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Methods for the calibration of vibration and shock transducers —

Part 43:
Calibration of accelerometers by model-based parameter identification

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

Partie 43: Étalonnage des accéléromètres par identification des paramètres à base de modèle

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Contents

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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.

ISO 16063-43 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 16: *Calibration by Earth's gravitation*
- Part 21: *Vibration calibration by comparison with a reference transducer*
- Part 22: *Shock calibration by comparison with a reference transducer*
- Part 31: *Testing of transverse vibration sensitivity*
- Part 41: *Calibration of laser vibrometers*
- Part 42: *Calibration of seismometers with high accuracy using acceleration of gravity*

The following parts are under preparation:

- Part 32: *Resonance testing – Testing the frequency and the phase response of accelerometer by means of shock excitation*
- Part 33: *Testing of magnetic field sensitivity*
- Part 43: *Calibration of accelerometers by model-based parameter identification*

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Introduction

The standard series of ISO 16063 describes in several of its parts (ISO 16063-1, ISO 16063-11, ISO 16063-13, ISO 16063-21 and ISO 16063-22) the devices and procedures to be used for calibration of vibration sensors. The approaches taken can be divided in two classes. One for the use of stationary signals, namely sinusoidal or multi-sinus excitation, the other for transient signals, namely shock excitation. While the first provides the lowest uncertainties due to the intrinsic, periodic repeatability the later is aiming at the high intensity range where periodic excitation is usually not feasible due to power constraints of the calibration systems.

The result of the first class is given in terms of a complex transfer sensitivity in the frequency domain and is hence not directly applicable to transient time-domain application.

The results of the latter class are given as a single value, the peak ratio, in the time domain which neglects (knowingly) the frequency dependent dynamic response of the transducer to transient input signals with spectral components in the resonance area of the transducer's response. As a consequence of this “peak ratio characterisation”, the calibration result might exhibit a strong dependence on the shape of the transient input signal applied for the calibration and therefore from the calibration device.

This has two serious consequences:

1) The calibration with shock excitation according to ISO 16063-13 or ISO 16063-22 is of limited use as far as the dissemination of units is concerned. That is, the shock sensitivities S_{sh} determined by calibrations on device in a primary laboratory might not be applicable to the customer's device in the secondary calibration lab, simply due to a different signal shape and thus spectral constitution of the secondary device's shock excitation signal.

2) A comparison of calibration results from different calibration facilities with respect to consistency of the estimated measurement uncertainties, e.g. for validation purposes in an accreditation process, is not feasible if the facilities apply input-signals of differing spectral composition.

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The approach taken here is a mathematical model description of the accelerometer as a dynamic system with mechanical input and electrical output, where the latter is assumed to be proportional to an intrinsic mechanical quantity (e.g. deformation). The estimates of the parameters of that model and the associated uncertainties are then determined on the base of calibration data achieved with the established methods (ISO 16063-11, ISO 16063-13, ISO 16063-21 and ISO 16063-22). The complete model with quantified parameters and their respective uncertainties can subsequently be used to either calculate the time-domain response of the sensor to arbitrary transient signals (including time dependent uncertainties) or as a starting point for a process to estimate the unknown transient input of the sensor from its measured time-dependent output signal (ISO 16063-11 or ISO 16063-13).

As a side effect, the method usually provides an estimate of a continued frequency-domain transfer sensitivity of the model, too.

In short the methods and procedures prescribed in this document enable the user to:

- calibrate vibration transducers for precise measurements of transient input,
- perform comparison measurements for validation using transient excitation,
- predict transient input signals and its time dependent measurement uncertainty,
- compensate effects of the frequency dependent response of vibration transducers (in real time) and thus expand the applicable bandwidth of the transducer.

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Methods for the calibration of vibration and shock transducers — Part 43: Calibration of accelerometers by model-based parameter identification

1 Scope

This International Standard prescribes terms and methods on the estimation of parameters used in mathematical models describing the input-output characteristic of vibration transducers together with the respective parameter uncertainties. The described methods estimate the parameters on the basis of calibration data collected with standard calibration procedures according to established standards ISO 16063-1, ISO 16063-11, ISO 16063-13, ISO 16063-21 and ISO 16063-22. The specification is provided as an extension of the existing procedures and definitions in those standards. The uncertainty estimation described conforms to the methods established by ISO/IEC Guide 98-3 and Supplement 1.

The new characterisation described in this document is intended to improve the quality of calibrations and measurement applications with broadband/transient input, like shock. It provides the means of a characterisation of the vibration transducer's response to a transient input and therefore provides a basis for the accurate measurement of transient vibrational signals with the prediction of an input from an acquired output signal. The calibration data for accelerometers used in the aforementioned field of applications should additionally be evaluated and documented according to the methods described below in order to provide measurement capabilities and uncertainties beyond the limits drawn by the single value characterisation given by ISO 16063-13 and ISO 16063-22.

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2 Normative references

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

ISO 2041, *Mechanical vibration, shock and condition monitoring — Vocabulary*

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

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

ISO 16063-13, *Methods for the calibration of vibration and shock transducers – Part 13: Primary shock calibration using 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 16063-22, *Methods for the calibration of vibration and shock transducers - Part 22: Shock calibration by comparison to a reference transducer*

ISO/IEC Guide 98-3, *Uncertainty of measurement — Part 3: Guide to the expression of uncertainty in measurement* (GUM:1995)

ISO/IEC Guide 98-3:2008/Suppl 1/2008, *Uncertainty of measurement — Part 3: Guide to the expression of uncertainty in measurement* (GUM:1995) – *Supplement 1: Propagation of distributions using a Monte Carlo method*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 2041 apply.

4 Consideration of typical frequency response and transient excitation

A typical acceleration transducer has a complex frequency response. This is usually given in terms of magnitude and phase with a shape as it is depicted in Figure 1. The magnitude is given in arbitrary units (a.u.).

This response function is subsequently sampled with lowest uncertainties by a calibration method according to ISO 16063-11 or ISO 16063-21 making use of periodic excitation.

In applications with transient input-signals such a sensor is then exposed to broadband excitation in terms of the frequency domain. The response in this case cannot be calculated with the help of a single (complex) value like the transfer sensitivity. Rather, the response can be considered to be a sensitivity that is weighted by those components in the frequency response which are excited by the spectral contents of the input signal.

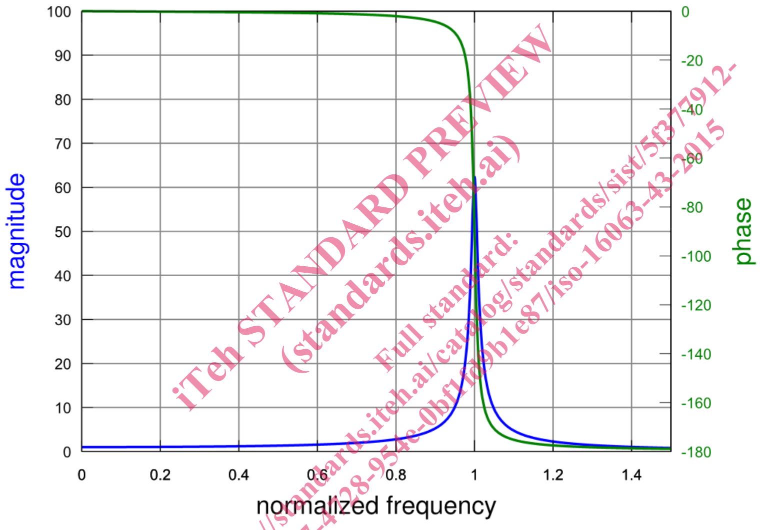

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Figure 1 — Complex frequency response of a typical accelerometer in terms of magnitude of sensitivity (blue) and phase delay (green) over the normalized frequency

Figure 2 gives a pictorial representation of three examples of possible shock excitation signals and their respective spectra as compared to the frequency response of a typical sensor. It shows the projection of the centre of mass of the magnitude of the spectral density curve onto the sensitivity curve of a typical accelerometer. This demonstrates, that a single value characterisation of a transducer by shock calibration cannot sufficiently describe the dynamic behaviour.

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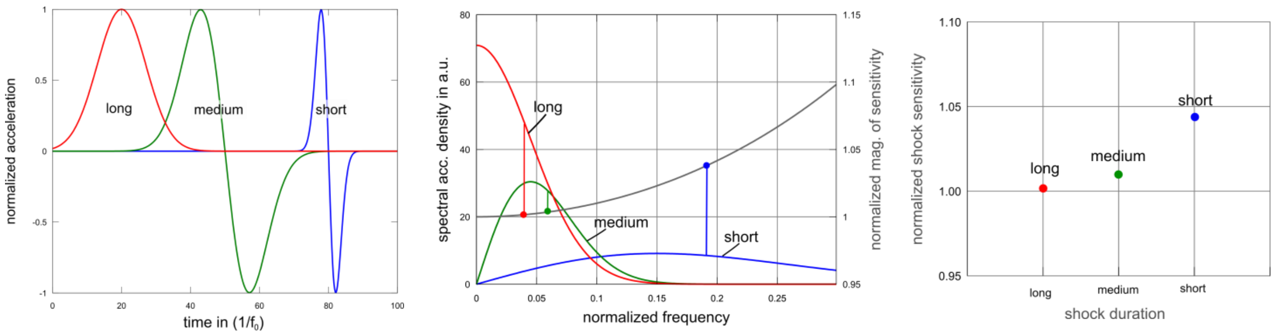

Figure 2 — Time domain representation (left) of three different shock signals (long monopole (red), medium dipole (green), short dipole (blue)) with the respective magnitude spectra (middle) with the projection of the spectral centre point onto the sensitivity curve of a typical accelero¬meter response, and the corresponding shock sensitivity (peak ratio) of a typical accelerometer (right)

5 General approach

The general idea behind “model based parameter identification” is to describe the input/output behavior of a transducer type of certain design and construction with the help of a dynamic mathematical model. The detailed properties of an individual transducer are represented in that model by a set of parameters[1]. Associated with the set of estimates of the model parameters is a respective set of uncertainties. The aim of the calibration is to provide measurement results which allow for the mathematical estimation of this parameter set and the evaluation of corresponding uncertainties.

This general approach is not new but already well established in science and engineering under the term “identification of dynamic systems”. However, in the field of transducer calibration special emphasis has to be put on the validation of the applicability of the methods used and on the reliable calculation of uncertainties and respective coverage intervals.

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NOTE In the subsequent text the procedure of model based parameter identification and further considerations are presented for a linear mass-spring-damper model of a seismic pick-up. However, this is only one example. The same approach can be used for more complicated mathematical models as long as they can be described as linear time-invariant (LTI) systems.

6 Linear Mass-Spring-Damper Model

6.1 Model

According to the investigation in [8,10 and 13] some accelerometers can be described by a simple linear mass-spring-damper model in their specified working range. That means they follow the general equation of motion of the form (c.f. [2])

$$\ddot{x} + 2\delta\omega_0\dot{x} + \omega_0^2 x = \rho a(t) \qquad (1)$$

with δ being the damping coefficient, ω_0 the circular resonant frequency of the system and ρ the electro mechanical conversion factor. This model describes the dynamic output $x(t)$ (e.g. charge or voltage) as a function of the acceleration input $a(t)$

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[1] The parameter sets may include functions of variables to cover temperature sensitivity or mass loading effects.

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For such a linear system the transfer function $H(\mathrm{i}\omega)$ in the frequency domain is independent of the acceleration amplitude and is given by:

$$\mathrm{H}(\mathrm{i}\omega) = \frac{\rho}{\omega_0^2 + 2\delta\omega_0 \mathrm{i}\omega + (\mathrm{i}\omega)^2} = \mathrm{S}(\omega) \cdot \mathrm{e}^{\mathrm{i}\phi(\omega)}. \tag{2}$$

The inverse of this transfer function is:

$$\mathrm{G}(\mathrm{i}\omega) = \mathrm{H}(\mathrm{i}\omega)^{-1} = \rho^{-1}(\omega_0^2 + 2\mathrm{i}\omega\delta\omega_0 - \omega^2) = \mathrm{S}^{-1}(\omega) \cdot \mathrm{e}^{-\mathrm{i}\phi(\omega)} \tag{3}$$

with $\mathrm{S}(\omega)$ representing the magnitude and $\phi(\omega)$ representing the phase of the response.

6.2 Identification by sinusoidal calibration data

6.2.1 Parameter identification

Starting from calibration measurements with sinusoidal excitation according to e.g. ISO 16062-11 or ISO 16062-21 one can directly determine the frequency response $H(i\omega)$ as described by Equation (2) taking into account the well known frequency response of any conditioning amplifier[2].

Substituting a parameter vector

$$\mu^T = (\mu_1, \mu_2, \mu_3) = \left(\frac{\omega_0^2}{\rho}, \frac{2\delta\omega_0}{\rho}, \frac{1}{\rho}\right) \tag{4}$$

Equation (3) transforms to

$$G(i\omega) = \frac{1}{H(i\omega)} = \mu_1 + i\mu_2\omega - \mu_3\omega^2 = g^T(\omega) \cdot \mu \tag{5}$$

with $g^T(\omega) = (1, i\omega, -\omega^2)$.

According to this relation the parameter vector μ can be estimated by weighted linear least squares, where the weights are chosen according to the uncertainties known from the calibration procedures according to ISO 16062-11 or ISO 16062-21 as follows.

Let $S_m = S(\omega_m)$, $\phi_m = \phi(\omega_m)$ denote the magnitude and the phase of the frequency response from calibration measurements with associated standard uncertainties $u(S_m)$, $u(\phi_m)$ at the frequencies ω_m, $m = 1,2,\ldots,L$. Then the real part $R(S^{-1} \cdot e^{-i\phi})$ and imaginary part $J(S^{-1} \cdot e^{-i\phi})$ are given by:

$$R(S,\phi) = R(S^{-1} \cdot e^{-i\phi}) = S^{-1} cos(\phi) \ ,$$

$$J(S,\phi) = \mathrm{Im}(S^{-1} \cdot e^{-i\phi}) = -S^{-1} sin(\phi) \tag{6}$$

This is in principle a non-linear transform which should be adequately handled for uncertainty calculations by ISO/IEC Guide 98-3, Supplement 1. However, given the case that the uncertainties of measurement are small enough the direct propagation of uncertainties can be calculated according to ISO/IEC Guide 98-3 as:

$$\begin{aligned}
u^2(R_m) &= \frac{u^2(S_m)}{S_m^4} cos^2(\phi_m) + \frac{u^2(\phi_m)}{S_m^2} sin^2(\phi_m) \\
u^2(J_m) &= \frac{u^2(S_m)}{S_m^4} sin^2(\phi_m) + \frac{u^2(\phi_m)}{S_m^2} cos^2(\phi_m) \\
u(R_m, J_m) &= \frac{-u^2(S_m)}{S_m^4} sin(\phi_m) cos(\phi_m) + \frac{u^2(\phi_m)}{S_m^2} sin(\phi_m) cos(\phi_m)
\end{aligned} \tag{7}$$

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[2] The model assumes that any additional response function of a measuring amplifier is eliminated prior to the identification process, which is usually the case.

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