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Dynamics of Structures

Theory and applications to Earthquake Engineering

(Second Edition)

结构动力学

理论及其在地震工程中的应用（第2版）

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影印版前言

在20世纪前四分之一的年代里，在全世界几乎都很难找到有关结构动力学方面的教科书，当然更谈不上有关地震工程方面的教科书了。在那个连科学家和工程师都只能依靠计算尺来进行科学和工程计算的年代，怎么能指望在大学的课程表中出现结构动力学的字样呢。

可是20世纪中叶以来，情况有了急剧的变化，对结构动力学的研究深度和应用广度有了飞速的进步。当然这一方面得益于现代计算机和计算理念及技术的迅猛发展，另一方面也得益于地震工程科学的发展。结构动力学本身是地震工程学的基础，但是由于地震工程的发展，特别是地震工程中对迫切需要解决的重要课题的研究无不丰富了结构动力学的内容并积极地推动着结构动力学的发展。值得一提的是20世纪30年代初由于强地震记录的取得，更使得结构动力学开始大踏步地从研究的深院大楼走向了广大的工程建设部门。也正是从这个时候开始，结构动力学与地震工程这两门学科结下了不解之缘；其后,在各种书籍与学术期刊中犹如孪生兄弟似的都会同时出现。而本书 *Dynamics of Structures: Theory and Application to Earthquake Engineering* 真实地反映了这一实际情况。

本书著者 Anil K. Chopra 教授是加州大学伯克利分校土木与环境工程专业（Civil and Environmental Engineering）的新生代教授和学科带头人。由于他对结构动力学和地震工程的重要贡献，自 1993 年到现今一直担任国际著名学术刊物《地震工程与结构动力学》（*Earthquake Engineering and Structural Dynamics*）的副主编和主编。这本身就说明了他是当今结构动力学和地震工程学界的一位大师，他的这种经历使他能最及时和充分地了解并融会世界上有关结构动力学和地震工程的最新的学术思想和进展，这为他能写出这本重要的著作提供了难得的机会。应该说20世纪下半世纪以来有关结构动力学的经典著作也时有问世，其中不乏名著，如由克拉夫教授（R.W. Clough，美国科学和工程两院院士）和彭津教授（J. Penzien）编写的英文版《结构动力学》流传世界各国；其中文译本在20世纪80年代初即由我国著名学者王光远教授等翻译出版，在国内影响深远。但是以地震工程作为切入点，并将地震工程与结构动力学如此密切结合，贴切地反映出这两门学科之间的血脉关系，就要首推 Chopra 教授的这本著作了。

本人有幸曾与 Chopra 教授见过数面，也曾有过若干交谈。他给我的印象是风趣幽默，但又是十分严谨和细心，细心的甚至有点接近繁琐。本书是 Chopra 教授专门为大学高年级学生以及研究生们编写的一本教科书，他的性格特点在这本书中得到了充分的反映。众所周知，结构动力学是现代结构工程中一门比较难学和难掌握的课程，他为了使他的书能为学生正确地理解，考虑得非常周到，从章节的考虑、例题的选用、进度的安排、习题和题

解的选择无不丝丝入扣，甚至语言的运用也都尽量避免使自学者产生歧义的可能。正像他在该书序言中所写的那样，这本教科书只需大学土木本科基础力学和数学的知识，就可以使初学者，甚至完全依赖自学的人都能将结构动力学学懂、学好，对此我深信不疑。这本书对中国学生来说，不仅能从中学到现代结构动力学和现代地震工程学的知识，而且更能从中学习许多治学的方法，诸如严谨的思考、缜密的洞察，甚至还可以从书本里的生动文字中学到不少在英语课堂上无法学到的英语知识和专业英语的写作能力。

这本《结构动力学——理论及其在地震工程中的应用》(*Dynamics of Structures: Theory and Applications to Earthquake Engineering*)是 Chopra 教授在第一版基础上修订、补充新的研究成果之后完成的。其中有他自己的创造性贡献，更有经他汇总了的世界上其他学者的重要贡献。说它是当今结构动力学方面的一本权威著作或经典著作，是一点也不过分的。

本书对结构动力学的基本知识、基础理论给予了系统、全面的阐述，内容深入浅出、循序渐进，在系统介绍基本理论知识的同时，密切结合地震工程的实践，对理论研究和工程应用，乃至抗震设计规范中的一些重要的结构动力学问题都给予了重点介绍，充分体现了理论联系实际的风格。书中还配有相当数量的例题，对掌握和理解结构动力学、对掌握和理解地震工程学都会有很大帮助。

本书可以作为土木工程专业和地震工程专业的研究生或大学高年级本科生的教科书，也可以作为相关专业教师和研究工作者，特别是那些想涉足结构动力学这门知识的工程设计人员的自学参考书。我高兴地得知，本书影印版已经作为清华大学土木工程专业研究生的教材。相信这仅仅是开始，今后一定会有更多的院校和更多的专业师生乃至科研工作者以及工程设计人员也都会毫不犹豫地选择 Chopra 的这本传世之作作为他们学习和了解结构动力学的教材的。

谢礼立
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2005 年 3 月 10 日

Foreword

The need for a textbook on earthquake engineering was first pointed out by the eminent consulting engineer, John R. Freeman (1855–1932). Following the destructive Santa Barbara, California earthquake of 1925, he became interested in the subject and searched the Boston Public Library for relevant books. He found that not only was there no textbook on earthquake engineering, but the subject itself was not mentioned in any of the books on structural engineering. Looking back, we can see that in 1925 engineering education was in an undeveloped state with computing done by slide rule and curricula that did not prepare the student for understanding structural dynamics. In fact, no instruments had been developed for recording strong ground motions, and society appeared to be unconcerned about earthquake hazards.

In recent years books on earthquake engineering and structural dynamics have been published, but the present book by Professor Anil K. Chopra fills a niche that exists between more elementary books and books for advanced graduate studies. The author is a well-known expert in earthquake engineering and structural dynamics, and his book will be valuable to students not only in earthquake-prone regions but also in other parts of the world, for a knowledge of structural dynamics is essential for modern engineering. The book presents material on vibrations and the dynamics of structures and demonstrates the application to structural motions caused by earthquake ground shaking. The material in the book is presented very clearly with numerous worked-out illustrative examples so that even a student at a university where such a course is not given should be able to study the book on his or her own time. Readers who are now practicing engineering should have no difficulty in studying the subject by means of this book. An especially interesting feature of the book is the application of structural dynamics theory to important issues in the seismic response and design of multistory buildings. The information presented in this book will be of special value to those engineers who are engaged in actual seismic design and want to improve their understanding of the subject.

Although the material in the book leads to earthquake engineering, the information presented is also relevant to wind-induced vibrations of structures, as well as man-made motions such as those produced by drophammers or by heavy vehicular traffic. As a textbook on vibrations and structural dynamics, this book has no competitors and can be recommended to the serious student. I believe that this is the book for which John R. Freeman was searching.

George W. Housner
California Institute of Technology

Preface

to the Second Edition

SCOPE OF THE REVISION

Dynamics of Structures has been well received in the five years since it was published. It is used as a textbook in universities in both the United States and abroad, and enjoys a wide professional readership as well. Reviews by academics and professionals have generally been favorable. Preparation of the second edition provided me with an opportunity to improve, expand slightly, and update the book.

Overall the reader will find a variety of fresh material. Prompted by the recent interest in seismic performance of bridges, several chapters now include examples on dynamics of bridges and their earthquake response. Chapter 7 expands the description of energy dissipation devices used to retrofit seismically vulnerable structures. In response to the growing need for simplified dynamic analysis procedures suitable for performance-based earthquake engineering, Chapter 7 also provides a fuller discussion relating the deformations of inelastic and elastic systems, and includes a new section on applications of the inelastic design spectrum to structural design for allowable ductility, seismic evaluation of existing structures, and displacement-based structural design. Chapter 20 incorporates additional description of base-isolation systems and recent applications of these systems to retrofit existing buildings and design new buildings. Chapter 21 has undergone major revision by incorporating the current editions of building codes; the International Building Code has replaced the Uniform Building Code and the Eurocode has been added.

The frequency-domain method of dynamic analysis has now been included, as requested by some readers, but presented as an appendix instead of weaving it throughout the book. This decision is motivated by my goal to keep the mathematics as simple as each topic permits, thus making structural dynamics easily accessible to students and professional engineers.

Using the book in my teaching and reflecting on it five years later suggested improvements. The text has been clarified and polished throughout, several sections have been reorganized, worked-out examples have been added, and new figures have been developed to enhance the effectiveness of the presentation.

In response to suggestions of professors who have adopted the book in their teaching, many new end-of-chapter problems have been added. There are 357 problems in the second edition, over one-half more than in the original edition. Solutions to these problems are available from the publisher, together with enlarged versions of the figures suitable for making transparencies for use in the classroom.

The preface to the first edition remains valid for this revision; I urge you to read it. In particular, *A Note for Professional Engineers* still applies, as does *A Note for Instructors* but with an addendum: Appendix A: Frequency-Domain Method of Analysis, in my opinion, belongs in a second graduate course on structural dynamics.

ACKNOWLEDGMENTS

I am grateful to many people who helped prepare this revision: Professor Rakesh K. Goel assisted in numerous ways and played an important role, as he did for the first edition. In particular, he developed and executed the computer software necessary to create the new figures. Several students, present and former, assisted in preparing solutions for the new worked-out examples and end-of-chapter problems: Ashraf Ayoub, Ushnish Basu, Shih-Po Chang, Garrett Hall, Petros Keshishian, Allen Kwan, Wen-Hsiung Lin, and Charles Menun. Eric Eisman did the word processing of the new material and changes to the text in TEX. Janine Hannel prepared several photographs for publication. Claire Johnson assembled and edited the Solutions Manual. In addition to several anonymous reviewers, Professors M. C. Constantinou, Takeru Igusa, Eduardo Miranda, and C. C. Tung provided incisive criticism and suggestions for improvement. Many individuals (students, professors, and practicing engineers)—too numerous to list here by name—offered valuable comments.

YOUR COMMENTS ARE INVITED

I repeat my request that instructors, students, and professional engineers write to me (chopra@ce.berkeley.edu) if they have suggestions for improvements or clarifications, or if they identify errors. I thank you in advance for taking the time and interest to do so.

Anil K. Chopra

Preface

PHILOSOPHY AND OBJECTIVES

This book on dynamics of structures is conceived as a textbook for courses in civil engineering. It includes many topics in the theory of structural dynamics, and applications of this theory to earthquake analysis, response, and design of structures. No prior knowledge of structural dynamics is assumed in order to make this book suitable for the reader learning the subject for the first time. The presentation is sufficiently detailed and carefully integrated by cross-referencing to make the book suitable for self-study. This feature of the book, combined with a practically motivated selection of topics, should interest professional engineers, especially those concerned with analysis and design of structures in earthquake country.

In developing this book, much emphasis has been placed on making structural dynamics easily accessible to students and professional engineers because many find this subject to be difficult. To achieve this goal, the presentation has been structured around several features: The mathematics is kept as simple as each topic will permit. Analytical procedures are summarized to emphasize the key steps and to facilitate their implementation by the reader. These procedures are illustrated by over 100 worked-out examples, including many comprehensive and realistic examples where the physical interpretation of results is stressed. Some 400 figures have been carefully designed and executed to be pedagogically effective; many of them involve extensive computer simulations of dynamic response of structures. Photographs of structures and structural motions recorded during earthquakes are included to relate the presentation to the real world.

The preparation of this book has been inspired by several objectives:

- Relate the structural idealizations studied to the properties of real structures.
- Present the theory of dynamic response of structures in a manner that emphasizes physical insight into the analytical procedures.
- Illustrate applications of the theory to solutions of problems motivated by practical applications.
- Interpret the theoretical results to understand the response of structures to various dynamic excitations, with emphasis on earthquake excitation.
- Apply structural dynamics theory to conduct parametric studies that bring out several fundamental issues in the earthquake response and design of multistory buildings.

This mode of presentation should help the reader to achieve a deeper understanding of the subject and to apply with confidence structural dynamics theory in tackling practical problems, especially in earthquake analysis and design of structures, thus narrowing the gap between theory and practice.

SUBJECTS COVERED

This book is organized into three parts: I. Single-Degree-of-Freedom Systems; II. Multi-Degree-of-Freedom Systems; and III. Earthquake Response and Design of Multistory Buildings.

Part I includes eight chapters. In the opening chapter the structural dynamics problem is formulated for simple elastic and inelastic structures, which can be idealized as single-degree-of-freedom (SDF) systems, and four methods for solving the differential equation governing the motion of the structure are reviewed briefly. We then study the dynamic response of linearly elastic systems (1) in free vibration (Chapter 2), (2) to harmonic and periodic excitations (Chapter 3), and (3) to step and pulse excitations (Chapter 4). Included in Chapters 2 and 3 is the dynamics of SDF systems with Coulomb damping, a topic that is normally not included in civil engineering texts, but one that has become relevant to earthquake engineering, because energy-dissipating devices based on friction are being used in earthquake-resistant construction. After presenting numerical time-stepping methods for calculating the dynamic response of systems (Chapter 5), the earthquake response of linearly elastic systems and of inelastic systems is studied in Chapters 6 and 7, respectively. Coverage of these topics is more comprehensive than in texts presently available; included are details on the construction of response and design spectra, effects of damping and yielding, and the distinction between response and design spectra. The analysis of complex systems treated as generalized SDF systems is the subject of Chapter 8.

Part II includes Chapters 9 through 17 on the dynamic analysis of multi-degree-of-freedom (MDF) systems. In the opening chapter of Part II the structural dynamics problem is formulated for structures idealized as systems with a finite number of degrees of freedom and illustrated by numerous examples; also included is an overview of methods for solving the differential equations governing the motion of the structure. Chapter 10 is concerned with free vibration of systems with classical damping and with the numerical calculation of natural vibration frequencies and modes of the structure. Also included are differences in free vibration of systems with classical damping and of systems with nonclassical damping, a topic not normally discussed in textbooks. Chapter 11 addresses several issues that arise in defining the damping properties of structures, including experimental data—from forced vibration tests on structures and recorded motions of structures during earthquakes—that provide a basis for estimating modal damping ratios, and analytical procedures to construct the damping matrix, if necessary. Chapter 12 is concerned with the dynamics of linear systems, where the classical modal analysis procedure is emphasized. Part C of this chapter represents a "new" way of looking at modal analysis that facilitates understanding of how modal response contributions are influenced by the spatial distribution and the time variation of applied forces, leading to practical criteria on the number of modes to include in response calculation. In Chapter 13, modal analysis procedures for earthquake analysis of structures are developed; both response history analysis and response spectrum analysis procedures are presented in a form that provides physical interpretation. The presentation and application of modal combination rules to estimate the peak response of MDF systems directly from the earthquake response or design spectrum is more comprehensive than in textbooks presently available. The procedures are illustrated by numerous examples, including coupled lateral-torsional response of unsymmetric-plan buildings and torsional response of nominally symmetric buildings.

Chapter 14 is devoted to the practical computational issue of reducing the number of degrees of freedom in the structural idealization required for static analysis in order to recognize that the dynamic response of many structures can be well represented by their first few natural modes. In Chapter 15 numerical time-stepping methods are presented for MDF systems not amenable to classical modal analysis: systems with nonclassical damping or systems responding into the range of nonlinear behavior. Chapter 16 is concerned with classical problems in the dynamics of distributed-mass systems; only one-dimensional systems are included. In Chapter 17 two methods are presented for discretizing one-dimensional distributed-mass systems: the Rayleigh–Ritz method and the finite element method. The consistent mass matrix concept is introduced, and the accuracy and convergence of the approximate natural frequencies of a cantilever beam, determined by the finite element method, are demonstrated.

Part III of the book contains four chapters concerned with earthquake response and design of multistory buildings, a subject not normally included in structural dynamics texts. Several important and practical issues are addressed using analytical procedures developed in the preceding chapters. In Chapter 18 the earthquake response of linearly elastic multistory buildings is presented for a wide range of two key parameters: fundamental natural vibration period and beam-to-column stiffness ratio. Based on these results, we develop an understanding of how these parameters affect the earthquake response of buildings and, in particular, the relative response contributions of the various natural modes, leading to practical information on the number of higher modes to include in earthquake response calculations. Chapter 19 is concerned with the important subject of earthquake response of multistory buildings deforming into their inelastic range. It includes discussion of the heightwise variation of story ductility demands, large ductility demand in the first story if it is "weak" or "soft" relative to the upper stories, ductility demands for buildings designed according to the lateral force distribution of the 1994 *Uniform Building Code,* and how these demands compare with allowable ductility. The currently active and expanding subject of base isolation is the subject of Chapter 20. Our goal is to study the dynamic behavior of buildings supported on base isolation systems with the limited objective of understanding why and under what conditions isolation is effective in reducing the earthquake-induced forces in a structure. In Chapter 21 we present the seismic force provisions in three building codes—*Uniform Building Code* (United States), *National Building Code of Canada*, and *Mexico Federal District Code*—together with their relationship to the theory of structural dynamics developed in Chapters 6, 7, 8, and 13. Subsequently, the code provisions are evaluated in light of the results of dynamic analysis of buildings presented in Chapters 18 and 19.

A NOTE FOR INSTRUCTORS

This book is suitable for courses at the graduate level and at the senior undergraduate level. No previous knowledge of structural dynamics is assumed. The necessary background is available through the usual courses required of civil engineering undergraduates. These include:

- Static analysis of structures, including statically indeterminate structures and matrix formulation of analysis procedures (background needed primarily for Part II)
- Structural design
- Rigid-body dynamics
- Mathematics: ordinary differential equations (for Part I), linear algebra (for Part II), and partial differential equations (for Chapter 16 only)

By providing an elementary but thorough treatment of a large number of topics, this book permits unusual flexibility in selection of the course content at the discretion of the instructor. Several courses can be developed based on the material in this book. Here are a few examples.

Almost the entire book can be covered in a one-year course:

- *Title:* Dynamics of Structures I (1 semester)

  Syllabus: Chapters 1 and 2; Parts A and B of Chapter 3; Chapter 4; selected topics from Chapter 5; Sections 1 to 7 of Chapter 6; Sections 1 to 7 of Chapter 7; selected topics from Chapter 8; Sections 1 to 4 and 8 to 11 of Chapter 9; Parts A and B of Chapter 10; Parts A and B of Chapter 12; Sections 1, 2, 7, and 8 of Chapter 13; and selected topics from Part A of Chapter 21

- *Title:* Dynamics of Structures II (1 semester)

  Syllabus: Chapter 6 (including review of Sections 1 to 7); Chapter 7 (including review of Sections 1 to 7); Sections 5 to 7 of Chapter 9; Part C of Chapter 10; Chapter 11; Parts C and D of Chapter 12; Sections 3 to 9 of Chapter 13; and Chapters 14 to 21

The selection of topics for the first course has been dictated in part by the need to provide comprehensive coverage, including dynamic and earthquake analysis of MDF systems, for students taking only one course.

An abbreviated version of the outline above covering two quarters can be organized as follows:

- *Title:* Dynamics of Structures I (1 quarter)

  Syllabus: Chapter 1; Sections 1 and 2 of Chapter 2; Sections 1 to 4 of Chapter 3; Sections 1 to 5 of Chapter 4; selected topics from Chapter 5; Sections 1 to 7 of Chapter 6; Sections 1 to 7 of Chapter 7; selected topics from Chapter 8; Sections 1 to 4 and 8 to 11 of Chapter 9; Parts A and B of Chapter 10; Parts A and B of Chapter 12; Sections 1, 2, 7, and 8 (excluding the CQC method) of Chapter 13; and selected topics from Part A of Chapter 21

- *Title:* Dynamics of Structures II (1 quarter)

  Syllabus: Chapter 6 (including review of Sections 1 to 7); Chapter 7 (including review of Sections 1 to 7); Sections 5 to 7 of Chapter 9; Chapter 11; Parts C and D of Chapter 12; Sections 3 to 9 of Chapter 13; and Chapters 18 to 21

A one-semester course emphasizing earthquake engineering can be organized as follows:

- *Title:* Structural Dynamics and Earthquake Engineering

  Syllabus: Chapter 1; Sections 1 and 2 of Chapter 2; Sections 1 to 4 of Chapter 3; Sections 1 to 5 of Chapter 4; Chapters 6 and 7; selected topics from Chapter 8; Sections 1 to 4 and 8 to 11 of Chapter 9; Parts A and B of Chapter 10; Part A of Chapter 11; Parts A and B of Chapter 12; Sections 1, 2, 7, and 8 of Chapter 13; and Part A of Chapter 21

As every instructor knows, solving problems is essential for students who are learning structural dynamics. For this purpose the first 17 chapters include 233 problems. Chapters 18 through 21 do not include problems, for two reasons: (1) no new dynamic analysis procedures are introduced in these chapters; (2) this material does not lend itself to short, meaningful problems. However, the reader will find it instructive to work through the examples presented in Chapters 18 to 21 and to reproduce some of the results. Most of the problems can be solved with an electronic hand calculator and a sufficient quantity of patience and perseverance; a computer is most helpful, of course. The computer is essential for solving some of the problems, and these have been identified. In solving these problems, it is assumed that the student will have access to computer programs such as MATLAB or CAL. A solutions manual is available.

In my lectures at Berkeley I use transparencies of figures in this book. Instructors wishing to utilize these visual aids can make transparencies from the enlarged versions of the figures available from the publisher.

A NOTE FOR PROFESSIONAL ENGINEERS

Many professional engineers have encouraged me to prepare a book more comprehensive than *Dynamics of Structures, A Primer,* a monograph published in 1981 by the Earthquake Engineering Research Institute. This need, I hope, is filled by the present book. Having been conceived as a textbook, it includes the formalism and detail necessary for students, but these features should not deter the professional from using the book because, to the extent possible, its philosophy and style are akin to those of the monograph.

For professional engineers interested in earthquake analysis, response, and design of structures, I suggest the following reading path through the book: Chapters 1 and 2; Parts A and B of Chapter 3; Chapters 6 to 9; Parts A and B of Chapter 10; Part A of Chapter 11; and Chapters 13, 18, 19, 20, and 21.

REFERENCES

In this introductory text it is impractical to acknowledge sources for the information presented. References have been omitted to avoid distracting the reader. However, I have included occasional comments to add historical perspective and, at the end of almost every chapter, a brief list of publications suitable for further reading.

YOUR COMMENTS ARE INVITED

Since this is a new book, I request that instructors, students, and professional engineers write to me (chopra@ce.berkeley.edu) if they have questions, suggestions for improvements or clarifications, or if they identify errors. I thank you in advance for taking the time and interest to do so.

Anil K. Chopra

Acknowledgments

I am grateful to the many people who helped in the preparation of this book.

- Dr. Rakesh K. Goel, a partner from beginning to end, assisted in numerous ways and played an important role. His most significant contribution was to develop and execute the computer software necessary to generate the numerical results and create the over 450 figures.
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- The late Professor Emilio Rosenblueth provided much valuable advice and background on the building code for the Mexico Federal District.
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- Julie Reynolds and Eric Eisman did the word processing of the text in TeX. Mr. Eisman also assisted in the preliminary editing of some of the material.
- Ms. Katherine Frohmberg helped in selecting and collecting several photographs.

- Professor Joseph Penzien assumed my duties as Associate Editor of *Earthquake Engineering and Structural Dynamics* from June 1993 until August 1994 while I was working on the book.

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This book has been influenced by my own research experience in collaboration with my students. Since 1969, several organizations have supported my research in earthquake engineering, including the National Science Foundation, U.S. Army Corps of Engineers, and California Strong Motion Instrumentation Program. I am especially grateful to the National Science Foundation, in particular Dr. S. C. Liu, for sustained support.

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Overview