An Approach to a vibration standard for buildings

Rainer, J. H.

National Research Council Canada
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Institute for Research in Construction
Institut de recherche en construction

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by J.H. Rainer

Appeared in
C.S.C.E. 1986 Annual Conference
"Specialty Conference on Computer Applications"
Toronto, Ontario, May 12-16, 1986
Proceedings, Vol. 4, Structures, 19p.
(IRC Paper No. 1387)

Price $2.00

NRCC 26052

Canada

SHORT ABSTRACT

A framework is presented for establishing a vibration standard for buildings. Its major components comprise a description of the source function, the response determination at the receiver, and the criteria of acceptable vibration applicable at the receiver.

COURT RÉSUMÉ

Cette communication propose d'établir une nouvelle norme de vibration pour les bâtiments qui serait principalement constituée d'une description de la source de vibration, d'une méthode pour calculer la réponse du récepteur et de critères de vibration acceptables au niveau du récepteur.

AN APPROACH TO A VIBRATION STANDARD FOR BUILDINGS

RAINER, J. Hans

ABSTRACT

It is proposed that a new vibration standard for buildings be subdivided in terms of source, transmission path, and receiver. Vibration problems would be classified according to methods employed to effect a solution. Detailed descriptions could then be allocated for common vibration sources and criteria applicable to buildings.

The vibration source is described as a force or displacement function; this includes excitation from people and machinery within buildings, traffic and construction activity propagated through the ground outside buildings, and fluid flow and impulse forces transmitted by air or water. The properties of the transmitting medium are described by the frequency response function, which can be calculated or obtained experimentally (in some cases wave propagation methods may be required). Response calculations are carried out according to standard mathematical techniques in the time or frequency domain. The applicable criteria are associated with the receiver of the vibrations, that is, the occupants of buildings, the contents, or the structure itself. Criteria, if available, are taken from national or international standards; others may need to be developed. A list of topics needing further study is provided.

1. INTRODUCTION

Vibrations occur everywhere in the natural and man-made environment. The earth trembles as a result of a rupture in its crust, a volcanic eruption, sea waves pound the shore, and wind moves water, trees and buildings. Machinery and people in buildings cause floors to vibrate, and rail and road traffic can shake entire buildings, often to the annoyance of occupants. But unperceived vibrations may also be detrimental to the proper functioning of such contents of buildings as sensitive instruments or certain industrial processes. While vibrations are rarely a safety hazard (with the obvious exception of large earthquakes and high winds), they can result in loss of function or serviceability ranging from simple annoyance to loss of economic benefits.

Problems with vibrations in buildings have generally been treated on an ad hoc basis after the problem has been encountered. As structures become lighter with the more efficient use of materials, however, vibration sources increase. At the same time, demands for vibration limits become more stringent and incorporation of vibration criteria into the design process becomes more important. A number of organizations, therefore, have recently addressed aspects of vibration problems in buildings and other structures. Among them are 65MDB Committee of RILEM, Task Group V/4 of CEB, and Working Group WG2 of ISO/TC98/SC2. The approach presented here has been prepared for submission to the ISO working group, "Vibration Criteria for Serviceability of Structures." It is desirable that the outline of such a standard should be presented to interested investigators, researchers, and other users so that they will be encouraged to contribute their expertise as well.

Vibration problems tend to be very complicated, and some may not be amenable to a full quantitative solution with a given set of resources. Simplifying assumptions and empirical methods often have to be employed. Methodologies and specialized techniques for the prediction of vibrations will continue to be developed so that a standard in this field will continue to be updated periodically.

2. OBJECTIVES OF A VIBRATION STANDARD

The objectives of a vibration standard for buildings are many. It should:

1) be able to deal with all cases within its scope;
2) reflect the current state of knowledge;
3) be sufficiently flexible to accommodate developments in the near future and act as a catalyst for the development of improved methods or techniques;
4) be useful: usefulness depends on the particular perspective of the users of the standard, who include
    a) international or national standards-writing bodies,
    b) vibration engineers,
    c) building designers and practitioners,
    d) consumers or users of the end product.

It can readily be appreciated that the degree of detail and sophistication required in a standard varies for each category. Nevertheless, a common framework should be useful.

An important role of the proposed standard is to standardize the source function for different actions and the criteria that apply to various receivers. The word "action" derives from the International Standard ISO/DIS 2394 (1) and is used as a general term to describe the source (forces or loads, deformations, temperature changes, etc.).

For the purposes of this proposed standard the term "building" is used in the sense defined in the 1985 National Building Code of Canada: "any structure used or intended for supporting or sheltering any use or occupancy."

3. OUTLINE FOR A VIBRATION STANDARD

3.1 Serviceability Limit State

As most vibration problems in buildings do not involve the immediate safety of the structure, the applicable design basis is the serviceability limit state (2); the materials usually behave elastically, and in current practice the load factors and resistance factors for this limit state are taken to be 1.0 (3). This implies that the given loads and criteria are treated as known deterministic quantities. Thus, no specific allowance is made for variability of dynamic loads, material properties, or the criteria that pertain to the sensitivity of the receiver. For certain cases it would be desirable to account for such variables, but neither the necessary simple methodology nor the required data on variability of loads (the structure and the criteria) are as yet available, although guidelines for their development have been addressed (1,2).

3.2 Structure of Proposed Vibration Standard

The structure of the proposed standard is outlined in Table 1. In physical terms the problem concerns a vibration source that affects a receiver (i.e., a person or an object) at some distance from the source; this vibration can be acceptable or objectionable. The prediction model thus needs to include 1) the source, 2) the transmitting medium from the source to the receiver and the determination of the resulting vibrations there, 3) the applicable criterion at the receiver. Using these major subdivisions, it is desirable to proceed in two stages.

Stage 1 is a general statement of principles for the proposed standard. It consists of a classification of available methods and the type of information required to solve vibration problems in buildings. It should prove useful to standards-writing bodies and other users by pointing out consistent sets of data that need to be considered. It could serve as an inspiration for development of new methods of solving vibration problems.

Stage 2 provides specific values for the various sources of vibrations and applicable criteria for the receivers in buildings. This would be of major interest to designers and analysts in solving vibration problems during the design process or in retrofitting existing buildings.

3.2.1 Stage 1: Classification

The classification scheme for vibration problems leads from the general type of solution to a simplified one, then to the approximate one. Three categories are formed according to type of information available or desired, as outlined in Table 2.

Category A comprises a general statement of a prediction model. The source description can be a function of time and space, possibly dependent on the response of the supporting medium or structure. This concerns dynamic sources, either stationary or moving, that interact with the supporting medium and thereby modify the forces applied to the structure. Examples are sprung vehicles moving on flexible structures or on the ground.

Determination of the response at the receiver employs methods of mechanics and mathematics; in practice, however, they may be difficult to carry out. The receiver may be in a fixed location or in a number of locations. For the latter, a probable worst case response would need to be established.

The criteria that apply to the receiver need to be determined by experimental or theoretical means or selected from existing international or national standards.

Category B comprises cases in which the source is stationary in space, or can be considered stationary. Various possible combinations of source descriptions, response determinations at the receiver, and applicable criteria are presented in Table 2. They need to be consistent in terms of variables employed at each step, from source to receiver to applicable criteria. Simplified models based on principles of mechanics such as equivalent single-degree-of-freedom models are included. The conditions that need to be satisfied in such simplified models should be described.

Category C encompasses cases that can be classified as empirical and are generally based on correlations with observed behaviour rather than on principles of mechanics. Examples include simple blasting criteria for the onset of building damage, and floor vibration criteria for walking (4,5). Empirical criteria should have well-defined scope, should confirm field observations, and state limits or ranges of applicability. The reliability and variability of the results should be determined whenever possible.

Although the listing of prediction models is generally in decreasing order of sophistication, it does not necessarily follow that the same rank ordering applies to the appropriateness of application to a specific problem or to the order of the degree of accuracy of the results that can be expected. Simple methods can often be more effective than highly sophisticated ones, although the latter may sometimes be necessary.

3.2.2 Stage 2: Specific Design Information

Source functions or dynamic actions: Source functions are specific to particular situations, including activity, machinery, traffic, small earthquakes, wind, and impulse sources such as blasting (Table 3). For some of these, specific quantitative values exist, but for others they need to be developed.

Response calculation: Determination of the response at the receiver arising from an action at the source can be complicated, and mathematical modelling of the problem generally requires skill and judgement. Methods of vibration analysis are available that employ differential equations, numerical techniques such as finite element methods, or modal analysis. Simplified methods such as equivalent single-degree-of-freedom oscillators are particularly useful in the design phase when such approximations are appropriate. The mathematical model needs to account for special features such as damping devices or vibration isolators for either components or the entire building. These analytical techniques would not be standardized unless the method of solution were to form part of an empirical procedure. Brief descriptions of analysis methods are presented in Table 4.

Vibration criteria: Vibration criteria, which are associated with the receiver, can be divided into three major classes: human occupancy, building contents, and building structure. Each can be further subdivided as summarized in Table 5. The criteria pertaining to various receivers are taken from available standards, but their applicability to a specific situation has to be carefully assessed. The suggested criteria at this early stage of development are illustrative only and may not assure satisfactory performance in all situations.

4. REMEDIAL MEASURES

A vibration standard should concern itself with measures to alleviate unacceptable vibration levels in existing buildings. This would involve the following steps:

1) assessment of existing vibrations;
2) comparison with acceptable criteria and establishment of desired vibration levels;

3) implementation of necessary changes;

4) verification of effectiveness of changes.

The recommendations, except for the criteria, would be advisory only.

4.1 Assessment of Existing Vibrations

This aspect usually involves vibration measurements taken at or near the source or the receiver and analysis and interpretation of the results. Such a program can vary from simple determination of vibration levels by means of a hand-held vibration meter (or observing the effects of vibrations) to full-scale determination of modal properties involving dynamic excitation tests. In general, such work must be carried out by specialists. Few standards for measurement of structural vibrations exist, although some are now being developed at national and international levels.

4.2 Comparison with Criteria

If the criteria of acceptability have a rational basis, they can be used in assessing existing vibrations. Care must be taken not to misuse those associated with a specific type of excitation or environment, or those forming part of an empirical procedure, e.g., criteria associated with the heel impact test for assessment of floor vibrations, or criteria associated with onset of blasting damage for structures. Analysis of existing vibration levels and the desired criteria will indicate the necessary changes in vibration levels and vibration characteristics.

4.3 Implementation

Once the desired reduction in vibration levels has been established, the method of achieving it has to be devised. This can take the form of additional damping, changes in the frequency of excitation and the resonance frequency of the structural system, moving or removing the source or receiver, and adding (or removing) stiffness and mass. The effect of possible remedial measures needs to be carefully assessed so as not to cause inadvertent deterioration in the vibration environment.

4.4 Verification

Verification of the effectiveness of any recommendations is important.

4.5 Retrofit

Where the design against vibration is not clearly a practical one or the uncertainties are too great, it may be desirable to proceed on the understanding that further measures may have to be taken if the vibration behaviour of the finished structure should prove unsatisfactory. This can be an acceptable design strategy. By providing appropriate access routes or mountings for possible damping devices one can often simplify the implementation of needed retrofit measures.

5. VIBRATION DESIGN GUIDELINES

The following examples illustrate how existing vibration guidelines can fit into the proposed scheme.

5.1 Floor Vibrations from Coordinated Activity

The forces F(t) generated by coordinated activity such as jumping, dancing, and excercises can be expressed by (6,7):

$$F(t) = \sum_n \alpha_n w_p \sin(2\pi nf + \phi_n) \tag{1}$$

where α_n = dynamic load factor,

w_p = weight of people,

f = frequency of excitation,

ϕ = phase angle,

n = integer referring to the harmonic component.

Suggested values of α_n and w_p are given in Commentary A, Supplement No. 1 to the National Building Code of Canada 1985 (6).

The response has to be evaluated at the actual location, or hypothetical receiver. A general description of the dynamic floor properties would consist of the frequency response function (8), but for a full solution of the vibration signature the convolution between forcing function and entire impulse response function of the vibrating structure is required. For most practical problems, however, knowledge of the natural frequency and damping of the equivalent single-degree-of-freedom oscillator of the lowest few modes suffices; often only the fundamental mode needs to be considered. The method presented in Commentary A (6) employs the latter simplified approach.

Criteria that express the limits of acceptable vibrations are not always well defined. Not only does acceptability change with type and duration of vibration, but it also depends on the environment in which the vibrations are perceived. This is reflected in the criteria presented in References 6 and 7, where 5% gravity is suggested for acceptability in active occupancies; for normal residences 0.5% g is suggested for walking vibrations occurring on an intermittent basis (4).

Other criteria have recently been presented: ANSI S3.29-1983 (9), BS 6472 (10), and the draft standard ISO/DIS 2631/2 (11). In terms of the proposed standard, the source function would be given by item 1b, Table 3, and the criteria by source 1b, Table 5, under Occupancy. Concerning the classification of the solution method, Stage 1, this vibration guideline would correspond to item B1 in Table 2, for which the frequency response function is the simplified, equivalent single-degree-of-freedom oscillator model for the floor.

5.2 Vibrations of Footbridges

A method of determining the adequacy of vibrations of footbridges over highways is contained in the 1983 Ontario Highway Bridge Design Code Commentary (12) and in the British Standard BS 5400 (13). A source function, F, in newtons is suggested,

$$F = 180 \sin wt \qquad (2)$$

It is not, however, used explicitly. Instead, a response calculation for acceleration, a, is employed as follows:

$$a = 4\pi^2 f_1^{\,2} w_s K \phi \qquad (3)$$

where f_1 = first natural frequency,

w_s = maximum static superstructure deflection (m) due to a vertical concentrated force of 700 N,

K = configuration factor to account for continuity,

a = acceleration (m/s^2),

ϕ = response amplification factor, in graphical form.

The resulting acceleration is compared with the acceptability criterion. For example, BS 5400 (13) specifies $\frac{1}{2}\sqrt{f_1}$ (m/s^2) for highway footbridges, whereas OHBC (12) specifies half that value. For footbridges that connect buildings or carry pedestrians within buildings, however, more stringent requirements similar to those applicable to floors are needed.

This procedure can be rationalized to conform to the proposed standard where the source function for walking may be found in Table 3, item 1a), the criteria in Table 5 under Occupancy and source 1a). The method of response calculation would be carried out according to Table 2, item B1. Again, an equivalent single-degree-of-freedom model is used as a simplified frequency response function to represent dynamic properties of the span. The basis for this rationalization has been described (14).

5.3 Blasting Criteria for Basement Walls

From the amount of explosive, W, per ignition delay at the source, the peak particle velocity, V, at a certain distance, R, can be predicted according to the empirical relation

$$V = c\left(\frac{R}{W^a}\right)^b \qquad (4)$$

where a, b, and c are constants.
This should not exceed a specified peak particle velocity, commonly taken as 50 mm/s for ordinary building foundations; for more detailed criteria, see Reference 15. For historic buildings smaller values are indicated. Because of the large possible scatter in the results, a monitoring program is frequently employed.

In terms of the proposed standard this is an empirical procedure and thus falls under category C, Table 2. The source description is given in Table 3, item 4a, the criteria in Table 5, item 4a, for the various types of receiver. For other than basement walls, structural amplification factors need to be applied to the ground motions in order to obtain the vibration levels at the various receiver locations in the building.

6. FURTHER RESEARCH NEEDS

Although there is available considerable information suitable for use in establishing a vibration standard for buildings, some areas require more study. These are indicated below, subdivided for the proposed standard.

6.1 Source Functions or Dynamic Actions

1. Forces generated by human activities; additional information has recently become available (16-18).
2. Source functions for various types of road and rail traffic.
3. Dynamic wind loading functions for buildings.

6.2 Response Calculation

1. Improved methods for modelling the ground as a propagating medium for vibrations.
2. Ground-building coupling effects.
3. Simplified methods of evaluating transmission of vibrations within buildings.

6.3 Criteria

1. Verification of applicability of proposed standards (ISO, ANSI) for different occupancies and vibration characteristics (duration, composite signals, etc.).
2. Vibration criteria for certain classes of building contents (e.g., electron microscopes, photographic processes, computers, etc.). Some are available from manufacturers or from previous experience (19,20), but they have not been codified. For other situations existing criteria are perhaps too sweeping (21) or unavailable.
3. Evaluation of fatigue behaviour of common building materials, old and new. Fatigue may be important for large numbers of loading cycles.
4. Further rationalization of empirical criteria such as those for blasting and construction activity.

6.4 General

1. Integration of the various components into a coherent vibration standard.

2. Design-oriented methods for certain vibration problems.
3. Development of appropriate load and resistance factors for the serviceability limit state.

7. SUMMARY AND CONCLUSION

A framework has been presented for the establishment of a vibration standard for buildings. The major components include a description of the source function, the response determination at the receiver, and the criteria of acceptable vibration applicable at the receiver. After a broad classification based on the type of information needed, specific subdivisions of the types of source are considered: people, machinery, traffic, small earthquakes, impulse sources, and flow-induced vibrations. Receivers constitute occupants and contents of buildings, and the building structure itself. Specific examples of existing vibration guidelines are presented in the context of the proposed standard, and areas are indicated for which additional information is needed.

8. ACKNOWLEDGEMENT

Acknowledged are fruitful discussions with S. Kraemer, D.E. Allen, and members of the International Standards Organization, working group ISO/TC98/SC2/WG2.

This paper is a contribution from the Institute for Research in Construction, National Research Council of Canada.

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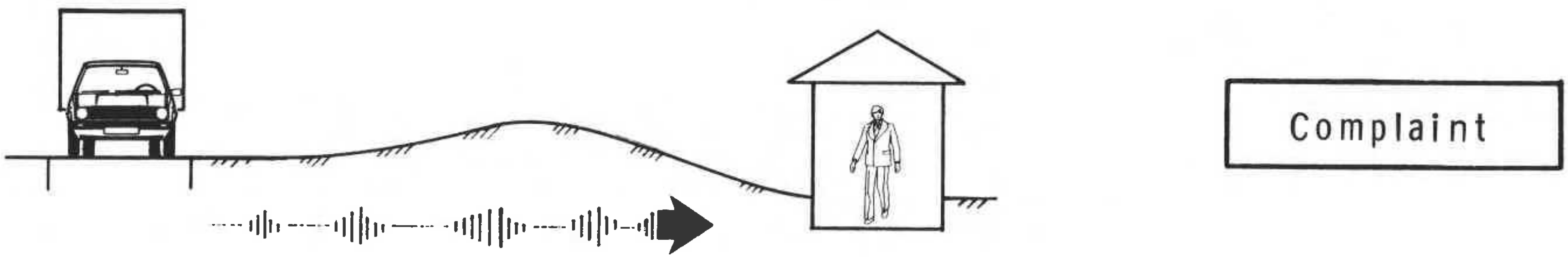
Table 1. GENERAL DESCRIPTION OF VIBRATIONS IN BUILDINGS

Physical State

Vibration source	Supporting structure or transmitting medium	Receiver	Adequacy of vibration environment



Mathematical Model

Source description:	Dynamic model:	Determination of response at receiver:	Applicable criteria:
Action	Mathematical model of dynamic properties for supporting and transmitting medium	Response calculation at receiver by analytical or numerical methods	Comparison of response with serviceability limit state

Table 2. CLASSIFICATION OF METHODS FOR EVALUATING VIBRATIONS FOR THE SERVICEABILITY LIMIT STATE

Source Description	Dynamic Model	Determination of Response	Criteria
Category A			
Force or displacement source is a function of time and space, may depend on the response of the supporting medium	Dynamic model of continuum in 1, 2, or 3 dimensions (wave propagation, continuum dynamics)	Evaluation of response at receiver (solution of differential equations, numerical methods)	Appropriate response criteria
	Discretized representation of transmitting medium (F.E.M. method, lumped parameter etc.)	Evaluation of response by numerical methods	
Category B			
Force or displacement source is a function of time			
1. Dynamic force functions	Frequency response functions, impulse response function	Numerical solutions, Closed form solutions, Convolution integral	Peak or rms criteria
2. Dynamic displacement functions	Transfer function H, frequency amplification function	Numerical solutions, Closed form solutions, Convolution integral	Peak or rms criteria
3. Amplitude or power spectrum of source	Amplification function $\|H\|$ or $\|H\|^2$	Amplitude or power spectrum of response	Narrow band or broad band criteria
4. Source vibration level (rms, peak)	Amplification factors	Response level (rms, peak)	Response criteria in rms or peak levels
5. Energy imparted at source	Propagation or attenuation laws in medium	Closed form or numerical solutions	Acceptable energy levels or vibrations at receiver
Category C			
Specific source descriptions	Empirical method of response evaluation		Empirical criteria

Table 3. DYNAMIC ACTIONS OR SOURCE FUNCTIONS FOR BUILDING VIBRATIONS

Source	Information
1. People:	
a) walking, running	Time history; sinusoidal force functions
b) coordinated activity	Time history; sinusoidal force functions
c) isolated jumps	Time history; triangular force pulse; amplitude P_{max}, duration t_d; impulse
2. Machinery:	
a) rotating	Sinusoidal force function
b) reciprocating	Sinusoidal force components, spectrum
c) repetitive impacts	Force pulse; repetitive pulses; impulse
3. Traffic:	
a) exterior to building	Force or deformation time history; source spectrum
b) interior to building	Force or deformation time history; source spectrum
4. Impulsive Source:	
a) seismic and paraseismic	Displacement-time history; source functions; ground motion spectrum; peak ground motion values; energy release
b) structure borne	Force or displacement time history; impulse; peak levels
c) air pressure	Source spectrum; time-pressure variation
d) water blasts	Energy release at source
5. Fluid flow	
wind	Wind spectrum; statistical properties of source function; vortex generation relations

Table 4: SOME METHODS OF VIBRATION ANALYSIS

Supporting or Transmitting Medium	Method of Analysis
Structures or structural components	Superposition of normal modes of vibration; equivalent single-degree-of-freedom response; force vibration response using frequency response function; impulse response; wave propagation methods; empirical methods; random vibrations
Ground and ground-structure interaction	Attenuation laws of continuum mechanics; wave propagation; discretization methods (F.E.M., lumped parameter); modal response to band-limited excitation; frequency response functions; modal response using actual or simulated ground motions or response spectra; simplified methods (impulse response, equivalent S.D.F.); empirical methods
Fluids	Random vibration methods; wave propagation methods; aerodynamic admittance functions; interaction of vortex shedding with structural response; simplified methods; empirical methods

Table 5: SUGGESTED VIBRATION CRITERIA

Source	Receiver									
	Occupancy			Building Contents		Building Structures				
	Quiet	Regular	Active	Sensitive	Normal	Foundation	Beams Floors	Walls etc.	Sensitive Parts	Historic Buildings
1. People:										
a) walking	Curve 1	Curve 2-4 or empirical	Curve 50 or Ref.6							
b) coordinated activity										
c) isolated jumps		Curve 16	Curve 128							
2. Machinery:										
a) rotating b) reciprocating c) impacting	Curve 1	Curve 2-4	Curve 50	Instrument or process criteria or previous experience		Maximum stress or strain (including fatigue); empirical criteria				
3. Traffic:										
a) exterior b) interior	Curve 1	Curve 4	Curve 50							
4. Impulse Source:										
a) paraseismic b) structure borne	Curve 1	Curve 16	Curve 128							
c) air pressure d) seismic e) water blasts										
5. Fluid Flow: (wind, water)										

NOTE: All references to Curve X refer to multiplier X to the base curve given in ISO/DIS 2631/2 (11)

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