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Implementation of ISO 9611:1996

Acoustics — Characterization of sources of structure-borne sound with respect to sound radiation from connected structures — Measurement of velocity at the contact points of machinery when resiliently mounted

ICS 17.140.20

Committees responsible for this British Standard

The preparation of this British Standard was entrusted to Technical Committee EH/1, Acoustics, to Subcommittee EH/1/4, Machinery noise, upon which the following bodies were represented:

Advanced Manufacturing Technology Research Institute
Agricultural Engineers Association
British Cement Association
British Compressed Air Society
British Industrial Truck Association
British Occupational Hygiene Society
Construction Industry Research and Information Association
Department of Environment (Building Research Establishment)
Department of Trade and Industry (National Engineering Laboratory)
Department of Trade and Industry (National Physical Laboratory)
Department of Trade and Industry (Technology and Innovation Policy Division)
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Engineering Equipment and Materials Users Association
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Institution of Engineering Designers
Institution of Mechanical Engineers
National Specialist Contractors Council
Rotating Electrical Machines Association (BEAMA Limited)
Society of Environmental Engineers
Society of Motor Manufacturers and Traders Limited
University of Liverpool
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Contents

National foreword

This British Standard reproduces verbatim ISO 9611:1996 and implements it as the UK national standard.

This British Standard is published under the direction of the Health and Environment Sector Board whose Technical Committee EH/1 has the responsibility to:

- — aid enquirers to understand the text;
- — present to the responsible international committee any enquiries on interpretation, or proposals for change, and keep UK interests informed;
- — monitor related international and European developments and promulgate them in the UK.

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Summary of pages

This document comprises a front cover, an inside front cover, pages i and ii, the ISO title page, pages ii to iv, pages 1 to 18, an inside back cover and a back cover.

This standard has been updated (see copyright date) and may have had amendments incorporated. This will be indicated in the amendment table on the inside front cover.

INTERNATIONAL
STANDARD

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9611

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Acoustics — Characterization of sources of structure-borne sound with respect to sound radiation from connected structures — Measurement of velocity at the contact points of machinery when resiliently mounted

Acoustique — Caractérisation des sources de bruit solidien pour estimer le bruit rayonné par les structures auxquelles elles sont fixées — Mesurage de la vitesse aux points de contact des machines à montage élastique

Reference number
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Foreword

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

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.

International Standard ISO 9611 was prepared by Technical Committee ISO/TC 43, *Acoustics*, Subcommittee SC 1, *Noise*.

Annex A to Annex D form an integral part of this International Standard. Annex E to Annex J are for information only.

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Introduction

This International Standard is one of a series of frame documents specifying various methods for the characterization of machines or equipment as sources of structure-borne sound with respect to sound radiation from connected structures.

The application of this International Standard to a certain family of machines needs additional requirements such as, for example, well-defined operating conditions given in a specific test code. This International Standard describes how, at each connection point for a resilient element, six components of the vibration can be measured and gives estimated standard deviations for their measurement uncertainty for frequencies in a given range of frequency. For a specific machine, a family of machines or for a specific application, fewer components may be sufficient to characterize the source, thus the number of components measured could be reduced and the defined frequency range could be appropriately expanded or reduced.

0.1 General considerations

Airborne sound in buildings, ships and vehicles and the underwater sound radiated by ships is very often caused by vibrations of machinery or equipment. In general, such sound is emitted in at least two ways:

a) directly from the outer surface of the machine into surrounding air; measurement methods for its determination are given in the series ISO 3740 to ISO 3747 and in ISO/TR 7849; and

b) from structures connected to the machine; this sound radiation results from structure-borne sound being emitted by the machine into the connected structures such as foundation, pipes, other coupled machines or linked auxiliary equipment.

This International Standard deals according to b) with machines or equipment which are sources of structure-borne sound emission into connected structures with respect to airborne or liquid-borne sound radiation of connected structures.

The measurement and evaluation of machinery vibration with respect to human response, trouble-free operation of coupled or connected machinery, as well as structural fatigue and the lifetime of the machine itself are outside the scope of this International Standard. These fields are covered by International Standards of Technical Committee ISO/TC 108, *Mechanical vibration and shock* (see, for example, ISO 10816-1).

A major problem associated with the measurement of structure-borne sound emission is the choice of the quantities that characterize the "strength" of a source. The complete and fully accurate characterization of a source of structure-borne sound would involve an extremely large number of measurements; thus, one has somehow to trade accuracy against the simplicity of the method. In the context of standardization, emphasis is on simplicity; therefore an attempt has been made to describe the "strength" by a limited number of frequency-dependent quantities.

Simplified source descriptions are possible when the two following assumptions are both satisfied:

a) the connections of the machine with the surrounding structure can be treated as "points"; and

b) there is a considerable mobility mismatch for all degrees of freedom of vibration at the connection points.

In such cases, the sources can be described with a limited number of force spectra if the source has relatively high mobilities, and with a limited number of velocity spectra if the source has relatively low mobilities as compared with the corresponding point mobilities of the receiving structure. An important feature is the fact that, for a certain range of receiving structures, these source descriptions are independent of the precise characteristics of the receiving structure.

For many practical purposes, the resulting source descriptions are still too complicated and a further simplification to one-, two- or three-frequency dependent quantities is necessary. The annexes give guidelines for the selection of circumstances under which further simplifications are possible.

0.2 Specific considerations

This International Standard is one of a series specifying various methods for the characterization of sources of structure-borne sound (i.e. for the characterization of sources of vibrations) in the frequency range of audible sound. It gives a detailed description of a first method of a series[1]. The results of this International Standard may be used for the following purposes:

a) obtaining data for preparing technical specifications;

b) comparing the structure-borne sound emission of resiliently mounted machines of the same type and size;

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[1] International Standards describing the other methods and one giving a basic summary are in preparation.

c) obtaining input data for planning and noise purposes (e.g. input data for the calculation of structure-borne sound transmission through resilient mountings into the connected structure).

The method concerns the measurement of translational and angular velocity levels on the supports and other contact points of a machine which is mounted on resilient mountings (isolators). In the frequency range of the method, the selected isolators, flexible connections and foundation are such that the vibration of the contact point is not significantly affected by their presence. Consequently the results represent the free vibratory velocity levels of the contact points. The method is further restricted by the requirement that a machine support or the contact structure of a machine to another flexible connection can be considered to vibrate as a rigid body. This implies an upper frequency limit.

The direct application of the results is limited by the above restrictions. In spite of these restrictions, there is a large variety of machines for which the method may be valuable. Examples are diesel engines, diesel generators, electric motors, compressors, fans, lathes and presses. For most of these machines, it will be possible to apply the method in the frequency range between about 20 Hz and at least 1 kHz, which is the most important frequency range for practical problems of structure-borne sound.

This International Standard describes measurements for all six degrees of freedom, i.e. six components of velocity (three orthogonal translations and three orthogonal rotations) at each contact. For specific machines and specific applications, some of these components can be neglected.

There is significant experience with the method for some types of machines (e.g. diesel generators for shipboard applications) which provides the basis for this International Standard.

This International Standard should be taken as a general document which may be used to define a standard measurement procedure for a specific class of machine. Details about the operational conditions of the machine under test, the type of mounting and foundation to be applied, the vibrational components to be taken into account, the procedure for selecting or averaging data, checks of the test arrangements and the accuracy of the method and the applicability of the results should be given.

The following International Standards were mainly consulted when preparing this International Standard: ISO 1683, ISO 2017, ISO 2041, ISO 5347-1 (and other parts), ISO 5348, ISO 7626-1, ISO 10816-1, IEC 651 and IEC 1260. To a certain extent, this International Standard is a further elaboration of ISO 10816-1, especially with respect to the solution of acoustical problems.

1 Scope

1.1 General

This International Standard specifies an approximate method of characterizing sources of structure-borne sound by the measurement of one-third-octave-band free velocity level spectra (or, if appropriate, octave-band velocity level spectra) on the supports or other connection points of machines mounted on resilient isolators. This structure-borne sound emission is considered with respect to the airborne or liquid-borne sound radiation of structures connected to the source under test. The results are only valid for applications in which the machine is mounted on sufficiently soft isolators on a sufficiently stiff and heavy foundation.

NOTE 1 More conditions are given in Annex H. A survey of the theoretical background is given in Annex E.

It is possible to satisfy the requirements for the test arrangement in almost any surroundings. Velocities measured at defined contact points give no complete description of structure-borne sound emission of the machinery. But, under specific conditions as described in this International Standard for resiliently mounted machinery, they give a subset of the source data required for a characterization.

The results can be used

a) to obtain data for technical specifications;

b) for comparison with machines of similar type and size; and

c) to obtain input data for computations on the transfer of structure-borne sound.

1.2 Frequency range

The frequency range for which the method is applicable is limited by a low frequency f_1 and an upper frequency f_2.

The low frequency limit f_1 is set by the requirement that the supports vibrate freely; i.e. they are not affected by the isolators and the foundation structure on which the isolators are mounted. Annex A gives instructions on how to determine f_1.

The upper frequency limit f_2 is determined by assuming that the supports behave as point sources of structure-borne sound. Annex B gives guidelines for the determination of f_2.

NOTE 2 For many machines, isolators can be selected which provide a frequency f_1 between 20 Hz and 40 Hz.

NOTE 3 Many machines have such a structure that f_2 has a value between 1 kHz and 4 kHz.

1.3 Type of noise

This International Standard applies to steady noise.

1.4 Degrees of freedom

The procedures are described for all six components of the velocity: three orthogonal translational velocities and three orthogonal angular velocities.

If it can be shown that, for a specific machine and a specific application, fewer components are sufficient to characterize the source, then it is permissible to reduce the number of measured components (see Annex F).

1.5 Types of connection point

The procedures in this International Standard are described for the main supports of a machine. The method is, however, applicable to other mounting faces at resilient elements such as the flange for a flexible coupling in the shaft of a diesel engine or the connection with pipes. In such cases, the methods for the determination of f_1 and f_2 (see Annex A and Annex B) can be adapted to the unique conditions that apply.

2 Normative references

The following standards contain provisions which, through reference in this text, constitute provisions of this International Standard. At the time of publication, the editions indicated were valid. All standards are subject to revision, and parties to agreements based on this International Standard are encouraged to investigate the possibility of applying the most recent editions of the standards indicated below. Members of IEC and ISO maintain registers of currently valid International Standards.

ISO 5348:1987, *Mechanical vibration and shock — Mechanical mounting of accelerometers.*

IEC 651:1979, *Sound level meters.*

IEC 804:1985, *Integrating-averaging sound level meters.*

IEC 1260:1995, *Electroacoustics — Octave-band and fractional-octave-band filters.*

3 Definitions

For the purposes of this International Standard, the following definitions apply.

3.1
structure-borne sound

vibrations transmitted through solid structures in the frequency range of audible sound

3.2
contact area

an area through which structure-borne sound is transmitted from the machine to the surrounding structure (See Figure 2.)

3.3
connecting point

a contact area connected to an isolator

3.4
structure-borne sound point source

a contact area which vibrates as a surface of a rigid body

3.5
translational velocity level, L_v

level given by

$$L_v = 10 \lg \frac{v^2}{v_0^2} \quad \text{dB} \qquad \text{... (1)}$$

where

v is the r.m.s. value of the vibratory translational velocity, in metres per second, in a specific direction and for a specific frequency band;

v_0 is the reference velocity (5×10^{-8} m/s)[a].

[a] The choice of a reference velocity of 10^{-9} m/s and 10^{-9} s^{-1} for translational or angular velocity, respectively, would result in a translational/angular velocity level 34 dB higher than that level obtained when using 5×10^{-8} m/s and 5×10^{-8} s^{-1}, respectively.

it is expressed in decibels

3.6
angular velocity level, L_Ω

level given by

$$L_\Omega = 10 \lg \frac{\Omega^2}{\Omega_0^2} \quad \text{dB} \qquad \text{...(2)}$$

where

Ω is the r.m.s. value of the vibratory angular velocity, in radians per second, about a specific axis and for a specific frequency band;

Ω_0 is the reference angular velocity (5×10^{-8} S^{-1})[a].

[a] The choice of a reference velocity of 10^{-9} m/s and 10^{-9} s^{-1} for translational or angular velocity, respectively, would result in a translational/angular velocity level 34 dB higher than that level obtained when using 5×10^{-8} m/s and 5×10^{-8} s^{-1}, respectively.

it is expressed in decibels

3.7
repeatability standard deviation, σ_r

the standard deviation of test results obtained under repeatability conditions

NOTE 4 It is a measure of the dispersion of the distribution of test results under repeatability conditions. (See also ISO 3534-1 and ISO 5725-1.)

3.8
repeatability conditions

conditions where independent test results are obtained with the same method on an identical test material in the same laboratory/test site by the same operator using the same equipment within short intervals of time (See also ISO 3534-1 and ISO 5725-1.)

3.9
reproducibility standard deviation, σ_R

the standard deviation of test results obtained under reproducibility conditions

NOTE 5 It is a measure of the scatter of the distribution of test results under reproducibility conditions. (See also ISO 3534-1 and ISO 5725-1.)

3.10
reproducibility conditions

conditions where test results are obtained with the same method on an identical test material in different laboratory/test sites with different operators using different equipment (See also ISO 3534-1 and ISO 5725-1.)

4 Quantities to be measured

The three orthogonal one-third-octave band translational velocity level spectra and the three one-third-octave band orthogonal angular velocity level spectra are measured on each of the machine supports (or, if appropriate, the corresponding octave band spectra) (see Figure 1).

5 Test arrangement

5.1 Test surroundings and background noise

The machine is mounted on isolators (see **5.2**). For other structural connections which may be necessary, see **5.3**. It is possible to locate the test arrangement outlined in Figure 1 in any surroundings, for example a manufacturer's workshop, a special test bed, any laboratory space which is sufficiently large, and *in situ*. It is essential that the velocity levels of the supports induced by other sources are at least 10 dB lower than the levels induced by the machine under test. Furthermore, it is essential that the velocity levels of the supports are not affected by airborne sound which is radiated by the machine under test. See also Annex D.

NOTE 6 Small, rigid machines (e.g. electric motors up to 10 kW) can also be tested while suspended in such a way that the machine can operate and the machine supports are not mechanically loaded; f_1 can be very low in such an arrangement.

5.2 Isolators and foundation

The isolators shall be flexible mountings capable of supporting the machine in a proper way. The dynamic characteristics of the isolators shall be such that the lower limiting frequency f_1 is sufficiently low (see clause **7** and Annex A), and that no significant transmission of structure-borne sound to the foundation occurs at frequencies above f_1. The isolator shall be mounted on a low-mobility foundation.

NOTE 7 In general, these conditions can best be satisfied with soft rubber mountings or air springs. Soft metal isolators with rubber pads at the contact planes are also suitable. More background information regarding the choice of isolators is presented in Annex G.

The flanges of the isolators at the side of the machine shall not significantly increase the mass or the stiffness of the feet of the machine.

NOTE 8 More specific guidelines should be given in machinery-specific documents.

Over the frequency range of the method, the foundation for the isolators shall be so heavy and stiff that the combination of isolators and foundation does not give a significant dynamic loading of the machine supports (see also **7.1** and Annex G).

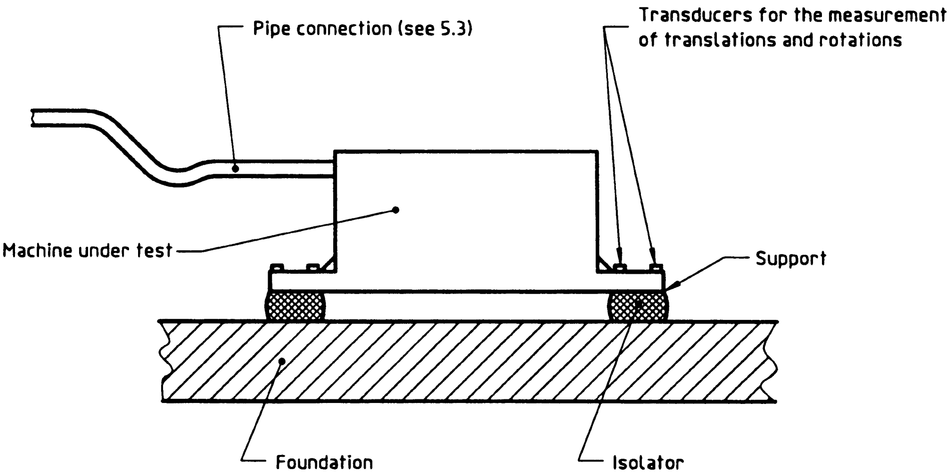

Figure 1 — Test arrangement

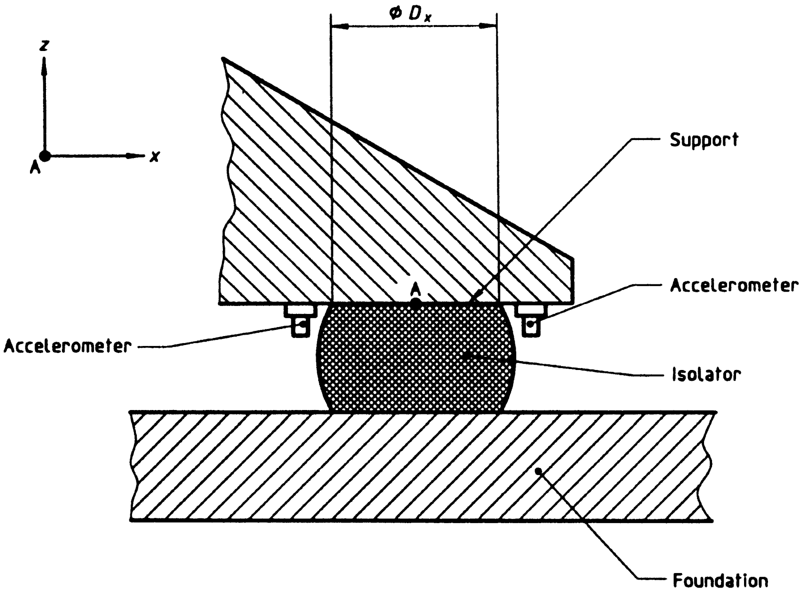

Figure 2 — Position of the accelerometers for measurement of L_{vz} and $L_{\Omega y}$

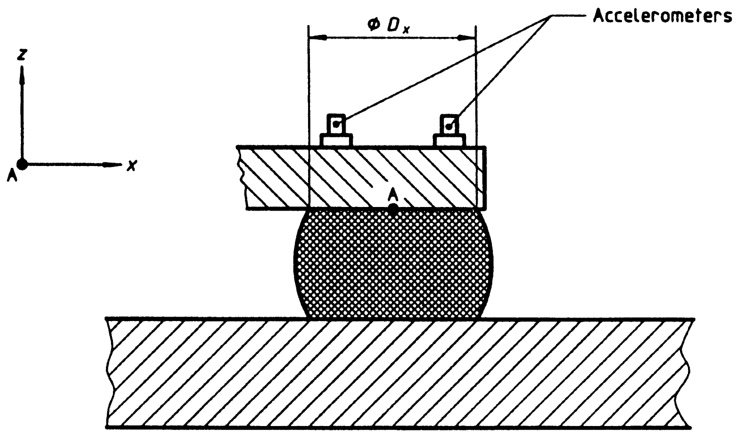

Figure 3 — Position of the accelerometers for measurement of L_{vz} and $L_{\Omega y}$ when there is no space alongside the isolator and the machinery foot has a surface parallel to the mounting face of the isolator

5.3 Other structural connections between the machine and the test surroundings

In many cases, machines require connections to be made to their surroundings (e.g. pipes, shafts, cables or secondary supports). These connections shall have flexible elements so that they result in either no increase or only a very slight increase in the lowest natural frequencies of the system consisting of the mass of the machine and the stiffness of the main isolator.

Further information about “flanking paths” is given in Annex D.

5.4 Position and orientation of vibration

5.4.1 *Recommended arrangement*

It is recommended that the translational and the angular velocity of the machine supports be measured with the aid of accelerometer pairs.

For the measurement of L_{vz} and $L\Omega_y$, the accelerometers shall either be mounted as shown in Figure 2 or, if there is insufficient space alongside the isolator, the accelerometers shall be mounted at positions as indicated in Figure 3. The distance between the two accelerometers shall not be smaller than $0{,}5D_x$ and not larger than $1{,}5D_x$, where D_x is the width of the contact area in the x-direction. The orthogonal coordinates shall be as follows: z is normal to the contact area, and y is parallel to the length axis of the machines. In all cases the accelerometers shall be placed at symmetrical positions referred to as A in Figure 2 and Figure 3; A is the geometric centre of the support (i.e. the area in contact with the isolator).

For the determination of $L\Omega_x$, use a set of accelerometers with the same orientation at similar positions as shown in Figure 2 and Figure 3, but rotated by 90° around the z-axis.

For the measurement of L_{vx} and L_{vy}, orient pairs of accelerometers in the x- and y-directions, respectively. Position the accelerometers so that they are either

a) symmetrically positioned about A at distances between $0{,}25D_x$ and $0{,}75D_x$ or $0{,}25D_y$ and $0{,}75D_y$ from A or, if this is not possible,

b) in the position shown in Figure 3.

The accelerometer pairs which are suitable for the measurement of L_{vx} and L_{vy} can also be used for the measurement of $L\Omega_x$.

In cases where the centres of sensitivity of the accelerometers are not mounted on a line through A, some of the translational components are not measured correctly and it is necessary to apply corrections as indicated in Annex C.

The accelerometers shall be attached to the support structure by methods which are in accordance with ISO 5348.

5.4.2 *Alternative arrangement*

Under certain conditions it is allowable to measure the vibration components of the support with the aid of one vibration sensor. These conditions are different for the different components.

L_{vz} may be measured with the aid of one translational vibration sensor positioned on top of the support structure, provided that the following conditions are satisfied (see also Figure 4):

$$h < \frac{1}{5} D_x \quad \text{and} \quad h < \frac{1}{5} D_y$$

$$x < \frac{1}{20} D_x$$

$$y < \frac{1}{20} D_y$$

L_{vy} may be measured with one translational vibration sensor provided that is positioned at one of the three areas shown in Figure 5.

Position 1 is on or near the z-axis on top of the support structure. The conditions are as follows:

$$h < \frac{1}{20} D_x \quad \text{and} \quad z_1 < \frac{1}{20} D_y$$

$$y_1 < \frac{1}{10} D_y$$

$$x_1 < \frac{1}{10} D_x$$

Position 2 is at the side of the support structure. The conditions are as follows:

$$h > \frac{1}{10} D_y$$

$$y_2 < D_y$$

$$z_2 < \frac{1}{20} D_y$$

Position 3 is at the side of the mounting flange of the isolator. The condition is as follows:

$$-z_3 < \frac{1}{20} D_y$$

The conditions for the measurement of L_{vx} with one sensor are similar to those for L_{vy} (replace above every y by x and every x by y).

Each of the rotational components may be measured with one rotational vibration sensor which may be located at any position on the support structure which has a distance from A of less than the smaller of the two following values:

$$\frac{1}{2} D_x \quad \text{or} \quad \frac{1}{2} D_y$$

NOTE 9 Drafting committees for machinery-specific documents which are based on this International Standard may decide whether or not it will be allowable to measure vibration components with one sensor. If it is allowable, the committee will have to provide an alternative for Annex B, which deals with the determination of f_2 based on the application of accelerometer pairs. Such an alternative may consist of a list of f_2 values for specific support structures.

5.5 Operation of the source

During measurements, the operating conditions specified in the relevant noise test code shall be used. If there is no test code, the source shall be operated, if possible, in a manner which is typical of normal use. In such cases, one or more of the following operating conditions shall be selected:

a) normal load at normal speed;

b) full load [if different from a)];

c) no load (idling);

d) a condition corresponding to maximum generation of structure-borne sound;

e) a condition with simulated load;

f) a specified operating cycle;

g) a condition as used for the airborne noise test for the specific family of machines under test.

6 Measuring equipment

6.1 Vibration sensors

Accelerometers shall be of the type which is suitable for measurements of translational acceleration in a well-defined direction. The sensitivity for transverse translations and rotations shall be small (typically a transverse sensitivity less than 4 % of that for the main axis of sensitivity). Alternative sensors are permissible but shall be at least equal in performance to accelerometers.

For contacting sensors, the total mass shall not significantly load the structure of which the response is to be measured. Therefore, at each contact point, the mass of the flange of the isolators at the source side plus the total mass of the sensors shall be less than 10 % of the mass of the footing structure directly above the isolator.

Within the frequency range for which the method is valid (see **1.2**), the frequency response of the accelerometers shall be "flat". The sensitivity shall be independent of frequency within 1 dB in the one-third-octave bands of interest. The sensitivities of the accelerometers which form a pair shall not differ by more than 1 dB.

If the measurement of rotational velocity is performed with a single rotational transducer, the sensitivity for the five other components of the vibrations shall be small. The sensitivity for rotations normal to the main axis of sensitivity shall be at least 20 dB less than for the main axis.

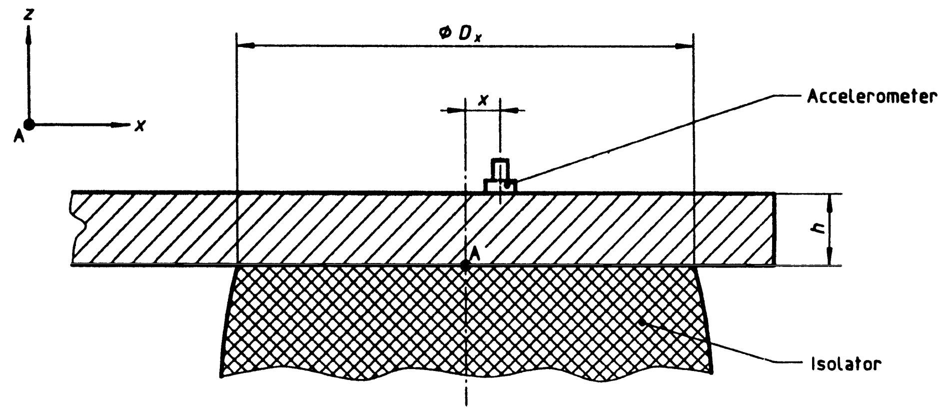

Figure 4 — Location of the sensor for measurement of L_{vz}

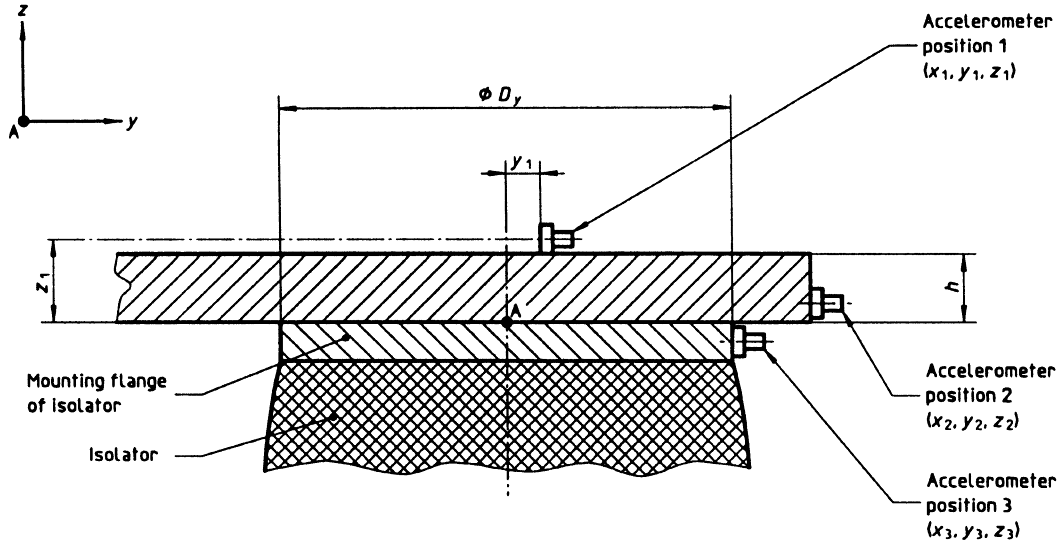

Figure 5 — Possible locations of the sensor for measurement of L_{vy}

6.2 Instrumentation for addition and subtraction of electrical signals

The electrical signals of the two accelerometers of a pair shall be added to obtain the translation, and subtracted to obtain the rotation of the machinery foot.

Addition and subtraction of electrical signals can be done by special analog devices or by general digital (FFT) equipment. Before addition and subtraction of the signals, possible differences in sensitivities and phase shifts of accelerometers and analog devices shall be corrected. This holds true also for FFT analysers due to non-negligible phase shifts of the antialiasing filters. When the total phase shift is less than 0,1°, the correction may be omitted.

The subtraction shall be replaced by addition, and addition replaced by subtraction, if one of the accelerometers of a pair is mounted in a reverse direction.

6.3 Amplifier, filters and level recorder

The equipment used for this purpose shall satisfy the requirements specified for type 0 or type 1 instrument in IEC 651 or IEC 804 with the microphone replaced by an accelerometer. The filter characteristics shall comply with IEC 1260.

The output signals of the electronic addition device shall be amplified, filtered in one-third-octave bands (octave bands if appropriate), indicated as r.m.s. values, and presented as translational velocity levels L_v or angular velocity levels L_Ω.

6.4 Calibration

Before commencing a series of measurements, the entire measuring system shall be calibrated for amplitude and phase at one or more frequencies with the aid of a known reference acceleration source (the two accelerometers are mounted simultaneously on the calibration exciter). In addition, the measuring system shall be tested electrically over the entire frequency range of interest at least every half year. In cases where the signals are not directly analysed but recorded on magnetic tape, an amplitude and phase calibration shall be carried out at the beginning and at the end of each measurement series. Each track of magnetic tape shall contain at least two electrical and one mechanical vibration calibration signals.

NOTE 10 In the case when only translational velocities are to be measured (see Annex F), it may not be useful to calibrate the accelerometers in phase.

7 Test procedure

7.1 Test of the arrangement

Before commencing the measurements, determine the lower and upper limiting frequencies f_1 and f_2 for defining the frequency range of validity in accordance with Annex A and Annex B.

If it is possible to remove an isolator without disturbing the mounting of the machine, measure the one-third-octave velocity spectrum (or octave velocity spectrum, if appropriate) of the particular support with and without the isolator. The difference shall be less than 2 dB. Results for one-third-octave bands (or octave bands) in which a larger difference occurs shall not be given in the test report.

If it is not possible to remove the isolator, carry out the following test. Stop the machine and excite the foundation with a continuous random signal, for example with the aid of an electrodynamic shaker. The velocity levels (six components, see **7.2**) are measured at both mounting sides of the isolators. The difference between corresponding components at both sides shall be at least 10 dB.

For a test on background noise, see **5.1**.

7.2 Measurement of velocity level (translation or angular)

The principle of the measurement is as follows (see Figure 6).

The translational acceleration a_z is found from the addition of the accelerations a_1 and a_2:

$$a_z = 0{,}5(a_1 + a_2) \qquad \text{...(3)}$$

The translational velocity v_z follows from

$$v_z = \frac{a_z}{2\pi f} = \frac{0{,}5(a_1 + a_2)}{2\pi f} = \frac{(a_1 + a_2)}{4\pi f} \qquad \text{...(4)}$$

where f is the centre frequency of the frequency band.

NOTE 11 Equation (4) is an approximation. For broad-band noise, in extreme cases, the application of equation (4) results in random errors of up to ± 0,2 dB for one-third-octave bands and up to ± 0,8 dB for octave bands. For discrete tones, in extreme cases, the application of equation (4) may cause errors up to ± 1 dB for one-third-octave bands. These errors are avoided if direct velocity measurements are carried out instead of acceleration measurements.

The r.m.s. velocity vz(r.m.s.) is then

$$v_{z(\text{r.m.s.})} = \left[\frac{1}{T}\int_0^T v_z^2(t)\,\mathrm{d}t\right]^{1/2} \qquad \text{...(5)}$$

and the velocity level, L_{vz}, in decibels, is

$$L_{vz} = 10\lg\frac{v^2_{z(\text{r.m.s.})}}{v_0^2}\ \text{dB} \qquad \text{...(6)}$$

where

v_0 = 5×10^{-8} m/s;

T is the integration time, in seconds.

The angular velocity, Ω_y, is given by

$$\Omega_y = \frac{a_1 - a_2}{2\pi f l} \qquad \text{...(7)}$$

NOTE 12 Note 11 is also applicable to equation (7).

The angular velocity level, $L\Omega_y$, in decibels, is given by

$$L_{\Omega y} = 10\lg\frac{\Omega^2_{y(\text{r.m.s.})}}{\Omega_0^2}\ \text{dB} \qquad \text{...(8)}$$

where

$$\Omega_0 = 5 \times 10^{-8}\ \text{s}^{-1}$$

$$\Omega_{y(\text{r.m.s.})} = \left[\frac{1}{T}\int_0^T \Omega_y^2(t)\,\mathrm{d}t\right]^{1/2}$$

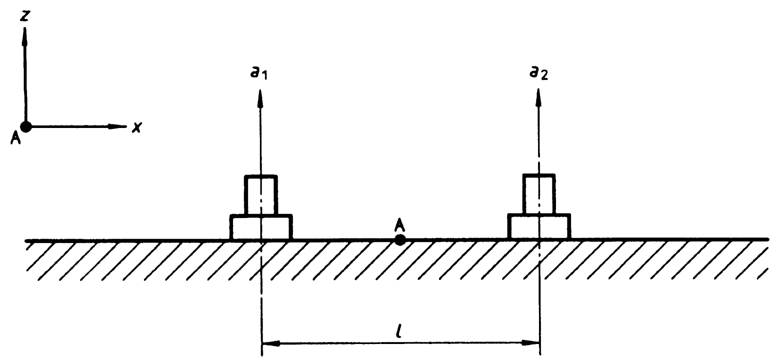

Figure 6 — Geometry for measurement of rotations and translations

Ensure that the integration time *T* is sufficiently long to enable a stable result to be obtained. If the machine has a specific cycle of operation, or if specific parts of the cycle are of interest, *T* shall cover several of the relevant time intervals; furthermore *T* shall have a value of at least 1 280/f_1 s (e.g. when f_1 = 20 Hz, *T* shall be at least 64 s, also for frequency bands with centre frequencies higher than f_1).

7.3 Reduction of data

Express the result as one-third-octave band (or octave band, if appropriate) spectra for each of the six velocity components for each separate support.

If it is wished to reduce these data, apply the following procedure. For each frequency band the levels of the corresponding component at each support are averaged in the following way:

$$\overline{L_{vx}} = 10\,\lg\left[\frac{1}{N}\sum_{i=1}^{N}10^{L_{vxi}/10}\right]\ \text{dB} \qquad \ldots(9)$$

$$0\,\lg\left[\frac{1}{N}\sum_{i=1}^{N}10^{L_{\Omega xi}/10}\right]\ \text{dB} \quad \text{etc.} \qquad \text{etc.}\ \ldots(10)$$

where

$\overline{L_{vx}}$	is the mean translational velocity level, in decibels, in the *x*-direction of the machinery support;
$\overline{L_{\Omega x}}$	is the mean angular velocity level, in decibels, about the *x*-axis of the machinery feet;
N	is the total number of machinery supports;
L_{vxi}	is the translational velocity level, in decibels, in the *x*-direction at the *i*th support;
$L_{\Omega xi}$	is the angular velocity level, in decibels, about the *x*-axis at the *i*th support.

8 Precision

The precision of the test procedure for a specific family of machines is described by the repeatability standard deviation σ_r and the reproducibility standard deviation σ_R (see **3.7** and **3.9**). The values of σ_r and σ_R depend on the frequency and on the type of machine. For well-defined test conditions and for a specific family of machines, it can be expected that $\sigma_r \approx 2$ dB and $\sigma_R \approx 4$ dB in a significant part of the frequency range between f_1 and f_2.

If measurements with single vibration sensors according to the alternative arrangement of subclause **5.4.1** are included, the values of σ_r and σ_R will become larger.

NOTE 13 In order to obtain the necessary information for a specific family of machines, it is recommended that an interlaboratory test in accordance with ISO 5725-1 and ISO 5725-2 be organized.

9 Test report

The test report shall make references to this International Standard and shall include the following information:

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

b) the date of the test;

c) a description of the machine (type, mass, power, supports, etc.);

d) a description of the test site and the test arrangement (special emphasis on the resilient elements used); description of connections other than the supports;

e) the operating condition(s) of the machine;

f) a description of the way in which f_1 and f_2 were determined;

g) the results of measurements as described in **7.1**, if relevant;

h) a description of tests on the possible influence of background noise as described in **5.1**, if relevant;

i) the position, orientation and mounting of the vibration sensors;

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

k) the velocity levels relevant for the family of machines under test for each separate support;

l) the mean spectra determined in accordance with **7.3**, if relevant;

m) the repeatability standard deviation σ_r, if calculated.

Annex A (normative) Determination of the lower limiting frequency, f_1

The lower limiting frequency f_1 is the centre frequency of the lowest one-third-octave band (or octave band) for which it can be assumed that the reaction forces from the isolators used during the test do not change the velocity of the machine supports. If the machine can be regarded as a rigid mass in the frequency region below f_1, f_1 is assumed to be three times $\hat{f}_0$, with $\hat{f}_0$ being the highest of the six natural frequencies of the mounted system. Determine the natural frequencies by transient or sweep excitation of the machine and measurement of narrow-band accelerations, taking relationships between force and acceleration into account.

For the determination of $\hat{f}_0$, excite one of the supports not located in a symmetry plane of the source structure by means of transient or sweep excitation and determine the six natural resonance frequencies. The highest of these is $\hat{f}_0$.

Determination of $\hat{f}_0$ by calculations combined with an experimental check with the aid of one-third-octave band (or, if appropriate, octave band) measurement equipment is also acceptable.

Annex B (normative) Determination of the upper limiting frequency, f_2

The upper limiting frequency f_2 is defined as the centre frequency of the highest one-third-octave frequency band (or octave band, if appropriate) for which the results are accepted (i.e. the machine supports do behave sufficiently as structure-borne sound point sources).

To determine f_2 on a support, place the two accelerometers at a minimum and a maximum distance from each other, respectively (see Figure B.1). The one-third-octave band velocity level spectra (or octave band spectra, if appropriate) are measured with the equipment described in clause **6**, applying the principles described in **5.4** and **7.2**. Compare the results: f_2 is the centre frequency of the highest one-third-octave band (or octave band, if appropriate) for which there are no differences larger than 4 dB in any of the measured components.

If a distance of 1,5D cannot be achieved, use a distance of at least D. In this context, D is the largest length dimension of the contact area. If measurements in a plane through A are not possible, positions as indicated in Figure 3 are also acceptable.

NOTE 14 The procedure given in this annex may be used to find a relation between f_2 and the dimensions of typical machinery supports when preparing a test code for a specific family of machines.

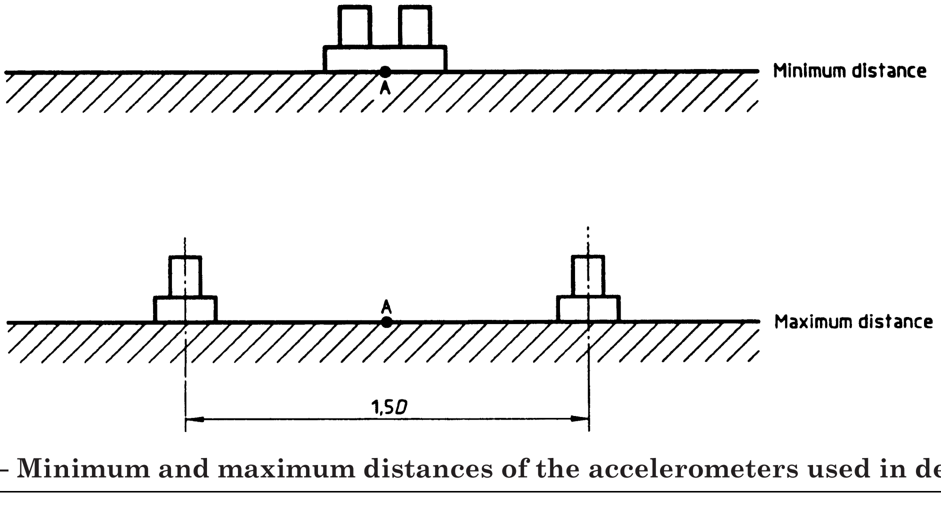

Figure B.1 — Minimum and maximum distances of the accelerometers used in determining f_2

Annex C (normative) Corrections if the accelerometers are not in the contact plane between the machinery foot and isolator

If the velocities are measured in a plane parallel to the contact area between the machinery foot and isolator, two of the measured quantities contain a systematic error which shall be corrected in the following way.

Suppose that the measured velocities are v'_x , v'_y , v'_z , Ω'_x , Ω'_y , and Ω'_z and that the velocities of the contact area through A are v_x, v_y, v_z, Ω_x, Ω_y and Ω_z (see Figure C.1).

The angular velocities and the translational velocity in the z-direction are identical:

$$\begin{aligned} \Omega_x &= \Omega'_x \\ \Omega_y &= \Omega'_y \\ \Omega_z &= \Omega'_z \\ v_z &= v'_x \end{aligned}$$

Adopting the sign conventions indicated in Figure C.1, the two other translational velocities are related in the following way:

$$\begin{aligned} v_x &= v'_x - h\Omega'_y \\ v_y &= v'_y - h\Omega'_x \end{aligned}$$

in which v_x etc. are now instantaneous values of the velocities, which means that the correction can only be done if the correct phase relations are taken into account. In general, this procedure requires the use of FFT equipment (see **6.2**).

NOTE 15 The procedure given in this annex may be used to investigate the importance of the height correction when preparing a test code for a specific family of machines. It may then be decided to neglect the height correction or to define a simplified rule for the correction.

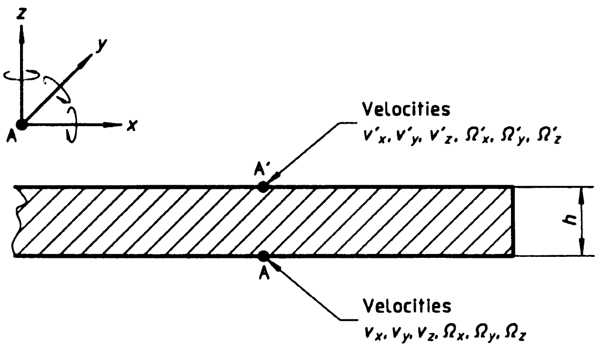

Figure C.1 — Velocities of points A and A′ at a distance h [h being much smaller than D ($h \leqslant D/10$)]

Annex D (normative) Other connections between the machine and test surroundings

During the tests, any possible influences of the test surroundings on the vibration levels of the machine supports should be considered. There are two causes of undesirable influences:

- structural connections other than the supports and the isolators, and
- directly radiated or reflected airborne sound.

Examples of other structural connections are an exhaust pipe, an intake pipe, a cooling water pipe, a shaft, secondary supports and electric cables. With the exception of the electric cables, such connections shall be provided with suitable flexible elements. Electric cables shall not have a stiff covering and shall not be rigidly fixed to the surrounding structure over a distance of $100d_{\mathrm{EC}}$, where d_{EC} is the diameter of the electric cable. Another helpful measure is a free bend. over at least 90°.

In principle, the tests should be performed in an acoustical free field over a reflecting plane. In most cases, however, it is not necessary to require such surroundings because the directly radiated and reflected sound does not significantly affect the vibration levels of the supports. Exceptions may occur in the following cases:

a) when the machine has an extremely light support structure; such a structure is very poor with respect to structure-borne sound isolation and should be improved;

b) when a machine of light construction is tested in very reverberant surroundings; in this case the set-up can be tested and improved by the addition of extra sound absorption in the test room;

c) when there is a thin layer of air between the machine and the foundation or between the machine and another part of the surrounding structure; such a layer shall, of course, not influence the lowest natural frequencies of the system but, even if this requirement is fulfilled, there may be influences on the test results due to the reverberant sound field in the layer. These influences are acceptable if the layer is typical for practical applications of the machine. In other cases, the influence shall be minimized by

- application of a layer which is as thick as possible,
- perforation of the foundation (or another relevant part of the surrounding structure),
- application of sound absorption, or
- a combination of these measures.

Annex E (informative) Background to the method

The theoretical background to the method is extensively considered in references [8] and [9]. Only a few main aspects will be repeated here.

Essential aspects of the method are as follows:

a) the supports are considered as structure-borne sound sources;

b) above a certain frequency, the vibrations of the supports are assumed to be independent of the precise properties of the various types of isolators and foundations on which the machine can be mounted;

c) the coupling and phase relations between the vibration components of different supports are neglected;

d) the coupling and phase relations between the six vibration components of one support are neglected.

In other words, it is assumed that the structure-borne sound source strength of the machine can be adequately characterized by six independent low-mobility (high-impedance) point sources which are located on each machinery support.

The procedure described requires that the validity of the aspects a) and b) is verified (see **7.1** and Annex A and Annex B). Instead of the test described, it is also possible to check the validity of aspect a) by an experimental study of the modal pattern of the supports as a function of frequency, and the validity of aspect b) by the measurement of the point mobility matrices of the machinery supports and of the statically loaded isolators when these are mounted on the foundation. However, such tests are very difficult to perform and are less direct than the tests described in **7.1**.

For the purposes of this method (utilizing r.m.s. one-third-octave or octave band data), neglecting coupling and phase relationships between the vibration components of different supports is justified when

- the distance between the supports is large compared with the modal patterns in the receiving structure (foundation, etc.); this is only true above a certain frequency; and/or
- the interest is limited to a general characterization of the machine of which it is not yet precisely known on which isolators and in which surroundings it will be installed in practice.

The coupling and phase relations of the components of one support can be neglected if

— one of the components is predominant with respect to the final sound immission in the receiving system(s) (this is not necessarily the predominant component on the machinery support); or

— the interest is limited to a general characterization of the machine with respect to a range of isolators and structural surroundings (each surrounding having its own response and structural behaviour).

The consequence of these limitations is that, for the low-frequency range (typically the range below 200 Hz), one should be careful with the use of the results as an input for noise predictions in a specific receiving system (the errors may be rather large). In other words, the method has a statistical character (averaging in time, averaging of the response of different modes in a frequency band, and possibly, averaging of the response of different receiving systems). Consequently, the results are not suitable for deterministic computations.

Annex F (informative) Reduction of the number of degrees of freedom

In general, six degrees of freedom are necessary to describe the structure-borne sound emission of a machine through a contact area, but for practical applications and for certain purposes, it is advisable to consider the possibility of reducing the number of degrees of freedom. Such a reduction requires specific investigations which should be carried out before preparing test codes for specific families of machines. Two approaches to such investigations involve

a) looking for components which are predominant or negligible with respect to the airborne sound pressure caused in a typical receiving system;

b) investigating whether one, two or three components can sufficiently well characterize the total excitation.

Approach a) is most useful at relatively low frequencies, for periodic excitation, and for isolators and seatings and further receiving systems which have very different response and transmission characteristics for the various degrees of freedom. Approach b) is at its best at relatively high frequencies (multimode domain), stochastic excitation and for receiving systems with reasonably homogeneous transmission characteristics for the different degrees of freedom of excitation.

A well-founded decision to reduce the number of source velocity components must be based on experimental checks performed on a number of typical receiving systems consisting of an isolator, a foundation and a receiving system (e.g. a building). For the system between the upper flange of the (statically loaded) isolator and a typical receiving position in a room or a cabin, six transfer functions pressure/velocity are determined (one for each degree of freedom of the velocity of the isolator flange). The determination is very difficult when direct excitation of the flange is applied. It is somewhat easier when reciprocal measurements are applied (see reference [11]), but can best be performed when the 36 transfer functions (velocity/blocked force of the isolator) are separately measured in a special test rig and the six transfer functions force/pressure of the system consisting of the foundation and the “further system” are determined be reciprocal measurements (see references [8], [9], [10], [11]).

When, by combination of the results, the six transfer functions (pressure/velocity) have been determined, typical measured values of the velocity (three orthogonal translational and three orthogonal angular velocities) are substituted and six separated contributions to the total pressure are derived. Reduction of the number of degrees of freedom is possible when either some of the contributions to p_1 are much smaller or much larger than others [approach a)], or the six contributions to p_1 are approximately equal [approach b)]. In general, the results of this analysis will be different for different frequency ranges.

Cases in which considerable simplifications may be acceptable (always at a price with respect to accuracy) are the following:

— the isolators have reasonably homogeneous transmission characteristics (such as a rubber cube) and are mounted on a thick concrete foundation; in this case, at least three excitation components can probably be neglected;

— the isolators have reasonably homogeneous transmission characteristics and are mounted on a foundation which has reasonably homogeneous input mobilities for the six degrees of freedom and a high modal density;

— the isolators have very different transmission characteristics for the different degrees of freedom.

Annex G (informative) Selection of isolators and foundations

The selection of suitable isolators and foundations adequate for the purposes of this International Standard is very important and should be done with utmost care.

In order to obtain a sufficiently low value of f_1 it is necessary that the isolator has a sufficiently low dynamic stiffness for the various degrees of freedom. At frequencies above f_1 each machinery support is supposed to vibrate freely; i.e. it is assumed that the isolator and connected foundation do not form a significant dynamic loading for the machinery support. This implies that the modules of the driving point mobilities of the support and those of the foundation must be low compared with the corresponding mobility matrix elements, of the isolators while mounted on a rigid foundation. This is true unless

a) excessively strong undamped wave effects occur in the isolator;

b) the machinery supports are of too light a construction;

c) the foundation is of, too light a construction.

Whether or not these conditions are satisfied can be checked by the measurement of multi-dimensional point mobilities of the support, the isolator and the foundation. In general, however, such tests are not necessary because

a) it is known from experience that certain types of isolators are well suited and others are not (see **5.2**);

b) a sufficiently rigid and heavy foundation can be chosen;

c) the final result can be tested in a simple way (see **7.1**); if the result is not favourable, the application of other isolators and/or foundations can be tried.

The support is part of the machine. If it is of too light a construction this will be revealed by the test carried out in accordance with **7.1**. There are two solutions for this situation:

a) to choose an isolator which gives a lower loading for the support;

b) to take measurements without an isolator present.

Relatively light machinery supports will have a relatively low value of f_2 and a relatively high vibration level, and have an unfavourable effect on the efficiency of vibration isolators. The method of this International Standard gives unfavourable results for such machines, which may stimulate manufacturers to design acoustically better machinery supports.

Annex H (informative) Application of the results

As stated in **1.1**, the results are only valid for applications in which the machine is mounted on sufficiently soft isolators on a sufficiently stiff and heavy foundation. The first requirement is especially important: if isolators stiffer than in the test arrangement are used, a measurement or a computation must be made of the lowest natural frequencies of the mass-spring system; a frequency f_1 is then determined as described in Annex A. This frequency is the low limiting frequency for application of the results of the tests for the specific type of isolator.

In practice the machine may be mounted on types of isolators (helical or other) other than those used in the tests. If steel isolators are used (which is not recommended from the acoustical point of view), tests as described in **7.1** or driving-point mobility tests are necessary to check for which one-third-octave bands (with centre frequencies between f_1 and f_2) the results are valid and for which they are not. Such tests are also recommended for compound mountings with various rubber and steel parts. For airsprings, these tests are not necessary.

Many isolators have end plates (flanges) which are sufficiently stiff or heavy to influence the vibrations of relatively light machinery supports, especially at higher frequencies. For such cases, care should be taken in the application of the results of the method (which are obtained with isolators and end plates which do not influence the vibrations of the supports). It is recommended that the user checks experimentally which frequency bands show a significant effect of the presence of the end plate. If there is such an effect, the reliability of conclusions based on the results of the method is less for these specific frequency bands than for the other bands. Better results can be obtained for the specific case if measurements are performed with supports that are stiffened with end plates which are similar to those of the specific isolators. In fact, in that case a machine with stiffer and heavier supports should be investigated.

The results of the method can be used as an input for the computation of the sound pressure at a receiving location due to the structure-borne sound from the machine which is transmitted through the isolators. To perform such computations, it is necessary to have adequate data on the transmission of structure-borne sound through resilient isolators in the form of transfer functions for each degree of freedom of the excitation. An International Standard for the determination of these transfer functions is in preparation. In addition to the transfer properties of the resilient isolators, it is also necessary to have data on the transmission of sound through the foundation and the other parts of the receiving system.

In practice, the contributions to the sound pressure due to the transmission of structure-borne sound through the "isolator path" is very often not the predominant one. In many cases the contributions of so-called "flanking noise" are more important. Important types of flanking noise may be the following:

a) noise due to direct airborne sound emission;

b) noise transmitted through a shallow cavity between the machine and a part of the receiving structure;

c) structure-borne sound transmitted through cables, hoses, shafts and pipes;

d) exhaust or intake noise.

In practice, due to the flanking paths, the effect of very good resilient isolators is often limited to only 5 dB or 10 dB and can only be improved by a further reduction of the flanking noise (see for example references [8], [12], [13] and [14]).

The results of the method do not include information about the phase relations between the vibration components of different supports. The consequences for the application of the results are discussed in Annex E.

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[2)] See also parts 2 to 20.

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