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Mechanical vibration — Ground-borne noise and vibration arising from rail systems —

Part 31:
Guideline on field measurements for the evaluation of human exposure in buildings

Vibrations mécaniques — Vibrations et bruits initiés au sol dus à des lignes ferroviaires —

Partie 31: Lignes directrices de mesurages in situ pour l'évaluation de l'exposition des individus dans les bâtiments

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Foreword

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

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

This document was prepared by Technical Committee ISO/TC 108, *Mechanical vibration, shock and condition monitoring*, Subcommittee SC 2, *Measurement and evaluation of mechanical vibration and shock as applied to machines, vehicles and structures*.

A list of all parts in the ISO 14837 series can be found on the ISO website.

Mechanical vibration — Ground-borne noise and vibration arising from rail systems —

Part 31: Guideline on field measurements for the evaluation of human exposure in buildings

1 Scope

This document gives guidelines to encourage reporting of field measurements of ground-borne noise and vibration in a metric that allows international comparison and future development of empirical models. It also sets out the basic minimum requirements and good practice when taking measurements for the evaluation of human exposure in residential buildings to ensure they are reliable. While national standards or requirements based upon project-specific purposes would normally take priority, this guidance can be used where there are no particular requirements or to provide supplementary guidance. Thereby, this document provides a means of improving general quality and reporting of field measurements in a preferred format.

There are a number of reasons for carrying out field measurements of ground-borne noise and vibration arising from rail operations, from complaint investigations to validation of prediction models, diagnostics and research as detailed in ISO 14837-1:2005, 7.2. In the present document, two levels of evaluation are considered.

— Scope 1 corresponds to basic measurements of floor vibration and noise in rooms in buildings to evaluate the human exposure to ground-borne vibration and ground-borne noise. Requirements are presented under two levels of accuracy:

  a) basic measurements with minimum accuracy;

  b) measurements with reduced uncertainty, also more reproducible and more appropriate for prediction.

Ground-borne noise is noise generated by vibrating building elements (e.g. floors, walls and ceilings) in the room of interest and is therefore best expressed by both an acoustic and a vibrational quantity. Its identification as ground-borne noise (as opposed to airborne noise, potentially also present) requires simultaneous noise and vibration measurements. Nevertheless, there are also cases of very low frequency vibration (below 10 Hz to 16 Hz) where only vibration measurements are relevant. Rattle can also arise from vibration, which can be from building components or furniture. This document does not set out to characterize this phenomenon, but to note its presence when it occurs.

NOTE In some cases, Scope 1 can relate to measurements on the ground outside a building (to resolve access issues or to comply with national regulations), although measurements at the building are generally preferred.

— Scope 2 corresponds to measurements extended to evaluate the vibration immission to buildings, which includes vibration measurements at or near the building foundations and vibration measurements on ground next to the building so that the building coupling loss and building transmissibility can be estimated.

Vibration measurements near the tracks (on ground surface or in tunnels) for a proper characterization of the source are outside the scope of this document.

Certain requirements are specified in the interest of achieving a consistent minimum data set for each investigation, allowing data comparison between sites.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 1996-2:2017, *Acoustics — Description, measurement and assessment of environmental noise — Part 2: Determination of sound pressure levels*

ISO 14837-1:2005, *Mechanical vibration — Ground-borne noise and vibration arising from rail systems — Part 1: General guidance*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 14837-1 and the following apply.

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

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

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

3.1
building coupling loss
frequency-dependent vibration level difference (typically in the vertical axis and sometimes also in the horizontal plane), in decibels, between the ground surface (free field) and the building foundation (which can be a measurement at or near this foundation), which is influenced by the building as a whole

Note 1 to entry: Care is required to interpret this quantity, which can be approximated in situations where measurements of the ground are performed close to the building such that it is not an ideal free field (see 4.5 and Annex B).

3.2
building transmissibility
frequency-dependent vibration level difference, in decibels, between the building foundation and the building floors

Note 1 to entry: The building transmissibility can be applicable to both the vertical and the horizontal directions. It can be based on either metric, velocity, acceleration, etc. (see Annex B).

3.3
room corner
3D ceiling corner (3D cc) or 3D floor corner (3D fc), which refers to noise measurements in a corner with a vertex formed from three surfaces (two walls and a ceiling, or two walls and a floor), with eight such 3D corners in a rectangular room

Note 1 to entry: A measurement in accordance with this document is usually equidistant from all the surfaces.

Note 2 to entry: A 2D corner is formed from two surfaces, typically two walls of a room (2D ww). In practice, a 2D corner measurement is at a given height from a floor (usually 1,2 m to 1,5 m), whereas the distance from the wall is usually 1 m, but not less than 0,5 m and needs to be measured and stated. A 2D corner could also arise from a floor and a wall (2D fw), or wall and a ceiling (2D wc), but is not used in this document.

3.4
category of rail events
set of rail events corresponding to the same train types passing at a typical speed, within which mean values (and standard deviations) of the exposure descriptors measured for each pass-by can be estimated and used to characterize the category considered

EXAMPLE Train types can be freight, local commuter, intercity, high speed.

4 Requirements for field measurements in buildings

4.1 General

This clause specifies requirements for taking measurements in residential buildings at two levels of detail as shown in Table 1.

Table 1 — Scope details

Scope 1	Evaluation of human exposure to vibration and ground-borne noise
Scope 2	Vibration immission to building

Requirements are presented in Tables 2 to 9 consisting of three columns.

— For Scope 1, minimum requirements are given in the left column and requirements for reduced uncertainty (see ISO/IEC Guide 98-1 or Reference [40]) given in the middle column.

— For Scope 2, requirements are given in the right column.

Complementary guidance and explanation are given in footnotes (which clarify and can include specific requirements) and notes (which only clarify but do not include specific requirements).

4.2 Instrumentation

Requirements on instrumentation for taking measurements to address Scope 1 and Scope 2 are given in Table 2.

Table 2 — Requirements on instrumentation

Scope 1 Evaluation of human exposure		**Scope 2 Immission to building**
Minimum requirements	**Reduced uncertainty**	
— Ground-borne noise shall be measured when relevant, using a microphone (see Note 1). — The noise meter for audible ground-borne noise typically has a frequency range of 16 Hz (see Note 2) to 250 Hz, or in some cases higher at the top end in case of hard rock sites. — Accelerometers or geophones may be used to sense vibration.[a,b] — Vibration transducers, signal conditioning, recording and measurement equipment shall be suitable for use over the following frequency ranges: 1 Hz to 80 Hz for very low frequency vibration cases or 4 Hz to 250 Hz for cases with ground-borne noise (see Note 3).[c,d,e] — Noise equipment shall be field calibrated, a drift in calibration of 0,5 dB being acceptable.[f,g] Vibration equipment often only requires off-site calibration.[g,h] — Where possible, record the signals for subsequent analysis. — For digital acquisition, the sampling frequency shall satisfy the Nyquist criterion.[i]	— Both vibration and noise shall be measured (see Note 4). — Vibration transducers, signal conditioning, recording and measurement equipment shall be suitable for use over the extended frequency range of 1 Hz to 250 Hz. — Noise equipment shall be field calibrated;[f,g] measurements being discarded if calibration drifts by more than 0,3 dB. — Tolerances of equipment shall be stated in the report. — For digital acquisition, the sampling frequency to characterize time history shall be at least five times the upper frequency of interest.	— Equipment used in Scope 1 can also be used in Scope 2.

Table 2 *(continued)*

NOTE 1 Where the noise meter has the option between free-field and random incidence software correction, either option can be selected as the difference is not significant at the low frequencies typical of ground-borne noise.

NOTE 2 At the bottom end of the frequency range, equipment tolerances become increasingly wider (see IEC 61672-1).

NOTE 3 When both noise and vibration are measured, coupling between structural vibration and noise can easily appear, particularly at low frequencies. It is important to keep vibration recording up to typical frequency limits for ground-borne noise, although ground-borne noise which is audible need not go below 16 Hz.

NOTE 4 It is preferable to use the same data acquisition system and the same time base for simultaneous ground-borne noise and vibration measurements.

[a] Where a geophone is used, its frequency response should be electronically/digitally corrected to compensate for the geophone's resonance frequency. Geophones have a better ability to sense frequencies below 5 Hz, where acceleration signals are often physically low in this range; in the latter case a high sensitivity accelerometer becomes necessary.

[b] When using accelerometers, before integrating for velocity it is important to remove any DC offset and apply a high-pass filter to the data to exclude the frequencies below the range considered. It is also important to verify that the inherent electronic noise of the transducer and the signal acquisition system is not greater than the smallest signal that needs to be measured. The signal-to-noise ratio (SNR) should ideally be a factor of 10, which is not always achievable.

[c] The frequency range should be read as one-third-octave centre frequencies (see IEC 61260-1).

[d] A relaxed range of 4 Hz to 250 Hz for vibration can be acceptable as minimum requirements for different reasons: a) transducer (in the case of geophone) having difficulty covering the high frequencies for ground-borne noise (from 16 Hz) up to 250 Hz simultaneously; b) dominant building element responses occur at frequencies higher than 4 Hz. This limitation at the low frequencies should be reported.

[e] Rattle, which is one of the factors in annoyance, is high-frequency noise which should be reported qualitatively, its level being highly variable and not reproducible.

[f] Field calibration shall be carried out for noise equipment before and after each set of measurements. Any drift in calibration checks shall be noted.

[g] The calibrators used to check test equipment shall have current calibration traceable to national standards, carried out annually, while the test equipment itself can be certified for performance according to the manufacturer's specification or appropriate standards every two years (see, for example, ISO 8041-1) or a longer period in some countries (e.g. three years in Japan).

[h] Vibration equipment is usually stable over time, so does not require field calibration but simply a check of functionality for each set of measurements, and careful note of gain settings. A simple functional test on site, such as tapping the transducer is desirable. The vibration equipment chain should ideally be checked prior to site visits preferably with a traceable reference signal or on site if a field calibrator is practical (with regard to transducer mass and portable calibrator capacity), especially when measurement assurance is critical.

[i] To achieve the Nyquist criterion, either increase sampling frequency and/or impose cut-off filter (anti-aliasing filter) to ensure that the chosen sampling frequency meets the criteria by limiting frequency content in signal.

4.3 Fixing vibration transducers

Requirements on fixing vibration transducers for Scope 1 and Scope 2 are given in Table 3 (see also Annex C).

Table 3 — Requirements on fixing vibration transducers

Scope 1 Evaluation of human exposure		Scope 2 Immission to building
Minimum requirements	**Reduced uncertainty**	
— Vibration transducers can be fixed directly to the building element (see Note 1)[a]; or using attachment supports such as brackets or cubes (see Notes 1 and 2). — It is acceptable to simply park a heavy[b] attachment plate with three rounded feet (see Figure 1 a) or a heavy metal cube, as vibration magnitudes in buildings from rail systems are likely to have small acceleration values preventing transducer creep. — Where carpet (or linoleum) is present, it is preferable to temporarily lift the carpet to fix transducers directly to the floor. Where this is not possible, transducers may be fixed via a heavy steel plate with no internal resonances in the frequency range of interest supported on three spikes, as shown in Figure 1 b)[c]. — Care shall be taken in the fixing of vibration transducers to avoid effects of any mounted resonances (see Note 3)[d]. — Placement or fixing details shall be clearly stated in the report.	— For fixing vibration transducers, see column minimum requirements.	— For fixing vibration transducer at or near foundations, see Scope 1 requirements. — Several ways of fixing the vibration transducer on the ground next to the building are possible (see Annex C)[e]: — stake pushed into ground, on which the transducer is fixed (see Note 4), — aluminium plate cast into the soil with plaster of Paris (see Note 5), — transducer buried in soil or inside canister buried in soil near the ground surface less than 300 mm depth[f], — transducer attached to a heavy plate or transducer block with three feet, parked or levelled on the ground surface (see Figure 1)[g], and — transducer attached to the ground surface with an appropriate adhesive or expanding anchor bolt[g].

NOTE 1 Transducer fixing arrangements within residential buildings are likely to be constrained by internal finishes and occupant preferences.

NOTE 2 Transducers can be attached to a cube instead of a bracket for triaxial measurements (cube made from metal or lighter engineering grade plastic; consider impedance contrast, size and properties to avoid resonances in the frequency range of interest). The cube can be attached to concrete floor, or a wall or column of the building using epoxy resin, or just placed with gravity if heavy enough (in the latter care is needed to avoid rocking due to inevitable variations in number and distribution of contact points). Transducers can be attached to the cube, according to the material, for example, magnet, double-sided tape and even thin layer of reusable putty-like adhesive, checked according to the frequency range of interest.

NOTE 3 There are some floor finishes related to impact sound control that are not coupled to the structural floor, and the coupling situation can be improved with some applied mass, although this can vary according to mass applied and floor finish type.

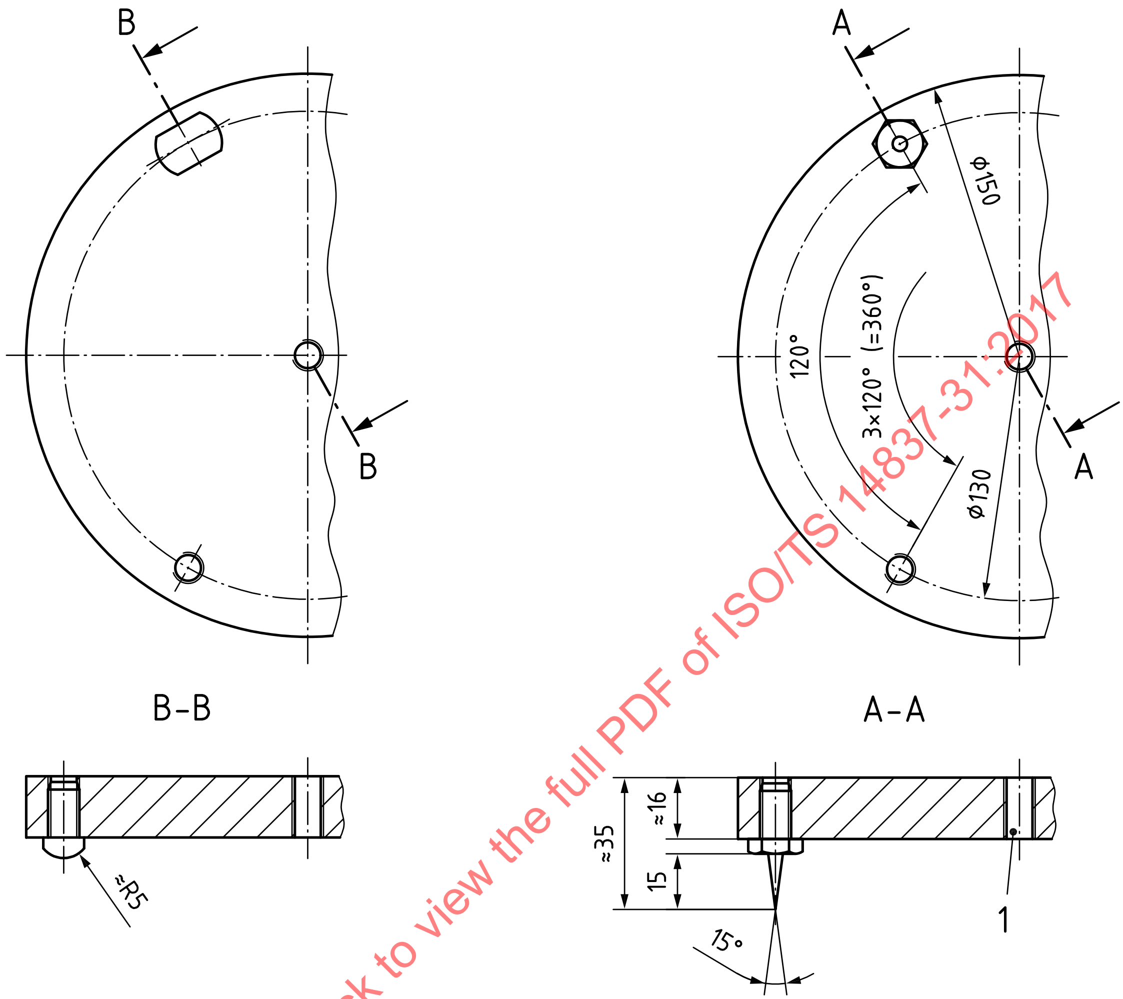
NOTE 4 The spike (stake) made as a cruciform or angle section from a length of 30 cm can according to the ground be pushed into the soil, although there are risks that the stake might be loose in the soil, and such a situation can be made worse when the stake is hammered into the ground. It is advisable to use a functional test, such as tapping the stake, which often reveals if the stake is loosely coupled, although such a test does not ensure that there is good coupling.

NOTE 5 According to Reference [26], using an aluminium plate cast into ground with plaster of Paris or using a stake pushed into the ground leads to similar vibration magnitudes, except at high frequencies.

Table 3 *(continued)*

[a] Where practical and if vibration magnitudes are strong enough, vibration transducers should be fixed via rigid adhesive to solid structural components of the building; where this is not possible, a thin layer of temporary adhesive – such as beeswax or double-sided adhesive tape – may be used. Where double-sided adhesive tape is used, it shall be a thin version that excludes any supplemental elastic layer. Refer to manufacturer specification for transducer mounting methods based on transducer weight/design, testing surface and anticipated vibration frequencies and amplitude, as well as with regard to environmental influences, electrical noise and their management.
[b] According to the acceleration of the surface being measured, at low levels, a "heavy" attachment can when simply parked provide sufficient friction under the weight to prevent the transducer moving (creep) across the surface. The friction is not just dependent upon weight, but the materials at the interface and the distribution of contact points and their surface condition. However, it shall not be so heavy as to cause a mounted resonance in the frequency range of interest. To ensure this lies outside the range of interest, usually it is desirable to make the attachment as light as possible, so there is a balance to be achieved in that circumstance. However, under high accelerations of the surface to be measured, relative to gravity, an attachment that is simply parked cannot faithfully follow the motion of the surface, and a change to attachment mass cannot improve the coupling. A secure coupling by a stud, magnet or adhesive is then essential, and the consideration of attached mass, depending upon what it is being attached to might affect its frequency. In the absence of detailed consideration of friction and acceleration levels of the surface, a secure coupling is usually preferable.
[c] Where a spiked plate is used, ensure spikes are long and slender enough to get through the thickness of the carpet and underlay. There should be a small clearance between the plate and the carpet so as to ensure the resilient carpet or underlay is not compressed so as to loosen the spiked feet from the underlying hard structure.
[d] Ensure transducer mass (especially for a heavy transducer) does not cause resonance within the frequency range of interest, when for example coupled to a circular plate for floor measurements or brackets that facilitate triaxial measurements.
[e] For surface measurements in urban areas, there may be tarmac or hardstanding which can provide a surface measurement position, albeit there are differences to a ground without such surface treatments. The tarmac or hardstanding should be checked to ensure it is well coupled, this may be obvious from listening to site tapping, or in some special cases could be explored with more detailed mobility measurements to check dynamic response of the chosen location.
[f] The buried transducer can be mounted in a small rigid (and water tight, if needed) canister. The volume of the canister, the material, the wall thickness and the mass of the transducer is combined such that the whole assembly has close to the same mass as its corresponding volume of soil (and preferably its centre of gravity close to its centre). Dig a small hole in the ground, flatten and slightly compact the bottom surface, insert the transducer assembly, and fill back part of the soil, carefully compacting towards the walls of the assembly. The assembly should be fully covered in the ground. It is recognized that such an arrangement may be more appropriate under a research investigation (see Annex C).
[g] Where the ground surface is rock, concrete, asphalt or otherwise hard (such as very compacted dry soils) and using care to avoid any loose surface or laminations, the transducer attached to a heavy plate or transducer block with three feet can be parked and levelled on the ground surface, if vibration magnitudes are low. The coupling for direct transducer attachment to the ground surface can be achieved with an appropriate adhesive or expanding anchor bolt, with simple functional test (e.g. tap or manipulate lightly by hand) to identify any poor coupling. Check that such transducers have not become inadvertently dislodged during tests from passers-by who fail to see hazard cones or markings used to delineate the transducer. In long-term deployments, consider how the ground properties and transducer coupling will change under wet conditions, etc. (see also Annex C).

Dimensions in mm



a) With three rounded feet for mounting on hard surfaces

b) With three spiked feet of tempered steel for mounting on soft surfaces

Key

1 threaded hole for attaching the transducer(s)

NOTE There is a distinction between round and spiked feet. A spiked foot made from tempered steel is sharp enough to penetrate a soft material such as carpet. It can also couple to a (preferably timber) floor, into which the spikes can penetrate. It is a compromise when the floor below the carpet is hard, since on a hard surface it is undesirable to have a sharp point, which could create mounted resonance of the plate on the sharp point, in either the vertical or horizontal axis. Yet the spikes are needed to penetrate a carpet which it is assumed could not be removed. On hard surfaces, the rounded feet are, however, more appropriate.

Figure 1 — Mounting fixtures — heavy attachment plate made from steel (see DIN 45669-2)

4.4 Measurement locations in the building

Requirements on general measurement locations in the building for Scope 1 and Scope 2 are given in Table 4.

Table 4 — Requirements on measurement locations in the building

<table>
<tr><th colspan="2">Scope 1
Evaluation of human exposure</th><th rowspan="2">Scope 2
Immission to building</th></tr>
<tr><th>Minimum requirements</th><th>Reduced uncertainty</th></tr>
<tr><td>— As a minimum, ground-borne noise shall be measured in the room that is of interest (see Note 1).

— As a minimum, vibration shall be measured on the floor in the room that is of interest (see Note 1).

— The possibility of fixing vibration transducers on the ceiling shall also be considered[a].</td><td>— Additional measurements may be carried out at other locations within the building such as

— measurements in other habitable rooms[b, c],

— vibration measurements on any building elements that can help distinguish extraneous background events, and

— vibration measurements near the railway, which should be synchronized with those measurements at the building.</td><td>— Additional measurements shall be carried out at the following locations (see Note 2):

— vibration measurements at or near the foundation of the building (see Note 3 and Annex B);

— vibration measurements on ground surface next to the building (see Annex B).</td></tr>
<tr><td colspan="3">NOTE 1 The room of interest may be any habitable room on any floor of a building (including habitable basements) with due regard to locations where any complaints might have arisen.

NOTE 2 Such vibration measurement locations will be used to calculate the building coupling loss and building transmissibility, both common input data for empirical models (see details in Reference [32] and Annex B).

NOTE 3 Such vibration measurement locations can be used to evaluate the possibility of building damage to reassure an occupant or to evaluate mitigation effectiveness or changes over time. Such measurements are less variable, more indicative of the vibration exposure of the building, and can allow better comparison with prediction models; they are also useful to exclude internally generated vibration, not relevant for vibration assessment, by using the foundation transducer as master trigger and the rest as slaves, or for correlating in post processing of the recordings.

a Assuming the ceiling is similar to the base floor and in the absence of suspended ceiling or lining, vibration measurements of the ceiling can serve to estimate floor vibration when direct floor measurements are questionable because of the presence of floor covering. Also in basement rooms, where the floor is often a ground bearing slab (therefore very damped), ceiling vibration might be dominant in radiating ground-borne noise and should be measured.

b Vibration and ground-borne noise do vary with storey height, and so the locations should reflect that of the complainant, but also consider where practicable the exposure of other occupants in the building who could have influenced the adverse comment of the complainant at a particular site.

c Noise measurements conducted in rooms of a façade not facing the railway help minimize the airborne noise contribution, enabling better assessment of ground-borne noise if the latter is source of concern due to very close proximity to an at-grade railway, although the further distance of the room from the source should be a consideration.</td></tr>
</table>

4.5 Vibration measurement positions and orientation

It is important to recognize that in the case of ground-borne noise from railways, the predominant wavelengths are likely to be of the same order as wavelengths of plate modes in floors and other room surfaces. This means that the measured amplitude of the vibration of floor and other surfaces is strongly dependent on location, being lowest in the corners for most edge support conditions and highest at antinodes of plate eigenmodes. Careful measurement of the coordinates of chosen measurement locations shall be recorded (see Note). The topic is further discussed in Annex A. Consideration needs to be given to the uncertainty associated with choice of measurement location.

NOTE It is good practice to validate measurement position with dimensions from reference points that are clearly stated. Where *x* and *y* axes for vibration measurements are used, the *x* axis is horizontal, parallel to the wall of the building nearest the axis of the railway track, whereas the *y* axis is horizontal, but perpendicular to that wall.

Requirements on specific measurement positions and orientation of the transducers for Scope 1 and Scope 2 are given in Table 5.

Table 5 — Requirements on measurement positions and orientation

Scope 1 **Evaluation of human exposure**		**Scope 2** **Immission to building**
Minimum requirements	**Reduced uncertainty**	
— Vibration measurements shall be carried out at one position in the vertical direction at (or near) the mid-span of the floor (see Notes 1 and 2)[a, b]. However, it can in some cases be the horizontal axis that is dominant and should be measured, particularly at higher floor levels in the building or in some wooden framed structures (see Figure 2).	— Additional measurements, less variable, should be carried out on the same floor, close to a load-bearing wall, and performed in two directions (vertical and horizontal perpendicular to the tracks as shown in Figure 2). — Additional measurements can be carried out at other positions within the room (or additional axes), such as for the purpose of evaluating exposure at specific occupant locations, or potential noise sources (see Note 3), or the floor space average vibration magnitude (see Note 4), or the variation in magnitudes throughout the floor (see Note 5)[c, d].	— Additional measurements carried out at or near the foundation of the building should be positioned close to a load-bearing structure (see Figure 2) and performed in a vertical direction (see Note 6). — The additional measurements carried out on the ground surface should be positioned next to (and not in front of) but sufficiently remote from the building, to achieve free-field ground measurement condition and performed in a vertical direction (see Note 7, Figure 2 and Annex B).

NOTE 1 Floor measurement location is relevant as input to receiver and therefore complainant, but measurements are likely to be more variable. Changes in floor layout or support conditions can make measurements near to the centre more susceptible to such changes.

NOTE 2 The vertical axis for vibration measurement on a floor (typically the first floor) is likely to be the most dominant input, due to floor flexibility, and stronger near the mid-span as a result, which has relevance in terms of human perception of the event and possible annoyance.

NOTE 3 Vibration measurements of building walls in horizontal orientation can be carried out, particularly when noise is a concern from railways with diesel-electric locomotives or other low-frequency sources, and/or if rattling occurs of windows or wall-hung objects, and/or if the wall is a potential source of ground-borne noise.

NOTE 4 Three or more measurement positions on the floor (transducer orientation in vertical direction) or any other wall (transducer orientation in horizontal direction), which are potentially sources of ground-borne noise, can be useful to identify such a source and to estimate ground-borne noise from vibration measurements using space average quantities (see 4.6, 4.9 and Annex A). The relationship between vibration measurements and noise levels is sensitive to the relative positions of the measurement locations (see Annex A).

NOTE 5 Measurement locations can be to determine actual floor response mode shapes. If the natural frequency of a floor is important, the corresponding first mode shape (flexure of the floor) implies the centre of the room and is relevant for the highest magnitude. The even modes of floor vibration are not evident at mid-floor locations and cannot therefore be measured there.

Table 5 *(continued)*

NOTE 6 The horizontal direction (particularly radial to source) might be more relevant or used in addition to vertical orientation, in some cases. If in the nearfield to the source, measurements can be justified in all three orthogonal axes. NOTE 7 Where it is not possible to measure at alternative locations at the side of the building, and given that measuring at the front of the building is to be avoided due to nearfield effects (and consequently at a shorter distance from the source, which can be relevant), an alternative procedure is to measure at locations sufficiently further away in front of the building (i.e. between source and building), from which the value at the building location can be extrapolated (see Annex B). [a] The mid-span needs to be found and locations within the middle 15 % of the length and width of the floor area considered; but if uncertain, more locations should be considered. [b] Where the optimum choice for the position of a floor vibration transducer is limited by site constraints, this shall be noted. Some floor areas are simply not accessible, which limits the choice for equipment deployment. [c] The spatial variation of vibration is determined by the modal behaviour of a floor, and could be established by leaving one transducer fixed whiles the other "roving" transducers are moved to sample different locations under common events. The reference transducer should ideally be placed at a position that characterizes the source well and for repeatability, for example, near a wall location or even on the ground outside. This can help ensure the monitoring locations samples the worst case and help provide an average value that is reproducible. [d] The optimum choice of the position of the floor vibration transducer is also not entirely evident in complicated floor arrangements, and in such cases there is a risk that the measurement choice taken will not be optimal, and such a risk is to be considered. In a complicated floor arrangement, more measurement locations can be considered, but it is desirable to ascertain the complicated floor structure to better dictate those choices.

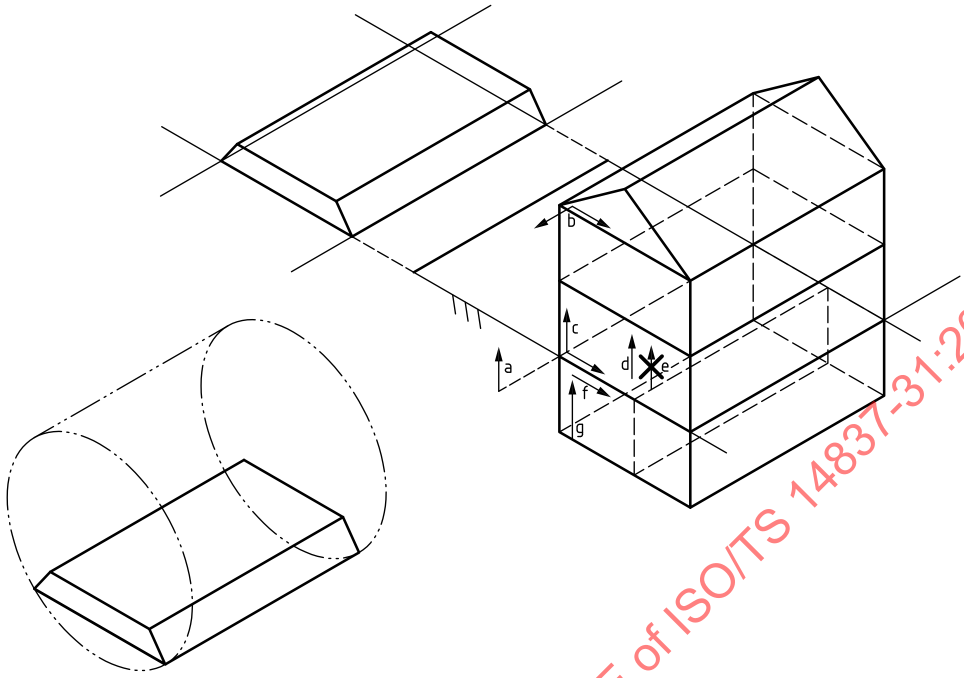


Figure 2 — Vibration measurement positions

Key

a possible free-field example at side of building

b upper storey horizontal plane, aligned to building axis, note relation to axis of railway track

c at or near building threshold, to structure or element representative of load bearing wall

d select mid-span (middle 15 % length and width) at ground floor (or ceiling below), first floor level and/or other upper floors

e avoid measurement at what appears to be floor mid-span, but actually has a supporting wall below

f mid-span of wall

g measurements at or near foundation/edge of basement ground slab

4.6 Noise measurement positions

It is important to recognize that in the case of ground-borne noise from railways, the predominant wavelengths are likely to be of the same order as room dimensions. This means that the sound field in the room is strongly modal and measured amplitudes are highly sensitive to location, being highest in the corners and lowest at nodes of eigenmodes. Careful measurement of the coordinates of chosen measurement locations shall be recorded (see Note). The topic is further discussed in Annex A. Consideration needs to be given to the uncertainty associated with choice of measurement location.

NOTE It is good practice to validate measurement position with dimensions from reference points that are clearly stated.

Requirements on specific noise measurement positions for Scope 1 and Scope 2 are given in Table 6.

Table 6 — Requirements on noise measurement positions

Scope 1 Evaluation of human exposure		Scope 2 Immission to building
Minimum requirements	**Reduced uncertainty**	
— Noise measurements shall be carried out using one microphone at the one-third point of a room's plan dimension (four options possible) (see Note 1)[a, b]. — The microphone shall be at a 1,2 m to 1,5 m height (see Note 2). — Additional noise measurement locations can be required to investigate specific locations identified by a complainant (see Note 3)[c, d].	— Additional noise measurement locations are required for reducing uncertainty. ISO 1996-2:2017, 9.2, shall be used, which refers to at least three noise measurement locations (see Note 4), including one near a 3D room corner where noise is predominantly low frequency, from which a space average noise level is calculated (see Note 5, 4.9 and Annex A). It should be noted that according to ISO 1996-2, where measured noise levels are not corrected for a measured reverberation time, an empirical adjustment can be made by subtracting 3 dB from an empty room noise measurement to achieve the effect of reverberation time in an equivalent furnished room.	— Some procedures are necessary to distinguish ground-borne noise from airborne noise: — measurements can be performed in rooms not facing the railway (see Table 4, footnote c); — façade airborne sound insulation measurements (although cumbersome) can be performed to estimate the indoor airborne noise contribution from various external sources, such as at-grade railway or otherwise, which are not the sources of direct interest, using their façade noise levels (see Note 6).
NOTE 1 Measurements at the centre of the room can underestimate the noise. When comparing the limit values with measured values, the measurement procedure of the corresponding limit value guideline needs to be applied. NOTE 2 This height corresponds to the typical ear height of a seated person. However, this position, often close to half the room height, can underestimate the noise. There can be three distinctions of height (0,6 m) recumbent on bed, (1,2 m) seated, and (1,55 m) standing. The range of 1,2 m to 1,5 m covers seated or standing. NOTE 3 Measurements at corner locations (3D cc) show the highest levels, and are less variable. The corner location (2D ww) can relate to a person seated and so might better correlate with the complainant's subjective response, which could be influenced by the highest levels. A position that better reflects the occupant/complainant location in the room could include a position for a person recumbent on a bed. NOTE 4 The moving microphone option, used in a situation such as sound insulation testing, is not appropriate to ground-borne noise from rail systems due to the short duration of the pass-by event and the spurious noise that could be generated by the technique such as movements of the person, and even the movements of air across the microphone, which will be a problem when low levels of sound are being measured. Moving microphone for spatial averaging is therefore not practical. An alternative is to use additional microphones simultaneously measuring at least three locations, which is likely to yield better spatial averaging.		

Table 6 *(continued)*

NOTE 5 Space average is an abstract metric and so caution is required when correlating this processed data with complaints that relate to actual levels experienced at actual locations. With a space average metric, some spatial information is lost, but it provides a metric that is less variable, and so more reproducible and can better provide empirical correlation to floor vibrations. This metric may also provide some statistical information of the standard deviation (see Annex A).

NOTE 6 Exterior noise measurements and outdoor-to-indoor façade sound insulation measurements (method defined in ISO 16283-3) can be desirable, to distinguish by calculation airborne from ground-borne noise contributions.

[a] If the room is small or contains large items, such that measurements can occur within 1 m of a wall or reflecting surface, this shall be noted. However, the minimum separating distance between microphone and room boundary is 0,5 m, and should preferably be exceeded.

[b] There is a preference that noise measurements should not be less than 1/4 wavelength and no less than 0,5 m from wall surface, although at low frequencies such absolute criteria cannot be met. There are radiation efficiency issues in nearfield less than 1/4 wavelength where sound can be absorbed by other nearby surfaces and not radiated into the room.

[c] Where furniture in the corners of a room prevent a 2D ww measurement location choice, a high-level corner location (3D cc) might be regarded as equivalent (for the abbreviations, see 3.3). But because noise radiated from a ceiling can differ to that radiating from a floor and given the difficulty of measuring there, the preference is not to use a 3D cc location, though this may be adopted by some practitioners and should be noted and justified accordingly.

[d] A 2D ww corner location might arise where a cupboard is placed in the corner, now forming a 2D corner comprising a wall surface and a cupboard surface panel. It may be that for practical reasons no other 2D ww position is available, in which case measurements — although undesirable — can be necessitated at the 2D corner formed by a wall surface and a cupboard surface. In this case, it is important to respect the minimum distance of 0,5 m (see footnote a) and be aware that the cupboard panel also acts as a radiating surface and such site issues shall be noted.

4.7 Measurement conditions

Requirements on measurement conditions for Scope 1 and Scope 2 are given in Table 7.

Table 7 — Requirements on measurement conditions

Scope 1 Evaluation of human exposure		Scope 2 Immission to building
Minimum requirements	**Reduced uncertainty**	
— Noise measurements shall be carried out with windows and doors closed. — As far as is practical, all sources of extraneous noise and vibration within the building (such as household appliances that are not normally operating continuously) shall be switched off[a]. — Any other sources of background noise and vibration, such as refrigeration, air-conditioning, heating systems, lift machinery, etc. or other trains, shall be reported and included in measurements of background noise and vibration before and after train passages[b, c]. — The measurement conditions shall be fully described in the report (see Note 1)[d, e, f].	— Additional measurements can be useful to quantify the extent of acoustic absorption in the room, such as reverberation time measurements[g].	— Measurements or recordings of vibration at or near foundations or on ground next to the building may help distinguish a rail source in the noise measurements from extraneous events and also serve to review any fluctuations over a 24 h period or more, often a perceived issue by complainants (see Notes 2, 3 and 4).

Table 7 *(continued)*

NOTE 1 There can be differences in measurements of floor vibration due to the presence of the occupant(s); this can be relevant on some floor types more so than others. In the case of measurement at “point of entry” to the human body, there can be a need to recognize the change in driving point impedance due to the human body itself on a floor. There can therefore be a case to be made to simulate human load on the floor, although it should be noted that human mass cannot be simply added but needs to simulate biodynamics, which is beyond the scope of most surveys and impractical.

NOTE 2 Longer monitoring can show events unrelated to rail source. Different sources of background vibration can be distinguished by different patterns of appearance, different probability distribution of levels and different frequency content. Extended vibration monitoring can also capture events missed in shorter survey, or capture events that arise at night time, or occasionally that might be the basis of complaint, and thereby help cross referencing to extended noise measurements (see Annex D for option to cross reference measurements to a diary of events logged by occupant).

NOTE 3 Rattle can occur. How it is addressed depends upon the situation for which the measurements are taken. For characterizing ground-borne noise, it is important to exclude rattle, but this may not be possible. For the evaluation of human exposure, it is sufficient to note the existence of rattle where it occurs, and if it happens to have been included in a measurement.

NOTE 4 Predicting ground-borne noise from vibration can overcome the interference caused in the measurement of ground-borne noise.

[a] It is desirable to minimize the number of occupants of the room undergoing monitoring. The engineer undertaking measurements shall be permitted to be in the room so that a subjective comment can be included and help exclude extraneous events. There shall in any case be no more than two persons in the room under test, noting any interference that may arise. The subjective judgment from the engineer should be noted (see Annex D).

[b] If some train vibration measurements are higher than the average, this might not be linked to contamination, but due to flat wheels or particularly bad rolling stock roughness conditions. If this case occurs, it should be reported as information describing the traffic.

[c] In cases of several railway lines, it can be necessary to distinguish the noise and vibration from the various lines, or ensure that the line of specific interest is established, noting possible contamination from other lines (see also Table 8, Note 1).

[d] Describe furnished/unfurnished state. Elaborate on floor finish and curtains if installed. Elaborate if furnished but vacant room or furnished and utilized. State the number of personnel in the room for the test (generally no more than two); a photo is a useful record of such measurement conditions for subsequent reference.

[e] Identify if the source can be seen, as that indicates a possible airborne path.

[f] Details of the building type (brick, timber framed, steel, concrete, etc.), floor type [timber, concrete (in situ/precast), beam and block, composite, spans, number of inhabited floors] and ground conditions (sand, gravel, clay, rock; see ground categories in ISO/TS 14837-32) should be reported in basic terms. Describe the track. Include a photo in the report of building elevation.

[g] If the room is not in normal furnished condition, a survey method for estimating the reverberation time is defined in ISO 10052 which, however, is valid in the octave band range 125 Hz to 2 kHz and therefore not relevant for ground-borne noise. Field measurements of reverberation time at low frequencies (at least down to 50 Hz) and in small rooms should therefore be performed according to ISO 16283-1 where the reverberation time is measured in octave bands at lower frequencies and the value obtained used for each corresponding one-third-octave band.

4.8 Measurement procedure

Requirements on measurement procedure for Scope 1 and Scope 2 are given in Table 8.

Table 8 — Requirements on measurement procedure

Scope 1 Evaluation of human exposure		Scope 2 Immission to building
Minimum requirements	**Reduced uncertainty**	
— Measure and evaluate background levels (see 4.7 and Note 1)[a]. — Where practical, measure at least five pass-by events, at typical speed, for each category of rail operation to be considered (see Notes 2 to 4)[b, c]. — Ensure that extraneous signals do not contaminate the measurement data (see 4.7). — Some basic site analysis is required and site notes clearly taken and recorded with suitable diagrams for subsequent recollection[d, e].	— A sample size of more than 15 events is preferred. This particularly applies to the category of rail operations that generates highest levels (or exposure). — Estimate duration of train pass-by using the time history, which shall be included as a sample plot in the report. — Some specific dynamic test on the floor should be undertaken to yield information about its dynamic characteristics (see Note 5). — Wherever possible, signals should be recorded for subsequent analysis (see Table 2, Note 4)[f].	— The vibration measurements taken "at" (e.g. on an exposed foundation) or "near to" (e.g. a basement, solid threshold, soil immediately adjacent that approximates the building foundations) and on ground "next to" the building (define either sufficiently far to be preferred free-field, or within free-field) should be performed using the same procedure as for Scope 1.

NOTE 1 The various levels of diagnostic that may help separate spurious events from train-related signature, relating to the study of the spectral signature that gives high-frequency components are more unlikely to be related to the train; there are unique cases, where for example an extreme case of wheel squeal might dominate a spectrum at high frequency. Comparing the L_{Amax} and L_{Cmax} could help when considering the frequency content of signals. It is however also noted that spurious background events might also contain energy at low frequencies and so cannot be separated from train events. Simply listening to the events can be a practical way to check that it is a train source, noting that a recording for subsequent listening is another level of scrutiny, albeit more involved.

NOTE 2 The duration of the measurement could be at least 15 s to characterize the low frequencies. However, rail sources are non-stationary and can often be an event less than 15 s. Therefore, there is significant uncertainty, more so at low frequencies, and this should be borne in mind as a practical limitation of measuring a rail source.

NOTE 3 If close to where a specific track makes a perceptible difference, then measuring five events on each track is preferred. The fact that there is a difference in the track used or a difference in the type of rolling stock might be obvious. There might be limited means to validate which track was used. At longer distances from the tracks, it can be sufficient to include five events in total from either track, but it is important to ensure that the sample is long enough to include trains on both tracks, in case the vibration is not just influenced by distance but due to differences in the condition of the tracks.

NOTE 4 In cases of urban areas with heavy traffic, measuring 10 or more pass-by events might be easy, allowing then to better perform statistical analysis (see 4.9).

NOTE 5 In some cases, it can be beneficial to evaluate the modal properties of a floor by means of some practical tests. The multi-modal response and decay can be measured at a number of locations and the results used to estimate modal properties. The floor may be excited by artificial impulse sources such as an impact hammer, a large damped heavy ball (dropped from a defined height) or heel-drops (person raising onto the balls of the feet and dropping onto the heels). The impact force can be measured through an instrumented load plate on the floor or using an instrumented hammer, to enable mobility measurements. In some cases, it can be necessary to limit the upper frequency of the impulse to minimize the response at high frequencies, by controlling the impulse period, using a resilient interface for the impact. As an isolated test, heel stamps imparted by an individual can be suitable, but as a measurement campaign for testing many floors, it can cause inappropriate strain on the individual and so its use might need to be limited or evaluated under site risk assessment.

Table 8 *(continued)*

[a] The background level shall be measured and reported along with the train event. But intrusive events can contaminate train events. With a number of train events that are measured, there could be an event that is stronger than the rest. While this stronger level could well be related to a particularly noisy train due to some fault or lack of maintenance, it might also be unrelated to a shortcoming in a train and simply due to intrusive noise coinciding with a measurement in a way that is not obvious to the observer. The likelihood of a spurious event coinciding with a train event might be gauged by the frequency of such spurious events alone, the greater frequency clearly indicating the risk of simultaneity with a train event, albeit a rare spurious event might still coincide with a train event, leaving an element of risk of contamination that can never be eliminated.
[b] In cases of several rail lines, tracks, tunnels or rolling stock types and/or operating conditions, effort shall be made to correlate each event with the relevant source and operating characteristics. This can be carried out by correlating the times of events observed at the receiver against records of operations at the railway (or by an observer on a platform).
[c] If only one or two events can be measured, e.g. a special type of train, or a track maintenance vehicle, check results on site and if possible collect more measurements, where the scatter in initial measurements is larger than ±25 % or ±2 dB. This is relative to overall single number values, as differences in spectra can be much more.
[d] It is essential that some analysis of the measurements is undertaken on site, to ensure that measurements are suitably recorded. For example, to ensure adequate quantisation of signal, ensure signal is not clipped, etc.
[e] It is good practice to take photographs of the different measurement set-ups on site with a photographic record of notes, and archive data. Record as much information as is relevant, include for instance details of track, switches, known radius, situation plan, etc. Any information on the track either obtained visually (for surface track) or through the owner of the track (joints, roughness measurements, corrugation, etc.) should also be reported.
[f] Where a simultaneous noise measurement channel is to record with vibration, it shall be unweighted, and ideally a calibration signal recorded noting measurement range, which might need to be temporarily changed to facilitate this.

4.9 Analysis, evaluation and reporting procedures

Requirements on analysis, evaluation and reporting procedures for Scope 1 and Scope 2 are given in Table 9.

There will be differences in the measurements taken by different teams, perhaps at different times, for a given situation, and even with the same team repeating the measurements. These differences can be reduced if each team follows the same procedure(s). This can be achieved by adopting the guidance in this document and clearly reporting the procedural choices taken. It is insufficient to only state that the measurements adopt the guidance of a particular standard, since standards permit choices according to particular circumstances, and such clarification should accordingly be given, especially on procedural matters that will significantly affect the measurement. The greater the detail that is reported, the greater the possibility of replicating the measurements, though inevitably they cannot be exactly the same.

Table 9 — Requirements on analysis, evaluation and reporting procedures

Scope 1 Evaluation of human exposure		Scope 2 Immission to building
Minimum requirements	**Reduced uncertainty**	
— Noise measurements shall be analysed and reported in terms of the number of readings obtained, the minimum, energy-average and maximum value of sound level, L_{pASmax}, in dB measured for rail events, and, L_{pASmax}, value of background noise (see Notes 1 and 2)[a]. — Vibration measurements shall be analysed and reported in terms of the number of readings obtained, the minimum, energy-average and maximum value of unweighted vibration velocity level, L_{vSmax}, in dB measured for rail events and the value of background vibration, L_{vSmax} (see Note 2)[a, b]. — Information on building and ground should be reported (see 4.7). — Refer to subjective comments when they are obtained (see Note 11).	— Calculate the room spatial average noise level if several microphone positions have been measured. — Calculate the floor (or wall) spatial average vibration level if several transducer positions have been measured (see Notes 3 and 4). — The following additional analysis and reporting steps should be carried out (for each relevant category of rail operations): — mean value and standard deviation of L_{pASmax}; — mean value and standard deviation of L_{vSmax}; — unweighted one-third-octave band spectrum that best corresponds to the mean value of L_{pASmax} (see Notes 5 and 6); — unweighted one-third-octave band spectrum that best corresponds to the mean value of L_{vSmax}. — The difference $L_{pCSmax} - L_{pASmax}$ should be calculated and reported (see Note 7). — Measurements should also be analysed and reported in terms of equivalent levels L_{pAeq} (and L_{peq}) and L_{veq}, obtained from r.m.s. values calculated during each train passage (duration used clearly justified such as from −10 dB points) and averaged within each relevant category of rail operations (see Notes 8 and 9). — The measured noise can be compared to estimated ground-borne noise from floor vibration (or other building elements) using empirical data or theoretical radiation functions (see Annex A).	— Vibration measurements on the ground next to the building, at or near foundations and on the floor shall be analysed and reported in terms of unweighted one-third-octave band spectrum that best corresponds to the energy-average value of L_{vSmax}, measured for same rail events. — One-third-octave band vibration velocity level differences between the ground and the foundations and between the foundations and the floor shall be calculated to estimate the building coupling loss (see Note 12) and building transmissibility (see Note 10 and Table 5, Note 7)[c].

NOTE 1 A-weighting calculated over the range 16 Hz to 250 Hz.

NOTE 2 Additional analysis and reporting can be required, such as for compliance with local or national standards, using other exposure descriptors such as vibration dose value (see ISO 2631-1 and BS 6472-1), L_{pAFmax}, frequency-weighted vibration, etc. (see more details in Reference [23]).

NOTE 3 Ground-borne noise is better predicted from floor or wall space average vibration (see Annex A).

NOTE 4 Ground-borne noise may be more reliably predicted from vibration measurements, since the room finishing and furniture can change from time to time and have a major influence on the noise measured, especially when a lot of time has lapsed between the assessment and the planned finish. Ground-borne noise predicted from vibration relate to simplified symmetrical situations which ignore furniture, whereas furniture can alter the sound distribution in a room. It is also evident that furniture can itself act as a vibrating sound source.

NOTE 5 The unweighted one-third-octave band sound spectrum can be compared to a reference curve for complaints, as proposed in some countries (see Reference [23]). The presence of rattle may be evident in this spectrum.

NOTE 6 The ground-borne noise spectrum in new rail line situations can show a peak that is shifted lower in frequency when compared with older lines. This shift to lower frequencies is influenced by vibration isolating provisions in new rail lines.

Table 9 *(continued)*

NOTE 7 A difference of 15 dB between the average values $L_{pCSmax} - L_{pASmax}$ indicates low-frequency noise, characteristic of ground-borne noise; conversely, a small difference may indicate the presence of airborne noise (see Reference [23]).
NOTE 8 Both maximum levels (related to sleep disturbance) and equivalent levels over a long period (related to long-term exposure) are relevant when a human response is concerned (see Reference [21] and Reference [32]).
NOTE 9 Equivalent levels over long periods (e.g. 24 h) can be estimated, assuming the traffic is known and average equivalent levels have been measured for each category of rail operations.
NOTE 10 These vibration velocity level differences might be variable and depend on train source (train type and location).
NOTE 11 When subjective comments of the occupants can be established using a questionnaire with a response scale, it can help the measured values be annotated with the occupant's reaction (and/or engineer's judgment) in a consistent way, that can over time provide useful data for future models (see Annex D).
NOTE 12 Building coupling loss encompasses the foundation and building superstructure together, whose mass and stiffness according to mode shape influence the coupling loss (see Annex B).
[a] Time constant S denotes 1 s. Other time constants are utilized and shall be quoted, e.g. 125 ms (time constant F) and 0,63 s (for vibration only) in Japan, which can lead to quantities better related to perception (see more details in Reference [23]).
[b] Vibration velocity levels shall be quoted in dB re 1 × 10^{-9} m/s as recommended in ISO 1683. For information, the value in mm/s can also be given.
[c] The vibration velocity difference between the ground and the building foundation shall be interpreted with care in the case when the wavelength of the Rayleigh wave is smaller than the depth of the building foundation (typically, at higher frequencies) or if the influence of the building on the ground vibration is too strong (typically at lower frequencies where the ground measuring point is within a wavelength distance from the building); see Annex B.

Annex A
(informative)

Predicting ground-borne noise from vibration

A.1 General

Noise measured inside buildings is often a mixture of ground-borne noise and airborne noise, which is transmitted through the façade and generated either by the same railway source if on the ground surface or by other sources (often road traffic). Predicting ground-borne noise from vibration measurements and comparing the result to noise measurements can be useful to identify ground-borne noise.

Only audible ground-borne noise is considered in this document, corresponding to vibration-induced indoor noise in the frequency range 16 Hz to 250 Hz, which can be roughly separated into two parts:

— the range from (40 to 50) Hz to 250 Hz, the lower limit of which corresponds to the first acoustic resonant modes for small building rooms, i.e. the usual domain of building acoustics considered in International Standards (e.g. ISO 16283-1);

— the range from 16 Hz to (40 to 50) Hz, which is not addressed in any existing standard.

NOTE Ground-borne infrasound, of frequencies below 16 Hz, has not been experienced within a rail system setting, although there could be a theoretical possibility in buildings with low-frequency base isolation; it is therefore not considered in this document.

It is difficult, at low frequencies, to quantify a link between the modal pattern of sound distribution within the room and the modal vibration patterns on the floor, walls and ceiling. It requires sophisticated calculation methods (such as numerical methods or a modal approach), applied to a detailed model of the room and associated building elements; and these methods are not only rather time consuming and expensive but also deterministic, thus leading to results which might not accurately represent the situation modelled because of the reduced knowledge of the input data (such as boundary conditions, thickness and material properties of the building elements involved). However, if applied to simple and idealized plate-room configurations (see Reference [30]), deterministic models such as the modal approach, can more easily be used, giving useful information on the variability of the point-to-point relationship between floor velocity and room sound pressure (more details are given in A.2).

Other methods exist, which can lead to useful approximations [empirical (statistical) models and energy based models].

a) Empirical models are based on measured data of floor vibration (often from one position at mid-span) and room noise (often from one position close to the middle) which are not very reproducible. The results are expressed as a frequency-dependent (in one-third-octave bands) relationship between vibration level and noise level, often over a reduced frequency range (20 Hz or 25 Hz to 125 Hz, or even to 80 Hz in order to exclude airborne noise; see Reference [29]). The statistical results expressed as mean values calculated over numerous often different situations, give useful tendencies. The standard deviation is of the order of 5 dB, thus showing the variability of this point-to-point relationship (see Reference [22]).

   NOTE Where empirical data are used, they relate to a room size range and use of space which needs to be relevant on a like-for-like basis. For example, room finishing, furniture and room size may differ from empirical database.

b) Building acoustic theory is mainly based on an energy approach (see Reference [27] for example), more robust because of involving space-averaged quantities, which can be used for predicting ground-borne noise from vibration, but with care at low frequencies and with caution when correlating these averaged data with complaints (see Reference [38]). This approach is detailed in A.3.

A.2 Deterministic relationship

A.2.1 Model theory

If applied to simple and idealized plate-room configurations, deterministic models such as the modal approach, can rather easily be used. Assuming a rectangular room (see Reference [30]), one surface of which being a vibrating simply supported plate, the complex ratio between the sound pressure p at a point (x, y, z) in the room and the velocity v at point (x, y) on the plate is given by Formula (A.1), which can be implemented numerically in a spreadsheet.

$$\frac{p_{x,y,z}}{v_{x,y}}=\frac{\mathrm{i}\omega\rho c^2}{\pi^2 L_z}\sum_{p,q,r=0}^{\infty}\frac{\Lambda_{p,q,r}\left(-1\right)^r\phi\left(x,y,z\right)\Sigma_{m,n=1}^{\infty}\frac{mn\left[\left(-1\right)^{m+p}-1\right]\left[\left(-1\right)^{n+q}-1\right]}{\left(p^2-m^2\right)\left(q2-n2\right)\psi\left(x,y\right)}}{\left(\omega_{p,q,\mathrm{r}}+\mathrm{i}\delta_{r,q,r}\right)^2-\omega^2} \quad \text{(A.1)}$$

where

c is the sound speed in air;

L_z is the height of the room;

ρ is the density of air;

ω is the angular frequency;

The shape function for the simply supported plate is given by Formula (A.2)

$$\psi\left(x,y\right)=\sin\frac{m\pi x}{L_x}\sin\frac{n\pi y}{L_y} \quad \text{(A.2)}$$

The room mode shape function is given by Formula (A.3)

$$\phi\left(x,y,z\right)=\cos\frac{p\pi x}{L_x}\cos\frac{q\pi y}{L_y}\cos\frac{r\pi z}{L_z} \quad \text{(A.3)}$$

The (lossless) room eigenfrequencies are given by Formula (A.4)

$$\omega_{p,q,r}=\pi c\sqrt{\left(\frac{p}{L_x}\right)^2+\left(\frac{q}{L_y}\right)^2+\left(\frac{r}{L_z}\right)^2} \quad \text{(A.4)}$$

The multiplying factor is given by Formula (A.5)

$$\Lambda_{p,q,r}=\varepsilon_p\varepsilon_q\varepsilon_r \quad \text{(A.5)}$$

with

ε_p = 1 for P = 0; ε_p = 2 for P > 0; ε_q = 1 for q = 0; ε_q = 2 for q > 0; ε_r = 1 for r = 0; ε_r = 2 for r > 0 the damping term δ is approximately related to the reverberation time, T, as given by Formula (A.6)

$$\delta \approx \frac{6{,}9}{T} \tag{A.6}$$

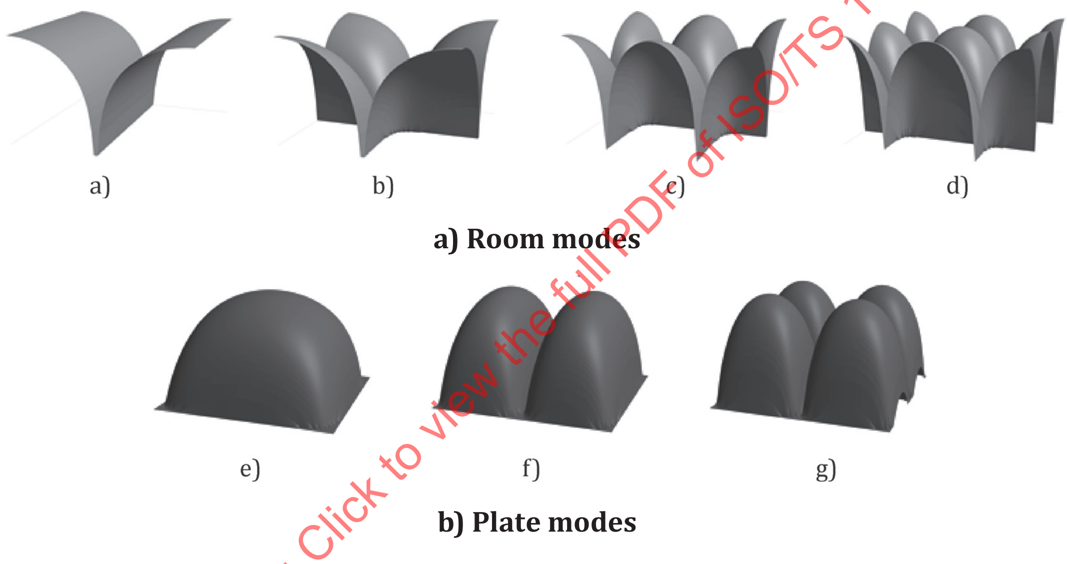
and the reverberation time T is approximately as given by Formula (A.7)

$$T \approx \frac{0{,}161}{\dfrac{\varepsilon_p \alpha_{y,z}}{L_x} + \dfrac{\varepsilon_q \alpha_{x,z}}{L_y} + \dfrac{\varepsilon_r \alpha_{x,y}}{L_z}} \tag{A.7}$$

with

$\alpha_{y,z}, \alpha_{x,z}, \alpha_{x,y}$ average absorption coefficients of the room surfaces in the y,z, x,z and x,y planes.

The contrasting forms of the shape functions for plate modes and room modes are shown graphically in Figure A.1 using a decibel scale.



Key

a mode 1,0,0
b mode 1,1,0
c mode 2,1,0
d mode 2,2,0
e mode 1,1
f mode 2,1
g mode 2,2

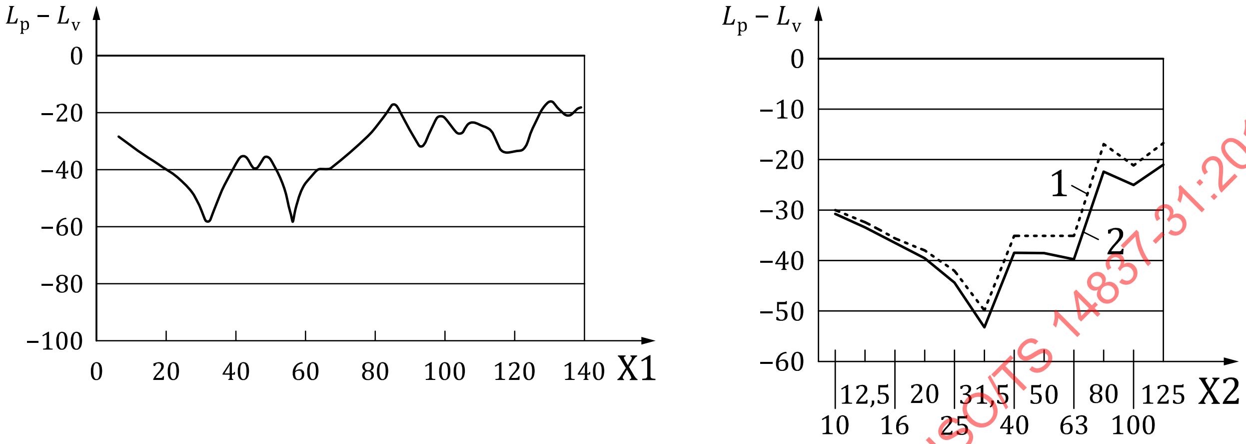
Figure A.1 — Room shape functions and corresponding plate mode shape functions (plotted as logarithmic squared amplitude)

When the measurement height $z < L_Z/m$, $m + p$ in the numerator should be replaced by 1; when $z < L_Z/n$, $n + q$ in the numerator should be replaced by 1. When $m = p$ or $n = q$, Formula (A.1) takes a different form, and $m + p$ or $n + q$ should be set to zero, respectively, avoiding a singularity.

These approximations are only valid for small values of α which is likely to be the case at low frequencies in most rooms. In such cases, wall absorption is not due to a lining of soft material, but due to transmission of sound through the wall.

The complex ratio given in narrow frequency bands in Formula (A.1) can be expressed in terms of squared magnitude summed in one-third-octave bands and provide useful information on the variability of the point-to-point relationship between floor velocity, v, and room sound pressure, p (see Reference [30] for more details).

An example evaluation of Formula (A.1) is plotted in Figure A.2.



a) 1 Hz bandwidth

b) One-third-octave bands

Key

X1 frequency, in Hz

X2 one-third-octave-band mid-frequency, in Hz

1 maximum

2 average

Figure A.2 — $L_p - L_v$ for a room 3,5 m × 4 m × 3 m high with reverberation time of 0,5 s

A.2.2 Main conclusions

The theoretical results obtained in Reference [30] clearly show the high variability of the two primary quantities themselves (floor vibration and room noise at one location) due to pronounced modal responses of floors and rooms, and the high variability of their relationship, depending on the relative position of the resonant frequencies of both floor and room modes. Consequently, careful measurement of the room dimensions and of the coordinates of chosen measurement locations should be recorded and reported (see 4.5 and 4.6).

A.3 Energy-based relationship

A.3.1 Model theory

Recent building acoustics are essentially based on an energy approach called Statistical Energy Analysis (SEA; see Reference [27]), where acoustic and vibrational fields are characterized by their energy stored in rooms or building elements, respectively, and where interactions between building elements and rooms are expressed as power flows. Diffuse-field assumptions are made and vibration and noise are measured in terms of space average levels, respectively, over the building element area and the room volume. Building acoustics theory leads to the relationship between the space average sound pressure level, $L_{p,\text{av}}$, in the room and the space averaged velocity level, $L_{v,\text{av}}$, of any wall or floor mechanically excited and radiating in the room, given by Formula (A.8).

$$L_{p,\text{av}} - L_{v,\text{av}} = 10 \lg \sigma + 10 \lg (4S/A) \tag{A.8}$$

where

σ is the radiation efficiency of the element;

S is its surface area;

A is the absorption area of the room.

In Formula (A.8), sound pressure levels and velocity levels are in dB ref. 2×10^{-5} Pa and 5×10^{-8} m/s, respectively.

NOTE The reference value 5×10^{-8} m/s is commonly used in building acoustics for velocity levels, thus leading to the simple formulae given in this annex. If 10^{-9} m/s is used, as recommended elsewhere in this document, −34 dB is to be added on the right-hand side of Formulae (A.8) and (A.11) to (A.14).

All the terms of Formula (A.8) are frequency dependent and Formula (A.8) applies for each one-third-octave band. The vibration and noise space average levels used in Formula (A.8) should be obtained from several measurement points, particularly at low frequencies; however, practically, a minimum of three positions is often used when measurements are performed in situ (see Table 5, Note 4 and Table 6, Note 4).

The absorption area, A, is related to the room reverberation time, T, (see Table 7, Note 1 for measurement procedure) and the room volume, V, as given by Formula (A.9).

$$A = 0{,}16\ V/T \tag{A.9}$$

Formula (A.8) can be used to predict noise from vibration measurement, assuming σ and A are known. If several building elements are potentially radiating, then Formula (A.8) can be applied to each radiating element and the sound levels obtained added energetically (assumed uncorrelated) to estimate the total space average sound level in the room.

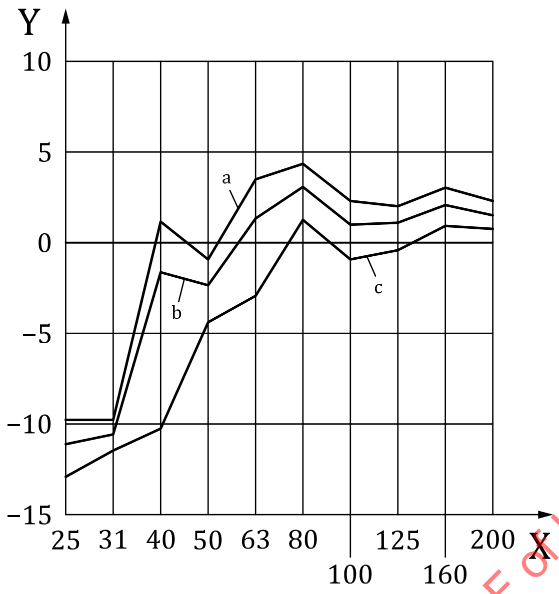
σ is usually measured in a laboratory under (more or less) diffuse-field conditions using several source positions and rather big rooms and large building elements. For homogeneous building elements, σ can also be calculated (see ISO 12354-1). The σ values obtained (see Reference [38]) are close to 1 at and above the so-called critical frequency of the building element considered and decrease continuously with decreasing frequency below. Heavy elements have rather low critical frequencies (typically around 100 Hz for a 20 cm concrete floor) and radiate at low frequencies more than lightweight elements, which have higher critical frequencies (typically around 1 600 Hz for a lightweight wood floor on joists).

A.3.2 Case of in situ ground-borne noise

Two frequency ranges should be considered separately (see A.1): the range from (40 to 50) Hz to 250 Hz, and the range from 16 Hz to (40 to 50) Hz.

Range from (40 to 50) Hz to 250 Hz

The calculated or laboratory measured values of σ (see A.3.1) can be used above 100 Hz, even in small rooms (10 m^2). However, at and below 100 Hz, these values become erroneous and shall not be used in Formula (A.8) for the following reason: at low frequencies in small rooms (in situ), very few room and building element resonant modes exist and the radiation efficiency becomes highly variable, depending on room size and building element size, thickness and boundary conditions. However, the modal responses of rooms or building elements can still be represented by spatially averaged levels, and Formula (A.8) can still be used to estimate σ, which becomes situation dependent. Such estimation has been done in a parametric study [25] using a numerical model in the (worst) case of heavy structures. On average, the calculated radiation efficiency spectra obtained do not decrease continously with decreasing frequency below the critical frequency, and show peaks due to modal coupling between room and building element (see Figure A.3 as an example); the room dimensions seem to be the dominant parameter associated with the location of these peaks. Such calculated data can be used for prediction.



Key

X one-third-octave-band mid-frequency, in Hz

Y radiation efficiency, in dB

a Mean value + *s*.

b Mean value.

c Mean value − *s*.

Figure A.3 — Radiation efficiency (10 lg σ) mean value ±*s* from Reference [25] for a 12 m² room with a floor of (20 to 30) cm thickness with different boundary conditions (critical frequency in the range 63 Hz to 100 Hz), and radiating in a room of (2,5 to 3) m height

Simplifying further, a rough estimate can be obtained by taking $\sigma = 1$ over the whole frequency range, down to (40 to 50) Hz.

A Statistical Energy Analysis (SEA) not only gives access to the space average noise level radiated, using Formula (A.8), but also to the space variation of the radiated sound field from an estimated standard deviation, *s*, of the sound field, which, according to Reference [39] can be approximated at low frequencies from the room modal density, $n(f)$, and the frequency bandwith, $B(f)$, chosen (often one-third-octave band) as shown in Formula (A.10)

$$s = \frac{4{,}34}{-0{,}22 + \sqrt{1 + 0{,}319 B(f) n(f)}} \text{dB} \tag{A.10}$$

with

$n(f) = 4\pi V f^2/c^3 + \pi S f/(2c^2) + L/(8c)$ and $B(f) = 0{,}23\, f$ in one-third-octave band

where

$c = 340$ m/s is the sound speed in air in m/s;

f is the centre frequency of the band considered in Hz;

L is the total length of the room edges, in m;

S is the total surface of the room boundaries in m^2;

V is the room volume in m^3.

Range from 16 Hz to (40 to 50) Hz

A power based approach is no longer valid at very low frequencies, below the first room modes. Only numerical models can be used, based on narrow frequency band calculations and using complex quantities (see Reference [38]).

A.3.3 Further simplifications

Step 1: For heavy (concrete) structures, the radiation efficiency can be taken as equal to 1 over the whole spectrum as explained above, which leads for a normally furnished room (reverberation time of 0,5 s) of normal size (10 m^2) to a level difference as given by Formula (A.11).

$$L_{p,\text{av}} - L_{v,\text{av}} \approx 7 \text{ dB} \tag{A.11}$$

Step 2: Partition walls, usually lighter, radiate less at low frequencies and could be neglected; assuming then that both floor and ceiling are similar and are the main ground-borne noise sources in the room, floor velocity and total room noise can be related leads to a level difference as given by Formula (A.12).

$$L_{p,\text{av}} - L_{v,\text{av,floor}} \approx 7 \text{ dB} + 3 \text{ dB} = 10 \text{ dB} \tag{A.12}$$

It should be noted that the very simple Formula (A.12) relates the space average floor velocity level to the space average sound level in the room, but what is measured is the floor velocity at mid-span.

Step 3: It is shown in Reference [24] that for heavy structures, the floor velocity at mid-span is a few dB higher than the space average floor velocity level. Consequently, assuming that the floor vibration level at mid-span ($L_{v,\text{meas,floor}}$) is a few dB higher (say 3 dB) than the space average floor vibration level, assuming that the sound level measured in the middle of the room ($L_{p,\text{meas}}$) is a few dB lower (say 3 dB) than the space average sound level and taking into account that both floor and ceiling radiate noise, Formula (A.12) leads to a level difference as given by Formula (A.13)

$$L_{p,\text{meas}} - L_{v,\text{meas,floor}} = 4 \text{ dB} \tag{A.13}$$

which is close (within 3 dB) to the statistical vibration to noise factor obtained in Reference [29] and close to the statistical mean value obtained in Reference [22] which shows that average values obtained using energy-based models represent quite well measured values averaged statistically over different sites.

If the room space average sound level, more reproducible, is used, Formula (A.13) becomes Formula (A.14) which is valid for frequencies equal or above (40 to 50) Hz.

$$L_{p,\text{av}} \approx L_{v,\text{meas,floor}} + 7 \text{ dB} \tag{A.14}$$

Formula (A.14) simply relates the room average ground-borne noise to the floor velocity measured at mid-span with the following assumptions:

— both floor and ceiling are heavy (typically concrete) and are the main sources of ground-borne noise;

— partition walls are lighter, radiate less at low frequencies and are neglected;

— the room is normally furnished (reverberation time of 0,5 s) and of normal size (10 m^2);

— sound pressure levels and velocity levels are in dB ref. 2×10^{-5} Pa and 5×10^{-8} m/s, respectively. If 10^{-9} m/s is used, as recommended elsewhere in the present document, −34 dB is to be added on the right-hand side of Formula (A.14).

Annex B
(informative)

Vibration immission to building

B.1 General

In this document, vibration immission to building is characterized by two quantities: building coupling loss and building transmissibility from building foundation to floors. These two quantities are also defined and used for prediction in guidance elsewhere (e.g. VDI 3837 or Reference [20]), though care is required in interpreting and comparing definitions.

B.2 Building coupling loss

In this document, vibration transmission from ground to building is characterized by a quantity called building coupling loss defined as frequency dependent vibration level difference, in decibels, between the ground surface in free field (without the building) and the building foundation (see 3.1). The definition can be applied to any (railway) source location, which can be at grade or underground (in a tunnel), and has been chosen so that the building coupling loss can be practically (but approximately) measured on site. The same definition should then be applied when the building coupling loss is calculated using models.

The definition given in this document may not properly characterize the transmission loss, which should theoretically be defined as the difference between the ground-borne incident vibrational power level (without building) and the vibrational power level transmitted to the building.

NOTE Power is difficult to measure directly, and is the time-averaged product of force $F(t)$ and velocity $v(t)$. In the frequency domain, power is obtained as a product of the Fourier transforms $\mathcal{F}\,\{F(t)\}^*$ and $\mathcal{F}\,\{v(t)\}$ of the time domain signals where the asterisk denotes the complex conjugate.

It should be noted, however, that the practical choice of measurement at the ground surface may not be sufficient to characterize the incident ground-borne vibration field. This can be the case with the presence of

a) body waves from an at-grade source are not well characterized by measurements at the surface, which can undergo reflections from layering causing a deviation from monotonic decay giving zones of “hot spots”, which are areas suffering reflection from layers below, and “cold spots”, which are intermediate zones between source and measurement point where the reflections have not been directed to the surface, and

b) body waves from an underground rail source.

Indeed, vibration at soil surface and vibration at depth of foundation are different quantities, and characterize different inputs to a building according to source, either at grade or in tunnel.

It is usually difficult in an urban landscape to achieve free-field conditions for ground surface vibration measurements, which can be used to evaluate the building coupling loss. It is important to recognize that it is often only possible to at best try to approximate this free-field condition and note the site issues that can detract from free field. There are various considerations to be taken into account in choosing the appropriate distance from the building as well as practical considerations at the site (see also ISO/TS 14837-32:2015, 5.5).

i) Typically, there is a nearfield within a certain distance from a building, which is a function of some multiple of wavelengths and which varies from site to site according to frequency, and which is influenced by the ground dynamic properties, by the size of the structure, and by the type of embedment. Usually a distance greater than three wavelengths is necessary for free-field conditions and in an urban setting at low frequencies this may not be practical to achieve.

As an example of the nearfield effects, free-field conditions associated with surface Rayleigh waves and the corresponding retrograde elliptical particle orbits cannot be realized due to constrained ground in the nearfield due to building embedment. Other complications arise in the nearfield; for example, on the source side of a building exposed to an at-grade railway, the vibration can be reflected by the building embedment, according to frequency of vibration, its wavelength and how that relates to depth of embedment. In this case, measurements on the ground near a building should preferably take place at an appropriate distance to the side of the building, at the distance from the source that is of interest (see Figure 2), as opposed to measuring on the source side, or for that matter downstream of the building, which may result in some screening by the building itself. A practical distance to the side of the building can be taken as 3 m to 5 m, but should otherwise be more rigorously considered as some multiple (usually three) times the wavelengths according to frequency of interest.

ii) A distinction about the choice of building side from which measurements are taken is not necessary where the source is a rail system in a tunnel (although this depends upon its depth and the distance from the receptor), where it can be possible to choose measurements on the ground adjacent to any side of the building.

iii) Such considerations are more significant when dealing with low-frequency long-wavelength vibration and less so for short wavelengths associated with the higher end of the frequency spectrum for ground-borne noise.

iv) These considerations are entirely dependent upon ground conditions and lithology. Particular situations need to be considered, e.g. soft soils on shallow hard rock.

v) Dynamic interaction of the building foundation with the ground measurement location depends upon the distance from the building according to wavelength. In comparing measurements at the ground and the building, any significant difference in distance to the source should be considered, as should any differences in coupling to ground and building.

vi) There is an alternative to achieving a free-field measurement that is at the distance from a source that falls within the nearfield of a building. It is to measure at two distances placed in free-field conditions somewhere appropriate between the source and the receiver, from which one can deduce an attenuation rate and from which one could extrapolate the levels to an equivalent free-field condition but within the nearfield of a building which could not otherwise be measured due to interference of the actual building.

B.3 Building transmissibility

In this document, the vibration transmission from building foundation to floors is characterized by the building transmissibility as defined in 3.2, which includes the vibration variations from floor to floor, and the vibration amplification due to resonant modes of the floor considered, the latter phenomenon being dominant.

Annex C
(informative)

Transducer coupling

Transducer coupling should ensure that the transducer moves in phase with and at the same amplitude (velocity or acceleration) as the immediately surrounding structure or ground to which it is coupled, and so does not itself materially interfere with or modify that motion.

A transducer may itself be too small to achieve sufficient coupling to certain ground conditions, and so an intermediate coupling is necessary. Care is required to ensure that the transducer and any intermediate coupling method does not detract from the objectives mentioned above.

Such installation of vibration transducers to measure vibration induced by rail systems relies on the combined achievement of two elements:

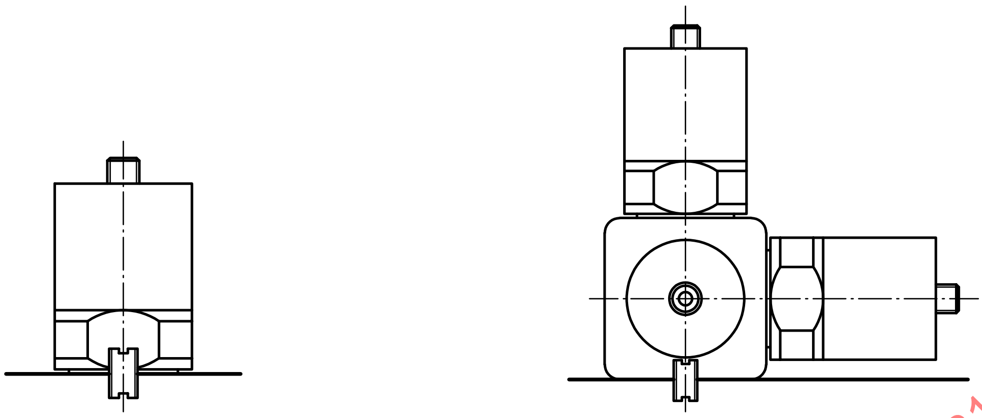
a) achievement of a flat and firm installation base, whose movements match as accurately as possible those that need to be measured (soil, wall, building surface, etc.);

b) achievement of a good coupling between the vibration transducer and the aforementioned installation base.

The specific case of field measurement of ground-borne vibration arising from rail systems has a significant variety of contexts and particular circumstances. Some site circumstances are going to impose greater challenges and also depend upon workmanship which are difficult to assess, more so for a), as described below.

Concerning b), a correct coupling between the vibration transducer and the installation base can be achieved by some of the following means.

— **Stud**: The preferred method of mounting an accelerometer on a flat surface base is the stud mount method. This stud is often a removable threaded piece, as shown in Figure C.1. The stud mount method yields the best results because the high clamping force of the stud ensures the exact duplication of motion of both bodies at all frequencies. A thin layer of silicone grease between the base surface and the accelerometer can further enhance coupling precision, by filling in any voids due to slight imperfections in the mounting surfaces. This precaution is, however, more important in the measurement of high-frequency vibration, which is beyond the range of interest in this document. When triaxial acceleration is measured, studs can be used to install vibration transducers on a machined cube [see Figure C.1 b)]. This machined installation cube can in turn be mounted by any of the coupling means described.



a) Seismic accelerometer installed on a flat surface by means of a removable stud

b) Triaxial vibration measurement, with accelerometers installed on a cube by means of removable studs

Figure C.1 — Transducer coupling with stud

- **Adhesive**: For short temporary sampling, an adhesive that does not mark the surface permanently is occasionally desirable. A material used in bulk is often flexible, such as reusable putty-like adhesive or beeswax, but when made into a very thin layer, can give a rigid enough coupling that is suitable for the frequency range intended, and provides a sufficiently tacky surface to hold a transducer under its weight in a vertical axis deployment. This is less suitable in horizontal axis deployment, unless the transducer is very lightweight. Another example can be certain non-resilient types of thin double-sided tape. Certain types of coupling may need to have regard to vibration magnitude, which is less of a concern at a distance from the vibration source. In all other cases cyanoacrylate or epoxy resin can be used. Coupling can be done either directly on the transducer surface, or using an intermediate pad (see Figure C.2). In this case, the pad is glued to the installation base, and the transducer is installed on the pad by means of a stud.

a) Seismic accelerometer installed on a glued stud pad

b) Seismic accelerometer with a direct adhesive installation

Figure C.2 — Transducer coupling with adhesive

- **Magnet**: In case the installation base is ferromagnetic (e.g. steel stakes in the ground), a magnet with a stud can also be used to attach the transducer, or a steel disc glued to a surface to which the magnet attaches. Generally, a magnetic coupling can introduce errors at frequencies higher than 1 000 Hz, but this limitation has no practical effects in the context of this document for measuring ground-borne noise and vibration arising from rail systems, because these higher frequencies fall beyond the range of interest. Where magnets have a high pull strength, which can be more necessary in the horizontal axis and inverted applications, it is important not to let the magnet, while connected to the accelerometer, snap onto the test structure, but to gently rock or slide the assembly into place, to avoid damaging accelerometers with high sensitivity.

NOTE 1 The transducer examples in the figures in this annex refer to accelerometers; they could also relate to geophones.

If a transducer is inadvertently dropped on site during deployment, its functionality must be questioned and shall be checked with a calibrator, in particular for accelerometers with high sensitivity, and the event noted accordingly.

NOTE 2 There are other routine considerations regarding transducer placement, such as environmental influences, electrical noise and their management, which can be obtained from manufacturer's installation guides.

Summing up, all three described mounting methods can be considered as valid, taking into account that the frequency range of interest in the context of this document is not very demanding (distortion because of improper mounting or surface unevenness usually occur at relatively high frequencies, beyond the range of interest). Notwithstanding this fact, all the above described mounting guidelines should be followed as accurately as possible.

Concerning a), somewhat more challenging is the achievement of a flat and firm installation base in the soil, wall or building part whose vibration magnitude is being measured. This is due to the very different degrees of consistency that can be encountered; from soft, wet soils to very hard surfaces (e.g. concrete). The evaluation of the most appropriate method of transducer coupling in the former examples is difficult to assess, and is strongly influenced by workmanship.

When measuring vibration on a very hard surface (e.g. a wall or building element), the decision depends on the flatness level of this surface. In case the surface is horizontal and flat enough (typical case of a pavement or a floor), a mere installation with adhesives can be used with advantage. In case the surface is not flat or not horizontal but can be drilled, an anchor can provide a suitable installation base (see Figure C.6). When drilling is not possible, surface unevenness can be remedied by locally applying some plaster of Paris in order to provide a flat installation base to the transducer. In all horizontal measurements where the transducer is not installed on a threaded element, the significant weight of seismic vibration transducers shall be taken into account in the selection of the bonding adhesive to be used, or the suitable pull strength of the magnet.

Measurement of soil vibration has been typically carried out by means of several installation strategies. Critical examination of common practices is available in the specialized literature (see Reference [26] and References [33] to [36] for details). The main conclusion that can be drawn from these comparative measurements shows that a proper installation base is particularly relevant in horizontal vibration measurements. Vertical *z*-direction measurements are more robust with respect to the installation base, but a number of details in any case need to be taken into account.

A good coupling between the soil and the vibration transducer is crucial, and not always easy to achieve. The several installation strategies for soil vibration measurements that have been traditionally used and have been experimentally compared are the following.

— **Plaster of Paris**: Pouring a base layer of plaster of Paris guarantees good contact with the soil, provided that the soil is relatively root free and undisturbed. The thickness of the plaster should be only that required to provide sufficient internal stiffness of the mounting pad; a few centimetres can be enough. Also, plaster of Paris can be used in combination of a metal plate, which is laid on the plaster surface when still not set. This method has the disadvantage of all the steps involved, and also the time needed for the plaster to set, which in wet soils can be significant.

— **Mounting blocks**: These blocks consist of a base, usually metallic, on whose surface the transducer is installed. Two variants have been tested: metal blocks just laid on the soil surface, and metal blocks partially buried in the terrain. First variant has shown bad results, particularly for horizontal vibration measurements. Partially burying the mounting block as shown in Figure C.3 greatly improves reliability.

NOTE 3 When considering the mass of the block, a lighter block may be preferable to avoid mounted resonances of the block on the stiffness of the ground in the frequency range of interest in all six degrees of freedom. Avoiding internal resonances of the block is a separate consideration. A hollow block to lighten it may address the mounted resonance issue although the internal resonances becomes a greater consideration.

NOTE 4 The mass of the block is modified by the participating mass of the half-space, which varies as a function of frequency.

The size of the block is a consideration and should be much smaller than the relevant wavelength for the ground at the upper end of the frequency range of interest, so that it follows the ground movement faithfully.

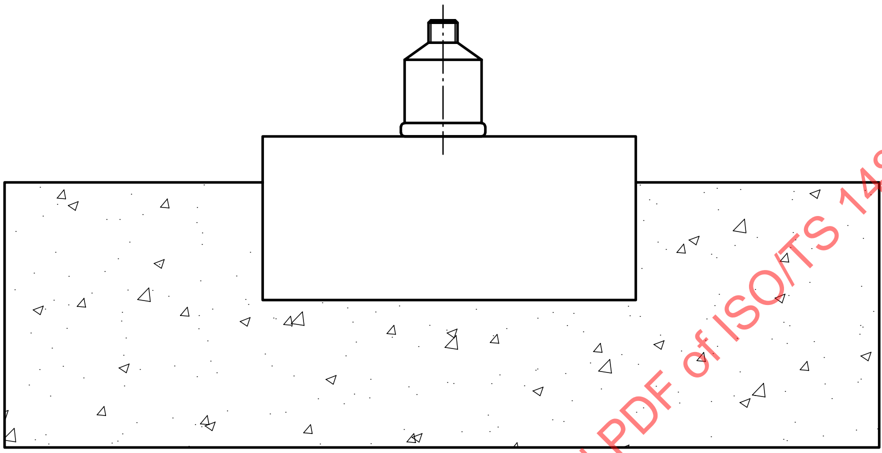
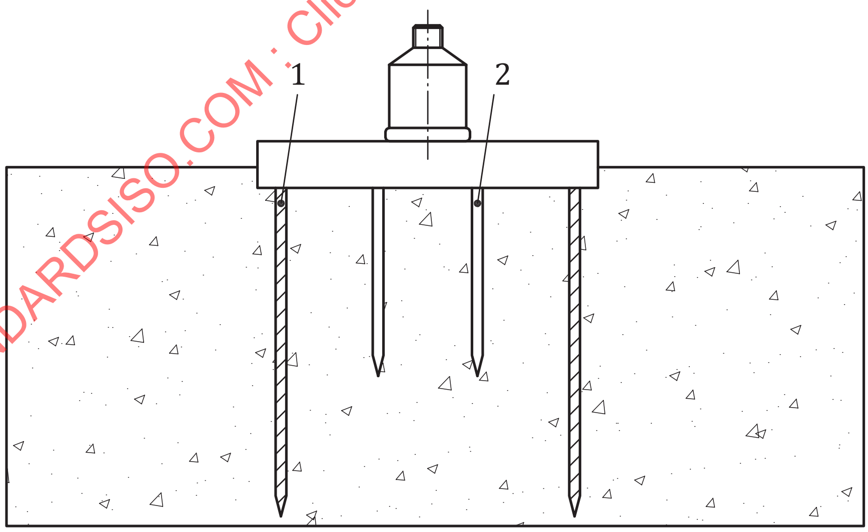


Figure C.3 — Mounting block, partially embedded in soil, with a vibration transducer installed on its surface

— **Nailed plates**: A variant of the mounting block approach has been successfully tested (see Reference [35]). This variant consists of a base plate, with some nails installed in the perimeter and also around the central part, which ensure good coupling with the soil (see Figure C.4).



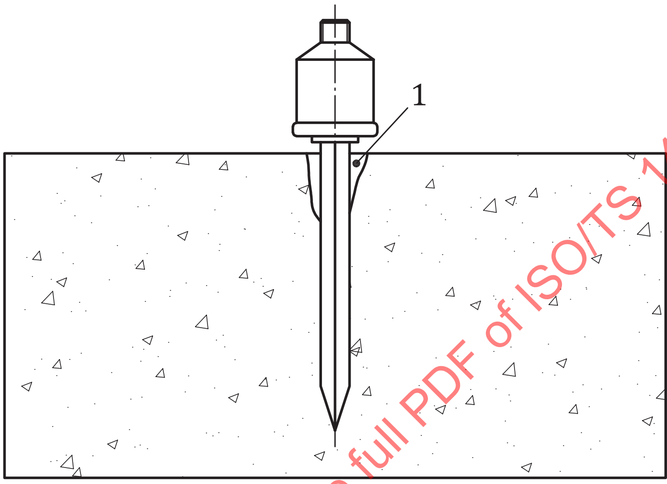
Key

1 long spiral nails (80 mm)

2 short finishing nails (50 mm)

Figure C.4 — Transducer mounting on a base plate partially embedded and multiply nailed to the soil

— **Stakes**: If the soil is soft enough to allow the installation of metal stakes, this is a good option, provided that a number of conditions are met. First, the section of the stakes shall be in the form of a cross, or shall be T-shaped, in order to ensure good coupling with the soil. Second, the stake should be almost completely driven into the terrain (ideally no more than 1 cm, and always less than one-third of the stake length, should be above the ground surface. Third, embedment depth should be enough (around 30 cm or more). For horizontal vibration measurements, only aluminium stakes have been reported to give satisfactory results (see Reference [33] and Figure C.8 for details). For vertical measurements, either steel or aluminium stakes are valid. Installation of stakes can leave gaps due to driving methods (see Figure C.5). To minimize the effect of these gaps on the measurement, soil shall be recompacted around the stake after being driven in it. Variants of the stake geometry can include a taper along the length (see Figure C.8).

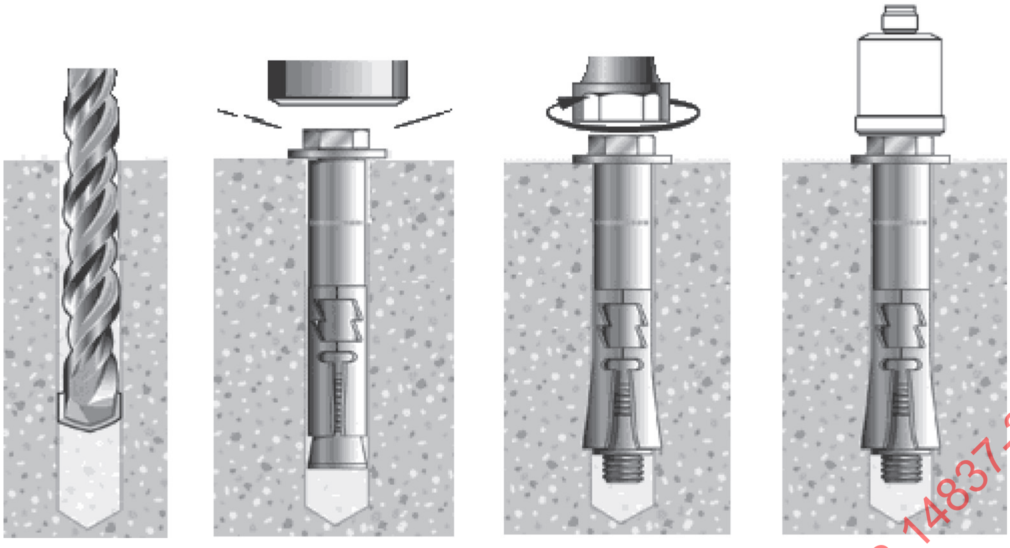


Key

1 gaps due to driving methods (shown accentuated)

Figure C.5 — Installation of a stake and possible side effects (gaps) due to driving methods

— **Anchor bolts**: It is not possible to drive a stake into some very hard soils and rocky surfaces. In this case, the soil can be drilled and a metallic anchor bolt can be installed and secured in the drilled hole (see Figure C.6).



NOTE From left to right: hole drilling, hammering anchor in the hole, screwing anchor to secure in place, installation of vibration transducer on top.

Figure C.6 — Transducer mounting on anchor bolts installed inside holes drilled in rocky soils

— **Buried canisters**: This method ensures a good coupling between soil movements and the vibration transducer (provided that soil disturbance is kept to a minimum), but for practical reasons, it is recognized that it is more appropriate to a research investigation. In this approach, the transducer is mechanically installed inside a rigid canister (see Figure C.7) by means of a threaded stud. The volume of the canister, the material, the wall thickness and the mass of the transducer are combined such that the whole assembly has close to the same mass as the corresponding volume of soil (and preferably has a centre of gravity close to its centre).

If necessary, the canister can be made water-tight, if it is intended to be used in a wet environment. A small hole is dug in the soil, roughly 20 cm to 30 cm deep but in any case deep enough to ensure that all the assembly is fully covered. The canister is closed, electrically connected and placed in the bottom of the hole, previously flattened and compacted. After that, the remaining space in the hole is filled back with part of the soil, carefully compacting towards the walls of the assembly to a consistency similar to the rest of the surrounding soil. The assembly should be fully covered in the ground.