Smart Structures

Smart structures and smart structural components have unusual abilities: they can sense a change in temperature, pressure, or strain; diagnose a problem; and initiate an appropriate action to preserve structural integrity while continuing to perform their intended functions. Smart structures can also store processes in memory and learn to repeat the actions taken. Among the varied applications of smart structures are aircraft sensors that warn of impending cracks and medical devices that monitor blood sugar and deliver insulin.

This text provides the basic information needed to analyze and design smart devices and structures. Among topics covered are piezoelectric crystals, shape memory alloys, electrorheological fluids, vibration absorbers, fiber optics, and mistuning. A final chapter offers an intriguing view of biomimetics and design strategies that can be incorporated at the microstructural level, deriving inspiration from biological structures.

The design of smart structures is on the cutting edge of engineering research and development, and there is a great need for an introductory book on the subject. This book will be welcomed by both students and practicing engineers.

A. V. Srinivasan is President of Strategic Technologies, Inc. and a Distinguished Visiting Professor at Worcester Polytechnic Institute.

D. Michael McFarland is the President of Caber Engineering in Glastonbury, Connecticut.

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ANALYSIS AND DESIGN

A. V. SRINIVASAN
Strategic Technologies, Inc.

D. MICHAEL McFARLAND
Caber Engineering, Inc.

CAMBRIDGE
UNIVERSITY PRESS

CAMBRIDGE UNIVERSITY PRESS
Cambridge, New York, Melbourne, Madrid, Cape Town, Singapore,
São Paulo, Delhi, Dubai, Tokyo, Mexico City

Cambridge University Press
32 Avenue of the Americas, New York NY 10013-2473, USA

www.cambridge.org
Information on this title: www.cambridge.org/9780521659772

First published 2001

A catalog record for this publication is available from the British Library

Library of Congress Cataloging in Publication data

Srinivasan, A. V

Smart structures : analysis and design / A. V. Srinivasan, D. Michael McFarland.

p. cm.

Includes bibliographical references and index.

ISBN 0-521-65026-7 – ISBN 0-521-65977-9 (pbk.)

1. Smart materials. 2. Adaptive control systems. 3. Piezoelectric devices. 4. Microactuators – Materials. 5. Shape memory alloys. 6. Biosensors. I. McFarland, D. Michael, 1962– II. Title.

TA418.9.S62 S65 2000
620.1′1 – dc21 00-023038

ISBN 978-0-521-65026-7 Hardback
ISBN 978-0-521-65977-2 Paperback

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Preface

Structural design in the traditional context once simply meant a selection of the dimensions of load-bearing components of a structure. Essentially two disciplines, mathematics and materials science, were integrated to obtain a structural design. Mathematics ensured equilibrium of the structure, and materials science provided material properties such an modulus of elasticity, yield stress and ultimate stress. A suitable material was chosen, and the design was considered complete upon establishing a factor of safety and a further check to ensure structural stability using a criterion such as Euler load to prevent buckling. Such an approach was considered adequate as long as the material selection was limited to wood and metals.

Advanced research in materials science resulted in man-made materials, such as plastics and composites. Selection of unusual shapes in the design of structural components and ideas of embedding sensors to monitor complex strain fields then took hold. Furthermore, materials with unusual properties were discovered: properties by which material behavior can be varied depending upon the phase of the material (e.g., shape memory alloys, such as NiTiNOL, whose phases change at critical temperatures), the poling direction (as in piezoelectric materials such as PZT), and the level of electric field (electrorheological fluids). These discoveries have opened up the design space to such an extent that possibilities of designing structures that can not only monitor themselves but also adapt to the environment are now contemplated by the research community.

This is the background that has ushered in an era of research efforts leading to "smartness" in structural design. As funds have become available to pursue research in this area, terminologies have been introduced to define the field of study. Not unexpectedly, a variety of names, such as smart materials, intelligent materials, and adaptive structures, have been proposed.

A certain amount of exaggeration is to be expected when a new field emerges, but to ascribe cognitive abilities to a structure would be, in our opinion, beyond the capabilities that can be integrated into a structural design. Similarly, we wish to emphasize that materials have properties that may be interesting and unusual, but smartness can be

defined in the context of structures only when materials properties are exploited to serve a design function better than is possible through a conventional structural design.

It is with this conviction that we introduce the concept of a complete structure that can be the basis, in the new millennium, to design structural components. The viewpoint proposed in this book is that functions of sensing, diagnosing, and assessing the health of structures and actuating structures should all be integrated to form the complete structure, and this philosophy forms the basis for developing smart structures. It is important to note that smartness can be inherent in a structure by virtue of the material microstructure or the design itself. For example, a rope is a smart structure because of the hierarchical design in which individual wires are assembled to form a strand and several strands woven into a wide variety of rope arhitectures. The concept of hierarchy is incorporated into the design and provides the basis for smartness. Rope structures simulate a similar biological structure, tendon, whose architecture is highly hierarchical, with seven levels varying from atomic to microlevels. Thus, one is tempted to examine structural systems in nature that could provide broad guidelines for the structural engineering design of man-made components. Although it is futile to look for engineering analogs in the biological world, certain strategies developed by biological structures through evolution could be helpful in conceiving, designing, developing, manufacturing and testing smart structures.

This book is developed through courses taught first as a graduate seminar at the University of Connecticut in 1994 and 1995 and later as a regular course open to senior undergraduate and graduate students at Worcester Polytechnic Institute in 1996 and 1997. Also, a special week-long course was conducted in June of 1997 at the University of Kassel in Germany covering piezoelectrics, shape memory alloys, gyroscopic vibration absorbers, mistuning and biomimetics. In addition, the organization of the chapters draws upon the authors' research efforts in the areas of vibration absorption, multiplexing shape memory wires in composites to enhance frequency bandwidth of plate-like structures, fiber optics, mistuning and biomimetics. The example problems chosen are aimed at driving home the principles discussed in the text and provide an opportunity to the student to apply the same in typical engineering structural design situations.

We believe that the time is ripe for innovation by means of which smartness in structures can come about through development of new materials with required properties and new designs that allow integration of multiple functions of sensing, diagnosing, and actuating the structure, leading to vastly enhanced structural integrity. Innovations are therefore needed in a variety of engineering disciplines that cover the functions described above. Analysis procedures that permit modeling at the microstructural level are needed, as are instruments that sense and actuate at the level. Manufacturing processes that allow tailoring structural components from the micro to macro levels are needed. We hope that the topics presented in this text book serve to provide some inspiration to scientists and engineers in academia, government and industry.

The first author thanks (1) his wife Kamla for her continuing support, encouragement and patience during the preparation of this book, (2) his coauthor without whose keen

interest and cooperation this effort would not have been possible and (3) Professor M. Noori for giving him the oppportunity to develop the course at WPI.

The second author wishes to thank the friends and family members whose sustained interest and encouragement were invaluable during the completion of this manuscript, and his coauthor for the example he has set through his scholarship and for the friendship that has made a sometimes arduous task much more rewarding than it would otherwise have been.

Many colleagues have helped in the course of preparing this textbook. Special thanks are due to Professor Dryver Huston of the University of Vermont for reviewing the chapter on fiber optics; to Dr. L. McD. Schetky and Dr. Ming Wu of Memry Corporation for help in obtaining permissions from Raychem Corporation to use several illustrations pertaining to the design of SMA actuators; to Professors B. F. Spencer and Erik A. Johnson of the University of Notre Dame for assistance with the chapter on electrorheological and magnetorheological fluids; to Professor Daniel J. Inman of the Virginia Polytechnic Institute, himself an authority in the field of smart structures, for his insights into the process of writing a textbook; and to Mr. Richard W. Monahan, whose patience and attention to detail have contributed in many ways to the quality of this book.