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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

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Foreword

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

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

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 $\varphi_M(t)$ of the interferometer output signal, or
- the velocity $v(t)$ at the input of the interferometer into a proportional frequency shift $f_D(t)$ (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 $u_1(t) = U_1\cos\varphi_{\mathrm{Mod}}(t)$ and $u_2(t) = U_2\sin\varphi_{\mathrm{Mod}}(t)$ 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

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