FINITE ELEMENT ANALYSIS IN MANUFACTURING ENGINEERING

A PC-BASED APPROACH

EDWARD R. CHAMPION, Jr.

Finite Element Analysis in Manufacturing Engineering

Edward R. Champion, Jr.

McGraw-Hill, Inc.
New York St. Louis San Francisco Auckland Bogotá
Caracas Lisbon London Madrid Mexico Milan
Montreal New Delhi Paris San Juan São Paulo
Singapore Sydney Tokyo Toronto

Library of Congress Cataloging-in-Publication Data

Champion, Edward R.,
Finite element analysis in manufacturing engineering /
Edward R. Champion, Jr.
p. cm.
Includes bibliographical references and index.
ISBN 0-07-010510-3
1. Finite element method. 2. Production engineering—Mathematics.
I. Title.
TA347.F5C45 1992 91-44248
670.42—dc20 CIP

1 2 3 4 5 6 7 8 9 0 DOC/DOC 9 8 7 6 5 4 3 2

ISBN 0-07-010510-3

The sponsoring editor for this book was Gail Nalven, and the production supervisor was Suzanne W. Babeuf. It was set in Century Schoolbook by North Market Street Graphics.

Printed and bound by R. R. Donnelley & Sons Company.

Finite Element Analysis in Manufacturing Engineering

Other McGraw-Hill Books of Interest

IRESON/COOMBS • *Handbook of Reliability Engineering and Management*

KAEWERT/FROST • *Developing Expert Systems for Manufacturing*

LUBBEN • *Just-in-Time Manufacturing*

MAYNARD • *Industrial Engineering Handbook, 4E*

NEVINS/WHITNEY • *Concurrent Design of Products and Processes*

STARK • *Managing CAD/CAM*

TEICHOLZ/ORR • *Computer Integrated Manufacturing Handbook*

CLELAND/BIDANDA • *The Automated Factory Handbook: Technology and Management*

TOMPKINS • *Winning Manufacturing*

WOODSON/TILLMAN • *Human Factors Design Handbook*

TILLMAN • *Human Factors Essentials*

BARAN • *Finite Element Analysis*

TAYLOR • *Optimization and Variation Reduction in Quality*

SLATER • *Integrated Process Management: A Quality Model*

To My Family

List of Tables

CHAPTER 2

2.1 Accelerator boards and CPU ratings. 18

CHAPTER 3

3.1 English and metric units. 35

CHAPTER 9

9.1 Material properties for cryo/heatsink problem. 240
9.2 First three fundamental frequencies. 242
9.3 Maximum deflections (in) modal analysis. 242
9.4 Maximum deflections (in) random vibration. 244
9.5 Modal correlation study (housing). 266
9.6 Stress analysis summary. 268

Preface

This book is intended to be a basic guide for the manufacturing engineer who wants exposure to the use of Finite Element Analysis (FEA) in a small to medium size manufacturing facility where either personnel or hardware (or both) resources are limited. No previous exposure to FEA is assumed. Moreover, this book is applicable to students in the science and engineering fields who wish to obtain a concise introduction to the subject of applied FEA, and who wish to learn how to apply this analysis technique to their particular situation.

In keeping with this theme, the reader will find the text directed toward helping the user solve general classes of engineering problems with FEA on personal computers. The types of problems that may be solved on personal computers are primarily limited by memory, hard disk space, and overall throughput of the system. Problems that previously involved cumbersome or intractable solutions can now be analyzed and solved if the engineer owns or has access to a personal computer and the proper software.

There are advantages and disadvantages in using a personal computer for finite element analysis. Certainly a motivating factor that has fostered the popularity of the PC/FEA combination has been the relatively low cost of this type of analysis. However, there are often restrictions on problem size coupled with long execution times.

With the newer and faster processors that continually

come to market, the availability of massive amounts of storage, and software refinements in algorithms and code that allow the fastest possible execution and minimize space requirements, rather complex problems can be handled. These types of problems range from linear analysis to fluid flow to highly nonlinear analysis.

All problems run in this book, with the exception of one in Chap. 9 that used ANSYS, were executed with the program SuperSAP (ALGOR Interactive Systems, Inc., 260 Alpha Drive, Pittsburgh, PA 15238, 412-967-2700. In addition, all problems were run using an 80386 25 MHz personal computer.

Chapter 1 addresses some of the basic requirements for finite element analysis and what to look for when considering using this tool.

The remainder of the text is divided into the following chapters:

Chapter 2 covers the practical aspects of hardware requirements plus recommendations for upgrades to your existing computer systems. Discussions in this chapter range from the basic PC unit and upgrades to the basic unit to get the most performance possible within a given budget.

Chapter 3 looks at the fundamental aspects of finite element analysis such as setting up problems and element types. There is discussion on selecting proper mesh sizes, elements, etc.

Chapter 4 gives an introduction to the ALGOR Interactive Systems, Inc. finite element program and explains how to use the program with sample verification problems and a detailed example, both from an FEA standpoint and a conventional solution.

Chapter 5 covers the finite element methodology in somewhat more detail and presents a FORTRAN program for calculation of two-dimensional heat transfer.

Chapter 6 offers real-world applications of FEA in a manufacturing environment with applications to tools, molds, and dies.

Chapter 7 illustrates finite element analysis uses in the automotive industry.

Chapter 8 presents a unique view of using FEA in a musical product modification.

Chapter 9 examines finite element analysis as used in some applications in a military environment.

Chapter 10 looks at a more commercial side as it examines applications to in-home medical products.

Chapter 11 applies the finite element concept to situations within the utility industry.

The Reference section contains useful references to common finite element texts and should serve as a stepping stone to further reading on the subject.

All references to specific trade names are copyrighted by the respective companies.

Acknowledgments

For their assistance in the development and writing of this book, I would like to thank the following individuals:

Dr. Joel Orr, the McGraw-Hill Series Editor

Ms. Gail Nalven, Senior Editor at McGraw-Hill

Ms. Christine Furry, North Market Street Graphics

ALGOR Technical Support, Mr. Mark Dekker, and Mr. Pat Cronin

WordPerfect Technical Support Staff

Mr. Harold Lawson, Moore Special Tool Company

Mr. Ken Woodard, Kollsman

Mr. Clark Wilson, Warn Industries

Mr. Marvin Zeigler, Wave Air, Inc.

Mr. Warren Peters, Electri-Glass, Inc.

Mr. Paul Levering, Webb Wheel Products

Mrs. Joyce Champion for the support and equipment

Last but certainly not least, I want to thank my wife, Ginger, and my daughter, Caroline, for putting up with the long office hours required to complete this task, in addition to performing all the activities required to maintain a home.

ABOUT THE AUTHOR

Edward R. Champion, Jr., Ph.D., is a consultant and registered Professional Engineer in the areas of fluid/heat transfer analysis and structural analysis for a wide variety of commercial and military applications. This interest in the application of numerical methods to solve many types of problems has led to the development of several PC-based analysis programs for both industry and business. Dr. Champion is the author/co-author of several books (including *Finite Element Analysis* and *Numerical Analysis*) and articles (covering subjects such as fabric combustion phenomena and waste heat transfer). He is a member of the ASME.

Contents

Preface xvii

Chapter 1. Applied Finite Element Analysis in Manufacturing Engineering 1

1.1 Introduction 1
1.2 Why FEA? 2
1.3 A Brief History of Finite Element Analysis 3
1.4 Applications of FEA for Practicing Engineers 5
1.5 Using This Book 6
1.5.1 The novice or casual user 7
1.5.2 The experienced user 8
1.6 Summary 8
1.7 What's in the Remainder of This Book? 10

Chapter 2. What Are the Minimum *Realistic* Hardware Requirements for Doing FEA on Personal Computers? 13

2.1 Introduction 13
2.2 General Hardware Requirements 14
2.3 The Main PC Unit 14
2.3.1 8086/8088 performance upgrades 16
2.3.2 80286 performance upgrades 18
2.4 Input Devices 20
2.4.1 Keyboards 20
2.4.2 Mice 20
2.4.3 Tablets 21
2.5 Data Output Devices 22
2.5.1 Graphics boards 22
2.5.2 CRT displays 23
2.5.3 Printers 24
2.5.4 Plotters 24
2.5.5 Software 25
2.6 Performance 25
2.6.1 Clock speed 25

2.6.2 Add-in coprocessors 25
2.7 System Enhancements 26
2.7.1 The 80×87 math coprocessor 26
2.7.2 Software additions 26
2.7.3 Hard drives and hard drive controllers 26
2.7.4 Front-end CAD for FEA applications 29

Chapter 3. Fundamentals of Applied Finite Element Analysis 31

3.1 Introduction 31
3.2 Basic Concepts 31
3.2.1 The physical problem 33
3.2.2 Criteria for using FEA 33
3.2.3 Using the correct engineering units 34
3.3 Discretization 34
3.3.1 Node points 36
3.3.2 Coordinate systems 36
3.4 Selecting the Proper Elements 37
3.4.1 Element types 37
3.4.2 Commonly used structural elements 37
3.5 Elements, Nodes, and Degrees of Freedom 49
3.5.1 General discussion 49
3.5.2 Mesh size 53
3.5.3 First runs with selected mesh 53
3.5.4 Solution accuracy 53
3.5.5 Refining the mesh in critical areas 54
3.5.6 Practical suggestions, limitations, and interfacing to mainframes 56
3.6 Preprocessing 57
3.6.1 Assembling the model 58
3.6.2 Defining constraints (restraints) 58
3.6.3 Defining loads 59
3.6.4 Defining nodal weights 60
3.7 Executing the Model 60
3.7.1 Static stress analysis 62
3.7.2 Thermal analysis 63
3.7.3 Vibration (dynamic) analysis 64
3.8 Postprocessing 66
3.9 Design Optimization 66

Chapter 4. Introduction to Using the Algor Interactive Systems, Inc. FEA Package and Verification Problems 69

4.1 Introduction 69
4.2 Three-dimensional Truss 69
4.3 Finite Element Solution 72
4.3.1 Nodes 72
4.3.2 Material properties 72
4.3.3 Real constant(s) 72
4.3.4 Truss connectivity 72
4.3.5 Restraints 73
4.3.6 Loads 73

4.3.7 Solution 73
4.4 Additional Verification Problems 78
4.4.1 Thick-walled cylinder with uniform internal pressure 78
4.4.2 Temperature induced stress in thick-walled cylinder 80
4.4.3 Lid-driven cavity flow 83
4.4.4 A nonlinear analysis example 90

Chapter 5. Applications of Finite Element Methods 97

5.1 Introduction 97
5.2 What is the Finite Element Method? 98
5.3 Building the Basics for the Finite Element Method 100
5.3.1 Basic steps in the finite element method 101
5.3.2 General flow diagram for solving sample problem 109
5.3.3 The problem 110
5.3.4 Variable definitions for sample FEA program 116
5.4 The Finite Element Program 118
5.5 Solution Results 125

Chapter 6. FEA in Tools, Molds, and Dies 129

6.1 Background and Introduction 129
6.2 The Problem 130
6.3 The Finite Element Approach to Solving the Problem 131
6.4 Heat Transfer in a Mold 143

Chapter 7. FEA in Automotive Support Industries 163

7.1 Introduction 163
7.2 Background 164
7.3 Description 165
7.4 Results of Spindle-Hub Analysis 193
7.5 Using FEA for Maximum Fatigue Life and Minimum Weight 193
7.6 Vehicle Aerodynamic Studies 205
7.7 Mini Van Model 217

Chapter 8. Music Products and FEA 219

8.1 Introduction 219
8.2 The Trumpet Mouthpiece Problem 219
8.2.1 Building the model 221
8.2.2 Results of the analysis 221
8.3 Modeling the Modified Mouthpiece 226
8.4 A Modified Heavy-Wall Design Mouthpiece 226

Chapter 9. Applications to Military Products 237

9.1 Minimizing the Product Design Cycle by Interfacing CAD and FEA 237

9.2 The Cryo/Heatsink Model 238
9.2.1 Analysis results of the cryo/heatsink model 242
9.3 Analysis of a Tray for Aircraft Electronic Storage 245
9.3.1 Tray analysis results—not modified 248
9.4 Production Support—FEA of Undersized Lenses 257
9.4.1 Summary of problem 257
9.4.2 Introduction to lens/housing stress problem 257
9.4.3 System level finite element analysis for E-O systems 260
9.4.4 Finite element model validation and modal testing 264
9.4.5 Conclusions 268

Chapter 10. FEA in Consumer Medical Products 273

10.1 Introduction 273
10.2 The Nozzle Problem 274
10.3 The Flow Chamber Problem 278
10.4 Analysis of a Vibration Isolator for an Impeller Mount Assembly 278
10.4.1 Equations of the physical phenomena 286
10.4.2 The FEA model 291

Chapter 11. An Example of FEA in the Utility Industry 293

11.1 Introduction to Transformer Pad Analysis 293
11.2 The Finite Element Model 294
11.3 Results of the FEA Analysis 297
11.4 Conclusions on Modeling of the Box Pad 300

Appendix A 301

References 305
Further Reading 307
Index 309

List of Figures

CHAPTER 3

3.1	Three-dimensional truss element.	38
3.2	Three-dimensional beam element.	40
3.3	Membrane three-dimensional plane stress.	42
3.4	Two-dimensional solid elasticity.	43
3.5	Three-dimensional solid (brick) elasticity.	44
3.6	Three-dimensional plate/shell.	46
3.7	Boundary elements.	47
3.8	Two-dimensional thermal conductivity.	48
3.9	Three-dimensional thermal conductivity.	50
3.10	Temperature boundary element.	51

CHAPTER 4

4.1	Three-dimensional truss problem.	70
4.2	Stress analysis results—three-dimensional truss problem.	79
4.3	Stress distribution for 10,000 psi loading.	81
4.4	Deflection plot.	82
4.5	Temperature distribution.	84
4.6	Temperature-induced stress distribution.	85
4.7	Y-component velocity distribution.	86
4.8	Z-component velocity distribution.	87
4.9	Pressure distribution.	88
4.10	Velocity vector plot.	89
4.11	Finite element model of rubber sheet.	91
4.12	Nodes and elements of model.	92
4.13	Deformed shape at load step four.	93
4.14	Deflection contours of rubber sheet.	94
4.15	Stress values in rubber sheet.	95