Third Edition

SHOCK & VIBRATION HANDBOOK

Cyril M. Harris

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THIRD EDITION

Edited by

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First Edition of the Shock and Vibration Handbook (1961)
Edited by
Cyril M. Harris and Charles E. Crede

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PREFACE

The First Edition of the "Shock and Vibration Handbook," published in 1961, recognized for the first time the full scope of the field of shock and vibration and brought together under one title classical vibration theory combined with modern applications of the theory to current engineering practice, including the topics of mechanical shock and the instrumentation of shock and vibration. Each chapter covered the particular subject matter in the most comprehensive manner possible. Many chapters contained more material than had been found collectively in all books previously published on that topic; others contained considerable material that had not been summarized in the literature. As a result, the Handbook became a standard reference work throughout the world. My co-editor for the First Edition, Charles E. Crede, a remarkable engineer and a special friend, died three years after its publication.

The Second Edition was published in 1976. Rising production costs dictated that the total number of pages of the original three-volume edition of the Handbook be reduced by one-third and that the new edition be bound in a single volume. This was done by eliminating archival material and highly specialized information of interest to relatively few engineers; at the same time, the coverage of problems of current general interest was increased. Since the Second Edition, technical developments have continued at a rapid pace. For example, modal analysis (the subject of Chap. 21 of this volume) was then relatively unknown; in recent years, conferences on this topic have drawn large numbers of attendees and contributed papers. Other topics also have become important, warranting inclusion in the Handbook as new chapters, for example, vibration induced by fluid flow, seismic qualifications of equipment, condition monitoring of machinery, and measurement instrumentation. In addition, some chapters required major revisions because of new technological developments. These include piezoelectric and piezoresistive transducers, special-purpose transducers, measurement techniques, transducer calibration, vibration standards, introduction to testing, data analysis and environmental specification, vibration of structures induced by ground motion, shock testing machines, types and characteristics of isolators, application of isolators, air springs and servo-controlled isolation systems, application of damping treatments, and torsional vibration in reciprocating and rotating machines. These and other developments in many specialized areas of shock and vibration have brought about the need for a Third Edition of the Handbook to reflect current engineering practice. Comprehensive coverage has continued to be a primary objective.

The Third Edition, a unified treatment of the subject of shock and vibration, is the equivalent in content of at least five textbooks of the usual size. The 44 chapters were written by 60 authorities from industry, government laboratories, and universities. Each chapter covers a particular topic. Chapters dealing with related topics are grouped together. The first group of chapters provides a theoretical basis for shock and vibration. The second group considers instrumentation and measurements. This is followed by a chapter on vibration standards. The next group of chapters deals with analysis and testing, concepts in the treatment of data obtained from measurements, and procedures for analyzing and testing systems subjected to vibration and shock, including the use of digital computers. Vibration which is induced by ground motion and by fluid flow is considered next. Then, the important subject of methods of controlling shock and vibration is discussed in a group of chapters dealing with isolation, damping, and balancing. This is followed by chapters devoted to equipment design, packaging, and the effects of shock and vibration on humans. Duplication of material between chapters is avoided insofar as this is desirable, cross-references to other chapters being used frequently. There are extensive references to available technical literature.

The new edition of the Handbook reflects changes in terminology which have taken place during the past decade. Thus in the new chapters and those which have been completely rewritten, the term *hertz* (abbreviated *Hz*) has replaced *cycles per second* (abbreviated *cps*). In the other chapters, replacement of *cps* by *Hz* in the text and illustrations would have resulted in a significant increase in the cost of the Third Edition. Making the Handbook less affordable for students for the sake of such uniformity did not seem warranted at this time, since clarity or quality of presentation is not affected.

Although this Handbook is not intended primarily as a textbook, many teachers will find the classical and rigorous treatment suitable for classroom use; in particular, the extensive discussion of practical examples will be of value as a supplement to the usual classroom theory. The control of shock and vibration is of practical importance in many aspects of engineering. The Handbook is particularly intended to be used as a working reference by engineers and scientists in the mechanical, civil, acoustical, aeronautical, electrical, air-conditioning, transportation, and chemical fields. Engineers in manufacturing, including plant maintenance, measurement and control, environmental testing, and packing and shipping, will find much of value, as will those engaged in development and design work.

In the preparation of the Third Edition, many persons and organizations made useful suggestions and contributions; these are far too numerous to acknowledge individually, but I am grateful to them all. However one individual deserves special thanks for his suggestions for the content of the new edition—Rudolph H. Volin of the Shock and Vibration Information Center at the Naval Research Laboratory. The contributors worked diligently with me toward the objective of making each chapter the definitive treatment in its field, and I appreciate their commitment to excellence. Finally I wish to express my appreciation to the government agencies and industrial organizations with whom some of our contributors are associated for clearing the material presented in chapters written by these contributors.

Cyril M. Harris

About the editor

Cyril M. Harris is Charles Batchelor Professor of Electrical Engineering and Professor of Architecture at Columbia University in New York City. He holds a Ph.D. degree in physics from M.I.T. and has achieved international recognition in architectural acoustics and noise control. He is a member of both the National Academy of Sciences and the National Academy of Engineering and has been a recipient of the Gold Medal of the Acoustical Society of America, the Gold Medal of the Audio Engineering Society, the Franklin Medal, and the AIA Medal of the American Institute of Architects. Dr. Harris was the acoustical consultant for several prominent concert halls and auditoriums including the John F. Kennedy Center for the Performing Arts and the Metropolitan Opera House. He also is the editor of the *Handbook of Noise Control*, Second Edition, and *Dictionary of Architecture and Construction*, both published by McGraw-Hill.

CONTENTS

1

INTRODUCTION TO THE HANDBOOK

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CONCEPTS OF SHOCK AND VIBRATION

Vibration is a term that describes oscillation in a mechanical system. It is defined by the frequency (or frequencies) and amplitude. Either the motion of a physical object or structure or, alternatively, an oscillating force applied to a mechanical system is vibration in a generic sense. Conceptually, the time-history of vibration may be considered to be sinusoidal or simple harmonic in form. The frequency is defined in terms of cycles per unit time, and the magnitude in terms of amplitude (the maximum value of a sinusoidal quantity). The vibration encountered in practice often does not have this regular pattern. It may be a combination of several sinusoidal quantities, each having a different frequency and amplitude. If each frequency component is an integral multiple of the lowest frequency, the vibration repeats itself after a determined interval of time and is called *periodic*. If there is no integral relation among the frequency components, there is no periodicity and the vibration is defined as *complex*.

Vibration may be described as *deterministic* or *random*. If it is deterministic, it follows an established pattern so that the value of the vibration at any designated future time is completely predictable from the past history. If the vibration is random, its future value is unpredictable except on the basis of probability. Random vibration is defined in statistical terms wherein the probability of occurrence of designated magnitudes and frequencies can be indicated. The analysis of random vibration involves certain physical concepts that are different from those applied to the analysis of deterministic vibration.

Vibration of a physical structure often is thought of in terms of a model consisting of a mass and a spring. The vibration of such a model, or system, may be "free" or "forced." In *free vibration*, there is no energy added to the system but rather the vibration is the continuing result of an initial disturbance. An *ideal system* may be considered undamped for mathematical purposes; in such a system the free vibration is assumed to continue indefinitely. In any *real system*, damping (i.e., energy dissipation) causes the amplitude of free vibration to decay continuously to a negligible value. Such free vibration sometimes is referred to as *transient vibration*. *Forced vibration*, in contrast to free vibration, continues under "steady-state" conditions because energy is supplied to the system continuously to compensate for that dissipated by damping in the system. In general, the frequency at which energy is supplied (i.e., the forcing frequency) appears in the vibration of the system. Forced vibration may be either deterministic or random. In either instance, the vibration of the system depends upon the relation of the excitation or forcing function to the properties of the system. This relationship is a prominent feature of the analytical aspects of vibration.

Shock is a somewhat loosely defined aspect of vibration wherein the excitation is nonperiodic, e.g., in the form of a pulse, a step, or transient vibration. The word "shock" implies a degree of suddenness and severity. These terms are relative rather than absolute measures of the characteristic; they are related to a popular notion of the characteristics of shock and are not necessary in a fundamental analysis of the applicable principles. From the analytical viewpoint, the important characteristic of shock is that the motion of the system upon which the shock acts includes both the frequency of the shock excitation and the natural frequency of the system. If the excitation is brief, the continuing motion of the system is free vibration at its own natural frequency.

The technology of shock and vibration embodies both theoretical and experimental facets prominently. Thus, methods of analysis and instruments for the measurement of shock and vibration are of primary significance. The results of analysis and measurement are used to evaluate shock and vibration environments, to devise testing procedures and testing machines, and to design and operate equipment and machinery. Shock and/or vibration may be either wanted or unwanted, depending upon circumstances. For example, vibration is involved in the primary mode of operation of such equipment as conveying and screening machines; the setting of rivets depends upon the application of impact or shock. More frequently, however, shock and vibration are unwanted. Then the objective is to eliminate or reduce their severity or, alternatively, to design equipment to withstand their influences. These procedures are embodied in the control of shock and vibration. Methods of control are emphasized throughout this Handbook.

CONTROL OF SHOCK AND VIBRATION

Methods of shock and vibration control may be grouped into three broad categories:

1. Reduction at the Source

a. Balancing of Moving Masses. Where the vibration originates in rotating or reciprocating members, the magnitude of a vibratory force frequently can be reduced or possibly eliminated by balancing or counterbalancing. For example, during the manufacture of fans and blowers, it is common practice to rotate each rotor and to add or subtract material as necessary to achieve balance.

b. Balancing of Magnetic Forces. Vibratory forces arising in magnetic effects of electrical machinery sometimes can be reduced by modification of the magnetic path. For example, the vibration originating in an electric motor can be reduced by skewing the slots in the armature laminations.

c. Control of Clearances. Vibration and shock frequently result from impacts involved in operation of machinery. In some instances, the impacts result from inferior design or manufacture, such as excessive clearances in bearings, and can be reduced by closer attention to dimensions. In other instances, such as the movable armature of a relay, the shock can be decreased by employing a rubber bumper to cushion motion of the plunger at the limit of travel.

2. Isolation

a. Isolation of Source. Where a machine creates significant shock or vibration during its normal operation, it may be supported upon isolators to protect other machinery and personnel from shock and vibration. For example, a forging hammer tends to create shock of a magnitude great enough to interfere with the operation of delicate apparatus in the vicinity of the hammer. This condition may be alleviated by mounting the forging hammer upon isolators.

b. Isolation of Sensitive Equipment. Equipment often is required to operate in an environment characterized by severe shock or vibration. The equipment may be protected from these environmental influences by mounting it upon isolators. For example, equipment mounted in ships of the navy is subjected to shock of great severity during naval warfare and may be protected from damage by mounting it upon isolators.