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Evaluation and measurement for vibration in buildings —

Part 1: Guide for measurement of vibrations and evaluation of their effects on buildings

Committees responsible for this British Standard

The preparation of this British Standard was entrusted by the General Mechanical Engineering Standards Policy Committee (GME/-) to Technical Committee GME/21, upon which the following bodies were represented:

Department of Trade and Industry (National Engineering Laboratory)
Electricity Supply Industry in England and Wales
Engineering Equipment and Materials Users' Association
Institute of Sound and Vibration Research
Institution of Mechanical Engineers
Lloyds Register of Shipping
Ministry of Defence
Power Generation Contractors Association (BEAMA Ltd.)
Society of British Aerospace Companies Ltd.
Society of Environmental Engineers
Society of Motor Manufacturers and Traders Limited

The following bodies were also represented in the drafting of the standard, through subcommittees and panels:

British Aggregate Construction Materials Industries
British Coal Corporation
British Compressed Air Society
British Railways Board
Federation of Civil Engineering Contractors
Institute of Explosives Engineers
Institution of Civil Engineers
National Federation of Demolition Contractors

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National foreword

This Part of BS 7385 has been prepared under the direction of the General Mechanical Engineering Standards Policy Committee. It is identical with ISO 4866:1990 "Mechanical vibration and shock — Vibration of buildings — Guidelines for the measurement of vibrations and evaluation of their effects on buildings", which was prepared by Technical Committee ISO/TC108, Mechanical vibration and shock, of the International Organization for Standardization (ISO) and in the development of which the United Kingdom played an active part.

Cross-references

International standard	Corresponding British Standard
ISO 5348:1987	BS 7129:1989 *Recommendations for mechanical mounting of accelerometers for measuring mechanical vibration and shock* (Identical)
IEC 68-2-27:1987	BS 2011 *Environmental testing* Part 2.1 Ea:1988 *Test Ea. Shock* (Identical)

The Technical Committee has reviewed the provisions of ISO 2041, ISO 2631-2 and ISO 4356, to which reference is made in the text, and has decided that they are acceptable for use in conjunction with this standard. A related British Standard to ISO 2041 is BS 3015:1976 "*Glossary of terms relating to mechanical vibration and shock*".

A British Standard does not purport to include all the necessary provisions of a contract. Users of British Standards are responsible for their correct application.

Compliance with a British Standard does not of itself confer immunity from legal obligations.

Summary of pages

This document comprises a front cover, an inside front cover, pages i and ii, pages 1 to 18, an inside back cover and a back cover.

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

Introduction

It is increasingly recognized that buildings must sustain vibrations, and recognition of this is needed both in design for structural integrity, serviceability and environmental acceptability, and in the preservation of historic buildings.

Measurement of vibration in a building is carried out for a variety of purposes:

— **Problem recognition**

Where it is reported that a building is vibrating at such a level as to cause concern to occupants, it may be necessary to establish whether or not the levels warrant concern for structural integrity.

— **Control monitoring**

Where maximum permitted vibration levels have been established by some agency and those vibrations have to be measured and reported.

— **Documentation**

Where dynamic loading has been recognized in design and measurements are made to verify the predictions of response and provide new design parameters. These may use ambient or imposed loading. Strong motion seismographs, for example, may be installed so as to indicate whether or not the responses to earthquake warrant changes on operating procedure in a structure.

— **Diagnosis**

Where it has been established that vibration levels require further investigation, measurements are made in order to provide information for mitigation procedures.

Another diagnostic procedure is to use structural response to ambient or imposed loading to establish structural condition, for example, after a severe loading, such as an earthquake.

Such diverse purposes call for a variety of measuring systems ranging from the simple to the sophisticated, deployed in different types of investigation (see **9.2**).

Technical guidance is needed by many interested parties on the most appropriate ways of measuring, characterizing and evaluating those vibrations that affect buildings. This applies both to buildings already in existence, which may be subjected to some new or changed source of excitation, and to the design of buildings to be erected in an environment where the building may be excited significantly.

The effects of vibration may also be taken into account by calculation (see **9.1**).

Although the material in this International Standard may be used in appraising the relative severity of structural vibration, it is not to be regarded as suggesting acceptable or non-acceptable levels. Nor does it consider economic and social aspects, which would be dealt with, as appropriate, by national regulatory bodies.

1 Scope

This International Standard establishes the basic principles for carrying out vibration measurement and processing data, with regard to evaluating vibration effects on buildings. It does not cover the source of excitation except insofar as the source dictates dynamic range, frequency or other parameters. The evaluation of the effects of building vibration is primarily directed at structural response, and includes appropriate analytical methods where the frequency, duration and amplitude can be defined. This International Standard only deals with the measurement of structural vibration and excludes the measurement of airborne sound pressure and other pressure fluctuations although response to such excitations is taken into consideration.

A building, for the purposes of this International Standard, is defined as any above-ground structure, which man frequently inhabits. This excludes from consideration certain items of plant, for example columns, stacks, headframe, containments, even though they may receive intermittent visits from operating staff.

The structural response of buildings depends upon the excitation; to this end this International Standard examines the methods of measurements as affected by the source, i.e. frequency, duration, and amplitudes as induced by any source, such as earthquakes, explosions, wind effects, sonic booms, internal machinery, traffic, construction activities and others.

NOTE 1 There are differences between earthquakes and man-made vibrations which affect recording conditions. Earthquake-fault-rupture sources are large in size and much deeper than most man-made sources. They can cause damage at great distances, have much greater energy flux and duration and a different pattern of wave propagation. Consequently, for the same parameter value (for example peak particle velocity), the effects on buildings are different.

2 Normative references

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

ISO 2041:1975, *Vibration and shock—Vocabulary.*

ISO 2631-2:1989, *Evaluation of human exposure to whole-body vibration — Part 2: Continuous and shock-induced vibrations in buildings (1 to 80 Hz).*

ISO 4356:1977, *Bases for the design of structures — Deformations of buildings at the serviceability limit states.*

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

IEC 68-2-27:1987, *Environmental testing — Part 2: Tests — Test Ea and Guidance: Shock.*

3 Source-related factors to be considered

3.1 Characteristics of vibration responses in buildings

The types of vibration can be classified as

a) deterministic,

b) random,

and further subdivided as given in **8.2**.

For each type of vibration, a minimum amount of information is needed so that adequate definition of the type of vibration can be drawn up (see ISO 2041).[1]

3.2 Duration

The duration of the dynamic exciting force is an important parameter. For the purposes of this International Standard, the response can be regarded as continuous or transient, and the type of response will be dictated by the relationship between the time constants associated with the structural response and the forcing function.

The time constant of a resonance response for resonance, r, in seconds, τ_r, is given by

$$\tau_r = \frac{1}{2\pi\ \xi_r f_r}$$

where

ξ_r represents the influence of the damping and depends on the kind of excitation (linear or non-linear);

f_r is the resonance frequency.

Two cases can thus be defined (without regard to whether or not the excitation is deterministic or random):

— **Continuous**

If the forcing function impinges on the structure continuously for more than $5\tau_r$, then the vibration is regarded as continuous.

— **Transient**

If the forcing function exists for a time which is less than $5\tau_r$, then the response is regarded as transient.

Since forcing functions which occur naturally are often not well behaved it may be that responses do not fall easily into a single category. For example blasting even with several intervals would be considered transient.

3.3 Frequency and range of vibration intensity

The frequency range of vibrations of interest depends upon the distribution of spectral content over the frequency range of the excitation and upon the mechanical response of the building. This pinpoints the spectral content as a most important property of vibration input. For simplicity's sake, this International Standard deals with frequencies ranging from 0,1 Hz to 500 Hz; it covers the response of buildings of a wide variety and building elements to excitation from natural (wind and earthquake) and to man-made (construction, blasting, traffic) causes. Internal machinery may require higher frequencies to be recorded.

Most building damage from man-made sources occurs in the frequency range from 1 Hz to 150 Hz. Natural sources, such as earthquakes, usually contain energy at lower frequencies in the range from 0,1 Hz to 30 Hz at damaging intensities. Wind excitation tends to have significant energy in the frequency range from 0,1 Hz to 2 Hz.

Vibration levels of interest range from a few to several hundred millimetres per second depending on frequency.

4 Building-related factors to be considered

The reaction of buildings and building components to dynamic excitation depends upon response characteristics (for example natural frequencies, mode shapes and modal damping) as well as the spectral content of the excitation. Cumulative effects should be considered, especially at high response level and long exposure times where fatigue damage is a possibility.

4.1 Type and condition of buildings

In order to describe properly and categorize the visible effects of vibration and the results of instrumental measurements, a classification of buildings as defined in clause **1** is needed. For the purposes of this International Standard, a classification of buildings is set out in annex A.

4.2 Natural frequencies and damping

The fundamental natural frequencies of a building or of parts of the building influence its response and need to be known to allow the several methods of evaluating vibration to be applied. This may be achieved by spectral analysis of low-level response to ambient excitation or by the use of exciters.[2]

Where a full response analysis is not undertaken and an assessment of potential vibration severity is needed, empirical expressions relating the height of a building to the fundamental period can be used.[3], [4], [5]

Experimental studies[6] have indicated the range of fundamental shear frequency of low-rise buildings 3 m to 12 m high to be from 4 Hz to 15 Hz. Damping behaviour is generally amplitude-dependent. The natural frequency and damping behaviour of stationary structures will be dealt with in a future addendum to this International Standard.

4.3 Building base dimensions

Ground-borne vibrations may have wavelengths of a few metres to several hundreds of metres. The response excitation from shorter wavelengths is complex and the foundations may act as a filter. Smaller domestic buildings would generally have base dimensions smaller than the characteristic wavelengths of all but the highest-frequency sources (for example precision blasting in rock).

4.4 Influence of soil

It is now common in earthquake engineering studies to take into account the influence of the soil.[3]

An evaluation of such interaction effects is sometimes justified for man-made vibrations; such an evaluation demands that the shear wave velocity or dynamic rigidity modulus in an appropriate volume of ground material be determined. Empirical, numerical and analytical procedures may be obtained from several sources.[7]

Foundations on poor soils and fill may suffer from settlement or loss of bearing capacity due to ground vibration. The risk of such effects is a function of the particle size of the soil, its uniformity, compaction[1], degree of saturation, internal stress state, as well as the peak multiaxial acceleration and duration of the ground vibration. Loose, cohesionless, saturated sands are especially vulnerable and in extreme circumstances may undergo liquefaction. This phenomenon needs to be taken into consideration in evaluating vibrations and explaining their effects. [8], [9] (See also annex A.)

5 Quantity to be measured

The characterization of both the nature of vibration input and the response may be effected by a variety of displacement, velocity or acceleration transducers. These can furnish a record as a function of time. It is the usual practice to sense a kinematic quantity, such as velocity or acceleration. From knowledge of the appropriate transfer function of the sensing system, each quantity can be derived from another by integration or differentiation. Integration at lower frequencies calls for care and confidence in amplitude-phase response of the transducer and instrument chain (see clause **6**). As long as the requirement on data collection, treatment and presentation (see clause **6**) can be met, the sensor may respond to any chosen quantity. Experience suggests that there are preferred measuring quantities for different situations (see Table 1)

6 Measuring instrumentation

6.1 General requirements

Vibration is measured with a view to using the data in some evaluatory or diagnostic procedure or to monitoring a vibration with some established target level in mind. For evaluation, the minimum performance shall be sufficient to meet the requirements laid down in clause **3** and clause **7** with regard to the evaluatory procedures described in clause **9**.

It is not expected that a single instrumentation system would meet all the requirements of frequency and dynamic range for the wide range of structures and inputs for which this International Standard is applicable.

The measuring system includes the following instrumentation:

- transducers (see **6.2**);
- signal-conditioning equipment;
- data recording system.

[1] Soil compaction may be monitored by precise levelling.

The frequency response characteristics (amplitude and phase) need to be specified for the complete measuring system when connected together in the manner to be used.

The degree to which measured motion needs to approach true motion will depend upon the character of the investigation and the evaluation method used.

The minimum requirement for **9.2.2** and **9.2.3** is that the vibration shall be characterized by a continuous measurement of the peak particle velocity values.

The minimum requirement for **9.2.4** is that the time history of the vibration shall be recorded over sufficient duration and with sufficient accuracy to establish its spectral characteristics. Analog or digital methods are available subject to the stipulations laid down in this clause.

6.2 Choice of transducers

The choice of transducers is important for the correct evaluation of vibratory motion. In general, transducers may be divided into two groups producing a linear output either above or below the natural resonance of the sensing mechanism. The so-called "velocity pick-up" or "geophone" widely used in structural vibration measurement is typical of an electromagnetic sensor operating at a frequency above its natural resonance; whereas a piezo-electric accelerometer usually operates below the resonance. There are electromagnetic sensors which operate below their natural frequency, such as are widely used strong-motion seismographs.

In practice, care should be exercised in using the phase information from the "velocity pick-up" type of transducer at the lower frequencies. If both amplitude and phase response are critical, linear performance of the whole measuring chain should be ensured. A low-frequency cut-off ten times the lowest required measured frequency is often recommended as a good compromise and, in general, the measured signal should be 5 dB above the back-ground noise.

Velocity pick-ups generate a relatively high signal thus simplifying the instrument chain. If particle velocity is needed, the piezo-electric accelerometer output needs integrating, and with transients the response of the whole chain should be verified.

6.3 Signal-to-noise ratio

The signal-to-noise ratio should generally be not less than 5 db.If the signal-to-noise ratio is between 10 dB and 5 dB, the measured value should be corrected (i.e. diminished) and the correction method reported. Background noise is defined as the sum of all the signals not due to the phenomenon under investigation.

Table 1 — Typical range of structural response for various sources

Vibration forcing function	Frequency range Hz	Amplitude range µm	Particle velocity range mm/s	Particle acceleration range m/s^2	Time characteristic	Measuring quantities
Traffic road, rail, ground-borne	1 to 80	1 to 200	0,2 to 50	0,02 to 1	C/T	pvth
Blasting vibration ground-borne	1 to 300	100 to 2 500	0,2 to 500	0,02 to 50	T	pvth
Pile driving ground-borne	1 to 100	10 to 50	0,2 to 50	0,02 to 2	T	pvth
Machinery outside ground-borne	1 to 300	10 to 1 000	0,2 to 50	0,02 to 1	C/T	pvth/ath
Acoustic traffic, machinery outside	10 to 250	1 to 1 100	0,2 to 30	0,02 to 1	C	pvth/ath
Air over pressure	1 to 40				T	pvth
Machinery inside	1 to 1 000	1 to 100	0,2 to 30	0,02 to 1	C/T	pvth/ath
Human activities a) impact b) direct	 0,1 to 100 0,1 to 12	 100 to 500 100 to 5 000	 0,2 to 20 0,2 to 5	 0,02 to 5 0,02 to 0,2	T	pvth/ath
Earthquakes	0,1 to 30	10 to 10^5	0,2 to 400	0,02 to 20	T	pvth/ath
Wind	0,1 to 10	10 to 10^5			T	ath
Acoustic inside	5 to 500					

Key

C = continuous
T = transient
} (simplified categories, see **3.1** and **3.2**)

pvth = particle velocity time history

ath = acceleration time history

NOTE 1 The ranges quoted are extremes but indicate the values which may be experienced and which may have to be measured (see also note 3). Extreme ranges of amplitude of displacement and frequency have not been used to derive particle velocity and acceleration.

NOTE 2 The frequency range quoted refers to the response of buildings and building elements to the particular type of excitation. It is indicative only.

NOTE 3 Vibration values within the ranges given may cause concern. There are no standards which cover all varieties of building, condition and duration of exposure, but many national codes associate the threshold of visible effects with peak particle velocities at the foundation of a building of more than a few millimetres per second. A significant probability of some damage is linked to peak particle velocities of several hundred millimetres per second. Vibration levels below the threshold of human perception (see ISO 2631-2) may be of concern in delicate and industrial processes.

7 Position and fixing of transducers

7.1 Positions

7.1.1 *General*

The proper characterization of the vibration of a building requires a number of positions of measurement which depend upon the size and complexity of the building.

Where the purpose is to monitor with regard to imposed vibration, the preferred position is at the foundation, a typical location being at a point low on the main load-bearing external wall at ground floor level when measurements on the foundations proper are not possible.

Measurements of vibration response generated by traffic, pile-driving and blasting, especially at a great distance, show that the vibration may be amplified within the building and in proportion to the height of the building. It may, therefore, be necessary to carry out simultaneous measurements at several points within the building. Simultaneous measurements on the foundation and the ground outside will serve to establish a transfer function.

Where a building is higher than 4 floors (≈ 12 m), subsequent measuring points should be added every 4 floors and at the highest floor of the building.

Where a building is more than 10 m long, measuring positions should be installed at horizontal intervals of approximately 10 m.

Additional measuring points may have to be made in response to requests by occupants and as a consequence of initial observations.

For investigations of the analytical type, positioning will depend upon the modes of deformation to be considered. Most practical cases are economically limited to identification of fundamental modes and measurement of maximum responses in the whole structure together with observations on elements such as floors, walls and windows.

7.1.2 ***Measurement in a building***

Transducer placement in a building depends on the vibration response of concern. As described in **7.1.1**, assessment of the vibration being input to a building from ground-borne sources is best done by measurements on or near the foundation. Determination of structural racking or of shear deformation of the building as a whole requires measurements directly on the load-bearing members which afford the structures' stiffness. This usually means three components of measurement in corners, although other arrangements are possible.

Sometimes, floor or wall motions are of concern, with maximum amplitudes at mid-span locations. Although sometimes very severe, these vibrations are usually unrelated to structural integrity.[11]

Investigations associated with sources within a building usually involve a trial-and-error exploratory phase.

In cases where measurements related to equipment are to be made, such as when monitoring computers, relays and other installations sensitive to vibration, the measurement should reflect the incoming vibration. The point of measurement should be placed on or at the foundation or on the frame of the equipment. In this case, the equipment should if possible be switched off for the measurement.

In cases where measurements related to ground-transmitted vibration are to be made, such as where ground vibration sources are being studied, it is usual to orientate the sensors with respect to radial direction defined as the line joining the source and the sensor. When studying structural response to ground vibration, it is more realistic to orientate with respect to the major and minor axes of the structure. It is often not possible to make measurements at the foundation proper so instruments have to be coupled to the ground.

Vibration measurements made on or below the ground surface may be affected by the variation of the amplitude of a surface wave with the depth. Building foundations may then be exposed to a motion which is different from the one observed on the ground surface depending on the wavelength, foundation depths and geotechnical conditions.

For wind-induced vibration, vertical components are often dispensed with and test instrument disposition should be made with rotational and translational modes in mind.

7.2 Fixing of transducers

7.2.1 ***Coupling to structural elements***

The mounting of vibration transducers to vibrating elements or substrate should comply with ISO 5348 with regard to accelerometers. The aim should be to reproduce faithfully the motion of the element or substrate without introducing additional response. Care should be taken with triaxial assemblies to avoid rocking or bending.

The mass of the transducer and monitoring unit (if any) shall not be greater than 10 % of the building element to which it is fixed. Mounting shall be as stiff and as light as possible.

Brackets should be avoided. It is better to fix three uniaxial transducers to three faces of a metal cube rigidly mounted by means of studs or quick-setting, high modulus resin. The transducer mounting can be secured to the frame of the building by expansion bolts. Gypsum joints are preferred when measuring on lightweight concrete elements.

In special circumstances, it is acceptable to glue the transducer or attach it using magnetic attraction. For measurements indoors on horizontal surfaces, double-sided adhesive tape may be used on all hard surfaces for accelerations below 1 m/s^2, although mechanical fixings are preferred.

Measurements on floors having compliant coverings tend to give distorted results and should be avoided. Where it is not possible to relocate the transducers, comparative measurements with different mass and coupling conditions for the mounting block should be made to evaluate the effect of the compliant coverings.

7.2.2 *Coupling to the ground*

Soil conditions permitting, the transducer may be fixed to a stiff steel rod (having a diameter of not less than 10 mm), driven through a loose surface layer. This rod should not project more than a few millimetres above ground surface. Care should be taken to ensure close contact between the transducer and the ground. In cases where acceleration greater than 2 m/s^2 is expected, a firm ground mounting is needed to prevent slippage. Where transducers have to be mounted in the ground in order to minimize coupling distortion, they should be buried.

Where transducers have to be mounted in the ground, in order to minimize coupling distortion, they should be buried to a depth at least three times the main dimension of the transducer/mounting unit. Alternatively, they can be fixed to a rigid surface plate with a mass ratio ($m/\rho r^3$) not more than 2, where m is the mass of the transducer and plate and r is the equivalent radius of the plate. The rigid surface plate may, for example, be a well-bedded paving slab. For most soils, the mass density, ρ, ranges from 1 500 kg/m^3 to 2 600 kg/m^3.

8 Data collection, reduction and analysis

8.1 General

The aim of measurement is to acquire sufficient information to enable the selected method of evaluation (see clause **9**) to be carried out with a sufficient degree of confidence.

The amount of information required to characterize vibration properly increases as the complexity of the vibration increases from simple periodic to non-stationary random and transient motion.

Data collection systems which are adequate for defining a periodic motion over a specified frequency range may not be adequate for establishing even a single pararmeter index (for example peak particle velocity) for a more complex motion.

8.2 Description of data

Any data resulting from the observation of a physical process can broadly be described as deterministic or random. Deterministic data are those that can be described by an explicit mathematical function.

Figure 1 illustrates categories of the types of data that may be encountered. A description of each category is given in ISO 2041.

8.3 Data analysis procedures

Having decided into which of the main categories illustrated in Figure 1 the data fall, the type of analysis will normally be apparent. If the data is categorized as deterministic, then a simple analysis (r.m.s., peak-to-peak, mean square) will often suffice.

If the special case of non-periodic deterministic data, peak amplitude should be determined without preconditioning (although a d.c. component may be compensated by analysis of a section of the record prior to capture of the signal). Details are given in [10] and [12]. A dynamic range of 40 dB is adequate for most purposes, but 50 dB is preferred.

Random data should be tested for stationarity (see [13]).

If the data are deemed to be stationary, the procedures outlined in annex C are appropriate and are described in more detail in [10], [12], [13] and [14].

9 Method of data evaluation

9.1 General

Evaluation of measurements should reflect both the purpose of those measurements and the type of investigation.

A full response analysis for predictive purposes requires information on structural details and conditions not usually readily obtainable. An investigator may, therefore, need to have an appropriate method of assessing the severity of vibration of a structure or a component with regard to the probability of damage. In such an assessment, the following factors need to be taken into account:

a) resonant frequencies of basic structure and component pads (walls, floors, windows);

b) damping characteristics of basic structure and component pads;

c) type of construction, its condition and material properties;

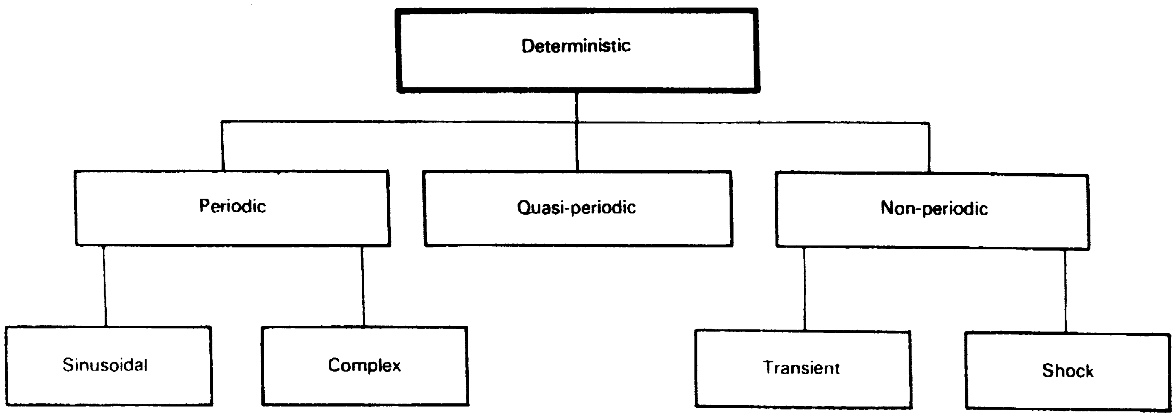
d) spectral structural features;

e) characteristics of excitation;

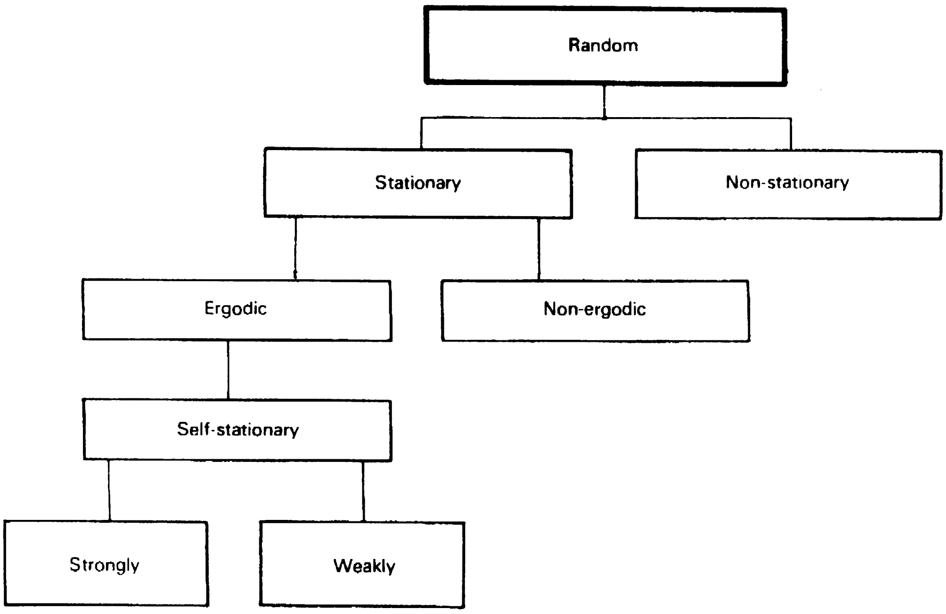
f) deflected form;

g) non-linearity in amplitude response.

Although this International Standard is primarily concerned with the measurement and evaluation of the response, the chain of action, source, transmission path and transfer-function have to be borne in mind when evaluation is being made.



a) Deterministic data



b) Random data

Figure 1 — Categories of the types of data

9.2 Types of investigation

For many of the parameters of interest, listed in **9.1** a) to g), the choice of instrumentation, its location within the building, the type of recording device and the number of data channels or measurement points desired, the duration of monitoring for the phenomena and the speed of data collection will immediately be decided. The outlining of instrumentation requirements in clause **6** and annex C has been arranged in such a way as to facilitate the selection of instrumentation to meet particular requirements. Beyond this it is important to delineate the degree of sophistication to be applied to the investigation. Instruments which characterize the vibration environment by a single quantity, such as those used in connection with human response and machine condition, may be used in a preliminary survey so long as the limited frequency responses are taken into account. For the purposes of this International Standard, a preliminary assessment, a monitoring program, a field survey and a detailed engineering analysis are under consideration.

9.2.1 *Preliminary assessment*

Situations may arise where an assessment has to be made of vibration problems by desk study alone, usually before field measurements. Empirical methods can be used to estimate response provided that data on the source parameters and building response characteristics, such as fundamental frequency and damping, are available.

9.2.2 *Exploratory monitoring*

Very limited measurement of vibration on a building or over an area can indicate the existence of a problem requiring further investigation. High errors are not uncommon and this fact has to be kept in mind. (See also final paragraph in **9.2.3**.)

9.2.3 *Field survey*

A field survey would consist of a limited number (see also **7.1**) of vibration measurement locations in order to assess the vibration severity often in comparison with values stipulated in codes or regulations.

In the case of vibrations which can be reproduced for a sufficient time, the same transducers can be used for the different points keeping a reference point at the foundation level near the source.

As regards exploratory monitoring (see **9.2.2**) and field surveys, measurements should be of an accuracy compatible with the uncertainties implicit in the vibration indices and empirical relationship used. Single parameter indices, such as peak particle velocity or peak acceleration and r.m.s, values, need, generally, only to be known to within ± 10 % at the 68 % confidence level.

9.2.4 *Engineering analysis*

When complex structures of vital importance are being subjected to vibration excitation of a magnitude that requires serious consideration of the consequences, the structural behaviour needs to be assessed in a more detailed way.

Instrumentation for monitoring the time history should be mounted at a number of locations to ensure that specific values for that structure are not exceeded.

If the ground-to-foundation transfer function is of concern, simultaneous recording outside and on the foundation should be carried out. The recording position on the foundation is at a point on the main wall at ground floor level or the basement.

The number of measuring points and their location have to be defined and modified according to the characteristics of the building and the observations noticed during monitoring.

The natural frequencies of buildings should be determined, if possible.

In the case of vibrations which can be reproduced for a sufficient time, the same transducers can be used for the different points keeping a reference point at the foundation level near the source.

For structures of vital importance, response analysis should be carried out as well as an estimate of structure loading. A full engineering analysis requires a system which would enable frequency to be estimated to ± 1 % and damping to ± 10 %.

9.3 Reporting of control activities

The style of reporting should be consistent with the type of investigation (see **9.2**), but as a minimum the report should include the following:

a) Risk analysis
   1) Description of the source.
   2) Type and condition of building, in accordance with annex A.
   3) Purpose of the measurement.
   4) Reference to the standard being used and type of investigation.

b) Measurements
   1) Position of transducer and manner of coupling.
   2) Type and make of transducer, signal conditioning and recording equipment.
   3) Calibration factors for the instrumentation system.
   4) Frequency range and linearity.
   5) Assessment of the sources of error.

6) — For monitoring or survey investigation (see **9.2.2** and **9.2.3**), it is sufficient to make continuous registrations of peak particle velocity values.

— For further investigation (see **9.2.4**), a permanent record of time history should be made available.

c) Building inspection

1) Inspection of buildings before vibration exposure, with graphical reporting of cracks and other damage.

2) Inspection of the same buildings after the vibration exposure.

3) Evaluation of observed damage.

d) Reference to other relevant International Standards.

9.4 Evaluation for prediction

An existing building may be exposed to a new source, external or internal, and some assessment of the expected vibration response is needed. Given sufficient information about the characteristics of the input and the properties of the structure, numerical analyses using one or other well known techniques of response spectra, Fourier response, time step integration[15] may be used for important buildings. Alternatively, a characteristic index, such as a kinematic quantity (displacement, velocity, acceleration) (see **9.6**), can be related to expected performance using empirical data appropriate to the type of building.[7]

A convenient way of expressing a vibration in the frequency domain is the "response spectrum", widely used in engineering.[7] (See IEC 68-2-27.) For the special case of zero damping, it is close to the Fourier amplitude spectrum.

In most cases, the response characteristics of the structure are ill defined although dynamic test procedures are now available.[7]

9.5 Evaluation for vibration study in existing buildings

The evaluation of vibration status in existing buildings may be carried out at different levels of sophistication consistent with the investigative procedures outlined in **9.2**. Indications of vibration severity may be in terms of stresses or kinematic quantities. In some cases, the direct observation of crack opening or extension affords valuable information on the response and may indicate progressive deterioration.[15], [16]

9.6 Kinematic quantities as indices of vibration severity in structures

For several decades studies have been carried out to relate the vibration severity in terms of a quantity such as peak displacement, velocity, acceleration, related to visible effects on structures.

Where measurements are made upon a component, a kinematic quantity, such as peak velocity, can be expressed as a stress (see annex B) and, in turn, related in structural terms to allowable stress. When the kinematic quantity refers to whole-body structural response measured at some chosen position, the response frequency and damping of the structure, and duration of the input affect vibration severity. The kinematic quantity is then an empirical index and shall be qualified by the kind of building to which it refers (see **3.3**).

Some account of these factors is embodied in the use of the peak spectral acceleration or velocity as a damage index [6],[11] applicable to low-rise (one to three storeys high) and "whole" building response.[16]

The dependence of severity rating on response frequency of both building and frequency content of the excitation is also recognized in the empirical correlations which strictly apply to buildings with a limited range of fundamental frequency in shear, and identify different severity ratings in different frequency bands. A broad guide to vibration levels of interest is given in Table 1.

9.7 Probabilistic aspects

There is increasing evidence that the criteria relating vibration to visible effects on buildings (cosmetic, minor and major damage) should be approached in a probabilistic way.

For possible combinations of age and condition of a building, it may not be possible to establish an economic absolute lower limit.

This is particularly the case where either a peak kinematic value (usually particle velocity) of ground motion within a specified frequency band or a peak spectral velocity response spectrum acceleration or displacement is being used as an index of damage potential. Minimal risk for a named effect is usually taken as a 95 % probability of no effect.

The evaluation of the response of a building or component part may be assisted by measurements of local strain or relative displacement (for example crack monitoring), although this would not constitute a measure of vibration status. It may, however, permit (with difficulty) a direct evaluation of composed dynamic stress for comparison with design criteria.

9.8 Fatigue factors

Repeated stress reversal over many cycles carries a risk of increasing fatigue failure. Reference for steel members can be made to appropriate design codes. Such guidance is not available for concrete, masonry and other building materials. Reference would have to be made to research. Long-term, low-level vibration amounting to 10^{10}load reversals may have to be taken into account for special structures, monuments, etc.[17]

9.9 Description of damage

For the purposes of this International Standard, the damage is classified into the following categories:

— **Cosmetic**

The formation of hairline cracks[2)][21] on drywall surfaces, or the growth of existing cracks in plaster or drywall surfaces; in addition, the formation of hairline cracks in mortar joints of brick/concrete block construction.

— **Minor**

The formation of large cracks or loosening and falling of plaster or drywall surfaces, or cracks through bricks/concrete blocks.

— **Major**

Damage to structural elements of the building, cracks in support columns, loosening of joints, splaying of masonry cracks, etc.

NOTE 2 The description of damage has its equivalent in the intensity scales used by seismologists.

[2)] See ISO 4356.

Annex A (informative) Classification of buildings

A.1 General

This annex provides simplified and helpful guidelines for classifying buildings according to their probable reaction to mechanical vibrations transmitted by the ground.

A dynamic system, for the purposes of this classification, consists of the **soil and strata**, in which are set the **foundations** (if existing), together with the **building structure** itself.

Table A.2 gives 14 simplified classes taking into consideration the following factors:

— type of construction (as ascertained from Table A.1);

— foundation (see clause **A.5**);

— soil (see clause **A.6**);

— political importance factor.

The frequency range is taken from 1 Hz to 150 Hz (see also **3.3**), which covers most events met in industrial practice, blasting, piling and traffic. Shock directly introduced into the structure by industrial machinery is not included though its effects at some distance are. Shock produced by blasting, piling and other sources outside the strict confines of the structure are not included but the effects on the structure are. The buildings referred to exclude very tall structures with more than 10 storeys.

A.2 Structures involved

A.2.1 The following structures are included in the classification:

— all buildings used for living and working (houses, offices, hospitals, schools, prisons, factories, etc.);

— publicly used buildings (town halls, churches, temples, mosques, heavier industrial mill-type buildings, etc.);

— elderly, old and ancient buildings of architectural, archeological and historical value;

— lighter industrial structures, often designed to the codes of building practice.

A.2.2 The following structures are not included in the classification:

— heavier structures such as nuclear reactors and their adjuncts and other heavy power plants, rolling mills, heavier chemical engineering structures, all types of dams, and containing structures for fluids and granular materials, for example water towers and tanks, petroleum storage, grain and other silos, etc.;

— all underground structures;

— all marine structures.

A.3 Definition of classes (see Table A.2)

The classes are defined by taking as a reference a well maintained building in good repair. The reference building shall not have any constructional defects nor shall it have sustained accidental damage from earthquakes. If the construction does not fulfil these requirements, it shall be allocated to a lower class.

The order in which the structural types are classified depends on their resistance to vibrations, and also on the tolerances that can be accepted for the vibrational effects on structures, given their architectural, archeological and historical value.

Three important elements enter into the reaction of a structure under the effects of mechanical vibrations. The three elements are as follows:

— the category of the structure — Table A.1 gives a preliminary classification of the categories of structures based on the groups defined in clause **A.4**;

— the foundation (see clause **A.5**);

— the nature of the soil (see clause **A.6**).

A.4 Categories of structures

A.4.1 *Group 1 — Ancient and elderly buildings or traditionally built structures*

The types of buildings considered in this group can be divided into the two following sub-groups:

a) elderly, old or ancient buildings;

b) all modern buildings constructed in older, traditional style using traditional kinds of materials, methods and workmanship.

This group, generally, is of heavier construction and has a very high damping coefficient, for instance due to soft mortar or plaster. This group also includes traditionally resilient structures in earthquake zones. Buildings in this group seldom have more than six storeys.

A.4.2 *Group 2 — Modern buildings and structures*

The types of buildings considered in this group are all of modern structure using relatively hard materials tied together in all directions, usually light in weight overall, and with little damping coefficient.

This group includes frame buildings as well as calculated load-bearing wall kinds. Buildings vary from being single- to multi-storey. All types of cladding are included. This group also includes some older types of buildings which are constructed using modern materials, tying and damping.

A.5 Categories of foundations

A.5.1 *Class A*

Class A includes the following types of foundation:

- — linked reinforced concrete and steel piles;
- — stiff reinforced concrete raft;
- — linked timber piles;
- — gravity retaining wall.

A.5.2 *Class B*

Class B includes the following types of foundation:

- — non-tied reinforced concrete pile[3];
- — spread wall footing;
- — timber piles and rafts.

A.5.3 *Class C*

Class C includes the following types of foundation:

- — light retaining walls;
- — large stone footing;
- — no foundations — walls directly built on soil.

A.6 Types of soil

Soils are classified into the following types:

Type a: unfissured rocks or fairly solid rocks, slightly fissured or cemented sands;

Type b: compact, horizontal bedded soils;

Type c: poorly compacted, horizontal bedded soils;

Type d: sloping planes; surfaces with potential slip;

Type e: open granular, sands, granular (non-cohesive), and cohesive saturated clays;

Type f: fill.

[3] Piles, structurally connected, usually at level of pile caps.

Table A.1 — Categorization of structures according to group of building

Category of structure		Group of building (see clause A.4) 1	2
←Resistance to vibration decreasing	1	Heavy industrial multi-storey buildings, five to seven storeys high, including earthquake-resistant forms Heavy structures, including bridges, fortresses, ramparts	Two- and three-storey industrial, heavy-frame buildings of reinforced concrete or structural steel, clad with sheeting and/or infilling panels of blockwork, brickwork, or precast units, and with steel, pre-cast or *in situ* concrete floors Composite, structural steel and reinforced concrete heavy industrial buildings
	2	Timber frame, heavy, public buildings, including earthquake-resistant forms	Five- to nine-storey (and more) blocks of flats, offices, hospitals, light-frame industrial buildings of reinforced concrete or structural steel, with infilling panels of blockwork, brickwork, or precast units, not designed to resist earthquakes
	3	Timber-frame, single- and two-storey houses and buildings of associated uses, with infilling and/or cladding, including “log cabin” kinds, including earthquake-resistant forms	Single-storey moderately lightweight, open-type industrial buildings, braced by internal cross walls, of steel or aluminium or timber, or concrete-frame, with light, sheet-cladding, and light panel-infilling, including earthquake-resistant types
	4	Fairly heavy multi-storey buildings, used for medium warehousing or as living accommodation varying from five to seven storeys or more	Two-storey, domestic houses and buildings of associated uses, constructed of reinforced blockwork, brickwork or precast units, and with reinforced floor and roof construction, or wholly of reinforced concrete or similar, all of earthquake-resistant types
	5	Four- to six-storey houses, and buildings of associated urban uses, made with blockwork or brickwork, load-bearing walls of heavier construction, including “stately homes” and small palace-style buildings	Four- to ten-storey domestic and similar buildings, constructed mainly of lightweight load-bearing blockwork and brickwork, calculated or uncalculated, braced mostly by internal walls of similar material, and by reinforced concrete, preformed or *in situ* floors at least on every other storey.
	6	Two-storey houses and buildings of associated uses, made of blockwork, brickwork or pis-à-terre, with timber floors and roof Stone- or brick-built towers, including earthquake-resistant forms	Two-storey domestic houses and buildings of associated uses, including offices, constructed with walls of blockwork, brickwork, precast units, and with timber or precast or *in situ* floors and roof structures
	7	Lofty church, hall and similar stone- or brick-built, arched or “articulated” type structures, with or without vaulting, including arched smaller churches and similar buildings Low heavily constructed “open” (i.e. non-cross-braced) frame church and barn type buildings including stables, garages, low industrial buildings, town halls, temples, mosques, and similar buildings with fairly heavy timber roofs and floors	Single- and two-storey houses and buildings of associated uses, made of lighter construction, using lightweight materials, pre-fabricated or *in situ,* separately or mixed
	8	Ruins and near-ruins and other buildings, all in a delicate state All class 7 constructions of historical importance	

Table A.2 — Classification of buildings according to their resistance to vibration and the tolerance that can be accepted for vibrational effects

	Class of building[a]	Category of structure (see Table A.1)							
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
		Categories of foundations (capital letters) and types of soil (lower case letter) (see clause **A.5** and clause **A.6**)							
← Level of acceptable vibration decreasing	1	A a							
	2	A b	A a	A a	A a				
	3		A b B a	A b B a	A b	A a A b			
	4		A c B b	B b	A c	A c B a B b			
	5		B c	A c		B c	B a		
	6		A f		A d	B d	B b C a	B a	
	7			A f	A e	B e	B c C b	B b C a	
	8						B e C c	B c C b	
	9		B f				C d	B d C c	A a
	10			B f			C e	B e C d	A b
	11				C f	C f		C e	B a
	12						C f		B c C a
	13							C f	B d C b C c
	14								C d C e C f

[a] High class number = high degree of protection required.

Annex B (informative) Estimation of peak stress from peak particle velocity

The stresses in beams or plates vibrating close to resonance can be calculated from measurement of velocity or displacement and frequency, if the measurement is performed at the points of maximum vibrating displacements. In this case a knowledge of the boundary conditions and the stiffness is not necessary for estimating the stresses.

For beams with full rectangular cross-section and constant stiffness and weight loading, the following relationship applies, independent of the length, height and width of the beam, between the largest bending stress $\sigma_{max,}$ and the vibration velocity v_{max}:

$$\sigma_{max} \approx \sqrt{E_{dyn}\,\rho} \times \sqrt{3\frac{G_{tot}}{G_{beam}}} \times k_n\,\hat{v}_{max}$$

where

- $\hat{v}_{max}$ $= \hat{x}_{max} \times \omega$ is the maximum amplitude of the vibration velocity occurring at a point at the beam length [where ω is the forcing frequency approximately equal to ω_n (natural frequency of the beam)];
- E_{dyn} is the dynamic elasticity modulus;
- ρ is the mass density;
- $\frac{G_{tot}}{G_{beam}}$ is the load coefficient, where the beam is stressed by other evenly distributed loads in addition to its own weight ($G_{tot} = G_{beam} + G_{other\ loads}$);
- k_n is the mode coefficient (dimensionless), 1 to 1,33; the eigenmode coefficient k_n depends on the boundary conditions and the degree of the mode, which only has a slight influence.

For further details, see [18].

Annex C (informative) Random data

C.1 General

Random data may be encountered in practice (wind loading, crusher machinery). Spectral analysis techniques can be used to estimate response characteristics. The estimate may be more or less precise depending on the structural characteristics (frequency and damping of a selected mode) and the precision required of the analysis.[14] Two kinds of error, bias and variance, are involved.[14] Choice of recording duration depends on the permissible errors chosen. If bias error is to be 4 % and variance error 10 %, for example, the recording duration, T_r, in seconds, may be calculated using the following common formula:

$$T_r = \frac{200}{\eta\, f_n}$$

where

- η is the modal damping ratio;
- f_n is the natural frequency of mode n, under consideration, in hertz.

For instance, if η = 1 % of critical and f_n = 1 Hz, then a recording duration of 20 000 s is needed to estimate to the bias and variance errors selected above. If η is 2 % of critical and f_n is 10 Hz, a recording duration of 1 000 s is needed. Acceptance of higher errors would reduce the required recording duration.

These requirements are independent of the type of equipment used for analysis. (It is common practice to use magnetic type recorders.) Structural damping will be dealt with in a future addendum to this International Standard.

Non-stationary random data presents special problems and reference should be made to appropriate literature; see [14].

The analysis of random data is conducted in one of two domains, frequency and time, and these are considered in clause **C.2** and clause **C.3**.

C.2 Frequency domain

In general vibration analysis, the quantity most often used is the Power Spectral Density (PSD). In the analysis of structural vibration, the amplitude spectral density itself may be presented. Other types of analysis in this domain include transfer function, cross PSD, coherence function, and quadrate spectral density. These results are presented as the "physical quantity" squared per hertz versus frequency, respectively as dimensionless numbers and ratios of physical quantities.

C.3 Time domain

In the time domain covariance, autocorrelation, cross-correlation, and covariance analyses may be carried out. The autocorrelation function, which is the inverse of the power spectrum, is the most commonly used. Many of the quantities in the time domain can be used with deterministic data. However, the more complex functions are often used with random data. Time-domain analysis covers mean, root-mean-square, peak counting, zero crossing counting as well as probability density, probability distribution, skewness and Kurtosis.

Annex D (informative)
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