早稲田大学大学院理工学研究科

博 士 論 文 概 要

論 文 題 目

Enhancement of Electromagnetic Field Computation for Electric Machine Design

電気機器設計への応用に向けた
電磁界数値解析手法の高度化に関する研究

申 請 者

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1. Background of the thesis

In recent years, there is growing attention to the use of electromagnetic field computation for the purpose of precisely estimating characteristics of various electric machines. Nowadays manufacturers of electric machines are strongly required to make them cost-competitively with high quality. Furthermore, due to the viewpoint of preservation of the global environment, these products are to be energy-saving design with keeping at least the same characteristics. The above demands are usually competitive to each other, which makes them difficult to be designed only by the conventional design methodology. One easiest way to overcome the above stated problem is to introduce the so-called Computer Aided Engineering (CAE). From the viewpoint of utilizing CAE, there are several stages that the manufacturer introduces to the design of electric machines. The most primitive stages, which are already in common use, are for estimating electromagnetic fields more precisely and make them visible. Then we can newly obtain the useful information of understanding complex physical phenomenon inside the machines. However, this primitive approach of utilizing CAE is not always a powerful tool for design of practical electric machines. Needless to say, in the case of practical designing, the extent of making good use of the primitive CAE still too much depends on the engineers' understanding level of electromagnetics. Furthermore, the ability to make decision of designing also depends on the experience of designing. As a consequence, when the primitive one is applied to such cases, it is far difficult to steadily achieve the meaningful design of electric machines. After all, it seems that product designs are still basically obliged to determine by try and error. Therefore, more sophisticated utilization of CAE must be required to design the practical electric machines. For the above reason, the computational design optimization has been further considered an important CAE technique for most of the electrical engineering industry. There have been many studies on the optimization algorithms for efficiently finding optimal solution and they have, in fact, been successfully applied to some practical cases. However, in the design of electric machines, it is still difficult to apply them to practical problems due to the huge computational burden.

With the background mentioned above, this study intends to enhance the electromagnetic computation of designing electric machines by several techniques. First, the surface charge analysis is proposed to design the optimal conductor shape in the electric machines. Without the computational design optimization, post-processing the results from conventional analysis, the method gives us the useful information of grasping the physical phenomena and how and where to modify the conductor shape. Second, the response surface methodology is effectively introduced to the computational design optimization to dramatically reduce the CPU-time. The method also provides us the useful information of grasping the tendency of objective physical quantities in the design variable space. Third, methods to solve the multiobjective optimization problems and the effective approach to combine the response surface methodology are discussed. The approach can also provide us the additional characteristics of optimization problem. Last, the topology optimization, which can give us more useful information of designing the layout of model compared to the general shape optimization, is implemented by adopting the spline functions to describe the topology.

2. Outline of the thesis

Chapter 1: Introduction The backgrounds that motivate the works in this dissertation, and the summary of topics of each chapter, are briefly described.

Chapter 2: Surface Charge Analysis for Conductor Design in Eddy Current Problems A novel analysis method of surface charge is proposed to design conductors in eddy current problems. In the designing of induction motors, especially in the case of the modification of conductor shape for improving characteristics, it always comes to be time consuming to calculate field quantities, since it usually needs the three dimensional transient analysis of eddy current field. In that case, it can be easily understood the application of computational design optimization, in which hundreds or thousands of field calculations are required, is no more practical in terms of computational burden. On the other hand, utilizing the information by the surface charge analysis in addition to the conventional eddy current analysis, we can effectively design the electric machine configuration without computational design optimization. The method of the surface charge analysis method is based on both the three-dimensional A-ϕ edge finite element method (FEM) and the boundary integral equation method that enables us to precisely calculate the surface charge. The feature of the proposed method is that we impose the Coulomb gauge condition on the scalar potential derived from A-ϕ edge FEM.

Chapter 3: Response Surface Methodology for CPU-time Reduction in Shape Design Optimization At the present time, the use of computational design optimization is limited to apply due to its huge computational burden. Therefore, the response surface methodology (RSM) is effectively introduced in the optimization process to shorten the CPU-time. By using the RSM, we can easily comprehend the relationships between the objective physical quantities and the design variables, which can help the engineers design the robust and effective machine structure. To confirm the validity of the proposed method, design optimization of the structure of outer-rotor type permanent magnet synchronous motor is conducted.

Chapter 4: Effective Methods of Multiobjective Design Optimization In the practical designing, we have to consider many kinds of objective physical quantities to be improved simultaneously under the several constraints in the optimization process. In this case, the application of multiobjective optimization technique based on the GA (MOGA) is considered to be preferable. However, it is quite difficult to achieve an optimal solution within an acceptable CPU-time. Therefore, a lot of previous studies of this kind have been done by weighted sum of plural objectives to convert the problem into single objective function. But the optimized results largely depend on the previously fixed weighting factors that are hard to determine before conducting optimization. To overcome the above difficulties, two kinds of multiobjective optimization are investigated. One is that the weighting factors are iteratively determined by the RSM based optimization procedure before the optimization of converted objective function. The other is that the MOGA is combined with the RSM as a search method. This approach also results in an overall increase in the optimization speed without degrading solution. Furthermore, the obtained solution provides us the useful information of grasping the tendency of objective physical quantities.

Chapter 5: Topology Optimization Using Spline Function The topology optimization is developed using spline function. Design optimization is generally categorized into the three distinct classes. In order of complexity, there are size optimization, shape optimization, and topology optimization. The main advantage of topology optimization is that we can optimize the investigated model with more flexible with respect to the layout of model. On the other hand, unlike size or shape optimization, topology optimization generally does not require the explicit definition of design variables. The approaches of topology optimization reported so far have been mostly based on discretization of finite element. This approach usually results in an increase of the number of design variables because the each finite element is treated as a design variable. Then the local minimum solutions are possibly obtained. Some other researchers further combine the sensitivity analysis to avoid the difficulties. The topology optimization developed has an ability to describe the topology with less design variables. As a validation of the approach, topology optimization of hole shape is conducted in magnetic circuit. As a result, an adequate solution has been obtained without combining sensitivity analysis.

Chapter 6: Conclusions Chapter 6 gives conclusions of the overall results from the former chapters to summarize up this dissertation. Some directions or suggestions to continue to extend the research are also showed as a future work.

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