INTERNATIONAL STANDARD

ISO 10137

Second edition
2007-11-15

Bases for design of structures — Serviceability of buildings and walkways against vibrations

Bases du calcul des constructions — Aptitude au service des bâtiments et des passerelles sous vibrations

Reference number
ISO 10137:2007(E)

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Published in Switzerland

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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.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. 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.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 10137 was prepared by Technical Committee ISO/TC 98, *Bases for design of structures*, Subcommittee SC 2, *Reliability of structures*.

This second edition cancels and replaces the first edition (ISO 10137:1992) and differs from the previous edition as follows:

— information on relevant International Standards have been updated;

— treatment of vibrations from rock bursts has been added;

— actions due to human activities have been updated (Annex A);

— serviceability criteria for occupants of buildings subjected to wind-induced vibrations have been added (Annex D);

— the bibliography has been revised and updated;

— editorial changes and clarifications of text have been made.

Introduction

Economic use of high-strength and lightweight materials has resulted in a trend towards more dynamically responsive structures. This trend is exacerbated by the emergence of new sources of vibration acting on buildings and walkways, and is compounded by an increasing demand for "vibration free" environments for proper functioning of industrial and laboratory processes and instruments, and for work efficiency and personal comfort. In the past, vibrations in buildings have largely been controlled by specified loads or limitation of static deflections, or they have simply not occurred because of the massive nature of buildings. A number of unsatisfactory vibration levels in buildings have been observed, however, and this seems to indicate that the indirect criteria are no longer adequate. Hence, this International Standard was developed with the objective of presenting the principles for predicting vibrations at the design stage, in addition to assessing the acceptability of vibrations in existing structures.

The recommendations presented here are for serviceability and not for safety. It is, however, possible that some vibrations (usually associated with resonance) can become a safety hazard. Therefore, for severe dynamic loading, a check on the possible occurrence of resonance and associated limit stresses, deflections and fatigue effects shall be carried out. The vibration effects discussed here represent a serviceability limit state in accordance with ISO 2394.

The serviceability limit state for vibrations is described by constraints, generally consisting of vibration values (displacement, velocity or acceleration), usually in combination with frequency or a frequency range and possibly with other parameters. The constraints can also be connected to stress, strain, cracking occurrence and duration. The constraints can be determined statistically, but are generally prescribed in codes deterministically.

The design or evaluation criteria employed for achieving satisfactory vibration behaviour of buildings and walkways in the serviceability limit state should consider, among others, the following aspects:

a) variability of tolerance of human occupants due to cultural, regional or economic factors;

b) sensitivity of building contents to vibrations and changing use and occupancy;

c) emergence of new dynamic loadings which are not explicitly addressed by this International Standard;

d) use of materials whose dynamic characteristics may change with time;

e) impracticality of analysis due to the complexity of the structure or complexity of the loading;

f) social or economic consequences of unsatisfactory performance.

Bases for design of structures — Serviceability of buildings and walkways against vibrations

1 Scope

This International Standard gives recommendations on the evaluation of serviceability against vibrations of buildings, and walkways within buildings or connecting them or outside of buildings.

It covers three recipients of vibrations:

a) human occupancy in buildings and on walkways;

b) the contents of the building;

c) the structure of the building.

It does not include bridges that carry vehicular traffic, even in conjunction with pedestrian traffic, nor the design of foundations or supporting structures of machinery.

For the purposes of this International Standard, it is assumed that the building structure responds linearly to the applied loads. This means that the structure does not yield or fail, nor is it subject to significant non-linear effects.

2 Normative references

The following referenced documents are indispensable for the application 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 2041, *Mechanical vibration, shock and condition monitoring — Vocabulary*

ISO 2372, *Mechanical vibration of machines with operating speeds from 10 to 200 rev/s — Basis for specifying evaluation standards*

ISO 2394:1998, *General principles on reliability for structures*

ISO 2631-1:1997, *Mechanical vibration and shock — Evaluation of human exposure to whole-body vibration — Part 1: General requirements*

ISO 2631-2:2003, *Mechanical vibration and shock — Evaluation of human exposure to whole-body vibration — Part 2: Vibration in buildings (1 Hz to 80 Hz)*

ISO 3010:2001, *Basis for design of structures — Seismic actions on structures*

ISO 3898, *Bases for design of structures — Notations — General symbols*

ISO 4354, *Wind actions on structures*

ISO 4866:1990, *Mechanical vibration and shock — Vibration of buildings — Guidelines for the measurement of vibrations and evaluation of their effects on buildings*

ISO 6897, *Guidelines for the evaluation of the response of occupants of fixed structures, especially buildings and off-shore structures, to low-frequency horizontal motion (0,063 to 1 Hz)*

ISO 8041, *Human response to vibration — Measuring instrumentation*

ISO 8569, *Mechanical vibration and shock — Measurement and evaluation of shock and vibration effects on sensitive equipment in buildings*

ISO 8930, *General principles on reliability for structures — List of equivalent terms*

ISO/TS 10811-1, *Mechanical vibration and shock — Vibration and shock in buildings with sensitive equipment — Part 1: Measurement and evaluation*

ISO/TS 10811-2, *Mechanical vibration and shock — Vibration and shock in buildings with sensitive equipment — Part 2: Classification*

ISO 10816 (all parts), *Mechanical vibration — Evaluation of machine vibration by measurements on non-rotating parts*

ISO 14837-1, *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 2041 and ISO 8930 and the following apply.

NOTE See also ISO 3898 and ISO 2394.

3.1
amplification
increase of vibration amplitudes relative to a reference amplitude

3.2
attenuation
loss of vibration energy along a transmission path

3.3
broadband spectrum
spectrum with the vibration distributed over broad frequency bands (e.g. octave-band spectrum, one-third-octave band spectrum)

3.4
damping
dissipation of energy in a vibrating system

3.5
dynamic actions
actions varying so quickly that they give rise to vibrations

3.6
dynamic forces
forces varying so quickly that they give rise to vibrations

3.7
Fourier transformation
mathematical procedure that transforms a time record into a complex frequency spectrum (Fourier spectrum) without loss of information

3.8
frequency components
centre frequencies of narrow bands in which the energy of a spectrum is concentrated

3.9
frequency response function
frequency spectrum function of the output signal divided by the frequency spectrum function of the input signal

NOTE The frequency response is usually given graphically by curves showing the amplitude relationship and, where applicable, phase shift or phase angle, as a function of frequency. Alternatively, it is the Fourier transformation of the response of the structure to an impulse.

3.10
geometric spreading
decay of vibration amplitudes with increasing distance from the source as the energy is spread over a larger volume

3.11
impulsive source
source which gives a dynamic action of a short duration compared with the natural period of the structure under consideration

3.12
mode of vibration
deflected shape at a particular natural frequency of a system undergoing free vibration

3.13
narrow-band spectrum
spectrum with the vibration concentrated in narrow frequency bands

3.14
natural frequency
frequency at which a mode of vibration will oscillate under free vibrations

3.15
octave-band spectrum
spectrum determined by means of a filter cutting off frequencies outside a band, where the maximum frequency in each band is equal to the minimum frequency multiplied by 2

3.16
receiver
person, structure or contents of a building subjected to vibrations

3.17
response spectrum
maximum responses of a series of single-degree-of-freedom systems subjected to a given dynamic base motion, plotted as a function of natural frequencies for specific values of damping

3.18
shock
dynamic action with a duration that is short compared to the natural period of the receiver

3.19
shock spectrum
response spectrum for a shock motion

3.20
source
origin of the vibration

3.21
spectrum
plot of a time-varying function transformed into the frequency domain

3.22
sustained vibration
vibration having a duration of many periods

3.23
third-octave-band spectrum
spectrum determined by means of a filter cutting off frequencies outside a band, where the maximum frequency in each band is equal to the minimum frequency multiplied by $2^{1/3}$

3.24
transfer function
for a system, a mathematical relation in the frequency domain between the output and the input to the system

3.25
transmission path
path from the source to the receiver

3.26
unbalanced force
force originating from unbalance of a rotating mass at the source

3.27
walkway
footbridge
pedestrian bridge
structure carrying pedestrian traffic, but no motorized vehicles, within buildings, between buildings or outside of buildings

4 Description of the vibration problem

4.1 General remarks

Vibrations arise from the interaction between time-varying disturbances and the inertia properties of the affected medium. The disturbance can be in the form of forces or displacement functions; the affected media can be solids, liquids or gases. The vibration process can be described mathematically by employing Newton's laws of motion and incorporating the appropriate deformational properties of the affected medium.

The evaluation of vibrations in buildings and walkways has to take account of the characteristics of the vibration source, the transmission path and the receiver. The vibration source produces the dynamic forces or actions. The medium or the structure between the source and receiver constitutes the transmission path, and the resulting vibrations at the receiver are then subject to the applicable criteria of the specified serviceability limit state. The dynamic actions are, in general, a function of time and space and are described in Clause 5. Clause 6 deals with methods of response analysis and Clause 7 with applicable vibration criteria. The values of actions, effects and criteria presented in this International Standard are some of the other representative values given in ISO 2394:1998, 6.2.1. Whenever data are available, the method of partial coefficients, in accordance with ISO 2394, should be employed for verification of the serviceability.

4.2 Vibration source

The vibration source can be inside or outside the building.

4.2.1 Vibration sources inside a building

Vibration sources inside a building include:

— human excitation;

— rotating and reciprocating machinery;

— impact machinery (punches, presses, etc.);

— moving machinery (trolleys, lift trucks, elevators, conveyors, overhead cranes, etc.);

— construction or demolition activity in other parts of the building.

4.2.2 Vibration sources outside a building

Vibration sources outside a building can occur on the ground surface, underground, in the air, or in water, such as:

— construction, mining or quarry blasting;

— construction activity (pile driving, compaction, excavation, etc.);

— road and rail traffic;

— sonic boom or air blast;

— fluid flow (wind or water);

— punching presses or other machinery in nearby buildings;

— impact of ships on nearby wharves;

— rock bursts,

4.3 Transmission path

The transmission path has the effect of modifying the vibrations from the source to the receiver due to discontinuities, attenuation due to geometric spreading and material damping, and possible amplification or attenuation in certain frequency ranges.

4.4 Receiver

The receiver of the vibrations is the object or person for which the vibration effects are to be assessed. This can encompass the building structure (or components such as beams, slabs, walls, windows, etc.), the contents of the building (instruments, machines, etc.), or the human occupants of the building.

5 Dynamic actions

5.1 General remarks

The dynamic actions are the forces, displacements, velocities, accelerations or energy associated with the vibration source. In many cases, the dynamic actions cannot be predicted in a deterministic sense, in which case it may be appropriate to consider the actions as random.

5.2 Machinery

5.2.1 Rotating machinery

Values for the unbalanced forces of rotating machinery should be supplied by the manufacturers. In the absence of such data, the maximum acceptable unbalanced forces for the respective category of machines can be taken from ISO 2372 for electrical machines, or ISO 10816 for large rotating machines, or from other applicable standards. The forces produced by unbalance change with the flexibility of support conditions, and whether the operating frequency is above or below the mounted resonance frequency of the machine. There is also a trend for unbalanced forces to increase as machines age, and allowance for this effect should be made. Machines and their components can induce large forces during breakdowns or rapid stoppages. These actions should be considered in assessing the serviceability limit state. Unbalanced forces from attachments to machines (transmissions, rotors, etc.) also need to be considered.

Start-up and run-down conditions shall be considered when the operating frequency is above any of the resonance frequencies of the mounted machine or any of the support elements or structures.

5.2.2 Reciprocating machinery

The actions of reciprocating machinery depend on the type and construction of the machine, the operating conditions such as rotational speed and load, mounting details, and the age and state of maintenance of the machine. The quantitative descriptions of actions should be available from the manufacturer, but can be measured or calculated in the form of time histories of forces or displacement functions (accelerations, velocities or displacements) or the spectra of these quantities.

5.2.3 Impacting machinery

This includes machines such as forge hammers, stamping presses and pile drivers. The forces generated are usually very large. The action can be described in terms of a displacement (or velocity or acceleration)-time history or energy per impact. These values should be provided by the manufacturer but can be derived by measurements or calculations.

5.2.4 Other machinery

Certain machinery (e.g. grinding mills) combine random-type excitations with other types of excitation, such as rotational or, possibly, impact.

5.3 Vehicular traffic (road and rail)

5.3.1 General remarks

Motor vehicles with pneumatic tyres and trains on rails are two major sources of vibrations. The action can be described by force-time functions, displacement functions, or by a source spectrum. Stationary point sources, line sources, area sources, or moving sources shall be considered as applicable. Because of the complexity of the problem, empirical methods based upon measurements are often required. These may be combined with analytical and numerical modelling, as appropriate.

5.3.2 Motor vehicles

Vibrations induced by motor vehicles depend on suspension characteristics, mass, speed, traffic density, type and roughness of the road (including discrete irregularities), and subgrade properties.

The effects of these factors are interrelated and cannot be described by simple formulae.

5.3.3 Railway trains

Major factors that affect vibrations induced by railway trains are the following;

- type of train (high speed, ordinary, subway, etc.);
- weight;
- speed;
- type of track, or type of rail (continuous rails, jointed rails, surface irregularities, etc.);
- ballast, subgrade and general soil conditions.

The effects of these factors are interrelated and cannot be described by simple formulae. General guidance on vibrations from trains is given in ISO 14837-1.

5.4 Impulsive sources

5.4.1 General remarks

The characteristics of the vibration source are described in terms of the time variation of force, pressure or displacement function (including velocity and acceleration). Approximate descriptions include the following:

- peak values and duration for impulsive sources;
- root-mean-square (r.m.s.), or peak and frequency content for sustained vibrations;
- statistical descriptions, such as r.m.s., third-octave, octave and narrow-band spectra;
- response (or shock) spectra.

When r.m.s. quantities are used, attention should be paid to the method of averaging. It is assumed that there are only a few occurrences per day and that the total duration of the activity is of a temporary nature (e.g. construction). It is recommended to use a 1 s averaging time as given in 6.3.1 of ISO 2631-1:1997.

5.4.2 Impulsive sources in the ground

The main characteristic of impulsive sources, such as construction blasting, surface mining and pile driving is the energy released into the ground. The ground motion parameters at a given distance from the source can be obtained by empirical methods based on measurements, resulting in ground motion bounds and estimated response spectra.

Rock bursts, caused by collapse of underground cavities or localized re-arrangement of rock as a result of previous or ongoing mining activity, share many characteristics with earthquakes, albeit on a smaller scale. The ground motion characteristics at a building site can be described by peak values, time series and/or response spectra. These characteristics will vary with the geology and mining history at or near the building site. Methods of characterizing ground motions from rock bursts for the serviceability limit state can be found in ISO 3010.

5.4.3 Controlled intermittent and impulsive sources within a structure

Vibrations can be induced by controlled demolition operations and also by particular production processes which are not regular in time and intensity. These sources include the following:

- use of heavy equipment (vehicles, vibratory rollers or breakers, wrecking tools, etc.);
- controlled blasting within the structure;
- falling of heavy objects.

Cranes and lifts (elevators) can also induce impulsive forces during starting and stopping operations.

NOTE Accidental explosions or other types of accident which produce vibrations are not considered in this International Standard.

5.4.4 Airborne or waterborne impulsive sources

For explosive charges, the action is described in terms of the energy release or the overpressure-time variation. Sonic boom resulting from supersonic aircraft can be described in the form of pressure-time variations.

5.5 Human activity

5.5.1 Repetitive coordinated activities over a fixed area

For many repetitive coordinated human activities, the dynamic action is distributed more or less uniformly over a major portion of the structure. The active participants do not change their position, or the entire group of people moves so as to maintain a more or less uniform loading. This includes gymnastic exercises, dancing, coordinated jumping, running of a group of people, spectator action in halls or stadiums, or similar activities. The actions can be described by force-time histories or their spectral components.

5.5.2 Persons traversing structures

The dynamic actions of one or more persons can be presented as force-time histories or as their corresponding frequency components. This action varies with time and position as the person or persons traverse the supporting structure.

NOTE Special attention needs to be paid to avoid resonance effects in walkways with low horizontal and vertical natural frequencies. Some guidance is given in Annex A and Annex C.

5.5.3 Single pulses

Single pulses result from

— persons jumping off objects,

— persons jumping off steps on staircases or in floors,

— accidental or deliberate dropping of objects onto floors, or

— a single coordinated action, such as spectators jumping to their feet (for example at a sports event).

The action can be described in terms of force-time variations (or their Fourier transformation) or the impulse of the event.

NOTE Some descriptions of dynamic actions from human activities are given in Annex A.

5.6 Wind

The actions induced in structures by wind are specified in ISO 4354.

5.7 Earthquakes

The actions induced in structures by earthquakes are specified in ISO 3010.

6 Evaluation of response

6.1 General remarks

The analysis of response requires a calculation model that incorporates the characteristics of the source and of the transmission path and which is then solved for the vibration response at the receiver. The type and complexity of the calculation model depends on the dynamic behaviour it must represent and by the accuracy required in the prediction of the vibration response. The simplifying assumptions employed in establishing and solving the calculation model shall be noted. The analysis may concern existing structures or may be a part of the design of new structures.

Vibrations in existing building structures should be evaluated by measurements, whenever possible, in order to complete and to check eventual calculations.

Approximate methods for predicting vibrations may be employed where

a) the approximating assumptions correspond closely to known reality, or

b) the overall effect has been verified by field experience and/or more refined calculations.

6.2 Methods of analysis

6.2.1 General remarks

Vibration problems can be classified in many ways, for example by amplitude, duration and frequency content. The analysis required is, in turn, dictated by the type of vibration source and the transmission path. If the dynamic actions are random, it may be appropriate to use random vibration theory.

Two broad classes of vibration problems can be identified:

— Class A: the actions of the vibration source change in time and space.

— Class B: the actions of the vibration source change in time but either are, or can be considered to be, stationary in space.

NOTE Examples of Class A: a vehicle moving along a street, a person walking across a floor; examples of Class B: vibrations from a mounted piece of machinery, people jumping in unison on a floor; examples of empirical methods: prediction of blasting vibrations, prediction of traffic vibrations.

Empirical methods are employed when the complete analytical solution of a problem may not be practical. Empirical methods can be used when they have been derived from a large number of experimental or theoretical results and where bounds of applicability have been established. When empirical methods and criteria are used for problems other than those for which they were derived, the applicability to the new situation needs to be verified.

The exact characteristics of the vibration source, transmission path and receiver may not always be well defined. This is particularly so when humans are both the vibration source and receivers, and when the very presence of humans on the structure may change its dynamic properties, as is the case for crowd loading on assembly structures. Similar uncertainties may exist in other problems involving vibrations. Therefore, some form of reliability analysis may need to be carried out (ISO 2394).

6.2.2 Actions that vary with time and space

When the action varies both in time and space, vibration problems become very difficult to solve analytically. For this reason, suitable simplifications are often sought in order to eliminate or uncouple the space variable. The complexity of these problems is one reason why many of them have been treated by empirical methods, or by extensive use of measurements on similar existing structures.