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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

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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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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.

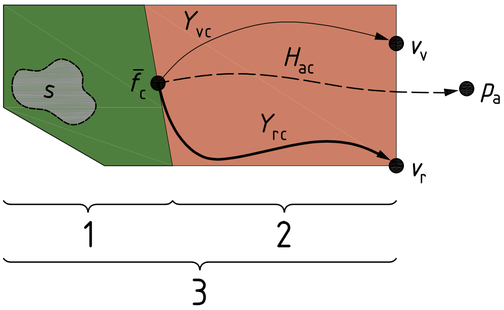
Note 2 to entry: By definition, there are no source mechanisms within the receiver so it is a purely passive structure.

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)
$\bar{\boldsymbol{f}}_\text{c}$	in situ blocked force vector at the set of contact DOFs, *c*
$\boldsymbol{v}_\text{v}$	validation velocity (or acceleration) vector at the set of validation DOFs, *v*
$\boldsymbol{v}_\text{r}$	indicator velocity (or acceleration) vector at the set of validation DOFs, *r*
$\boldsymbol{Y}_\text{vc}$	typical structural FRF between validation DOFs, *v*, and contact DOFs, *c*
$\boldsymbol{Y}_\text{rc}$	typical structural FRF between indicator DOFs, *r*, and contact DOFs, *c*
$\boldsymbol{H}_\text{ac}$	typical vibro-acoustic FRF between prediction DOFs, *a*, and contact DOFs, *c* (see NOTE 3)
$\boldsymbol{p}_\text{a}$	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 ($\boldsymbol{v}_\text{r}$) in, or structure-borne sound ($\boldsymbol{p}_\text{a}$) 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 $\bar{\boldsymbol{f}}_\text{c}$, inferred from $\boldsymbol{v}_\text{r}$ and the assembly FRF matrix $\boldsymbol{Y}_\text{rc}$. Additional structural, $\boldsymbol{Y}_\text{vc}$, and vibro-acoustic FRFs, $\boldsymbol{H}_\text{ac}$, 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 × 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

$\boldsymbol{Y}_{\text{rc}}$

m × *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:

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

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

$\boldsymbol{Y}_{\text{vc}}$

p × *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):

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

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].