency and the fringe frequency with a ratio counter (2.7).

Then determine the calibration factor at the other selected standard acceleration levels and frequencies. The results shall be given as a percentage deviation from the reference calibration factor.

For every frequency and acceleration combination, the distortion, the transverse, bending and rocking accelerations, hum and noise shall be measured and the values shall be within the limits specified in 2.3.

5.2 Expression of results (see also B.1, annex B)

Calculate the acceleration amplitude, a, of the accelerometer, expressed in metres per second squared, from the fringe frequency readings using the following formula:

$$a = 3{,}122\ 8 \times 10^{-6} \times f \times f_f$$

and calculate the calibration factor, S, from the following formula:

$$S = 0{,}320\ 2 \times 10^{6} \times \frac{V}{f \times f_f}$$

where

V is the accelerometer output, in volts (single) amplitude;

f is the frequency of the vibrator, in hertz;

f_f is the number of fringe signal periods over a time period which is long compared with the vibration period — the number of periods is divided by the time in order to obtain the fringe frequency in hertz;

If a ratio counter is used, calculate the acceleration amplitude, a, expressed in metres per second squared, using the following formula:

$$a = 3{,}122\ 8 \times 10^{-6} \times f^2 \times R_f$$

and calculate the calibration factor, S, from the following formula:

$$S = 0{,}320\ 2 \times 10^{6} \times \frac{V}{f^2 \times R_f}$$

where R_f is the ratio between the vibration frequency and the fringe frequency, f_f, over at least 100 vibration periods.

When the calibration results are reported, the total uncertainty of the calibration and the corresponding confidence level, calculated in accordance with annex A, shall also be reported.

A confidence level of 99 % shall be used (second choice: 95 % confidence level).

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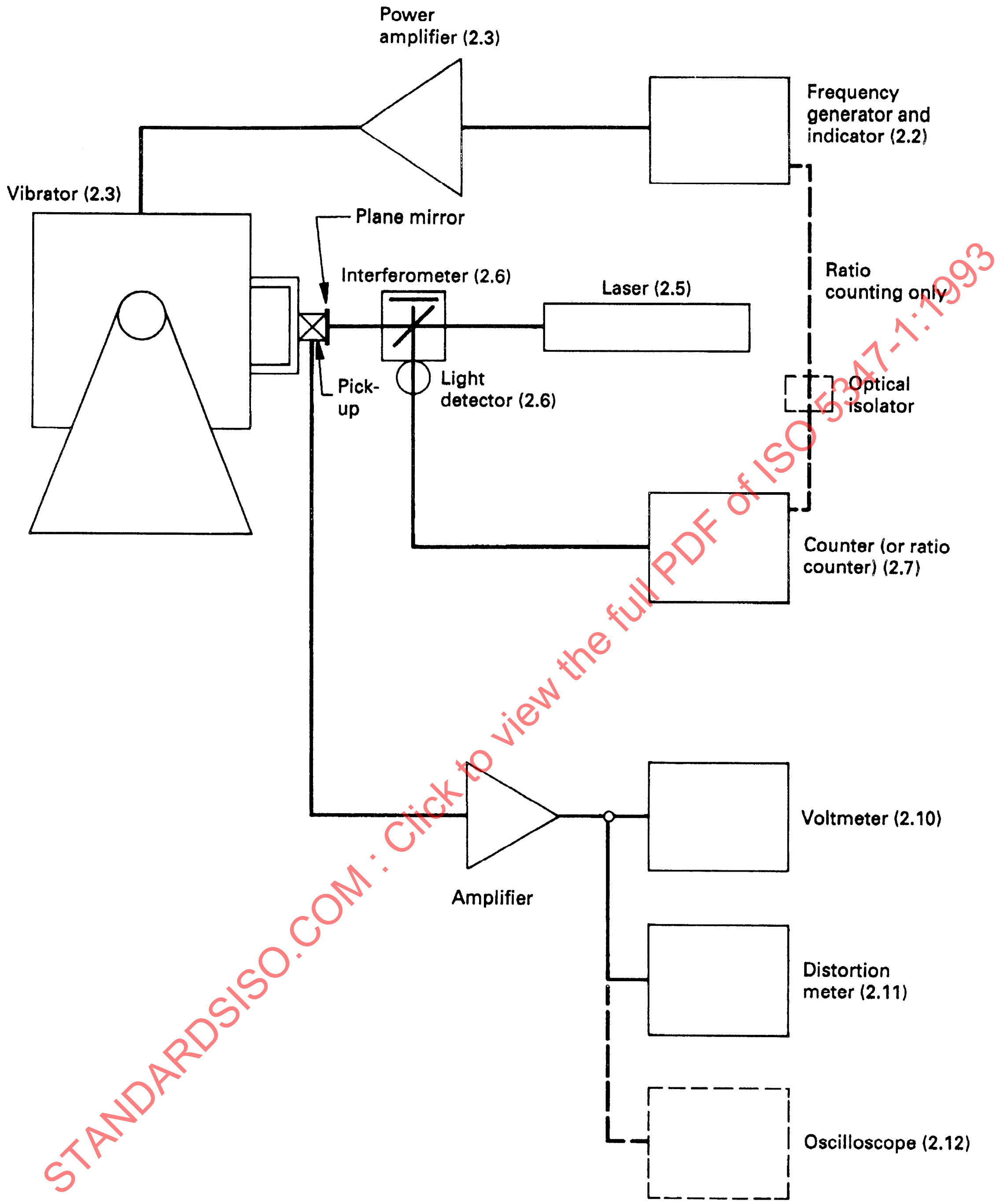

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Figure 1 — Measuring system for the fringe-counting method (Method 1)

6 **Method 2,** for frequency range from 800 Hz to 5 000 Hz

6.1 Test procedure

Filter the signal from the light detector (2.6) through a bandpass filter (2.8) with the centre frequency equal to the accelerometer frequency. This filtered signal has a number of minimum points at accelerometer displacements in accordance with table 1.

After setting the frequency, adjust the vibrator amplitude from zero to the value at which the filtered light detector signal, after reaching maximum value, returns to a minimum value. This minimum value is minimum point No. 1, at which the amplitude is 0,193 0 µm. The amplitude for the other minimum points in order can be taken from table 1. The measuring system for the minimum point method is shown in figure 2.

Table 1 — Displacement amplitudes for minimum points

Minimum point No.	Displacement amplitude, d µm
0	0
1	0,193 0
2	0,353 3
3	0,512 3
4	0,670 9
5	0,829 4
6	0,987 8
7	1,146 1
8	1,304 4
9	1,462 7
10	1,621 0
11	1,779 2
12	1,937 5
13	2,095 7
14	2,253 9
15	2,412 2
16	2,570 4
17	2,728 6
18	2,886 8
19	3,045 0
20	3,203 3
21	3,361 5
22	3,519 7
23	3,677 9
24	3,836 1
25	3,994 3
26	4,152 5
27	4,310 7
28	4,468 9
29	4,627 1
30	4,785 3

6.2 **Expression of results** (see also B.2, annex B)

Calculate the acceleration, a, expressed in metres per second squared, from the following formula:

$$a = 39{,}478 \times 10^{-6} \times d \times f^2$$

and calculate the calibration factor, S, from the following formula:

$$S = 0{,}253\,31 \times 10^5 \times \frac{V}{d \times f^2}$$

where

V is the accelerometer output, in volts (single) amplitude;

d is the displacement amplitude, in micrometres, for the different minimum points in accordance with table 1;

f is the frequency of the vibrator, in hertz.

The different calibration factors determined are used to calculate the deviations relative to the 160 Hz (80 Hz)/100 m/s^2 (10 m/s^2) value obtained in accordance with Method 1 (see clause 5).

When the calibration results are reported, the total uncertainty of the calibration and the corresponding confidence level, calculated in accordance with annex A, shall also be reported.

A confidence level of 99 % (second choice: 95 % confidence level) shall be used.

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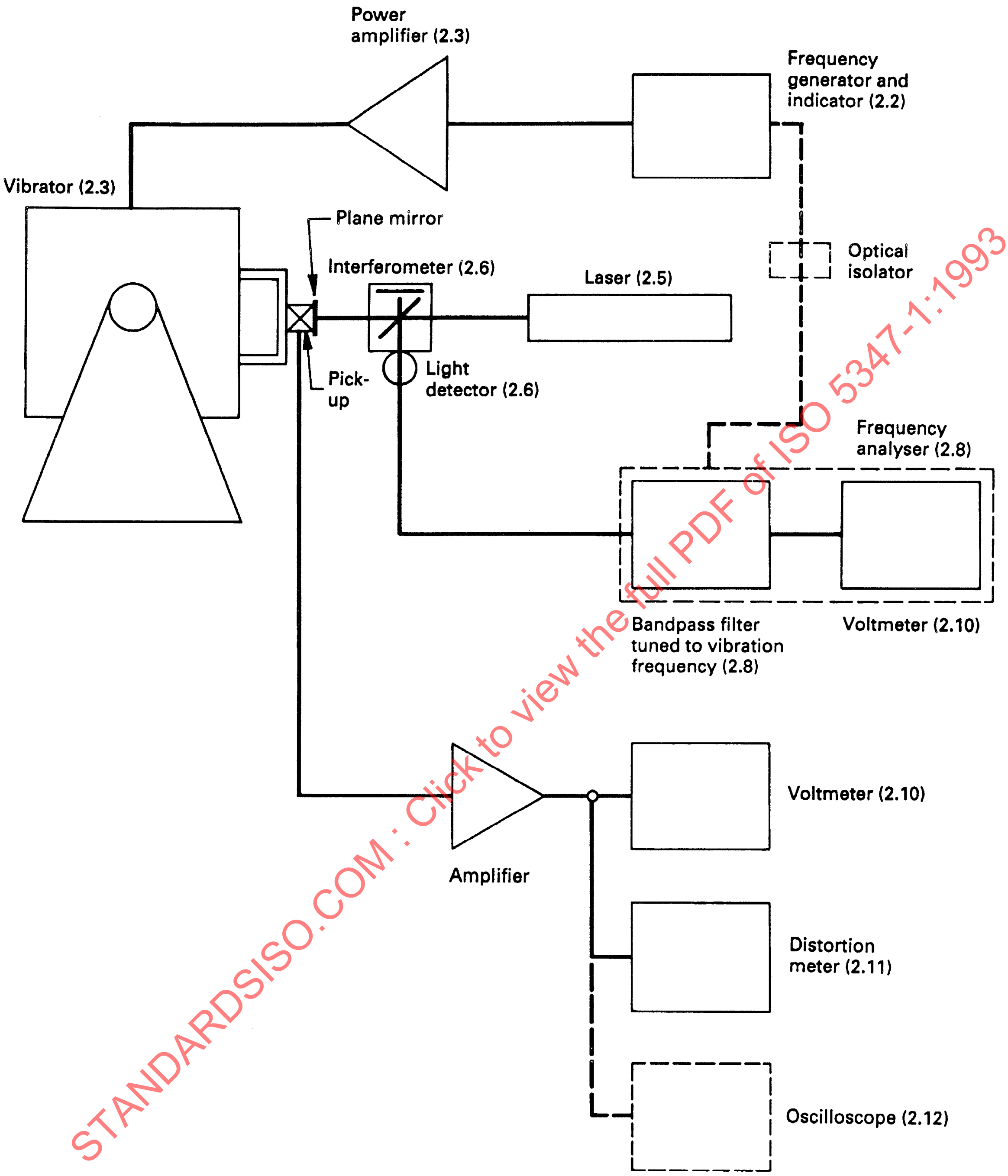

Figure 2 — Measuring system for the minimum-point method (Method 2)

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Annex A
(normative)

Calculation of uncertainty

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A.1 Calculation of total uncertainty

The total uncertainty of the calibration for a specified confidence level CL (for the purposes of this part of ISO 5347, CL = 99 % or 95 %), X_{CL}, shall be calculated from the following formula:

$$X_{CL} = \pm \sqrt{X_r^2 + X_s^2}$$

where

X_r is the random uncertainty;

X_s is the systematic uncertainty.

The random uncertainty for a specified confidence level, $X_{r(CL)}$, is calculated from the following formula:

$$X_{r(CL)} = \pm t \left[\frac{e_{r1}^2 + e_{r2}^2 + e_{r3}^2 + \dots + e_{rn}^2}{n(n-1)} \right]^{1/2}$$

where

e_{r1}, e_{r2}, etc. are the deviations from the arithmetic mean of single measurements in the series;

n is the number of measurements;

t is the value from Student's distribution for the specified confidence level and the number of measurements.

The systematic errors shall, first of all, be eliminated or corrected. The remaining uncertainty, $X_{s(CL)}$, shall be taken into account by using the following formula:

$$X_{s(CL)} = \frac{K}{\sqrt{3}} \times e_S$$

where

K equals 2,0 for the 95 % confidence level (CL = 95 %) or K equals 2,6 for the 99 % confidence level (CL = 99 %);

e_S is the absolute uncertainty for the calibration factor at calibration frequency, amplitude and amplifier gain settings, expressed in volts per (metre per second squared) (see A.2).

A.2 Calculation of the absolute uncertainty for the calibration factor, e_S, for calibration frequencies, amplitudes and amplifier gain settings

A.2.1 Calculation of e_S for Method 1

The absolute uncertainty for the calibration factor, e_S, for the calibration frequencies, amplitudes and amplifier gain settings is calculated by the law of combination of errors from the following formula:

$$\frac{e_S}{S} = \pm \left\{ \left(\frac{e_V}{V}\right)^2 + \left(\frac{e_f}{f}\right)^2 + \left(\frac{e_{f_f}}{f_f}\right)^2 + \left(\frac{V_f}{V}\right)^2 + \left[\frac{1}{2}\left(\frac{d_{tot}}{100}\right)^2\right]^2 + \left(\frac{a_T T}{100 a_{rms}}\right)^2 + \left(\frac{a_H}{a_{rms}}\right)^2 + \left(\frac{B}{100}\right)^2 + \left(\frac{1}{9}\frac{d_{tot}}{100}\right)^2 \right\}^{1/2}$$

If a ratio counter is used, the following formula applies:

$$\frac{e_S}{S} = \pm \left\{ \left(\frac{e_V}{V}\right)^2 + \left(\frac{2e_f}{f}\right)^2 + \left(\frac{e_{R_f}}{R_f}\right)^2 + \left(\frac{V_f}{V}\right)^2 + \left[\frac{1}{2}\left(\frac{d_{tot}}{100}\right)^2\right]^2 + \left(\frac{a_T T}{100 a_{rms}}\right)^2 + \left(\frac{a_H}{a_{rms}}\right)^2 + \left(\frac{B}{100}\right)^2 + \left(\frac{1}{9}\frac{d_{tot}}{100}\right)^2 \right\}^{1/2}$$

where

S is the calibration factor, in volts per (metre per second squared) [V/(m/s²)] (see 5.2);

V is the accelerometer output, in volts (single) amplitude;

e_V is the absolute uncertainty for the accelerometer voltmeter output, in volts;

f is the frequency of the vibrator, in hertz;

e_f is the absolute uncertainty for the frequency of the vibrator, in hertz;

f_f is the fringe frequency, in hertz;

e_{f_f} is the absolute uncertainty for the fringe frequency, in hertz;

V_f is the absolute uncertainty for the fringe detection which is equal to the change in accelerometer output voltage when the last-used digit of the fringe frequency counter changes one step;

d_{tot} is the total distortion and is equal to $100\left(\frac{a_{tot}^2 - a_{rms}^2}{a_{rms}^2}\right)^{1/2}$, expressed as a percentage,

in which

a_{tot} is the total true r.m.s acceleration, in metres per second squared;

a_{rms} is the true r.m.s acceleration at driving frequency, in metres per second squared;

a_T is the transverse, rocking and bending acceleration, in metres per second squared;

T is the accelerometer maximum transverse sensitivity, expressed as a percentage of the accelerometer sensitivity in the measuring direction;

a_H is the acceleration amplitude caused by hum and noise, in metres per second squared;

B is the error for the laser wavelength and interferometer function, expressed as a percentage of the wavelength;

R_f is the ratio between the vibration frequency and the fringe frequency over at least 100 vibration periods (see 5.2);

e_{R_f} is the absolute uncertainty for the ratio over the measured period.

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A.2.2 Calculation of e_S for Method 2

The absolute uncertainty for the calibration factor, e_S, expressed in volts per (metre per second squared), for calibration frequencies, amplitudes and amplifier gain settings is calculated by the law of the combination of errors from the following formula:

$$\frac{e_S}{S} = \pm \left\{ \left(\frac{e_V}{V} \right)^2 + \left(\frac{V_z}{V} \right)^2 + \left[\frac{1}{2} \left(\frac{d_{tot}}{100} \right)^2 \right]^2 + \left(\frac{a_T T}{100 a_{rms}} \right)^2 + \left(\frac{a_H}{a_{rms}} \right)^2 + \left(\frac{2e_f}{f} \right)^2 \right\}^{1/2}$$

where

- S is the calibration factor, in volts per (metre per second squared) (see 6.2);
- V is the accelerometer output, in volts (single) amplitude;
- e_V is the absolute uncertainty for the accelerometer voltmeter output, in volts;
- V_z is the minimum point resolution, which is equal to the change in accelerometer output, in volts, at which the minimum point voltmeter changes from the smallest measurable value before the minimum to the smallest measurable value after the minimum;
- d_{tot} is the total distortion and is equal to $100 \left(\frac{a_{tot}^2 - a_{rms}^2}{a_{rms}^2} \right)^{1/2}$, expressed as a percentage,

  in which

  - a_{tot} is the total true r.m.s acceleration, in metres per second squared;
  - a_{rms} is the true r.m.s acceleration at driving frequency, in metres per second squared;
- a_T is the transverse, rocking and bending acceleration, in metres per second squared;
- T is the accelerometer maximum transverse sensitivity, expressed as a percentage of the accelerometer sensitivity in the measuring direction;
- a_H is the acceleration amplitude caused by hum and noise, in metres per second squared;
- f is the frequency of the vibrator, in hertz (see 6.2);
- e_f is the absolute uncertainty for the frequency of the vibrator, in hertz.

A.3 Calculation of the total uncertainty for the calibration factor, e_{S_1}, over the complete frequency and amplitude range

The absolute uncertainty for the calibration factor, e_S, calculated in accordance with A.2.1 or A.2.2, is only valid for the calibration frequencies, amplitudes and amplifier gain settings. The total absolute uncertainty for the calibration factor, e_{S_1}, in volts per metre per second squared, for the complete frequency and amplitude range is calculated from the following formula:

$$\frac{e_{S_1}}{S} = \pm \left\{ \left(\frac{e_S}{S} \right)^2 + \left(\frac{L_{fA}}{100} \right)^2 + \left(\frac{L_{fP}}{100} \right)^2 + \left(\frac{L_{aA}}{100} \right)^2 + \left(\frac{L_{aP}}{100} \right)^2 + \left(\frac{I_A}{100} \right)^2 + \left(\frac{I_P}{100} \right)^2 + \left(\frac{R}{100} \right)^2 + \left(\frac{E_A}{100} \right)^2 + \left(\frac{E_P}{100} \right)^2 \right\}^{1/2}$$

where

- S is the calibration factor, in volts per (metre per second squared) (see 5.2 or 6.2);
- e_S is the absolute uncertainty for the calibration factor, in volts per (metre per second squared), at reference frequency, amplitude and amplifier gain settings, calculated in accordance with A.2.1 or A.2.2 ;

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L_{fA} is the frequency linearity deviation, expressed as a percentage of the reference calibration factor for the reference amplifier;

L_{fP} is the frequency linearity deviation, expressed as a percentage of the reference calibration factor for the reference accelerometer;

L_{aA} is the amplitude linearity deviation, expressed as a percentage of the reference calibration factor for the reference amplifier;

L_{aP} is the amplitude linearity deviation, expressed as a percentage of the reference calibration factor for the reference accelerometer;

I_A is the instability error for the reference amplifier gain and source impedance error, expressed as a percentage of the reference calibration factor;

I_P is the instability error for the reference accelerometer, expressed as a percentage of the reference calibration factor;

R is the tracking error for the reference amplifier range (errors in gain for different amplification settings), expressed as a percentage of the reference calibration factor;

E_A is the error caused by environmental effects on the reference amplifier, expressed as a percentage of the reference calibration factor;

E_P is the error caused by environmental effects on the reference accelerometer, expressed as a percentage of the reference calibration factor.

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Annex B
(normative)

Formulae for the calculation of acceleration

B.1 Procedure 1

According to the *Handbook of Chemistry and Physics*, the wavelength of the principal lines in the emission spectrum of neon is 0,632 815 µm at a pressure of 100 kPa.

In the interferometer, the displacement corresponding to the distance between two fringes (intensity maxima or intensity minima) is given by

$$d = \frac{\lambda}{2}$$

The number of maxima for one vibration cycle is therefore given by

$$\frac{4d}{\lambda/2} = \frac{f_f}{f}$$

$$d = \frac{\lambda}{8} \times \frac{f_f}{f}$$

The acceleration is given by the following formulae:

$$a = 4\pi^2 \times f^2 \times d$$

$$a = \frac{\pi^2 \times \lambda}{2} \times f_f \times f$$

where

f is the frequency of the vibrator;

f_f is the fringe frequency.

B.2 Procedure 2

By considering the frequency spectrum of the intensity and adjusting the vibration amplitude to a level at which the component of the same frequency as the vibration frequency is zero, it is possible to calculate the displacement and the acceleration as follows:

$$d = J_n \times \frac{\lambda}{4\pi}$$

$$a = 4\pi^2 \times f^2 \times d$$

where J_n are arguments from the different zero points of the Bessel function as given in table B.1.

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Table B.1 — Values for J_n for zero points of the Bessel function

Zero point No.	J_n
1	3,831 70
2	7,015 59
3	10,173 46
4	13,323 69
5	16,470 63
6	19,615 86
7	22,760 09
8	25,903 68
9	29,046 83
10	32,189 68
11	35,332 30
12	38,474 77
13	41,617 09
14	44,759 32
15	47,901 46
16	51,043 53
17	54,185 56
18	57,327 53
19	60,469 45
20	63,611 36
21	66,753 23
22	69,895 07
23	73,036 90
24	76,178 70
25	79,320 49
26	82,462 27
27	85,604 02
28	88,754 77
29	91,887 52
30	95,029 24

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