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INTERNATIONAL ORGANIZATION FOR STANDARDIZATION•МЕЖДУНАРОДНАЯ ОРГАНИЗАЦИЯ ПО СТАНДАРТИЗАЦИИ•ORGANISATION INTERNATIONALE DE NORMALISATION

Acoustics — Estimation of airborne noise emitted by machinery using vibration measurement

Acoustique — Estimation du bruit aérien émis par les machines par mesurage des vibrations

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- type 1, when the necessary support within the technical committee cannot be obtained for the publication of an International Standard, despite repeated efforts;
- type 2, when the subject is still under technical development requiring wider exposure;
- type 3, when a technical committee has collected data of a different kind from that which is normally published as an International Standard ("state of the art", for example).

Technical reports are accepted for publication directly by ISO Council. Technical reports types 1 and 2 are subject to review within three years of publication, to decide if they can be transformed into International Standards. Technical reports type 3 do not necessarily have to be reviewed until the data they provide are considered to be no longer valid or useful.

ISO/TR 7849 was prepared by Technical Committee ISO/TC 43, *Acoustics.*

The reasons which led to the decision to publish this document in the form of a technical report type 2 are explained in the Introduction.

0 Introduction

0.1 Reasons for publication as a technical report type 2

The proposal to prepare an International Standard on measurement and characterization of noise radiated by structure-borne components of machinery was initiated in 1979 at the ISO/TC 43/SC 1 meeting. A draft proposal was prepared for discussion. However, in 1982 it was decided that the text of this DP should be amended on the basis of the member body comments, and as the subject had not sufficiently advanced to prepare an International Standard, the amended text should be submitted for adoption as a Technical Report. This proposal to publish as a Technical Report was supported by the majority of participating members of TC 43.

This document is published in the form of a technical report type 2 as the subject cannot yet be considered suitable for an International Standard because of the lack of present knowledge on some measurement characteristics; the accuracy of the method remains, for example, uncertain when applied to specific families of machines which are most relevant in noise radiation. The subject is still under study and this Technical Report may encourage further practical investigation in this field, producing basic data to change this Technical Report into an International Standard in future.

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ISO/TR 7849 : 1987 (E)

0.2 General

The determination of airborne noise emission of a machine by measuring vibrations of the machine's outer surface may be of [illegible] in the following cases:

- when undesired background noise (e.g. noise from other machines or sound reflected by room boundaries) is high co[illegible] with the noise radiated directly by the machine under test;

- when the noise radiated by structural vibration is to be separated from noise of aerodynamic origin (also in cases whe[illegible] new noise intensity measuring technique cannot easily be applied);

- where the structure-borne noise from only a part of a machine, or from a component of a machine set, is to be determined in the presence of noise from the other parts of the whole source.

This Technical Report gives a procedure for estimating the sound power of the airborne noise emitted by machinery from vibration measurements. Under certain conditions, the measurement procedure can be applied without great difficulty if

- the shape of the machine's outer surface is more or less simple;

- vibrations at different measurement locations are not significantly correlated, and a large number of resonant modes of [illegible]tion are found within the frequency band.

Certain well correlated sources of simple shape can also be treated (vibration of a source of zero order, piston vibration). If these conditions are not fulfilled, some problems arise as described in 0.3. For such cases it is not yet possible to give exact requirements for the measurement procedures, but some measurement procedures are put forward in this Technical Report.

0.3 Assumptions and problems in determining the sound power from a knowledge of the mean square value of the surface velocity of vibration of machines

0.3.1 The airborne sound power radiated by a machine or equipment caused by structural vibrations of its outer surface only, P_S, can be estimated by using the following equation:

$$P_S = \varrho c \, \overline{v^2} \, S_S \sigma$$

where

ϱc is the fluid characteristic impedance,

where

ϱ is the mean density of the fluid (i.e. air),

c is the velocity of sound in the fluid (i.e. air);

$\overline{v^2}$ is the mean square value of the normal vibratory velocity averaged over the surface area S_S;

S_S is the area of the defined outer surface of the machine;

σ is the radiation factor.

As the characteristic impedance ϱc is a constant for known meteorological conditions, the formula given above requires the three quantities $\overline{v^2}$, S_S and σ to be determined.

0.3.2 The value of $\overline{v^2}$ is obtained from measurements of the r.m.s. vibratory velocity component perpendicular to the machine's outer surface and taken for a sufficient number of measurement locations distributed over the relevant outer surface of the machine. The array and number of measurement locations can be regarded as sufficient if the value of $\overline{v^2}$ remains stable within the precision of the method for an increasing number and changed array of measurement locations. A random distribution of vibration pick-ups appears to be desirable. Guidelines on a practical approach are given in 7.2 and 7.3.

It may be desirable to subdivide the machine's surface area in order to rank the sound power radiated from different components. The implication of this subdivision is that each area radiated sound independently.

The spatial variation of vibration velocity depends on

a) the number of resonant modes excited simultaneously in the frequency band;

b) the degree of non-uniformity of the structure (e.g. presence of stiffness, holes variation and thickness of material).

c) the spatial distribution of the exciting forces.

The major problem occurs when very few modes are excited at resonance in a frequency band.

0.3.3 The area of the relevant outer surface of the machine, S_S, can be calculated easily if the shape of the outer surface of the machine is simple (e.g. cylindrical, spherical, composition of flat plates, etc.).

One problem is the radiation from connected structures, such as pipes, mounts, supports, etc., and the radiation from grid-work, rib surfaces, perforated surfaces and supporting structures.

It is recommended to define S_S for specific kinds of machinery in connection with the relevant radiation factor (see the "Bibliography").

0.3.4 The radiation factor, σ, depends on the following factors:

a) The dimension of the radiating surface compared with the wavelength of the sound in air for the relevant frequencies.

b) The shape of the radiating surface.

c) The modal pattern in the frequency band.

The value of σ is determined not only by the structure, but also by the distribution and manner of excitation and by the internal loss factor. So for a certain machine, σ may vary if the field of exciting forces changes (e.g. between idling and load).

The radiation factor of individual modes of certain idealized uniform structures, such as spheres, flat plates and circular cylinders is known. The modal-average radiation factor of such structures is also known on the assumption of equal modal energy. Certain kinds of excitation may result in non-uniform modal energy, e.g. airborne excitation, single excitation, impulsive excitation

d) The time characteristics of the process (stationary or non-stationary).

The radiation factor can be determined as follows:

a) Theoretically, as described above (see the "Bibliography").

b) Experimentally from measurements on one or more structures being representative of a certain family of machines or equipment.

This method uses the equation given in 0.3.1 in the following form:

$$\sigma = \frac{P_S}{\varrho c S_S \overline{v^2}}$$

where

P_S is the airborne sound power determined either in accordance with ISO 3741, ISO 3742, ISO 3743, ISO 3744, ISO 3745 or ISO 3746 or by using sound intensity measurement;

ϱc, S_S and $\overline{v^2}$ are determined as described previously.

c) By assuming estimated σ-values as a function of frequency

Such values may be derived for machines having similar acoustical behaviour as compared with sound sources being investigated carefully according to methods a) and b).

According to some investigations the radiation factor $\sigma(f)$ of a spherical source of zero order (see 8.3.2) approximates, for example, the radiation factor of a large number of sound sources (machines, equipment).

A very rough estimation of σ is given by the value $\sigma = 1$. In general, this assumption allows one to estimate an upper value for the radiated sound power, P_S.

1 Scope and field of application

This Technical Report gives basic requirements for reproducible methods for estimating the sound power emitted by machines or equipment by using surface vibration measurements. The method is especially applicable in cases where accurate direct airborne noise measurements as specified in ISO 3741, ISO 3742, ISO 3743, ISO 3744 and ISO 3745 are not possible because of high background noise or other parasitic environmental influences. The methods are only applicable to noise which is emitted by vibrating surfaces of solid structures and not to noise generated aerodynamically. The method described in this Technical Report applies mainly to processes which are stationary with respect to time. Research into the possibility of extending these techniques to non-stationary processes is, however, encouraged.

Guidelines for the estimation of the radiation factor variation with frequency are given in annex D. Recommendations on the selection of frequency bands are given in annex E.

This Technical Report specifies procedures by which the sound power radiated from individual parts of the whole of the vibrating surface of large machines can be estimated by vibration measurements.

2 References

ISO 1683, *Acoustics — Preferred reference quantities for acoustic levels.*

ISO 3741, *Acoustics — Determination of sound power levels of noise sources — Precision methods for broad-band sources in reverberation rooms.*

ISO 3742, *Acoustics — Determination of sound power levels of noise sources — Precision methods for discrete-frequency and narrow-band sources in reverberation rooms.*

ISO 3743, *Acoustics — Determination of sound power levels of noise sources — Engineering methods for special reverberation test rooms.*

ISO 3744, *Acoustics — Determination of sound power levels of noise sources — Engineering methods for free-field conditions over a reflecting plane.*

ISO 3745, *Acoustics — Determination of sound power levels of noise sources — Precision methods for anechoic and semi-anechoic rooms.*

ISO 3748, *Acoustics — Determination of sound power levels of noise sources — Engineering method for small, nearly omnidirectional sources under free-field conditions over a reflecting plane.* [1]

ISO 5348, *Mechanical vibration and shock — Mechanical mounting of accelerometers.* [1]

IEC Publication 225, *Octave, half-octave and third-octave band filters intended for the analysis of sounds and vibrations.*

IEC Publication 651, *Sound level meters.*

3 Definitions

For the purposes of this Technical Report, the following definitions apply.

3.1 structure-borne sound: Vibration transmitted through solid structures of a machine in the frequency range of audible sound. It is determined either from the vibratory velocity or the vibratory acceleration of the surface of the solid structure.

3.2 machine:

(1) Item of equipment which incorporates a single noise source.

(2) Assembly of items of equipment which incorporates several noise sources.

3.3 vibratory velocity: Component of the velocity of the vibrating surface in the direction normal to the surface. The root-mean square (r.m.s.) value of the vibratory velocity is designated by the symbol v.

NOTE — The vibratory displacement is the time integral of the vibratory velocity. The r.m.s. displacement for sinusoidal vibration, s, with frequency f is given by the following equation:

$$s = \frac{v}{2\pi f} \qquad (1)$$

The vibratory acceleration is the time derivative of the vibratory velocity. The r.m.s. acceleration for sinusoidal vibration, a, with frequency f is given by the following equation:

$$a = 2\pi f v \qquad (2)$$

1) At present at the stage of draft.

3.4 vibratory velocity level, L_v: Velocity level, in decibels, given by the following equation:

$$L_v = 10 \lg \frac{v^2}{v_0^2} \qquad (3)$$

where

v is the r.m.s. value of the vibratory velocity within the frequency band of interest;

v_0 is the reference velocity[1] and is equal to 5×10^{-8} m/s (= 50 nm/s).

NOTES

1 For airborne and structure-borne sound, the reference velocity, v_0, has the property that the intensity level, the sound pressure level and the vibratory velocity level for a progressive plane wave in air are almost equal in magnitude (se ISO 1683).

2 The determination of the vibratory velocity level, L_v, from the vibratory acceleration level, L_a, is described in annex F.

3.5 radiation factor, σ: Factor expressing the efficiency of sound radiation and given by the following equation:

$$\sigma = \frac{P_S}{\varrho c S_S \overline{v^2}} \qquad (4)$$

where

P_S is the airborne sound power emitted by the vibrating surface of the machine;

ϱc is the characteristic impedance of air,

where

ϱ is the mean density of air,

c is the velocity of sound in air;

S_S is the area of the vibrating surface (vibrating measurement surface; see 3.8);

$\overline{v^2}$ is the squared r.m.s. value of the vibratory velocity averaged over the area S_S.

The three quantities σ, P_S and $\overline{v^2}$ relate to the same period of time.

3.6 radiation index: Index defined by the expression $10 \lg \sigma$.

3.7 airborne sound power level, L_W: Ten times the logarithm to the base 10 of the ratio of a given sound power to the reference sound power. The width of a restricted frequency band is indicated, e.g. octave-band power level, one-third octave-band power level etc. The airborne sound power level is expressed in decibels (reference sound power: 1 pW). The airborne sound power level for a particular part of the surface of the machine, L_{WS}, is given by the following equation:

$$L_{WS} = 10 \lg \frac{P_S}{P_0} \qquad (5)$$

where

P_S is the sound power radiated by the relevant part of the surface of the machine;

P_0 is the reference sound power (= 10^{-12} W = 1 pW).

3.8 vibrating measurement surface: The surface or parts of the surface of the machine on which the measurement positions lie; its area is designated by the symbol S_S.

1) The choice of $v_0 = 10^{-9}$ m/s (as specified in ISO 1683) would result in a vibratory velocity level which is 34 dB higher than the level used in this Technical Report. In equations (6), (10), (11) and (17) 34 dB shall therefore be subtracted from the right-hand side.

3.9 extraneous structure-borne vibratory velocity level: Vibratory velocity level determined when the machine is not working or caused by other undesired sources. Extraneous structure-borne sound originates from structures other than the machine under consideration, e.g. from coupled assemblies.

3.10 spherical source of zero order: Sphere vibrating with uniform phase and the same amplitude over the whole surface.

4 Principle

4.1 General

The method described in this Technical Report is based on the assumption that the airborne sound power output of a vibrating surface is directly proportional to the mean-square vibratory velocity averaged over the vibrating surface and directly proportional to the area of the vibrating surface.

4.2 Method

Vibratory velocity levels in frequency bands are determined at a specified number of locations on the measurement surface of the vibrating structure (the sound source), using vibration measurement equipment. The average vibratory velocity level in frequency bands plus a term for the area of the measurement surface plus a term for the efficiency of sound radiation of the structure gives the airborne sound power level in frequency bands.

Three ways of estimating the radiation factor, σ, and hence the airborne sound power level are described as follows:

a) If a radiation factor $\sigma = 1$ is assumed, an approximate upper limit to the radiated airborne sound power is obtained. Thus an upper limit for the A-weighted airborne sound power level can be estimated from the A-weighted vibratory velocity level.

b) If, for a given structure, the sound radiation model of a spherical source of zero order can be justified (e.g. for compact machines), the frequency-dependent radiation factor σ can be obtained from a theoretical curve. By using vibratory velocity levels determined in frequency bands, airborne sound power levels in frequency bands can be determined; from these levels the A-weighted airborne sound power levels may be calculated.

c) For more accurate determination, the frequency-dependence of the radiation factor σ for the structure or family of machines under test is determined. This also requires the determination of vibratory velocity levels in frequency bands and results in band sound power levels and, if required, the A-weighted airborne sound power level.

5 Measuring instrumentation

5.1 General

In this clause, measuring instrumentation using vibration pick-ups is described. In most cases it will be convenient to make use of light accelerometers; however, for special purposes, other kinds of equipment and measuring techniques may be needed (e.g. non-contact devices, laser-doppler methods).

5.2 Vibration pick-up

The vibration pick-up can load the vibrating surface.

For vibration measurements covering a wide frequency range, piezoelectric accelerometers should be preferred. When selecting an accelerometer for a particular application, allowance should be made for the parameters of the transducer and the environmental conditions in which it is to be used.

Measurements are normally confined to using the linear portion of the frequency-response curve of the accelerometer which, at the high frequency end, is limited by the resonance of the transducer. As a rule-of-thumb the upper frequency limit for measurements can be set to one-third of the resonance frequency of the accelerometer so that vibration components measured at this limit will deviate by no more than 1 dB.

Small, low-mass accelerometers may have high resonance frequencies but in general they have low sensitivity (dynamic range). So a compromise has to be made because high sensitivity normally entails a large piezoelectric assembly and, consequently, a relatively large, heavy unit with low resonance frequency.

The mass of the accelerometer becomes important when measuring on light test objects. To avoid mass-loading errors, the dynamic mass of the transducer should be much less than the dynamic mass of the structure at the point of attachment [0,2 $\rho_S c_L h^2$] in the case of a flat plate, see equation (13)].

5.3 Amplifier and filter

The signals generated by the vibration pick-up shall be amplified, filtered and indicated as r.m.s. values. The structure-borne noise shall be measured with a sound level meter or an equivalent measurement system complying with the requirements for a type 0 or type 1 instrument as specified in IEC Publication 651 with the microphone replaced by the vibration pick-up. The filters shall be in accordance with IEC Publication 225.

5.4 Integrator

If an integrator to transform acceleration signals to velocity signals is used, it shall have characteristics which match the dynamic range of the measuring system. If this requirements is not satisfied and the signal to be measured is too low, the vibratory velocity levels shall be calculated directly from the vibratory acceleration levels (see annex F).

5.5 Calibration

The entire measuring system shall be calibrated at one or more frequencies before each series of measurements is begun. The peak value of an acceleration signal corresponding to an acceleration of 9,81 m/s² may serve as the calibration signal. In addition, the pick-up and the electrical measuring instrumentation should be checked as a unit electrically over the entire frequency range of interest at least every other year.

Example :

If the vibration pick-up is calibrated by a sinusoidal acceleration signal, the resulting vibratory velocity level (reference velocity[1]), v_0 = 5 × 10⁻⁸ m/s), L_v, in decibels, is given by the following equation :

$$L_v = 20 \lg \frac{\hat{a}}{2\pi f v_0 \sqrt{2}} \quad \ldots (5)$$

Hence, for a calibration with a peak acceleration value of $\hat{a}$ = 9,81 m/s² and a frequency, f, of 100 Hz, the vibratory velocity level is 106,9 dB.

6 Description, installation and operating conditions

6.1 General

In most cases, the emitted sound power will depend on both the installation and the operating conditions, and general recommendations on these are given in 6.2 to 6.4. If, however, airborne sound measurement test codes for the relevant family of machines exist, the installation and operating conditions specified in those codes shall be used.

6.2 Description of the machine

If the machine features auxiliary equipment or components which emit sound, these should be identified. The items of auxiliary equipment required to be running during the test shall be specified.

Sources of extraneous structure-borne sound should be identified.

NOTE — The procedures specified in this Technical Report do not allow the direct measurement of extraneous structure-borne sound. The use of correlation measurements or the comparison of vibration spectra of coupled assemblies may be necessary.

6.3 Installation

The installation and mounting of the machine shall, as far as possible, be that intended for its final application. If the structural surfaces of the machine are covered by non-structural materials (e.g. insulation), the vibration pick-up shall be mounted on a non-structural surface (see also annex B).

1) See footnote to 3.4.

6.4 Operating conditions

The machine shall be operated in a manner representative of normal use. One or more of the following operating conditions may be appropriate (see also 6.1) :

a) machine under nominal load/nominal operating conditions;

b) machine under full load, if different from a);

c) machine under no load (idling);

d) machine under operating conditions corresponding to maximum sound radiation representative of normal use;

e) machine under simulated load, operating under precisely defined conditions.

7 Determination of the vibratory velocity on the vibrating measurement surface

7.1 General

The specifications given in 7.2 to 7.8 are of a general nature, but if test codes for the relevant family of machine exist, the specific requirements in those codes shall be used.

NOTE — The accuracy of the measurement results depends to a large extent on the number and distribution of the measurement positions and the distribution of the vibratory velocity on the vibrating measurement surface.

Where an individual bandwidth contains a single strong tonal component, the uncertainty of the estimate determined by the method might be high.

7.2 Vibrating measurement surface

7.2.1 General

Suitable measurement surfaces shall be selected according to the criteria outlined in 7.2.2 to 7.2.4.

NOTE — The results of any preliminary investigations (see 7.2.4) and the structures of the radiating areas (e.g. the presence of stiffeners) should be taken into account when selecting the measurement surface.

7.2.2 Uniformly repeated structures

If the machine possesses uniformly repeated structures and if there are geometrical symmetries and symmetries in the excitation forces, then, provided that preliminary investigations have proved all elements to be equivalent with respect to the mean vibratory velocity level in any frequency band, measurements may be carried out on a single structure.

7.2.3 Uniformly distributed measurement positions

The vibrating measurement surface shall be divided into N parts of equal area S_S/N. One measurement position shall be situated in the centre of each partial surface.

7.2.4 Non-uniformly distributed measurement positions

If parts of the vibrating measurement surface are known from preliminary investigations to vibrate more intensely than others, the measurement positions may be distributed more densely over those parts vibrating more intensely.

In this case, each measurement position i represents one partial surface S_{S_i} (see 8.2).

7.3 Number of measurement positions

The initial number of measurement positions on the vibrating measurement surface may be chosen according to table 1.

Table 1 — Initial number of measurement positions

Area of the vibrating measurement surface, S_S m²	Number of measurement positions
$S_S < 1$	10
$1 < S_S < 10$	20
$S_S > 10$	$2 \frac{S_S}{S_0}$
	where $S_0 = 1$ m²

The number of measurement positions shall be increased if the difference between the highest and lowest vibratory velocity level, in decibels, in any frequency band is larger than the number of positions given in table 1. Such an increase in the number of measurement positions may, for example, be necessary if a predominant pure tone exists within the relevant bandwidth.

The number of measurement positions shall be progressively doubled until the mean vibratory velocity level, $\overline{L_v}$ (see 8.2), stays constant within a range of 1 dB.

7.4 Environmental conditions

The measuring equipment shall be selected according to the environmental condition (see 5.2), account being taken of the manufacturer's specifications. The influence of any cable (see clause A.2) may be reduced by using pick-ups with integrated impedance transducers.

7.5 Measurement procedure

For the specified operating conditions, the vibratory velocity level, L'_v, shall be determined at each measurement position for all frequency bands within the frequency range of interest. The vibratory velocity level, L'_v, may be determined from the vibratory acceleration level, L'_a, in accordance with annex F or from the acceleration signal by direct integration (see 5.4), thus avoiding calculations[1]. The measurement shall be carried out by using the time-weighting characteristic S ("slow") of the sound level meter or by an integrating sound level meter.

The measurement time should be chosen so that it is appropriate for the type of sound radiated by the structure and the signal processing techniques.

For steady sound, for example, the measurement time should be at least 10 s for centre frequencies of 200 Hz and higher. For time-varying sound, the measurement time shall be chosen in such a way that the noise of the machine is measured unambiguously for the specified operating mode.

If the preliminary investigations have shown that at particular measurement positions the vibratory velocity levels (or acceleration levels, see annex E) of the extraneous structure-borne sound are less than 10 dB below the levels of the machine when operating, they shall also be determined by a suitable method (see note in 6.2) and a correction made (see 8.1).

NOTE — If it is not possible to determine the levels of the extraneous structure-borne sound separately (e.g. owing to the inseparable coupling of the machine with other assemblies), the results calculated in accordance with clause 8 will be too high.

7.6 Mounting of the vibration pick-up

The vibration pick-up shall be mounted so that it senses as closely as possible the true velocity of the vibrating surface at the measurement position over the frequency range of interest. It shall be mounted in accordance with ISO 5348 with its vibration axis normal to the vibrating surface. For recommendations on mounting methods, see annex A.

7.7 Influence of the mass of the vibration pick-up

It is strongly recommended to use a light pick-up (see 5.2 for explanations). If such a pick-up is not available, the correction according to annex B for uniform structures (plates, cylinders) may be applied. For other structures, the accuracy of this correction is unknown.

7.8 Determination of the radiation factor

The radiation factor of the machine shall either be measured in accordance with the recommendations given in annex D or estimated in accordance with 8.3.2.

1) If only A-weighted vibratory velocity levels are to be determined, integration is necessary.

8 Calculations

8.1 Correction for extraneous structure-borne sound

The measured levels shall be corrected for extraneous structure-borne sound according to table 2.

Table 2 — Correction factor for extraneous structure-borne sound

Values in decibels

Difference between the vibratory velocity levels (or acceleration levels) of the machine when operating and the levels of the extraneous structure-borne sound	Correction factor K_1 to be subtracted from the vibratory velocity levels (or acceleration levels) in order to obtain the level generated by the machine alone
3	3
4	2
5	2
6	1
7	1
8	1
9	1
10	0

8.2 Determination of the mean vibratory velocity level on the vibrating measurement surface

The vibratory velocity levels, determined in accordance with 7.5 and corrected, if necessary, in accordance with 8.1 and annex B, with the measurement positions $i = 1, \ldots, N$ for each frequency band, are given by the following equation:

$$L_{vi} = L'_{vi} - K_{1i} + K_{Mi} \qquad \ldots (7)$$

where

L'_{vi} is the uncorrected measured vibratory velocity level[1];

K_{1i} is the correction factor for extraneous structure-borne sound (see 8.1);

K_{Mi} is the correction factor for the mass of the pick-up (see annex B).

The mean value $\overline{L_v}$, in decibels, as an average over the vibrating measurement surface, S_S, is calculated in accordance with one of the following two equations, as appropriate:

a) **Uniformly distributed measurement positions in accordance with 7.2.3**

$$\overline{L_v} = 10 \lg \left(\frac{1}{N} \sum_{i=1}^{N} 10^{0.1 L_{vi}} \right) \qquad \ldots (8)$$

b) **Non-uniformly distributed measurement positions in accordance with 6.2.4**

$$\overline{L_v} = 10 \lg \left(\frac{1}{S_S} \sum_{i=1}^{N} S_{Si} \, 10^{0.1 L_{vi}} \right) \qquad \ldots (9)$$

8.3 Calculation of the airborne sound power level caused by radiation of structure-borne sound

8.3.1 General

From the values of $\overline{L_v}$, calculated in accordance with 8.2, the sound power level, L_{WS}, in decibels, is calculated from the following equation (derived from equations (4) and (5)):

$$L_{WS} = \overline{L_v} + \left[10 \lg \frac{S_S}{S_0} + 10 \lg \sigma + 10 \lg \frac{\varrho c}{(\varrho c)_0} \right] \qquad \ldots (10)$$

1) See footnote to 3.4

where

$\overline{L_v}$ is the mean vibratory velocity level[1)] (reference velocity: 50 nm/s) on the vibrating measurement surface, calculated in accordance with 8.2.

S_S is the area of the relevant vibrating measurement surface;

S_0 = 1 m²;

σ is the radiation factor;

ϱc is the characteristic impedance of air;

$(\varrho c)_0$ = 400 N·s/m³ [i.e. the impedance of the air at 20 °C and atmospheric pressure of 1 000 mbar (10⁵ Pa)].

The A-weighted airborne sound power level, if required, shall be calculated from the sound power levels in frequency bands in accordance with annex C.

8.3.2 Case where the radiation index, 10 lg σ, is measured

If the radiation index is measured in accordance with annex D for the relevant frequency band, the airborne sound power level for the frequency band shall be determined in accordance with equation (10).

8.3.3 Case where radiation index, 10 lg σ, is assumed

If, for the machine under test, the sound radiation model for a spherical source of zero order can be adopted (e.g. for compact sources), the radiation index shall be estimated from figure 1 or from the following equation:

$$10 \lg \sigma = -10 \lg \left[1 + 0{,}1 \frac{c^2}{(fd)^2} \right]$$

where

f is the frequency;

d is the typical dimension of the source (diameter of spherical source of zero order), e.g. $d = \sqrt{S/\pi}$ or $d = \sqrt[3]{2V}$, where S is the approximate radiating surface of the source and V is the approximate volume of the source;

c is the velocity of sound in air.

The airborne sound power level shall then be calculated from equation (10).

NOTES

1 The result will be an upper estimate of the sound power level.

2 For radiation indexes of other sound sources, see the Bibliography.

8.3.4 Case where radiation index, 10 lg σ, is unknown

If the radiation index can be neither measured (see 8.3.2) nor estimated (see 8.3.3), an upper limit for the airborne sound power level caused by structure-borne sound radiation may be given. For such a limit, it may be sufficient to calculate the A-weighted airborne sound power level from the A-weighted mean vibratory velocity levels.

An upper estimate of the airborne sound power level [illegible] can be calculated using the assumption σ = 1, i.e. 10 lg σ = 0 and is, therefore, given by the following equation

$$L_{WS} = \overline{L_v} + 10 \lg \frac{S_S}{S_0} \qquad (11)$$

1) See footnote to 3.4

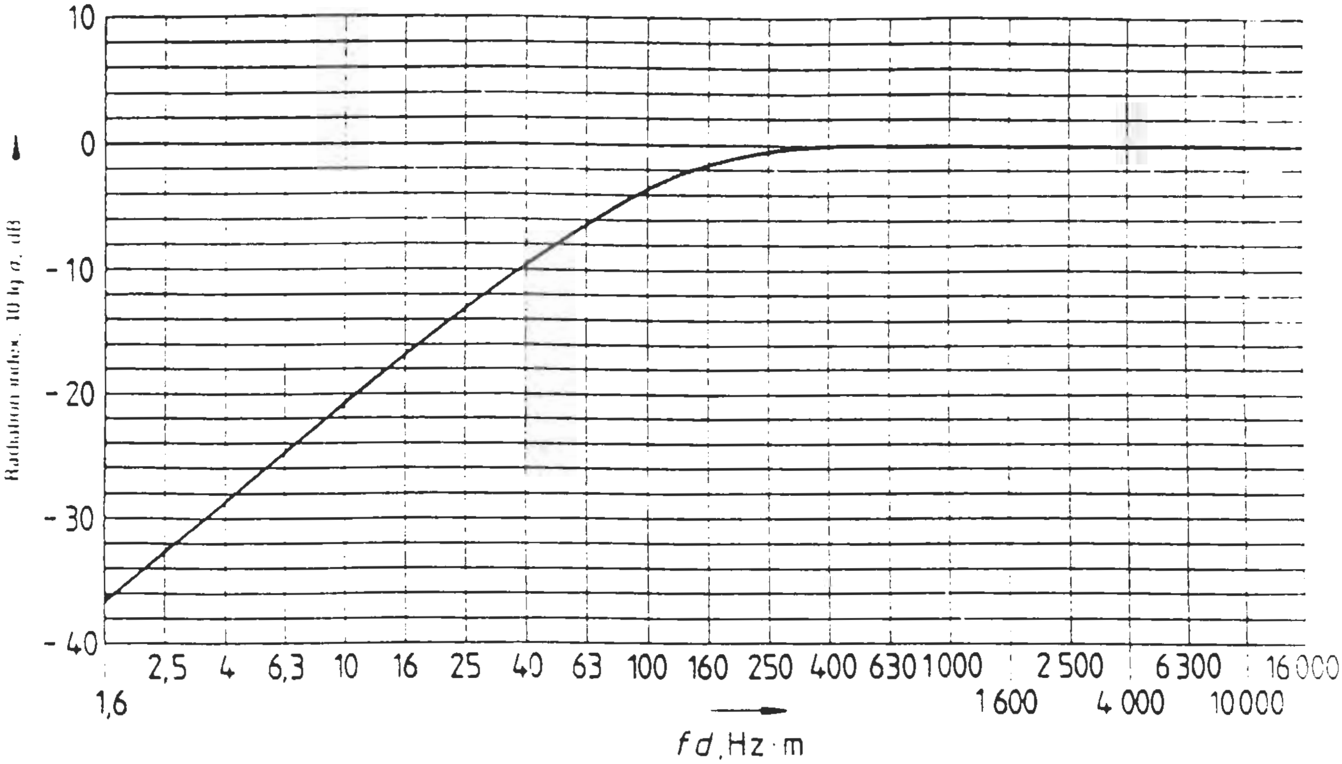

Figure 1 — Radiation index, 10 lg σ, for a spherical source of zero order as a function of frequency, f, and typical dimension, d

9 Information to be recorded

9.1 Machine under test

The following information shall be recorded:

a) a description of the machine (dimensions, construction elements of the radiating structure);

b) the installation conditions;

c) the operating condition;

d) the test environment;

e) identification of the different sound sources of the machine operating during the measurement, if relevant;

f) the date of test.

9.2 Measurement conditions

The following information shall be recorded:

a) atmospheric temperature, in degrees Celsius;

b) barometric pressure, in millibars.

9.3 Measuring instrumentation

The following information shall be recorded:

a) the measuring instrumentation used, including type, serial number and manufacturer;

b) the bandwidth of the frequency analyser;

c) the frequency response of the measuring system;

d) the calibration method used for the measuring system, and the date and place of calibration;

e) the mounting of the vibration pick-up.

9.4 Acoustical data

The following information shall be recorded:

a) a description of the vibrating measurement surface, its dimensions and distribution of measurement positions (drawing);

b) the vibratory velocity level for each measurement position (for each frequency band or A-weighted);

c) the corrections, in decibels, if applied, in each frequency band (or A-weighted), for extraneous structure-borne sound and for the mass of the vibration pick-up;

d) the mean vibratory velocity level, $\overline{L_v}$ in each frequency band (or A-weighted), together with the reference velocity;

e) the area of the relevant vibrating measurement surface, S_S;

f) the radiation index, 10 lg σ, and the method of derivation (see 8.3.2 to 8.3.4);

g) the airborne sound power level, L_{WS}, for the structure-borne sound in each frequency band and/or A-weighted sound power levels.

Annex A

Use of the vibration pick-up

(This annex forms an integral part of this Technical Report.)

A.1 Recommendations on mounting the vibration pick-up

The recommendations outlined in ISO 5348 should be followed.

The preferred method of mounting is to screw the vibration pick-up to the vibrating surface, but for measurements up to 10 kHz it is more convenient to use adhesives recommended by the manufacturer. Adhesive wax, used in thin layers, is also suitable up to 10 kHz, but not for surfaces at elevated temperature.

For smooth flat surfaces of steel, clamping magnets may also be used at frequencies below 2,5 kHz. The maximum acceleration which can be measured depends on the adhering force and the mass of magnet plus vibration pick-up. For a typical magnet, the maximum adhering force as a function of plate thickness is shown in figure 2.

If a magnet, with a mass of 110 g, is used in combination with a 30 g vibration pick-up, the maximum admissible acceleration would be 1 000 m/s^2 provided that the steel plate exceeds 4 mm in thickness. The advice of the vibration pick-up manufacturer should be followed.

The adhering force of a magnet is considerably diminished if the vibrating surface is not smooth and flat or if it is painted; this can lead to unreliable measurements. Smoothing the surface may be much more time-consuming than using adhesives.

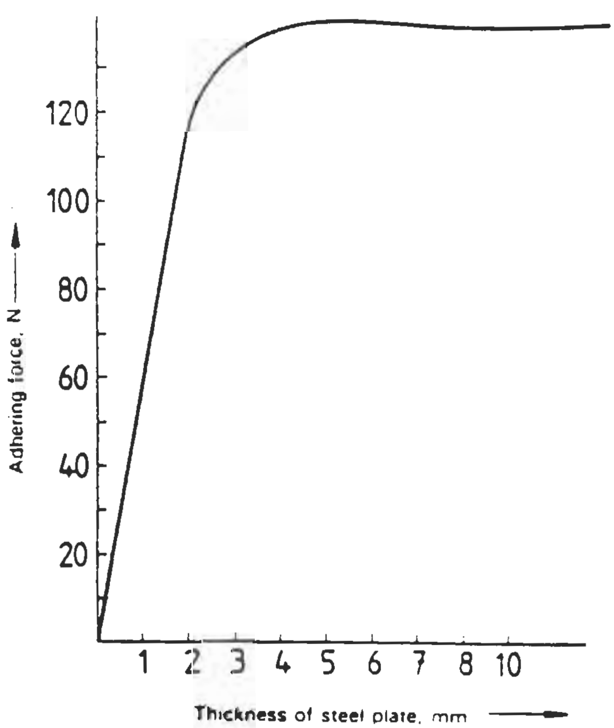

Figure 2 — Maximum adhering force as a function of plate thickness for a typical magnet

A.2 Recommendations on positioning the cable of the vibration pick-up

Vibration of the cable relative to the vibration pick-up may induce extraneous voltages in the circuit. In order to avoid this, the cable should be fixed on the machine at a point as close as possible to the vibration pick-up (see figure 3).

The problem can also be solved by using the pick-ups with integrated impedance transducers (see 7.4).

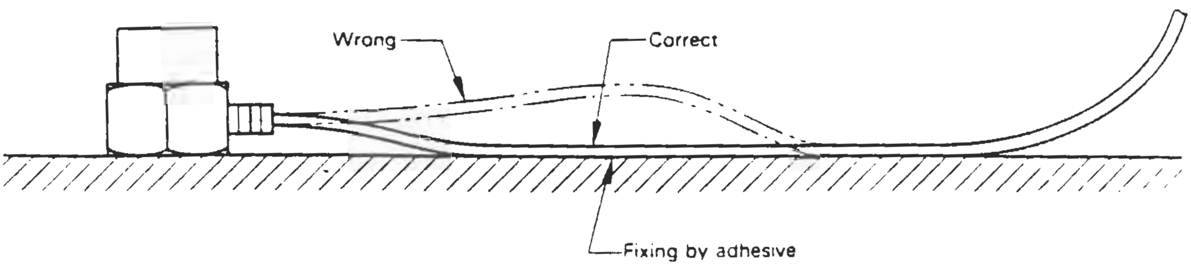

Figure 3 — Cable mounting

Annex B

Correction for the influence of the mass of the vibration pick-up

(This annex forms an integral part of this Technical Report.)

The correction to the vibratory velocity at frequency ω ($= 2\pi f$) is given by the following equation:

$$v^{*} = v' \left| 1 + \underline{Z}_{a} / \underline{Z} \right| \qquad \ldots (12)$$

where

v^{*} is the vibratory velocity in the absence of the vibration pick-up;

v' is the measured vibratory velocity;

$\underline{Z}_{a}$ is the complex mechanical impedance of the isolated accelerometer system at frequency ω in the direction of acceleration measurement;

$\underline{Z}$ is the complex mechanical driving point impedance of the structure at frequency ω at the vibration pick-up mounting point in the direction of acceleration measurement.

In cases where the detailed variation of Z with ω is unknown and where broad-band vibration is being measured in frequency bands, a frequency-average correction may be applied. In the case of a flat plate or of a singly curved shell of which the radius of curvature is greater than c_{L}/ω, the correction is approximately given by the following equation:

$$v^{*} = v' \left[1 + \frac{8{,}6\,(f_{c}\,m_{a})^{2}}{(\varrho_{S}\,c_{L}\,h^{2})^{2}} \right]^{1/2} \qquad \ldots (13)$$

where

f_{c} is the centre frequency of the band;

m_{a} is the mass of the vibration pick-up and any adaptor;

ϱ_{S} is the density of the plate material;

is the longitudinal wave velocity in the plate;

h is the thickness of the plate (shell).

This equation has been derived assuming that $\underline{Z}$ is the point impedance of an infinite uniform flat plate.

This correction is most accurate where the frequency bandwidth of measurement substantially exceeds the average modal resonance frequency spacing: the latter is the inverse of the average of the average modal density of the structure. For a flat plate or shell of large radius of curvature, this condition will be satisfied provided that

$$\Delta f > \frac{3 h c_{L}}{S}$$

where

Δf is the frequency bandwidth of measurement;

S is the surface area of the plate or shell (one side).

Equation (13) does not strictly apply to single frequency vibrations or to measurement positions in the immediate vicinity of structural boundaries of stiffeners. The correction K_{M}, for the mass of the vibration pick-up can be added to the vibratory velocity level, L_{v} [in accordance with equation (7)], and is calculated from the following equation:

$$K_{M_i} = 20 \lg \frac{v^{*}}{v'} \qquad \ldots (14)$$

where v^{*}/v' is taken from equations (12) and (13), as appropriate.

Annex C

Procedures for calculating A-weighted sound power level from octave or one-third octave band power levels

(This annex forms an integral part of this Technical Report.)

C.1 Calculate the A-weighted sound power level, L_{WA}, in decibels (reference sound power : 1 pW), from the following equation

$$L_{WA} = 10 \lg \sum_{j=1}^{j_{max}} 10^{0,1(L_{Wj} + C_j)} \qquad \dots (15)$$

where

L_{Wj} is the level in the jth octave or one-third octave band;

j_{max} and C_j are given in clauses C.2 and C.3 for octave-band and one-third octave band data, respectively.

C.2 For calculations with octave-band data, j_{max} = 7 and C_j is given in table 3.

Table 3 — Values of j and C_j for octave-band data

j	Octave-band centre frequency Hz	C_j dB
1	125	− 16,1
2	250	− 8,6
3	500	− 3,2
4	1 000	0
5	2 000	+ 1,2
6	4 000	+ 1
7	8 000	− 1,1

C.3 For calculations with one-third octave-band data, j_{max} = 21 and C_j is given in table 4.

Table 4 — Values of j and C_j for one-third octave-band data

j	One-third octave-band centre frequency Hz	C_j dB
1	120	− 19,1
2	125	− 16,1
3	160	− 13,4
4	200	− 10,9
5	250	− 8,6
6	315	− 6,6
7	400	− 4,8
8	500	− 3,2
9	630	− 1,9
10	800	− 0,8
11	1 000	0
12	1 250	0,6
13	1 600	1
14	2 000	1,2
15	2 500	1,3
16	3 150	1,2
17	4 000	1
18	5 000	0,5
19	6 300	− 0,1
20	8 000	− 1,1
21	10 000	[illegible],5

Annex D

Guidelines for determining the radiation index, 10 lg σ

(This annex forms an integral part of this Technical Report.)

The radiation index, 10 lg σ, should be determined under the installation and operating conditions specified in 6.3 and 6.4. For specific investigations, use should be made of tonal or broad-band exciters to produce vibrations in the machine corresponding to the required operating condition (6.4). The sound power level in frequency bands, $L_{W S}$, should be determined either in a reverberation room or in a free field according to one of the methods specified in ISO 3741, ISO 3742, ISO 3743, ISO 3744, ISO 3745 or ISO 3748.

The vibratory velocity level, $\overline{L_v}$, is determined in accordance with clause 7 and 8.2.

The values of $L_{W S}$, $\overline{L_v}$ and 10 lg S_S/S_0 (see 8.3) are then substituted into equation (10) to give values of 10 lg σ which are plotted against frequency.

NOTE — If the bandwidth is small, the curve may show numerous peaks.

If prior experimental or theoretical evidence concerning a group of related machine structures is available, a basis for smoothing the curve may be suggested. Extrapolations and interpolations obtained from this will be useful for the purposes of 8.3.2.

Annex E

Recommendations concerning the frequency band of interest

(This annex forms an integral part of this Technical Report.)

The frequency band of interest normally contains either all octave bands with centre frequencies between 125 and 8 000 Hz or all the one-third octave bands with centre frequencies between 100 and 10 000 Hz. All frequency bands in which vibratory velocity levels are at least 50 dB lower than the highest vibratory velocity level measured in any one frequency band may be disregarded. In special cases, the frequency range may be expanded on both sides provided that the measurement equipment still fulfils the requirements laid down in clause 5. The frequency range can be restricted (non-symmetrically, if necessary) provided that the sound is radiated predominantly at high or low frequencies.

Annex F

Determination of the vibratory velocity level from the vibratory acceleration level

(This annex forms an integral part of this Technical Report.)

The vibratory acceleration level, L_a, in decibels, is given by the following equation:

$$L_a = 10 \lg \frac{a^2}{a_0^2} \qquad \ldots (16)$$

where

a is the r.m.s. value of the vibratory acceleration within the relevant frequency band;

a_0 is the reference acceleration (= 10^{-6} m/s²).

The relation between the measured vibratory velocity level[1], L'_v, in decibels, and the measured acceleration level, L'_a, using $v_0 = 5 \times 10^{-8}$ m/s for a frequency band with a centre frequency, f_m, is expressed by the following equation [which is derived from equations (2) and (3)]:

$$L'_v = L'_a - \left(20 \lg \frac{f_m}{f_0} - 10 \right) \qquad \ldots (17)$$

where

f_m is the centre frequency of the frequency band;

f_0 is the reference frequency (= 1 Hz).

NOTE — Since the highest velocity level for tonal components will not normally appear exactly at the centre frequency of the frequency band, the value of L'_v could be wrong by up to as much as $20 \lg \sqrt{2}$ dB (= 3 dB) for octave bands. This error can be reduced by using one-third octave-band measurements.

Equation (17) is not valid for A-weighted levels; A-weighted velocity levels can only be determined from integrated acceleration signals (see 5.4).

When measuring vibration with a sound level meter connected to an acceleration transducer, the indicated level L_x is not the acceleration level L'_a. Precision sound level meters usually indicate voltage level (reference voltage: 1 µV). By taking into consideration the voltage response U of the acceleration transducer used, the acceleration level, L'_a (reference acceleration: 10^{-6} m/s²), in decibels, is calculated from the following equation:

$$L'_a = 20 \lg \left(\frac{10^{(L_x/20)}}{U \times 10^{-6}} \right) \qquad \ldots (18)$$

where U is expressed in microvolts per metre per second squared.

Theoretical example:

Where

$$U = 51 \text{ mV}/g_0 = \frac{51\,000 \text{ µV}}{9{,}81 \text{ m/s}^2} = 5\,200 \text{ µV/(m/s}^2)$$

$$L_x = 100 \text{ dB}$$

equation (18) gives L'_a = 145,7 dB.

1) See footnote to 3.4.

Bibliography

JUNGER, M.C. and FEIT, D. *Sound structures and their interaction,* M.I.T. Press, Cambridge, MA, USA, and London, 1972

HUBNER, G. Analysis of errors in measuring machine noise under free field conditions, *J. Acoust. Soc. Am.*, **54**, 1973: pp. 967 977

GOSELE, R. and KOTTER, W. Einfluß der Befestigung von Schwingungsaufnehmern auf die Meßgenauigkeit. *Konstruktion im Maschinen-, Apparate- und Geratebau,* **31**, *Heft 10,* Springer Verlag, Berlin, 1979: pp. 393-398.

RICHARDS, E.J. Noise from industrial machines, in: *Noise and vibration* (ed. WHITE, R.G. and WALKER, J.G.), J. Wiley, New York, 1982: chapter 22, pp. 525-545.

FAHY, F.J. Structure-fluid interaction, in: *Noise and vibration* (ed. WHITE, R.G. and WALKER, J.G.), J. Wiley, New York, 1982 chapter 11, pp. 247-267.

HUBNER, G. Determination of sound power radiated by structural components of machinery using vibration measurements — A direct finite element method, *Rev. d'acoust.*, **10**, ICA Paris and Lyons, 1983: pp. 163-166.

MILLOT, P., GUYADER, J.L. and BOISSON, L. Recommandations d'une procédure expérimentale pour la mesure d'énergie vibratoire des plaques, *Proc. 11. ICA Congress,* Lyons, 1983: pp. 133-136.

WALLACE, C.E. Radiation resistance of a rectangular panel, *J. Acoust. Soc. Am.*, **51** (3), Part 1, 1972: pp. 946-952.

BIJL, L.A. Measurement of vibrations complementary to sound measurements, *CONCAWE Report No. 8/77.* (Oil companies' international study group for conservation of clean air and water in Europe), The Hague, The Netherlands.

FOLLER, D. Der Abstrahlgrad von Platten, *Dtsch. A.G.A.*, VDE-Verlag, Berlin, 1980.