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Methods for the calibration of vibration and shock transducers —

Part 15:

Primary angular vibration calibration by laser interferometry

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

Partie 15: Étalonnage angulaire primaire de vibration par interférométrie laser

Reference number
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Foreword

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

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 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 16063-15 was prepared by Technical Committee ISO/TC 108, *Mechanical vibration and shock*, 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*

The following additional parts are under preparation:

- *Part 23, addressing the angular vibration calibration by comparison to reference transducers*
- *Part 31, addressing the testing of transverse vibration sensitivity*
- *Part 32, addressing the resonance testing*
- *Part 41, addressing the calibration of laser vibrometers*
- *Part 42, addressing the calibration of seismometers*

Methods for the calibration of vibration and shock transducers —

Part 15:
Primary angular vibration calibration by laser interferometry

1 Scope

This part of ISO 16063 specifies the instrumentation and procedures used for primary angular vibration calibration of angular transducers, i.e. angular accelerometers, angular velocity transducers and rotational angle transducers (with or without amplifier) to obtain the magnitude and the phase shift of the complex sensitivity by steady-state sinusoidal vibration and laser interferometry. The methods specified in this part of ISO 16063 are applicable to measuring instruments (rotational laser vibrometers in particular) and to angular transducers as defined in ISO 2041 for the quantities of rotational angle, angular velocity and angular acceleration.

It is applicable to a frequency range from 1 Hz to 1,6 kHz and a dynamic range (amplitude) from 0,1 rad/s^2 to 1 000 rad/s^2 (frequency-dependent).

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

Method 1A (cf. Clause 8: fringe-counting, interferometer type A) and method 1B (cf. Clause 8: fringe-counting, interferometer type B) are applicable to the calibration of the magnitude of complex sensitivity in the frequency range of 1 Hz to 800 Hz and under special conditions, at higher frequencies. Method 2A (cf. Clause 9: minimum-point method, interferometer type A) and method 2B (cf. Clause 9: minimum-point method, interferometer type B) can be used for sensitivity magnitude calibration in the frequency range of 800 Hz to 1,6 kHz. Method 3A (cf. Clause 10: sine-approximation method, interferometer type A) and method 3B (cf. Clause 10: sine-approximation method, interferometer type B) can be used for magnitude of sensitivity and phase calibration in the frequency range of 1 Hz to 1,6 kHz. Methods 1A, 1B and 3A, 3B provide for calibrations at fixed angular acceleration amplitudes at various frequencies. Methods 2A and 2B require calibrations at fixed rotational angle amplitudes (angular velocity amplitude and angular acceleration amplitude vary with frequency).

NOTE 1 The numbering 1 to 3 of the methods characterizes the handling of the interferometer output signal(s) analogous to ISO 16063-11: number 1 for fringe counting, number 2 for minimum-point detection and number 3 for sine-approximation. Each of these signal handling procedures can be used together with interferometer types A and B specified in this part of ISO 16063.

Interferometer type A designates a Michelson or Mach-Zehnder interferometer with retro-reflector(s) located at a radius, R, from the axis of rotation of the angular exciter. This interferometer type is limited to rotational angle amplitudes of 3° maximum. Interferometer type B designates a Michelson or a Mach-Zehnder interferometer using a circular diffraction grating implemented on the lateral surface of the circular measuring table. This interferometer type is not limited as regards the rotational angle amplitude if the diffraction grating covers the whole lateral surface of the disk (i.e. 360°). Usually, the maximum angular vibration is, in this case, limited by the angular vibration exciter.

NOTE 2 Though the calibration methods specified in this part of ISO 16063 are applicable to angular transducers (according to definition in ISO 2041) and, in addition, to measuring instrumentation for angular motion quantities, the specifications are given for transducers as calibration objects, for the sake of simplified description. Some specific information for the calibration of rotational laser vibrometers is given in 4.11 and Figure 11.

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 2041:1990, *Vibration and shock — Vocabulary*

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

3 Uncertainty of measurement

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

a) for the magnitude of sensitivity:

   - 0,5 % of the measured value at reference conditions,
   - $\leqslant$ 1 % of the measured value outside reference conditions;

b) for the phase shift of sensitivity:

   - 0,5° of the measured value at reference conditions,
   - $\leqslant$ 1° of the reading outside reference conditions.

Recommended reference conditions are as follows:

- frequency: 160 Hz, 80 Hz, 40 Hz, 16 Hz or 8 Hz (or radian frequency, ω: 1 000 rad/s, 500 rad/s, 250 rad/s, 100 rad/s or 50 rad/s);
- angular acceleration: (angular acceleration amplitude or r.m.s. value): 100 rad/s^2, 50 rad/s^2, 20 rad/s^2, 10 rad/s^2, 5 rad/s^2, 2 rad/s^2 or 1 rad/s^2.

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

The uncertainty of measurement is expressed as the expanded measurement uncertainty in accordance with ISO 16063-1, for the coverage factor $k = 2$ (referred to, in short, as “uncertainty”).

4 Requirements for apparatus

4.1 General

Clause 4 gives recommended specifications for the apparatus necessary to comply with the scope of Clause 1 and to obtain the uncertainties of Clause 3.

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

NOTE The apparatus specified in Clause 4 covers all devices and instruments required for any of the six calibration methods described in this part of ISO 16063. The assignment to a particular method is indicated (cf. Figures 2, 3, 4, 5, 6, 7, 8 and 10).

4.2 Frequency generator and indicator

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

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

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

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

4.3 Power amplifier/angular vibration exciter combination

4.3.1 General

A power amplifier/angular vibration exciter combination having the following characteristics shall be used:

a) total harmonic distortion: 2 % maximum;

   NOTE 1 This specification relates to the input quantity for the transducer to be calibrated.

   NOTE 2 If method 3A or method 3B is used, greater harmonic distortions can be tolerable.

b) transverse, and rocking angular acceleration: sufficiently small to prevent excessive effects on the calibration results. For interferometer type A, a transverse motion of less than 1 % of the tangential motion component at the minimum rotational angle displacement can be required. For interferometer type B, a maximum lateral motion (including eccentricity) of 2 µm is tolerated, which can be achieved only if the moving part (measuring table) of the angular exciter is carried in a high-precision rotational air bearing;

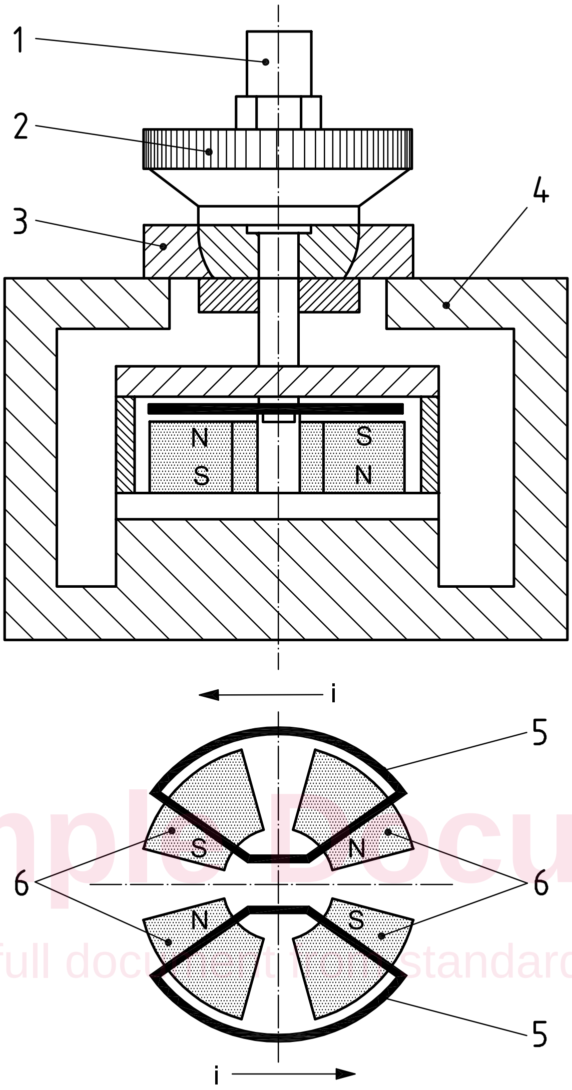
c) hum and noise: 70 dB minimum below full output;

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

4.3.2 Electro-dynamic angular vibration exciter

An electrodynamic vibration exciter is based on the Lorentz force acting on electric charge carriers when these move through a magnetic field.

In analogy to common electrodynamic vibration exciters designed to generate rectilinear vibration, the coil located in the magnetized air gap of a magnetic circuit can be so designed that the Lorentz force generates a dynamic torque exciting the measuring table with the angular transducer to be calibrated to angular vibration. In the working frequency range (i.e. 1 Hz to 1,6 kHz), the amplitude of angular acceleration is proportional to the amplitude of the electric current carried through the coil. An example of an angular vibration exciter is shown in Figure 1. The maximum rotational amplitude is in this case limited to 30° (i.e. double amplitude: 1 rad). Another example of an angular acceleration exciter (amplitude of 60°, i.e. 1 rad) is described in Reference [14].



Key

1	angular accelerometer
2	diffraction grating
3	air bearing
4	housing
5	coil
6	magnet

Figure 1 — Example of an angular exciter (mode of function)

4.3.3 Angular vibration exciter based on a brushless electric motor

Special angular exciters have been designed and manufactured for angular transducer calibration using commercial electric motors.

For the testing of inertial navigation sensors, so-called “rate tables” have been developed for many years. These are often equipped with brushless, three-phase, hollow-shaft motors that are electronically commutated and servo-controlled, in particular for the angular velocity, i.e. angular rate operating mode. Normally, a constant angular velocity is generated. Often, sinusoidal angular velocities with low distortion are achieved.

The progress in control made over the last few years allows this exciter type to be used even to generate angular acceleration. A basic requirement is the use of an air bearing as in the flat-coil exciter (cf. 4.3.2).

As the distortion increases after differentiation, the calibration of angular accelerometers can require a frequency-selective measurement of the transducer output signal, which is ensured by the use of method 3A or 3B (i.e. sine-approximation).

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

The angular 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, this should have a moment of inertia at least 2 000 times that of the moving mass. This causes less than 0,05 % reactive angular vibration of angular transducer and interferometer. If the moment of inertia of the seismic block is smaller, its motion generated by the vibrator shall be taken into account.

To suppress disturbing effects of ground motion, the seismic block(s) used in the frequency range of 1 Hz to 1,6 kHz should be suspended on damped springs designed to reduce the uncertainty component due to these effects to less than 0,1 %.

4.5 Laser

A laser of the red helium-neon type or a single-frequency laser with another wavelength of known value shall be used. Under laboratory conditions (i.e. at an atmospheric pressure of 100 kPa, a temperature to 23 °C and a relative humidity of 50 %), the wavelength of a red helium-neon laser is 0,632 81 µm.

If the laser is provided with a manual or automatic atmospheric compensation device, this shall be set to zero or switched off.

4.6 Interferometer

4.6.1 General

The interferometer may be used to transform

- the rotational angle, $\Phi(t)$, into a proportional phase shift, $\varphi_M(t)$, of the interferometer output signal,
- the angular velocity, $\Omega(t)$, into a proportional frequency shift, $f_D(t)$ (Doppler frequency), of the interferometer output signal.

For both transformations, a homodyne or a heterodyne interferometer (cf. Figures 3 to 8 and 10) and a one-channel or two-channel arrangement (cf. Figures 3 to 8 and 10) may be used.

The first transformation of $\Phi(t)$ into $\varphi_M(t)$ is specified in this part of ISO 16063 as a standard procedure whereas the latter transformation of $\Omega(t)$ into $f_D(t)$ is given as an option with reference to detailed descriptions in the literature.

The interferometer types A and B basically have in common that the measuring beam senses a translational displacement motion component so that an interferometer arrangement designed for rectilinear vibration measurements can be used. To make the application of such conventional interferometers possible, the quantity of rotational motion to be measured is converted into a representative translational displacement motion component using retro-reflector(s) as measuring reflector(s) for interferometer type A, and a diffraction grating arranged on the rotary measuring table for interferometer type B. In the latter case, an optically reflecting diffraction grating is to be arranged on the lateral surface of an air-borne rotary table to meet the requirement of the tolerable eccentricity of 2 µm.

For methods 1A, 1B (see Figures 3 and 4) and Methods 2A, 2B (see Figures 5 and 6), a common Michelson interferometer with a single light detector is sufficient.

The Michelson interferometer can be realized with a single measuring beam or with two measuring beams.

For methods 3A, 3B, (see Figures 7 and 8), a modified Michelson interferometer with quadrature signal outputs, with two light detectors for sensing the interferometer signal beams, shall be used. The modified Michelson interferometer may be designed according to Figure 9. A quarter wavelength retarder converts the incident, linearly polarized light into two measuring beams with perpendicular polarization states and a phase shift of 90°. After interfering with the linearly polarized reference beam, the two components with perpendicular polarization shall be separated in space using appropriate optics (e.g. a Wollaston prism or a polarizing beam splitter), and detected by two photodiodes.

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

At large rotational angles, it can be difficult to maintain the tolerances stated above for the deviations of the two outputs of the modified Michelson interferometer. To comply with the uncertainty of measurement of Clause 3, the above tolerances shall be complied with at least for small rotational angles of up to 2×10^{-2} rad. For greater amplitudes, greater tolerances are permitted.

EXAMPLE For a rotational angle of $2{,}5 \times 10^{-2}$ rad (i.e. angular acceleration amplitude of 1 rad/s^2 at a frequency of 1 Hz), the tolerances can be extended to ± 10 % for the offsets and for the relative amplitude deviations, and to ± 20° for the deviation from the nominal angle of 90° (see also NOTE 1 of 10.2).

The tolerances stated above are valid without correction of quadrature fringe measurement errors in interferometer. If the correction procedure after Heydemann[6] is applied, greater tolerances are permitted.

For methods 1A, 1B, 2A, 2B, 3A or 3B, another suitable interferometer, e.g. a (modified) Mach-Zehnder heterodyne interferometer (cf. Figure 10) may be used in the place of the (modified) Michelson interferometer.

An interferometer of type A (cf. 4.6.2) or B (cf. 4.6.3) shall be used with a light detector to sense the interferometer signal bands and with a frequency response covering the bandwidth necessary. The maximum bandwidth (frequency f_{max}) needed can be calculated from the maximum angular velocity amplitude, Ω_{max} using Equation (1):

$$f_{\text{max}} = \frac{\Omega_{\text{max}} R}{\Delta s} \tag{1}$$

where

R is the effective radius (cf. 4.6.2 for the definition for interferometer of type A and 4.6.3, for interferometer of type B);

Δs is the displacement quantization interval of the interferometer.

For interferometer type A, $\Delta s = \lambda/2$ in the single measuring beam arrangement and $\Delta s = \lambda/4$ in the two-beam arrangement with the laser wavelength, λ. For interferometer type B, $\Delta s = g$ in the single measuring beam arrangement and $\Delta s = g/2$ in the two-beam arrangement with the grating constant, g.

4.6.2 Interferometer type A (retro-reflector interferometer)

For methods 1A and 2A, an interferometer of the Michelson type with retro-reflector(s) as measuring reflector(s) shall be used with a light detector for sensing the interferometer signal bands and a frequency response covering the necessary bandwidth (cf. 4.6.1). To compensate the influence of the disturbing motion, a two-beam arrangement (for an example, cf. Figures 3 and 5) shall be used with two retro-reflectors mounted symmetrically (i.e. shifted by 180°) at a distance, R, from the axis of rotation.

The laser beam emitted by the laser passes to a beam splitter which splits up the beam into two components that are fed in parallel to the retro-reflectors. The reflected beams are superimposed on each other and the relevant part of the resulting light intensity is transformed by the photodetector into an electrical signal (briefly referred to as interferometer signal).

NOTE The two-beam arrangement leads not only to compensation of the disturbing motion (e.g. from ground vibration) but also to doubling of the sensitivity (quantization interval of $\lambda/4$ instead of $\lambda/2$). The retro-reflectors (instead of plane mirrors) compensate (in a certain range, cf. Appendix B) for the tilting effect of the rotational motion. Moreover, the interferometer accommodates (in a certain range) disturbing motion in the transverse direction without the uncertainty of measurement being affected.

For method 3A, a quadrature interferometer with retro-reflectors, measuring and reference reflectors shall be used. In the homodyne interferometer version shown in Figures 7 and 9, the light source is a stabilized single-frequency laser. The diameter of the laser beam is expanded by lenses to reduce the divergence of the beam. The polarized laser beam is split by the beam splitter into a measuring beam and a reference beam. The reference beam is reflected and shifted in parallel by a retro-reflector (reference reflector). As the $\lambda/8$ retardation waveplate is traversed twice, a path difference of $\lambda/4$ is obtained. At the same time, the reflected laser beam is split into two beams, each with a direction of polarization orthogonal to the other, that show a phase shift of 90° (i.e. circular polarization). The measuring beam is also shifted in parallel when reflected by the retro-reflector mounted on the measuring table, retaining its linear polarization. The linearly polarized reflected measuring beam and the circularly polarized reference beam are superimposed. When passing the Wollaston prism, which is inclined by 45° with reference to the direction of polarization of the reflected measuring beam, two linearly polarized beam components are obtained whose directions of polarization are perpendicular to each other. After separation of the two components in space, two different interference systems are derived having a phase shift of 90° with respect to each other. The two photodetectors transform the relevant parts of the light intensities into electrical signals that show a sinusoidal and a cosinusoidal dependence on the displacement of the measuring reflector.

4.6.3 Interferometer type B (diffraction-grating interferometer)

An interferometer with a diffraction grating as measuring reflector shall be used (e.g. a Michelson interferometer) with a light detector for sensing the interferometer signal bands and with a frequency response covering the necessary bandwidth (cf. 4.6.1).

For methods 1B and 2B, a modified Michelson interferometer with diffraction grating is used (cf. Figures 2, 4 and 6).

The angular acceleration, the angular velocity or the rotational angle are measured by a special diffraction grating interferometer developed on the basis of a high-resolution grating (e.g. a sine-phase grating of 2 400 grooves/mm or 3 000 grooves/mm, manufactured by holography) (examples are described in References [12] and [13]). An optical reflection grating is located on the air-borne measuring table of the angular vibration exciter, concentrically to the axis of rotation (cf. Figure 2). The light beam emitted by a frequency-stabilized single-frequency He-Ne laser is split into two parallel beams striking the grating symmetrical to the axis of rotation at the angle at which the first-order beams diffracted by reflection (according to the diffraction formula for oblique incidence) return into the direction of the incident beam. The first-order diffracted light beams are superposed in the optical arrangement. When the moving part is rotated, these light beams undergo a frequency change opposite in sign and of the same amount that is proportional to the tangential velocity and, thus, also to the angular velocity. The interfering beams give rise to a light intensity whose significant component shows a periodic dependence on the rotational angle.

For method 3B, a homodyne quadrature interferometer with diffraction grating is used (cf. Figure 8).

In the quadrature diffraction-grating interferometer in the single measuring beam arrangement, the light beam is split into the reference beam and the measuring beam. The measuring beam strikes the grating at the angle at which the first-order beam diffracted by reflection returns into the direction of the incident beam. The first-order beam diffracted in accordance with the diffraction equation for oblique incidence and the reference beam are superimposed in the optical arrangement. The interfering light beams yield a light intensity whose significant component depends sinusoidally on the rotational angle.

For high-accuracy requirements (relative uncertainty of calibration smaller than 0,5 %), a grating interferometer calibration procedure shall be carried out once for a measuring table with an individual diffraction grating disk, to accurately determine the quantization intervals of the displacement, Δs, and of the rotational angle, $\Delta \Phi$ (cf. procedure in Clause 7).

4.7 Instrumentation for interferometer signal processing

4.7.1 General

The instrumentation used has in common that the phase-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. amplitude and initial phase of the sinusoidal rotational angle). Different techniques are to be used for methods 1A, 1B (cf. 4.7.2), methods 2A, 2B (cf. 4.7.3) and methods 3A, 3B (cf. 4.7.4).

4.7.2 Instrumentation for fringe counting (for methods 1A and 1B)

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.

4.7.3 Instrumentation for zero-point detection (for methods 2A and 2B)

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

a) frequency range: $\leqslant$ 800 Hz to $\geqslant$ 1,6 kHz;

b) bandwidth: $<$ 12 % of centre frequency;

c) filter slopes: equal to or greater than 24 dB per octave;

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

e) dynamic range: greater than 60 dB.

Instrumentation for zero detection (not needed with spectrum analyser), with a frequency range from 800 Hz to 1,6 kHz shall be used. The range shall be sufficient for detecting output noise from the bandpass filter.

4.7.4 Instrumentation for sine-approximation (for methods 3A and 3B)

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

A sufficient number of samples (cf. 10.3) are required of the shortest period of the interferometer output signal occurring at maximum velocity. For a particular angular acceleration amplitude, at decreasing frequencies, larger displacement amplitudes occur that require higher sampling rates and larger memories. If such capabilities are not available, the angular acceleration amplitude shall be reduced.