INTERNATIONAL STANDARD

ISO 10137

First edition
1992-04-15

Bases for design of structures — Serviceability of buildings against vibration

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

Reference number
ISO 10137:1992(E)

Contents

		Page
1	Scope	1
2	Normative references	1
3	Definitions	1
4	Description of the vibration problem	2
5	Dynamic actions	3
6	Analysis of serviceability	5
7	Vibration criteria	9
8	Vibration control	11
9	Vibration isolation	12

Annexes

A	Dynamic actions	13
B	Examples of vibration analysis	17
C	Examples of vibration criteria	23
D	Examples of methods of vibration isolation	28
E	Bibliography	30

International Organization for Standardization
Case Postale 56 • CH-1211 Genève 20 • Switzerland

Printed in Switzerland

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

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

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 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 should 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 amplitudes (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 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 complexity of the structure or complexity of the loading;

f) social or economic consequences of unsatisfactory performance.

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Bases for design of structures — Serviceability of buildings against vibration

1 Scope

This International Standard gives recommendations on the serviceability of buildings against vibrations.

It covers three recipients of vibrations:

a) human occupancy in buildings and on pedestrian bridges;

b) the contents of the building;

c) the structure of the building.

This International Standard applies to buildings, pedestrian bridges and walkways found within buildings or connecting them. 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.

NOTE 1 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 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 2041:1990, *Vibration and shock — Vocabulary*.

ISO 2372:1974, *Mechanical vibration of machines with operating speeds from 10 to 200 rev/s — Basis for specifying evaluation standards*.

ISO 2394:1986, *General principles on reliability for structures*.

ISO 2631-1:1985, *Evaluation of human exposure to whole-body vibration — Part 1: General requirements*.

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 3898:1987, *Bases for design of structures — Notations — General symbols*.

ISO 3945:1985, *Mechanical vibration of large rotating machines with speed range from 10 to 200 r/s — Measurement and evaluation of vibration severity in situ*.

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

ISO 6897:1984, *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 8569:1989, *Mechanical vibration — Shock-and-vibration-sensitive electronic equipment — Methods of measurement and reporting data of shock and vibration effects in buildings*.

ISO 8930:1987, *General principles on reliability for structures — List of equivalent terms*.

3 Definitions

For the purposes of this International Standard, the definitions given in ISO 2041 and ISO 8930 and the following definitions apply. See also ISO 3898.

3.1 amplification: Increase of vibration amplitudes.

3.2 attenuation: Loss of energy along a transmission path.

3.3 broad-band 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: The centre frequencies of narrow bands, in which the energy of a spectrum is concentrated.

3.9 frequency response function: The frequency spectrum function of the output signal divided by the frequency spectrum function of the input signal. 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 equipment subjected to vibrations.

3.17 response spectrum: Maximum responses of a series of a 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 single pulse: Dynamic force of short duration compared with a natural period and not having repeated values in any direction.

3.21 source: Origin of the vibration.

3.22 spectrum: Plot of a time-varying function transformed into the frequency domain.

3.23 sustained vibration: Vibration having a duration of many periods.

3.24 sustainable vibration: Vibration that is acceptable in accordance with applicable criteria or long-term experience.

3.25 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 $2^{1/3}$.

3.26 transfer function: For a system, a mathematical relation in the frequency domain between the output and the input to the system.

3.27 transmission path: Path from the source to the receiver.

3.28 unbalanced force: Force originating from unbalance of a rotating mass at the source.

4 Description of the vibration problem

4.1 General

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 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 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 2394:1986, 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.

EXAMPLES

a) Inside sources of vibration:

- 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 adjoining parts of the building;

b) Outside sources of vibration can be found 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.

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.

EXAMPLES

- ground, air, or water;
- structural components (foundations, floors, columns, walls, etc.);
- non-structural components (pipes, partitions, etc.).

4.4 The 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

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 3945 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 need to 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

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 source, line source, area source, or moving sources should be considered as applicable. Because of the complexity of the problem, empirical methods based upon measurements are often required.

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

- 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 and subgrade conditions.

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

5.4 Impulsive sources

5.4.1 General

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

- 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).

NOTE 2 Further details will be given in ISO 4865 [1].

5.4.2 Impulsive sources in the ground

The main characteristic of the source is the energy released (blasting, pile driving). For blasting, the ground motion parameters for an explosive charge at a given distance can be obtained by empirical methods based on measurements resulting in ground motion bounds and estimated response spectra.

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 actions include

- 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 3 Accidental explosions or other types of accident which produce vibrations are not considered in this International Standard. They will be covered in ISO 10252 [2].

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.

NOTE 4 Some descriptions of dynamic actions are given in annex A.

5.5.2 Persons walking or running

The actions of one or more person(s) walking or running 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.

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.

5.6 Other actions

The actions induced in buildings by wind are the subject of ISO 4354 [3]. The actions by earthquakes are presented in ISO 3010 [4]. For serviceability problems, the return period for wind and earthquakes is generally shorter than that used in the design of the building for the ultimate limit state.

6 Analysis of serviceability

6.1 General

Although vibration analysis procedures are available that follow established principles of structural mechanics, certain simplifications and approximations are necessary in order to make the methods suitable for purposes of design. Sometimes two or more rational methods of analysis can be used or developed to achieve essentially the same results, namely a quantitative evaluation of the vibration levels for the structure. 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;

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

The values of actions, effects and criteria presented in this International Standard are representative values (see ISO 2394).

6.2 Methods of analysis

6.2.1 General

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.

Empirical methods are employed when the analytical solution of a problem is too complicated. 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.

EXAMPLES

Class A: a vehicle moving along a street; a person walking across a floor.

Class B: vibrations from a mounted piece of machinery; people jumping in unison on a floor.

Empirical methods: prediction of blasting vibrations; prediction of floor vibrations using the heel impact criterion; prediction of traffic vibrations.

6.2.2 Actions that vary with time and space

When the action varies both in time and space, these problems become very difficult to solve, requiring step-by-step numerical techniques such as dynamic finite element methods or solutions to complicated differential equations. 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.

6.2.3 Actions that vary with time

When the vibration source does not move in space, many analysis methods can be employed to solve vibration problems. Common solution techniques involve the derivation of an equivalent single-degree-of-freedom system or modal analysis for both continuous and discrete systems.

6.3 Evaluation of serviceability by calculation

6.3.1 General

For the determination of the vibration levels at the receiver, in general a two-step procedure is necessary:

a) mathematical modelling of the dynamic characteristics of the structure or component;

b) calculation of the response at the receiver, taking account of the vibration source characteristics.

The mathematical model can either be based on continuous mass distribution or discrete mass distribution (multi-degree-of-freedom system).

NOTE 5 Some examples of mathematical modelling and response calculations are given in annex B.

6.3.2 Damping for the serviceability limit state

Damping is an important property that governs the response at or near resonances. Damping depends on the materials employed, construction details, and the presence of non-structural components such as floor coverings, ceilings, mechanical equipment and partitions. Also, people will add to the overall level of damping. In general, damping cannot be calculated or predicted reliably, and experience with similar types of construction provides a likely source of appropriate damping data. Whenever possible, the damping data should be established by measurements. It should be noted that damping in buildings and building components is often amplitude dependent, and this should be taken into account when measured data is employed for calculating dynamic response at various amplitudes. A number of damping mechanisms can be identified (e.g. viscous, frictional, hysteretic and a combination thereof), and are modelled mathematically in different ways. Care should be taken in designating the damping mechanism and the limits associated with it.

NOTE 6 Specific examples of damping values can be found in annex B. Values of damping for various serviceability limit states need to be chosen to reflect, among other things, the level of response (e.g. earthquake versus traffic vibrations; cracked versus uncracked state for concrete).

6.3.3 Vibrations propagating in continuous media

Continuous media (or continua) are those physical systems for which the wavelength of the action is substantially shorter than the physical dimensions of the medium. For such cases, the calculation of transmission of vibrations needs to employ principles of wave propagation theory.

Calculations of vibrations propagating in continua need to consider the following:

a) coupling effects at source

b) material properties of transmitting medium

- mass (density)
- degree of saturation
- stiffness
- damping

c) geometric spreading of transmitting medium

- layering
- discontinuities and shielding
- geometric attenuation with distance from source

d) effects of soil; structure or fluid/structure interaction

e) transmission within building to receiver.

Layering and changes in geometry along the propagation path can lead to local amplification or attenuation in selected frequency ranges. For soils, the degree of compaction, saturation (e.g. location of the water table) and internal friction of the materials affect the attenuation characteristics of vibration with distance. In general, these situations are too complicated to be treated quantitatively, consequently they are assessed by empirical methods.

The transmission properties should be determined analytically or experimentally as functions of frequency (i.e. frequency response functions, transfer functions) or as functions of time (i.e. impulse response functions). Analytical methods should be verified as to their applicability to the given situation and the results should be checked subsequently. Approximate or empirical formulations for the transmission function may be used where their applicability to the given situation has been substantiated by appropriate theoretical or experimental methods. In addition to transmission properties of the ground, possible changes in physical characteristics such as densification, settlement, liquefaction and formation of slides need to be considered. These are generally associated with vibrations of large amplitude or of long duration.

Pressure pulses and total impulse from underwater detonation of explosives along the line of sight can be calculated from charge/distance relationships. Rock or soil cover and air bubble curtains result in substantial reductions of peak pressure, but they lengthen the pulse. Reflections from solid boundaries and the water surface boundaries, and diffraction around obstacles in the line of sight between source and receiver need to be considered.

6.3.4 Vibrations of discrete media

Media that can be discretized are those structures or components of structures that can realistically be modelled mathematically by discrete masses, stiffnesses and energy-dissipating devices. This permits the derivation of equivalent single-degree-of-freedom analogues or the consideration of normal modes of vibration, for which many solution methods are available. Whether a component can be discretized will depend on the particular application, however. For example, the response of a floor slab subjected to persons jumping on it may be carried out by the (discretized) approach of superposition of normal modes, whereas the same floor needs to be treated by a continuum approach (using wave propagation techniques) when high-frequency effects such as structure-borne sound or impact response are to be assessed.

6.4 Evaluation of serviceability by measurement

6.4.1 General

When the serviceability states in existing buildings are to be assessed by measurements, the measurement procedures, instrumentation and evaluation of results should be carried out according to the following recommendations, and in accordance with ISO 4866.

NOTE 7 Further details will be given in ISO 4865 [1].

6.4.2 Quantities to be measured

The vibration parameters measured and evaluated include displacements, velocity, acceleration and sometimes strain, all in conjunction with frequencies. The choice of measured parameters depends on the method of analysis used and the appropriate vibration criteria, although each quantity of acceleration, velocity or displacement can be derived from one another by integration or differentiation. It is generally preferable to measure the desired quantity directly or, alternatively, to integrate. Differentiation is usually not recommended for other than harmonic signals because of possible numerical inaccuracies.

6.4.3 Measuring apparatus and range of parameters

The measuring apparatus should be selected in consideration of the vibration parameter to be measured and the expected range of the parameter.

EXAMPLES

Commonly encountered ranges of measured quantities of building vibrations are:

a) frequency: 0,15 Hz to 100 Hz, except that for measuring impulsive responses it may be higher than 100 Hz;

b) accelerations: 10^{-3} m/s^2 to 10 m/s^2;

c) velocities: 10^{-5} m/s to 10^{-1} m/s;

d) displacements: 10^{-7} m to 10^{-3} m.

A basic vibration measuring set includes:

— measuring sensors,

— signal-conditioning circuitry,

— recording or monitoring instrument.

For complex vibrations, either analog or digital recording should be employed; direct analysis instruments may also be used. The measuring accuracy