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Methods for the calibration of vibration and shock transducers —

Part 11:
Primary vibration calibration by laser interferometry

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

Partie 11: Étalonnage primaire de vibrations avec interféromètre de laser

Reference number
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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. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 3.

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.

Attention is drawn to the possibility that some of the elements of this part of ISO 16063 may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

International Standard ISO 16063-11 was prepared by Technical Committee ISO/TC 108, *Mechanical vibration and shock*, Subcommittee SC 3, *Use and calibration of vibration and shock measuring instruments*.

This first edition of ISO 16063-11 cancels and replaces ISO 5347-1, which has been technically revised.

ISO 16063 consists of the following parts, under the general title *Methods for the calibration of vibration and shock transducers*:

- *Part 1: Basic concepts*
- *Part 11: Primary vibration calibration by laser interferometry*
- *Part 12: Primary vibration calibration by the reciprocity method*
- *Part 13: Primary shock calibration using laser interferometry*
- *Part 21: Secondary vibration calibration*
- *Part 22: Secondary shock calibration*

Annexes A and B form a normative part of this part of ISO 16063.

INTERNATIONAL STANDARD **ISO 16063-11:1999(E)**

Methods for the calibration of vibration and shock transducers —

Part 11:
Primary vibration calibration by laser interferometry

1 Scope

This part of ISO 16063 specifies the instrumentation and procedure to be used for primary vibration calibration of rectilinear accelerometers (with or without amplifier) to obtain magnitude and phase lag of the complex sensitivity by steady-state sinusoidal vibration and laser interferometry.

It is applicable to a frequency range from 1 Hz to 10 kHz and a dynamic range (amplitude) from 0,1 m/s^2 to 1 000 m/s^2 (frequency-dependent).

These ranges are covered with the uncertainty of measurement specified in clause 2. Calibration frequencies lower than 1 Hz (e.g. 0,4 Hz, which is a reference frequency used in other International Standards) and acceleration amplitudes smaller than 0,1 m/s^2 (e.g. 0,004 m/s^2 at 1 Hz) can be achieved using Method 3 specified in this part of ISO 16063, in conjunction with an appropriate low-frequency vibration generator.

Method 1 (fringe-counting method) is applicable to sensitivity magnitude calibration in the frequency range 1 Hz to 800 Hz and, under special conditions, at higher frequencies (cf. clause 7). Method 2 (minimum-point method) can be used for sensitivity magnitude calibration in the frequency range 800 Hz to 10 kHz (cf. clause 8). Method 3 (sine-approximation method) can be used for magnitude of sensitivity and phase calibration in the frequency range 1 Hz to 10 kHz (cf. clause 9).

Methods 1 and 3 provide for calibrations at fixed acceleration amplitudes at various frequencies. Method 2 requires calibrations at fixed displacement amplitudes (acceleration amplitude varies with frequency).

2 Uncertainty of measurement

The limits of the uncertainty of measurement applicable to this part of ISO 16063 shall be as follows.

a) For the magnitude of sensitivity:

0,5 % of the measured value at reference conditions;

$\leqslant$ 1 % of the measured value outside reference conditions.

b) For the phase shift of sensitivity:

0,5° of the measured value at reference conditions;

$\leqslant$ 1° of the reading outside reference conditions.

Recommended reference conditions are as follows:

— frequency in hertz: 160, 80, 40, 16 or 8 (or radian frequency $\omega = 1\,000$, 500, 250, 100 or 50 radians per second);

— acceleration in metres per second squared (acceleration amplitude or r.m.s. value): 100, 50, 20, 10, 5, 2 or 1.

Amplifier settings shall be selected for optimum performance with respect to noise, distortion and influence from cut-off frequencies.

NOTE The uncertainty of measurement is expressed as the expanded measurement uncertainty in accordance with ISO 16063-1 (referred to in short as uncertainty).

3 Requirements for apparatus

3.1 General

This clause gives recommended specifications for the apparatus necessary to fulfil the scope of clause 1 and to obtain the uncertainties of clause 2.

If desired, systems covering parts of the ranges may be used, and normally different systems (e.g. exciters) should be used to cover all the frequency and dynamic ranges.

NOTE The apparatus specified in this clause covers all devices and instruments required for any of the three calibration methods described in this part of ISO 16063. The assignment to a given method is indicated (cf. Figures 1, 2 and 3).

3.2 Frequency generator and indicator

A frequency generator and indicator having the following characteristics shall be used:

a) uncertainty of frequency: maximum 0,05 % of reading;

b) frequency stability: better than ± 0,05 % of reading over the measurement period;

c) amplitude stability: better than ± 0,05 % of reading over the measurement period.

3.3 Power amplifier/vibrator combination

A power amplifier/vibrator combination having the following characteristics shall be used.

a) Total harmonic distortion of acceleration: 2 % maximum.

b) Transverse, bending and rocking acceleration: sufficiently small to prevent excessive effects on the calibration results. At large amplitudes, preferably in the low-frequency range from 1 Hz to 10 Hz, transverse motion of less than 1 % of the motion in the intended direction may be required; above 10 Hz to 1 kHz, a maximum of 10 % of the axial motion is permitted; above 1 kHz, a maximum of 20 % of the axial motion is tolerated.

c) Hum and noise: 70 dB minimum below full output.

d) Acceleration amplitude stability: better than ± 0,05 % of reading over the measurement period.

The attachment surface shall introduce minimal base strain to the accelerometer (see 3.15).

3.4 Seismic block(s) for vibrator and laser interferometer

The vibrator and the interferometer shall be mounted on the same heavy block or on two different heavy blocks so as to prevent relative motion due to ground motion, or to prevent the reaction of the vibrator’s support structure from having excessive effects on the calibration results.

When a common seismic block is used, it should have a mass at least 2 000 times the moving mass. This causes less than 0,05 % re-active vibration of accelerometer and interferometer. If the mass of the seismic block is smaller, its motion generated by the vibrator shall be taken into account.

To suppress disturbing effects of ground motion, the seismic block(s) used in the frequency range from 10 Hz to 10 kHz should be suspended on damped springs designed to reduce the uncertainty component due to these effects to less than 0,1 %.

3.5 Laser

A laser of the red helium-neon type shall be used.

Under laboratory conditions (i.e. at an atmospheric pressure of 100 kPa, temperature of 23 °C and relative humidity of 50 %), the wavelength is 0,632 81 µm, which is the value used in this part of ISO 16063.

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

Alternatively, a single-frequency laser may be used with another stable wavelength of known value.

3.6 Interferometer

An interferometer of the Michelson type shall be used, with a light detector for sensing the interferometer signal bands and having a frequency response covering the necessary bandwidth.

The maximum bandwidth needed can be calculated from the velocity amplitude, v_{max}, which has to be measured using

$$f_{\text{max}} = v_{\text{max}} \times 3{,}16 \times 10^6 \text{ m}^{-1}$$

For Method 1 (see Figure 1) and Method 2 (see Figure 2), a common Michelson interferometer with a single light detector is sufficient. For Method 3 (see Figure 3), a modified Michelson interferometer, with quadrature signal outputs, with two light detectors for sensing the interferometer signal beams, shall be used. The modified Michelson interferometer may be constructed according to Figure 4. A quarter wavelength retarder converts the incident, linearly polarized light into two measuring beams with perpendicular polarization states and a phase shift of 90°. After interfering with the linearly polarized reference beam, the two components with perpendicular polarization shall be separated in space using appropriate optics (e.g. a Wollaston prism or a polarizing beamsplitter), and detected by two photodiodes.

The two outputs of the modified Michelson interferometer shall have offsets of less than ± 5 % in relation to the amplitude, relative amplitude deviations of less than ± 5 % and deviations of less than ± 5° from the nominal angle of 90°. To keep these tolerances, appropriate means shall be provided for adjusting the offset, the signal level and the angle between the two interferometer signals.

At large displacements, it may be difficult to maintain the above-stated tolerances for the deviations of the two outputs of the modified Michelson interferometer. To comply with the uncertainty of measurement of clause 2, the above tolerances shall be kept at least for small displacement amplitudes up to 2 µm. Greater tolerances are permitted for higher amplitudes.

EXAMPLE For a displacement amplitude of 2,5 mm (i.e. acceleration amplitude of 0,1 m/s^2 at a frequency of 1 Hz), the tolerances may be extended to ± 10 % for the offsets and for the relative amplitude deviations, and to ± 20° for the deviation from the nominal angle of 90° (see also note 1 of 9.2).

NOTE The (modified) Michelson interferometer for Method 1, 2 or 3 may be replaced by another suitable two-beam interferometer, e.g. a (modified) Mach-Zehnder interferometer.

3.7 **Counting instrumentation** (for Method 1)

Counting instrumentation (for Method 1) having the following characteristics shall be used.

a) Frequency range: 1 Hz to the maximum needed frequency. (Typically 20 MHz is used.)

b) Maximum uncertainty: 0,01 % of reading.

The counter may be replaced by a ratio counter having the same uncertainty.

3.8 **Tunable bandpass filter or spectrum analyser** (for Method 2)

A tunable bandpass filter or spectrum analyser (for Method 2) having the following characteristics shall be used.

a) Frequency range: 800 Hz to 10 kHz.

b) Bandwidth: $<$ 12 % of centre frequency.

c) Filter slopes: greater than 24 dB per octave.

d) Signal-to-noise ratio: greater than 70 dB below maximum signal.

e) Dynamic range: greater than 60 dB.

3.9 **Instrumentation for zero detection** (for Method 2)

Instrumentation for zero detection (for Method 2, not needed with spectrum analyser), with a frequency range from 800 Hz to 10 kHz shall be used. The range shall be sufficient for the detection of output noise from the bandpass filter.

3.10 Voltage instrumentation, measuring true r.m.s. accelerometer output

Voltage instrumentation, measuring true r.m.s. accelerometer output, having the following characteristics shall be used.

a) Frequency range: 1 Hz to 10 kHz.

b) Maximum uncertainty: 0,1 % of reading.

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

For Methods 1 and 2, a r.m.s. voltmeter shall be used. For Method 3, a special voltage measuring instrumentation according to 3.13 shall be used; a r.m.s. voltmeter may be applied in addition (optionally).

3.11 Distortion-measuring instrumentation

Distortion-measuring instrumentation, capable of measuring total harmonic distortion of $<<$ 1 % to 5 % and having the following characteristics shall be used.

a) Frequency range: 1 Hz to 10 kHz with the capability of measuring up to the 5th harmonic.

b) Maximum uncertainty: 10 % of reading in the distortion range 0,5 % to 5 %.

3.12 **Oscilloscope** (optional)

An oscilloscope for optimizing the interferometer and for checking the waveform of the interferometer and accelerometer signals, with a frequency range from 1 Hz to minimum 2 MHz, may be used.

3.13 Waveform recorder with computer interface (for Method 3)

A waveform recorder with a computer interface (for Method 3), capable of analog-to-digital conversion and storage of the two interferometer quadrature outputs and the accelerometer output shall be used. The amplitude resolution, the sampling rate and the memory shall be sufficient for calibration in the intended amplitude range with the uncertainty specified in clause 2. Typically, an amplitude resolution of $\geqslant 10$ bits is used for the accelerometer output. For the interferometer quadrature signal outputs, a resolution of $\geqslant 8$ bits is sufficient. A two-channel waveform recorder may be used for the interferometer output signals, and another waveform recorder (with higher resolution and lower sampling rate) for the accelerometer output signal. In each case, conversion of the data from the interferometer and the accelerometer output signals shall begin and end at the same point in time, with an uncertainty appropriate for the calibration measurement uncertainty requirements of clause 2.

A sufficient number of samples (cf. 9.3) is required of the shortest period of the interferometer output signal that occurs at maximum velocity. For a given acceleration amplitude, at decreasing frequencies, larger displacement amplitudes occur which require that higher sampling rates and larger memories be applied. If such capabilities are not available, the acceleration amplitude shall be reduced.

EXAMPLE To calibrate an accelerometer at a vibration frequency of 1 Hz and an acceleration amplitude of 0,1 m/s^2, a memory of $\geqslant$ 4 Mbytes should be used if a sampling frequency of $\geqslant$ 512 kHz is applied.

3.14 Computer with data-processing program (for Method 3)

A computer with data-processing program (for Method 3) in accordance with the procedure for the calculations stated in 9.4 shall be used.

3.15 Other requirements

In order to achieve the required measurement uncertainty of 0,5 %, the accelerometer and the accelerometer amplifier should preferably be considered as a single unit and calibrated together.

The accelerometer shall be structurally rigid. The base strain sensitivity, the transverse sensitivity and the stability of the accelerometer/amplifier combination shall be taken into account in the calculation of the uncertainty of measurement (cf. annex A).

If a back-to-back reference accelerometer is calibrated, its sensitivity (magnitude and/or phase shift) shall be measured with a dummy mass that is the equivalent of the mass of the transducer to be calibrated by the comparison method (cf. ISO 16063-21) using the back-to-back reference accelerometer. Typically, a 20 g mass is used. The laser light spot can be at either the top (outer surface) of the dummy mass or the top surface of the reference accelerometer.

If the motion is sensed at the top of the dummy mass, then the dummy mass should have an optically polished top surface, and the position of the laser-light spot should be close to the geometrical centre of this surface. In cases where the motion of the mass departs from that of a rigid body, the relative motion between the top (sensed) and bottom surfaces shall be taken into consideration. To simulate a mass of 20 g of typical transfer standard accelerometers, a dummy mass in the form of a hexagonal steel bar 12 mm in length and 16 mm in width over flats of hexagonal faces can be used. At a frequency of 5 kHz, for example, the relative motion introduces systematic errors of 0,26 % in amplitude measurements and 4,2° in phase shift measurements.

When the motion is sensed at the top surface of the reference accelerometer via longitudinal holes in the dummy mass, there may be acoustic resonances that occur in the holes at particular frequencies that influence (increase) the uncertainty of measurements made at, or near, those frequencies. These influences shall be included in the uncertainty calculation.

4 Ambient conditions

Calibration shall be carried out under the following ambient conditions:

a) room temperature, (23 ± 3) °C;

b) relative humidity, 75 % max.

Care should be taken that extraneous vibration and noise do not affect the quality of measurements.

5 Preferred accelerations and frequencies

The accelerations (amplitude or r.m.s. value) and frequencies equally covering the accelerometer range should preferably be chosen from the following series.

a) Acceleration (Methods 1 and 3), in metres per second squared:

— 0,1, 0,2, 0,5, 1, 2, 5, 10, 20, 50, 100, 200, 500, 1 000 (1 000 m/s^2 is valid for amplitude only).

b) Frequency, in hertz:

— selected from the standardized one-third-octave frequency series (ISO 266) between 1 Hz and 10 kHz (or the series of radian frequencies evolving from ω = 1 000 radians per second).

6 Common procedure for all three methods

For every combination of frequency and acceleration, the distortion, the transverse, bending and rocking accelerations, hum and noise shall be at a level to meet the uncertainty requirements of clause 2 (cf. 3.3).

The settings of the accelerometer amplifier (gain and frequency range) shall be set and recorded according to the calibration requirements.

7 Method 1: Fringe-counting method

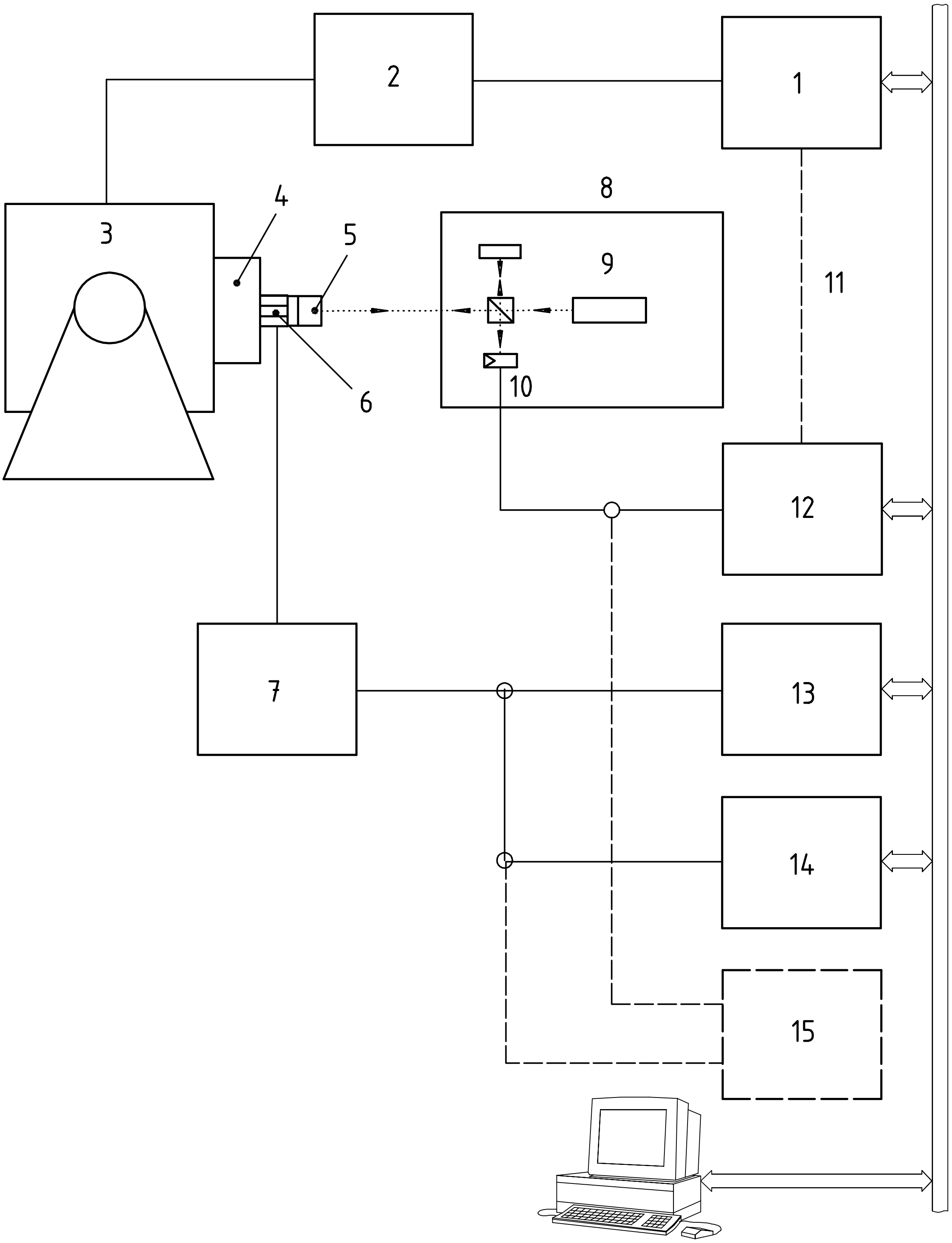
7.1 General

This method is applicable to sensitivity magnitude calibration in the frequency range from 1 Hz to 800 Hz.

NOTE Method 1 may also be applied at higher frequencies if the quantization error is suppressed by special means (see references [2] and [4]). This allows a calibration at a given acceleration amplitude (e.g. 100 m/s^2) to be performed at higher frequencies.

7.2 Test procedure

After optimizing the interferometer (see 3.6), determine the sensitivity at the vibration frequencies and acceleration amplitudes demanded (see clause 5) by measuring either the fringe frequency with the counter (3.7) (the fringe-counting method in accordance with Figure 1 shall be used) or the ratio between the vibration frequency and the fringe frequency with a ratio counter (3.7).



Key

1 Frequency generator (3.2)
2 Power amplifier (3.3)
3 Vibrator (3.3)
4 Moving part of vibrator
5 Dummy mass
6 Accelerometer
7 Amplifier
8 Interferometer (3.6)
9 Laser (3.5)
10 Light detector
11 With ratio counter (3.7)
12 Counter (or ratio counter) (3.7)
13 Voltmeter (3.10)
14 Distortion meter (3.11)
15 Oscilloscope (3.12)

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

7.3 Expression of results

See B.1, annex B.

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

$$\hat{a} = f f_\mathrm{f} \times 3{,}123 \times 10^{-6}\ \mathrm{m}$$

and calculate the sensitivity (magnitude), S, expressed in volts per metre per second squared, from the following formula:

$$S = \frac{\hat{u}}{f f_\mathrm{f}} \times 0{,}320\,2 \times 10^{6}\ \mathrm{m}^{-1}$$

where

$\hat{u}$ is the accelerometer output voltage amplitude;

f is the frequency of the vibrator;

f_f is the fringe frequency, i.e. the number of fringes counted over a sufficiently long time period divided by the time.

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

$$\hat{a} = f^{2} R_\mathrm{f} \times 3{,}123 \times 10^{-6}\ \mathrm{m}$$

and calculate the sensitivity (magnitude), S, expressed in volts per metre per second squared, from the following formula:

$$S = \frac{\hat{u}}{f^{2} R_\mathrm{f}} \times 0{,}320\,2 \times 10^{6}\ \mathrm{m}^{-1}$$

where R_f is the ratio of the fringe frequency, f_f, to the vibration frequency, f, over a sufficient number of vibration periods (frequency-dependent, e.g. at least 100 vibration periods at 160 Hz).

When the calibration results are reported, the expanded uncertainty of measurement in the calibration shall be calculated and reported in accordance with annex A.

8 Method 2: Minimum-point method

8.1 General

This method is applicable to sensitivity magnitude calibration in the frequency range from 800 Hz to 10 kHz.

NOTE The method illustrated in this clause is based on the determination of displacement using the arguments corresponding to the zero crossings of the Bessel function of the first kind and first order (see B.2, annex B). An equally valid approach is to determine displacement using the arguments corresponding to the zero crossings of the Bessel function of the first kind and zero order. However, this technique requires modulation of the position of the reference mirror in order to be implemented (see reference [5]).

8.2 Test procedure

Filter the signal from the light detector (3.6) through a bandpass filter (3.8) with the centre frequency equal to the frequency of the vibrator. This filtered signal has a number of minimum points at accelerometer displacements in accordance with Table 1.

Set the calibration frequency and adjust the vibrator amplitude from zero to a level at which the filtered light detector signal after reaching a maximum value returns to a minimum value. This minimum value is minimum point No. 1, at which the amplitude is 0,1930 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.

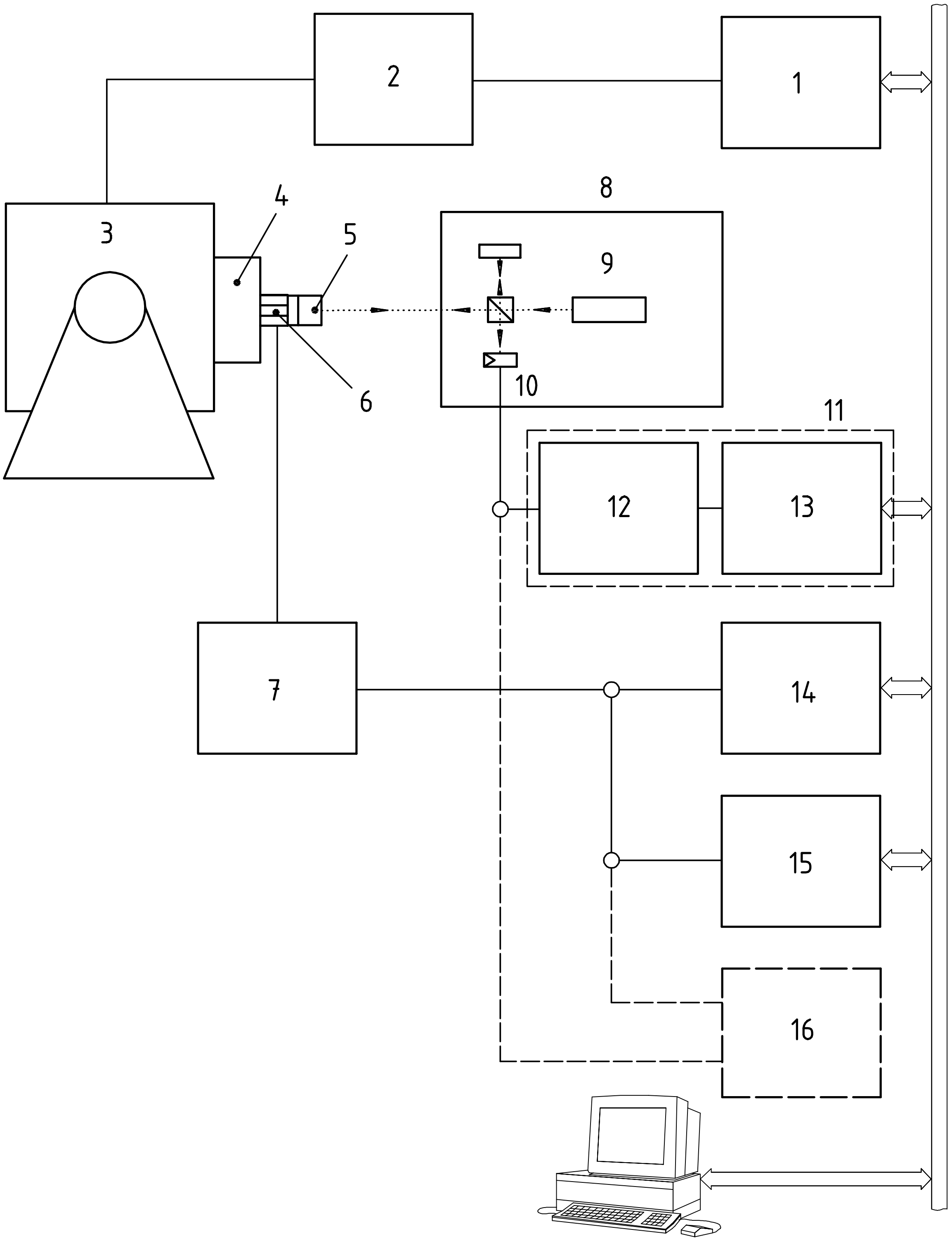
NOTE 1 The sensitivity of an accelerometer may also be determined using the Bessel function of the first kind and zero order by modulating the position of the reference mirror at a frequency that is small, relative to the frequency of calibration, and setting the centre frequency of the bandpass filter, or frequency analyser, to that of the modulation frequency of the mirror (see reference [6]).

NOTE 2 A modulation of the position of the reference mirror may also be used to improve the efficiency of the minimum-point method using the Bessel function of first kind and first order (see reference [7]).

Table 1 — Displacement amplitudes for minimum points (λ = 0,632 81 µm)

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

When the calibration results are reported, the expanded uncertainty of measurement in the calibration shall be calculated and reported in accordance with annex A.



Key

1	Frequency generator (3.2)
2	Power amplifier (3.3)
3	Vibrator (3.3)
4	Moving part of vibrator
5	Dummy mass
6	Accelerometer
7	Amplifier
8	Interferometer (3.6)
9	Laser (3.5)
10	Light detector
11	Frequency analyser (3.8)
12	Bandpass filter tuned to vibration frequency (3.8)
13	Voltmeter
14	Voltmeter (3.10)
15	Distortion meter (3.11)
16	Oscilloscope (3.12)

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

8.3 Expression of results

See also B.2, annex B.

Calculate the acceleration amplitude, $\hat{a}$, expressed in metres per second squared, from the following formula:

$$\hat{a} = 39{,}478 \times \hat{s}\, f^2$$

and calculate the sensitivity (magnitude), S, expressed in volts per metre per second squared, from the following formula:

$$S = 0{,}025\,33 \times \frac{\hat{u}}{\hat{s}\, f^2}$$

where

$\hat{u}$ is the accelerometer output voltage amplitude;

$\hat{s}$ is the displacement amplitude for the different minimum points in accordance with Table 1;

f is the frequency of the vibrator.

9 Method 3: Sine-approximation method

9.1 General

This method is applicable to sensitivity magnitude and/or phase calibration in the frequency range from 1 Hz to 10 kHz.

9.2 Test procedure

Install the equipment according to Figures 3 and 4.

The laser interferometer (for an example, see Figure 4) shall be adjusted to give output signals u_1 and u_2 in phase quadrature within the tolerances stated in 3.6.

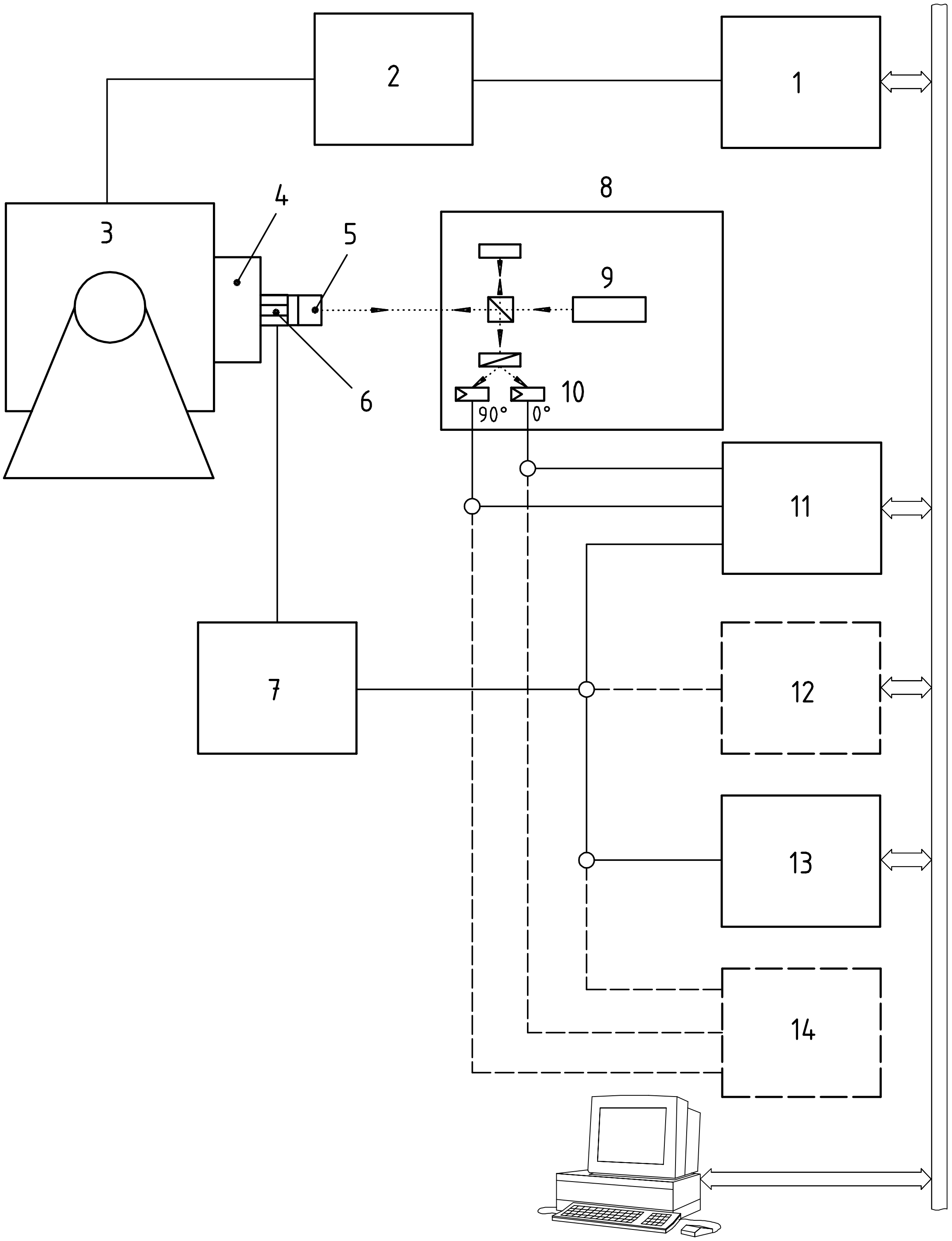
After the interferometer (3.6) settings have been optimized, carry out measurement of the magnitude and the phase shift of the sensitivity of the accelerometer at the specified vibration frequencies and acceleration amplitudes (see clause 5) as follows.

The transducer shall be vibrated sinusoidally. The displacement amplitude should be large enough to give at least one full bright/dark cycle of the interferometer output.

NOTE 1 At displacement amplitudes $\leqslant 0{,}5\ \mu\text{m}$, a worst-case error component $\geqslant 0{,}3\ \%$ in the sensitivity magnitude measurement and $\geqslant 0{,}3°$ in the phase shift measurement could be caused by the combined effects from the disturbing parameters of the quadrature output signals within the tolerances stated in 3.6. A suppression of this error component is possible by more careful adjustment than tolerated in 3.6 (see reference [8]) or by application of the correction procedure given in reference [9]).

NOTE 2 To measure the magnitude and the phase shift of the complex sensitivity of accelerometers down to small displacement amplitudes in the nanometer range, the sine-approximation method in conjunction with an appropriate heterodyne technique may be applied as reported in references [10] and [11]. This allows a calibration at a preferred moderate acceleration amplitude (e.g. 100 m/s^2) to be performed at high vibration frequencies (e.g. 20 kHz).

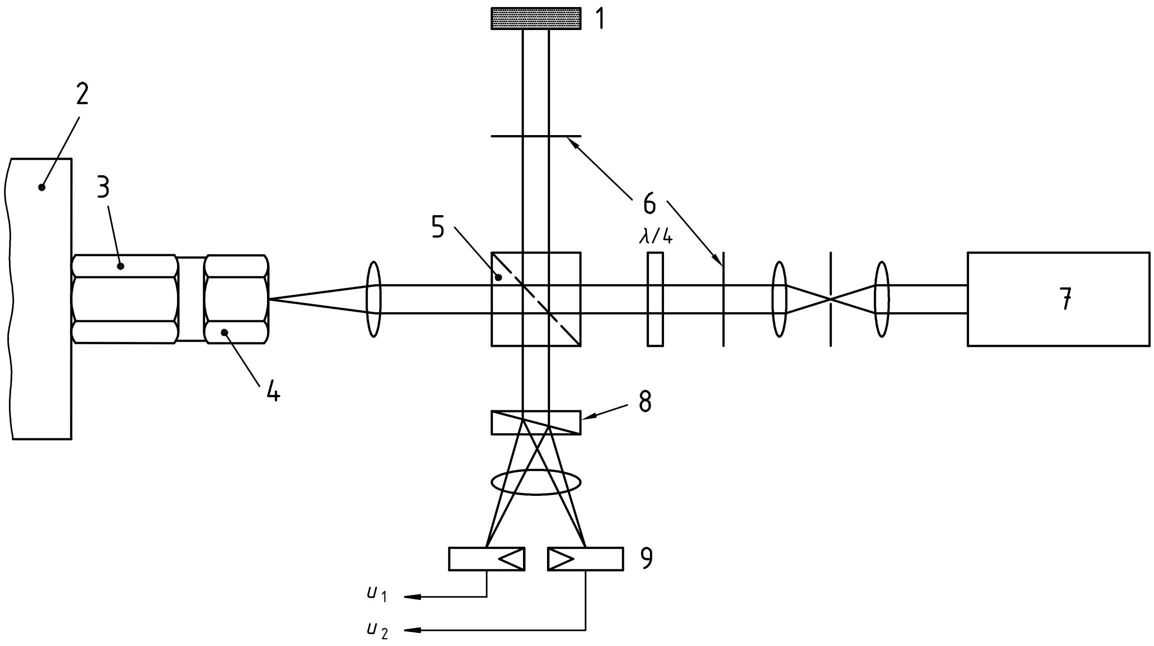
NOTE 3 In order to enhance the rejection efficiency of the sine-approximation procedure, windowing of the displacement values or modulation phase values may be applied [12] if the procedure has proved to meet the uncertainty requirements of clause 2.



Key

1	Frequency generator (3.2)
2	Power amplifier (3.3)
3	Vibrator (3.3)
4	Moving part of vibrator
5	Dummy mass
6	Accelerometer
7	Amplifier
8	Interferometer (3.6)
9	Laser (3.5)
10	Light detectors
11	Digital waveform recorder (3.13)
12	Voltmeter (3.10)
13	Distortion meter (3.11)
14	Oscilloscope (3.12)

Figure 3 — Measuring system for the sine-approximation method (Method 3)



Key

1	Reference mirror	6	Polarizer
2	Moving part of vibrator	7	Laser
3	Accelerometer	8	Wollaston prism
4	Dummy mass	9	Photodetectors
5	Beamsplitter		

Figure 4 — Laser interferometer with quadrature output

9.3 Data acquisition

The cut-off frequencies of low-pass filters and, if any, high-pass filters shall be chosen so that disturbing influences from low- and high-pass filtering on the calibration results are tolerable (cf. reference [8]). To fulfil Nyquist's theorem, the sampling rate shall be set so that the highest frequency content is lower than half the sampling rate.

The analog-to-digital conversion of the accelerometer output voltage may be performed at the same or lower sampling rate as the conversion of the interferometer output signals. The three sampling processes shall start and end at the same points of time and at least for both interferometer signals be synchronized by a single system clock.

The quadrature signals shall be equidistantly sampled during a measurement period $t_0 < t < t_0 + T_{\mathrm{Meas}}$. The series of measurement values $\{u_1(t_i)\}$ and $\{u_2(t_i)\}$ sampled within $t_0 < t < t_0 + T_{\mathrm{Meas}}$ shall have a sampling interval $\Delta t = t_i - t_{i-1} = \mathrm{const.}$

The sampled series of accelerometer output values is $\{u(t_i)\}$.

Transfer the data to the computer memory.

9.4 Data processing

9.4.1 Obtain the magnitude and the phase shift of the accelerometer sensitivity by the following steps.

9.4.2 Calculate a series of modulation phase values $\left\{\varphi_{\text{Mod}}(t_i)\right\}$ from the sampled interferometer output values $\left\{u_1(t_i)\right\}$ and $\left\{u_2(t_i)\right\}$ using the relationship:

$$\varphi_{\text{Mod}}(t_i) = \arctan\frac{u_2(t_i)}{u_1(t_i)} + n\pi$$

where $n = 0, 1, 2, \ldots$.

Choose an integer number n so that discontinuities of $\left\{\varphi_{\text{Mod}}(t_i)\right\}$ are avoided for the values $n\pi$.

NOTE A procedure for calculating the number n is described in reference [13].

9.4.3 Approximate the obtained series of modulation phase values $\left\{\varphi_{\text{Mod}}(t_i)\right\}$ by solving the following system of $N+1$ equations for the three unknown parameters A, B and C using the least-squares sum method:

$$\varphi_{\text{Mod}}(t_i) = A\cos\omega t_i - B\sin\omega t_i + C$$

where

$i = 0, 1, 2, \ldots, N$;

$A = \hat{\varphi}_{\text{M}} \cos\varphi_s$

$B = \hat{\varphi}_{\text{M}} \sin\varphi_s$

C is a constant;

ω is the vibration radian frequency, $\omega = 2\pi f$;

φ_s is the initial phase angle of the displacement;

$N+1$ denotes the number of samples synchronously taken over the measurement period given in 9.3.

From the resulting parameter values of this "sine-approximation", the parameter C is not used in this context.

9.4.4 Calculate the modulation phase amplitude $\hat{\varphi}_{\text{M}}$ and the displacement initial phase angle φ_s from the parameter values A and B obtained through the sine-approximation, using the following formulae:

$$\hat{\varphi}_{\text{M}} = \sqrt{A^2 + B^2}$$

$$\varphi_s = \arctan\frac{B}{A}$$

9.4.5 Calculate the acceleration amplitude $\hat{a}$ and acceleration initial phase angle φ_a from $\hat{\varphi}_{\text{M}}$ and φ_s using the formulae:

$$\hat{a} = \pi\lambda f^2 \hat{\varphi}_{\text{M}}$$

$$\varphi_a = \varphi_s + \pi$$

9.4.6 Approximate the series of sampled accelerometer output values, $\{u(t_i)\}$, by the sine-approximation method according to 9.4.3. Rewritten for the accelerometer output denoted u, the following system of $N+1$ equations is to be solved:

$$u(t_i) = A_u \cos\omega t_i - B_u \sin\omega t_i + C_u$$

where

$A_u = \hat{u}\cos\varphi_u$

$B_u = \hat{u}\sin\varphi_u$

C_u is a constant;

$\hat{u}$ is the accelerometer output amplitude;

φ_u is the output initial phase angle.

9.4.7 Calculate the accelerometer output amplitude $\hat{u}$ and initial phase angle φ_u from the parameter values A_u and B_u obtained through the sine-approximation using the formulae:

$$\hat{u} = \sqrt{A_u{}^2 + B_u{}^2}$$

$$\varphi_u = \arctan\frac{B_u}{A_u}$$

9.4.8 Calculate the magnitude $\hat{S}_a$ and the phase shift $\Delta\varphi$ of the complex accelerometer sensitivity from the values $\hat{u}$, φ_u obtained in 9.4.7, and the values $\hat{a}$, φ_a obtained in 9.4.5, using the formulae:

$$\hat{S}_a = \frac{\hat{u}}{\hat{a}}$$

$$\Delta\varphi = (\varphi_u - \varphi_a)$$

When the calibration results are reported, the expanded uncertainty of measurement in the calibration shall be calculated and reported in accordance with annex A. In A.1.3.1 and A.2.1, the magnitude of the complex sensitivity is denoted by S.

10 Report of calibration results

When the calibration results are reported, in addition to the calibration method at least the following conditions and characteristics shall be stated:

a) ambient conditions:

- temperature of the accelerometer,
- ambient air temperature;

b) mounting technique:

- material of mounting surface,

  - mounting torque (if the accelerometer is stud-mounted),
  - oil or grease (if used),
  - cable fixing,
  - orientation (vertical or horizontal);

c) dummy mass (if used):

  - material (e.g. steel), dimensions (length, diameter) and mass,
  - mounting torque,
  - values of correction factor for the sensitivity (magnitude) and of the correction for the phase shift to compensate the effects of relative motion between top and bottom surfaces (whenever used);

d) laser light reflection:

  - reflector (polished surface or mirror),
  - position of laser light spot on reflecting surface;

e) all amplifier settings (if adjustable), for example:

  - gain,
  - cut-off frequencies of filters;

f) Calibration results:

- values of calibration frequencies and acceleration amplitudes,
- values of sensitivity (magnitude and phase shift, if measured),
- expanded uncertainty of measurement, k factor if different from $k = 2$.

Annex A
(normative)

Uncertainty components in the primary calibration by laser interferometry of vibration and shock transducers

A.1 Calculation of the relative expanded uncertainty for the sensitivity (magnitude) and the expanded uncertainty for the phase shift for calibration frequencies, amplitudes, and settings of amplifier gain and cut-off frequencies

A.1.1 Calculation of $U_{\mathrm{rel}}(S)$ for Method 1

The relative expanded uncertainty of measurement of the sensitivity (magnitude), $U_{\mathrm{rel}}(S)$, for the calibration frequencies, amplitudes, and settings of amplifier gain and cut-off frequencies shall be calculated in accordance with ISO 16063-1 from the following formulae:

$$U_{\mathrm{rel}}(S) = k u_{\mathrm{c,rel}}(S)$$

$$u_{\mathrm{c,rel}}(S) = \frac{u_{\mathrm{c}}(S)}{S} = \frac{1}{S}\sqrt{\sum_i u_i^2(S)}$$

with the coverage factor $k = 2$ (see Table A.1).

Table A.1

i	**Standard uncertainty component** $u(x_i)$	**Source of uncertainty**	**Uncertainty contribution** $u_i(y)$
1	$u(\hat{u}_{\mathrm{V}})$	accelerometer output voltage measurement (voltmeter)	$u_1(S)$
2	$u(\hat{u}_{\mathrm{D}})$	effect of total distortion on accelerometer output voltage measurement	$u_2(S)$
3	$u(\hat{u}_{\mathrm{T}})$	effect of transverse, rocking and bending acceleration on accelerometer output voltage measurement (transverse sensitivity)	$u_3(S)$
4	$u(\hat{s}_{\mathrm{Q}})$	effect of displacement quantization on displacement measurement	$u_4(S)$
5	$u(\hat{s}_{\mathrm{H}})$	effect of trigger hysteresis on displacement measurement	$u_5(S)$
6	$u(\hat{s}_{\mathrm{F}})$	filtering effect on displacement measurement (frequency band limitation)	$u_6(S)$
7	$u(\hat{s}_{\mathrm{VD}})$	effect of voltage disturbance on displacement measurement (e.g. random noise in the photoelectric measuring chain)	$u_7(S)$
8	$u(\hat{s}_{\mathrm{MD}})$	effect of motion disturbance on displacement measurement (e.g. total distortion; relative motion between the accelerometer reference surface and the spot sensed by the interferometer)	$u_8(S)$
9	$u(\hat{s}_{\mathrm{PD}})$	effect of phase disturbance on displacement measurement (e.g. phase noise of the interferometer signal)	$u_9(S)$
10	$u(\hat{s}_{\mathrm{RE}})$	residual interferometric effects on displacement measurement (interferometer function)	$u_{10}(S)$
11	$u(f_{\mathrm{FG}})$	vibration frequency measurement (frequency generator and indicator)	$u_{11}(S)$
12	$u(S_{\mathrm{RE}})$	residual effects on sensitivity measurement (e.g. random effect in repeat measurements; experimental standard deviation of arithmetic mean)	$u_{12}(S)$

A.1.2 Calculation of $U_{\text{rel}}(S)$ for Method 2

This shall be calculated as under A.1.1 but using the table of uncertainty components, Table A.2.

Table A.2

i	**Standard uncertainty component** $u(x_i)$	**Source of uncertainty**	**Uncertainty contribution** $u_i(y)$
1	$u(\hat{u}_{\text{V}})$	accelerometer output voltage measurement (voltmeter)	$u_1(S)$
2	$u(\hat{u}_{\text{D}})$	effect of total distortion on accelerometer output voltage measurement	$u_2(S)$
3	$u(\hat{u}_{\text{T}})$	effect of transverse, rocking and bending acceleration on accelerometer output voltage measurement (transverse sensitivity)	$u_3(S)$
4	$u(\hat{s}_{\text{Z}})$	effect of minimum-point resolution on displacement measurement	$u_4(S)$
5	$u(\hat{s}_{\text{VD}})$	effect of voltage disturbance on displacement measurement (e.g. hum and noise)	$u_5(S)$
6	$u(\hat{s}_{\text{MD}})$	effect of motion disturbance on displacement measurement (e.g. relative motion between the accelerometer reference surface and the spot sensed by the interferometer)	$u_6(S)$
7	$u(\hat{s}_{\text{RE}})$	residual interferometric effects on displacement measurement (interferometer function)	$u_7(S)$
8	$u(f_{\text{FG}})$	vibration frequency measurement (frequency generator and indicator)	$u_8(S)$
9	$u(S_{\text{RE}})$	residual effects on sensitivity measurement (e.g. random effect in repeat measurements; experimental standard deviation of arithmetic mean)	$u_9(S)$

A.1.3 Calculation of $U_{\mathrm{rel}}(S)$ and $U(\Delta\varphi)$ for Method 3

A.1.3.1 Calculation of $U_{\mathrm{rel}}(S)$

This shall be calculated as under A.1.1 but using the table of uncertainty components, Table A.3.

Table A.3

i	**Standard uncertainty component** $u(x_i)$	**Source of uncertainty**	**Uncertainty contribution** $u_i(y)$
1	$u(\hat{u}_{\mathrm{V}})$	accelerometer output voltage measurement (waveform recorder; e.g. ADC-resolution)	$u_1(S)$
2	$u(\hat{u}_{\mathrm{F}})$	voltage filtering effect on accelerometer output amplitude measurement (frequency band limitation)	$u_2(S)$
3	$u(\hat{u}_{\mathrm{D}})$	effect of voltage disturbance on accelerometer output voltage measurement (e.g. hum and noise)	$u_3(S)$
4	$u(\hat{u}_{\mathrm{T}})$	effect of transverse, rocking and bending acceleration on accelerometer output voltage measurement (transverse sensitivity)	$u_4(S)$
5	$u(\hat{\varphi}_{\mathrm{M,Q}})$	effect of interferometer quadrature output signal disturbance on phase amplitude measurement (e.g. offsets, voltage amplitude deviation, deviation from 90° nominal angle difference)	$u_5(S)$
6	$u(\hat{\varphi}_{\mathrm{M,F}})$	interferometer signal filtering effect on phase amplitude measurement (frequency band limitation)	$u_6(S)$
7	$u(\hat{\varphi}_{\mathrm{M,VD}})$	effect of voltage disturbance on phase amplitude measurement (e.g. random noise in the photoelectric measuring chains)	$u_7(S)$
8	$u(\hat{\varphi}_{\mathrm{M,MD}})$	effect of motion disturbance on phase amplitude measurement (e.g. drift; relative motion between the accelerometer reference surface and the spot sensed by the interferometer)	$u_8(S)$
9	$u(\hat{\varphi}_{\mathrm{M,PD}})$	effect of phase disturbance on phase amplitude measurement (e.g. phase noise of the interferometer signals)	$u_9(S)$
10	$u(\hat{\varphi}_{\mathrm{M,RE}})$	residual interferometric effects on phase amplitude measurement (interferometer function)	$u_{10}(S)$
11	$u(f_{\mathrm{FG}})$	vibration frequency measurement (frequency generator and indicator)	$u_{11}(S)$
12	$u(S_{\mathrm{RE}})$	residual effects on sensitivity measurement (e.g. random effect in repeat measurements; experimental standard deviation of arithmetic mean)	$u_{12}(S)$

A.1.3.2 Calculation of $U(\Delta\varphi)$

The expanded uncertainty of measurement of the phase shift, $U(\Delta\varphi)$, for the calibration frequencies, amplitudes, and settings of amplifier gain and cut-off frequencies shall be calculated in accordance with ISO 16063-1 from the following formulae:

$$U(\Delta\varphi) = k u_\mathrm{c}(\Delta\varphi)$$

$$u_\mathrm{c}(\Delta\varphi) = \sqrt{\sum_i u_i^2(\Delta\varphi)}$$

with the coverage factor $k = 2$ (see Table A.4).

Table A.4

i	**Standard uncertainty component** $u(x_i)$	**Source of uncertainty**	**Uncertainty contribution** $u_i(y)$
1	$u(\varphi_{u,\mathrm{V}})$	accelerometer output phase measurement (waveform recorder; e.g. ADC-resolution)	$u_1(\Delta\varphi)$
2	$u(\varphi_{u,\mathrm{F}})$	voltage filtering effect on accelerometer output phase measurement (frequency band limitation)	$u_2(\Delta\varphi)$
3	$u(\varphi_{u,\mathrm{D}})$	effect of voltage disturbance on accelerometer output phase measurement (e.g. hum and noise)	$u_3(\Delta\varphi)$
4	$u(\varphi_{u,\mathrm{T}})$	effect of transverse, rocking and bending acceleration on accelerometer output phase measurement (transverse sensitivity)	$u_4(\Delta\varphi)$
5	$u(\varphi_{s,\mathrm{Q}})$	effect of interferometer quadrature output signal disturbance on displacement phase measurement (e.g. offsets, voltage amplitude deviation, deviation from 90° nominal angle difference)	$u_5(\Delta\varphi)$
6	$u(\varphi_{s,\mathrm{F}})$	interferometer signal filtering effect on displacement phase measurement (frequency band limitation)	$u_6(\Delta\varphi)$
7	$u(\varphi_{s,\mathrm{VD}})$	effect of voltage disturbance on displacement phase measurement (e.g. random noise in the photoelectric measuring chains)	$u_7(\Delta\varphi)$
8	$u(\varphi_{s,\mathrm{MD}})$	effect of motion disturbance on displacement phase measurement (e.g. drift; relative motion between the accelerometer reference surface and the spot sensed by the interferometer)	$u_8(\Delta\varphi)$
9	$u(\varphi_{s,\mathrm{PD}})$	effect of phase disturbance on displacement phase measurement (e.g. phase noise of the interferometer signals)	$u_9(\Delta\varphi)$
10	$u(\varphi_{s,\mathrm{RE}})$	residual interferometric effects on displacement phase measurement (interferometer function)	$u_{10}(\Delta\varphi)$
11	$u(\Delta\varphi_\mathrm{RE})$	residual effects on phase shift measurement (e.g. random effect in repeat measurements; experimental standard deviation of arithmetic mean)	$u_{11}(\Delta\varphi)$

A.2 Calculation of the relative expanded uncertainty for the sensitivity (magnitude) and the expanded uncertainty for the phase shift over the complete frequency and amplitude range

A.2.1 Calculation of $U_{\mathrm{rel}}(S_{\mathrm{t}})$

The relative expanded uncertainty of measurement of the sensitivity (magnitude), $U_{\mathrm{rel}}(S)$, calculated in accordance with A.1.1, A.1.2 or A.1.3.1, is only valid for the calibration frequencies, amplitudes, and settings of amplifier gain and cut-off frequencies. The relative expanded uncertainty of measurement of the sensitivity $U_{\mathrm{rel}}(S_{\mathrm{t}})$ for the complete frequency and amplitude range, at any time during the interval between successive calibrations, shall be calculated from the following formulae:

$$U_{\mathrm{rel}}(S_{\mathrm{t}}) = k u_{\mathrm{c,rel}}(S_{\mathrm{t}})$$

$$u_{\mathrm{c,rel}}(S_{\mathrm{t}}) = \frac{u_{\mathrm{c}}(S_{\mathrm{t}})}{S} = \frac{1}{S}\sqrt{\sum_i u_i^2(S_{\mathrm{t}})}$$

with the coverage factor $k = 2$ (cf. ISO 16063-1) (see Table A.5).

Table A.5

i	Standard uncertainty component $u(x_i)$	Source of uncertainty	Uncertainty contribution $u_i(y)$
1	$u(S)$	uncertainty of sensitivity calculated at calibration frequencies, amplitudes and amplifier gain settings in accordance with A.1.1, A.1.2 or A.1.3.1	$u_1(S_{\mathrm{t}})$
2	$u(e_{\mathrm{T,A}})$	reference amplifier tracking (deviations in gain for different amplification settings)	$u_2(S_{\mathrm{t}})$
3	$u(e_{\mathrm{L},f,\mathrm{A}})$	deviation from constant amplitude-frequency characteristic of reference amplifier	$u_3(S_{\mathrm{t}})$
4	$u(e_{\mathrm{L},f,\mathrm{P}})$	deviation from constant amplitude-frequency characteristic of reference accelerometer	$u_4(S_{\mathrm{t}})$
5	$u(e_{\mathrm{L},a,\mathrm{A}})$	amplitude effect on gain of reference amplifier	$u_5(S_{\mathrm{t}})$
6	$u(e_{\mathrm{L},a,\mathrm{P}})$	amplitude effect on sensitivity (magnitude) of reference accelerometer	$u_6(S_{\mathrm{t}})$
7	$u(e_{\mathrm{I,A}})$	instability of reference amplifier gain, and effect of source impedance on gain	$u_7(S_{\mathrm{t}})$
8	$u(e_{\mathrm{I,P}})$	instability of sensitivity (magnitude) of reference accelerometer	$u_8(S_{\mathrm{t}})$
9	$u(e_{\mathrm{E,A}})$	environmental effects on gain of reference amplifier	$u_9(S_{\mathrm{t}})$
10	$u(e_{\mathrm{E,P}})$	environmental effects on sensitivity (magnitude) of reference accelerometer	$u_{10}(S_{\mathrm{t}})$

A.2.2 Calculation of $U(\Delta\varphi_\text{t})$

The expanded uncertainty of measurement of the phase shift of the complex sensitivity, $U(\Delta\varphi)$, calculated in accordance with A.1.3.2, is only valid for the calibration frequencies, amplitudes, and settings of amplifier gain and filter cut-off frequencies. The expanded uncertainty of measurement of the phase shift $U(\Delta\varphi_\text{t})$ for the complete frequency and amplitude range, at any time during the interval between successive calibrations, shall be calculated from the following formulae:

$$U(\Delta\varphi_\text{t}) = k u_\text{c}(\Delta\varphi_\text{t})$$

$$u_\text{c}(\Delta\varphi_\text{t}) = \sqrt{\sum_i u_i^2(\Delta\varphi_\text{t})}$$

with the coverage factor k = 2 (cf. ISO 16063-1) (see Table A.6).

Table A.6

i	**Standard uncertainty component** $u(x_i)$	**Source of uncertainty**	**Uncertainty contribution** $u_i(y)$
1	$u(\Delta\varphi)$	uncertainty of phase shift calculated at calibration frequencies, amplitudes and amplifier gain settings in accordance with A.1.3.2	$u_1(\Delta\varphi_\text{t})$
2	$u(e^*_{\text{T,A}})$	reference amplifier tracking (deviations in phase for different amplification settings)	$u_2(\Delta\varphi_\text{t})$
3	$u(e^*_{\text{L},f,\text{A}})$	deviation from linear phase-frequency characteristic of reference amplifier	$u_3(\Delta\varphi_\text{t})$
4	$u(e^*_{\text{L},f,\text{P}})$	deviation from linear phase-frequency characteristic of reference accelerometer	$u_4(\Delta\varphi_\text{t})$
5	$u(e^*_{\text{L},a,\text{A}})$	amplitude effect on phase shift of reference amplifier	$u_5(\Delta\varphi_\text{t})$
6	$u(e^*_{\text{L},a,\text{P}})$	amplitude effect on phase shift of reference accelerometer	$u_6(\Delta\varphi_\text{t})$
7	$u(e^*_{\text{I,A}})$	instability of reference amplifier phase shift, and effect of source impedance on phase shift	$u_7(\Delta\varphi_\text{t})$
8	$u(e^*_{\text{I,P}})$	instability of reference accelerometer phase shift	$u_8(\Delta\varphi_\text{t})$
9	$u(e^*_{\text{E,A}})$	environmental effects on phase shift of reference amplifier	$u_9(\Delta\varphi_\text{t})$
10	$u(e^*_{\text{E,P}})$	environmental effects on phase shift of reference accelerometer	$u_{10}(\Delta\varphi_\text{t})$

Annex B
(normative)

Formulae for the calculation of acceleration

B.1 Procedure for Method 1

The wavelength of the principal lines in the emission spectrum of neon is 0,632 81 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:

$$\Delta s = \frac{\lambda}{2}$$

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

$$\frac{4\hat{s}}{\lambda / 2} = \frac{f_\mathrm{f}}{f}$$

$$\hat{s} = \frac{\lambda}{8} \times \frac{f_\mathrm{f}}{f}$$

The acceleration is given by the following formulae:

$$\hat{a} = 4\pi^2 \times f^2 \, \hat{s}$$

$$\hat{a} = \frac{\pi^2 \lambda}{2} \times f_\mathrm{f} \, f$$

where

f is the frequency of the vibrator;

f_f is the fringe frequency.

B.2 Procedure for Method 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:

$$\hat{s} = x_n \times \frac{\lambda}{4\pi}$$

$$\hat{a} = 4\pi^2 \times f^2 \, \hat{s}$$

where x_n are the arguments corresponding to the zero points of the Bessel function as given in Table B.1.

Table B.1 — Values for the arguments x_n corresponding to the zero points of the Bessel function of the first kind and first order

Zero point No. n	x_n
0	0
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	88,745 77
29	91,887 52
30	95,029 24

B.3 Procedure for Method 3

According to ISO 16063-1, the complex acceleration sensitivity $\underline{S_a}$ of an accelerometer is

$$\underline{\hat{S}_a} = \hat{S}_a \exp \mathrm{j}\left(\varphi_u - \varphi_a\right) \tag{B.1}$$

where

$$\hat{S}_a = \frac{\hat{u}}{\hat{a}} \tag{B.2}$$

is the magnitude of the acceleration sensitivity;

$\hat{u}$ is the amplitude of the accelerometer output u (preferably output voltage of the accelerometer/amplifier combination);

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

φ_u is the initial phase angle of the output;

φ_a is the initial phase angle of the acceleration;

$\Delta\varphi = \varphi_u - \varphi_a$ is the phase shift of the complex sensitivity. (B.3)

The amplitude and phase of the acceleration can be obtained from the displacement amplitude $\hat{s}$, frequency f (radian frequency $\omega = 2\pi f$) and displacement initial phase angle φ_s by the formulae:

$$\hat{a} = \omega^2 \hat{s} \tag{B.4}$$

$$\varphi_a = \varphi_s + \pi \tag{B.5}$$

When the vibration exciter generates a sinusoidal displacement

$$s = \hat{s}\cos(\omega t + \varphi_s) \tag{B.6}$$

the accelerometer output signal follows the relationship

$$u = \hat{u}\cos(\omega t + \varphi_u) \tag{B.7}$$

The output of the first photodetector can be written as follows:

$$u_1(t) = \hat{u}_1 \cos\varphi_{\mathrm{Mod}}(t) = \hat{u}_1 \cos\left[\varphi_0 + \hat{\varphi}_{\mathrm{M}}\cos(\omega t + \varphi_s)\right] \tag{B.8}$$

where the modulation phase

$$\varphi_{\mathrm{Mod}} = \varphi_0 + \hat{\varphi}_{\mathrm{M}}\cos(\omega t + \varphi_s) \tag{B.9}$$

is composed of the initial phase angle of the photodetector signal, φ_0, and a modulation term, φ_{M}, whose amplitude $\hat{\varphi}_{\mathrm{M}}$ is proportional to the displacement:

$$\varphi_{\mathrm{M}} = \hat{\varphi}_{\mathrm{M}}\cos(\omega t + \varphi_s) \tag{B.10}$$

with

$$\hat{\varphi}_{\mathrm{M}} = \frac{4\pi\hat{s}}{\lambda} \tag{B.11}$$

It is presupposed that there is no phase shift between the displacement $s(t)$ and the sinusoidal phase term $\varphi_{\mathrm{M}}(t)$.

A second photodetector output that is in quadrature is then expressed by:

$$u_2(t) = \hat{u}_2 \sin\varphi_{\mathrm{Mod}}(t) = \hat{u}_2 \sin\left[\varphi_0 + \hat{\varphi}_{\mathrm{M}}\cos(\omega t + \varphi_s)\right] \tag{B.12}$$

where $\hat{u}_2 = \hat{u}_1$.

The quadrature signals are equidistantly sampled during a measurement period $t_0 < t < t_0 + T_{\mathrm{Meas}}$. The series of measurement values $\{u_1(t_i)\}$ and $\{u_2(t_i)\}$ sampled within $t_0 < t < t_0 + T_{\mathrm{Meas}}$ have a sampling interval:

$$\Delta t = t_i - t_{i-1} = \text{const}$$

From both quadrature signals, the phase values $\varphi_{\mathrm{Mod}}(t_i)$ are calculated successively in the course of the measurement period using the following relationship:

$$\varphi_{\mathrm{Mod}}(t_i) = \arctan\frac{u_2(t_i)}{u_1(t_i)} + n\pi \tag{B.13}$$

where $n = 0, 1, 2, ...$

The required procedures, especially the calculation of the arctan function with successive "phase-unwrapping" (see reference [13]), are standard procedures in digital signal processing. From the values $\varphi_{\text{Mod}}(t_i)$, the parameters $\hat{\varphi}_{\text{M}}$ and φ_s of the displacement-proportional modulation phase term $\varphi_{\text{M}}(t)$ can be calculated by solving the system of $N + 1$ equations:

$$\varphi_{\text{Mod}}(t_i) = A \cos \omega t_i - B \sin \omega t_i + C \tag{B.14}$$

where $i = 0, 1, 2, ..., N$,

which is linear with respect to the parameters

$$A = \hat{\varphi}_{\text{M}} \cos \varphi_s, \qquad B = \hat{\varphi}_{\text{M}} \sin \varphi_s \tag{B.15}$$

and C, which is a constant.

$N + 1$ denotes the number of samples synchronously taken over the above measurement period. The parameters A, B and C are calculated using the least-squares sum method (sine-approximation). From their values, the modulation phase amplitude $\hat{\varphi}_{\text{M}}$ and the displacement phase φ_s can be obtained by the relationships

$$\hat{\varphi}_{\text{M}} = \sqrt{A^2 + B^2} \tag{B.16}$$

$$\varphi_s = \arctan \frac{B}{A} \tag{B.17}$$

NOTE For a simplified description of the sine-approximation method (Method 3) in this clause, no new symbols are introduced that would be needed to distinguish between the estimate of a quantity, e.g. $\hat{\varphi}_{\text{M}}$ in equation (B.16) and its "true" value, e.g. $\hat{\varphi}_{\text{M}}$ in equation (B.11). For the description of errors and uncertainties, such a distinction is introduced in reference [8].

To establish a relationship for the calculation of the acceleration amplitude, thus saving an explicit calculation of the displacement amplitude by means of equation (B.11), the latter relationship can be introduced into equation (B.4). In this way, the following formula is obtained:

$$\hat{a} = \pi \lambda f^2 \hat{\varphi}_{\text{M}} \tag{B.18}$$

For calculating the acceleration phase, equation (B.5) shall be used. The amplitude $\hat{u}$ and the phase φ_u of the accelerometer output u can be determined in the same way as the respective modulation phase parameters $\hat{\varphi}_{\text{M}}$ and φ_s through a sine-approximation of the series of sampled output values $\{u(t_i)\}$; cf. equations (B.14) to (B.17). By introducing in equations (B.2) and (B.3) the resulting values for $\hat{u}$, φ_u and the values obtained for $\hat{a}$ and φ_a, the magnitude $\hat{S}_a$ and the phase shift $\Delta\varphi$ of the accelerometer sensitivity can be calculated.

The above relationships, especially equations (B.8) and (B.12), presuppose ideal conditions that are not fulfilled in reality. Under practical conditions, the signals from the photodetectors deviate with respect to their amplitudes $\hat{u}_1$, $\hat{u}_2$ and the nominal phase shift $\pi / 2$, and different offsets $u_{0,1}$, $u_{0,2}$ may occur. The influences from non-ideal quadrature signals within the tolerance ranges stated in 3.6 are briefly characterized in note 1 of 9.2 (for a detailed investigation, cf. reference [8]).

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