INTERNATIONAL STANDARD

ISO 20270

First edition
2019-11

Acoustics — Characterization of sources of structure-borne sound and vibration — Indirect measurement of blocked forces

Acoustique — Caractérisation des sources de bruit solidien et de vibrations — Mesurage indirect des forces bloquées

Reference number
ISO 20270:2019(E)

ISO copyright office
CP 401 • Ch. de Blandonnet 8
CH-1214 Vernier, Geneva
Phone: +41 22 749 01 11
Fax: +41 22 749 09 47
Email: copyright@iso.org
Website: www.iso.org

Published in Switzerland

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 43, *Acoustics*, Subcommittee SC 1, *Noise*.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

This document has been developed in response to demand from mechanical industries for an agreed method of specifying the "source strength" of sources of structure-borne sound and vibration. Quantities which independently characterize a source are the free velocity and blocked force: ISO 9611[2] specifies a measurement procedure for the former in which the machine, a vibration source, is mounted on soft mounts to approximate free suspension. The blocked forces are the forces the operating machine would exert when constrained by a perfectly rigid foundation. They can potentially be measured directly by inserting force transducers in between the operating machine and a rigid foundation. However, this document describes an indirect method for measurement of blocked forces using an inverse method. Whereas the measurement of free velocity requires the source to be resiliently mounted and direct measurement of blocked forces requires the machine mounts to be blocked, the indirect measurement, as defined in this document, can theoretically be carried out with the source attached to any receiver structure. Essentially the same measurement techniques are used in the diagnosis of structure-borne sound using "transfer path analysis" (TPA), also called "source path contribution" analysis (SPC).

A method of characterizing sources of structure-borne sound and vibration by the indirect measurement of blocked forces at the points of connection to supporting, or receiver, structures is described in this document. The measurement method is applied in situ, which means that the source is connected to a receiver structure while the measurements are performed. In theory, the use of any receiver structure is valid provided the vibration source mechanisms of the specimen remain representative of those in a real installation. Therefore, the receiver structure can be part of a real installation, such as a machine foundation or a building, but can also be a specially designed test stand if it provides representative dynamic loading for the source.

The method specifies a two-stage measurement procedure comprising, first, a passive test in which frequency response functions (FRF) of the assembled source-receiver structure are measured, and secondly, measurement of vibration in an operational test. The blocked forces are obtained by solving the inverse problem. It is well known that inverse solutions of this type can result in very large errors, particularly if there is inconsistency in the input data. Such errors vary significantly depending on the case and the skill of the operator. Therefore, a means of estimating the uncertainties in the blocked force, through a process called on-board validation, forms an essential part of this measurement procedure.

The blocked forces are obtained in narrow frequency bands that can subsequently be converted to approximate octave or third octave frequency bands.

The in situ blocked force method is intended to complement the reception plate method of EN 15657[3]. The reception plate method offers a simplified approach in which forces and velocities are effectively averaged over the feet of an operating machine by mounting on a standard plate. The approximations allow measurements to be simplified but information about distribution and phase of the forces and velocities is lost. This document aims to provide an alternative for structure borne sound sources not compatible with the reception plate approach or where more detail is needed about the distribution of the forces.

The blocked forces obtained from this document can be used for the following purposes:

a) obtaining data for preparing technical specifications for vibrationally active components (sources);

b) obtaining input data for prediction of vibration in, or sound radiated sound from, structures connected to the source;

c) obtaining diagnostic information about the contribution of particular blocked forces to a target vibration or sound pressure (in situ transfer path analysis).

Prediction of sound and vibration in a new assembly [as in b) above] does not form a normative part of this document, although guidelines for prediction are provided in Annex E. For prediction purposes, extra data are needed in addition to the measured blocked forces. Specifically, the frequency response functions (FRFs) of the new assembly (which consists of the source connected to the new receiver structure) need to be known. These FRFs can in principle be measured (if the assembly is available for measurement), calculated (for example using numerical methods) or calculated by combining the FRFs of the separate source and the receiver structures (dynamic substructuring) whether measured or calculated.

Acoustics — Characterization of sources of structure-borne sound and vibration — Indirect measurement of blocked forces

IMPORTANT — The electronic file of this document contains colours which are considered to be useful for the correct understanding of the document. Users should therefore consider printing this document using a colour printer.

1 Scope

This document specifies a method where a vibrating component (a source of structure-borne sound or vibration) is attached to a passive structure (or receiver) and is the cause of vibration in, or structure-borne sound radiation from, the assembly. Examples are pumps installed in ships, servo motors in vehicles or machines and plant in buildings. Almost any vibrating component can be considered as a source in this context.

Due to the need to measure vibration at all contact degrees of freedom (DOFs) (connections between the source and receiver), this document can only be applied to assemblies for which such measurement is possible.

This document is applicable only to assemblies whose frequency response functions (FRFs) are linear and time invariant.

The source can be installed into a real assembly or attached to a specially designed test stand (as described in 5.2).

The standard method has been validated for stationary signals such that the results can be presented in the frequency domain. However, the method is not restricted to stationary signals: with appropriate data processing, it is also applicable to time-varying signals such as transients and shocks (provided linearity and time invariance of the FRFs are preserved).

This document provides a method for measurement and presentation of blocked forces, together with guidelines for minimizing uncertainty. It provides a method evaluating the quality of the results through an on-board validation procedure but does not comment on the acceptability or otherwise of the results.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements 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 7626-1, *Mechanical vibration and shock — Experimental determination of mechanical mobility — Part 1: Basic terms and definitions, and transducer specifications*

ISO7626-2, *Mechanical vibration and shock — Experimental determination of mechanical mobility — Part 2: Measurements using single-point translation excitation with an attached vibration exciter*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.1
blocked force
dynamic force applied by an operational *source* (3.4) to a perfectly rigid *receiver* (3.5) structure

3.2
frequency response function
FRF
frequency-dependent ratio of the motion-response Fourier transform to the Fourier transform of the excitation force of a linear system

Note 1 to entry: Excitation can be harmonic, random or transient functions of time. The test results obtained with one type of excitation can thus be used for predicting the response of the system to any other type of excitation.

Note 2 to entry: Motion may be expressed in terms of velocity, acceleration or displacement; the corresponding frequency-response function designations are mobility, accelerance and dynamic compliance or impedance, effective (i.e. apparent) mass and dynamic stiffness, respectively.

[SOURCE: ISO 2041:2018, 3.1.53]

3.3
in situ blocked force vector
$\bar{\boldsymbol{f}}_{\mathbf{c}}(f)$
complex *blocked force* (3.1) at the *contact degrees of freedom (DOFs)* (3.8), arranged into an $n \times 1$ vector at each frequency according to:

$$\bar{\boldsymbol{f}}_{\mathbf{c}}(f)=\begin{Bmatrix} \bar{f}_{c,1}(f) \\ \bar{f}_{c,2}(f) \\ \vdots \\ \bar{f}_{c,n}(f) \end{Bmatrix}$$

where $\bar{f}_{c,i}(f)$ is the complex Fourier spectrum component of the blocked force at frequency f and at contact degree of freedom (DOF) i

Note 1 to entry: Forces can be considered as generalized forces, that is, including rotational components like moments.

3.4
source
active substructure which contains the mechanisms of structure-borne sound or vibration generation and comprises all parts of the *assembly* (3.6) on the active side of the *source-receiver interface* (3.7)

Note 1 to entry: Typically, the source is a separable component although this is not a requirement for the method.

Note 2 to entry: See Figure 1.

3.5
receiver
passive substructure comprising all parts of the *assembly* (3.6) on the passive side of the *source-receiver interface* (3.7)

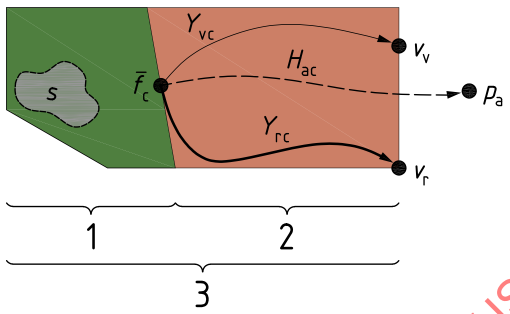
Note 1 to entry: The receiver may comprise the remaining parts of an assembled machine other than the source, a test bench or a foundation structure such as a building.

Note 2 to entry: By definition, there are no source mechanisms within the receiver so it is a purely passive structure.

Note 3 to entry: See Figure 1.

3.6
assembly
installation comprising the *source* (3.4) and *receiver* (3.5) connected together

Note 1 to entry: See Figure 1.



Key

1 source (active structure)

2 receiver (passive structure)

3 assembly

s internal source excitation (not accessible)

$\bar{\boldsymbol{f}}_c$ in situ blocked force vector at the set of contact DOFs, c

$\boldsymbol{v}_v$ validation velocity (or acceleration) vector at the set of validation DOFs, v

$\boldsymbol{v}_r$ indicator velocity (or acceleration) vector at the set of validation DOFs, r

$\boldsymbol{Y}_{vc}$ typical structural FRF between validation DOFs, v, and contact DOFs, c

$\boldsymbol{Y}_{rc}$ typical structural FRF between indicator DOFs, r, and contact DOFs, c

$\boldsymbol{H}_{ac}$ typical vibro-acoustic FRF between prediction DOFs, a, and contact DOFs, c (see NOTE 3)

$\boldsymbol{p}_a$ structure-borne sound predicted at DOFs, a, in the fluid around the receiver (see NOTE 3)

NOTE 1 Indicator DOFs can be located anywhere on the receiver, including the source-receiver interface.

NOTE 2 The obtained blocked force vector can be used to predict vibration in, and radiated sound from, the receiver structure (see Annex E).

NOTE 3 A vibration source (1) connected to a passive receiver (2) causes vibration ($\boldsymbol{v}_r$) in, or structure-borne sound ($\boldsymbol{p}_a$) radiated from, the assembly (3) at interfaces (r, v) and (a), respectively. The internal excitation, s, is unknown, requiring the source to be characterized at the source-receiver interface by blocked forces $\bar{\boldsymbol{f}}_c$, inferred from $\boldsymbol{v}_r$ and the assembly FRF matrix $\boldsymbol{Y}_{rc}$. Additional structural, $\boldsymbol{Y}_{vc}$, and vibro-acoustic FRFs, $\boldsymbol{H}_{ac}$, can be used for validation and prediction purposes.

Figure 1 — Test assembly

3.7
source-receiver interface
hypothetical surface which separates the *source* (3.4) structure from the *receiver* (3.5) structure

3.8
contact degrees of freedom
contact DOFs
DOFs located on the source receiver interface through which structure-borne sound or vibration is transmitted from the *source* (3.4) to the *receiver* (3.5) structure

Note 1 to entry: n is the number of DOFs and c is the subscript used for contact DOFs.

Note 2 to entry: See 4.3 for a full definition.

3.9
indicator degrees of freedom
indicator DOFs
DOFs on the *receiver* (3.5) at which vibration responses are measured

Note 1 to entry: m is the number of DOFs and r is the subscript used for indicator DOFs.

Note 2 to entry: See 4.4.

3.10
validation degrees of freedom
validation DOFs
DOFs on the *receiver* (3.5) structure (not at the contact area) at which "spare" vibration responses are measured so as to provide a comparison for the on-board validation

Note 1 to entry: p is the number of DOFs and v is the subscript used for validation DOFs.

Note 2 to entry: See 4.5.

Note 3 to entry: The validation is described in Clause 9.

3.11
indicator velocity vector
$\boldsymbol{v}_{\mathrm{r}}(f)$
complex velocity (or acceleration) at the *indicator DOFs* (3.9), arranged into an $m \times 1$ vector at each frequency according to:

$$\boldsymbol{v}_{\mathrm{r}}(f) = \begin{Bmatrix} v_{r,1}(f) \\ v_{r,2}(f) \\ \vdots \\ v_{r,m}(f) \end{Bmatrix}$$

where $v_{r,j}(f)$ is the complex Fourier spectrum component of the velocity (or acceleration) at frequency f and at indicator DOFs j

Note 1 to entry: Consistent quantities shall be used throughout: either velocity and mobility, or acceleration and accelerance.

3.12
measured validation velocity vector
$\boldsymbol{v}_{\mathrm{v}}(f)$

complex velocity (or acceleration) at the *validation DOFs* (3.10), arranged into a $p \times 1$ vector at each frequency according to:

$$\boldsymbol{v}_{\mathrm{v}}(f) = \begin{Bmatrix} v_{v,1}(f) \\ v_{v,2}(f) \\ \vdots \\ v_{v,p}(f) \end{Bmatrix}$$

where $v_{v,k}(f)$ is the complex Fourier spectrum component of the velocity (or acceleration) at frequency f and at indicator degree of freedom k

3.13
predicted validation velocity vector
$\boldsymbol{v}_{\mathrm{v}}'(f)$
complex velocity (or acceleration) vector which has the same form as the *measured validation velocity vector* (3.12) but contains predicted rather than measured data

Note 1 to entry: It is calculated according to Clause 8.

3.14
operational test
test in which vibration responses are measured at the *indicator* (3.9) and *validation DOFs* (3.10) while the *source* (3.4) is in operation under a given set of *operational conditions* (3.16)

3.15
operational test using artificial excitation
test in which vibration responses are measured at the *indicator* (3.9) and *validation DOFs* (3.10) in the same way as for an *operational test* (3.16) except that the *source* (3.4) is switched off and excitation is provided by an instrumented hammer or shaker

3.16
operational conditions
defined set of circumstances under which the *source* (3.4) operates for the *operational test* (3.14), including speed, load and any other settings or conditions particular to the source which can affect source operation

3.17
artificial excitation
set of circumstances similar to *operational conditions* (3.16) except that the *source* (3.4) is switched off and the source structure is excited artificially by a controlled force from an instrumented hammer or shaker

3.18
background noise conditions
conditions similar to *operational conditions* (3.16) except that the *source* (3.4) is switched off while any other auxiliary equipment required to operate or load the source, e.g. hydraulic pumps, generators or actuators, and/or other secondary sources of noise, e.g. wind noise, are active

3.19
on-board validation
procedure used for determining the quality of the *blocked force* (3.1) data

Note 1 to entry: The on-board validation is described in Clause 9.

3.20
frequency response function test
FRF test
test in which the response to a unit point force (mechanical mobility or accelerance) matrix is measured with the *source* (3.4) switched off, i.e. under passive conditions

3.21
inversion frequency response function matrix
inversion FRF matrix
$\boldsymbol{Y}_{\mathrm{rc}}$
$m \times n$ matrix of *FRFs* (3.2) in which the columns correspond to the *contact DOFs* (3.8) and the rows to the *indicator DOFs* (3.9) according to:

$$\boldsymbol{Y}_{\mathrm{rc}}(f)=\begin{bmatrix} Y_{r_1c_1}(f) & Y_{r_1c_2}(f) & \dots & Y_{r_1c_n}(f) \\ Y_{r_2c_1}(f) & \ddots & & \vdots \\ \vdots & & \ddots & \vdots \\ Y_{r_mc_1}(f) & Y_{r_mc_2}(f) & & Y_{r_mc_n}(f) \end{bmatrix}$$

where $Y_{r_jc_i}(f)$ is the complex mobility (or accelerance) at frequency f for excitation at contact DOF c_i and response at indicator DOF r_j

Note 1 to entry: Consistent quantities shall be used throughout: either velocity and mobility, or acceleration and accelerance.

Note 2 to entry: The mobility (accelerance) shall be dimensionally consistent with the contact DOFs and particular care is required if rotational components (moments) are included in the definition of the blocked force vector.

3.22
validation frequency response function matrix
validation FRF matrix
$\boldsymbol{Y}_{\mathrm{vc}}$
$p \times n$ matrix of *FRFs* (3.2) in which the columns correspond to the *contact DOFs* (3.8) and the rows to the *validation DOFs* (3.10):

$$\boldsymbol{Y}_{\mathrm{vc}}(f)=\begin{bmatrix} Y_{v_1c_1}(f) & Y_{v_1c_2}(f) & \dots & Y_{v_1c_n}(f) \\ Y_{v_2c_1}(f) & \ddots & & \vdots \\ \vdots & & \ddots & \vdots \\ Y_{v_pc_1}(f) & Y_{v_pc_2}(f) & \dots & Y_{v_pc_n}(f) \end{bmatrix}$$

where $Y_{v_kc_i}(f)$ is the complex mobility (or accelerance) at frequency f for excitation at contact DOF c_i and indicator at validation DOF v_k

3.23
direct excitation
excitation applied to the *contact DOFs* (3.8) for the *FRF test* (3.20), as opposed to reciprocal excitation (7.3.3)

4 Selection of degrees of freedom (DOFs)

4.1 General

Selection of the appropriate DOFs is an essential part of the procedure which can have an important bearing on the reliability of the results. It is difficult to provide comprehensive guidelines since every case is unique, however, some general guidelines are given below.

The main sources of error are likely to be related to inconsistency or incompleteness of the data set:

a) incompleteness due to transmission via DOFs not included in the definition of the contact DOFs;

b) inconsistency due to differences in location or direction of the frequency response function (FRF) excitation compared with the actual operational forces.

Therefore, selection of the appropriate DOFs is important.

It is advisable to agree on the contact DOFs, indicator DOFs and validation DOFs with the client prior to testing. Also, a preliminary test is recommended (as described in 7.4) in order to test and, if necessary, refine the selection of contact DOFs.

Particular care is required in determining the DOFs to be included at the interface since small details can have a strong influence on the results. Examples of particular interface types are provided in Annex C.

At each DOF, it is essential to adopt a sign convention for the direction of the force and velocity (or acceleration) and this convention shall be adopted consistently between the operational and FRF tests. Large errors can result from errors in sign.

NOTE See ISO 7626-1 for advice on polarity of transducers.

4.2 Source receiver interface

The source receiver interface is a hypothetical surface between the source and receiver structures. The part of the interface where there is solid contact between the source and receiver is known as the contact area. The contact area need not be continuous and typically consists of one or more points, lines or areas of contact, such as flanges. The contact area typically coincides with the connections between separable components, such as a pump and its support structure. However, the choice of the interface is arbitrary provided that all the source mechanisms which generate structure-borne sound and vibration are on the source side of the interface.

4.3 Contact DOFs

The contact area typically consists of one or more points, lines or areas of contact at which the source and receiver structures are physically connected. The *n* contact DOFs are selected so as to account for the excitation and coupling between the receiver and the source through these connections. In order to select the correct DOFs, it is important to understand how the receiver structure is coupled to, and excited by, the source. Important DOFs can include moments, and in-plane forces as well as normal forces. Omission of important DOFs can lead to significant errors in the calculation of blocked forces. On the other hand, inclusion of unnecessary DOFs increases the possibility for inversion errors, particularly if the corresponding FRF data quality is poor, which is more likely for DOFs that are difficult to excite, such as moments. Experimentation prior to data acquisition can be required to determine relevant DOFs, for example using the artificial excitation procedure (see 7.4) combined with onboard validation (see 9.2). Additionally, the "Interface Completeness Coefficient"[27] may be employed to help define the contact DOFs.

For point contact, excitation can occur, in general, in up to six DOFs at each point (three forces and three moments on orthogonal axes). Continuous line interfaces may, for example, be represented by a set of discreet points distributed along the line. Small contact areas (small in comparison with a structural wavelength) may be represented as single equivalent points with up to six DOFs, or as a grid of points. In all cases, sufficient accelerometers need to be employed so as to capture the dynamics of the structures in all significant DOFs.

Each contact DOF may correspond directly to an accelerometer. Alternatively, the contact DOFs may be obtained by combining the signals from several accelerometers, for example by subtracting signals to give rotational DOFs using the "Finite Difference Method"[30,18]. Other methods of defining contact DOFs from combinations of accelerometer signals include, but are not limited to, the "Virtual Point Transformation"[26] and "Interface Mobilities"[31].

4.4 Indicator DOFs

4.4.1 General

The indicator DOFs may coincide fully or partially with the contact DOFs (4.3). Indicator DOFs may be located anywhere on the receiver including, ideally, at the contact interface. The system shall be "determined" or "over-determined", which means that there shall be at least as many indicator DOFs as contact DOFs (i.e., $m \geq n$). The indicator DOFs may be fully coincident with the contact DOFs, partially coincident or not coincident, in other words all, none or some of the indicator DOFs may be at the contact area.

4.4.2 All indicator DOFs at contact area

In this case, the indicator DOFs are the same as the contact DOFs. The inversion FRF matrix is then square and symmetrical. For reasons not fully understood[28], this arrangement often appears to provide better results than when the indicator DOFs are away from the interface. However, this option demands direct excitation at the contact DOFs during the FRF measurement and is not always possible.

4.4.3 No indicator DOF at contact area

In this case, the indicator DOFs are all located away from the contact area. It is thus strongly advised to over-determine the system by adding more indicator DOFs than contact DOFs, typically by a factor between 2 and 3. The measured responses should have as much linear independence as possible and therefore it is advisable to select indicator DOFs which capture different aspects of structural response, for example by using well-spaced locations and different directions. If reciprocal excitation is to be used for FRF measurement, then the ease with which these DOFs can be excited in the FRF test is also a factor to consider since practical difficulties in excitation are a common reason for poor quality FRF data.

4.4.4 Some indicator DOFs at contact area

A third option is to locate some of the indicator DOFs at the contact interface and some elsewhere on the receiver. In this case, it is also advisable to over-determine the system.

4.5 Validation DOFs

The validation DOFs shall be selected so as to provide responses which are, as far as possible, linearly independent from those at the indicator DOFs (4.4) which are used in the solution (Clause 8). They shall not be located at the contact area. They shall be at different locations and/or in different directions to any of the indicator DOFs so as to provide as much linear independence as possible.

5 Test arrangement

5.1 General

The test may be conducted in situ, i.e. with the source installed in a real installation, or on a specially designed test stand. The factors to consider in the choice of test arrangement are:

a) representativeness of the receiver in terms of its effect on source mechanisms;

b) design of the test receiver structure for ease of access, avoidance of resonances and non-linearities;

c) the need to avoid secondary noise sources.

5.2 Representativeness of the receiver

Provided the source mechanisms remain constant, the blocked force is theoretically an independent property of the source and therefore is, in principle, not affected by the installation. However, dynamic loading of the source by the receiver structure can influence source mechanisms, for example due to quasi-static deformation of a gearbox under load which can affect gear misalignment. There is little information available on any such dynamic loading effects; however, it is advisable to ensure that the test arrangement is representative of any intended installation in order to minimize such effects.

In the case of an in situ test, the test environment is representative by definition. However, some sources are designed for a range of receivers, in which case it can be desirable to test the same source on a range of receiver structures representing the intended installations.

If the test receiver is different from that of the intended installation, either because a special test rig is used or because the intended receivers' properties are variable, then it is necessary to consider the representativeness of the receiver. The assumption in this document is that source mechanisms are not unduly affected if the receiver structure for the test is dynamically similar to that of the intended installation. Without further study, the requirements for dynamic similarity cannot be precisely defined. However, for the purposes of this document, the following shall apply:

a) A source intended to be resiliently mounted shall be resiliently mounted for the blocked force test on mounts of similar dynamic stiffness; it shall be specified whether the mounts are included as part of the source or the receiver.

b) A source intended to be rigidly mounted shall be rigidly mounted for the blocked force test, preferably on a structure with dynamic stiffness similar to the intended receiver structure. Test rigs of the same material and thickness similar to the intended installation are considered sufficiently similar.

5.3 Design of test receiver

To a large extent, the reliability of the blocked forces obtained by inversion is determined by the completeness and consistency of the entire data set, including in particular the frequency response function (FRF) matrix. Therefore, in addition to ensuring representativeness of the test setup, as described above, the test structure should be designed so as to facilitate the measurements. In particular, it is desirable to

a) optimize access to the contact degrees of freedom;

b) avoid strong resonances; and

c) avoid secondary noise sources.

Poor access to the excitation points, particularly the contact DOFs, is a major cause of errors in the FRF matrix which can be amplified on inversion. Therefore, if access to the contact DOFs is restricted in a real installation, it can be advantageous to employ a specifically designed test rig.

The presence of strong, undamped resonances in the assembly generally makes it more difficult to obtain reliable blocked forces by inversion. Damping can be added to the test rig without affecting the dynamic similarity (5.2) and thus it is generally desirable to provide as much damping as possible in the test receiver. No damping shall be added at the interface or on the source side of the interface.

Non-linearity in the receiver is to be avoided as far as possible. Structures that rattle when struck are likely to behave non-linearly and should be avoided.

5.4 Avoidance of secondary noise sources

Secondary noise sources are those which are not part of the source under test, but which contribute to the measured response at the indicator or validation DOF. Examples include devices used to load the source, such as dynamometers or brakes, and sources which occur during operational conditions, such as wind noise. A check on such noise sources is included as part of the test procedure described in Clause 7. Where possible, the test arrangement should be designed so as to minimize the influence of secondary sources, e.g., by conducting tests on a dynamometer rather than a test track so as to avoid wind noise.

6 Measuring equipment

6.1 General

The usual measuring equipment and, in particular, the following should be used. Equipment shall be calibrated in accordance with ISO 7626-1 and ISO 7626-2.

6.2 Multi-channel analyser

The multi-channel analyser shall have a minimum of two channels and ideally sufficient channels to allow simultaneous measurement at all indicator and validation DOFs, that is, to have at least $m+p$ channels.

The sampling rate of the analyser shall be sufficient to allow the maximum frequency of interest for blocked forces to be obtained.

6.3 Vibration sensors

There should ideally be sufficient vibration sensors so as to allow simultaneous measurement of all indicator and validation DOFs, that is, at least $m + p$ sensors. The sensitivity and noise floor of the sensors shall be such as to allow measurement of the indicator velocity vector and measured validation velocity vector during the operational test and also for FRF measurement during the FRF test.

In the event that all responses are not measured simultaneously then sequential measurement shall be used with one sensor kept in a fixed position so as to provide a phase reference. Sequential measurements may only be used when the source excitation is precisely repeatable.

NOTE Advice is provided in ISO 7626-1.

6.4 Means of excitation

It is required to excite the assembly in order to measure the FRF matrices during the FRF test. In principle, an instrumented hammer or shaker can be used, however, the hammer has significant advantages in terms of flexibility and has proved to provide reliable results.

The means of excitation shall supply excitation forces over a sufficient frequency range to allow FRFs to be measured over the desired frequency range.

7 Test procedure

7.1 General

The test consists of two parts, the operational test and the FRF test. In addition, a preliminary operational test using artificial excitation shall be conducted. The steps in the procedure are summarized in the flow chart in Figure 2.

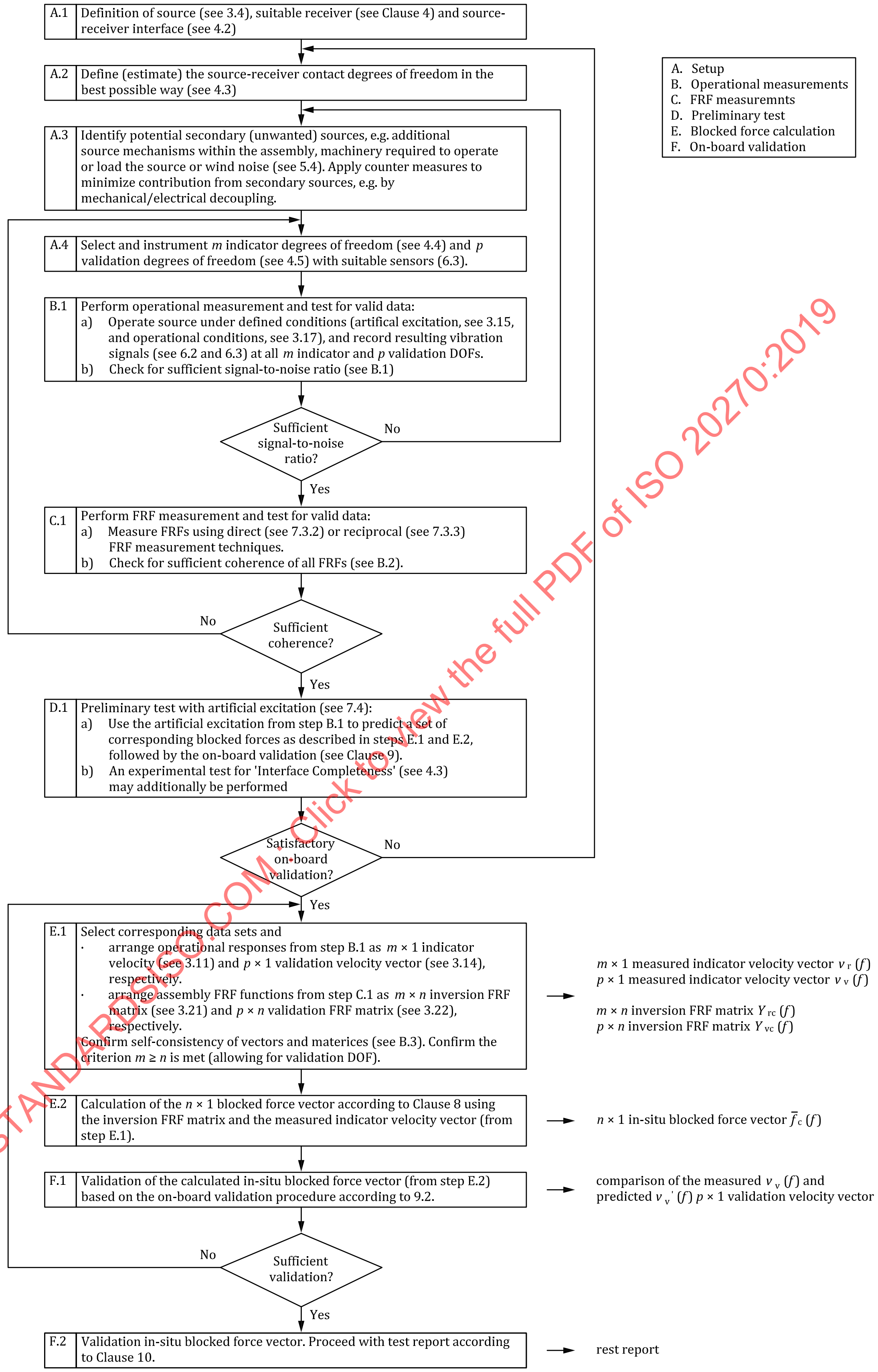


Figure 2 — Test procedure

The frequency resolution of the analyser shall be the same for the operational and FRF tests.

Prior to testing, the following shall be defined:

a) the source-receiver interface;

b) the contact DOFs;

c) the indicator DOFs;

d) the validation DOFs;

e) the operational conditions;

f) the background noise conditions.

7.2 Operational test

The operational test shall comprise the following steps:

1. Vibration sensors shall be mounted on the receiver at the indicator DOFs and the validation DOFs.
2. The source shall be operated under the defined operational conditions.
3. The indicator velocity vector $\boldsymbol{v}_{\mathbf{r}}$ and the measured validation vector $\boldsymbol{v}_{\mathbf{v}}$ shall be recorded simultaneously, if possible, from the corresponding sensors.
4. The source shall be switched off and the resulting background noise shall be measured for all indicator and validation DOFs according to the defined background noise conditions.
5. Sufficient signal-to-noise ratio of the operational indicator vector $\boldsymbol{v}_{\mathbf{r}}$ and validation velocity vector $\boldsymbol{v}_{\mathbf{v}}$ from step 3 and the corresponding background noise vectors from step 4 shall be confirmed according to B.1.

7.3 Frequency response function (FRF) test

7.3.1 General

The source shall be switched off for the FRF test. If there is sufficient access to allow excitation to be applied to all the contact DOFs, then the sensors shall be left in place at the indicator and validation DOFs and a direct FRF measurement shall be employed (as per 7.3.2). If access to the contact DOFs is not sufficient to allow a reliable excitation to be applied there, then a reciprocal FRF measurement shall be conducted (as per 7.3.3). Sufficient coherence shall be confirmed for all conducted FRF measurements (as per B.2).

Typically, the FRF matrix is measured by applying excitation one DOF at a time with an instrumented hammer so as to build up columns of the FRF matrix. However, other measurement approaches are not excluded if they can be shown, through the on-board validation, to produce reliable results.

7.3.2 Direct FRF measurement

Excitation shall be applied at the contact DOFs and the responses measured at the indicator and validation DOFs. The resulting point-to-point FRFs shall be assembled into FRF matrices $\boldsymbol{Y}_{\mathbf{rc}}$ and $\boldsymbol{Y}_{\mathbf{vc}}$.

7.3.3 Reciprocal FRF measurement

Where direct excitation of the contact DOFs is not possible for the FRF test, then reciprocal excitation may be used where the excitation and response positions are reversed. Excitation is then made at all indicator and validation DOFs and the response is measured at the contact DOFs. The resulting matrices have columns corresponding to indicator and validation DOFs and rows corresponding to the contact DOFs and shall be transposed in order to obtain the required FRF matrices $\boldsymbol{Y}_{\mathbf{rc}}$ and $\boldsymbol{Y}_{\mathbf{vc}}$ according to:

$$\boldsymbol{Y}_{\mathrm{cr}}^{\mathrm{T}} = \boldsymbol{Y}_{\mathrm{rc}}$$

$$\boldsymbol{Y}_{\mathrm{cv}}^{\mathrm{T}} = \boldsymbol{Y}_{\mathrm{vc}}$$

where T represents the matrix transpose. For a reciprocal FRF measurement, vibration sensors shall be removed from the indicator and validation DOFs and placed at the contact DOFs. Excitation shall be applied at the indicator and validation DOFs and the responses measured at the contact DOFs. The resulting point-to-point FRFs shall be assembled into matrices and transposed so as to obtain the FRF matrices $\boldsymbol{Y}_{\mathrm{rc}} = \boldsymbol{Y}_{\mathrm{cr}}^{\mathrm{T}}$ and $\boldsymbol{Y}_{\mathrm{vc}} = \boldsymbol{Y}_{\mathrm{cv}}^{\mathrm{T}}$.

7.4 Preliminary test with artificial excitation

The preliminary test shall follow the same steps as the full test described in 7.2 and 7.3 with the exception that, during the operational test, rather than operating the source, it shall be excited into vibration artificially, typically by exciting the source structure with an instrumented hammer or shaker. The on-board validation for this test (see Clause 9) can be useful for improving the results of the inversion, for example by optimizing the locations of the indicator or validation points, checking the consistency of the sign convention and, in particular, for refining the description of the contact interface and the contact DOFs.

Annex B provides various tests for validity of measurement data.

Annex D provides criteria for selection of indicator and validation DOFs.

Annex E provides an extension of the method for the prediction of sound and vibration.

8 Analysis procedure

The in situ blocked force vector shall be obtained by solving Formula (1) at every frequency:

$$\boldsymbol{v}_{\mathrm{r}} = \boldsymbol{Y}_{\mathrm{rc}} \overline{\boldsymbol{f}_{\mathrm{c}}} \tag{1}$$

where

$\boldsymbol{v}_{\mathrm{r}}$ is the indicator velocity (or acceleration) vector;

$\overline{\boldsymbol{f}_{\mathrm{c}}}$ is the vector of blocked forces at the contact DOFs;

$\boldsymbol{Y}_{\mathrm{rc}}$ is the mobility matrix connecting the indicator and contact DOFs.

Typically, Formula (1) is solved using matrix inverse or pseudo inverse:

$$\overline{\boldsymbol{f}_{\mathrm{c}}} = \boldsymbol{Y}_{\mathrm{rc}}^{+} \boldsymbol{v}_{\mathrm{r}} \tag{2}$$

where $\boldsymbol{Y}_{\mathrm{rc}}^{+}$ is the pseudo inverse of $\boldsymbol{Y}_{\mathrm{rc}}$.

NOTE The units for the measured quantities are shown in Table 1.

Table 1 — Units of measured quantities

<table>
<tr><th colspan="3">Response units</th></tr>
<tr><th colspan="2">Response</th><th>Units</th></tr>
<tr><td colspan="2">Velocity</td><td>ms^{-1}</td></tr>
<tr><td colspan="2">Angular velocity</td><td>s^{-1}</td></tr>
<tr><td colspan="2">Acceleration</td><td>ms^{-2}</td></tr>
<tr><td colspan="2">Angular acceleration</td><td>s^{-2}</td></tr>
<tr><td colspan="2">Sound pressure</td><td>Pa</td></tr>
<tr><th colspan="3">Force units</th></tr>
<tr><th colspan="2">Excitation</th><th>Units</th></tr>
<tr><td colspan="2">Force</td><td>N</td></tr>
<tr><td colspan="2">Moment</td><td>Nm</td></tr>
<tr><th colspan="3">FRF units</th></tr>
<tr><th>Excitation</th><th>Response</th><th>Units</th></tr>
<tr><td>Force</td><td>Velocity</td><td>$ms^{-1}N^{-1}$</td></tr>
<tr><td>Force</td><td>Angular velocity</td><td>$s^{-1}N^{-1}$</td></tr>
<tr><td>Moment</td><td>Velocity</td><td>$ms^{-1}(Nm)^{-1}$</td></tr>
<tr><td>Moment</td><td>Angular velocity</td><td>$s^{-1}(Nm)^{-1}$</td></tr>
<tr><td>Force</td><td>Acceleration</td><td>$ms^{-2}N^{-1}$</td></tr>
<tr><td>Force</td><td>Angular acceleration</td><td>$s^{-2}N^{-1}$</td></tr>
<tr><td>Moment</td><td>Acceleration</td><td>$ms^{-2}(Nm)^{-1}$</td></tr>
<tr><td>Moment</td><td>Angular acceleration</td><td>$s^{-2}(Nm)^{-1}$</td></tr>
<tr><td>Force</td><td>Sound pressure</td><td>PaN^{-1}</td></tr>
<tr><td>Moment</td><td>Sound pressure</td><td>$Pa(Nm)^{-1}$</td></tr>
</table>

Self-consistency of the employed indicator velocity vector and the mobility matrix shall be confirmed before solving for the in situ blocked force vector (as per B.3). Commercial software exists and may be employed to facilitate consistent ordering of the matrices and vectors and for solving Formula (1).

When solving inverse problems, such as Formula (1), it is common practice to employ "regularization" to stabilize the mathematical solution. Regularization works by reducing the influence of the smallest singular values of the matrix for example by setting those below a tolerance to zero. However, regularization may provide a false sense of the reliability of the inversely determined blocked forces. Therefore, Formula (1) shall be solved initially without regularization and the unregularized solution shall be employed in the on-board validation and reported.

The solution of Formula (1) may be considered unregularized if the tolerance value is less than or equal to $m|\boldsymbol{Y}|\epsilon$ where $|\boldsymbol{Y}|$ is the 2 norm of the mobility (or accelerance) matrix and ϵ is the spacing of floating point numbers for the computer being used.

9 Uncertainties and validation

9.1 General

It is recognized that uncertainties in blocked forces can vary considerably from case to case. Therefore, in this document, an on-board validation approach is adopted to provide an indication of the reliability of the results on a case by case basis. The procedure consists of comparing the measured and predicted validation velocity vectors. Differences between the predicted and measured velocity provide the most reliable indication, at current state of the art, of possible measurement error for the specific case in question. What constitutes a satisfactory agreement should be determined on a case by case basis normally by the end user. The on-board validation does not provide a fully independent validation of the results, or a guarantee of the transferability of the blocked forces and caution is required even when a satisfactory on-board validation is obtained.

Evaluation of measurement uncertainty is also recommended for which procedures have been proposed[29], although at current state of the art there are few published examples.

9.2 On-board validation

Test results shall be accompanied by the results of an on-board validation consisting of a comparison of predicted and measured validation velocity (or acceleration) vectors. The operation shall be conducted for operational test data using both operational (7.2) and artificial (7.4) excitation.

The predicted validation velocity (or acceleration) vector $\boldsymbol{v}_\mathrm{v}$ shall be obtained using Formula (3):

$$\boldsymbol{v}_\mathrm{v}' = \boldsymbol{Y}_\mathrm{vc}\,\overline{\boldsymbol{f}_\mathrm{c}} \tag{3}$$

where

$\boldsymbol{v}_\mathrm{v}'$	is the predicted validation velocity (or acceleration) vector (3.13);
$\boldsymbol{Y}_\mathrm{vc}$	is the FRF matrix of validation degrees of freedom (3.22);
$\overline{\boldsymbol{f}_\mathrm{c}}$	is the vector of blocked forces obtained from the analysis procedure in Clause 8.

NOTE 1 The units for the measured and predicted quantities are shown in Table 1.

The measured validation velocity (or acceleration) vector $\boldsymbol{v}_\mathrm{v}$ shall be measured at the validation DOFs during the operational test as per 7.2.

The predicted validation velocity (or acceleration) $\boldsymbol{v}_\mathrm{v}'$ shall be compared with the measured velocity (or acceleration) $\boldsymbol{v}_\mathrm{v}$ by plotting on the same axis in narrow frequency bands. A separate plot shall be produced for each validation DOF. Additional comparisons in third octave or other bandwidths are also recommended.

NOTE 2 The term "on-board" is used to indicate that the validation is done for the same receiver as the operational test (not necessarily on board a vehicle).

9.3 Preliminary validation using artificial excitation

A preliminary validation shall be conducted using a simulated operational test. The advantages are, first, that it provides a verification check in which errors in sign convention, ordering of data in matrices and vectors, or calculation procedures can be detected. Secondly, it provides an indication of the likely quality of the FRF data with respect to obtaining an inverse solution.

In a simulated operational test, the source structure shall be excited with a controlled excitation from a shaker or instrumented hammer when the source is switched off. The excitation is ideally broadband and shall allow a reliable phase reference to be obtained. The validation shall be conducted in accordance with Clause 7 and the on-board validation in accordance with 9.2 exactly as for an on-board validation, except that the operational conditions are replaced by simulated operational conditions.

10 Test report

The test report shall include the following information:

a) reference to this document, i.e. ISO 20270:2019;

b) the name of the organization that performed the test;

c) the date of the test;

d) a description of the source (type, manufacturer, serial number, supports and any other relevant details);

e) a description of the test setup including details of the receiver structures and its connections to that of the source;

f) the operating condition(s) of the source (e.g. speed, load and other conditions particular to the source);

g) a description of the source-receiver interface and the contact DOFs including sign convention;

h) the position, orientation, mounting and mass of the vibration sensors for the operational test;

i) the position, orientation, mounting and mass of the vibration sensors together with the position and orientation of the excitation positions for the FRF test;

j) the measurement equipment used, including type, serial number, sensitivity and manufacturer;

k) a description of the means of excitation for the FRF test, including type, serial number, sensitivity and manufacturer of the force transducer;

l) a plot of the FFT (both magnitude and phase) of the unregularized blocked force at each contact DOF; the caption of the figure shall include the statement *"FFT, magnitude and phase, of the blocked force for contact DOF i. Resolution xx Hz"*, where *i* and *xx* are replaced with actual values;

m) a plot of the FFT (both magnitude and phase) of the measured and predicted (unregularized) validation response; the measured result shall be plotted in a solid black line and the predicted response in a dotted and/ or red line; the caption of the figure shall include the statement *"FFT, magnitude and phase, of the velocity (or acceleration) at validation DOF i. Measured response in solid black, predicted response in red (and/ or dotted). Resolution xx Hz"*, where *i* and *xx* are replaced with actual values;

n) if a regularized solution to Formula (1) is presented (in addition to the unregularized solution required in l), then it shall be accompanied by a description of the regularization employed;

o) if the source is tested on a receiver structure which is not part of a real installation, then the reasons for considering it to be representative of a real installation (5.2) shall be stated.

Annex A provides an example of a possible report.

Annex C provides examples of test cases that were studied in the development of this method.

Annex A
(informative)

Example of a test report: Electric rear axle drive in a passenger car; transfer path analysis (TPA) and estimation of blocked forces in situ according to ISO 20270:2019

A.1 General information

Measurements carried out by Volvo Car Corporation, March 25-26th 2014, at the Volvo Torslanda R&D center.

A.2 Test object

Electric rear axle drive (ERAD) including a 50 kW permanent magnet synchronous machine with a planetary gearbox, supported by four rubber mounts to a subframe which in turn is supported to the car body by four rubber mounts. Installed in a Volvo V60 D6 plugin hybrid vehicle[1)]. See Figure A.1 for details.

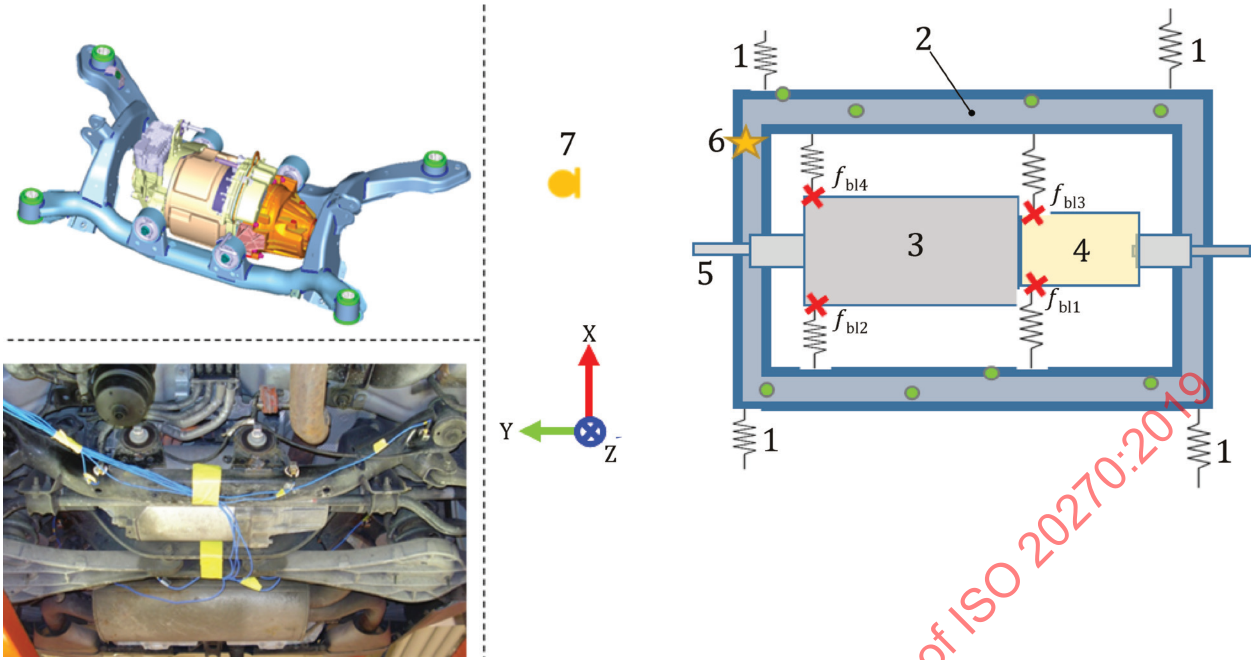
A.3 Operating condition of the source

From stand still to 15 km/h uphill with part open throttle (slow acceleration), pure electric drive mode. The 30th order with respect to electric motor mechanical rpm was extracted.

A.4 The source-receiver interface

Figure A.2 depicts two of the four source-receiver interface points including the coordinate system. The blocked forces were defined on the active side of the ERAD mounts, at the screw heads of the screws which are penetrating the inner part of the mount and attached to the bosses of the ERAD housing. For accessing the screw heads properly with the impact hammer, aluminium cubes were glued to each screw head (Figure A.3 and Figure A.4). Only translational forces in Z-direction (vertical direction) were included in this model for simplification.

1) This information is given for the convenience of users of this document and does not constitute an endorsement by ISO of this product.



Key

✖	blocked force/impact hammer points
●	indicator accelerometer points
◖	on board validation point (microphone)
★	on board validation point (accelerometer)
1	body
2	sub frame
3	stator
4	gearbox
5	driveshaft
6	obv2
7	obv1

Figure A.1 — Images and schematic top view of the suspension of the ERAD

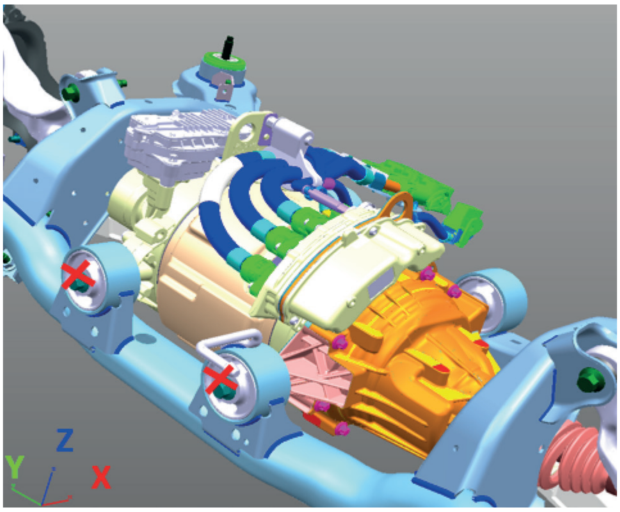


Figure A.2 — Illustration of the source-receiver interface including points where the blocked forces were defined (red crosses)

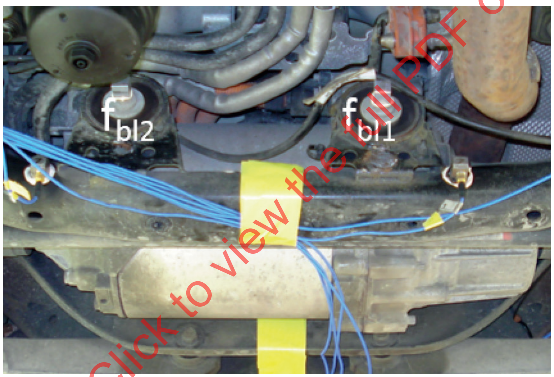


Figure A.3 — Close up view of the source-receiver interface, showing the aluminium cubes at contact points 1 and 2

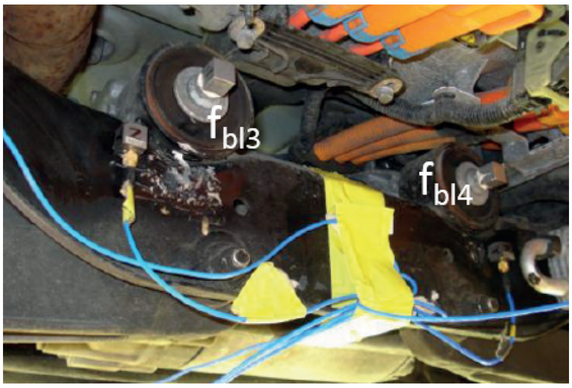


Figure A.4 — Close up view of the source-receiver interface, showing the aluminium cubes at contact points 3 and 4

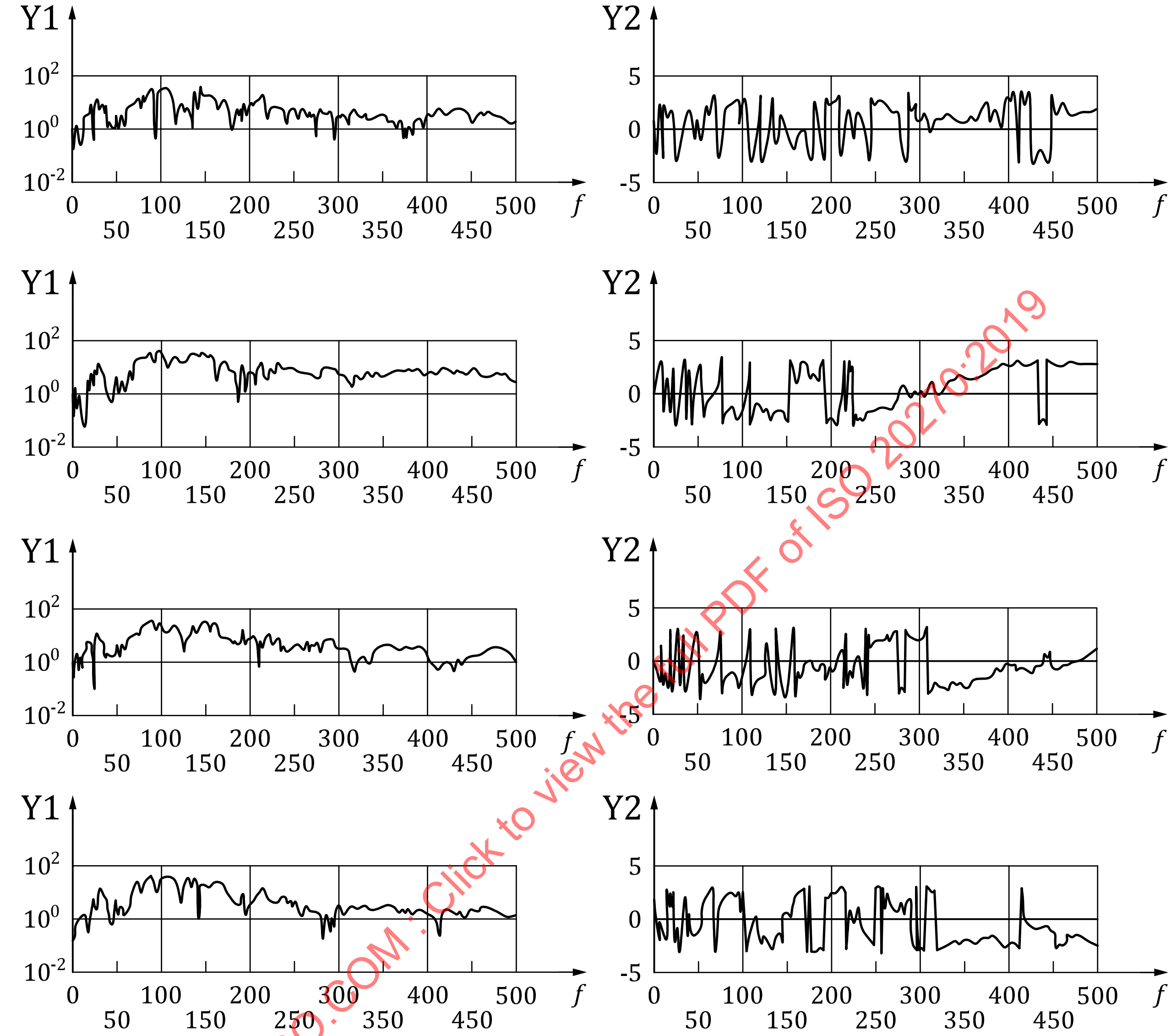
A.5 Instrumentation

The sensors were positioned in the same way for the operational test as for the FRF test case. Table A.1 provides information about the mounting direction with respect to vehicle coordinates and sensor details.

Table A.1 — Information about sensors and their orientation throughout the tests

Label	Direction	Sensor type	Serial no	Sensor weight	Sensitivity
Indicator 1	X/-Y/-Z	PCB HT356A15	127060	10 g	Nom. 10 mV/ms^{-2}
Indicator 2	X/-Y/-Z	PCB HT356A15	127258	10 g	Nom. 10 mV/ms^{-2}
Indicator 3	X/-Y/-Z	PCB HT356A15	137234	10 g	Nom. 10 mV/ms^{-2}
Indicator 4	X/-Y/-Z	PCB HT356A15	137236	10 g	Nom. 10 mV/ms^{-2}
Indicator 5	Z/Y/-X	PCB HT356A15	137238	10 g	Nom. 10 mV/ms^{-2}
Indicator 6	Z/Y/-X	PCB HT356A15	151718	10 g	Nom. 10 mV/ms^{-2}
Indicator 7	Z/-Y/X	PCB HT356A15	152076	10 g	Nom. 10 mV/ms^{-2}
Indicator 8	Z/-Y/X	PCB HT356A15	152077	10 g	Nom. 10 mV/ms^{-2}
Phase ref.	X	PCB HT356A15	152077	10 g	Nom. 10 mV/ms^{-2}
obv 1	S	B&K 4189-AO21	2617432	—	Nom. 50 mV/ms^{-2}
obv 2	Z	PCB HT356A15	152077	10 g	Nom. 10 mv/Pa
Hammer	Z	Dytran 5800B5	3496	—	1,17 mV/N

A.6 Results



Key

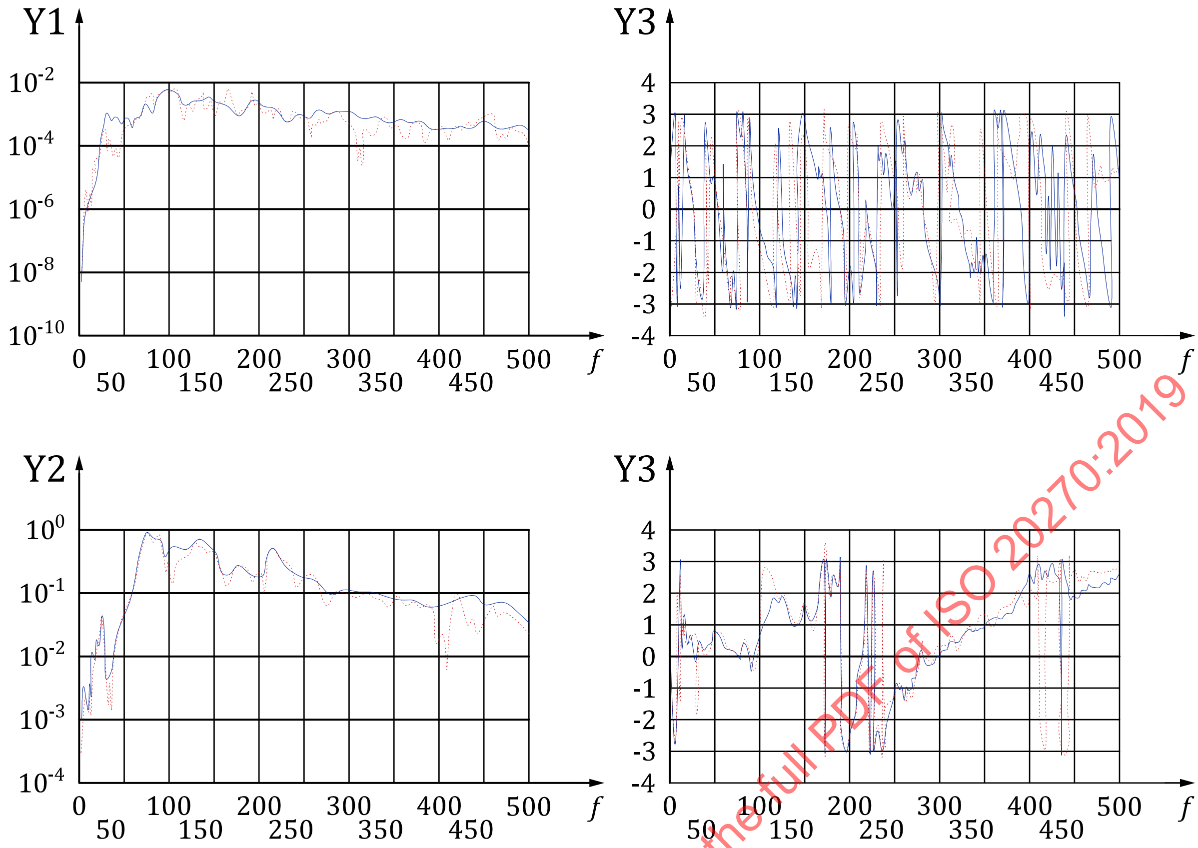
Y1 magnitude (N)

Y2 phase (rad)

f frequency (Hz)

Variable frequency resolution.

Figure A.5 — FFT, magnitude and phase, of the blocked forces f_{bl1}, f_{bl2}, f_{bl3} and f_{bl4} from top to bottom



Key

Y1 magnitude (Pa(A))

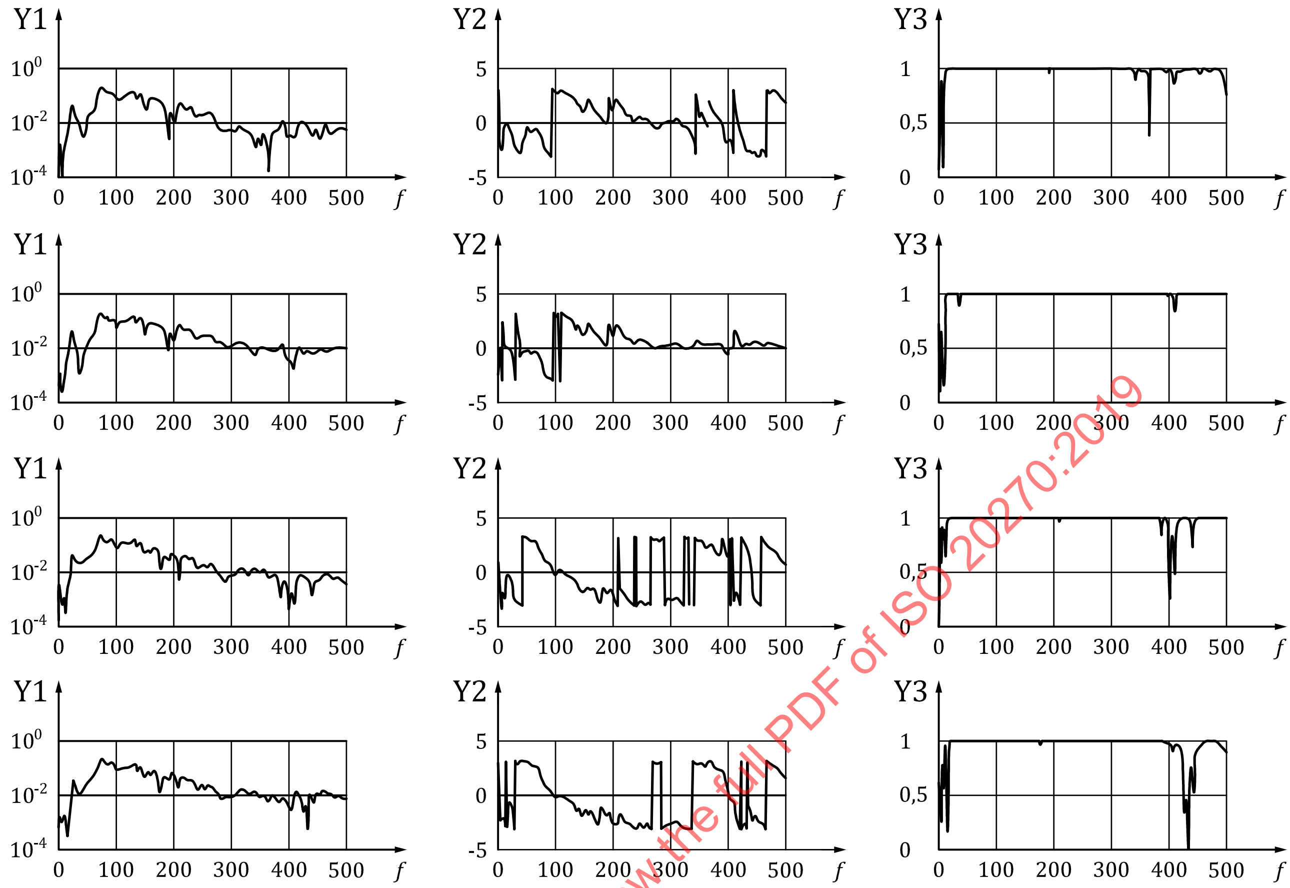
Y2 magnitude (m/s²)

Y3 phase (rad)

f frequency (Hz)

Solid blue: measured response; dotted red: predicted response; variable frequency resolution.

Figure A.6 — FFT, magnitude and phase, of the on-board validation microphone obv1 (upper) and the on-board validation accelerometer obv2 (lower)



Key

Y1 magnitude (m/s² /N)

Y2 phase (rad)

Y3 coherence (-)

f frequency (Hz)

Frequency resolution: 1 Hz.

Figure A.7 — FRFs, magnitude, phase and coherence, between the four source-receiver interface points f_{bl1}, f_{bl2}, f_{bl3} and f_{bl4} (from top to bottom respectively) to obv2

Annex B
(informative)

Tests for validity of measurement data

B.1 Test for valid operational data

As a preliminary test for the validity of operational response data, the signal-to-noise ratio, expressed as a vector in decibel (dB), shall be calculated to check if, at each frequency f, the source is sufficiently contributing to all indicator and validation response DOFs.

The signal-to-noise ratio vector, $\boldsymbol{R}_{\text{SNR dB}}(f)$, is defined as the ratio of signal power to the noise power expressed in dB. In order to test for valid operational data (see 7.2), the condition

$$\boldsymbol{R}_{\text{SNR dB,r}}(f) = 20\log_{10}\left(\frac{\boldsymbol{v}_\text{r}(f)}{\tilde{\boldsymbol{v}}_\text{r}(f)}\right)\text{dB} \geq 10\,\text{dB}$$

and

$$\boldsymbol{R}_{\text{SNR dB,v}}(f) = 20\log_{10}\left(\frac{\boldsymbol{v}_\text{v}(f)}{\tilde{\boldsymbol{v}}_\text{v}(f)}\right)\text{dB} \geq 10\,\text{dB}$$

shall be met, where

$\boldsymbol{v}_\text{r}$, $\boldsymbol{v}_v$ are the desired indicator and validation response vectors, measured while the source is operated under the defined operating conditions, and

$\tilde{\boldsymbol{v}}_\text{r}$, $\tilde{\boldsymbol{v}}_\text{v}$ are the corresponding noise vectors, measured under the background noise conditions (see 7.1).

Lower signal-to-noise ratios indicate that:

a) secondary sources contribute significantly to the selected indicator and/or validation response DOFs (consider relocation of sensors, see Annex D for guidance and/or reduce secondary source contributions, e.g. by mechanical/electrical decoupling); or

b) the structure's ability to vibrate is generally low, e.g. at distinct frequencies related to anti-resonances of the assembly or within broad frequency ranges, if the receiver structure is generally stiff and rigid, such as massive test bench beds (see 5.3 for guidance on design of the test receiver and/or identify sensor locations at which the structure vibrates sufficiently); or

c) the source of interest is generally weak and does not contribute sufficiently to certain sensor positions (see 6.3 for guidance on suitable vibration sensors, Annex D for guidance on sensor locations and/or try to identify sensor locations at which the structure vibrates sufficiently).

B.2 Test for valid FRF data

See ISO 7626-2 for checks of coherence, reciprocity and linearity.

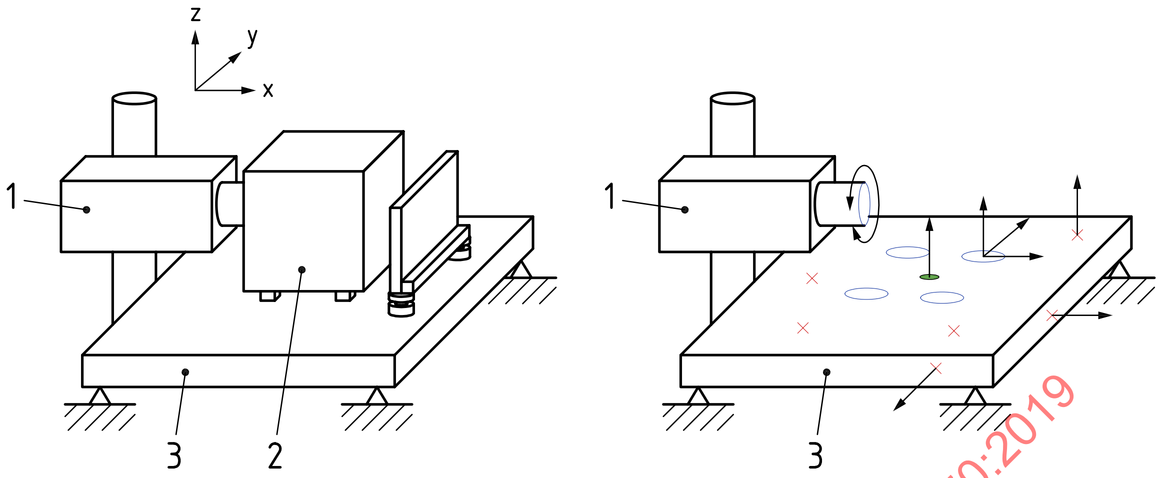
B.3 Test for self-consistency of vectors and matrices

It should be confirmed that vectors and matrices are self-consistent in terms of the position and direction of each entry, e.g. it should be confirmed that a consistent coordinate and sign convention is used. For large (symmetric) FRF matrices, the frequency response assurance criterion (FRAC) and the phase assurance criterion (PAC) may be used to check self-consistency. References may be found in Reference [19] for instance.

Annex C
(informative)

Case studies

Guidance	Example of case Optional short description of application
Source:	Description of source
Type:	Motor, pump, compressor, gear, others...
Loading:	No loading, external loading by additional machinery to be specified, internal mechanisms apply load to source, others...
Notes:	e.g. requirements on external load source, dimensions, material, etc.
Receiver:	Description of receiver
Notes:	e.g. dimensions, material, test setup or original installation, potential interaction of receiver on source mechanisms, etc.
Contact interface:	Description of contact interface and degrees of freedom (DOFs)
Type:	Rigid, soft mounts, others...
DOFs:	Transversal (X,Y,Z), rotations
Notes:	— Additional information on interface, e.g. moving interface such as motor shafts, drive belts or gears — Additional information on instrumentation, e.g. surface sensors or embedded sensors — Additional information on assumptions, e.g. point contact, line contact or surface contact
Cause-response:	Collocated, non-collocated, partially collocated
Validation points:	Description of points used for validation
DOFs:	Number of points and directions
Notes:	Additional information concerning contributing transfer paths according to appendix, etc.



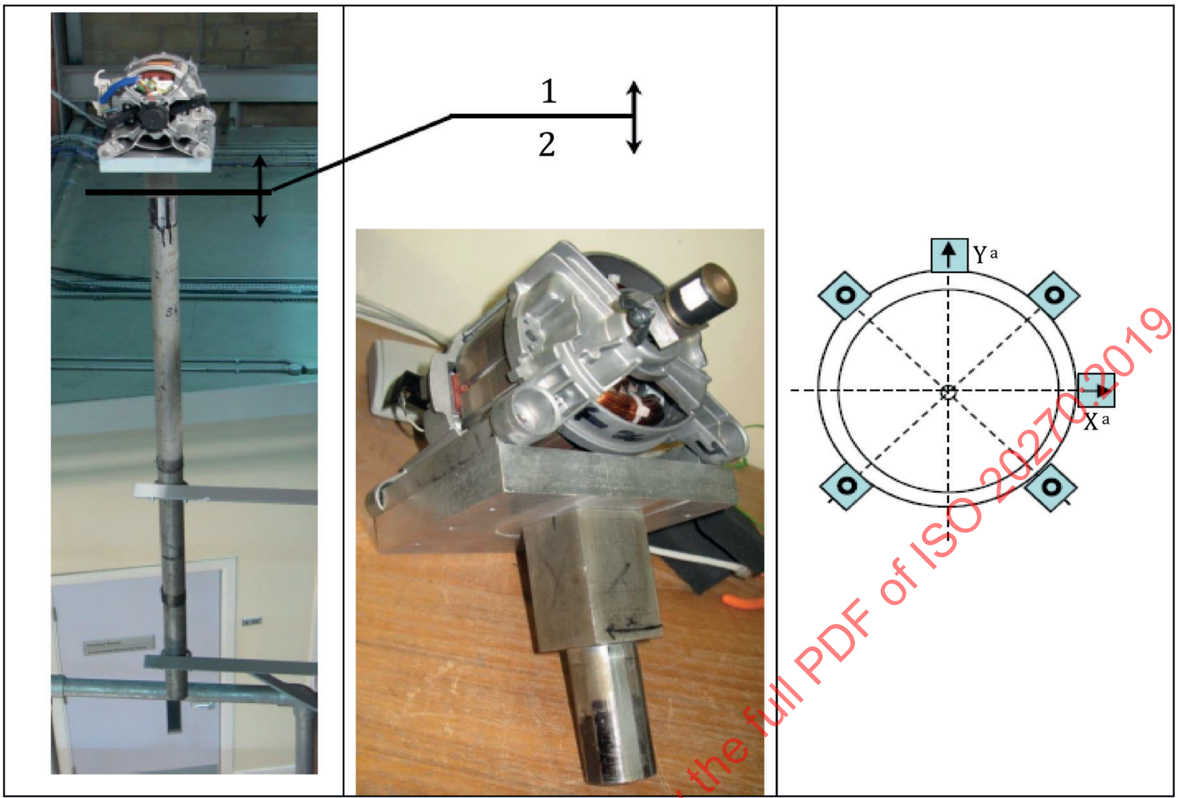
Key

○	contact points
×	response points
●	validation points
↻	rotary DOF
→	translational DOF
1	external load source
2	source
3	receiver

Figure C.1 — Description of figure and legend

Additional notes: Conclusions, advice, expected difficulties, reference to publication ...

Example 1	**Building mounted wind turbine** (laboratory test setup)
Source:	Wind turbine nacelle and blade
Type:	Electric motor with unbalanced mass
Loading:	Free running.
Notes:	Stub shaft is part of the source
Receiver:	Mounting pole with brackets attached to building
Notes:	Pole length: 134cm, distance from wall: 40cm to pole center, bracket length: 49cm, bracket spacing: 51cm
Contact interface:	Section through mounting pole
Type:	Rigid
DOFs:	1 point with 5 degrees of freedom (DOFs) in X,Y and Z directions plus rotations about horizontal axes
Notes:	Surface mounted sensors
Force/Indicator relationship:	Collocated indicator and force DOF
Validation points:	On upper mounting bracket
DOFs:	Y-direction only parallel to wall
Notes:	A second point on the bracket at the point of attachment to the wall was not used.



a) Unbalanced electric motor mounted on a wind turbine mast showing source-receiver interface

b) Source including stub shaft

c) Accelerometers attached to interface

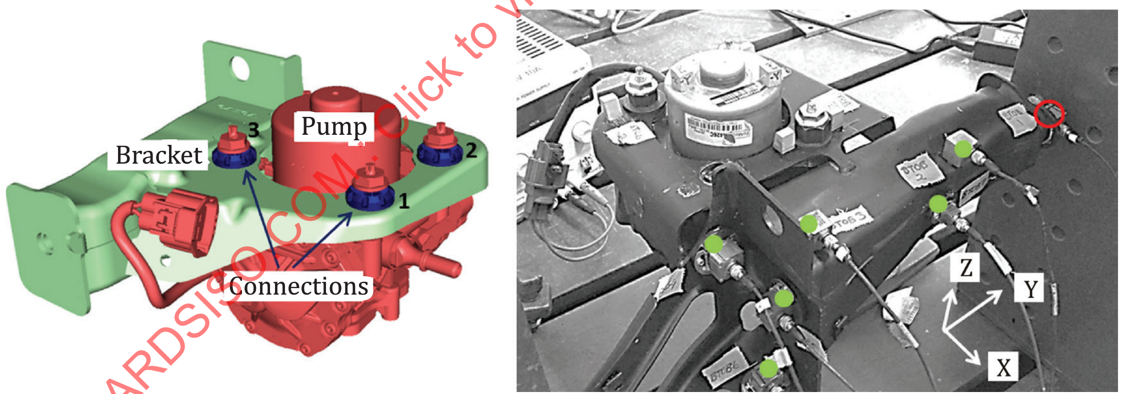
Key

○	out of page (vertical), Z
→	horizontal (in direction of arrow)
1	source
2	receiver

Figure C.2 — Illustrative material

SOURCE: Elliott, A.S. and Moorhouse, A.T., 2010, In-situ characterization of structure borne noise from a building mounted wind turbine, Proceedings of ISMA2010, reproduced with the permission of the authors

Example 2	**Automotive pump mounted to a bracket** (laboratory test setup)
Source:	Pump
Type:	Electrically driven, for an automotive application
Loading:	No loading
Notes:	Fed by 12V, stationary condition
Receiver:	Bracket mounted to a frame work (laboratory setup)
Notes:	In its real environment, the bracket is mounted to the car body in white
Contact interface:	In this laboratory setup, there were three connections between pump and bracket.
Type:	Soft mounts
DOFs:	Transversal (X,Y,Z) rotations
Notes:	Surface mounted trial accelerometers on bracket
Force/Indicator relationship:	Non-collocated indicator and force DOF
Validation points:	On the bracket
DOFs:	X,Y and Z



a) Pump/source (in red) connected to the bracket/receiver (in green) through three interface points (in blue)

b) Assembly setup for the experiments including the six indicator accelerometers (marked with green dots) and the target accelerometer (red circle)

Figure C.3 — Illustrative material

SOURCE: D. Lennström, F. Wullens, M. Olsson, A. Nykänen: "Validation of the Blocked Force Method for Various Boundary Conditions for Automotive Source Characterization", Applied Acoustics vol. 102, p. 108-119, 2016, reproduced with the permission of the authors.

Example 3	**Indoor air vacuum pump** (laboratory test setup)
Source:	
Type:	Electrical motor air vacuum pump, installed with vibration isolators
Loading:	No loading
Notes:	93,2 Watt, continuous pressure 2,76 × 10^5 Pascal
Receiver:	Flat structure with a mechanical mobility of 5 × 10^{-4} (m/s/N)
Notes:	A 4,8 mm steel plate has the approximate characteristics mobility
Contact interface:	
Type:	Resiliently mount on a flat surface
DOFs:	4 point contacts, dominant component in the vertical direction (z)
Notes:	Additional sensors used for over-determination
Force/Indicator relationship:	Partially collocated force and indicator DOF
Validation points:	
DOFs:	6 validation points in the vertical direction (z)
Notes:	On the receiver plate, at 50~100 cm away from mount points.

Figure C.4 — Air vacuum pump mounted on a steel plate with vibration isolators, and instrumented accelerometers near the vibration source

Additional notes: Test setup complexity is greatly reduced for the source showing only one dominant component in the vertical (z) direction.

SOURCE: H. Lai, A. Moorhouse, B. Gibbs, Experimental round-robin evaluation on structure-borne sound source force-power test methods, Proceedings of Inter-Noise 2015, reproduced with the permission of the authors