Structural Engineering Documents

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VIBRATIONS IN STRUCTURES

Induced by Man and Machines

International Association for Bridge and Structural Engineering IABSE
Association Internationale des Ponts et Charpentes AIPC
Internationale Vereinigung für Brückenbau und Hochbau IVBH

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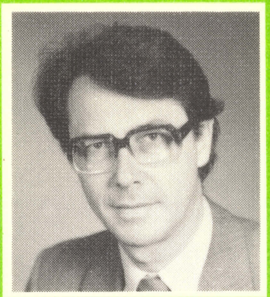

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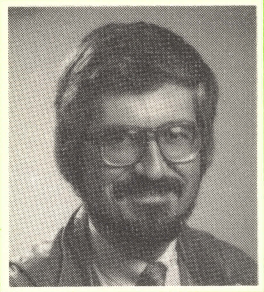

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PREFACE

Increasingly, the practising engineer sees himself confronted with the effects of loads on a structure which vary with time, that is to say, which are dynamic by nature. The following are some of the main reasons:

- Structures planned or constructed today are often more prone to vibrations than those of former years. Because of the use of high-quality material and the exploitation of their strength, larger and larger spans are chosen while the thicknesses of beams and slabs have kept decreasing. Hence, of the total load – mostly assumed to be non-dynamic – the dead or permanent load constitutes a smaller part. Slender structures with a small stiffness and a low mass are more prone to vibrations than more squat and stiffer structures with a larger mass. If such a modern-type structure is exposed to dynamic loads, considerable vibration problems can arise.
- Several dynamic actions have increased in intensity latterly. For example, rationalization has led to the installation of more efficient machinery in manufacturing plants. Efficiency is enhanced by, for instance, a higher production frequency which may raise the demands on the structure to sustain higher dynamic loads.
- Also, the demands on a structure for serviceability to the user have been increased. The environmental stress level being generally higher, people have become more sensitive to vibrations. Therefore, normative values for admissible vibrations are becoming stricter, and vibration amplitudes must be reduced. There is also a higher demand from the point of the precision of certain manufacturing processes (e.g. milling, weaving) requiring a lower vibration level of their machines.

Apart from this, new engineering tasks have called for a more exact consideration of loading types and of the dynamic behaviour of certain structures. This has been the case, for example, with offshore structures subject to high dynamic wave loads and with nuclear power plants required to remain safe under exceptional loading such as earthquakes. These kinds of problems, however, have evolved into comprehensive subjects of their own and are not treated here.

This book is more or less limited to vibrations of structures as excited by human motion or machine operation. *Man-induced* vibrations may arise from walking, running, skipping, dancing, etc. They occur mostly in pedestrian structures and particular buildings, such as office buildings, gymnasia and sports halls, dancing and concert halls, spectator galleries, etc. Existing publications treat by and large some isolated aspects of the problem; the present one attempts a systematic survey. *Machine-induced* vibrations occur during the operation of all sorts of machinery and tools with rotating, oscillating or thrusting parts. A substantial literature can be found on machine foundations, concerned with the support of mostly heavy machines on purpose-built substructures. The present treatise concentrates rather on small and medium size machinery placed on ordinary floors of industrial buildings and creating a source of undesirable vibrations. The associated questions have rarely been tackled to date. They entail problems similar to those of man-induced vibrations. Questions beyond this range, such as, for instance, machine-induced ground vibrations interacting with adjacent buildings or affecting other parts of the structure, are excluded.

The book is consciously intended to serve the *practising structural engineer* and not primarily the dynamics specialist. It should be noted that its aim is not to provide directions on how to perform comprehensive dynamic computations.
Instead, it attempts the following:

1. To show where dynamic problems could occur and where caution is necessary.
2. To further the understanding of the encountered phenomena as well as of the underlying principles.
3. To impart the basic knowledge for assessing the dynamic behaviour of the structures or structural members.
4. To describe suitable measures, either preventative to be applied in the planning stage or improving inadequate performance.

This limitation often compels simplifications and approximations to be made, which always need to be verified in terms of their applicability. More complex situations may well require more detailed investigations with the aid of the references given or the help of a specialist.

The book is divided into the following sections:

- Chapter 1 gives a concise survey of the diverse dynamic problems encountered in civil engineering. They are characterized in broad terms, whereby some themes are mentioned which are not covered in this book.
- Chapter 2 is concerned with man-induced vibrations. The dynamic loads resulting from human motion, their effects and possible countermeasures are treated in depth, discussing vibrations in pedestrian structures, office buildings, gymnasia, dancing and concert halls, and high-diving platforms in swimming pools.
- Chapter 3 deals with machine-induced vibrations of the category defined above. The dynamic loads, their effects and some countermeasures are treated within these limits.
- Chapter 4 derives acceptance criteria for the effects of dynamic loading. Depending on the circumstances, they could be used as admissible values for an appraisal of a given vibration problem.

- Appendix A reports on cases where man- or machine-induced vibrations in structures were a problem. Improvements are discussed for some of them. Practical cases like these, particularly when damage occurred, can provide valuable insight.
- Appendix B furnishes the fundamentals of structural dynamics. Included are a collection of formulas to determine the eigenfrequencies of beams and slabs, basics of tuned vibration absorber design, and comments on the dynamic properties of important construction materials including the question of damping.

For some of the questions and problems addressed, research results and practical experience are still rather limited; this is particularly the case for man-induced vibrations. Therefore, any advice, criticism or additional practical case reports will be very welcome.

The authors wish to express their gratitude to all colleagues who contributed case reports or supported the work by their open discussion and competent advice. They particularly acknowledge the substantial contributions of Dr. D. Somaini to several sections. They further feel indebted to other former and present members of the Institute of Structural Engineering at the Swiss Federal Institute of Technology (ETH), who typed and proofread the manuscript and produced the figures: Ms. S. Burki, Ms. R. Feusi, Mrs. S. Schenkel (Dipl. Ing. ETH), Ms. H. Ungricht (Dipl. Ing. ETH), Mr. K. Baumann (Dipl. Ing. ETH), Mr. R. Vogt (Dipl. Ing. ETH) and Mr. L. Sieger. The translation from German by Mr. J.-M. Hohberg (MSc.) and Dr. E. G. Prater is also gratefully acknowledged.

Zurich, July 1987 H. Bachmann, W. Ammann

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1 SURVEY OF PROBLEMS IN STRUCTURAL DYNAMICS

In this chapter the different types of dynamic loads are characterized, followed by a description of their possible effects and existing measures for their limitation.

1.1 Characterization of Dynamic Loads

1.1.1 General Aspects

In broad terms, a major part of the loads encountered in civil engineering can be designated as dynamic because they vary with time. In practice, however, slowly varying loads can be treated as quasi-static since the inertia and damping forces are negligible. The presence of inertia and damping forces is in fact the important distinction between dynamic and static loading. These forces arise from the accelerations and velocities induced in the structural member, and they have to be included in the calculation of stress resultants and support reactions. The magnitude of these forces and their function against time depend both on the kind of excitation from outside and on the intrinsic dynamic behaviour of the structural member, i. e. its dynamic properties.

According to their time function, dynamic loads can be categorized (Figs. 1.1 and 1.2) as

- harmonic
- periodic
- transient
- impulsive.

Additional aspects and criteria, respectively, are the number of load cycles, the ensuing loading or strain rate in the affected member, the probability of occurrence of the load or the peak values it may attain (Tab. 1.1, Section 1.1.6).

2 MAN-INDUCED VIBRATIONS

2.1 General Aspects

In an increasing number of cases, structures are found to be unduly responsive («lively») to human motion, resulting in disturbing or even harmful vibrations. Structures intended for moderate live loads of an assumed static nature are often designed with rather slender dimensions, the possibility that dynamic loading might govern the design being overlooked or underestimated. Another factor is the advent of new kinds of user activities such as fitness classes to the accompaniment of strongly rhythmic music in gymnasia, which may bring about a considerable dynamic loading. Although overloading of the structure itself is not the primary concern, secondary building elements (e.g. cladding, windows) can be damaged and the comfort of people impaired. They may feel alarmed enough to leave their places precipitately (see [2.1] and Case No. 7). One is usually more sensitive to vibrations induced by someone else than those which are partly due to one's own activity. Thus, man-induced vibrations are basically a problem of serviceability.

This chapter first describes the dynamic loading functions (force vs. time) resulting from various human motions. It then shows their effects. The countermeasures are classified according to categories of structures in which man-induced vibrations are to be expected.

2.2 Dynamic Loading from Human Motions

Man can cause various types of dynamic loads by his physical activity. The loads may be of periodic or transient nature (Fig. 1.2).

Periodic loads are mainly the result of the following forms of human motion:

- walking
- running
- skipping
- dancing.

Of course, this is just a crude categorization. Other forms of motion such as rhythmic skipping during fitness classes, jazz dance sessions, foot stamping, hand clapping and body rocking at a concert, etc., are included or may be a combination of those forms.

Transient loads result primarily from a jolting motion imparting a single impulse to a structural member (e.g. take-off from a diving platform, landing on a floor after jumping from an elevated position, bumping against a wall with the shoulder, etc.).

3 MACHINE-INDUCED VIBRATIONS

3.1 General Aspects

Machine-induced vibrations of buildings and their structural members have an increasing practical importance due to several reasons. A contribution from the structural side is the continuing trend to higher exploitation of material strength and larger spans; another part of the problem is the switch to larger machinery or one operated at higher speed. The observed vibrations may possibly impede or even prevent the opening of new production facilities. In most cases not the structural integrity and the overall safety are at risk, but either the personnel operating these machines is continuously or temporarily irritated, or production problems arise such as substandard goods due to unforeseen motion of the machinery. Machine-induced vibrations are thus – similar to man-induced vibrations – mainly a problem of serviceability.

The following chapter characterizes in its first part the dynamic loading exerted from various types of machinery. The second part deals with possible effects on buildings or structural members and with suitable countermeasures. The emphasis is thereby on small and medium size machinery which is typically installed on floors of buildings and liable to cause vibration problems there.

3.2 Dynamic Loads of Various Types of Machinery

Depending on its manufacturing purpose, state of maintenance and design details, a machine causes distinct loads on the structural member it rests on. The loads depend primarily on the type of motion the machine parts describe: whether it is rotating, oscillating, or of an impacting type. The following descripton of the dynamic loads is hence grouped into these three categories.

The time function of the exerted loading is periodic in general, sometimes even harmonic (see Section 1.1, Figs. 1.1 and 1.2). In any case can a periodic load be decomposed by means of a Fourier analysis into a number of harmonic components. The relevant theory is explained in Appendix B 4.

3.2.1 Machines with Rotating Parts

Dynamic loads may arise from rotating parts of machinery if they are insufficiently balanced or if electrodynamic fields are active.

4 ACCEPTANCE CRITERIA

4.1 General Aspects

In civil engineering practice, measured or calculated vibration magnitudes (e.g. accelerations, velocities, displacements) need to be evaluated as to whether or not the vibration effects can be tolerated. To this end, the following acceptance criteria are introduced. Magnitudes exceeding these values or falling short of them do not necessarily indicate an inadmissible state of vibration. In only a few cases the acceptance criteria represent more or less agreed bounds; much more often they indicate a practicable order of magnitude with a certain scatter. Nevertheless, these criteria may be used as bounds of admissibility, for instance if made a part of the contract or some other form of obligation.

Criteria for vibrations of buildings and pedestrian structures may be stipulated with respect to the following effects:

- overstressing of structural members (deformation, fatigue, strength)
- physiological effects on people (mechanical, acoustic, optical)
- impediment of production processes (problems of product tolerances, etc.) as well as overstressing of machinery (deformation, fatigue, strength).

How to derive the acceptance criteria, is quite a complex problem. Tolerable values for vibration effects on machinery and installations and – still more so – for the physiological effects on people are most difficult to agree upon, implying a considerable range of discretion. Somewhat more reliable are the values of tolerable stressing of structures, because their vibrations are relatively easy to measure and to assess.

Vibration bounds may be given as physical quantities such as

- displacement amplitude
- velocity amplitude
- acceleration amplitude

or as

- empirically derived quantities (e.g. KB intensity [4.1]).

The above categorization of the various vibration effects leads to the following division into

- structural criteria
- physiological criteria
- production-quality criteria.

Appendix A

CASE REPORTS

In the following, several practical cases are described where vibrations induced by man or machines were observed in structures. Most cases involve problems with interesting features, cases in which there had been complaints and for which in part improvement measures have been carried out. For the sake of the practical lessons they teach, these cases are described in a practice-oriented manner, and more abstract aspects are deliberately left out.

Some cases stem from the authors' own expertise, others are cited from the literature or were made available by colleagues of the engineering community with their permission for publication. Their courtesy is specially acknowledged. The authors would also be grateful for their readers' reporting further interesting cases, because they feel that in learning from experience, designs which were found inadequate in hindsight are often the most valuable.

No. 1: Footbridge of 1.92 Hz

Designed as a simply supported beam with a 40 m span, the bridge vibrated vertically with clearly perceptible amplitude when used under normal conditions (pedestrian walking) [A1.1]. In order to clarify the nature and intensity of the vibrations, tests and measurements were made.

Figure A1.1a gives an excerpt of a typical plot of the vertical vibration velocity. Characteristic is the surging effect which was observed under normal walking conditions as well as under deliberate excitation by three persons skipping continuously in midspan. Figure A1.1b shows a similar excerpt of a decay measurement following a single impulse due to the synchronous jumping of three persons.

As results of two different readings, the peak displacement amplitude for a rate of ca. 29 people crossing per minute was ±4.6 mm, corresponding to an acceleration of 6.7% g. The damping ratio was evaluated from three decay measurements to 2.3%, 1.8% and 2.4%, i.e. an average of 2.2% of critical damping. The three persons skipping produced a displacement amplitude of ±9.4 mm, more than double the one at crossing of 29 persons/min.

Appendix B

FUNDAMENTALS OF VIBRATION THEORY

Appendix B provides a summary of fundamental structural dynamics sufficient to understand the material presented in Chapters 2 and 3. Examples are given for common practical problems. Problems beyond this scope will necessitate the consultation of standard textbooks on the subject.

The following is divided into the sections:

B 1 Systems with a single degree of freedom (SDOF)
B 2 Systems with many degrees of freedom (MDOF)
B 3 Systems with distributed parameters
B 4 Harmonic analysis
B 5 Frequency tuning
B 6 Structural behaviour under impulsive loading
B 7 Tuned vibration absorbers
B 8 Material properties under dynamic loading.

The differential equation of motion is usually written in complex state variables which include implicitly the phase angle. In some applications, however, the classical notation with sine and cosine functions is preferable. The agreed nomenclature for displacement is accordingly

$u(t)$ = complex displacement
$x(t)$ = real displacement.

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