弹药发射安全性导论

Direction to Launch Safety of Ammunition

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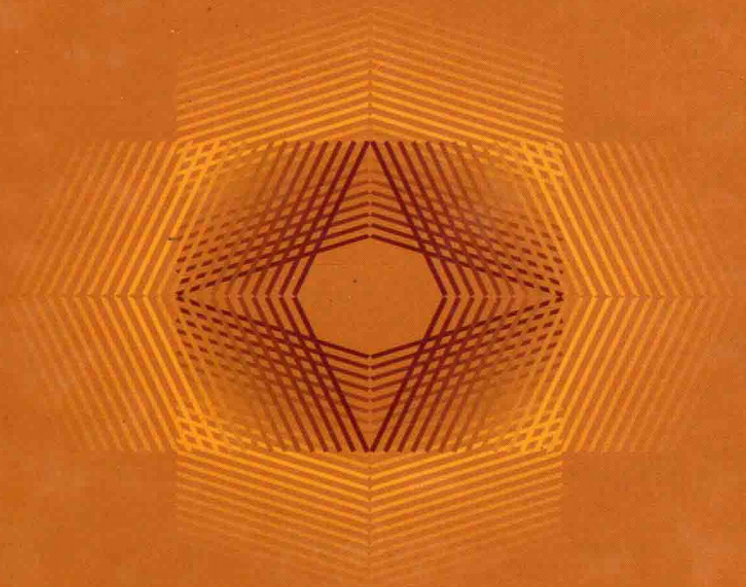

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内 容 简 介

本书首次系统介绍了弹药发射安全性的最新研究成果，提出并实现了基于武器系统发射动力学规律评估弹药发射安全性的思想，利用发射动力学和多体系统动力学国际最新理论和技术，立足于对弹、炮、药、引信武器系统一体化动力学过程的定量描述，首次从武器系统的角度研究发射装药、炸药装药、引信系统发射安全性，系统地建立了弹药发射安全性评估基本理论、数值仿真系统和物理仿真系统，建立了弹、炮、药、引信武器系统总体参数与发射装药燃烧过程及膛压、炸药装药力学行为及应力分布、引信机构运动及失效规律等武器系统动态性能之间的定量关系，数值与物理仿真再现了弹药膛炸和早炸的物理过程，为突破制约武器发展的弹药发射安全性瓶颈，提供了评估和提高弹药发射安全性的理论依据和技术手段。

本书可作为火炸药、引信、弹箭、火炮、弹道、工程力学专业工程技术人员、教师和研究生的参考书或教材。

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Direction to Launch Safety of Ammunition

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National Defense Industry Press

·Beijing·

Contents Introduction

In this book, the latest research results of launch safety of ammunition are introduced systematically. The thought to evaluate launch safety of ammunition according to the style of launch dynamics of weapon system is presented and realized. Using the newest theory and technology of launch dynamics and multibody system dynamics in the world, based on the quantitative description of dynamics process of weapon system including projectile, gun, propellant and fuze, the problems of launch safety of propellant charge, explosive charge and fuze are studied from the point of whole weapon system for the first time. The basic theory, numerical simulation system and physical simulation system for launch safety evaluation are established systematically. The quantitative relationship between the parameters of the global weapon system (including projectile, gun, propellant and fuze) and the dynamic performance of the weapon system (such as, the combustion process of propellant charge and bore pressure, dynamics behavior and stress distribution of explosive charge, mechanism motion and invalidation mode of fuze) is founded. The physical process of bore burst and early burst of ammunition are simulated. It provides theory basis and technology tools for evaluating and improving launch safety of ammunition, in order to break through the bottleneck restricted weapon development in launch safety of ammunition.

This book can be used as a textbook or a reference book for engineers teachers and graduated students in the specialties of propellant, explosive, fuze, projectile, gun, ballistics, engineering mechanics.

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、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、国防科技工业百名优秀博士学位获得者、创新团队带头人，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，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和发明奖 20 多项，获科技图书出版基金资助出版学术著作 5 部，在国内外发表学术论文 189 篇，SCI、EI 收录 80 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多项，国家发明专利 20 项，培养国内外博士后、博士研究生 30 多名。被世界级刊物 *Multibody System Dynamics* 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、Karlsruhe 大学应用力学研究所所长 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、Ernst-Mach 弹道研究所所长 Klaus Thoma 教授、Hamburg 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重大项目资助，分别作为上述 6 所大学和研究所的客座教授，在欧洲 14 所大学和研究所作了 30 多场特邀报告。作为国际理论与应用力学联合会主办“IUTAM Symposium on Multiscale Problems in Multibody System Contacts 2006”学术委员会亚洲区唯一委员，以及多个其它国际会议学术委员会委员，参与组织和主持国际会议并作大会特邀主题报告，中国、美国、俄罗斯、波兰、印度、奥地利等国多位院士肯定了其研究成果。

Author's Resume

Prof. Dr. Xiaoting Rui, 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 innovative group in science and technology of Jiangsu province. He is 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. He is vice-president of Applied Mechanics Society of China Ordnance Society, member of European Mechanics Society. He is "511" expert, one of 100 gainers of excellence doctor degree, head of innovative group 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. He has finished over 20 national key scientific research projects, and has obtained over 20 Chinese national and provincial prizes in science and technology and in invention. He has published 5 books supported by excellent science and technology fund, and 189 papers including 80 papers indexed by SCI and EI. He has obtained many book prizes, such as, the seventh China Book Prize, the army book prize and the first-class book prize of Jiangsu province etc. He has presented 20 national invention patents. More than 30 students home and abroad from his group have got post-doctor's and doctor's degrees respectively. He was invited as the co-editor of Special Issue of the world-class journal *Multibody System Dynamics*. He was invited respectively by famous scientists including Professor Werner Schiehlen, President of International Union of Theoretical and Applied Mechanics; Professor Jens Wittenburg, Head of Institute of Applied Mechanics in Karlsruhe University; 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 University of Technology; supported several times by key projects of German Research Council, as guest professors of above 6 universities and institute and gave over thirty invited academic lectures in fourteen universities and institutes in Europe. As the only member of Scientific Committee in Asia area of "IUTAM Symposium on Multiscale Problems in Multibody System Contacts 2006" sponsored by International Union of Theoretical and Applied Mechanics, and members of Scientific Committee of several International Conferences, he has taken part in organizing and presiding these international conferences and given invited keynote reports. His research results have won praises from members of academy of sciences and academy of engineering of some countries such as China, America, Russia, Poland, India, and Austria.

致 读 者

本书由国防科技图书出版基金资助出版。

国防科技图书出版工作是国防科技事业的一个重要方面。优秀的国防科技图书既是国防科技成果的一部分，又是国防科技水平的重要标志。为了促进国防科技和武器装备建设事业的发展，加强社会主义物质文明和精神文明建设，培养优秀科技人才，确保国防科技优秀图书的出版，原国防科工委于 1988 年初决定每年拨出专款，设立国防科技图书出版基金，成立评审委员会，扶持、审定出版国防科技优秀图书。

国防科技图书出版基金资助的对象是：

1. 在国防科学技术领域中，学术水平高，内容有创见，在学科上居领先地位的基础科学理论图书；在工程技术理论方面有突破的应用科学专著。

2. 学术思想新颖，内容具体、实用，对国防科技和武器装备发展具有较大推动作用的专著；密切结合国防现代化和武器装备现代化需要的高新技术内容的专著。

3. 有重要发展前景和有重大开拓使用价值,密切结合国防现代化和武器装备现代化需要的新工艺、新材料内容的专著。

4. 填补目前我国科技领域空白并具有军事应用前景的薄弱学科和边缘学科的科技图书。

国防科技图书出版基金评审委员会在总装备部的领导下开展工作，负责掌握出版基金的使用方向，评审受理的图书选题，决定资助的图书选题和资助金额，以及决定中断或取消资助等。经评审给予资助的图书，由总装备部国防工业出版社列选出版。

国防科技事业已经取得了举世瞩目的成就。国防科技图书承担着记载和弘扬这些成就，积累和传播科技知识的使命。在改革开放的新形势下，原国防科工委率先设立出版基金，扶持出版科技图书，这是一项具有深远意义的创举。此举势必促使国防科技图书的出版随着国防科技事业的发展更加兴旺。

设立出版基金是一件新生事物，是对出版工作的一项改革。因而，评审工作需要不断地摸索、认真地总结和及时地改进，这样，才能使有限的基金发挥出巨大的

效能。评审工作更需要国防科技和武器装备建设战线广大科技工作者、专家、教授，以及社会各界朋友的热情支持。

让我们携起手来，为祖国昌盛、科技腾飞、出版繁荣而共同奋斗！

国防科技图书出版基金

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序　一

由于共同的学术兴趣，我与芮筱亭教授由相遇到相识，由相识到熟悉，至今已近 20 个春秋。

1995 年，芮筱亭教授在其专著《多体系统发射动力学》中，首次将弹炮系统作为多刚柔体系统，把多体系统传递矩阵法作为系统动力学分析的基本工具，获得发射过程中全系统的运动情况，创建的多体系统发射动力学的理论体系与基本方法，突破了传统火炮发射动力学的基本物理数学模型，避免了冗繁的计算过程，已引起相关领域专家的广泛关注，是一项突破。为芮筱亭教授的后续科研工作奠定了理论基础，是芮筱亭教授科研征途上的一座里程碑。

谈起芮筱亭教授踏进弹药发射安全性研究，与其说是“主动请缨”，不如说是“被拉上马”，确有“奉命于危难之时”之势。粗看起来，芮筱亭教授擅长的发射动力学，是研究武器在发射过程中的受力及运动规律，进而研究控制受力与运动规律的理论、技术和试验测试方法，为科学评价和提高武器系统性能提供强有力的手段。乍看发射动力学似乎与弹药发射安全性毫不相干，可是，“树欲静而风不止”，由诸多复杂因素引起的膛炸、早炸等发射事故，国内时有发生，已引起国家管理部门的高度关注。武器装备的使用价值，主要表现在末端毁伤效应。武器装备末端毁伤作用实施的基本条件是，发射过程安全，飞行弹道稳定和准确命中目标。因此，确保弹药发射安全是武器系统正常运行的首要前提，也就是说，弹药发射安全性是武器系统总体可靠性的第一道关卡。战场上发生膛炸、早炸等发射事故，不仅造成自我损伤，甚至可能贻误战机；在非作战情况下发生膛炸、早炸等发射事故，不仅影响相关工作的正常进行，而且可能对有关人员造成心理压力。排除人为因素，发生膛炸、早炸等发射事故的根本原因在技术层面，但其影响却具有社会性。由此看来，膛炸、早炸等发射事故直接影响武器装备研制工作的正常进行及使用效益的正常发挥，在技术层面上形成武器装备发展的桎梏，在管理层面上成为武器装备系统工程正常运行的枷锁。面对膛炸、早炸等发射事故的出现，国家有关管理部门自然诚邀各路群贤出谋划策，协同攻关，芮筱亭教授列属其中并非偶然。面对国家的急需，芮筱亭教授凭借自己的理论底蕴和必胜信心，欣然步入弹药发射安全性研究领域，“敢问路在何方？路在脚下。”

弹药发射安全性是指在发射过程中弹药系统不出事故的性能。所谓事故，一般指膛炸、膛胀以及在安全距离内引信系统解除保险或早炸等现象；弹药在发射过程中发生事故，是世界性的普遍现象，不用说发展中国家，就是武器装备先进的国家，也难免屡有发生。因此，弹药发射安全性问题便成为世界公认的难题，即使是当事故发生后查明事故原因，寻求解决办法，往往绞尽专家的脑汁也不得其解，更不用说确保弹药发射安全是多么困难。面对这种世界性的难题，芮筱亭教授及其合作者以独特的视角，进行了长期探索，取得一系列成果，构成本专著的基本内容。

在弹药发射过程中发生的武器系统运动复杂多变，主要包括：发射药燃烧过程的化学——热功——机械等运动，弹体在膛内的径向运动及旋转运动，发射药、弹体及发射装置的多体系统运动，弹体脱离炮口在后效期火药气体和空气动力等作用下的空间飞行运动；还包括弹体与引信零部件的多体系统运动，等等。如何科学地处理这些复杂多变的运动，是研究弹药发射安全性的首要问题。

作者们依靠自身的理论优势，利用发射动力学理论和多体系统动力学理论，精确定量描述弹药发射过程中发生的武器系统一体化动力学过程，准确揭示弹药发射过程的物理本质，构成了全书基本的理论框架，比通常的局部分析方法或表象分析方法具有明显的先进性。这是本书的第一特点。

作者们运用系统工程的观点，深入研究发射装药发射安全性、炸药装药发射安全性和引信系统发射安全性基础理论与工程应用；研究弹、炮、发射装药、炸药装药、引信大系统的总体结构参数与系统动态性能之间的定量关系。这是本书的第二特点。

作者们以本书基本的理论框架为基础，阐明了一系列重要成果，以此构成本书的基本内涵，也是本书科学价值的主要表现。现将主要成果略摘于后。

研究内弹道两相流理论，建立了两相流动力学模型、方程及算法，创建发射装药燃烧与力学环境物理仿真系统，实现了挤压破碎的物理仿真，为发射装药系统发射安全性理论研究及工程评估提供一种有效方法。书中建立的发射装药挤压破碎动力学模型和数值仿真技术，实现了挤压破碎的随机数值模拟，为药床挤压破碎研究提供数值基础模型。

研究炸药装药发射安全性理论及相关试验技术，建立的炸药装药发射安全性仿真系统，是炸药装药发射安全性评估的重要手段。

建立了弹、炮、药、引信大系统的总体结构参数与发射装药的燃烧性能参数、

炸药装药发射环境参数和引信机构运动参数等之间的数量关系的数字仿真系统，可为弹药发射安全性研究提供相关的弹道环境参数。

开发引信机构运动的模拟试验装置，实现引信机构运动和引信运动弹道环境的物理仿真，进而建立了引信机构安全性试验物理仿真系统和试验技术，为引信系统发射安全性评估提供新型技术手段。面对我国曾经发生的几起引信早炸事故，在排查造成事故的直接物理因素时，芮筱亭教授及其合作者利用引信安全机构物理仿真系统和引信发射安全性试验技术，对相关的引信系统做仿真试验，获得了其安全机构的运行规律，复现了其早炸的物理过程，找到了引发事故的真实物理原因，为其改进设计提供了最关键的依据。这是本书在工程应用中最具闪光意义的表征。

本书揭示出弹药发射过程的基本规律，建立了新的试验、测试方法，确立了获得弹药发射安全性判据的过程，提出了提高弹药发射安全性措施，综合起来，构成本书的总体特点。

本书虽非鸿篇巨著，但内容十分丰富，是弹药发射安全性领域具有重要理论价值和应用前景的学术专著。本书以作者们近 10 多年来在弹药发射安全性领域的理论研究成果及其工程实践为重点，但又博采众长，系统全面地介绍国内外相关研究的整体概貌和最新成果。全书总体结构层次分明，数理方法新颖灵巧，试验程序精练可行，具有理论的严谨性和工程应用的可操作性。

本书的出版犹如春风化雨，必将为弹药发射安全性研究及工程应用带来勃勃生机。

我坦然写下以上言词，是我阅本书原稿的体会与拙见，也是对芮筱亭教授及其合作者多年辛勤工作的祝愿和希望，但愿也能为读者阅读本书提供一些背景材料和有益的引导。是为序。

中国人民解放军总装备部科学技术委员会顾问 马殿荣

2008 年 6 月 18 日

马殿荣，武器发展战略专家，少将。

Foreword One

Because of the same academic interest between Professor Rui and me, it has gone through near 20 years that the relationship between us from encounter to know and then becoming familiar.

In 1995, Professor Rui in his book *Launch Dynamics of Multibody System*, firstly treats projectile and gun system as multi-rigid-flexible-body system, takes transfer matrix method of multibody system as a basic tool to analyze the multibody system dynamics, studies the movement of entire system during the launch process. The theory system and basic method of launch dynamics of multibody system developed by Professor Rui have broken through the basic physical and mathematical model in traditional launch dynamics of gun, and avoided the burdensome computation process, to which has been paid widely attention by experts in correlative research field. It is a breakthrough and settled a theory foundation for his following science research, was a milestone on his journey of science research.

Describing Professor Rui setting foot in study of launch safety of ammunition, it would be better to said "have to do" than to said "like to do". In fact, he received the task at difficult time. Professor Rui was good at launch dynamics, in which the force acted and movement style of weapon in launch process are studied, then the theory, technology and testing method controlled these force and movement are studied, and which provides powerful tool for scientifically evaluating and improving the performance of weapon system. It seems that launch dynamics is no relation to launch safety of ammunition. But, launch accidents, such as, bore burst and early burst caused by many complex factors occurs frequently, has been paid great attention by national management department. The value of weapon equipment in practice mainly is its terminal damage effect. The basic conditions of weapon equipment carrying out its terminal damage effect are launching safety, flight stability and accurate hitting the target. Therefore, guaranteeing launch safety of ammunition is the first precondition of weapon system working in order, in other words, the launch safety of ammunition is the

first gate of whole reliability of weapon system. If the launch accidents, such as, bore burst and early burst taking place in battlefield, it not only produce self-damage, but may procrastinate the military opportunity. If it taking place under the situation of non-battle, not only the correlative routine work will be influenced, but may result in the mentality pressure to correlative persons. Excluding the artificial factor, the basic reason of bore burst and early burst belongs to the level of technology, but it has the influence to sociality. By this token, launch accidents, such as, bore burst and early burst directly interfere with the routine research work and ordinary value of weapon equipment in practice, and form a huge obstacle in technology to weapon equipment development and in management to weapon equipment system engineering. Facing to the launch accidents, such as, bore burst and early burst, national management department invites honestly experts in many fields to supply ideas and tackle key problem corporately. So, it is not occasional that Professor Rui was arranged in them. Under the case of urgent requirement of country, Professor Rui resolutely set foot in the field of launch safety of ammunition based on his own theory foundation and successful confidence. "Where is the way? Road is under your foot."

The launch safety of ammunition is the performance that the ammunition system does not take place accidents in the launch process. The so-called accident commonly refers to the phenomena, such as, bore burst, fuze system release from insurance or early burst within safe distance. It is a worldwide universal phenomenon that accidents occur in launch process of ammunition, not only in developing country, but also in the developed country with advanced weapon equipment. Therefore, the launch safety of ammunition becomes a worldwide difficult problem. It is very difficult to find out the reason even after accidents take place. To solve the difficult problems, experts rack their brains sometimes is not enough, say nothing of insuring the launch safety of ammunition. Facing to the worldwide difficult problem, Professor Rui and his co-workers have carried on a long-term exploration from a unique angle, and acquired a series of achievements, all which forms the basic content of this book.

The movement of weapon system in launch process is complex and changeful, mainly includes: the motion of chemistry, thermodynamics and mechanism etc during

propellant combustion; the radial and rotary motion of projectile in gun tube; the motion of multibody system including propellant, projectile and launching device; the flying motion of projectile in space under the action of aerodynamic pressure and propellant gas pressure; the motion of multibody system including projectile and parts of fuze etc. How to scientifically deal with these complex movements is chief problem to study the launch safety of ammunition.

Depending on their own advanced theory, the authors describe quantitatively and exactly the dynamics process of weapon system as an integrative in launch process by using the theory of launch dynamics and multibody systems dynamics. The physical mechanism of launch process is disclosed exactly. These forms the basic theory frame of this book, the method used in this book has obvious virtues compared to the ordinary partial analysis method. This is the first feature of this book.

Using the viewpoint of system engineering, the authors deeply study the foundation theory and engineering application of launch safety of propellant charge, launch safety of explosive charge and launch safety of fuze system, study quantitative relationship between the structural parameters of big system (including projectile, gun, propellant charge, explosive charge and fuze) and the dynamic performance of system. This is the second feature of this book.

Based on the theory frame of this book, the authors expatiate on a series of important achievements, which compose the basic contents of this book and are the main characteristics of science value of this book. Some of the main achievements are resumed in the following.

The theory of two-phase flow interior ballistics is studied, the model, equation and algorithm of two-phase flow dynamic are established, and the physical simulation system of combustion and mechanics situation of propellant charge in tube is invented and developed, the physical simulation of compression and fracture of propellant charge is realized, provide a effective method for theoretical research and engineering evaluation of launch safety of propellant charge. The compression and fracture dynamics model of propellant charge and the corresponding numerical simulation technology is established, the stochastic numerical simulation of compression and