国际著名力学图书 —— 影印版系列 23

PEARSON Prentice Hall

Dynamics of Structures
Theory and Applications to Earthquake Engineering
(Third Edition)

结构动力学
理论及其在地震工程中的应用 （第3版）

（美）Anil K. Chopra 著

清华大学出版社

DYNAMICS OF STRUCTURES

Theory and Applications to Earthquake Engineering

结构动力学

理论及其在地震工程中的应用（第3版）

Anil K. Chopra

University of California at Berkeley

清华大学出版社
北京

北京市版权局著作权合同登记号　图字：01-2009-2811

图书在版编目(CIP)数据

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：3rd edition：英文/（美）肖帕（Chopra, A. K.）著. —影印本. —北京：清华大学出版社，2009.6
（国际著名力学图书. 影印版系列）
ISBN 978-7-302-20218-9

Ⅰ. 结…　Ⅱ. 肖…　Ⅲ. 结构动力学－英文　Ⅳ. O342

中国版本图书馆 CIP 数据核字（2009）第 075630 号

责任编辑：徐晓飞
封面设计：何凤霞
责任印制：孟凡玉

出版发行：清华大学出版社　　**地　　址**：北京清华大学学研大厦 A 座
http://www.tup.com.cn　　**邮　　编**：100084
社　总　机：010-62770175　　**邮　购**：010-62786544
投稿与读者服务：010-62776969，c-service@tup.tsinghua.edu.cn
质　量　反　馈：010-62772015，zhiliang@tup.tsinghua.edu.cn
印 刷 者：北京市四季青印刷厂
装 订 者：三河市金元印装有限公司
经　　销：全国新华书店
开　　本：185×230　　**印张**：57.25
版　　次：2009 年 6 月第 1 版　　**印　　次**：2009 年 6 月第 1 次印刷
印　　数：0001~2000
定　　价：90.00 元

第 3 版影印前言

用我国现今一句时髦的话来形容 Chopra 博士，他是一位“与时俱进”的教授。Chopra 教授 1995 年出版了他的力作 *Dynamics of Structures*: *Theory and Applications to Earthquake Engineering*，6 年以后，于 2001 年修订出版了该书的“第 2 版”，再经 6 年于 2007 年该书的“第 3 版”又接着问世。

概略地说，我们可以从该书新旧版本的差别中窥视出世界地震工程特别是结构抗震学科在这段时期的发展趋势。比如，他在 2007 年出版的 *Dynamics of Structures*: *Theory and Applications to Earthquake Engineering* “第 3 版”与 2001 年出版的“第 2 版”的主要变化基本上反映了这时段内结构抗震学科的新的进展。

与旧版本比，“第 3 版”的第 19 章和第 21 章有了较大的变化，同时又增添了第 22 章，此外在其他章节中也做了必要的修订和增订。“第 3 版”的第 19 章基本上是重写的，加进了最近在地震分析中建筑物非线性反应方面的进展，这是近十年来的热门话题。

第 21 章做了较大的修改，主要是新增了国际上 4 部抗震设计规范在这期间或新增加或新修改的内容。这 4 部重要的抗震设计规范是：美国的 IBC (International Building Code 2006)，加拿大的 NBC (National Building Code of Canada 2005)，欧洲规范(Eurocode 8，2004)和墨西哥联邦地区规范(Mexico Federal District Code 2004)。值得提出的是他的新版著作不只是介绍规范内容的变化，而更重要和难能可贵的是，作者都会从结构动力学的角度对这些增加或变化的内容予以阐释。这恰恰是从事抗震设计的广大工程技术人员和师生十分希望获得的而在其他著作中或在规范本身内容中很难获得的背景知识。从这个角度来讲，Chopra 教授是真正地将结构动力学理论“一竿子”插到了工程应用的“底”了，这是很值得我国广大力学工作者、设计规范编制者和结构工程研究者学习的。

“第 3 版”第 22 章是完全新增的。这部分内容总结和吸纳了近十余年来基于性态的抗震设计理论的研究成果。当然要在一章中全面介绍这方面的成果是不可能的。作者只是介绍了其中比较关键的问题，即，如何在估算既有建筑物在较低性态水平时，也即为了确保生命安全或不倒塌时的地震需求时，充分考虑建筑物的非弹性性质。可是，即使只研究地震需求的估算也是一个十分复杂的问题，不仅涉及科学技术的内容，也还涉及社会的需求，但是作者在讨论中定位得很有分寸，只限于结构动力学方面的内容展开讨论，因此在第 22 章的取材中大量地应用了第 7 章中提到的结构动力学的基础理论和刚修改后的第 19 章中的内容。

除此以外，“第 3 版”第 6 章、第 7 章和第 13 章的内容也做了一些修改，虽然修改的篇幅不大，但是修改的内容却是极其重要的。这是因为近十多年来获取了大量的接近断层

地区的强地震动记录。第 6 章增加的内容中讨论了近断层地震动的特征，并将它们与远离断层的地震动做了对比，这部分内容还在第 22 章中进一步展开了讨论。严格来说，Chopra 教授并不擅长近断层地震动的研究，但是这部分内容对从事结构抗震研究和设计的人员来说实在是太重要了；他不仅进行了研究，而且还能进一步将它们扩展应用到结构抗震研究领域，这一点很值得我国广大结构抗震研究者借鉴：不要只满足于从设计规范给定的地震动和设计谱来研究结构抗震，要适当地拓宽视野，更多地关注强地震动，特别是近源地震动的进展及其可能对结构抗震带来的影响。本书第 7 章增加的内容主要是针对构建非弹性设计谱的。在第 13 章中则增加了作者本人的一些研究成果，如，怎样进一步改进由于采用反应谱分析造成的对振型组合分析方法所产生的误差。

很巧的是就在我应清华大学出版社的要求为影印出版 Chopra 教授的 *Dynamics of Structures*: *Theory and Applications to Earthquake Engineering* “第 3 版” 写序时，他正好应我的邀请在哈尔滨工业大学讲学。当他获知中国正要出版他新版著作的影印版时，和以往一样他关心的不是版权问题，而只是再三的要我转告中国的读者，一定要将他们在书中发现的问题和对他的书的建议及时的告诉他。

谢礼立

中国工程院 院士
中国地震局工程力学研究所 研究员
哈尔滨工业大学土木工程学院 教授

2009 年 5 月 3 日

第 2 版影印前言

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

中国工程院 院士
中国地震局工程力学研究所 研究员
哈尔滨工业大学土木工程学院 教授

2005 年 3 月 10 日

Dedicated to Hamida and Nasreen with gratitude for suggesting the idea of working on a book and with appreciation for patiently enduring and sharing these years of preparation with me. Their presence and encouragement made this idea a reality.

UNITS

Quantity	English System	S.I. System
force	1 lb	4.448 Newtons (N)
mass	1 lb sec^2/ft (slug)	14.59 kg (kilograms)
length	1 ft	0.3048 meters (m)
mass density	1 lb/ft^3	16.02 kg/m^3
torque or moment	1 lb in.	0.113 N m
acceleration	1 ft/sec^2	0.3048 m/s^2
accel. of gravity	32.2 ft/s^2 or 386 $in./sec^2$	9.81 m/s^2
spring constant	1 lb/in.	175.1 N/m
rotational spring constant	1 lb in./rad	0.113 N m/rad
damping constant c	1 lb sec/in.	175.1 N s/m
(mass) moment of inertia	1 lb. in. sec^2	0.1129 kg m^2
modulus of elasticity	10^6 $lb/in.^2$	6.895×10^9 N/m^2
angle	1 degree	1/57.3 radian

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

SCOPE OF THE REVISION

Dynamics of Structures has been well received in the 11 years since it was first published. It continues to be used as a textbook at universities in the United States and many other countries, and enjoys a wide professional readership as well. Translations in Japanese, Korean, and Persian have been published, and translations to Chinese, Greek, and Turkish are in progress. Preparation of the third edition provided me with an opportunity to improve, expand, and update the book.

Most extensively changed were Chapters 19 and 21, and Chapter 22 has been added. Chapter 19 has been rewritten completely to incorporate recent advances in the earthquake analysis and response of inelastic buildings, a subject that has seen a flurry of renewed research activity since 1990. Chapter 21 has undergone major revision by incorporating the current editions of four building codes. The addition of Chapter 22 has been motivated by changes in the structural engineering profession and practice that have occurred over the past decade. Performance-based guidelines for evaluating existing buildings consider inelastic behavior explicitly in estimating seismic demands at low performance levels, such as life safety and collapse prevention. In Chapter 22, selected aspects of these seismic evaluation guidelines for computing seismic demands are discussed in light of structural dynamics theory presented in Chapter 7 and the revised Chapter 19.

Chapters 6, 7, and 13 have undergone slight but important revision. Prompted by recent recordings of ground motions in the proximity of the causative fault, Chapter 6 now identifies the special features of near-fault ground motions and compares them with the usual far-fault ground motions, a topic also covered in Chapter 22. Chapter 7 now provides a fuller discussion of concepts underlying construction of the inelastic design spectrum. In

Chapter 13, the discussion of modal combination errors in the response spectrum analysis procedure has been refined based on recent research results.

The third edition includes 357 end-of-chapter problems. Solutions to these problems are available to instructors as a download, together with enlarged versions of many of the figures, which are suitable for making transparencies for use in the classroom.

The Preface to the First Edition remains valid for this revision and I urge you to read it. In particular, *A Note for Professional Engineers* still applies, except that Chapter 22 should be added to the reading list. *A Note for Instructors* is also valid, with an addendum: Chapter 22 and Appendix A belong in a second graduate course on structural dynamics and earthquake engineering.

ACKNOWLEDGMENTS

I am grateful to a number of people who helped prepare this revision: Rakesh K. Goel and Chatpan Chintanapakdee developed and executed the computer software necessary to generate numerical results and create many of the new figures. Akshay Gupta and Aladdin Nassar provided numerical data from their published research for several figures in Chapter 19, which were prepared by Gabriel Hurtado. Charles D. James of the Earthquake Engineering Research Center, University of California, Berkeley, helped in selecting and collecting the new photographs. Claire Johnson prepared the text and assembled the revised parts of the manuscript. Barbara Zeiders served as the copy editor for this edition, just as she did for the first two.

In addition, five experts advised on the interpretation of the updated versions of the four building codes included in Chapter 21: Ronald O. Hamburger (*International Building Code*); Jagmohan L. Humar (*National Building Code of Canada*); Eduardo Miranda (*Mexico Federal District Code*); and Michael N. Fardis and Peter Fajfar (*Eurocode*).

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 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 to the First Edition

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