多体系统传递矩阵法及其应用

芮筱亭
贠来峰　陆毓琪　何　斌　王国平 ◎ 著

科学出版社
www.sciencep.com

本书获如下资助：
中国跨行业基金和跨行业重点项目
德国科学基金委员会重大项目(SFB)

多体系统传递矩阵法及其应用

芮筱亭
贠来峰　陆毓琪　何　斌　王国平　著

科学出版社
北京

This book supported by:
China Multi-industry Fund, National Defense Multi-industry Key Projects
Key Projects (SFB) of German Research Council

TRANSFER MATRIX METHOD OF MULTIBODY SYSTEM AND ITS APPLICATIONS

Rui Xiaoting

Yun Laifeng Lu Yuqi

He Bin Wang Guoping

Science Press
Beijing

内 容 简 介

本书首次全面系统地介绍了高度程式化的多体系统传递矩阵法，包括作者创立的线性多体系统传递矩阵法和一般多体系统离散时间传递矩阵法及其在重大工程技术领域中的应用，为多体系统动力学研究提供了全新的方法和手段。线性多体系统传递矩阵法，给出了各种传递矩阵的推导方法，提出了线性多体系统的体动力学方程、增广算子、增广特征矢量新概念，解决了复杂多刚柔体系统固有振动特性计算问题，证明了复杂多刚柔体系统增广特征矢量正交性，实现了用模态分析方法对复杂多刚柔体系统动力响应的精确分析。多体系统离散时间传递矩阵法及多体系统传递矩阵法与其他动力学方法的混合方法，应用多体系统传递矩阵法解决多刚体系统动力学、多刚柔体系统动力学和受控多体系统动力学问题。本书介绍了用多体系统传递矩阵法解决多管火箭发射动力学、自行火炮发射动力学和舰炮发射动力学等当今国际兵器科学热点问题的几项重大成果，建立的若干新理论、新技术经大量实践检验证明对解决工程实际问题行之有效，例如，减少多管火箭试验用弹量新技术使多项国家高新工程项目多管火箭密集度试验用弹量比常规试验方法分别减少了 50%～86%，提高武器密集度新技术大幅提高了多项国家高新工程项目多管火箭和自行火炮射击密集度；建立了各种力学元件和受控元件的传递矩阵库，包括线性多体系统传递矩阵库和一般多体系统离散时间传递矩阵库。利用本书传递矩阵库提供的各种力学元件和受控元件的传递矩阵，可方便地拼装各种多体系统，实现了无需系统总体动力学方程即可进行复杂多体系统动力学建模和快速计算。

本书可作为机械系统动力学师生和科研人员的参考书，还可作为兵器专业研究生的教材。本书对从事兵器、航空、航天、车辆、机器人研究和工程技术应用的科技人员具有重要参考价值。

图书在版编目(CIP)数据

多体系统传递矩阵法及其应用 / 芮筱亭等著. —北京：科学出版社，2008
ISBN 978-7-03-021625-0

Ⅰ. 多… Ⅱ. 芮… Ⅲ. 系统动力学 Ⅳ. N941.3

中国版本图书馆 CIP 数据核字(2008)第 049817 号

责任编辑：刘宝莉 王贻社 徐步政 / 责任校对：张小霞
责任印制：刘士平 / 封面设计：耕者设计工作室

科学出版社出版
北京东黄城根北街 16 号
邮政编码：100717
http://www.sciencep.com

中国科学院印刷厂印刷
科学出版社发行 各地新华书店经销
*
2008 年 5 月第 一 版 开本：B5(720×1000)
2008 年 5 月第一次印刷 印张：41 1/2 插页：2
印数：1—3 000 字数：761 000

定价：100.00 元

(如有印装质量问题，我社负责调换(科印))

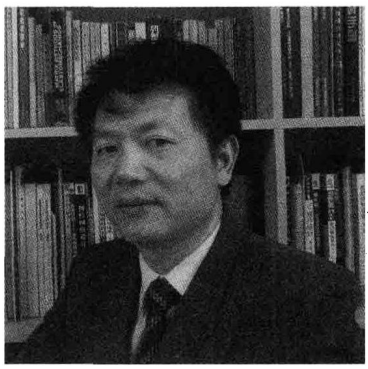
Contents Introduction

The high programming transfer matrix method of multibody system is introduced systematically for the first time in the book. It includes: matrix method of linear multibody system and discrete time transfer matrix method of general multibody system developed by author, and its applications in the important engineering technology field. It provides a totally new method and means for studying dynamics of multibody system. The first part develops transfer matrix method of linear multibody system. The deduction method of all kinds of transfer matrices is presented. The new concepts of body dynamics equation, augmented operator and augmented eigenvector of linear multibody system are put forward. The natural vibration characteristics of complex multi-rigid-flexible-body system are solved. The orthogonality of augmented eigenvector of complex multi-rigid-flexible-body system is verified. The exact analysis of dynamics response of complex multi-rigid-flexible-body system is realized using mode method. The second part develops discrete time transfer matrix method of multibody system, and mixed methods of these methods with other dynamics methods. The multi-rigid-body system dynamics, multi-rigid-flexible-body system dynamics, and controlled multibody system dynamics are computed using transfer matrix method of multibody system. The third part shows the practical application results of transfer matrix method of multibody system in some important engineering including launch dynamics of multiple launch rocket system, launch dynamics of self-propelled artillery and launch dynamics of shipboard gun, which are the hotspots of weapon science in the world field at present. It is validatied by many practices and research results that these new theories and technologies are very effective for solving practical engineering problems. For example, the number of rockets consumption in the test of firing dispersion of multiple launch rocket system are decreased 50%～86% than the general test method in many national high-tech engineering projects using new technology of decreasing the number of rockets consumption. The firing dispersion of multiple launch rocket system and self-propelled artillery are improved in many national high-tech engineering projects using the new technology of improving the firing precision of wenpon. The library of transfer matrices of various basic mechanics

elements and controlled elements are formulated, which include library of transfer matrix method of linear multibody system and library of discrete time transfer matrix method of multibody system. It is convenient to compose the various multibody systems using these matrices. It is realized to model and compute complex multibody system dynamics with high computational speed without global dynamics equation of the system.

This book can be used as reference book for teachers, students and scientific researchers in the specialty of mechanical system dynamics. And also can be used as textbook for graduate students in the field of weapon. This book has important reference worth for science and technology researchers and engineers in the fields of weapon, aeronautics, astronautics, vehicle and robot.

作 者 简 介



芮筱亭，博士，南京理工大学教授、博士生导师、力学学科首席学科带头人，江苏省中青年首席科学家、有突出贡献的中青年专家、发射动力学科技创新团队带头人，总装备部科技委兼职委员、专业组副组长、国防科技图书出版基金评审委员会委员，中国兵工学会应用力学学会副主任，欧洲力学学会会员，国防科技工业“511”人才、百名优秀博士学位获得者，享受国务院政府特殊津贴。长期从事发射动力学和多体系统动力学的科研和教学工作，作为项目组组长，主持完成国家和部委级重点科研项目20多项，获国家和省部级科技进步奖20多项，获科技图书出版基金资助出版学术著作4部，在国内外发表学术论文168篇，SCI、EI、ISTP收录68篇，获第七届中国图书奖、解放军图书奖、江苏省优秀图书一等奖等图书和论文奖30多项，国家发明专利14项，培养国内外博士后、博士研究生30多名。在世界级刊物 *Multibody System Dynamics* 上发表的系列论文被评价为“具有原始创新性”，并被该刊邀请为Special Issue副主编。应国际理论与应用力学联合会主席Werner Schiehlen教授、Wittenburg方法的创立者Jens Wittenburg教授、德国力学学会主席Erwin Stein教授、Stuttgart大学工程与计算力学研究所所长Peter Eberhard教授、Hannover大学机器人研究所所长Bodo Heimann教授、Cottbus工业大学工程力学与汽车动力学研究所所长Dieter Bestle教授、Mach弹道研究所所长Klaus Thoma教授、Hamburg-Harburg工业大学校长Edwin Kreuzer教授等10多位著名力学家邀请，由德国科学基金委员会（DFG）重大项目资助，分别作为Stuttgart大学、Karlsruhe大学、Hannover大学、Cottbus工业大学、Mach弹道研究所、Hamburg-Harburg工业大学客座教授，在欧洲14所大学和研究所作了30多场特邀学术报告。作为国际理论与应用力学学会主办“IUTAM Symposium on Multiscale Problems in Multibody System Contacts 2006”学术会议学术委员会亚洲区唯一委员，以及多个其他国际会议学术委员会委员，参与组织和主持了多个国际会议并作了多场大会特邀主题报告，中国、美国、俄罗斯、波兰、印度、奥地利等国多位院士对其研究成果给予了肯定。

Author's Resume

Prof. Dr. Rui Xiaoting, doctor advisor and presiding professor of mechanics in Nanjing University of Science & Technology. He is presiding young and middle-aged scientist, outstanding young and middle-aged expert, head of launch dynamics innovative group of Jiangsu province, member of Science and Technology Committee, vice-president of Expert Committee, member of Committee of Books Publishing Foundation for National Defense of General Armament Department of China, vice-president of Applied Mechanics Society of China Ordnance Society, member of European Mechanics Society, "511" expert and gainer of excellence doctor degree of Science Technology and Industry for National Defense of China. He gained the special reward of State Council of China. He has engaged himself in the science research and teaching in the field of launch dynamics and multibody system dynamics. As project leader, he has finished over 20 national key scientific research projects, and has obtained over 20 Chinese national and provincial prizes in science and technology. He has published 4 books supported by excellent science and technology fund, and 168 papers including 68 papers indexed by SCI, EI and ISTP. He has obtained more than 30 book and paper prizes, such as, the seventh China book prize, the army book prize and the first-class book prize of Jiangsu province. He has 14 national invention patents, and more than 30 students home and abroad from his group have got post-doctor's and doctor's degrees respectively. A series of papers published in the world-class journal *Multibody System Dynamics* are appraised as "a new and original contribution". He is invited as the co-editor of special issue of this journal. He was invited respectively by famous scientists including Professor Werner Schiehlen, President of International Union of Theoretical and Applied Mechanics; Professor Jens Wittenburg, developer of "Wittenburg Method"; Professor Erwin Stein, President of Germany Mechanics Society; Professor Peter Eberhard, Head of Institute of Engineering and Computational Mechanics in Stuttgart University; Professor Bodo Heimann, Head of Robot Institute in Hannover University; Professor Dieter Bestle, Head of Institute of Engineering and Vehicle Dynamics in Cottbus Technology University; Professor Klaus Thoma, Head of

Ernst-Mach Institute; Professor Edwin Kreuzer, President of Hamburg-Harburg Technology University; supported several times by key projects of German Research Council (DFG), as guest professors of Stuttgart University, Karlsruhe University, Hannover University, Ernst-Mach Institute, Cottbus Technology University, Hamburg-Harburg Technology University, and gave over thirty invited academic lectures in fourteen universities and institutes in Europe. As the only member of Scientific Committee of Asia of "Symposium on Multiscale Problem in Multibody Systems Contacts 2006" sponsored by International Union of Theoretical and Applied Mechanics, members of Scientific Committee of several other International Conferences, he has took part in organizing and presiding these international conferences and given several invited keynote reports. His research results has won praises from members of academy of sciences and academy of engineering of some countries such as China, America, Russia, Poland, India and Austria.

序　一

兵器、航空、航天、车辆、机器人、精密机械等领域的大量机械系统可被视为由若干个刚体和柔体铰接而成的多体系统，近40年发展迅速的多体系统动力学理论为机械系统动力学研究提供了强有力手段。现行风格迥异的各种多体系统动力学方法有如下共同特征：必须建立系统的总体动力学方程，复杂系统总体动力学方程涉及的矩阵阶次高而使计算工作量大。经典传递矩阵法为解决一维线性系统弹性结构力学问题提供了简捷有效的方法，但它不能解决线性多刚柔体系统振动特性和一般多体系统动力学问题。刚柔动力耦合作用使线性多体系统特征值问题非自共轭，特征矢量不具有通常意义下的正交性，多体系统特征矢量的正交性是目前用经典模态方法精确分析线性多体系统动力响应的急需。

针对上述这些国内外机械系统动力学特别是大量工程问题亟须解决的难题，芮筱亭教授及其合作者在《多体系统传递矩阵法及其应用》专著中，创造性地将传递矩阵法与现代计算方法相结合，建立了多体系统动力学的新方法——多体系统传递矩阵法。该方法具有无需建立系统总体动力学方程、程式化程度高、系统矩阵阶次低、计算效率高等优点。该书是作者多年研究成果的结晶，首次建立了多体系统传递矩阵法概念和理论体系，取得了多项创造性的研究成果。包括系统阐述了作者建立的线性多体系统传递矩阵法、线性受控多体系统传递矩阵法、多维系统传递矩阵法，解决了多刚柔体系统特征值快速计算问题，大幅提高了计算效率；提出了多体系统增广特征矢量和增广算子的概念，首次构造了多刚柔体系统增广特征矢量的正交性，用模态方法实现了复杂多体系统动力响应的精确分析；建立了多刚体系统离散时间传递矩阵法、多刚柔体系统离散时间传递矩阵法、受控多体系统离散时间传递矩阵法、多体系统传递矩阵法与其他力学方法的混合方法，实现了用多体系统传递矩阵法对复杂多体系统动力学的快速分析；被广泛用于多管火箭、自行火炮及舰炮等世界各军事强国亟须解决的重大工程难题，实现了对现代工程大型复杂多体系统动态性能的快速分析和预测；在国际上率先获得了严格的用非满管射击替代满管齐射的多管火箭试验技术，并被直接验证大大优于俄罗斯等国的多管火箭试验技术；大幅度提高了国家高新工程项目多管火箭的射击密集度；产生了重大经济效益，表明了多体系统传递矩阵法的强大功能和广阔的应用前景。

该书撰写经历了15个春秋，三易其稿，表现了作者严谨的科学精神。作者的

研究工作得到了国内外众多研究机构和知名科学家的长期支持和关爱，芮筱亭教授应国际理论与应用力学联合会主席 Schiehlen 教授、Karlsruhe 大学工程力学研究所所长 Wittenburg 教授等 10 多位知名科学家的邀请，多次由多项德国科学基金委员会（DFG）重大项目资助，作为欧洲 5 所大学的客座教授，在欧洲 14 所大学和研究所就书中内容作了 30 多场特邀学术报告，中、美、俄、波、印、奥等国多位院士给予高度评价。

该书具有重大的理论与实用价值，我相信该书的出版必将推动多体系统动力学理论与应用的发展，并为机械系统动态设计提供有力的新手段。

哈尔滨工业大学力学教授
中国工程院院士　黄文虎

2007 年 11 月 18 日

黄文虎：力学家，中国振动工程学会原理事长，哈尔滨工业大学原校长。

Foreword One

Lots of mechanical system can be considered as multibody system composed of many rigid and flexible bodies jointed with hinges, in the fields of weapon, aeronautics, astronautics, vehicle, robot and precision machinery. Theory of multibody system dynamics developing rapidly in recent 40 years has provided a powerful tool to study mechanical system dynamics. Various existing methods of multibody system dynamics have widely different style, however they have two same characteristics as follows: (1) It is necessary to develop the global dynamics equations of system; (2) The order of involved matrix of the global dynamics equations of system is very high for complex system, which causes corresponding computational scale rather large. Classical transfer matrix method provides a simple and effective method to solve elastic structure mechanics problems for one dimension linear system, but it can not be used to solve the problems of vibration characteristics of linear multi-rigid-flexible system and dynamics of general multibody system. The coupling dynamic action between rigid bodies and flexible bodies makes the eigenvalue problem of linear multibody system non-orthogonal, which leads eigenvectors not to satisfy the orthogonality under ordinary meaning. Now, the orthogonality of eigenvectors of multibody system is urgent requirement to analyse exactly the dynamics response of linear multibody system with classical mode method.

Faced above urgent difficult problems at home and abroad in mechanical system dynamics, especially, in plenty of engineering, by creatively combining transfer matrix method and modern computational methods, Professor Rui Xiaoting and his co-authors developed a new method for multibody system dynamics——transfer matrix method of multibody system in their monograph *Transfer Matrix Method of Multibody System and Its Application*. The new method has the advantages as follows: without the global dynamics equations of system, high programming, low order of system matrix and high computational efficiency, etc. In the book, the study results of authors in many years are concentrated, the concept and theory system of transfer matrix method of multibody system are developed for the first time, and many creative research results are obtained. All methods developed by the authors of this book, such as transfer

matrix method of linear multibody system, transfer matrix method of linear controlled multibody system, and transfer matrix method of multi-dimension system, are expatiated systemically. The problem of rapid computation of the eigenvalue of multi-rigid-flexible body system is solved, and the computational efficiency is improved greatly. The concepts of augmented eigenvector and augmented operator of multibody system are presented, the orthogonality of augmented eigenvectors of multi-rigid-flexible body system is constructed for the first time, and the exact analysis of dynamics response of complex multibody system is realized using mode method. The discrete time transfer matrix method of multi-rigid-body system, the discrete time transfer matrix method of multi-rigid-flexible-body system, the discrete time transfer matrix method of controlled multibody system, and the mixed method of transfer matrix method of multibody system with other mechanics methods are developed respectively, the rapid analysis of dynamics of complex multibody system is realized using transfer matrix method of multibody system. These research results have been widely used to solve urgent important engineering problems of every military powerful country, such as, multiple launch rocket system, self-propelled artillery and shipboard gun. The rapid analysis and forecast of dynamic performances of complex large multibody system in modern engineering are realized. Strict test technology substituting non-full charge loading rockets for full charge loading rockets in the test of multiple launch rocket system is developed at first in the world. It has been directly verified by test that the technology is much better than the technology of Russia and other countries in the test of multiple launch rocket system. The firing dispersion of multiple launch rocket systems of national high-tech engineering projects is improved greatly. The important economical benefits are produced. These shows that the method has powerful functions and wide application foreground.

It shows the religious science spirit of the authors to write the book take fifteen years and rewrite the manuscripts three times. The research works of the authors have been supported and interested for a long time by lots of famous scientists and research organizations at home and abroad. Invited by Professor Werner Schiehlen, President of International Union of Theoretical and Applied Mechanics; Professor Jens Wittenburg, Head of Engineering Mechanics Institute in Karlsruhe University; and other more than 10 famous scientists, and supported several times by key projects of German Research Council (DFG), as guest professor of 5 universities in Europe, Professor Rui Xiaoting has given over 30 invited academic lectures about the contents of this book in 14

universities and institutes in Europe. Some members of the academy of science and the academy of engineering of several countries, including China, America, Russia, Poland, India and Austria, have given him high appraisal.

This book has a great value in theory and practicality. I believe that the publication of this book will sure enough to make the development of multibody system dynamics in theory and application, and provide a new powerful tool for dynamics design of mechanical system.

Professor Huang Wenhu
Mechanics Professor of Harbin Institute of Technology
The member of Chinese Academy of Engineering
November 18, 2007

序　二

经典传递矩阵法源于20世纪20年代，研究弹性构件组成的线性系统，本质上适合于解决一维问题。本书作者芮筱亭教授等十余年来完成了国家和国防重大科研任务，成功解决了多项难题，取得重要的技术突破，获得了国家和部委数十项科技奖励。在完成这些任务的过程中，本书作者取得了系统的理论成果：在1993年建立了多体系统传递矩阵法，并首先用于复杂多体发射系统特征值问题的研究；在1997年提出了多体系统增广特征矢量和增广算子的概念，建立了刚/弹性耦合的多体系统增广特征矢量正交性，并首次用模态方法实现了复杂多体发射系统动力响应的精确分析；在1998年提出了多刚体系统离散时间传递矩阵法，在1999年提出了多刚柔体系统离散时间传递矩阵法，首次实现了用多体系统传递矩阵法解决多刚体系统动力学问题和多刚柔体系统动力学问题，并用多体系统离散时间传递矩阵法实现了复杂多体发射系统动力学研究。

本书是作者曾参与其发展的多体系统传递矩阵法的总结，力求系统阐述该方法的基本原理、算法和应用。第一编（2~7章）线性多体系统传递矩阵法，第二编（8~11章）多体系统离散时间传递矩阵法，第三编（12~14章）多体系统传递矩阵法工程应用。部分内容曾主要在国内学术刊物上发表，我相信本书的出版必将有利于机械系统动力学和兵器专业，以及其他工程技术专业的师生和科技人员。

我认为值得向本书作者学习的不仅是书中的学术内容，而且还有作者们努力面向我国国家经济和国防建设主战场，科研与国家建设及国防结合、理论与实际结合的良好作风。

清华大学力学教授
中国科学院院士　黄克智

2007年12月

黄克智：力学家，俄罗斯科学院院士，国际断裂学会原副主席。

Foreword Two

The classical transfer matrix method was developed in 1920s and used to study the linear system composed of elastic components, essentially, applied to solve one dimension problems. Great research projects of Chinese government and national defense have been accomplished in recent over ten years. Many difficult problems have been solved successfully and important breakthroughs in technology have been acquired. Tens of prizes of science and technology of Chinese government, ministries and commissions have been gained by the authors of this book, Professor Rui Xiaoting etc. In the process of accomplishing these works, the theory has been developed systematically by the authors of this book as follows. Transfer matrix method of multibody system was developed in 1993 and it was used to study the eigenvalue problem of complex multibody launch system firstly. In 1997, the concept of augmented eigenvector and augmented operator was presented, the orthogonality of augmented eigenvectors of multibody system coupled with rigid and flexible bodies was developed, and the dynamics response of complex multibody launch system was exactly analyzed firstly using mode method. Discrete time transfer matrix method of multi-rigid-body system was developed in 1998. Discrete time transfer matrix method of multi-rigid-flexible-body system was developed in 1999. It is realized firstly to solve the dynamics problems of multi-rigid-body system and multi-rigid-flexible-body system using transfer matrix method of multibody system, and to study dynamics of complex multibody launch system using discrete time transfer matrix method of multibody system.

This book is a summarization of transfer matrix method of multibody system developed by the authors, strives to expatiate on the basic principle, algorithm and application of the method systematically. In this book, transfer matrix method of linear multibody system is introduced in the first part (chapter 2~7), discrete time transfer matrix method of multibody system is introduced in the second part (chapter 8~11), and the application of transfer matrix method of multibody system is introduced in the third part (chapter 12~14). Some contents of this book had been published in academic journals mainly in Chinese. I believe that the teachers, students, and researchers of

science and technology in the fields of mechanical system dynamics, weapon and other engineering technology will be surely benefited from this book.

I think, the most worth study from the authors of this book is not only the academic contents, but also their excellent feature in research facing to the main fields of construction of the national economy and national defense, combining the science research with national construction and national defense, and combining theory with practice.

Professor Huang Kezhi
Mechanics Professor of Tsinghua University
The member of Chinese Academy of Science
December, 2007