Finite Element Analysis for Electromechanical Design

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Finite Element Analysis (FEA) is indispensable to design and development of electromagnetic field applications in industry as well as academic and several software packages for FEA are commercially available today. The basics of ElectroMagnetic (EM) FEA, use cases and future work will be explained here. It should be noted that electromagnetic applications can be classified into two categories, i.e. High Frequency (HF) and Low Frequency (LF) and this explanation will focus on the LF. Although the names imply that there exists a frequency as the divider, no such a clear boundary frequency exists since the divider is significance of the displacement current in the application's phenomena. Typical applications of HF are antennas, microstriplines and waveguides. LF, on the other hand, has motors, transformers and sensors, in which the magnetic field is dominant over the electric field.

The EM FEA was started in late of 1970 in the electrical engineering by utilizing the structural FEA technology which was originally developed for computational vibration analysis for aircraft in late 1960[1)]. The applications in the early stage were power transformers and generators[2)] for both of which prototyping is difficult due to the size and sophisticated design is required to achieve high efficiency and reliability for power supply in social infrastructure. Those successes expanded its application range to other systems and products such as TV tubes[3)4)], solenoid valves[5)], magnetic recording heads[6)], EM shields[7)], induction heating systems[8)], non-destructive testing[9)]. In the mid of 1990, as well known as Kyoto Protocol, the energy efficiency improvement became a must time in most electrical applications such air-conditioners[10)] and electric vehicles (EV)[11)] and hybrid vehicles (HV)[12)13)] which have to have very high efficient motors. To achieve the super high efficiency, the FEA was heavily used and it is still going on today.

The basic equation of the EM FEA is the Maxwell's equations with two constitutive equations which represent material characteristics and the displacement current term is omitted from them for LF. This modification decouples electric field from magnetic field so that it becomes easier to solve three equations rather than all the four equations. The drawback is, of course, one cannot see electric field effects such as displacement current flowing in a capacitor.

It does not mean LF is easier than HF in which one has to solve the four equations because, in LF, there exists magnetic saturation that leads to the non-linear problem and many applications have motion which is difficult to handle for EM where both space and objects are have to be modeled.

The remaining three equations can be unified by introducing magnetic vector potential instead of handling magnetic field directly.

The unified equation is transformed by Finite Element Method (FEM) into a form which can be solved by computers. In FEM, an analysis region, which includes magnetic materials, conductors and spaces, and time are discretized into small elements and time intervals. The union of elements is called mesh. The field value, which is magnetic vector potential in this case, is represented with a polynomial using interpolation functions. It means that the accuracy of the solution depends on the discretization, that is that smaller elements and time interval will give more accuracy.

The resulting discretized equation forms a matrix equation in which the coefficient matrix contains material characteristics and the load vector contains currents/voltage/permanent magnet. It is solved by a linear equation solver to obtain the magnetic vector potential. Recalling that the magnetic materials usually have complex behavior such as magnetic saturation and hysteresis characteristics, the equation is basically non-linear and needs to be solved with iterative manner. It should be noted that the dimension of the matrix increases as the number of the elements increases so that efficient meshing techniques is important to generate efficient meshes which have enough elements only for sensitive regions minimizing the total number of elements. After obtaining the magnetic vector potential, several physical quantities are naturally derived, such as magnetic flux density, magnetization, eddy current, losses, force and torque.

Today's challenges in the EM FEA are material modeling and high speed calculation for large scale models. Since material characteristics are basically given parameters for the equation[14)], the accuracy of the characteristics will directly affect the accuracy of the solution. On the other hand, behavior of material is so complex[15)] that it is difficult to have a material model which reproduces the behavior with reasonable costs. Although it is, of course, possible to use the micro magnetic simulation techniques such as the material model, there are two significant problems which are enormous calculation cost and the fact that it is difficult to obtain parameters for the model by usual material measurements. Eventually, relatively simple material models, which is costless and can be constructed with measurable parameters, are employed in today's practical situations accepting certain inaccuracy. In this context, several new material models have been proposed and being examined.

The high speed calculation is natural sequence of pursuing highly accurate solution which is required for today's sophisticated detail design in advanced applications such as EV/HV. The main stream of speeding up is utilizing multi-/many cores equipped in the latest computing systems, that is parallel computing. However, the calculation scheme of EM FEM is not easily parallelized by its nature and many new ideas are required.

The EM FEA is actively used for wide range of applications and is still attracting users because of its powerful and flexible functionality. The technical challenges are going on to enhance the functionality and it is still evolving.

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