論 文 の 内 容 の 要 旨

論文題目　Development of Three-Dimensional Electromagnetic Analysis Method using Thin Plate Approximation for REBCO Superconducting Coils and its Application to Coupled Analysis with Heat Transfer

（REBCO超電導コイルを対象とする薄板近似を用いた三次元電磁界解析手法の開発及び伝熱との連成解析）

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The RE (rare earth) $Ba_2Cu_3O_x$ (REBCO)-coated conductor has shown its advantages in various applications such as high field magnet, accelerator, superconducting fault current limiter (SFCL), etc., because of its high critical temperature, critical current density, axial tensile stress, and heat capacity. The developments of such applications using REBCO-coated conductors have become increasingly active in recent years since the commercialization of long-length REBCO-coated conductors. However, some problems are still hindering the practical use of REBCO coils such as quench, AC loss, cooling, cost, and so on.

Experimental and numerical approach are the main method to study such problems to find the solutions. Although experiments are essential to study the actual physical phenomena and to conclusively verify a certain idea, it is still difficult to measure all the accurate and detailed information such as the current density, electric field, magnetic field, temperature, etc. at a certain point because of the limitation of the measurement technology. Hence, the numerical analysis is necessary and useful in today’s research, and has contributes greatly with the detailed analysis. In this thesis, the author focuses on the numerical analysis method especially for the REBCO-coated conductors and coils.

In the research of applications using REBCO-coated conductors, the electromagnetic and thermal behaviors are two of the most important aspects. Because the REBCO-coated conductors have to be cooled to superconductive, and the electromagnetic characteristics of superconductors are functions of the temperature, while the temperature is also affected by the conductor’s Joule heat. To study the electromagnetic and thermal behaviors, numerical simulation using equivalent circuit models, finite element method (FEM), etc. has been proposed and widely utilized. Equivalent circuit model of electric circuit elements (and thermal equivalent circuit elements in some cases) is a very fast numerical solution to simulate simple applications of REBCO-coated conductors, meanwhile, the improvement of analysis accuracy, which depends on the parameters of the equivalent circuit, is still a problem especially in the cases with complicated structures. Finite elements method is the most developed and widely used method today, allowing the use of different formulations for electromagnetic analysis: $\boldsymbol{A}$-V ($\boldsymbol{A}$: magnetic vector potential; V: electric scalar potential), $\boldsymbol{T}$–Ω ($\boldsymbol{T}$: current vector potential; Ω: magnetic scalar potential), $\boldsymbol{H}$ ($\boldsymbol{H}$: magnetic field), and $\boldsymbol{E}$ ($\boldsymbol{E}$: electric field). Among them, the $\boldsymbol{T}$–Ω formulation has shown better convergence in both two-dimensional (2D) and three-dimensional (3D) situations, although extra variables are needed at each node. Some methods, such as the thin plate appropriation and the fast multipole method, were proposed to reduce variables and computation load. Because of the importance of thermal analysis, some electromagnetic and heat transfer coupled analysis tools up to 2D have been developed in some research. However, performing a 3D electromagnetic and heat transfer coupled analysis is still difficult, because the operating characteristics of REBCO-coated conductors are extremely non-linear and strongly affected by the temperature, then the convergence could significantly deteriorate in 3D problems.

In this thesis, the author has developed a three-dimensional electromagnetic analysis method using finite elements method and thin plate approximation for REBCO-coated conductors and coils. Furthermore, the author has applied the electromagnetic analysis method to coupled analysis with heat transfer. Thin plate approximation and coordinate transformation (from Cartesian coordinates system to orthogonal curvilinear coordinate system) are utilized to realize the electromagnetic analysis of REBCO coils, which have 3D structures, in 2D calculation space. The governing electromagnetic equation is given by $\nabla\times(\rho\nabla\times\boldsymbol{T}) = -\partial\boldsymbol{B}/\partial t$ ($\boldsymbol{T}$: current vector potential; ρ: electric resistivity; $\boldsymbol{B}$: magnetic flux density), where $\boldsymbol{T}$ is defined by $\boldsymbol{J} = \nabla\times\boldsymbol{T}$ ($\boldsymbol{J}$: current density). With the proposed method, the number of variables is reduced to one-third, namely, only one direction (the normal direction) component of variables is needed in the orthogonal curvilinear coordinate system while three direction components of variables are needed in the Cartesian coordinates system. Therefore, a significant reduction in the computational load is achieved as well as a better convergence property in comparison with normal three-dimensional electromagnetic analysis method. Moreover, no limitation of the REBCO coil shape exists in this method, and REBCO coils with any structures can be modeled and analyzed by simply inputting the Cartesian coordinates of certain REBCO coils. Additionally, a nonlinear E-J relation (E: electric field) as well as the temperature dependence is used for modelling the electromagnetic characteristic of superconductors. In heat transfer analysis, the 3D structure of REBCO coils is modeled and the temperature change is calculated under the condition of Joule heating, heat conduction, heat transfer, and cooling characteristics. In addition, the temperature dependence of thermal characteristics is also considered in the analysis.

Verifications and some case studies are then conducted with the developed analysis program that based on the proposed analysis method.

Firstly, verifications of the proposed three-dimensional electromagnetic analysis method are conducted by comparing the analysis results with theoretical formula and commercial simulation software JMAG. Good agreement is observed which verifies the correctness and accuracy of the proposed analysis method.

Next, two case studies based on the three-dimensional electromagnetic analysis are conducted and indicate the capability of the developed electromagnetic analysis tool to analyze various electromagnetic characteristics of REBCO coils in any shape. One is an analysis of a solenoid REBCO coil for magnet application, which requires high magnetic field as well as high stability and homogeneity of the field. The author has modelled a solenoid REBCO coil and assumed some different patterns of excitation to study the magnet field stability and homogeneity with detailed distribution of magnetic field, screening current induced field, current density, and screening current density. The other case study is an analysis of a saddle-shaped REBCO coil for accelerator application, which requires accurate and homogeneous magnetic field with the frequently changing coil current. The author has modelled a saddled-shaped REBCO coil and assumed the change pattern of coil current to study the space magnetic field distribution and the influence of screening current with detailed distribution of magnetic field, screening current induced field, current density, and screening current density.

Moreover, two case studies based on electromagnetic and heat transfer coupled analysis are conducted to study the quench phenomenon in certain applications. One is an analysis of a REBCO coil for resistive type SFCL application, in which quench is a problem because high resistance is generated to limit the overcurrent through the SN transition with a significant temperature rise. The author has analyzed the transient electromagnetic and thermal behaviors of two solenoid REBCO coils under overcurrent: one with uniform critical current density (J_C) distribution and the other with local J_C degradation. The other case study is an analysis of a REBCO coil for magnet application, in which a quench usually occurs after an external energy input during the normal operation or the excitation process. The author has analyzed the influence of different energy input power, area, and different time constants of current decrease on the quench of a solenoid REBCO coil, as well as the electromagnetic and thermal behaviors before and after the quench.