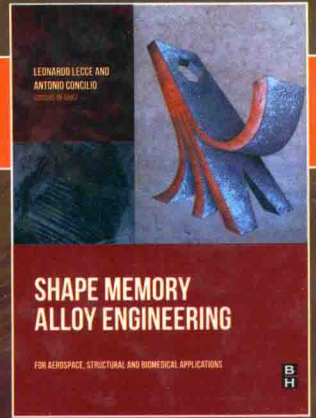




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Leonardo Lecce,  
Antonio Concilio 编著

# 形状记忆合金工程学： 航空航天、结构和生物医学应用

Shape Memory Alloy Engineering:  
For Aerospace,  
Structural and Biomedical Applications

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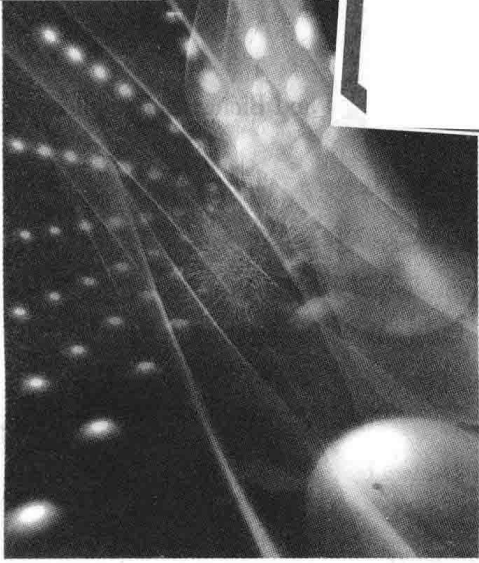
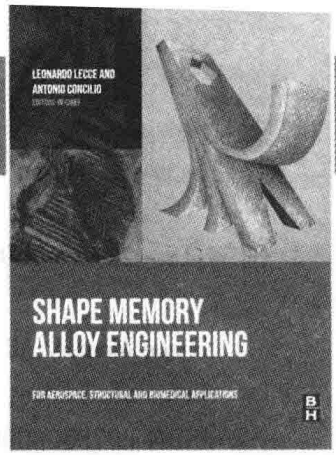


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# 内容简介

本书主要介绍了形状记忆合金(SMA)行为、建模、工程潜力及其在航空学、生物医学以及土木工程中的应用,探讨了SMA设计、数值(FE)表征和可用材料的最新进展,论述了SMA装置的案例研究、成功应用、典型故障和局限性。本书讨论了一系列新的形状记忆合金材料的表征过程和结果,将数值(FE)模拟和积分程序集成到商业软件,实现基于形状记忆合金的驱动系统的程序设计和优化。该书适用于材料、机械和航空航天研究人员以及在形状记忆合金领域从事航空和其他应用的研究生使用。

## 作者简介

**Leonardo Lecce** 那不勒斯费德里克二世大学教授。2000—2006年,任航空工程系主任。多次担任欧盟专家委员会评估研究计划成员及意大利航空航天研究中心(CIRA)科学委员会成员。2013年任意大利航空航天协会主席。主要研究领域为运输系统噪音和振动的预测和控制、开发集成创新智能材料的结构和系统、结构的损坏检测和健康监测以及飞机机翼和控制面的变形。发表的论文超过250篇。

**Antonio Concilio** 意大利航空航天研究中心教授。1988年获得意大利那不勒斯费德里克二世大学航空工程荣誉学位,并于1995年获得航空工程博士学位。1989年以来,任意大利航空航天研究中心(CIRA)研究员。主要研究领域为车辆噪声和振动控制、智能结构系统设计以及飞机机翼和控制面的变形。

# 序

本书的目标读者是博士研究生、博士后研究员和业内的专业人士，编写本书的目的是为了帮助他们完整地理解形状记忆合金(SMA)的主要特点和在不同领域中的应用，从而推动其实际应用。本书为读者广泛理解 SMA 行为、建模及其工程潜力提供详细信息，专门论述了 SMA 在航空学中的应用。超弹性和形状记忆效应是 SMA 单一的微观行为的不同证据。这种全面的方法使本书在当前已有的同类出版物中独树一帜。为了给读者一个完整的印象，本书在结束部分阐述了 SMA 在生物医学和土木工程中的相关应用；探讨了 SMA 设计、FE 表征和可用材料的最新进展；报道了 SMA 装置的案例研究、成功应用、典型故障和局限性，描述了当前制造技术的最新水平。

本书按照专题方式编排，每一专题针对 SMA 的某一特定主题，从一般概述到真正的结构项目实施进行论述。本书第 1 部分为绪论——回顾与展望，其余部分结构如下：第 2 部分——材料；第 3 部分——建模；第 4 部分——航空航天学；第 5 部分——生物医学和土木工程应用。按照每一步骤进行全面分析，借助广泛的参考书目，展开具体和深入的研究。每部分分成 3 章，分别就相关主题展开专门讨论，涉及与热力学、晶体学、弹性理论、结构动力学等有关的一些基本概念，其中部分引自参考书目。

本书以关于 SMA 发展和应用展望的绪论开篇(第 1 章)，带领读者进入 SMA 的起源、现状和应用展望的时间旅行。本书探讨 SMA 的发现、应用与根据需求和技术指标进行的进一步开发，可为读者提供必备的知识应对作为智能材料和结构领域一部分的 SMA 工程学。

本书第 2 部分研究 SMA 材料的基本原理、实验现象、主要性

能(第2章)、表征方法(第3章)、材料设计与制造(第4章),主要探讨目前影响最为广泛的镍钛化合物 SMA,顺便提及多孔 SMA 等新材料的研究进展。最后,概述 SMA 与腐蚀、时效和疲劳有关的宏观行为。

第3部分探讨众多研究者构建的弹性本构模型及其采用的不同方法。概述不同模型的特点、正反评价和重要讨论,包括一维(第5章)和三维线性与非线性建模(第6章)。非线性模型用作 FE 表征的方法,为读者在已有方法的基础上开发自己的仿真代码提供机会。第7章展示一些采用商业代码开发的可用的 SMA 模型。

本书第4部分描述 SMA 结构系统设计准则及其应用。首先讨论 SMA 设备的制造方法和基本设计准则(第8章)。然后确定一个逻辑流程图,图示制备和优化基于 SMA 结构的步骤,开发和编制选择标准(第9章)。接下来,阐述航空航天集成系统的实例和与标准解决方案有关的新挑战(第10章)。最后全面论述航空航天领域的构想设备和正在运行的设备。

本书以广泛综述 SMA 在其他有关技术部门,即生物医学和土木工程的当前应用结束。由于这些材料的高度生物相容性, SMA 最大的全球用途可能出现在生物医学领域,从口腔正畸学到普通外科和骨科(第11章)。第12章专门讨论 SMA 系统在心血管领域中使用的日益增长,这可能是顶级的科学和商业分支。最后回顾 SMA 在土木工程中的其他应用实例: SMA 相关技术有潜力用于其他有关部门,包括抗震设防、考古遗迹和历史建筑物保护(第13章)。

本书主编在研究其他形式的智能材料,即压电材料和磁致伸缩材料的漫长过程中,发现了 SMA 这一引人入胜的领域。当发现 SMA 的极强性能和广泛应用时,他们简直被迷住了。随后开展的工作难以置信地振奋人心,并在航空航天结构变形领域取得了丰富的有趣的成果。本书是主编与许多科学家和同行在共同探索 SMA 这一广泛领域及其应用过程中的幸运成果。

主编衷心感谢所有特约作者，正是他们积极的参与和专业的奉献精神，才使这么多的知识和专业经验有可能收集在本书中。主编还要感谢出版商爱思唯尔，尤其是感谢 Stephen Merken 和 Jeff Freeland，他们指导主编克服困难，组织众多的有关作者并最终完成本书。

**Leonardo Lecce**

**Antonio Concilio**

## ABOUT THE EDITORS-IN-CHIEF



**Prof. Leonardo Lecce** graduated in 1971 with honors in Aeronautical Engineering at the University of Naples Federico II and has spent his academic career at the same University. Currently, he is Full Professor of Aerospace Structures. From 2000 to 2006 he was the Aeronautical Engineering Department Chair. He has supervised more than 250 Graduation and 20 Doctoral (PhD) theses. He has been a member of the EU Expert Commission for the evaluation of research proposals many times. He has taken up appointment as a member of the Scientific Committee at the Italian Aerospace Research Centre (CIRA) many times, too. He is a member of the Board of the Italian branch

of the Advisory Council for Aeronautics Research in Europe (ACARE), and since 2006, he is a member of the Executive Committee of the European Association of Structural Health Monitoring. Founder of the ex-Alumni Association of the Aerospace Engineers at the University of Naples Federico II (AIAN), he was its President for many years. In 2013, he was named President of the Italian Association of Aeronautics and Astronautics, after having directed the Naples Chapter since 2010.

Prof. Lecce's main research interests are prediction and control of noise and vibration in transportation systems; development of structures and systems integrating innovative smart materials; damage detection and health monitoring of structures; and morphing of aircraft wing and control surfaces. He was Scientific Responsible for the Federico II University for several EU and nationally funded research contracts. He was the European Scientific Coordinator of the MADAVIC (Magnetostrictive Actuators for Damage Analysis and Vibration Control, 5th Framework Programme, FP) and MESEMA (Magnetoelastic Energy Systems for Even More Electric Aircraft, 6th FP) projects. Within the 7th FP (2007–2013), he was the Coordinator of Airgreen (a company association made of nine partners), Associate Member of the Alenia-managed Green Regional Aircraft Consortium (GRA), a part of the EU Joint Technology Initiative (JTI), Clean Sky—Integrated Technological Demonstrator (ITD).

The results of his research activities are reported in more than 250 papers published in national and international journals and conference proceedings.



**Dr Antonio Concilio** was born in Salerno, Italy, on December 23, 1964. In 1988 he took his degree with honors in Aeronautical Engineering at the University of Naples Federico II, Italy, where in 1995 he also achieved his PhD in Aerospace Engineering. In 2008, he attained the ECATA ABI Diploma (European Consortium for Advanced Training in Aerospace—Aerospace Business Integration) on Aerospace Environment, Integrated Product Development, and International Project Management at the University of Pisa, Italy. Since 1989, he is Researcher at the Italian Aerospace Research Centre (CIRA). Between 1995 and 2000, he was Head of the Area of

Methods in Vibroacoustics. In 2000, he was appointed Head of the newborn Smart Structures Laboratory, later integrated with the Vibration and Acoustics Lab (2002). Since 2012, he is National Relationship Manager at CIRA. He has represented the company in a number of specific liaisons with external firms. Among the founders, he is Secretary of the ex-Alumni Association of the Aerospace Engineers at the University of Naples Federico II (AIAN) and member of the Italian Association for Aeronautics and Astronautics (AIDAA).

Since 2005, Dr Concilio is Lecturer at the Doctorate School at “Federico II” University (SCUDO) on “Smart Structures: Theory and Applications”. Since 2004, he has held courses on the same subject for postgraduate students from national programs funded by the Italian Ministry for Education and Research and Regione Campania. In 2007, he held a course on Smart Structures within a “Master in Systems Engineering”, jointly organized by the University of Missouri-Rolla and the Federico II University. His main research interests are vehicles’ noise and vibration control for increased comfort and devices protection; smart structural systems design; and morphing of aircraft wing and control surfaces. He was Scientific Responsible for CIRA of several EU and nationally funded research contracts on smart structures and noise and vibration control. He was the European Scientific Coordinator of the IDEA PACI project (Identification of an Aircraft Passenger Comfort Index, 1998–2001) and the National Project Manager of the PON SMART project (Design and Realization Methods of Intelligent Systems for the Monitoring and Control of Aeronautic and Aerospace Structures, 2002–2006). Since 2011, he has been leading an international team for developing an Adaptive Trailing Edge (release expected by 2015) within the EU SARISTU project (Smart Aircraft Intelligent Structures).

The results of his research activities are reported in over 140 papers, more than 20 of which were published in national and international journals.

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In 1998, he took his master degree in Aeronautical Engineering at the University of Naples Federico II, Italy, defending a thesis on heat transfer due to jets in cross-flow. In 2002, he defended his PhD thesis on morphing architectures for transonic performance enhancement. Since 2002, he is researcher at the Italian Aerospace Research Centre (CIRA), Italy, where he performs research activities in the Smart Structures & Vibroacoustics Laboratory, within National and European frames. He published more than 60 papers on international journals and symposia. Since 2009, he is a regular reviewer of the *Journal of Intelligent Material Systems and Structures*. In 2012, he applied for an EU patent concerning a droop nose architecture for aircraft wings (pending). In 2013, he was awarded an EU/US patent on an aircraft Shape Memory Alloys (SMA) morphing flap.

### **Vincenza Antonucci** (Section 2 Editor; Chapters 2 and 3)

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### **Edoardo Artioli** (Chapter 6)

He is assistant professor of mechanics of solids at the Department of Civil Engineering and Computer Science of the University of Rome — Tor Vergata, Italy. At the same university, he is member of the scientific board of the PhD program in civil engineering. His research interests are constitutive modeling of advanced materials, nonlinear finite element methods, and homogenization methods for functionally graded composite materials. He published 16 papers in international journals (h-index = 8 based on SCOPUS).

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He is full professor of mechanics of solids at the Department of Civil Engineering and Architecture of the University of Pavia, Italy (where he is also department chair), and research associate at the Institute of Applied Mathematics and Informatic Technologies (IMATI) of the National Research Council (CNR), Italy. He is main proponent of the PhD Program in Civil Engineering and Architecture at University of Pavia, Italy. He is vice-president of the European Community of Computational Methods in Applied Sciences (ECCOMAS). Recipient in 2012 of the International Association for Computational Mechanics' Fellow Award, he published more than 120 papers in international journals (h-index = 29 based on ISI and = 31 on SCOPUS).

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He is senior engineer in rotor structures at Sikorsky Aircraft, USA. Previously, he was research associate and adjunct faculty at Rensselaer Polytechnic Institute, USA, postdoctoral scholar at Penn State University, USA, and research officer at Swansea University, UK. He received his PhD in aerospace engineering at the University of Naples Federico II, Italy, with a thesis in smart materials and morphing structures for aeronautical applications. He published several papers in international peer-reviewed journals and has been awarded EU and US patents. He is member of American Institute of Aeronautics and Astronautics, American Society of Mechanical Engineers, and American Helicopter Society.

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**Antonio Concilio** Extended biographical information of Antonio Concilio are reported into the section "About the Editors-in-Chief" (Editor-in-Chief; Section 4 Editor; Chapter 1)

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Since 2004, he is researcher at the Vibroacoustics & Smart Structures Laboratory of the Italian Aerospace Research Centre (CIRA), Italy. In 2004, he received his master degree at the University of Palermo, Italy, and in 2012, he took his PhD in aeronautics at the Imperial College of London, UK. His research interests include adaptive structures, wing morphing, and smart materials for enhanced aircraft performance. He is author of more than 30 papers, published on national and international journals and conference proceedings. He is an independent reviewer for three international journals. In 2014, he received the “Best Paper Award” at the “Greener Aviation: Clean Sky Breakthroughs and Worldwide Status” Conference, Bruxelles, Belgium.

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**Leonardo Lecce** Extended biographical information of Leonardo Lecce are reported into the section “About the Editors-in-Chief” (Editor-in-Chief; Section 1 Editor; Chapter 1)

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**Alfonso Martone** (Chapter 2)

# PREFACE

The book is addressed to PhD students, postdegree researchers, and professionals in the industry who want to have a complete survey on the main characteristics of shape memory alloys (SMA) and their different fields of uses in order to proceed with practical implementations. The book provides the readers with details for a wide understanding of the SMA behavior, their modeling, and their potentialities in engineering. Superelastic and shape memory effects are considered, different evidences of a single microstructural behavior. This comprehensive approach makes the book a unique element of its kind in the current scenario of available publications. Aeronautics is specially addressed while, in order to give a complete vision, a conclusive section is dedicated to relevant employments in biomedical and civil engineering. The latest advances in design, FE representations, and available materials are dealt with. Case studies, successful applications, and typical failures and limitations of SMA devices are reported, together with a description of the current manufacturing technologies.

The book is arranged in monographic sections, each focusing on a particular topic concerning SMA, from a general overview to the utilization into real structural projects. Apart from a general introduction (Section 1—Historical survey and perspectives), the work is structured as follows: Section 2—The material; Section 3—Modeling; Section 4—Aeronautics; Section 5—Biomedical and civil engineering. A complete survey is performed at each step, forwarding to a wide bibliography for specific and deeper studies. Sections are further organized into three chapters dealing with a specific argument of the related topic. Propaedeutic matters are some basic concepts related to: thermodynamics, crystallography, theory of elasticity, structural dynamics, and others, some of which referred in bibliography.

The work starts with a general introduction about the evolution and the perspective applications of the SMA (Chapter 1). It gives the reader a sort of time trip, illustrating the origins of SMA, their status and, in perspective, the future use of these materials. How they were discovered, how they are used, and how they could develop according to further needs and specifications, may furnish the readers the necessary *forma mentis* to face with the relatively new world of SMA engineering as part of the more general field of the smart materials and structures.

The manuscript continues with the study of SMA as materials, moving from the fundamentals, highlighting their experimental appearance and their main properties (Chapter 2), illustrating the way and the strategy to characterize their behavior (Chapter 3), and discussing some operations connected to their manufacture, including material design concepts (Chapter 4). NiTi compounds are mainly considered, currently the

most diffused SMA. Hints about the recent development of new substances as porous SMA are also given. Finally, an overview about SMA macroscopic behavior, connected to corrosion, aging, and fatigue aspects is afforded.

The constitutive elastic models and the different philosophy they have been constructed by many and many researchers are then reckoned with. Characteristics, pro and contra of different formulations are outlined, together with critical discussions about different approaches, including 1D (Chapter 5) and 3D linear and nonlinear modeling (Chapter 6). How the nonlinear models are used to produce FE representations is shown, providing the readers with the opportunity to develop their own simulation codes, on the basis of the referred philosophy. A presentation of some available SMA modelizations in commercial codes concludes the section (Chapter 7).

The book refers finally to the description and the application of SMA structural systems design criteria. Before of all, how SMA devices are manufactured and what are the basic design criteria, are discussed (Chapter 8). A logic flow diagram is then formalized, schematizing the steps for outlining and optimizing SMA-based architectures. Selection criteria are developed and formulated (Chapter 9). The book then illustrates actual examples of integrated systems for aeronautics and the rise of new challenges with respect to standard solutions (Chapter 10). A wide survey of conceived or already operative devices in the aerospace field completes the section.

A wide overview of current applications in other relevant technological sectors concludes the work, namely biomedical and civil engineering. The first is perhaps the area where, thanks to the high biocompatibility level of these materials, the largest worldwide SMA usage takes place, from orthodontics to general surgery and orthopedics (Chapter 11). A single chapter is devoted to the more and more growing use of SMA-based systems in the cardiovascular field, perhaps the top scientific and commercial branch (Chapter 12). Other civil engineering examples are finally recalled: SMA-related technology potentialities are in fact opening to a lot of relevant sectors, including the seismic protection and the preservation of the archaeological patrimony and historical buildings (Chapter 13).

The editors have discovered the fascinating field of the SMA during their long activity, dealing with other form of smart materials, namely piezoelectrics and magnetostrictives. They were simply fascinated when they discovered the great capabilities and the wide field of use of SMA. The resulting work was incredibly stimulating and rich of interesting results in the field of the aerospace structures morphing. This book is the outcome of the editors' fortunate chance to meet during this adventure many other scientists and colleagues, carrying out very relevant activities in the same field of application or in the general field of the SMA.

The editors want to thank warmly all the contributing authors who with their strong engagement and professional dedication have made possible to collect in this book so

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