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Multiphysics Simulation

Electromechanical System Applications and Optimization

Springer

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Foreword

It was 1986, at the Technical University of Denmark, when Prof. Martin Bendsøe and I were working on ‘topology’ optimization in structural design by finding an optimal distribution of a linearly elastic porous microstructure defined by infinitely many very small-scale rectangular holes, which are appropriately rotated. To deal with a linearly elastic porous material defined by infinitely many small-scale rectangular holes (characterized by width, a, and height, b, in a unit cell with rotation, θ), we applied the homogenization method to calculate the equivalent macro-scale linearly elastic constitutive relation, $\sigma = \mathbf{C}^H(a, b, \theta)\varepsilon$. Instead of rectangular holes, square holes were assumed characterizing size, a, in the unit cell, and the elasticity matrix, $\mathbf{C}^H(a, b, \theta)$, was simplified to $\mathbf{C}^H(a, \theta)$. If rotation of micro-scale holes is not considered, then this problem is simplified even further as $\mathbf{C}^H(a)$. If $a = 1$, then the unit cell is completely occupied with a hole, that is, it is equivalent to no material in the macro-scale ‘porous’ structure. On the other hand, if $a = 0$, then the unit cell is completely occupied with elastic material, that is, it represents solid material in the macro-scale ‘porous’ material. Shape and topology of a solid structure, then may be defined by the portion where $a < 1$ in the unit cell. In other words, topology and shape optimization problems are transferred to finding the optimal distribution of porosity, that is, the optimal distribution of a solid material. This idea was published in the paper Bendsøe and Kikuchi [1] and then its concept was extensively extended by Bendsøe [2], Bendsøe and Sigmund [3].

In these books, we can find applications not only in elastic structures, but in heat conduction and also in fluid mechanics. However, at present, a dependable monograph cannot be found on topology optimization for electromagnetism and its industrial applications, which are now very critical to developing various advanced electrical/magnetic devices even for automobiles.

Thus, I have encouraged the writing of such a monograph to researchers at the Toyota Research Institute of North America, Ann Arbor, Michigan, USA, where the topology optimization approach is widely taken as a design tool for many devices and structures for automobiles. It is my great pleasure to endorse this monograph to many talented graduate students and researchers in the field of electromagnetism and its related applications in design.

April 2014 Noboru Kikuchi

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Preface

This book developed out of a collaboration by the authors at the Toyota Research Institute of North America, where multiphysics simulation and optimization is used on a daily basis for a variety of engineering studies related to electromechanical systems. Multiphysics simulation is a rapidly growing field, and the term itself is broad and may be applied to an extremely wide variety of coupled-physics problems. By nature, multiphysics simulation requires an array of technical skills in different intersecting disciplines. As such, this book aims to narrow down the topic by specifically focusing on multiphysics simulation for electromechanical systems, the original target application investigated by the authors. It is our hope that the collaborative aspects of such studies become apparent as the various technical topics throughout the book are presented.

Overview

Understanding and predicting the performance of electromechanical systems is of prime importance in the design of many of today's key products including computers, vehicles and consumer electronics. In these systems, increased efficiency and higher power density in a smaller package size is crucial. Success in design requires both analytical and numerical skills plus a foundation in mechanical and electrical engineering. Efficient analysis also necessitates an understanding of how best to build a numerical model that is accurate yet balances complexity and computational cost.

Beyond basic performance prediction, today's engineers and researchers are constantly seeking methods for optimizing complex electromechanical systems. The multiphysics aspects of these systems present constant challenges in terms of how best to arrive at an 'optimal solution.' Many optimization techniques exist, although the use of structural topology optimization is emphasized herein along with some aspects of discrete parameter optimization.

Organization and Features

Accordingly, this book highlights a unique combination of numerical tools including numerous strategies for handling the aforementioned simulation challenges. In Chap. 1, the concept of design via simulation is introduced along with the role of multiphysics simulation in today's engineering environment. The importance of structural optimization techniques in the design and development of electromechanical systems is additionally discussed. From there, an overview of the physics commonly involved with electromechanical systems is provided (Chap. 2) for applications such as electronics, magnetic components, radio frequency components, actuators and motors. Governing equations for the simulation of related multiphysics problems are reviewed in Chap. 3, while the relevant topology optimization and parametric size analysis methods for electromechanical systems are outlined in Chap. 4. Several multiphysics simulation and optimization example studies in both two and three-dimensions are then described in detail throughout Chap. 5. Extensions to new topics are suggested in Chap. 6. Sample numerical code for a related electro-thermal topology optimization example is provided in the appendix in Chap. 7.

A challenge in writing a book of this nature on the topic of multiphysics simulation is the preparation of the engineering nomenclature used for various physical constants, state variable, functions, etc. Specifically, the governing equations for the multitude of separate physical processes are often described using the same symbols for different variables. As such, every effort has been made to provide a comprehensive list of nomenclature with distinct variable usage wherever possible.

In addition to the above features, extensive references are provided at the end of each chapter. These references are related to prior research on multiphysics simulation and optimization methods, techniques, and application studies.

Target Audiences

It is our hope that the content presented in this book will serve as a reference for industry and academic researchers and engineers in the field of advanced electromechanical system design. The topics in this book are appropriate for undergraduate and graduate level students, although many of the design examples may be of interest to anyone curious about the unique design solutions that arise when optimization methods are coupled with multiphysics simulation strategies.

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Ann Arbor, April 2014
Goyang

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Contents

Acronyms

2-D	Two-dimensional
3-D	Three-dimensional
ABC	Absorbing boundary condition
AC	Alternating current
ALE	Arbitrary Lagrangian–Eulerian
AVM	Adjoint variable method
BC	Boundary condition
CAD	Computer-aided design
CAE	Computer-aided engineering
CFD	Computational fluid dynamics
CTE	Coefficient of thermal expansion
CVW	Coulomb Virtual Work
DARPA	Defense Advanced Research Projects Agency
DBC	Direct bonded copper
DC	Direct current
DOF	Degrees-of-freedom
DRA	Dielectric resonator antenna
EMC	Electromagnetic compatibility
EMI	Electromagnetic interference
FDTD	Finite difference-time domain
FEA	Finite element analysis
FE-BI	Finite element-boundary integration
FEM	Finite element method
GA	Genetic algorithm
HPC	High performance computing
HV	Hybrid vehicle
IC	Integrated circuit
IPMSM	Interior permanent magnet synchronous motor
LSM	Level set method
MEMS	Microelectromechanical systems
MMA	Method of Moving Asymptotes
MST	Maxwell Stress Tensor
NASA	National Aeronautics and Space Administration
OC	Optimality criteria

PCB	Printed circuit board
PDE	Partial differential equation
PEC	Perfect electric conductor
PM	Permanent magnet
PML	Perfectly matched layer
PSO	Particle swarm optimization
RF	Radio frequency
RMS	Root mean square
RPM	Revolutions per minute
SAR	Specific absorption rate
SAW	Surface acoustic wave
SIMP	Solid isotropic material with penalization
SLP	Sequential linear programming
SRM	Switched reluctance motor
TBC	Transition boundary condition
TEM	Transverse electric and magnetic
TIM	Thermal interface material
US	United States

Symbols

Scalar Quantities

A_s	Surface area
B	Magnitude of magnetic flux density
B_{r_PM}	Permanent magnet strength
B_{rx}	x-direction component of residual magnetic flux density
B_{ry}	y-direction component of residual magnetic flux density
C	Curie constant
C_p	Specific heat capacity
D	Extended design domain
E	Elastic (or Young's) modulus
F	Force
f	Frequency
f_i	Inclusion volume fraction
g	Behavior constraint
H	Magnitude of magnetic field
h	Surface convection coefficient
h_c	Channel height
h_t	Heaviside function transition bandwidth
I, i	Electric current
J	Electric current density
k	Thermal conductivity
k_h	Hysteresis coefficient
L	Inductance
l	Mechanical compliance
M_w	Molecular weight
N	Nodal shape function
N_c	Number of coils
P	Pressure
p	Penalization parameter
P_r	Number of rotor poles
P_s	Number of stator poles
$\mathscr{P}$	Power

Q	Volumetric power density
q	Convex interpolation tuning parameter
q''	Heat flux
R	Electrical resistance
R_f	Helmholtz filter radius
R_{th}	Thermal resistance
R''_{th}	Unit thermal resistance
$R_{\mathrm{th(cnv)}}$	Convective thermal resistance
Re	Reynolds number
$\mathscr{R}$	Residual
S	Scattering parameter
s	Adaptive scaling factor
T	Temperature
t	Time
$\mathscr{T}$	Torque
u	Displacement
V	Voltage drop
v	Volume
v_e	Element volume
W	Energy or work
W_{co}	Co-energy
W_{mag}	Magnetic energy
w	Objective function weighting value
w_c	Channel width
Z_s	Surface impedance
α	Coefficient of thermal expansion
α_i	Inclusion aspect ratio
$\tilde{\alpha}$	Inverse permeability
χ	Fluid magnetic susceptibility
$\delta\varepsilon$	Virtual strain
δU	Virtual strain energy
δW	Virtual work
$\varDelta P$	Pressure drop
ϵ	Electric permittivity
ϵ_o	Electric permittivity of free space
ε_b	Bandwidth for smoothed surface convection coefficient function
η	Fluid dynamic viscosity
γ	Optimization design (density) variable
λ_{link}	Magnetic flux linkage
μ	Magnetic permeability
μ_o	Magnetic permeability of free space
μ_r	Relative magnetic permeability
μ_{r_mf}	Magnetic fluid permeability

ν	Poisson's ratio
Ω	Domain
Ω_d	Design domain
Ω_m	Material domain
ω	Angular frequency or velocity
Φ	Electric scalar potential
Φ_B	Magnetic flux
ρ	Density
ρ_e	Electric resistivity
ρ_q	Electric charge density
ς	Electric conductivity
θ	Inclusion angle
θ_r	Rotor angle
ζ	Channel aspect ratio

Vector, Matrix, or Tensor Quantities

$\mathbf{A}$	Magnetic vector potential
$\mathbf{B}$	Magnetic flux density
$\mathbf{B}_r$	Residual magnetic flux density
$\mathbf{B}_e$	Array of derivatives of element nodal shape functions
$\mathbf{C}$	Stiffness tensor
$\mathbf{D}$	Electric displacement
$\mathbf{E}$	Electric field
$\mathbb{E}$	Electric field variable
$\hat{\mathbf{e}}$	Target unit vector
$\mathbf{F},\mathbf{f}$	Force (global, element)
$\mathbf{H}$	Magnetic field
$\mathbf{J}$	Electric current density
$\mathbf{J}_e$	External current density
$\mathbf{J}_{\mathrm{eddy}}$	Eddy current density
$\mathbf{K},\mathbf{k}$	Stiffness matrix (global, element)
$\hat{\mathbf{n}}$	Normal unit vector
$\mathbf{Q}$	Magnetic load vector
$\mathbf{q}$	Heat flux vector
$\mathbf{t}$	Surface load vector
$\hat{\mathbf{t}}$	Tangential unit vector
$\mathbf{U},\mathbf{u}$	Displacement (global, element)
$\mathbf{v}$	Velocity
$\mathbf{x}$	Position
$\delta\mathbf{u}$	Virtual displacement
ε	Strain
$\hat{\lambda}$	Lagrange multipliers (adjoint variables)
σ	Stress

Functions

F_o	Optimization objective function
F_c	Convergence function
H	Heaviside function
$\tilde{\mathsf{H}}$	Regularized Heaviside function
L	Lagrangian
ϕ	Level set function
ψ	Scalar function
$\tilde{\psi}$	Filtered scalar function

Subscripts

avg	Average
d	Distributed
F,f	Fluid
in	Inlet
init	Initial
l	Lower
M	Magnetic
max	Maximum
min	Minimum
o	Reference value
out	Outlet
S	Structural
s	Solid
T	Thermal
u	Upper