INTERNATIONAL STANDARD

ISO 18649

First edition
2004-07-01

# Mechanical vibration — Evaluation of measurement results from dynamic tests and investigations on bridges

*Vibrations mécaniques — Évaluation des résultats de mesures relatives aux essais dynamiques et aux investigations sur les ponts*



Reference number
ISO 18649:2004(E)

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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 18649 was prepared by Technical Committee ISO/TC 108, *Mechanical vibration and shock*, Subcommittee SC 2, *Measurement and evaluation of mechanical vibration and shock as applied to machines, vehicles and structures*.

# Mechanical vibration — Evaluation of measurement results from dynamic tests and investigations on bridges

## 1 Scope

This International Standard provides methodology for the evaluation of results from dynamic tests and investigations on bridges and viaducts. It complements the procedure for conducting the tests as given in ISO 14963 and considers

— the objectives of the dynamic tests,

— the techniques for data analysis and system identification,

— the modelling of the bridge, and

— evaluation of the measured data.



NOTE 1 The evaluation may seek to define all of the dynamic characteristics of each mode of vibration examined, i.e. frequency, stiffness, mode shape and damping, and their non-linear variation with amplitude of motion. These can supply information on the dynamic characteristics of a structure for comparison with those assumed in design, or as a basis for condition monitoring or system identification.



The dynamic tests considered in this International Standard do not replace static tests.

This International Standard gives guidance on the assessment of measurements carried out over the life cycle of the bridge. The stages of the life cycle that are considered are

a) during construction and prior to commissioning,

b) during commissioning trials,

c) during specified periods throughout the life of the bridge, and

d) immediately prior to decommissioning the bridge.

This International Standard is applicable to road, rail and pedestrian bridges and viaducts (both during construction and operation) and also to other works, provided that they justify its application. The application of this International Standard to special structures (cable-stayed or suspension bridges) requires specific tests that take into account the particular characteristics of the work.

NOTE 2 Throughout this International Standard, “bridges and viaducts” are called “bridges”. The term “viaduct” is used only when it is necessary to distinguish between these.

## 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, *Vibration and shock — Vocabulary*

ISO 14963, *Mechanical vibration and shock — Guidelines for dynamic tests and investigations on bridges and viaducts*

ISO 14964, *Mechanical vibration and shock — Vibration of stationary structures — Specific requirements for quality management in measurement and evaluation of vibration*

## 3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 2041 and the following apply.

**3.1**
**buildability**
property of a structure that enables construction to proceed in a safe, timely and economic fashion

NOTE The buildability of bridges may require construction to proceed in a strong wind, so wind effects on vibration may need to be monitored.

**3.2**
**environmental compatibility**
environmental impact on a new bridge, which may need to be evaluated, involving wind effects, air noise and ground vibration

**3.3**
**serviceability**
limit state beyond which a structure no longer satisfies the operating requirements such that it is no longer fit for purpose



**3.4**
**monitoring**
programme of measurements, usually over a period of time, whereby changes in an appropriate parameter may be interpreted as indicating a change in the state of the structure

NOTE It is important to establish a benchmark and allow for changes attributable to cyclic environmental factors such as diurnal or seasonal changes of temperature and humidity.

**3.5**
**running safety**
property whereby traffic crossing a bridge at an appropriate speed is not deleteriously affected in maintaining direction or stability

**3.6**
**riding quality**
property whereby occupants of vehicles crossing a bridge at appropriate speed are not exposed to such levels of vibration as to adversely affect their comfort

## 4 Vibration measurement

### 4.1 General considerations

The guidelines for vibration measurements as given in ISO 14963 shall be observed and the quality requirements for these measurements as given in ISO 14964 shall be fulfilled. Measurements may be carried out on bridges under construction and in commissioning and on bridges in service.

## 4.2 Monitoring of a bridge during construction and for commissioning

### 4.2.1 Objectives of vibration monitoring

Figures 1 and 2 illustrate the relationships between the various stages involved in vibration monitoring.

The objectives of vibration monitoring shall be specified as follows:

a) evaluation of the accuracy and buildability of construction;

b) evaluation of structural performance during construction and upon completion;

c) assessment of the safety of the bridge during construction and upon completion;

d) evaluation of serviceability upon completion;

e) evaluation of environmental compatibility;

f) determination of the initial characteristics of vibration for maintenance and for calibration of the numerical model of the bridge in service;

g) feedback to structural design.

Uncertainty of results in each process of measurement and evaluation cannot be avoided and there is a possibility to include uncertainty as shown in Figure 1. Therefore, reduction and qualification of measurement uncertainty and error are needed in the process.



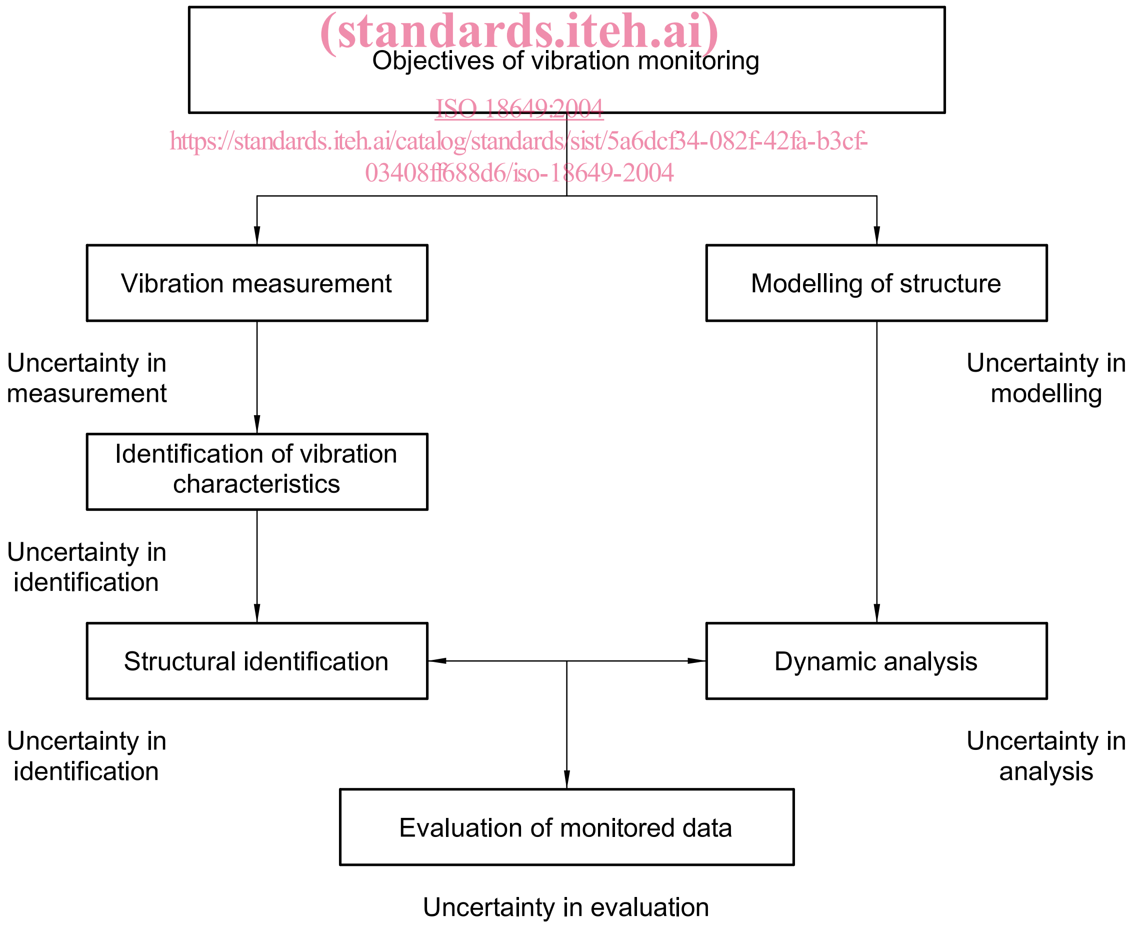


**Figure 1 — Flowchart of vibration monitoring of a bridge**

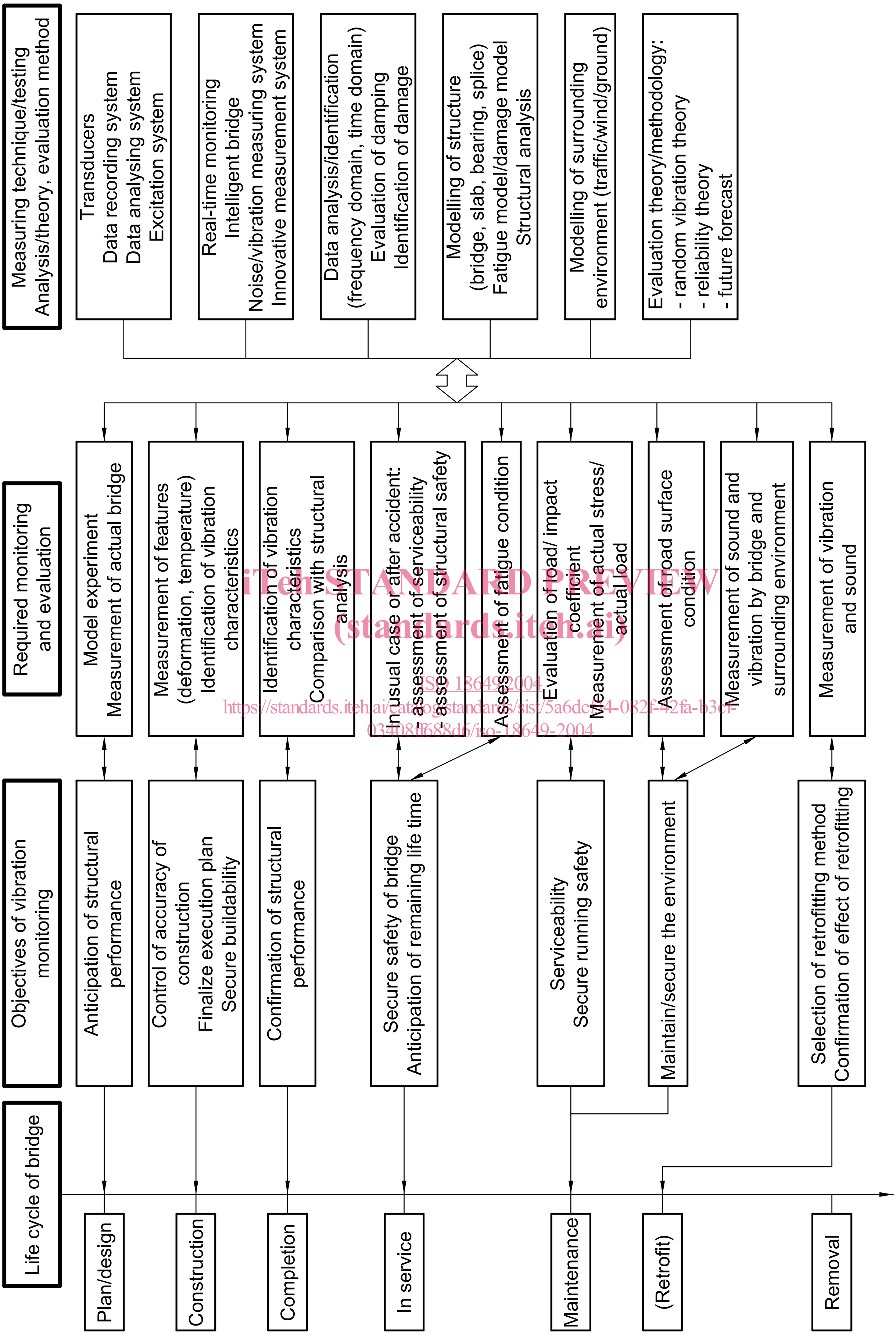




**Figure 2 — Overview of vibration monitoring of a bridge**

 

#### 4.2.2 Evaluation of construction management

##### 4.2.2.1 General

Vibration measurements on bridges may be conducted during construction. For example, vibration tests on cables of cable-stayed bridges or suspension bridges are used to control the tension of the cables. In order to control the profile of the bridge under construction, measurement of the vibration of cables is required. Dynamic measurements may also provide an indication of when high vibration levels will have an adverse effect on construction.

##### 4.2.2.2 Evaluation of cable tension

Dynamic characteristics are greatly influenced by the support conditions. Cable tension of a cable-stayed or suspension bridge is one of the main parameters for construction management. Vibration of cables is easily measured for the determination of the natural frequency of transverse vibration. This depends upon cable tension and is given by a well-known equation. In this case, the numerical model will need to consider bending rigidity and the end support of the cables.

##### 4.2.2.3 Evaluation of buildability of construction

Vibration measurements can provide the required information to determine when construction work is either unsafe or the quality control is likely to be adversely affected. If the bridge vibration and wind and earthquake excitation are continuously monitored, the decision can be made when an allowable limit is exceeded.

#### 4.2.3 Characteristics for the evaluation of structural performance



##### 4.2.3.1 General

The natural frequency, damping and dynamic response of the structure and the surrounding area and sound propagation from/through structure are measurable characteristics which can be used for the evaluation of structural performance.



##### 4.2.3.2 Natural frequencies and mode shapes

The natural frequency and its mode shape are easy parameters to measure. The support conditions and the temperature of the structure are major factors influencing natural vibration; hence they should be monitored before and after construction. Geometrical non-linearity of flexible bridges and material non-linearity of superstructures on the substructure are aspects that should be considered. These aspects are as follows:

— natural frequencies;

— modal shapes;

— movements of shoe and boundary conditions of structures;

— geometrical non-linearity effects of the structure;

— material non-linearity of the ground;

— effects of isolator and vibration control devices;

— effects of temperature.

NOTE Isolator and control devices to reduce vibration can also introduce non-linearities.

#### 4.2.3.3 Damping

The damping coefficient, or logarithmic damping ratio, can also be measured. The measurement of damped free vibration produced by stopping the forced vibration provides a direct measurement of damping characteristics, at least for the fundamental mode. Amplitude and temperature dependencies are important factors for damping measurement. It may be necessary to consider the effects of support condition and isolation devices. When damping characteristics are required for large-amplitude motion, forced vibration tests that generate high-amplitude vibration are appropriate. Evaluation for strong earthquakes or wind may require damping values for large-amplitude motion.

Elements affecting the damping characteristics of bridges are as follows:

— aerodynamic and hydrodynamic effects;

— connections and joints;

— bearings and shoes;

— pavement (rheology of materials);

— effects of substructures;

— effects of the foundation.

The amplitude dependencies of frequencies and damping characteristics of bridges require careful analysis of the data. Different damping characteristics will be provided by different structural types and in different locations, so the overall damping effect is the integral of these elements.



#### 4.2.3.4 Characteristics of the dynamic responses of a structure with the surrounding media

The measurement of dynamic response may involve strain, acceleration, velocity or displacement. It is also important to consider boundary conditions. The results from ambient vibration tests or impact tests may not be appropriate for some dynamic response evaluations because of the small amplitude of the loading. Using forced-excitation tests, resonance response curves can provide data for larger amplitude motion. Accurate analysis of ambient vibration for small amplitudes may be suitable for the structural health monitoring of bridges. Tests using moving vehicles can give the dynamic response related to the speed and pattern of the vehicles. Fatigue analysis requires dynamic response as a stress range histogram. The points to be considered are as follows:

— accuracy of the ambient vibration analysis;

— impact test for the dynamic property of the surrounding media;

— effects of water or tidal flow;

— excitation method.

#### 4.2.3.5 Sound radiation around/through the structure

Microphones placed on the surrounding ground can detect the sound radiation from bridges due to moving vehicles. Characteristics of sound propagation are used to evaluate the environmental effects on the surrounding area. Parameters to be measured are as follows:

— sound level;

— sound frequency;

— traffic density;

 

— traffic speed;

— types of vehicles;

— impulsive effects;

— roughness of road/track surface;

— ground stiffness and its interaction with the substructure.

#### 4.2.4 Assessment of safety during construction and upon completion

##### 4.2.4.1 Confirmation of design for earthquake performance

Vibration monitoring is needed for safe construction in a highly seismic area. Depending on the data, engineers can assess the risk during construction, and this may influence the construction. Data on vibration under severe loading conditions are important. The assessment is based on

— characteristics of natural vibration and its damping,

— dynamic response characteristics,

— reinforcement of the structure,

— isolation system on the bridge, and

— diagnosis of structural health after a disaster.



In the design process for earthquake performance, the numerical model for dynamic response should be constructed by a combination of the total/part of the superstructure used in static design and the substructure including the basement and surrounding ground. These data should be utilized in the evaluation analysis.



Measurement of the natural vibration of the substructure after its construction and the non-linear vibration properties of the ground should be taken into account. Evaluation of the damping characteristics is accomplished by comparison of the measured data with the assumed values used in the design process. Support condition and amplitude dependency should also be taken into account. The effect of temporary structures and the pavement on vibration properties should also be considered.

##### 4.2.4.2 Confirmation of design for wind

The dynamic response for wind can be measured and compared with assumed values. Assumed values may be obtained through experiments in a wind tunnel as a part of structural design process. Measured data can include the effects of the velocity and direction of the wind and its amplitude dependency. After analysing all these effects, damping devices may be considered.

##### 4.2.4.3 Confirmation of fatigue design

Fatigue design considers the dynamic stress range of members and the number of cycles encountered. In this case, the stress range is given by the sum of the static stress and the coupling effect with a moving vehicle. Monitored data for actual stress should be compared with the assumed values used in fatigue design. The dynamic amplification factor to amplify the static stress range is used and it depends on the road/track profile and travelling pattern of the traffic load. The coupling effects with vehicles are needed to monitor the structural health of the bridge. Non-stationary vibration due to irregular undulation of the surface of the track and road can be important.

#### 4.2.5 Serviceability of a completed bridge

The vibration perception of pedestrians, vibration effects on moving vehicles, and the comfort of passengers are part of potential serviceability problems. Vibration monitoring is undertaken to evaluate these effects and the design should be checked and necessary measures should be considered.

In the evaluation of the vibration perception of pedestrians, the amplitude of the dynamic response as well as the frequency of vibration should be considered. In the evaluation of the effects on moving vehicles and the comfort of the passengers, the amplitude of the dynamic response on the floors and wheel axles of the vehicle should be taken into account.

In the comparison between measured data and numerical results from modelling of the moving loads, coupling vibration effects should be taken into account. Bridge vibration due to moving vehicles and the comfort of passengers are also problems that should be considered for serviceability.

#### 4.2.6 Evaluation of environmental compatibility of a completed bridge

Environmental vibration, noise and change of wind direction should be taken into account in the evaluation of environmental compatibility. Monitored data are used to analyse these effects and are compared with the dynamic characteristics of the structure. Necessary modifications may be required depending on the results. Numerical simulation of the propagation of ground vibration and sound radiation may be used to identify the level of those effects.

#### 4.2.7 Determination of the initial vibration characteristics of a completed bridge



Long-term monitoring will start after construction and the initial values of vibration characteristics are required to monitor changes in parameters due to deterioration or damage. The effects of deterioration or damage on the vibration characteristics are generally small, so an effective method to extract the required information about damage should be used. Local excitation and the application of beating phenomenon due to those small differences of modal parameters are useful methods.



#### 4.2.8 Feedback to overall performance

Data given through the above-mentioned evaluation should be fed back to design engineers to apply to future designs. Classification of the data is also helpful when the data are used in the future for the design of all types of bridges.

### 4.3 Monitoring of a bridge in service

The objectives of vibration monitoring of a bridge in service are

- evaluation of the travelling load,
- evaluation of the structural performance,
- evaluation of wind effects and hydrodynamics,
- assessment of safety,
- assessment of serviceability, and
- assessment of environmental compatibility.

Normal and emergency monitoring of bridge vibration are used depending on the maintenance management of the bridge. Detailed analysis to identify the damage and defects is needed. Traffic conditions and the roughness of road and rail surfaces, and wind and hydrodynamic effects will have a significant impact on the fatigue stress. Dynamic effects should be monitored through measurement.

 