FEM Analysis of Hysteresis Using a Thermodynamic Model

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Thanks to great advances in computation technologies and computer performance, today FEM analysis can handle models that fairly closely approximate actual magnetic fields. However, modeling of magnetic materials is almost always carried out by considering only isotropic nonlinear characteristics; no general method has been established that addresses anisotropic nonlinearity and hysteresis. Highly accurate analysis of magnetic fields requires faithful reproduction of magnetic materials' magnetization characteristics. Since needs for highly accurate analysis of magnetic fields are expected to increase in the future, faithful modeling of such characteristics is an urgent matter.

The magnetic characteristics of magnetic steel sheets can be measured highly accurate with the aid of today's technologies. Given this fact, we examined anisotropic nonlinear magnetic characteristics in detail. Our results suggest that the magnetic characteristics of magnetic steel sheets can be formulated from a thermodynamic perspective. On the basis of this suggestion, we successfully reproduced the magnetic characteristics using the free energy of magnetic materials. However, free energy, which is a state quantity determined from physical quantities (e.g., magnetic flux density and temperature), seems difficult to use to address history-dependent characteristics such as hysteresis.

By contrast, the spontaneous magnetization of ferromagnetic materials can be formulated thermodynamically on the premise that a magnetic material has multiple possible local minimum values of free energy.

Since spontaneous magnetization is thought to contribute substantially to the occurrence of hysteresis, it seems history-dependent characteristics can be formulated on the assumption that when in thermal equilibrium, magnetic materials are not in a state having the minimum value of free energy but rather in a state having one of the local minimum values. However, formulation of hysteresis of actual magnetic materials requires the existence of free energy having a considerably complex form; such a complex free energy form is inappropriate for numerical modeling. Therefore, we take the following two-step approach to hysteresis analysis.

First, free energy is smoothed by removing local stabilization points; after smoothing, the equilibrium state of magnetic materials can be determined from the minimum value of free energy.

Next, an irreversible process as seen in frictional phenomena is introduced in order to take the influence of local minimization into consideration; consequently, magnetization characteristics can be treated as a history-dependent process. The effect compared to friction can be formulated by introducing a quantity called the hysteretic magnetic field, which corresponds to frictional force.

The free energy in question is a function of magnetic flux density and temperature. Accordingly, variable transformation from magnetic flux density to magnetic field intensity allows us to introduce a thermodynamic potential similar to the Gibbs free energy. In a state with a fixed magnetic field at a fixed temperature, the magnetic materials' thermodynamic potential takes its minimum value.

This approach enables us to formulate finite elements for numerical analysis by applying the variational method to the thermodynamic potential.

Compared to conventional FEM, which is based on the weighted residual method, this FEM, which is based on the variational method, offers substantial advantages in that it allows us to address spontaneous magnetization and hysteresis in a simpler manner.