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Methods for the calibration of vibration and shock transducers —

Part 41:
Calibration of laser vibrometers

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

Partie 41: Étalonnage des vibromètres à laser

Reference number
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Contents

Page

Foreword

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The main task of technical committees is to prepare International Standards. 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 document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 16063-41 was prepared by Technical Committee ISO/TC 108, *Mechanical vibration, shock and condition monitoring*, Subcommittee SC 3, *Use and calibration of vibration and shock measuring instruments*.

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 15: Primary angular vibration calibration by laser interferometry*
- *Part 21: Vibration calibration by comparison to a reference transducer*
- *Part 22: Shock calibration by comparison to a reference transducer*
- *Part 31: Testing of transverse vibration sensitivity*
- *Part 41: Calibration of laser vibrometers*

The following parts are under preparation:

- *Part 16: Calibration by Earth's gravitation*

Methods for the calibration of vibration and shock transducers —

Part 41:
Calibration of laser vibrometers

1 Scope

This part of ISO 16063 specifies the instrumentation and procedures for performing primary and secondary calibrations of rectilinear laser vibrometers in the frequency range typically between 0,4 Hz and 50 kHz. It specifies the calibration of laser vibrometer standards designated for the calibration of either laser vibrometers or mechanical vibration transducers in accredited or non-accredited calibration laboratories, as well as the calibration of laser vibrometers by a laser vibrometer standard or by comparison to a reference transducer calibrated by laser interferometry. The specification of the instrumentation contains requirements on laser vibrometer standards.

Rectilinear laser vibrometers can be calibrated in accordance with this part of ISO 16063 if they are designed as laser optical transducers with, or without, an indicating instrument to sense the motion quantities of displacement or velocity, and to transform them into proportional (i.e. time-dependent) electrical output signals. These output signals are typically digital for laser vibrometer standards and usually analogue for laser vibrometers. The output signal or the reading of a laser vibrometer can be the amplitude and, in addition, occasionally the phase shift of the motion quantity (acceleration included). In this part of ISO 16063, the calibration of the modulus of complex sensitivity is explicitly specified (phase calibration is provided in Annex D).

NOTE Laser vibrometers are available for measuring vibrations having frequencies in the megahertz and gigahertz ranges. To date, vibration exciters are not available for generating such high frequencies. The calibration of these laser vibrometers can be estimated by the electrical calibration of their signal processing subsystems utilizing appropriate synthetic Doppler signals under the following preconditions:

- the optical subsystem of the laser vibrometer to be calibrated has been proven to comply with defined requirements comparable to those given in 5.5.3;
- synthetic Doppler signals are generated as an equivalent substitute for the output of the photodetectors.

More detailed specifications of this approach (see Reference [25]) lie outside the scope of this part of ISO 16063.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 266, *Acoustics — Preferred frequencies*

ISO 5348, *Mechanical vibration and shock — Mechanical mounting of accelerometers*

ISO 16063-1:1998, *Methods for the calibration of vibration and shock transducers — Part 1: Basic concepts*

ISO 16063-11:1999, *Methods for the calibration of vibration and shock transducers — Part 11: Primary vibration calibration by laser interferometry*

ISO 16063-21, *Methods for the calibration of vibration and shock transducers — Part 21: Vibration calibration by comparison to a reference transducer*

ISO/IEC Guide 99, *International vocabulary of metrology — Basic and general concepts and associated terms (VIM)*

3 Classification of laser vibrometers and principles of test methods

3.1 Classification of laser vibrometers

3.1.1 A **laser vibrometer standard** (LVS) is a reference standard containing a laser interferometer, designed and intended to serve as a reference to calibrate laser vibrometers and/or vibration transducers.

NOTE Methods 1, 2, and 3 are applicable to the primary calibration of LVSs.

3.1.2 A **laser vibrometer** (LV) is a measuring instrument containing a laser interferometer, designed and intended to perform vibration measurements.

NOTE Methods 1, 2, and 3 are applicable to the primary calibration of LVs, and method 4 is applicable to the secondary calibration of LVs. The reference accelerometer used for method 4 is calibrated by method 1, 2 or 3. For specific requirements, see 5.11.

3.1.3 A **laser optical transducer** is a measurement transducer sensing, by laser light, the motion quantities of displacement or velocity and transforming these quantities into a proportional time-dependent output signal.

3.2 Principles of test methods

3.2.1 General. Four methods are specified in analogy to ISO 16063-11 (laser interferometry) and ISO 16063-21 (comparison to a reference transducer), respectively. Methods 1, 3, and 4 provide for calibrations at preferred displacement amplitudes, velocity amplitudes and acceleration amplitudes at various frequencies. Method 2 requires calibrations at fixed displacement amplitudes (velocity amplitude and acceleration amplitude vary with frequency).

For each interferometric method specified in this part of ISO 16063 (see 3.2.2 to 3.2.4), currently a specific frequency range applies. In fact, the applicability of the particular methods mainly depends on the displacement or velocity amplitudes measurable within given measurement uncertainties. These, however, not only depend on the measurement method itself but also on the frequency-dependent properties of the vibration exciters available. Using adequate vibration exciters to generate sufficient displacement or velocity amplitudes, the upper frequency limits of all methods can be expanded to 100 kHz and even beyond. The primary method 3 (see 3.2.4) and the comparison method 4 (see 3.2.5) are applicable at frequencies lower than 0,4 Hz.

3.2.2 Method 1, the **fringe-counting method**, is a vibration measurement method using a homodyne interferometer with a single output (see Note 2) in conjunction with instrumentation for fringe counting of the interferometer signal. Considering that the displacement corresponding to the distance between two fringes (intensity maxima or intensity minima) is given by half the wavelength of the principal lines in the emission spectrum of neon of the He-Ne laser, the displacement amplitude can be calculated from the number of fringes counted during a given number (e.g. 1 000) of vibration periods.

For details, see Clause 8 and, for further information, ISO 16063-11:1999, B.1.

NOTE 1 Method 1 is applicable to the primary calibration of the laser vibrometer (modulus only) in the frequency range 1 Hz to 800 Hz and, under special conditions, at lower and higher frequencies. In Reference [26], the applicability of method 1 has been demonstrated at frequencies up to 347 kHz.

NOTE 2 Alternatively, the homodyne interferometer signal from one of the two outputs of a quadrature interferometer can be used.

NOTE 3 The electronic fringe counting can be substituted by the signal coincidence method (see References [1] [23] [24]), which indicates a displacement amplitude of a quarter wavelength, $\lambda/4$, of the laser light (158,2 nm for a red helium-neon laser). In the general case, the interferometer signal shows relative maxima and minima at the times when the vibration displacement approaches its positive and negative peak values, respectively. In the discrete case (158,2 nm), the relative signal maxima and minima approach the same signal level from the negative and positive directions, respectively ("coincidence"). By observing the interferometer signal as a function of time on an oscilloscope and adjusting the vibration amplitude to the level where a bright sharp line appears, the discrete amplitude (158,2 nm) is identified. The bright line varies with time as the initial phase of the interferometer signal varies due to low-frequency motion. In Reference [26], the applicability of the signal coincidence method has been demonstrated at frequencies up to 160 kHz.

3.2.3 Method 2, the **minimum-point method**, is a vibration measurement method using a homodyne interferometer with a single output in conjunction with instrumentation for zero-point detection of a component of the frequency spectrum of the interferometer signal. Considering the frequency spectrum of the intensity and adjusting the vibration amplitude to the level at which the component of the same frequency as the vibration frequency is zero, the displacement amplitude can be calculated from the argument corresponding to the respective zero point of the Bessel function of the first kind and first order.

For details, see Clause 9 and, for further information, ISO 16063-11:1999, B.2.

NOTE 1 Method 2 can be used for modulus calibration in the frequency range 800 Hz to 10 kHz with an electro-dynamic vibration exciter, and up to 50 kHz and higher with a vibration exciter for large vibration amplitudes, preferably a piezo-electric vibration exciter. In Reference [27], the applicability of method 2 has been demonstrated at frequencies up to 50 kHz.

NOTE 2 For displacement amplitudes smaller than that of the first minimum point (193 nm for the J_1 Bessel function, 121 nm for the J_0 Bessel function), the Bessel function ratio method (e.g. see Reference [22]) can be applied if the uncertainty requirements of Clause 4 are complied with.

3.2.4 Method 3, the **sine-approximation method**, is a vibration measurement method using a homodyne or heterodyne interferometer with two electrical outputs in quadrature (i.e. phase-shifted by 90°) in conjunction with instrumentation for signal sampling and processing. A sine approximation of an equidistant sequence of calculated displacement or velocity values leads to the amplitude and the initial phase shift of the respective vibration quantity.

For details, see Clause 10 and, for further information, ISO 16063-11:1999, B.3.

NOTE Method 3 can be used for modulus and phase calibration if the laser vibrometer provides both measurement capabilities. Method 3 in the homodyne or heterodyne interferometer version provides calibrations in the frequency range 0,4 Hz to 50 kHz or wider. In Reference [26], the applicability of method 3 has been demonstrated at frequencies up to 347 kHz.

3.2.5 Method 4, the **comparison to a reference transducer**, is a vibration measurement method using a reference accelerometer calibrated by a suitable primary method (laser interferometry) or secondary method (comparison to a reference transducer), see 5.11. The acceleration amplitude, $\hat{a}$, is calculated using the equation

$$\hat{a} = \frac{1}{S_{a,\mathrm{R}}} \hat{u}$$

where

$S_{a,\mathrm{R}}$ is the acceleration sensitivity (magnitude) of the reference accelerometer;

$\hat{u}$ is the amplitude of the accelerometer output during laser vibrometer calibration.

For the calculation of the displacement and velocity amplitudes and other details, see Clause 11.

NOTE 1 Method 4 is applicable to the calibration of laser vibrometers (magnitude and phase) in a frequency range 0,4 Hz to 50 kHz or wider. For frequencies higher than 5 kHz, the reference transducer shall be calibrated by laser interferometry (see 5.11). The frequency range of method 4 is limited to the frequency range over which the reference transducer was calibrated.

NOTE 2 Vibration calibration of transducers by comparison to a reference transducer is specified in detail in ISO 16063-21. The same method can be used for calibration of laser vibrometers operated as laser optical transducers (see 3.1.3).

4 Uncertainty of measurement

All users of this part of ISO 16063 are expected to make uncertainty budgets in accordance with Annex A to document their uncertainty.

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

As this part of ISO 16063 covers three measurands (displacement, velocity and acceleration) in wide amplitude and frequency ranges with different accuracy requirements and different performances of the devices to be calibrated (laser vibrometer standards and laser vibrometers), the uncertainty of measurement may range from small to relatively large values. From knowledge of all significant sources of uncertainty affecting the calibration, the expanded uncertainty can be evaluated using the methods given in this part of ISO 16063.

Two examples are given in order to help set up systems that fulfil different uncertainty requirements. System requirements for each are set up and the attainable uncertainty is given. Example 1 is applicable to calibrations performed under well-controlled laboratory conditions resulting in relatively small uncertainties. Example 2 is applicable to calibrations in which relatively large uncertainties can be accepted or where calibration conditions are such that only less narrow tolerances can be maintained. These two examples are used throughout this part of ISO 16063.

EXAMPLE 1

A laser vibrometer standard is calibrated by primary means (method 1, 2 or 3 as specified in this part of ISO 16063) with documented small uncertainty. The temperature and other conditions are kept within narrow limits during the calibration as indicated in the appropriate clauses.

Figures 1 to 4 show examples for the calibration equipment applicable to fulfil high accuracy requirements represented by Example 1.

EXAMPLE 2

A laser vibrometer is calibrated using a laser vibrometer standard calibrated according to Example 1.

For both examples, the minimum calibration requirement on the reference transducer is a calibration at suitable reference conditions (i.e. frequency, amplitude and temperature). Normally, the conditions are chosen as indicated in Clause 5.

The typical attainable uncertainties specified in Table 3 are applicable for the parameters specified in Table 1.

Table 1 — Typical frequency and amplitude ranges of displacement, velocity and acceleration

Frequency range:	0,4 Hz to 50 kHz
Dynamic range (amplitude):	
• displacement	• 1 nm to 1 m
• velocity	• 0,1 mm/s to 1 m/s (frequency-dependent)
• acceleration	• 0,1 m/s^2 to 20 km/s^2 (frequency-dependent)
NOTE The indicated ranges are not mandatory, and calibrations performed at a single point or in smaller ranges of frequency, amplitude or both are also acceptable.	

At any given frequency and amplitude of acceleration, velocity or displacement, the dynamic range is limited by the noise floor and the amount of distortion produced by the vibration generation equipment (if no filtering is used) or its maximum power. In the case of spring-controlled vibration exciters, specific techniques may be used to compensate for inherent distortion occurring at large displacements by using an appropriate non-sinusoidal voltage at the input of the power amplifier. Typical frequency ranges and maximum vibration amplitude ranges of electro-dynamic and piezo-electric vibration exciters are given in 5.3.

The uncertainty components of the calibration methods characterized in Table 2 are specified in Annex A.

Table 2 — Applicability of calibration methods influencing the uncertainty of measurement

Marking of method	Characterization of method (Optical transducer/signal treatment)
Method 1	Homodyne interferometer (single output signal/fringe counting)
Method 2	Homodyne interferometer (single output signal/spectral analysis)
Method 3 (homodyne)	Homodyne interferometer (two output signals in quadrature/sine approximation)
Method 3 (heterodyne)	Heterodyne interferometer (output with frequency offset/sine approximation)
Method 4	Comparison to a reference transducer calibrated by method 1, 2 or 3

NOTE 2 Calibrations shall be traceable to a national measurement standard of the SI unit of acceleration, velocity or displacement and be performed by a competent laboratory, e.g. one that is in compliance with ISO/IEC 17025 (Reference [21]).

Typical uncertainties that are attainable for Example 1 and Example 2 given above are specified in Table 3. In practice, these uncertainty values may be exceeded or even smaller uncertainties may be achieved depending on the performance of the calibration apparatus and the quantities influencing the calibration result. It is the responsibility of the laboratory or end user to make sure that the reported values of expanded uncertainty are credible. This can be achieved by evaluating the expanded measurement uncertainty in accordance with Annex A and ISO 16063-1:1998, Annex A.

Table 3 — Typical attainable uncertainties

Frequency range	Example 1	Example 2
0,4 Hz to <1 Hz	0,25 %	1 %
1 Hz to 5 kHz	0,25 %	0,5 %
>5 kHz to 10 kHz	0,3 %	1 %
>10 kHz to 20 kHz	0,5 %	3 %
>20 kHz to 50 kHz	1 %	5 %
NOTE The expanded uncertainties given as examples (e.g. 0,5 % at 20 kHz) are based on concrete uncertainty budgets established in accordance with Annex A.		

5 Requirements for apparatus and other conditions

5.1 General

This clause gives recommended specifications for the apparatus necessary to fulfil the scope of Clause 1 and to obtain the uncertainties of Clause 4.

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

NOTE The apparatus specified in this clause covers all devices and instruments required for any of the four calibration methods specified in this part of ISO 16063. The assignment to a given method is indicated.

The examples referred to in this clause are those described in Clause 4.

If the recommended specifications listed below are met for each item, the uncertainties given in Clause 4 should be obtainable over the applicable frequency range. Special instrumentation may be required in order to meet the expanded uncertainties given in Clause 4 at frequencies less than 1 Hz and higher than 10 kHz. It is mandatory to document the expanded uncertainty using the methods of Annex A.

5.2 Environmental conditions

The calibration shall be carried out under the ambient conditions contained in Table 4.

Table 4 — Ambient conditions

Influence quantity	Example 1	Example 2
Room temperature	(23 ± 3) °C	(23 ± 5) °C
Relative humidity	75 % max.	90 % max.

Care shall be taken that external vibration and noise do not affect the quality of the measurements.

5.3 Vibration generation equipment

5.3.1 General

Vibration generation equipment shall fulfil the requirements listed in Table 5.

Table 5 — Requirements on vibration generation equipment

Disturbing influence	Unit	Example 1	Example 2
Frequency uncertainty	%	≤0,1	≤0,2
Frequency instability over the measurement period	% of reading	≤0,1	≤0,2
Acceleration amplitude instability over the measurement period	% of reading	≤0,1	≤0,3
Total harmonic distortion of the acceleration signal at frequencies >20 Hz	%	≤5	≤10
Total harmonic distortion over the whole frequency range	%	≤10	≤20
Transverse, bending and rocking acceleration	%	≤10 at $f \leq$ 1 kHz ≤30 at $f >$ 1 kHz	
Hum and noise ($f \geq$ 10 Hz) level below full output signal	dB	≥50	≥40
Hum and noise ($f <$ 10 Hz) level below full output signal	dB	≥20	≥10

The hum and noise influences are only important when present inside the measurement bandwidth used. For every combination of frequency and vibration amplitude (acceleration, velocity or displacement) used during calibration, the magnitude of the transverse, bending and rocking accelerations, hum and noise shall be consistent with the uncertainties given in Clause 4.

5.3.2 Electro-dynamic vibration exciter

Typical maximum vibration amplitudes for electro-dynamic vibration exciters designed for the frequency range from 10 Hz to 10 kHz are 5 mm displacement amplitude, 0,5 m/s to 1 m/s velocity amplitude and 200 m/s^2 to 1 km/s^2 acceleration amplitude. When measurements are performed at the lowest frequencies, the limiting factor is normally displacement. At 1 Hz, typical values for long-stroke vibration exciters are 80 mm displacement amplitude, 0,5 m/s velocity amplitude and 1 m/s^2 acceleration amplitude. Using resonance effects, electro-dynamic vibration exciters attain large vibration amplitudes in the range of 200 m/s^2 up to 5 km/s^2 at frequencies up to 50 kHz, but only with risk of damage to, or destruction of, the exciter.

5.3.3 Piezo-electric vibration exciter

Large vibration amplitudes at high frequencies (1 kHz to 50 kHz or higher) can be generated by piezo-electric vibration exciters.

NOTE For method 2 (minimum-point method based on using the J_1 Bessel function), a displacement amplitude of at least 193,0 nm needs to be generated in order to obtain minimum point No. 1. At a frequency of 50 kHz, this displacement amplitude corresponds to an acceleration amplitude of approximately 19 km/s^2.

5.4 Seismic block(s) for vibration exciter and laser interferometer

The vibration exciter 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 vibration exciter's support structure from excessively influencing the calibration results.

When a common seismic block is used, it should have a mass of at least 2 000 times that of the moving mass. This criterion results in a vibration of the interferometer induced by the motion of the exciter that is less than 0,05 % of the amplitude of vibration of the exciter. If the mass of the seismic block is smaller than 2 000 times that of the moving mass, the motion of the seismic block generated by the vibration exciter shall be taken into account.

When a common seismic block is used, it is further recommended to mount the vibrometer(s) on an additional block which is vibrationally isolated from said seismic block by another set of damped springs (see Figure 6).

To suppress the disturbing effects of ground motion, the seismic block(s) should be isolated by damped springs designed to reduce the uncertainty component due to these effects to less than 0,1 %.

5.5 Interferometer system

5.5.1 Common requirements for methods 1, 2 and 3

The interferometer system consists of a laser optical tranducer (briefly referred to as interferometer) and an electronic signal decoding subsystem.

The interferometer as laser optical transducer shall transform

- a displacement $s(t)$ at the input of the interferometer into a proportional phase shift $\varphi_\mathrm{M}(t)$ of the interferometer output signal, or
- the velocity $v(t)$ at the input of the interferometer into a proportional frequency shift $f_\mathrm{D}(t)$ (Doppler frequency) of the interferometer output signal.

For both transformations, a homodyne or a heterodyne interferometer (see Figures 2, 3, 4, 5 and 7) may be used.

For methods 1 and 2, an interferometer shall be used with a photodetector to sense the interferometric intensity modulation caused by the motion generated by the vibration exciter. The frequency response of the photodetector shall cover the highest Doppler frequency expected. A common Michelson interferometer with a single photodetector is sufficient (see Figures 2 and 3).

For method 3 either homodyne or heterodyne interferometer arrangements can be used.

In case of the homodyne approach, two optical outputs generating quadrature signals and two photodetectors are necessary in order to provide directional sensitivity. A modified Michelson interferometer may be designed for this purpose according to Figure 5. A quarter wavelength retarder plate 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 heterodyne interferometer is characterized by a frequency-shifting optical component in one of the light beams, which generates a carrier frequency at the output. A positive or negative frequency shift due to the Doppler effect is superimposed on this carrier frequency. With this arrangement, only one photodetector is needed to obtain the complete direction preserving Doppler information. A preferred optical design utilizes the modified Mach-Zehnder interferometer arrangement according to Figure 7, but other approaches which generate a carrier frequency at the output are also suitable.

A Mach-Zehnder interferometer may be designed according to Figure 7. The mode of operation is described in Annex B.

The interferometer for method 3 (homodyne or heterodyne version) may be implemented in a commercial laser vibrometer standard (LVS). Specific requirements for LVSs are given in 5.7.

5.5.2 Laser

A laser shall be used whose wavelength is known and stable within limits of 10^{-5} over a period of 2 years and a temperature interval of (23 ± 5) °C. Preferably, a laser of the red helium-neon type should be used. The wavelength of a red helium-neon laser is 0,632 81 µm at an atmospheric pressure of 100 kPa, a temperature to 23 °C and a relative humidity of 50 %.

5.5.3 Photodetector

The bandwidth of the photodetector unit(s) shall be sufficient to transfer the phase- and frequency-modulated signal(s) from the interferometer with tolerable distortions. The minimum bandwidth for homodyne interferometers, $b_{f\,\mathrm{min\ hom}}$, is given by the equation:

$$b_{f\,\mathrm{min\ hom}} = 2\left[\left(\frac{\hat{v}_{\mathrm{max}}}{\lambda}\right) + f\right]$$

and that for heterodyne interferometers, $b_{f\,\mathrm{min\ het}}$, by

$$b_{f\,\mathrm{min\ het}} = 4\left[\left(\frac{\hat{v}_{\mathrm{max}}}{\lambda}\right) + f\right]$$

where

$\hat{v}_{\mathrm{max}}$ is the maximum velocity amplitude;

λ is the wavelength of the laser;

f is the frequency of the vibration exciter.

Critical parameters of the detector-amplifier combination are flatness of the group time delay and the noise floor. Precautions have to be taken to fulfil the uncertainty requirements.

5.5.4 Laser light reflector and adjustment facilities

The measuring reflector shall be a plane surface located concentrically to the axis of the moving element (a retro-reflector shall not be used). The light-reflecting element shall have a reflectivity of 5 % or greater. This can be attained by a surface roughness $Rm \leq 0{,}2$ µm.

The adjustment of the laser optics of the laser vibrometer to be calibrated shall be possible in five degrees of freedom:

- translation in the x-, y- and z-direction (z-direction is axial to the vibrating element, i.e. direction of measuring laser beam);
- inclination of the reflector about the x- and y-axis (three-point support).

It is recommended that an optical arrangement consisting of a beamsplitter and an adjustable mirror according to Figures 1 and 6 in combination with an x-, y-, z-positioning stage supporting the laser optical transducer under calibration be used. Adjustment should be performed in such a way that both laser beams hit the vibrating surface at the same position and in orthogonal directions. For x- and y-positioning, a resolution of 0,1 mm is recommended, while the z-direction only requires a coarse adjustment in the millimetre scale.

The motion shall be sensed at a defined measurement position on the moving element (normally, at or near the centre of the reflecting surface of the measuring reflector specified in the first paragraph) of the vibration exciter.

The laser light spot at the reflecting moving element shall have an intensity distribution that is approximately Gaussian and an effective spot diameter that is of the order of 0,1 mm to 0,5 mm.

The optics of the LVS shall be adaptable to different working distances over a minimum range of 0,2 m to 1 m.

An arrangement for laser vibrometer calibrations using an adapter for reflection and vibration isolation is shown in Figure 6 as an example.

5.6 Instrumentation for interferometer signal processing

5.6.1 General

Either the phase-modulated or frequency-modulated electric current or voltage at the output(s) of the photodetector(s) is demodulated to extract the vibration parameter(s) of interest (e.g. displacement amplitude or velocity amplitude). Different instrumentation is used for method 1, method 2, and method 3 (homodyne version and heterodyne version).

5.6.2 Instrumentation for fringe counting (method 1)

The counting instrumentation shall have the following characteristics.

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

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

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

5.6.3 Instrumentation for zero-point detection (method 2)

A tunable bandpass filter or spectrum analyser with the following characteristics shall be used.

a) Frequency range: ≤800 Hz to ≥50 kHz.

b) Bandwidth: <12 % of centre frequency.

c) Filter slopes: ≥24 dB per octave.

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

e) Dynamic range: >60 dB.

NOTE If calibrations are limited to a maximum frequency that is lower than 50 kHz, the maximum frequency used in calibration is sufficient.

Instrumentation for zero detection with a frequency range from 800 Hz to 50 kHz shall be used (not needed with a spectrum analyser). The dynamic range shall be sufficient for the detection of output noise from the bandpass filter.

5.6.4 Instrumentation for sine approximation (method 3)

Decoding of the Doppler signal according to method 3 relies on calculation of the interferometric phase angle by means of the inverse tangent function. As a starting point, a quadrature signal pair consisting of the components $u_1(t) = U_1 \cos \varphi_{\text{Mod}}(t)$ and $u_2(t) = U_2 \sin \varphi_{\text{Mod}}(t)$ is needed. Synchronized sampling of $u_1(t)$ and $u_2(t)$ generates the data streams for numerical decoding of the motion quantities $s(t)$, $v(t)$ and $a(t)$. An example for a signal processing chain with analogue quadrature signals as an input is given in Figure 8.

In the case of a homodyne interferometer, the quadrature signals at its output can basically be fed to the synchronously sampling analogue-to-digital converters (ADCs) directly. In practice, additional means for amplitude stabilization and bandwidth limitation have to be provided because waveform distortions of the quadrature signals directly affect the measurement uncertainty, particularly at vibration amplitudes in the nanometer range. Heterodyne interferometers are often preferred since the high-frequency carrier signal is less sensitive to distortions.

When using a heterodyne interferometer, its original single carrier signal can be converted to quadrature format by means of an analogue down-mixing circuit as shown in Figure 9, and further processed by the same chain as shown in Figure 8. Alternatively, the conversion process can be performed in the digital domain. This is the most advantageous technique to obtain a distortion-free quadrature signal pair as an ideal input for numerical Doppler signal decoding.

A combination of analogue frequency conversion and digital quadrature signal synthesis for processing of a heterodyne interferometer signal is shown in Figure 10. The output signal of the photodetector and the Bragg cell drive signal, representing the heterodyne carrier frequency, are both down-mixed to a lower frequency which is matched to the input bandwidth of the subsequent transient recorder used for analogue-to-digital conversion. This process does not affect the Doppler signal with respect to measurement uncertainty. Multiplication with the sine and cosine of the reference signal and subsequent low-pass filtering yields the data streams $u_1(t_i)$ and $u_2(t_i)$ (the two outputs in quadrature processed according to method 3).

The amplitude resolution, sampling rate and linearity of the analogue-to-digital converters shall be sufficient for calibration over the desired amplitude and frequency ranges. For the quadrature signals, a linear amplitude resolution of 8 bits is sufficient to achieve sub-nanometer displacement resolution. It is necessary for the sampling rate to be at least twice that of the signal that occurs at the instant of the largest velocity. Enough memory shall be available for storing at least one period of the vibration signal at the lowest frequency of calibration.

For a given amplitude of acceleration, larger displacement amplitudes requiring higher sampling rates and larger memories occur as a result of decreasing vibration frequency. To calibrate a laser vibrometer at a vibration frequency of 1 Hz and an acceleration amplitude of 0,1 m/s^2, a memory ≥4 Mbytes should be used for a sampling frequency ≥512 kHz.

A separate signal acquisition channel with higher resolution and lower sampling rate can be used for the analogue output signal of the calibration object. In each case, acquisition of all signals shall begin and end at the same time and provide an accuracy which meets the uncertainty requirements specified in Clause 4. If phase calibration shall be performed, additional means for synchronization of the sample clocks for laser vibrometer standard and calibration object shall be provided.

5.7 Applicability of laser vibrometer standards (LVSs)

5.7.1 General consideration

A commercial LVS may implement all or portions of the data processing chain needed for method 3. So, for example, a conditioned quadrature signal pair can be output either in analogue or digital format for further processing in an external data management system. Alternatively, one or more digital data streams, representing the time histories $s(t)$, $v(t)$ or $a(t)$ or averaged magnitudes of these quantities, may be available at a standard serial interface. In any case, data-processing software in accordance with the procedure for the calculations stated in Clause 10 shall be used.

The LVS shall be applicable as a reference standard for the calibration of rectilinear vibrometers (laser vibrometers included) and vibration transducers under laboratory conditions. An example for a calibration setup with LVS as reference standard is given in Figure 1.

5.7.2 Laser optical transducer

The output signal of the optical receiver may be sampled, either internally in the LVS or by way of an external analogue-to-digital converter connected to the analogue Doppler signal output of the LVS following signal conditioning, if it is necessary. After the sampled waveform is processed according to procedures described in Clause 10, the laser optical transducer operates as a digital transducer transforming sinusoidal displacement $s(t)$ or velocity $v(t)$ into one or more sequences of time-discrete samples of displacement, $\{s(t_i)\}$, and/or velocity, $\{v(t_i)\}$, and optionally acceleration, $\{a(t_i)\}$.

5.7.3 Mode of operation

The mode of operation shall be based on the principle of a homodyne or heterodyne interferometer.

5.7.4 Motion sensing position

The motion of the vibration exciter shall be sensed at a defined measurement position on the moving element (normally in the centre position on the reflecting surface of an adapter attached to the moving element) of the vibration exciter.

5.7.5 Laser

A laser shall be used whose wavelength is known and stable within limits of 10^{-5} over a period of 2 years and a temperature interval of (23 ± 5) °C. Preferably, a laser of the red helium-neon type should be used. The wavelength of a red helium-neon laser is 0,632 81 µm at an atmospheric pressure of 100 kPa, a temperature to 23 °C and a relative humidity of 50 %.

5.7.6 Photodetector

The bandwidth of the photodetector unit(s) shall be sufficient to transfer the phase- and frequency-modulated signal(s) from the interferometer with tolerable distortions. The minimum bandwidth for homodyne interferometers, $b_{f\,\mathrm{min\ hom}}$, is given by the equation:

$$b_{f\,\mathrm{min\ hom}} = 2\left[\left(\frac{\hat{v}_{\mathrm{max}}}{\lambda}\right) + f\right]$$

and that for heterodyne interferometers, $b_{f\,\mathrm{min\ het}}$, by

$$b_{f\,\mathrm{min\ het}} = 4\left[\left(\frac{\hat{v}_{\mathrm{max}}}{\lambda}\right) + f\right]$$

where

$\hat{v}_{\max}$ is the maximum velocity amplitude;

λ is the wavelength of the laser;

f is the frequency of the vibration exciter.

Critical parameters of the detector and amplifier combination are flatness of the group time delay and noise floor. Precautions have to be taken to fulfil the uncertainty requirements.

5.7.7 Adaptability of optics

The optics of the LVS shall be adaptable to different working distances over a minimum range of 0,2 m to 1 m.

5.7.8 Laser light spot

The spot of the laser light at the reflecting surface of the moving element (adapter) shall have an intensity distribution that is approximately Gaussian and an effective diameter that is in the order of 0,1 mm to 0,5 mm.

5.7.9 Doppler signal conditioning

The amplitude and the bandwidth of the Doppler signal from the output of the photodetector shall be within the performance limits of the ADC.

NOTE Amplitude fluctuation can cause errors in signal decoding. For the bandwidth required, see 5.7.6.

5.7.10 Digital signal processing

The decoding of the Doppler signal shall be based on method 3 (sine-approximation method) specified in this part of ISO 16063 (the homodyne or the heterodyne version may be applied). The ADC resolution, linearity and other characteristics shall be adequate to meet the accuracy requirements. The numerical error caused by the algorithms for demodulation and filtering shall be $\leq$0,1 %.

5.7.11 Digital interface

Preferably, the output signal of the LVS should be available at a well-specified digital interface capable of transmitting a synchronous data stream at a sufficient rate. In addition, the measurement result which is typically the amplitude of displacement, velocity or acceleration may be displayed by an indication device.

5.7.12 Optional phase measurement

In the case of an LVS designed to measure phase shift, the specific procedure and instructions for phase calibration are given in Annex D.

5.7.13 Traceability

Traceability to SI units shall be established through calibration of the LVS using appropriate national measurement standards.

5.8 Voltage measuring instrumentation

For methods 1 and 2, an r.m.s. voltmeter shall be used. The r.m.s. value shall be multiplied by a factor of √2 to obtain the amplitude.

For method 3, special voltage measuring instrumentation shall be used in accordance with 5.6.4. In addition to this instrumentation, an optional r.m.s. voltmeter may be applied. To obtain the amplitude, the r.m.s. value shall be multiplied by a factor of √2.

For method 4, two alternative setups are considered.

a) A single voltmeter measuring true r.m.s. at the output of the amplifier of the reference transducer is used. The outputs from the reference transducer and the laser vibrometer to be calibrated are measured consecutively where the output of the reference transducer shall be measured at least twice. This equipment shall fulfil the requirements listed in Table 6.

Table 6 — Requirements on voltage measurement

Characteristic	Unit	Example 1	Example 2
Frequency range	Hz	1 to 50 000	1 to 50 000
Maximum deviation from linearity, for max. difference in output values	% of reading	0,1	0,3
Maximum deviation between two consecutive reference transducer measurements	%	0,1	0,3
NOTE 1 The last row describes the repeatability of the measurement. This includes more than the voltmeter repeatability, but is treated here as a general requirement. NOTE 2 The upper frequency limit may be lower depending on the maximum calibration frequency required.			

b) An instrument measuring voltage ratio between reference transducer amplifier output and laser vibrometer output is used. This equipment shall fulfil the characteristics listed in Table 7.

Table 7 — Requirements on voltage ratio measurement

Characteristic	Unit	Example 1	Example 2
Frequency range	Hz	0,4 to 50 000	0,4 to 50 000
Maximum uncertainty	%	0,2	0,5

5.9 Distortion measuring instrumentation

Distortion measuring instrumentation (limited use, see Note) capable of measuring total harmonic distortion of 1 % to 10 % shall have the characteristics listed in Table 8.

Table 8 — Requirements on distortion measurement

Characteristic	Unit	Example 1	Example 2
Frequency range	Hz	1 to 250 000	1 to 250 000
Maximum uncertainty	% of reading	10	10

NOTE Distortion measurement is not included in the standard procedure. It is used to check the performance of the vibration generating equipment initially and then only with suitable time intervals or in case of doubt.

5.10 Oscilloscope

An oscilloscope or similar display may be used for examining the waveforms of the interferometer signal and in method 4 of the reference transducer signal, with a frequency range from 0,4 Hz to 2 MHz minimum. Its use is strongly recommended, but is not mandatory.

5.11 Reference transducer

Between 0,4 Hz (or lower) and 5 kHz, the reference transducer shall be calibrated by a suitable primary method in accordance with ISO 16063-11 or by comparison to a transducer in accordance with ISO 16063-21. Primary vibration calibration of the reference transducer in accordance with ISO 16063-11 is also applicable at higher frequencies (up to 10 kHz), if it is performed in the same manner as that used for the secondary calibration of the laser vibrometer.

At frequencies higher than 10 kHz, the reference transducer shall be calibrated using primary method 1, method 2 or method 3 specified in this part of ISO 16063. The calibration of the reference transducer shall be performed in the same manner as that used for the secondary calibration of the laser vibrometer. The motion shall be sensed during calibration and application of the reference transducer at the same position on the moving element (normally, in the centre axis of an adapter with reflecting surface) of the vibration exciter.

In the case of a primary calibration of the sensitivity (modulus) of the reference transducer at the selected reference frequency and acceleration, the sensitivity shall be measured with an expanded uncertainty of ≤0,5 % using a coverage factor of 2. In the case of a comparison calibration of the reference transducer, the sensitivity shall be measured with an expanded uncertainty of ≤1 % using a coverage factor of 2. Larger uncertainty values are accepted at high and low frequencies (see ISO 16063-11 and ISO 16063-21).

A reference transducer with normal mounting provisions may be used underneath a fixture in line with the adapter with reflecting surface. The transducer shall not be removed and remounted on the fixture during the time between its calibration and application. The reference transducer may be an integral part of a moving element. In this case, the adapter with reflecting surface shall be mounted in line with the moving part as well.

5.12 Other requirements

All effects that influence the measurement result shall be included in the uncertainty calculation (see Annex A).

6 Preferred amplitudes and frequencies

The accelerations, velocities, displacements (amplitude or r.m.s. value), and frequencies covering the calibrated range should preferably be chosen from the following series.

a) Acceleration, velocity, and displacement (methods 1, 3 and 4):

   Magnitude values should be selected in 1 – 2 – 5 steps, e.g. 0,1; 0,2; 0,5; 1; 2; 5; 10 … .

   NOTE 1 Method 2 requires calibrations at fixed displacement amplitudes (velocity amplitude and acceleration amplitude vary with frequency).

b) Frequency:

   Selected from the standardized one-third-octave frequency series (ISO 266) or the series of angular (radian) frequencies evolving from $\omega = 1\,000$ rad/s.

   NOTE 2 It is possible to accept deviations from these standard frequencies, particularly if resonance effects are used to attain large vibration amplitudes at high frequencies up to 50 kHz (typically with piezo-electric vibration generators).

For method 4, values chosen should preferably be the same as those used in the calibration of the reference transducer. If the transducer is to be calibrated at frequencies and accelerations other than those at which the reference has been calibrated, the characteristics of the reference transducer should be assessed at those frequencies and accelerations. The resulting uncertainty component shall be taken into account in the uncertainty budget (see Annex A).

7 Common procedure for primary calibration (methods 1, 2 and 3)

Methods 1, 2 and 3 have in common that the interferometer senses a displacement at a target point on the moving part of the vibration exciter (preferably in the middle of an adapter mounted on the moving part for reflection).

From the displacement amplitude, $\hat{s}$, sensed by the interferometer, the amplitudes, $\hat{v}$ of the velocity v, and $\hat{a}$ of the acceleration a, are obtained using the equations

$$\hat{v} = 2\pi f \hat{s} \tag{1}$$

$$\hat{a} = (2\pi f)^2 \hat{s} \tag{2}$$

where f is the vibration frequency. In all cases, the measurement of $\hat{s}$ is based on the comparison with an accurately known value of a very small length in the sub-micrometer range. Preferably, this is the wavelength λ of the laser of the red helium-neon type, which is $\lambda = 0{,}632\,81$ µm under laboratory conditions (i.e. at an atmospheric pressure of 100 kPa, a temperature of 23 °C and a relative humidity of 50 %).

The laser interferometer system may be operated as an optical transducer which provides at the output a sequence of velocity values, $v(t_i)$, from which the velocity amplitude $\hat{v}$ is computed by sine approximation (see Clause 10). In this case, the amplitudes $\hat{s}$ of displacement and $\hat{a}$ of acceleration are obtained using the equations

$$\hat{s} = \frac{1}{2\pi f} \hat{v} \tag{3}$$

$$\hat{a} = 2\pi f \hat{v} \tag{4}$$

Using the means specified in Clause 5, the adjustment shall meet the following requirements.

- The measuring beams from the reference standard and the laser vibrometer to be calibrated shall be appropriately focused on the same spot of the light reflecting element.
- The light spot shall be located in the middle of the reflecting element at a distance of ≤1 mm from the centre axis.
- The measuring beams from both laser optic transducers shall travel concentrically or in close distance (1 mm maximum) in parallel, and hit the reflector orthogonally.
- The light travel path shall be as short as possible, taking into account the specified coherence maxima of the laser interferometer (affecting the signal-to-noise ratio).

8 Method using fringe counting (method 1)

8.1 General

This method is applicable to the calibration of the magnitude of sensitivity in the frequency range typically between 1 Hz and 800 Hz.

NOTE Using the fringe-counting method without special means to suppress the quantization error (see References [1] and [11]), displacement amplitudes down to 2 µm can be measured with an uncertainty specified in Clause 4. Method 1 may also be applied at smaller amplitudes if the quantization error is suppressed (see References [1] and [11]). This allows calibration at a specified acceleration amplitude (e.g. 100 m/s^2) or displacement amplitude (e.g. $\lambda/4 = 158{,}2$ nm) to be performed at higher frequencies.

For the interferometer types used in method 1, the number of signal periods (e.g. intensity maxima), N, is given by

$$N = \frac{4\hat{s}}{\Delta s}$$

so that

$$\hat{s} = \frac{N\,\Delta s}{4} = \frac{f_\mathrm{f}}{f} \tag{5}$$

where

$\hat{s}$ is the displacement amplitude sensed by the laser interferometer, needed to apply Equations (1) to (4);

Δs is the quantization interval which is $\Delta s = \lambda/2$ of the preferred interferometer type (see Figure 2);

f is the frequency of the vibration exciter;

f_f is the (mean) fringe frequency.

8.2 Specific procedure for method 1

After optimizing the interferometer (see 5.5), determine the sensitivity of the transducer to be calibrated at the vibration frequencies and amplitudes required (see Clause 6) by measuring either the fringe frequency with the counter (see 5.6.2) (fringe counting in accordance with Figure 2 may be used) or the ratio between the angular vibration frequency and the fringe frequency with a ratio counter (see 5.6.2).

8.3 Expression of results for method 1

Calculate the displacement amplitude from the fringe frequency readings using Equation (5) with

$$\Delta s = \frac{\lambda}{2} \tag{6}$$

for the arrangement shown in Figure 2, where λ is the wavelength $\lambda = 0{,}632\ 81$ µm of the laser of the red helium neon type under laboratory conditions (see 8.1).

Calculate the velocity amplitude and/or the acceleration amplitude using Equation (1) and/or (2).

9 Method using minimum-point detection (method 2)

9.1 General

This method is applicable to laser vibrometer calibration (modulus) at frequencies of 800 Hz and higher.

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. 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 References [2][3]).

9.2 Specific procedure for method 2

Filter the signal from the photodetector through a bandpass filter (5.6.3) 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 9.

Set the calibration frequency and adjust the vibrator amplitude from zero to a value at which the filtered photodetector signal after reaching a maximum value returns to a minimum value. This minimum value is minimum point No. 1, at which the amplitude is 0,193 0 µm. The amplitude for the other minimum points in order can be taken from Table 9. An example of the measuring system for the minimum-point method is shown in Figure 3.

NOTE 1 The sensitivity of an accelerometer can 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 References [2][3]).

NOTE 2 A modulation of the position of the reference mirror can also be used to improve the efficiency of the minimum-point method using the Bessel function of first kind and arbitrary order (see Reference [4]).

Table 9 — Displacement amplitudes for minimum points ($\lambda = 0{,}623\ 81$ 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.

9.3 Expression of results for method 2

If an interferometer with a quantization interval $\Delta s = \lambda/2$ (see example of Figure 3) with a laser of the red helium neon type is used, select the appropriate amplitude value $\hat{s}$ from Table 9 as the displacement amplitude applied to the input of the laser vibrometer under calibration. If the velocity amplitude $\hat{v}$ and/or acceleration amplitude $\hat{a}$ is the significant parameter for the calibration, use Equation (1) and/or (2).

10 Methods using sine approximation: method 3 (homodyne version) and method 3 (heterodyne version)

10.1 General

This method is applicable to laser vibrometer calibration (modulus and phase) in a frequency range from 0,4 Hz to 50 kHz or wider. This part of ISO 16063 specifies the calibration of the modulus (magnitude) in the frequency range from 0,4 Hz to 50 kHz.

10.2 Specific procedure for method 3

Doppler signal processing according to method 3 requires an in-phase and quadrature-phase (I & Q) signal pair, i.e. two signals $u_1(t)$ and u_2(t) in phase quadrature, representing the direction preserving output signal of the interferometer (see 5.6.4). When performing method 3 in the homodyne version in accordance with Figure 4, such a signal pair is generated directly by a quadrature Michelson interferometer. In this case the interferometer shall be adjusted to give output signals $u_1(t)$ and $u_2(t)$ in phase quadrature within tolerances appropriate to meet the uncertainty requirements. In the heterodyne version of method 3, the single output signal of the interferometer is converted to I & Q format by electronic means. In this case, the tolerances of the signals $u_1(t)$ and $u_2(t)$ are not affected by the optical alignment but are given by non-ideal properties of the conversion method used. An example for the heterodyne version utilizing digital signal conversion is shown in Figure 10.

After both reference interferometer and optical transducer of the laser vibrometer under calibration have been aligned and, if need be, their settings have been optimized, proceed with calibration at the specified vibration frequencies and amplitudes (see Clause 6) as described in the following paragraph.

The moving part of the vibration exciter shall be vibrated sinusoidally. In the homodyne version, the displacement amplitude should be large enough to give at least one full bright/dark cycle of the interferometer output. At smaller displacement amplitudes this can be attained by superimposing a low-frequency vibration on to the vibration to be measured.

NOTE 1 If calibrations are required up to high frequencies where only smaller amplitudes are attainable, use method 3 in the heterodyne version.

NOTE 2 In order to enhance the rejection efficiency of sine approximation (i.e. attenuation of the influence of disturbing signals), windowing of the displacement values or of the modulation phase values may be applied (Reference [8]) if the procedure has proved to meet the uncertainty requirements of Clause 4.

The cut-off frequencies of low-pass and, if any, high-pass filters shall be chosen so that disturbing effects of low- and high-pass filtering on the calibration results are tolerable (see Reference [6]). To fulfil Nyquist's theorem, the sampling rate shall be set so that the highest frequency content is smaller than half the sampling rate.

Analogue-to-digital conversion of the output voltage of the laser optical transducer to be calibrated may be performed at the same or at a lower sampling rate than that for the conversion of the interferometer output signals. The three sampling processes shall start and end at the same points of time and at least quantization of the two interferometer signals shall be synchronized by a common sampling clock.

The quadrature signals shall be equidistantly sampled during a measurement time $t_0 < t < t_0 + T_{\mathrm{Meas}}$. 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 $\Delta t = t_i - t_{i-1} = c$, where c is a constant.

The sampled series of output values from the calibration object is $\{u(t_i)\}$.

Transfer the data to the computer memory.

10.3 Data processing

10.3.1 Calibrate the laser vibrometer by the following steps.

10.3.2 Calculate a series of modulation phase values $\{\varphi_{\mathrm{Mod}}(t_i)\}$ from the sampled interferometer output values $\{u_1(t_i)\}$ and $\{u_2(t_i)\}$ using Equation (7):

$$\varphi_{\mathrm{Mod}}\left(t_i\right) = \arctan\frac{u_2\left(t_i\right)}{u_1\left(t_i\right)} + n\pi \tag{7}$$

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

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

A procedure for calculating the number n is described in Reference [9].

Calculate a series of displacement values $\{s(t_i)\}$ using Equation (8):

$$s(t_i) = \frac{\lambda}{4\pi}\varphi_{\mathrm{Mod}}(t_i) \tag{8}$$

10.3.3 Approximate the obtained series of displacement values by solving the following system of equations for the three unknown parameters A, B and C using the least-squares method:

$$s\left(t_i\right) = A\cos\omega\, t_i - B\sin\omega\, t_i + C \tag{9}$$

where

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

$A = \hat{s}\cos\varphi_s$;

$B = \hat{s}\sin\varphi_s$;

C is a constant;

ω is the vibration angular (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 10.2.

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

10.3.4 Calculate the displacement amplitude $\hat{s}$ from the parameter values A and B obtained through sine approximation using Equation (10):

$$\hat{s} = \sqrt{A^2 + B^2} \tag{10}$$

NOTE If phase calibration is demanded in addition, Annex D applies.

10.3.5 Approximate the series of sampled laser vibrometer output values, $\{u_1(t_i)\}$, by the sine-approximation method. Rewritten for the output of the calibration object denoted u, the following system of equations is to be solved:

$$\left\{u\left(t_i\right)\right\} = A_u \cos\omega t_i - B_u \sin\omega t_i + C_u \tag{11}$$

where

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

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

C_u is a constant;

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

φ_u is the output initial phase angle.

Calculate the laser vibrometer output amplitude $\hat{u}$ from the parameter values A_u and B_u obtained by sine approximation using Equation (12):

$$\hat{u} = \sqrt{A_u^2 + B_u^2} \tag{12}$$

NOTE 1 If phase calibration is demanded in addition, Annex D applies.

NOTE 2 The sine-approximation method can alternatively be applied in the version with time interval measurement, see B.2 and Figure B.1.

11 Method using comparison to a reference transducer (method 4)

11.1 Specific procedure for method 4

The interferometer senses a displacement at a specified target point on the moving part of the vibration exciter with integral reference transducer or at the top surface of a back-to-back accelerometer standard (preferably in the middle of an adapter for improved reflection), see Figure 11 as an example.

Back-to-back accelerometer standards used for comparison calibration of laser optical transducers shall have been calibrated primarily by laser interferometry. The exact laser spot position shall be specified in order to ensure reproducible results.

Using the means specified in Clause 5, the adjustment shall meet the following requirements.

- Mount the reference transducer on a fixture on the exciter using the recommended torque or use the exciter with integral working reference transducer.
- In the case of stud-mounted transducers, a thin film of light oil, wax or grease should be used between the mounting surfaces of the transducer(s) and exciter, particularly in the case of calibrations performed at high frequencies (see ISO 5348 for details).
- The measuring beam from the laser vibrometer to be calibrated shall be appropriately focused on a spot located in the middle of the reflecting element in a distance ≤1 mm from the axis.
- The measuring beam from the laser optic transducer shall hit the reflector orthogonally.
- The light travelling path shall be as short as possible, taking into account the specified coherence maxima of the laser vibrometer (affecting the signal-to-noise ratio).

11.2 Expression of results for method 4

From the acceleration amplitude $\hat{a}$ measured by the reference accelerometer as input of the laser vibrometer to be calibrated, the amplitudes $\hat{v}$ of the velocity v and $\hat{s}$ of the displacement s are obtained using Equations (13) and (14):

$$\hat{v} = \frac{1}{2\pi f}\hat{a} \tag{13}$$

$$\hat{s} = \frac{1}{(2\pi f)^2}\hat{a} \tag{14}$$

where f is the vibration frequency. Determine the indication (output) of the laser vibrometer at a reference frequency, preferably at 160 Hz, and at the reference amplitude, e.g. an acceleration amplitude of 100 m/s^2 (other choices: 10 m/s^2, 20 m/s^2 or 50 m/s^2), then determine the indication (output) at other calibration frequencies and accelerations. The results shall be given in absolute terms and/or as a relative deviation from the sensitivity at the reference point.

12 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:

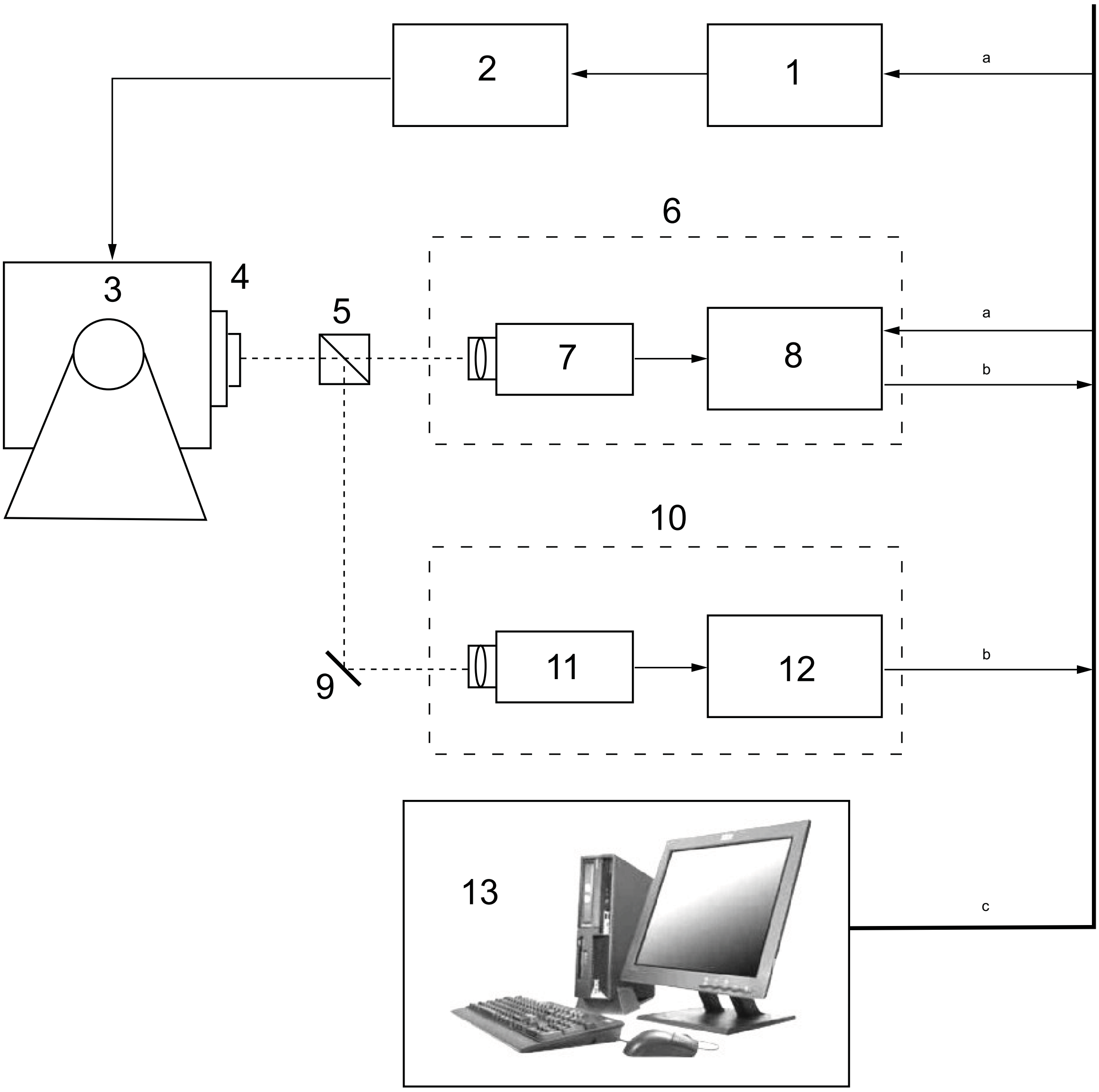
a) ambient conditions:
   - ambient air temperature,
   - relative humidity;

b) if method 1, 2 or 3 has been used — laser light reflection:
   - design of reflecting element,
   - position of laser light spots on reflecting surface,
   - effective distance between laser light spots (if applicable),
   - reflectivity of reflecting surface;

c) If method 4 has been used:
   - arrangement of reference transducer relative to the reflecting surface for laser light reflection (adapter),
   - arrangement and procedure chosen for calibration of the reference transducer,
   - mounting torque of reference transducer (if not built-in as an integral part of the moving element),
   - oil and grease if used;

d) all settings (if adjustable) of the laser vibrometer calibrated, for example:
   - measurement range,
   - cut-off frequencies of filters,
   - other special functions, if any;

e) calibration results:
   - values of calibration frequencies and amplitudes of the vibration quantity measured,
   - values of indication or output signal,
   - expanded uncertainty of measurement, coverage factor k (usually $k = 2$).



Key

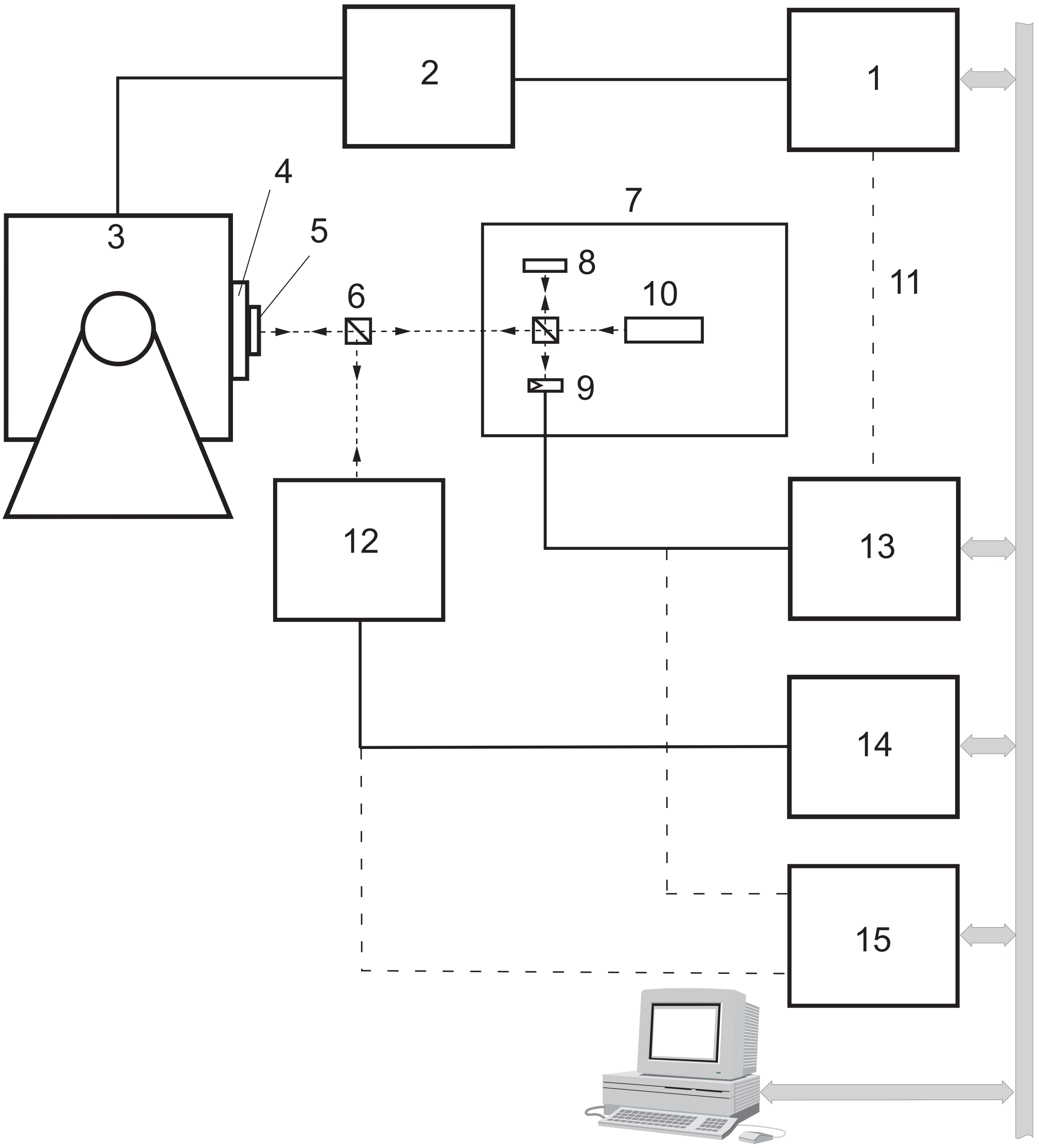
1 signal generator
2 power amplifier
3 vibration exciter
4 moving part with adapter for reflection
5 beamsplitter
6 laser vibrometer standard (LVS)
7 optical transducer
8 signal processor
9 adjustable mirror
10 laser vibrometer (LV) under calibration
11 optical transducer
12 signal processor
13 data acquisition and control system

[a] Control data.

[b] Signal data.

[c] Digital interface.

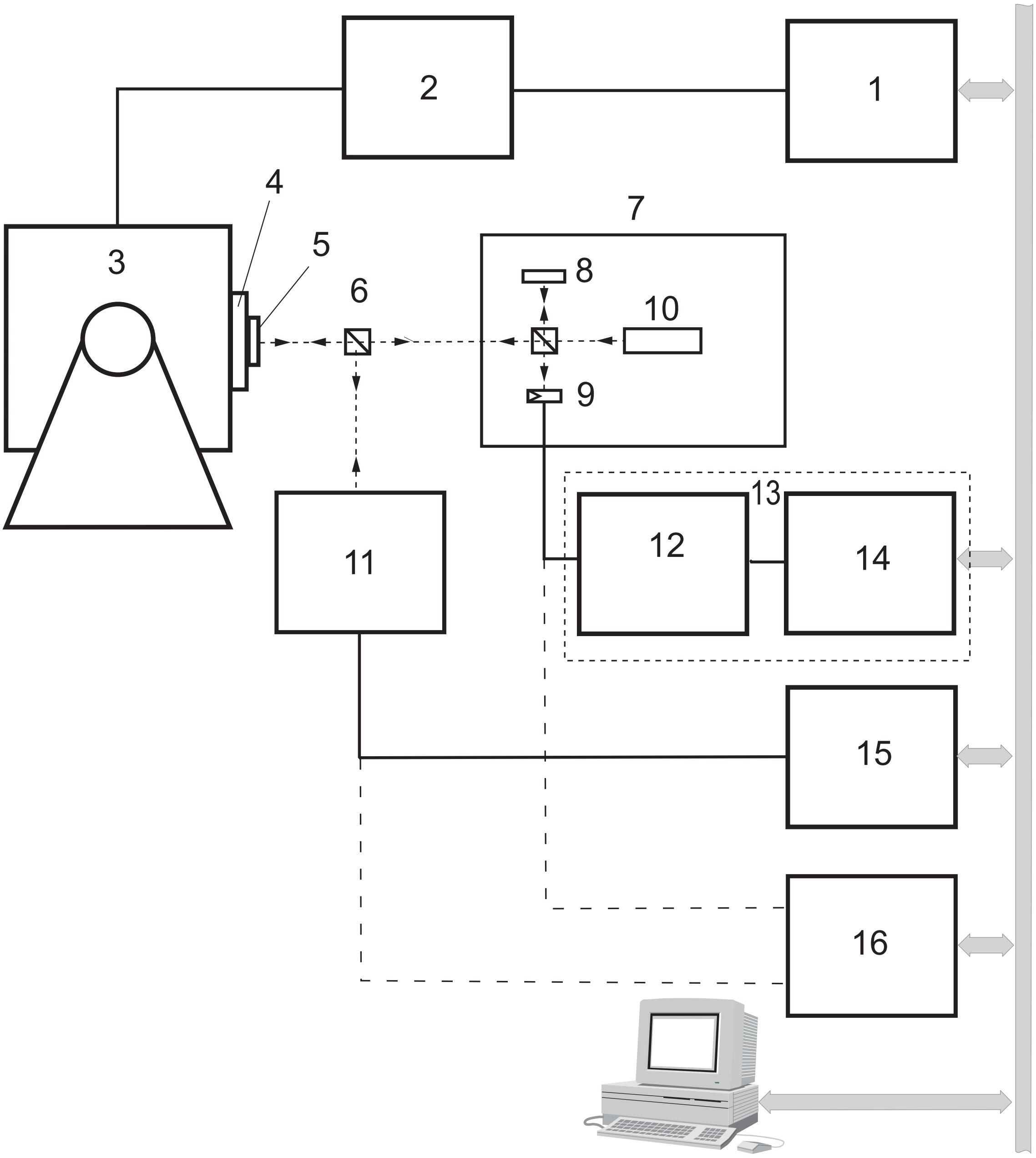
Figure 1 — Example of a calibration setup for laser vibrometers with digital output



Key

1 signal generator
2 power amplifier
3 vibration exciter
4 moving part of vibration exciter
5 adapter for reflection
6 beamsplitter
7 interferometer
8 reference mirror
9 photodetector
10 laser
11 with ratio counter
12 laser vibrometer under calibration
13 counter (or ratio counter)
14 voltmeter
15 oscilloscope

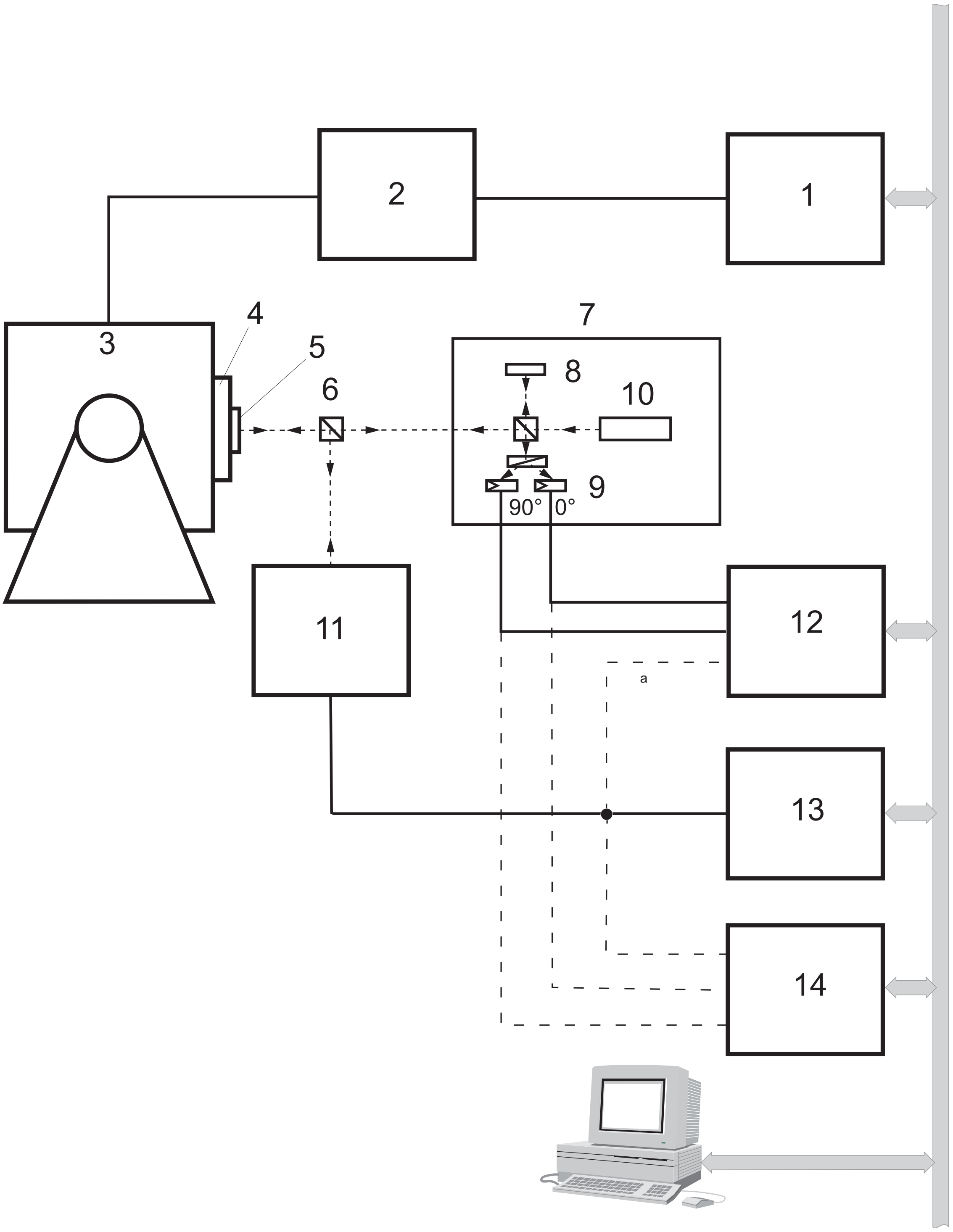
Figure 2 — Example of the measuring system for the fringe-counting method (method 1)



Key

1	signal generator
2	power amplifier
3	vibration exciter
4	moving part of vibration exciter
5	adapter for reflection
6	beamsplitter
7	interferometer
8	reference mirror
9	photodetector
10	laser
11	laser vibrometer under calibration
12	bandpass filter tuned to vibration frequency
13	frequency analyser
14	voltmeter
15	voltmeter
16	oscilloscope

Figure 3 — Example of the measuring system for the minimum-point method (method 2)

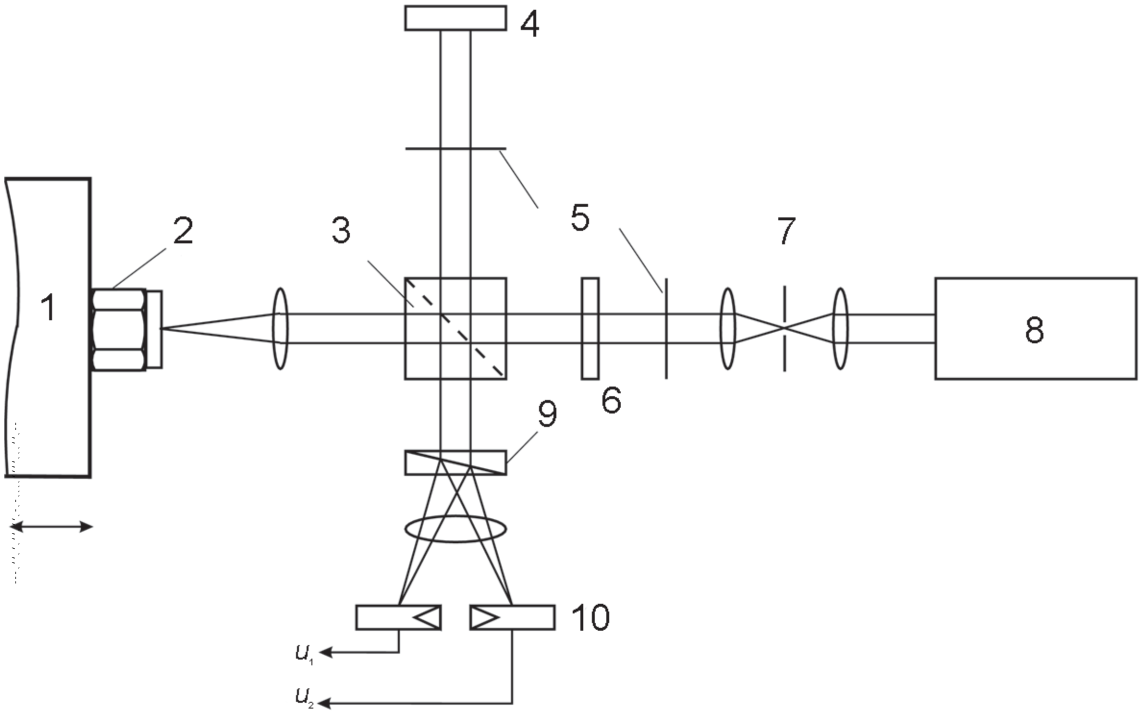


Key

1 signal generator
2 power amplifier
3 vibration exciter
4 moving part of vibration exciter
5 adapter for reflection
6 beamsplitter
7 interferometer
8 reference mirror
9 photodetectors
10 laser
11 laser vibrometer under calibration
12 digital waveform recorder
13 voltmeter
14 oscilloscope

[a] If sampled.

Figure 4 — Example of the measuring system for the sine-approximation method (method 3, homodyne version)

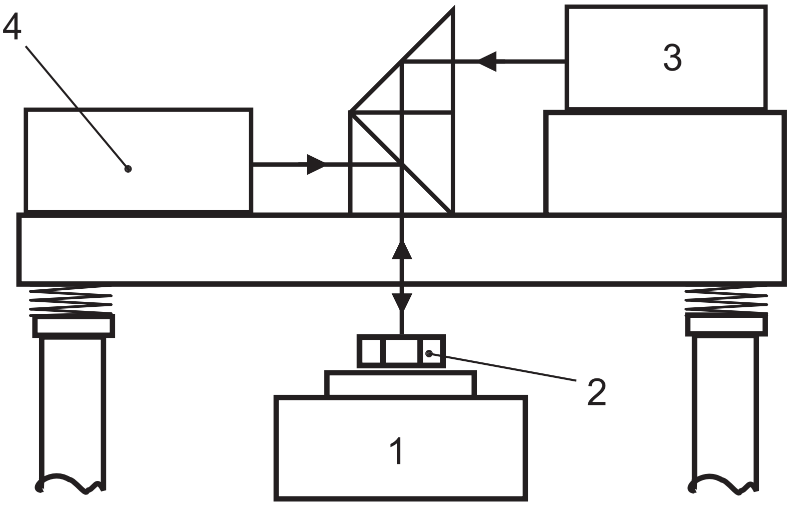


Key

1 moving part of vibration exciter
2 adapter for reflection
3 beamsplitter
4 reference mirror
5 polarizer
6 quarter wavelength (λ/4) plate
7 telescope
8 laser
9 Wolleston prism
10 photodetectors

$\left.\begin{matrix} u_1 \\ u_2 \end{matrix}\right\}$ quadrature signal pair

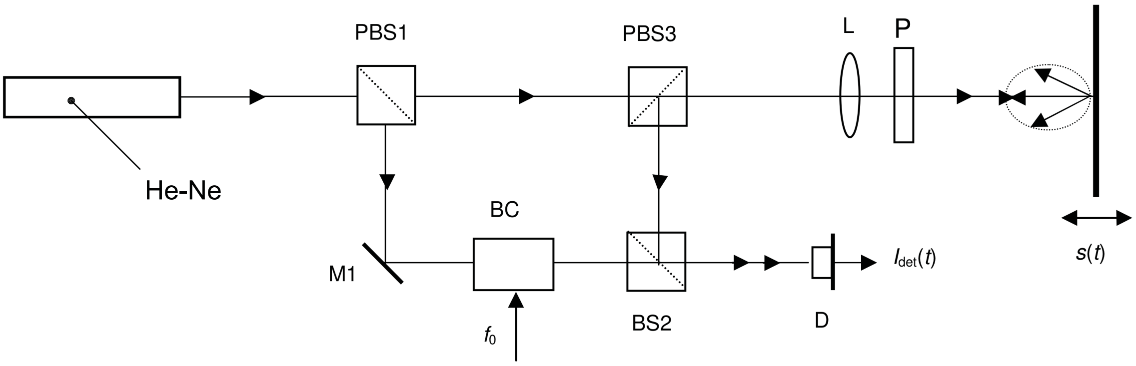
Figure 5 — Modified Michelson interferometer with retroreflector(s) and quadrature output



Key

1	high-frequency vibration exciter
2	adapter for reflection
3	optical transducer of reference standard
4	optical transducer of laser vibrometer under calibration

Figure 6 — Arrangement for laser vibrometer calibrations using an adapter for reflection and vibration isolation

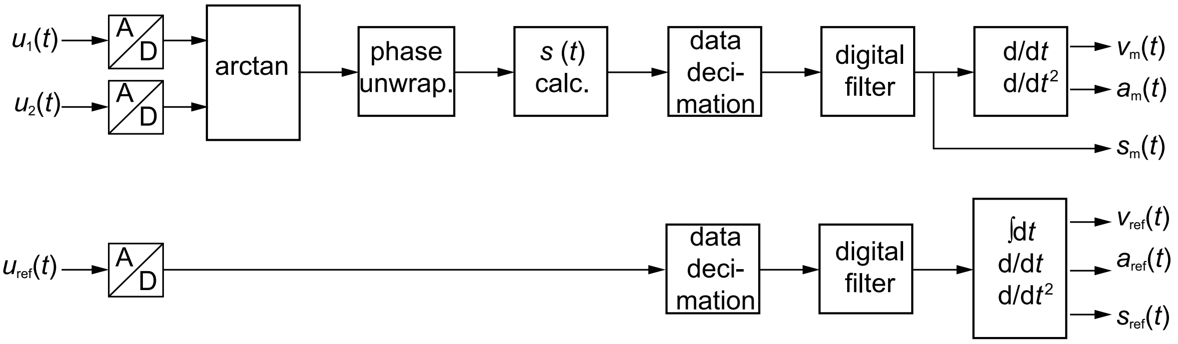


Key

BC	Bragg cell
BS	beamsplitter
D	detector
He-Ne	laser
L	lens
M	mirror
P	quarter-wave plate
PBS	polarizing beamsplitter

NOTE The variables are explained in B.1.

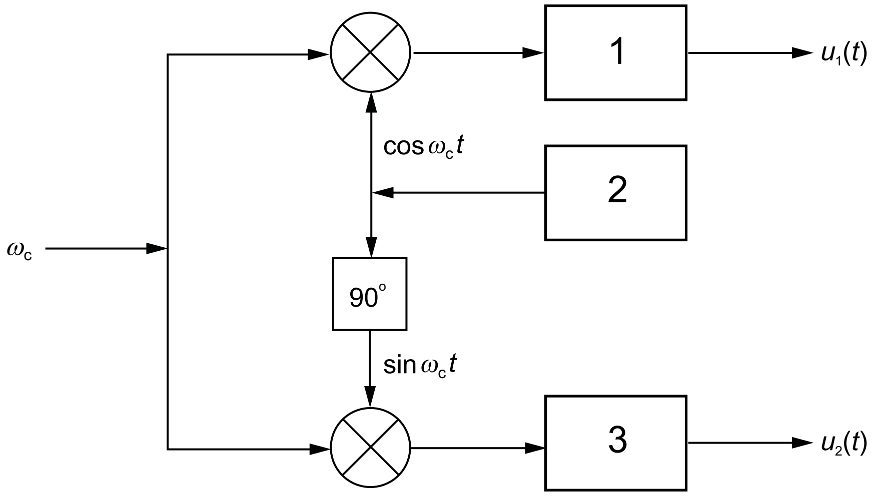
Figure 7 — Schematic of a modified Mach-Zehnder interferometer



Key

$a_m(t)$	measured acceleration as a function of time
$a_{ref}(t)$	reference acceleration as a function of time
$s_m(t)$	measured displacement as a function of time
$s_{ref}(t)$	reference displacement as a function of time
t	time
$u_1(t)$ $u_2(t)$	quadrature signal pair
$u_{ref}(t)$	reference voltage signal as a function of time
$v_m(t)$	measured velocity as a function of time
$v_{ref}(t)$	reference velocity as a function of time

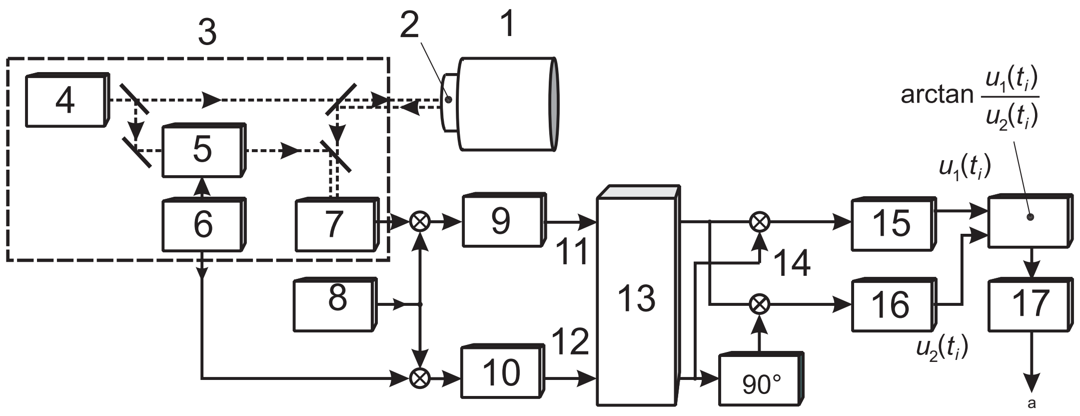
Figure 8 — Example of a numerical signal processing chain of a laser vibrometer standard



Key

1	low-pass filter
2	oscillator
3	low-pass filter
t	time
$u_1(t)$ $u_2(t)$	quadrature signal pair
ω_c	angular (radian) frequency of carrier

Figure 9 — Conversion of a heterodyne carrier to quadrature format

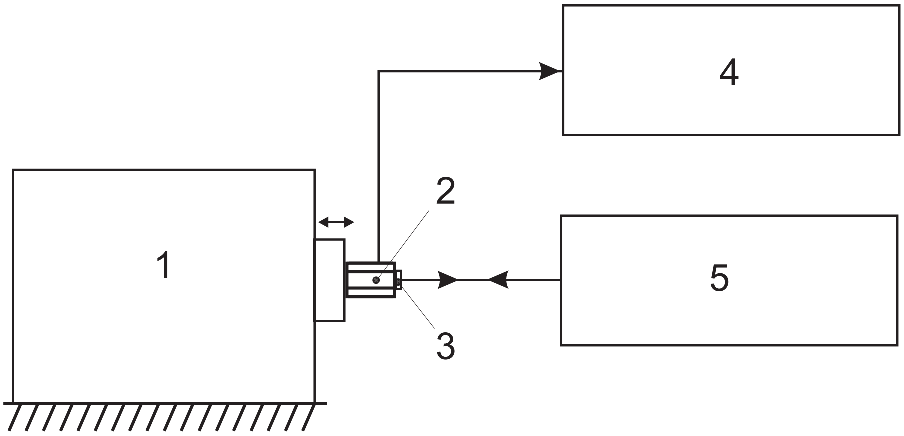


Key

1	vibration exciter
2	adapter for reflection
3	interferometer
4	laser
5	Bragg cell
6	quartz generator
7	photodetector
8	synthesis generator
9	low-pass filter
10	low-pass filter
11	measurement signal
12	reference signal
13	transient recorder
14	quadrature signal synthesis
15	low-pass filter
16	low-pass filter
17	algorithms
$u_1(t_i)$ $u_2(t_i)$	data streams of the quadrature signal pair

[a] Measured results (vibration and shock parameters).

Figure 10 — Example of a heterodyne interferometer calibration system (method 3) generating quadrature signals by digital signal processing



Key

1 vibration exciter
2 accelerometer standard
3 adapter for reflection
4 indicating instrument (reference)
5 laser vibrometer under calibration

Figure 11 — Arrangement for vibration calibration of a laser vibrometer by comparison to a reference transducer (example of method 4)

Annex A
(normative)

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

A.1 Calculation of $U_\mathrm{rel}(y)$ for method 1

The relative expanded uncertainty of measurement of the indication (output; magnitude), $U_\mathrm{rel}(y)$, for the calibration frequencies, amplitudes, and settings of laser vibrometer ranges shall be calculated in accordance with ISO 16063-1 from the following equations:

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

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

with the coverage factor $k = 2$. Table A.1 lists uncertainty components.

Table A.1 — Uncertainty components (method 1)

i	Standard uncertainty component $u(x_i)$	Source of uncertainty	Uncertainty contribution $u_i(y)$
1	$u(\hat{s}_\mathrm{Q})$	Effect of displacement quantization on displacement measurement	$u_1(y)$
2	$u(\hat{s}_\mathrm{H})$	Effect of trigger hysteresis on displacement measurement	$u_2(y)$
3	$u(\hat{s}_\mathrm{F})$	Filtering effect on displacement measurement (frequency band limitation)	$u_3(y)$
4	$u(\hat{s}_{u_\mathrm{s}})$	Effect of voltage disturbance by sinusoids on displacement measurement	$u_4(y)$
5	$u(\hat{s}_{u_\mathrm{N}})$	Effect of voltage disturbance by random noise in the photoelectric measuring chain on displacement measurement	$u_5(y)$
6	$u[\hat{s}_{a(f_\mathrm{n})}]$	Effect of motion disturbance by harmonics on displacement measurement (e.g. total distortion)	$u_6(y)$
7	$u[\hat{s}_{a(f_\mathrm{s})}]$	Effect of motion disturbance by parasitic sinusoids on displacement measurement	$u_7(y)$
8	$u(\hat{s}_{v_\mathrm{D}})$	Effect of motion disturbance by drift on displacement measurement	$u_8(y)$
9	$u(\hat{s}_\mathrm{PD})$	Effect of phase disturbance on displacement measurement (e.g. phase noise of the interferometer signal)	$u_9(y)$
10	$u(\hat{s}_\mathrm{RE})$	Residual interferometric effects on displacement measurement (interferometer function)	$u_{10}(y)$
11	$u(\hat{s}_\mathrm{E})$	Environmental effects on measurement (e.g. temperature)	$u_{11}(y)$
12	$u(f_\mathrm{FG})$	Vibration frequency measurement (signal generator and indicator)	$u_{12}(y)$
13	$u(x_\mathrm{RE})$	Residual effects on calibration result (e.g. random effect in repeat measurements; experimental standard deviation of arithmetic mean)	$u_{13}(y)$

NOTE The sources of uncertainties can be subdivided and numbered in a way differing from that listed here, provided that each effect significantly influencing the measurement result has been taken into account.

A.2 Calculation of $U_{\mathrm{rel}}(y)$ for method 2

This shall be calculated as specified in A.1, but using the uncertainty components listed in Table A.2.

Table A.2 — Uncertainty components (method 2)

i	**Standard uncertainty component** $u(x_i)$	**Source of uncertainty**	**Uncertainty contribution** $u_i(y)$
1	$u(\hat{s}_{\mathrm{Z}})$	Effect of minimum-point resolution on displacement measurement	$u_1(y)$
2	$u(\hat{s}_{\mathrm{VD}})$	Effect of voltage disturbance on displacement measurement (e.g. hum and noise)	$u_2(y)$
3	$u(\hat{s}_{\mathrm{MD}})$	Effect of motion disturbance on displacement measurement (e.g. relative motion between the accelerometer reference surface and the spot sensed by the interferometer)	$u_3(y)$
4	$u(\hat{s}_{\mathrm{RE}})$	Residual interferometric effects on displacement measurement (interferometer function)	$u_4(y)$
5	$u(\hat{s}_{\mathrm{E}})$	Environmental effects on measurement (e.g. temperature)	$u_5(y)$
6	$u(f_{\mathrm{FG}})$	Vibration frequency measurement (signal generator and indicator)	$u_6(y)$
7	$u(x_{\mathrm{RE}})$	Residual effects on calibration result (e.g. random effect in repeat measurements; experimental standard deviation of arithmetic mean)	$u_7(y)$

NOTE The sources of uncertainties can be subdivided and numbered in a way differing from that listed here, provided that each effect significantly influencing the measurement result has been taken into account.

A.3 Calculation of $U_{\mathrm{rel}}(y)$ for method 3

A.3.1 Calculation of $U_{\mathrm{rel}}(y)$ for method 3 with evaluation of uncertainty sources of interferometer

This shall be calculated as specified in A.1, but using the uncertainty components listed in Table A.3.

Table A.3 — Uncertainty components
(method 3 with evaluation of uncertainty sources of interferometer)

i	Standard uncertainty component $u(x_i)$	Source of uncertainty	Uncertainty contribution $u_i(y)$
1	$u(\hat{s}_{\mathrm{Q}})$	Effect of interferometer quadrature output signal disturbance on displacement amplitude measurement (e.g. offsets, voltage amplitude deviation, deviation from 90° nominal angle difference)	$u_1(y)$
2	$u(\hat{s}_{\mathrm{F}})$	Interferometer signal filtering effect on displacement amplitude measurement (frequency band limitation)	$u_2(y)$
3	$u(\hat{s}_{\mathrm{VD}})$	Effect of voltage disturbance (e.g. random noise in the photoelectric measuring chain)	$u_3(y)$
4	$u(\hat{s}_{\mathrm{MD}})$	Effect of motion disturbance on displacement amplitude measurement (e.g. drift; relative motion between the spot sensed by the interferometer and sensitive parts of the interferometer, due to reaction forces from the vibration exciter)	$u_4(y)$
5	$u(\hat{s}_{\mathrm{PD}})$	Effect of phase disturbance on displacement amplitude measurement (e.g. phase noise of the interferometer signals)	$u_5(y)$
6	$u(\hat{s}_{\mathrm{I}})$	Residual interferometric effects on measurement (interferometer function)	$u_6(y)$
7	$u(\hat{s}_{\mathrm{E}})$	Environmental effects on measurement (e.g. temperature)	$u_7(y)$
8	$u(f_{\mathrm{FG}})$	Vibration frequency measurement if measurand (e.g. acceleration) is different from vibration quantity sensed (e.g. displacement)	$u_8(y)$
9	$u(\hat{s}_{\mathrm{F}})$	Residual effects on calibration result (e.g. random effect in repeat measurements; experimental standard deviation of arithmetic mean)	$u_9(y)$

NOTE The sources of uncertainties may be subdivided and numbered in a way differing from that listed here, provided that each effect significantly influencing the measurement result has been taken into account.

A.3.2 Calculation of $U_{\text{rel}}(y)$ for method 3 with known uncertainty of velocity signal from interferometer (uncertainty of traceability)

This shall be calculated as specified in A.1, but using the uncertainty components listed in Table A.4.

Table A.4 — Uncertainty components (method 3 with known uncertainty of velocity signal from interferometer)

i	**Standard uncertainty component** $u(x_i)$	**Source of uncertainty**	**Uncertainty contribution** $u_i(y)$
1	$u(v_{\text{S}})$	Vibration velocity (including the uncertainty of traceability)	$u_1(y)$
2	$u(f_v)$	Frequency of vibration signal (v signal)	$u_2(y)$
3	$u(K_{\text{D}})$	Harmonic distortions	$u_3(y)$
4	$u(K_{\text{N}})$	Noise	$u_4(y)$
5	$u(K_{\text{MI}})$	Motion inhomogeneity over vibrating element	$u_5(y)$
6	$u(K_{\text{IM}})$	Interferometer motion	$u_6(y)$
7	$u(K_{\text{TK}})$	Temperature change	$u_7(y)$
8	$u(K_{\text{L}})$	Linearity	$u_8(y)$
9	$u(K_{\text{I}})$	Temporal instability of vibration signal (v signal)	$u_9(y)$
10	$u(K_{\text{RE}})$	Residual effects	$u_{10}(y)$

NOTE The sources of uncertainties can be subdivided and numbered in a way differing from that listed here, provided that each effect significantly influencing the measurement result has been taken into account.

A.4 Calculation of $U_{\mathrm{rel}}(y)$ for method 4

This shall be calculated as specified in A.1, but using the uncertainty components listed in Table A.5.

Table A.5 — Uncertainty components (method 4)

i	**Standard uncertainty component** $u(x_i)$	**Source of uncertainty**	**Relative uncertainty contribution** $u_i(y)$
1	$u(S)$	The combined standard uncertainty for the reference transducer	$u_1(y)$
2	$u(\hat{u}_\mathrm{A})$	Conditioning amplifier gain	$u_2(y)$
3	$u(\hat{u}_\mathrm{V})$	Voltage measurement	$u_3(y)$
4	$u(\hat{u}_\mathrm{D})$	Effect of total harmonic distortion	$u_4(y)$
5	$u(\hat{u}_\mathrm{H})$	Effect of hum and noise	$u_5(y)$
6	$u(\hat{u}_\mathrm{T})$	Effect of transverse, rocking and bending vibration	$u_6(y)$
7	$u(\hat{u}_\varepsilon)$	Effect of base strain	$u_7(y)$
8	$u(\hat{u}_\mathrm{M})$	Effect of mounting parameters (torque, cable fixing, etc.)	$u_8(y)$
9	$u(\hat{u}_\mathrm{MD})$	Effect of relative motion	$u_9(y)$
10	$u(\hat{u}_{\Delta t})$	Reference instability over time	$u_{10}(y)$
11	$u(\hat{u}_\vartheta)$	Effect of temperature	$u_{11}(y)$
12	$u(f)$	Vibration frequency measurement	$u_{12}(y)$
13	$u(\hat{u}_\mathrm{L,T})$	Effect of non-linearity of transducer	$u_{13}(y)$
14	$u(\hat{u}_\mathrm{L,A})$	Effect of non-linearity of amplifier	$u_{14}(y)$
15	$u(\hat{u}_\mathrm{G})$	Effect of gravitation	$u_{15}(y)$
16	$u(\hat{u}_\mathrm{B})$	Effect of magnetic field from exciter	$u_{16}(y)$
17	$u(\hat{u}_\mathrm{E})$	Effect of other environmental parameters	$u_{17}(y)$
18	$u(x_\mathrm{RE})$	Residual effects on calibration of the laser vibrometer (e.g. random effect in repeated measurements; experimental standard deviation of arithmetic mean)	$u_{18}(y)$

NOTE The sources of uncertainties may be subdivided and numbered in a way differing from that listed here, provided that each effect significantly influencing the measurement result has been taken into account.

Annex B
(informative)

Three versions of method 3 based on laser Doppler velocimetry

B.1 Sine-approximation method using quadrature signals

As described in detail in Reference [13], laser Doppler vibrometry relies on the fact that light back-scattered from a moving target contains information about its velocity and displacement. Displacement of the surface modulates the phase of the light wave while instantaneous velocity shifts the optical frequency. As the optical frequency of the laser is far too high to demodulate directly (about 5×10^{14} Hz), interferometric techniques are employed to reveal the measurement quantities. In an interferometer, the received light wave is mixed with a reference beam so that the two signals heterodyne on the surface of a photodetector.

The basic arrangement of a modified Mach-Zehnder interferometer, which is used as optical sensor in the majority of all laser Doppler vibrometers, is depicted in Figure 7. In the interferometer, coherent light emitted from the He-Ne laser is split into measurement and reference beams by polarizing beamsplitter PBS1. While the reference beam is directed via mirror M1, Bragg cell BC and BS2 directly to the photodetector D, the measurement beam is directed to the vibrating target via PBS3, focusing lens L and quarter-wave plate P. The polarized back-scattered portion (collected by lens L) is directed to the detector via PBS3 and BS2. The Bragg cell BC is an acousto-optical component, which pre-shifts the optical frequency of the reference beam by the frequency f_0 of an electric control signal.

The resulting intensity on the surface of the photodetector is determined by relative phase and frequency of the heterodyning light waves (see Reference [14]). Obviously, the phase difference between the reference and measurement beams depends on the optical length difference between the reference and measurement paths, which changes with the target displacement $s(t)$. In the case of a stationary target, the output current of the detector $I_{\text{det}}(t)$ is given by Equation (B.1):

$$I_{\text{det}}(t) = I_{\text{DC}} + \hat{I}\cos(2\pi f_0 t + \varphi_0) \quad \text{(B.1)}$$

where

I_{DC} is the DC component;

$\hat{I}$ is the AC amplitude;

f_0 is the Bragg cell drive frequency;

φ_0 is the offset phase angle, defined by the initial object position.

The second term of Equation (B.1) represents a high-frequency signal at frequency f_0 which is a characteristic of the so-called heterodyne interferometer. This signal can carry both direction-sensitive frequency and phase modulation information resulting from target motion. In case of a moving target, displacement $s(t)$ results in a phase modulation, i.e. φ_0 becomes superimposed by a time-dependent portion $\varphi_{\text{Mod}}(t)$:

$$\varphi_{\text{Mod}}(t) = \frac{4\pi s(t)}{\lambda} \quad \text{(B.2)}$$

where λ is the laser wavelength.

A phase modulation can also be expressed as frequency modulation. The corresponding frequency deviation is the time-derivative of the modulated phase angle $\varphi_{\mathrm{Mod}}(t)$. According to the basic relationships $\mathrm{d}\varphi/\mathrm{d}t = 2\pi f$ and $\mathrm{d}s/\mathrm{d}t = v$, object velocity $v(t)$ results in a frequency deviation $\Delta f(t)$ with respect to the carrier frequency f_0, commonly known as the Doppler frequency shift

$$\Delta f(t) = \frac{2v(t)}{\lambda} \tag{B.3}$$

Figures 8 and 9 depict the signal processing of the Doppler signal used for commercial laser vibrometer standards.

The sine-approximation method specified also in ISO 16063-11 and ISO 16063-15 is well described in the literature (e.g. see References [15] and [16]).

Recent progress has been achieved in implementing the sine-approximation method (SAM) in three versions: SAM1 using homodyne quadrature signals; SAM2 using heterodyne signals; and SAM3 using time-interval measurement. The aim of SAM is to measure the amplitude and initial phase of the six vibration quantities and to calibrate vibration transducers (magnitude and phase shift of sensitivity) and measuring instruments (see References [16] and [17]). Figure 10 shows a variant of the heterodyne signal version SAM2 whereby the quadrature signals are generated by digital data processing, after one frequency-converted measuring signal and the reference have been acquired by a transient recorder.

Figure 1 shows an example of the measuring system for the calibration of a laser vibrometer with digital output (e.g. a laser vibrometer standard) whereby a laser optical transducer is included in the reference standard measuring system and in the laser vibrometer under calibration as well (see Reference [18]). The reference standard is a modified Mach-Zehnder interferometer which supplies at its digital output a velocity signal

$$v_{\mathrm{dig}}(mT_{\mathrm{a}}) = S_{\mathrm{N}} v_{\mathrm{phys}}(mT_{\mathrm{a}} + \Delta T) = \underline{S}_{\mathrm{N}} v_{\mathrm{phys}}(mT_{\mathrm{a}}) \tag{B.4}$$

where

T_{a} is the cycle period time;

ΔT is a constant delay time that is dependent on the measuring range;

$\underline{S}_{\mathrm{N}}$ is the complex transfer coefficient of the vibrometer.

The same clock signal is also used for sampling the analogue signals in the analogue-to-digital converters of the two measuring channels, thus ensuring the fixed time relation that is needed for the measuring phase. The digitized velocity signal is a binary encoded signal. Sine approximation is applied to the output signal (Equation B.4) to determine the modulus and phase of the velocity signal. It is used in the same manner for processing the analogue signal. If the vibration velocity is known, the modulus of vibration acceleration is obtained by multiplying it by angular (radian) frequency ω and the phase angle is obtained by adding 90°. The measurement uncertainty of frequency is taken into consideration by a separate adjustment factor.

EXAMPLE As the cycle period time T_{a} the reciprocal of 96 kHz may be chosen. The digitized velocity signal may be a binary encoded 24 bit signal with full scale values of 20 mm/s, 100 mm/s or 500 mm/s. This is equivalent to a maximum resolution of 2,38 nm s^{-1}/LSB which means that the quantization error caused by sampling can be neglected, provided that care is taken always to select the optimum range of measurement and provide an excitation signal of sufficiently high amplitude.

The reference standard vibrometer is traced back to the national standard by direct comparison with an appropriate national measuring standard device in a national metrology institute, see calibration and measurement capabilities in Reference [28], Appendix C.

B.2 Sine-approximation method using time-interval measurement

SAM3 needs, in contrast to SAM1 and SAM2, only one (heterodyne) interferometer signal (see Reference [7]). This version is based on the transformation of the velocity $v(t)$ into a proportional frequency shift Δf_D (Doppler frequency) of the interferometers' output signal (see Figure B.1). The parameter, t_i, is the time of occurrence of the ith zero crossing of the sequence of zero crossings of the interferometer signal ($i = 1, 2 \ldots n$).

From the series of time intervals $\Delta t_i = t_{i+1} - t_i$, $i = 1, 2 \ldots N$ between successive zero crossings of the interferometer heterodyne signal, a series of instantaneous frequency values is calculated:

$$\Delta f(t_i^*) = \frac{1}{\Delta t(t_i^*)} \quad \text{with} \quad t_i^* = \frac{t_{i+1} - t_i}{2} + t_i, \quad i = 0, 1, 2 \ldots N \tag{B.5}$$

To obtain a series of velocity values from the series of instantaneous frequency values, the relationship

$$v(t_i^*) = \frac{\lambda}{2} \Delta f_i \tag{B.6}$$

can be used. A system of $N + 1$ equations

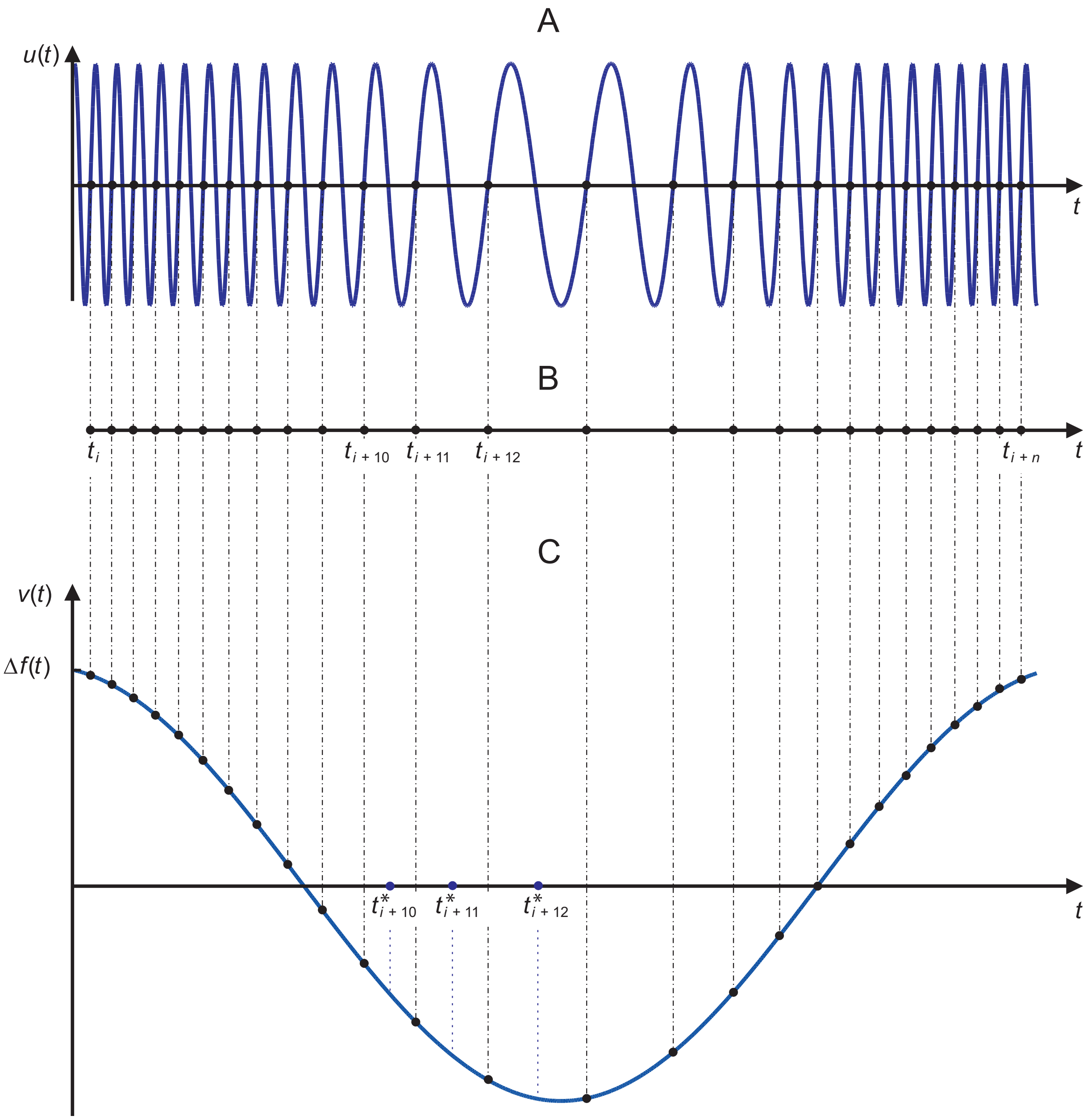
$$v(t_i^*) = A_v \cos \omega t_i^* - B_v \sin \omega t_i^* + C_v \tag{B.7}$$

is solved as is described for a sine-approximation method using homodyne quadrature signals (see Reference [1]). From the values A_v and B_v, the amplitude $\hat{v}$ and the initial phase angle φ_v of the velocity can be obtained by the relationships

$$\hat{v} = \sqrt{A_v^2 + B_v^2} \tag{B.8}$$

$$\varphi_v = \arctan \frac{B_v}{A_v} \tag{B.9}$$

A more detailed description of SAM3 is given in Reference [7].



Key

A output signal of a heterodyne interferometer

B sequence of time stamps measured by time interval analyser

C vibration velocity (demodulated by time interval method)

NOTE The variables are explained in B.2.

Figure B.1 — Option sine-approximation method using time interval analysis of a heterodyne interferometer signal

Annex C
(informative)

Example of calculation of measurement uncertainty in calibration of a laser vibrometer

If using a primary calibration system as shown in Figure 1 where the interferometer yields a digital velocity signal, Equation (C.1) defines the modulus of acceleration (acceleration amplitude):

$$\hat{a} = 2\pi f \hat{v} \tag{C.1}$$

Frequency f is known to the system with the exception of a small measurement uncertainty. In this case the defining equation with *best* estimates is in full detail:

$$Y = \hat{v} * 2\pi f * K_\mathrm{D} * K_\mathrm{N} * K_\mathrm{MI} * K_\mathrm{IM} * K_\mathrm{TK} * K_\mathrm{L} * K_\mathrm{I} * K_\mathrm{RE} \tag{C.2}$$

with the product terms as listed in Table C.1.

NOTE In this annex, the sources of uncertainties are subdivided and numbered in a different way to that used in Tables A.1 to A.5, which were originally developed for primary vibration calibration of rectilinear accelerometers preferably in a national metrology institute (see ISO 16063-11) and were adapted to laser vibrometer calibration for this part of ISO 16063. Tables C.1 and C.2 were originally developed for interferometric calibration of laser vibrometers in accredited calibration laboratories (see Reference [20]). The Notes to Tables A.1 to A.5 (similarly to those in ISO 16063-13 and ISO 16063-15) allow for different subdivision and numbering of the sources of uncertainties provided that each effect significantly influencing the measurement result has been taken into account.

Table C.1 — Denomination of product terms (calibration of vibration meters)

$Y = a_\mathrm{S}$	Result, generated acceleration
$X_1 = \hat{v}$	Amplitude of velocity signal $v(t)$ [a]
$X_2 = 2\pi f$	Angular (radian) frequency $2\pi f$ of the acceleration signal
$X_3 = K_\mathrm{D}$	Correction factor for harmonics
$X_4 = K_\mathrm{N}$	Correction factor for noise
$X_5 = K_\mathrm{MI}$	Correction factor for motion inhomogeneity over vibrating element
$X_6 = K_\mathrm{IM}$	Correction factor for interferometer motion
$X_7 = K_\mathrm{TK}$	Correction factor temperature fluctuation
$X_8 = K_\mathrm{L}$	Correction factor linearity
$X_9 = K_\mathrm{I}$	Correction factor for instability in the reference standard
$X_{10} = K_\mathrm{RE}$	Correction factor residual influence quantities

[a] The uncertainty of traceability is included in X_1.

Table C.2 — Specific uncertainty budget table for a calibration of a laser vibrometer standard using Method 3 (general uncertainty budget, see A.3.2)

Serial No.	Quantity X_i	Estimate x_i	Relative uncertainty $\lvert w(x_i)\rvert$	Probability distribution model	Divisor	Sensitivity coefficient[a] $\lvert c_i^*\rvert$	Relative uncertainty contribution[b] $w_i(y)$
1	$\hat{v}$	9,947 cm/s	$10{,}0 \times 10^{-4}$ [c]	Normal	2	1	$10{,}0 \times 10^{-4}$
2	ω	1 005,31 s^{-1}	$0{,}1 \times 10^{-4}$	Rectangular	√3	1	$0{,}1 \times 10^{-4}$
3	K_D	1	$0{,}1 \times 10^{-4}$	Rectangular	√3	1	$0{,}1 \times 10^{-4}$
4	K_N	1	$0{,}1 \times 10^{-4}$	Normal	2	1	$0{,}1 \times 10^{-4}$
5	K_MI	1	$4{,}0 \times 10^{-4}$	Rectangular	√3	1	$4{,}0 \times 10^{-4}$
6	K_IM	1	$0{,}1 \times 10^{-4}$	Rectangular	√3	1	$0{,}1 \times 10^{-4}$
7	K_TK	1	$0{,}15 \times 10^{-4}$	Rectangular	√3	1	$0{,}15 \times 10^{-4}$
8	K_L	1	$0{,}1 \times 10^{-4}$	Rectangular	√3	1	$0{,}1 \times 10^{-4}$
9	K_I	1	$0{,}1 \times 10^{-4}$	Rectangular	√3	1	$0{,}1 \times 10^{-4}$
10	K_RE	1	$5{,}0 \times 10^{-4}$	Rectangular	√3	1	$5{,}0 \times 10^{-4}$

[a] $c_i^* = (x_i / y)c_i$ where: y is the estimate of the value of the measurand Y; c_i is the partial derivative of the function Equation (2) to the variable X_i evaluated at its expectancy x_i (see Table C.1).

[b] Uncertainty contributions $w_i = u_i/y$ calculated from estimated limits of input quantities X_i with divisor 2 for normal distribution or divisor √3 for rectangular distribution, respectively, applied as distribution model.

[c] Including uncertainty contribution from traceability to national standard device.

Relative combined standard uncertainty

$$w(\hat{a}_\text{S}) = \sqrt{\sum_{i=1}^{N} w_i^2} = 1{,}2 \times 10^{-3}$$

Relative expanded measurement uncertainty for coverage factor $k = 2$:

$$W(\hat{a}_\text{S}) = k\ w(\hat{a}_\text{S}) = 2{,}4 \times 10^{-3}$$

In this example, the generated acceleration is 99,998 m/s^2 at a frequency of 160 Hz.

For more details, see Reference [20].

Annex D
(informative)

Phase shift calibration of laser vibrometers

D.1 General

As explained in 10.1, method 3 is applicable to laser vibrometer calibration (modulus and phase) in the frequency range from <0,4 Hz to >50 kHz. This part of ISO 16063 specifies the calibration of the phase shift of laser vibrometers in the frequency range from 0,4 Hz to 50 kHz.

If the LVS is designed for measurement of the phase shift (e.g. in calibration of vibration transducers), it is essential that the travelling time (delay time, time lag) caused by any signal handling step within the LVS does not depend on operating parameters (e.g. vibration frequency and amplitude, optical reflectivity) and shall be repeatable and stable in the long term. Its value shall be known with sufficient accuracy to meet the requirements of phase calibrations within the frequency range of interest. Based on the known delay time of the LVS, its phase lag can then be calculated as a linear function of frequency and taken into account for phase calibrations. Means for synchronization of LVS output data and output signal of the device under calibration shall be provided (e.g. trigger signals or time stamps).

NOTE 1 Typical non-linear phase shifts of analogue subsystems such as filters and variations of the signal propagation delay (jitter) in digital signal processing blocks can cause significant uncertainty contributions in phase calibrations.

NOTE 2 Phase shift calibration of laser vibrometers is specified in this annex for method 3. Alternatively, method 4 (comparison to a reference transducer) can be used if the reference transducer is calibrated as a phase standard by method 3 as described in 11.1.

D.2 Procedure

The procedure specified in 10.2 for the modulus calibration of laser vibrometers using method 3 applies in the same way for their phase calibration.

D.3 Data processing

D.3.1 Calibrate the laser vibrometer by steps 10.3.2 and 10.3.3 which are valid in the same way for magnitude and phase calibration of laser vibrometers. In particular, Equations (7), (8), and (9) apply.

D.3.2 Calculate the initial phase angle of the displacement φ_s from the parameter values A and B obtained through sine approximation using Equation (D.1):

$$\varphi_s = \arctan \frac{B}{A} \tag{D.1}$$

D.3.3 Approximate the series of sampled laser vibrometer output values, $\{u(t_i)\}$, by the sine-approximation method, using Equation (11) which is valid in the same way for magnitude and phase calibration of laser vibrometers.

D.3.4 Calculate the laser vibrometer output initial phase angle φ_u from the parameter values A_u and B_u obtained by sine approximation using Equation (D.2):

$$\varphi_u = \arctan \frac{B_u}{A_u} \tag{D.2}$$

D.3.5 Calculate the phase shift $\Delta\varphi_s$ of the complex laser vibrometer sensitivity from the value φ_u obtained in D.3.4, and the value φ_s obtained in D.3.2, using Equation (D.3):

$$\Delta\varphi_s = \varphi_u - \varphi_s \tag{D.3}$$

NOTE 1 Equation (D.3) is valid if the output of the LV is the displacement signal. If is the output is the velocity signal, the formulae are applicable in analogy.

When the calibration results are reported, the expanded uncertainty of measurement in the phase calibration shall be calculated and reported in analogy to A.3.

The value of the overall delay time (or phase lag at the calibration frequency, respectively) caused by the LVS shall be known with sufficient accuracy and is to be corrected in the phase calibration. The uncertainty of this value shall be taken into account in the uncertainty budget.

NOTE 2 The sine-approximation method may alternatively be applied in the version with time interval measurement, see B.2 and Figure B.1. Use Equation (B.9) to calculate the initial phase angle φ_v.

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