

Multiobjective Shape Design in Electricity and Magnetism

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*To Guia Angelica,
my beloved wife*

Preface

Electromagnetic devices are crucial to the operation of modern society. They are used to convert energy from mechanical or thermal to an electrical form that may be easily transported over great distances; they can convert electrical energy into mechanical work through the medium of an electric motor; and they can be used to send and receive information around the globe. At this point in time, with issues of energy efficiency and production costs being crucial to the success of a product and becoming more important daily as a growing part of the world's energy is consumed by electromagnetic systems, designers of these systems need to both understand and have access to effective design techniques and tools.

The basic theory underlying the operation of these devices was developed in the nineteenth century and culminated in the work of Maxwell in 1873. The equations he proposed describe the basis of the operation of an electromagnetic system. The main problem has been in the solution of these equations in the presence of the geometries, boundary conditions, excitations and material properties which are found in real devices. Over the past half century, the development of digital computers and the numerical systems needed to compute the field accurately for arbitrary devices has meant that physical prototypes can largely be replaced with computer models and performance results obtained which are, usually, as good as those achieved through experimental systems. However, the reason for performing the analysis often seems to have been forgotten – many times, it appears to be an end in itself. The prediction of performance is just one of the steps that a design engineer needs to execute as part of the process of creating and validating a device intended to meet a set of specifications. In fact, it could be argued that the real work that needs implementing is that related to searching a large space of possible solutions for the one which best matches the needs of the client. In addition, the requirements proposed by a client are more likely than not to result in a conflict where improving the design to meet one requirement may result in a degradation in performance for another. Put simply, real design problems require multiple objectives to be satisfied, in some sense, simultaneously.

Over the last two decades, the focus in research related to electromagnetic devices has slowly been moving from the analysis of device performance towards

the automatic optimisation of a particular device to meet the needs and requirements specified by an end user. While there have been significant improvements in the capabilities in this area, the uptake by industrial designers has been somewhat limited. There are, possibly, two reasons for this. The first is that the evidence, at the industrial level, that computer-based optimisation processes can actually enhance a designer's ability to create a better product has been lacking. The second relates to the fact that most optimisation packages currently available only handle a single objective and a limited number of design parameters. This latter has tended to restrict the designer's ability to examine a range of "what-if" scenarios and, in particular, to look at the trade-offs between several design objectives and parameters. In fact, to be of use to a designer, it almost goes without saying that an optimisation system must be easy to use in the sense that the objectives of a particular design can be expressed simply and flexibly. In addition, there needs to be no real restriction in the size of the parameter space to be explored.

The intention of this book is to try to dispel some of the myths surrounding computer-based optimisation. Professor Di Barba provides a comprehensive overview of the current state-of-the-art in both the theory and the algorithms involved in moving the design of an electromagnetic device towards the required goals. The book assumes that the reader is either a graduate student with a good foundation in electrical engineering or a practising designer of electromagnetic devices but it does not expect great expertise in the analysis or solution of field problems. While the goal is to explain how the shape of a device can be modified to try to satisfy several, possibly conflicting, objectives, the reader is gradually introduced to basic concepts in optimisation and field theory, starting with the concept of reaching the minimum (or maximum) value of a single objective. Of course, searching for the optimal value of an objective requires that the objective can be evaluated and this leads to a discussion on the numerical solution of electromagnetic field problems. Issues related to the accuracy of these solutions are crucial to the effective improvement of any design and so space is devoted to explaining these in an easily understandable manner without resorting to the large amount of mathematics which often has the result of obscuring the very point which is being made.

Since realistic design systems need to consider a multi-objective problem, this is the main thrust of this book. The concepts of multi-objective shape design are constructed on top of the basic idea of optimisation and objective function evaluation. The rationale for a multi-objective approach is set in context and the underlying theory and issues relating to constraints are simply explained. In particular, the concepts of Pareto fronts and sets, which can allow a designer to better understand the various trade-offs available, are described at length. The text provides an extremely useful survey of the existing algorithms in the area. Each is described in detail and a comparison between them is made. The issue of the cost of each evaluation, often seen as a major problem with stochastic algorithms, is considered and a brief introduction to surface response, or surrogate, modelling is provided.

This is a textbook which is intended to de-mystify optimisation and, in particular, stochastic processes and thus it is filled with practical examples. The test problems are drawn from a range of real, or at least realistic, electromagnetic

devices. These range from permanent magnet motors and generators to actuators. Some are benchmarks which have been developed over the years by the research community; others may well become benchmark problems in the future. The algorithms described in the book are applied to these examples so that their effectiveness can be seen in a real design environment, rather than on artificial analytical problems, which is often the case in publications where the goal is to demonstrate a new algorithm. As is stated by the author, no one algorithm can be shown to be optimal for all problems and thus the performance of each one on typical benchmarks provides key information for a user of an optimisation system.

The last part of the book delves into areas which are currently of research interest, including the area of the design of dynamic systems and the use of both sensitivity analysis and Bayesian logic in the optimisation process to try to handle issues related to the robustness of design. From a designer's point of view, these are crucial. In many practical situations, objectives and constraints are time dependent and thus optimisation of the shape to address the specifications at each point in time is critical. Also, a design must not only meet the nominal objectives but also perform to specifications, within a certain tolerance, in the face of uncertainties both in the manufacturing process and the material characteristics. If the design produced by an optimisation system is too sensitive to manufacturing issues, then many of the devices produced may "fail" in the sense that they do not meet the specifications. This can result in an increase in the cost of the successful designs.

Overall, this book provides an up-to-date and comprehensive overview of optimisation techniques related to electromagnetic devices and systems in a logical and consistent manner. An understanding of its contents can help a designer to use the computational resources that are now available in a much more effective manner.

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Contents

1	Introduction	1
1.1	Prologue	1
2	Inverse Problems and Error Minimisation	5
2.1	A Copernican Revolution: Direct and Inverse Problems	5
2.2	Insidiousness of Inverse Problems	6
2.3	Classification of Inverse Problems	7
2.4	Green Formula and Fredholm Equation	8
2.4.1	Case Studies	9
2.5	Solving Inverse Problems by Minimising a Functional	10
2.6	Constrained Minimisation	12
2.6.1	Classical Optimality Conditions	12
2.6.2	Managing Constraints	13
2.7	Local vs Global Search	14
2.7.1	A Deterministic Algorithm of Lowest Order: Simplex Method	16
2.8	Evolutionary Computing	17
2.8.1	An Evolution Strategy of Lowest Order	18
2.8.2	No Free-Lunch	20
2.9	Solving Inverse Problems by Means of Rectangular Systems of Algebraic Equations	21
2.9.1	Least Squares	22
2.9.2	Singular-Value Decomposition	23
2.9.3	Regularization	23
3	A Paretian Approach to MOSD Theory	27
3.1	Need of a Multiobjective Formulation	27
3.2	Multiobjective Formulation of a Design Problem	29
3.3	Paretian Optimality	30

4	Field Models and Shape Design	41
4.1	Maxwell Equations in Differential Form	41
4.2	Wave, Diffusion and Steady-State Equations in Terms of Vectors	42
4.3	Wave, Diffusion and Steady-State Equations in Terms of Potentials	45
4.4	Boundary and Transmission Conditions	50
4.5	Insidiousness of Direct Problems	54
4.6	Field-Based Inverse Problems	56
4.7	More Insidious Difficulties	58
4.8	A Unifying View of Analysis and Synthesis	59
5	Solving Multiobjective Optimisation Problems	63
5.1	Classical Methods of Multiobjective Optimisation	63
5.1.1	Objective Weighting	63
5.1.2	Epsilon-Constraint Formulation	65
5.1.3	Weighted Min-Max Formulation	66
5.1.4	Min-Max Formulation with Variable Goals	68
5.1.5	Goal-Attainment Method	69
5.2	Classical vs Paretian Formulation	70
5.3	Evolutionary Methods of Multiobjective Optimisation	71
5.3.1	Strength Pareto Evolutionary Algorithm (SPEA)	72
5.3.2	Non-Dominated Sorting Genetic Algorithm (NSGA)	72
5.3.3	Enhancing Diversity in the Objective Space with NSGA	75
5.4	Multi-Objective Evolution Strategy (MOESTRA)	76
5.4.1	MOESTRA Validation: Metrics and Convergence	79
5.4.2	MOESTRA Validation: Sample-and-Sort Technique	82
5.5	The Gradient-Balance (GB) Method for 2D Problems	84
5.5.1	Analytical Benchmarks	87
6	A Field-Based Benchmark	93
6.1	A Twofold Meaning of Benchmarking	93
6.2	Test Problem: Shape Design of a Magnetic Pole	95
6.2.1	Synthesis	95
6.2.2	Analysis	97
6.3	The Test Problem Simplified	99
6.4	Criticism to Pareto Optimality in the Static Case	100
7	Static MOSD	103
7.1	A Bibliographic Insight	103
7.1.1	Surrogate Modelling	105
7.1.2	Kriging-Assisted Design Optimisation	106
7.1.3	Topology Optimisation and Sensitivity Analysis	107
7.1.4	Multi-Level Design Optimisation	108
7.2	FEM-Assisted Optimal Design	108

7.3	Test Problem: <i>A Priori</i> Analysis of the Objective Space	109
7.3.1	Re-Aggregating Feasible Points in the Objective Space	113
7.4	Optimisation Strategies and Results	115
7.5	Processing Clusters	120
7.6	The Test Problem Solved by Means of the GB Method	122
7.6.1	Comparing Results	125
7.7	An Industrial Case Study: Permanent-Magnet Alternator	126
7.7.1	Design Problem	128
7.7.2	Analysis Problem	129
7.7.3	Elitist NSGA and MOESTRA in Action	131
8	Moving Along the Pareto Front	137
8.1	John Optimality	137
8.2	Reconsidering the Industrial Case Study	140
8.3	Exploring the Pareto Front	140
8.4	Optimising Along the Front	146
9	Sensitivity Analysis and MOSD	147
9.1	Discrete Sets and Perturbation Domains	147
9.2	Case Study: Superconducting Magnetic-Bearing Design	149
9.3	Design Optimisation of the PM-HTSC Interaction	150
9.4	An Inexpensive Evaluation of Sensitivity	151
9.5	Results	154
10	Non-Conflicting Multiple Objectives	157
10.1	Case Study: A System for Magnetic Induction Tomography	157
10.2	Design Problem	158
10.3	Analysis Problem	160
10.4	Optimal Shape Design of the MIT Antenna	161
11	Higher-Order Dimensionality	165
11.1	Case Study: An Electrostatic Micromotor	165
11.2	Field Analysis: Doubly-Connected Domain	166
11.3	Field Synthesis and Rotor Shape Design	169
11.4	Results	169
11.5	A Criterion for Decision Making	172
12	Multi-Scale Evolution Strategy	175
12.1	Industrial Electromagnetic Design	175
12.2	A Multi-Scale Evolutionary Search	177
12.3	Permanent-Magnet Alternator Design	178
12.4	Results	179
13	Game Theory and MOSD	185
13.1	From Pareto Front to Nash Equilibrium	185

13.2	Theoretical Background	185
13.3	Analytical Validation	187
13.4	Numerical Implementation	189
13.5	Case Study: Permanent-Magnet Motor Design	190
13.5.1	Direct and Inverse Model	190
13.5.2	Results	193
14	Dynamic MOSD	203
14.1	From Static to Dynamic Conditions	203
14.2	Theoretical Background	203
14.3	An Analytical Benchmark	204
14.4	Criticism to Dynamic Pareto Optimality	205
14.5	Numerical Benchmark	207
14.6	Direct Problem	207
14.7	Design Problem	208
14.8	Auxiliary Inverse Problems	209
14.8.1	Identifying Maximum Field	209
14.8.2	Identifying Time Threshold	210
14.9	Main Inverse Problem: Synthesising Device Geometry	210
14.10	Computational Aspects	212
14.10.1	Towards an Algorithm for Dynamic Optimisation	213
14.11	Results I	213
14.12	The Design Problem Revisited: Recovering Steady State from Time Evolution	217
14.13	Results II	219
15	An Introduction to Bayesian Probability Theory	223
15.1	Bayesian Conception of Probability	223
15.1.1	Basic Bayesian Rules	224
15.1.2	Bayes Theorem	228
15.2	Prior Distributions	230
15.2.1	Uniform Prior	230
15.2.2	Scale-Independent Prior	231
15.3	Bayesian Inference vs Maximum Likelihood	233
15.4	Bayesian Non-Parametric Problems	235
15.5	Model Choice	240
16	A Bayesian Approach to Multiobjective Optimisation	245
16.1	Reasons for a New Approach	245
16.2	Weak Regularity	247
16.3	Local Bayesian Formulation	249
16.3.1	The Stopping Term	250
16.3.2	The Back-Mapping Term	251
16.3.3	The Front-Mapping Term	251
16.4	Integral Bayesian Formulation	252

16.5	Computation of the Bayesian Terms	256
16.5.1	Paretian Distance	257
16.5.2	The Integral Back-Mapping Term	259
16.5.3	The Integral Front-Mapping Term	262
16.6	Bayesian Imaging	264
16.6.1	Clustering	264
16.6.2	Cluster Probabilistic Analysis	265
16.6.3	Cluster Space Analysis	268
16.6.4	Cluster Selection	269
17	Bayesian Imaging and Shape Design	271
17.1	Algorithmic Aspects	271
17.2	Implementation	272
17.2.1	Sampling	273
17.2.2	Details of Clustering	273
17.2.3	Improving Cluster Selection	274
17.2.4	Extracting New Samples	275
17.2.5	An Analytical Test Case	276
17.2.6	Algorithmic Cost	277
17.3	Case Study: Shape Design of a Linear Actuator	278
17.3.1	Magnetic Analysis of the Device	278
17.3.2	MOSD Problem	281
17.3.3	Optimisation Results	282
17.4	On the Meaning of Convergence	284
18	Conclusion	287
	References	291
	Index	303