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Mechanical vibration and shock — Vibration of buildings — Guidelines for the measurement of vibrations and evaluation of their effects on buildings

Vibrations et chocs mécaniques — Vibrations des bâtiments — Lignes directrices pour le mesurage des vibrations et évaluation de leurs effets sur les bâtiments

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Contents

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Foreword

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

Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

International Standard ISO 4866 was prepared by Technical Committee ISO/TC 108, *Mechanical vibration and shock*.

Annexes A, B, C and D of this International Standard are for information only.

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.

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Mechanical vibration and shock — Vibration of buildings — Guidelines for the measurement of vibrations and evaluation of their effects on buildings

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).

1) Soil compaction may be monitored by precise levelling.

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.

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

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/s²	Time charac-teristic	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 } (simplified categories, see 3.1 and 3.2)
T = transient }

pvth = particle velocity time history
ath = acceleration time history

NOTES

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.

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

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.

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 background 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.

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 ($\approx$ 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.