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 and up-to-date and comprehensive overview of optimisation techniques related to eletromagnetic 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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