Two and Three Dimensional Coupled Electromagnetic/Thermal Analysis for Induction Heating Application using the Boundary Element Method (BEM)

ABSTRACT

Over the past decade, a new numerical technique has been developed using the boundary element method (integral equations) which lends itself very well to open field electromagnetic and thermal problems. The boundary element method (BEM) approach is gaining recognition within the Induction Heating industry as being an effective and efficient approach to solving industry specific problems. BEM produces precise results with far less data as compared to conventional finite element method (differential equations). BEM caters to open region problems without any artificial truncation of the region and models problem geometries precisely. This makes the BEM approach ideal for solving Induction Heating problems.

Two and Three Dimensional Coupled Electromagnetic/Thermal Analysis for Induction Heating Application using the Boundary Element Method (BEM)

BY

BRUCE KLIMPKE AND CURTIS REBIZANT

OF

INTEGRATED
ENGINEERING SOFTWARE

February 19, 1997

Abstract

Today's highly competitive Induction Heating market demands that companies find new and better ways to increase productivity, decrease engineering and development costs and deliver high quality products to market faster than ever before. Companies that focus on reducing costly and time consuming prototyping through the use of Computer Aided Engineering (CAE) software can achieve these goals and enjoy enhanced competitive advantages.

Over the past decade, a new numerical technique has been developed using the boundary element method (integral equations) which lends itself very well to open field electromagnetic and thermal problems. The boundary element method (BEM) approach is gaining recognition within the Induction Heating industry as being an effective and efficient approach to solving industry specific problems. BEM produces precise results with far less data as compared to conventional finite element method (differential equations). BEM caters to open region problems without any artificial truncation of the region and models problem geometries precisely. This makes the BEM approach ideal for solving Induction Heating problems.

This presentation explains the new boundary element method in comparison to the traditional finite element method is used for Induction Heating problems.

Introduction

Simulating the Induction Heating process is complicated mainly due to the coupling of electromagnetic and thermal fields. In general one can not be solved independently of the other unless certain simplifications are assumed. An additional complicating factor is that the Induction Heating system is an open region problem. Meaning the solution process must account for the air space encompassing the induction coils and parts to be hardened. Using more traditional numerical methods, such as finite elements, requires the air space be discretized (i.e. divided up into smaller triangles or rectangles called elements). The discretization of the Induction Heating system including the surrounding air (finite elements) is more computationally demanding then discretizing just the induction coils and the parts (boundary elements).

Another difficulty associated with induction hardening is catering to the skin and proximity effects within the billet as the frequency increases. The induced current moves closer to the surface as the frequency increases requiring accurate models of the surface currents. This poses severe restrictions on traditional finite element solutions unless sophisticated techniques are employed. Using a boundary element approach eliminates the difficulty as elements (or equivalently unknowns) are only required on the geometry boundary and not throughout the entire geometry.

This presentation discusses the use of the boundary element method (integral equations) to simulate the Induction Heating process in contrast to the traditional finite element method (differential equations). Attention is paid to the advantages and disadvantages of both methods.

Problem Description

The object is to quickly heat a part's surface and then cool it. The first phase of the process requires coupled electromagnetic-thermal analysis and the second phase requires thermal analysis only. Heat is transferred to the part by exciting one or more coils located near the part. Heat is then induced in the part by eddy currents generated within the electrically conductive regions. Parameters that affect the part's heating include the geometry, magnetic permeability, electrical conductivity, thermal conductivity, specific heat, and frequency of system operation. These parameters (except the geometry and frequency) can be functions of the spatially dependent temperature. In addition, the magnetic permeability is dependent upon the magnetic field strength.

The Induction Heating designer is given the part's geometry and material and therefore has no control over the part's material parameters. The design variables are the operation frequency, the types and shapes of coils, and the geometry and material parameters of the flux concentrator. The designer requires software to account for these interrelated effects during the heating and cooling process to achieve an optimal induction heating system.

Numerical Simulation

When simulating any electromagnetic-thermal system, to determine the thermal and electromagnetic field distribution, two fundamentally different approaches are used. The elecromagnetic-thermal system can be solved using differential or integral equations (hybrid methods that use both techniques simultaneously have been suggested.) The two popular methods for solving equations posed in differential form are the finite difference (FD) and finite element methods (FEM). These two differential methods are used by most commercially available software. The two methods commonly associated with solving integral equations are the boundary element method (BEM) or the method of moments (mom). The two integral methods have had limited exposure for both historical and technical reasons but they are rapidly gaining in popularity.

Before the advent of the modern digital computer analytic methods were the only practical option to solving differential equations. Integral equations could only be used to solve problems that were spherical or cylindrical and had little practical use. With the advent of digital computers it was only natural to use numerical methods to solve differential equations as the formulations were easily applied to various geometries. This is especially true for finite differences. As well, providing an element mesh could be generated, finite element programming was relatively simple. On the other hand, dealing with integral equations was very difficult to do numerically (mainly due to the singularities). Once these numerical difficulties were overcome, the integral equation approach (e.g. boundary element method) and its related advantages became more accessible.

When using differential equations to solve most mechanical or heat conduction problems, only the problem's interior needs to be discretized. This is in contrast to most electromagnetic problems where the problem's interior and the exterior must be discretized. This poses insurmountable difficulties when problems have exterior regions requiring large numbers of finite elements that exceed computer resources (speed and memory).

Solving the same problem using integral equations requires only the problem's boundaries be divided into smaller pieces called boundary elements. This is illustrated for the case of a simple part being heated inductively (Figure 1).

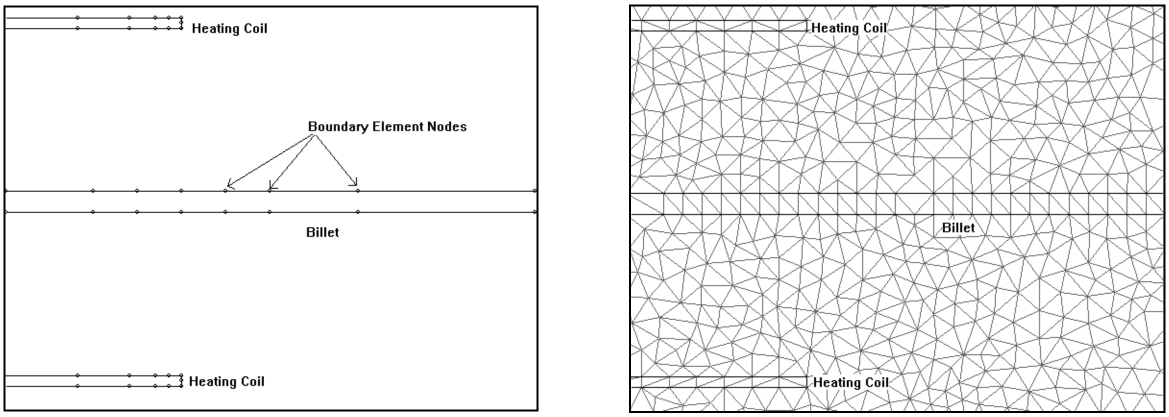

Figure 1: Boundary Element (left) and Finite Element (right) Discretizations of the Same Problem

The illustration shows that boundary elements reduce the problem dimensionality by one (e.g. for a two-dimensional problem the boundary elements are one-dimensional). The simplicity of discretizing a problem using boundary elements is apparent. Also, as the frequency of the system increases many more finite elements will be required near the part's surface due to the skin depth. However, only a moderate increase is required for boundary elements as the frequency increases. In addition, the finite element method produces large matrices with many zero entries whereas the boundary element method produces small matrices with few zero entries.

Perhaps the major limitation to using boundary elements in the past was dealing with nonlinear problems where the material properties depend strongly on the temperature or other quantities. In this event some of the elegance of the boundary element approach is lost. For such cases the nonlinear regions are divided into smaller areas which we refer to as subareas. These look graphically the same as finite elements but serve a completely different purpose. When solving differential equations, either a scalar or vector quantity is determined throughout the problem domain (such as temperature for a thermal analysis). Integral equations solve for a source on the boundary which supports the actual field (heat source for thermal analysis). If the problem is nonlinear then equivalent sources must be determined in the domain.

Solution Time Versus Simplifications

The ideal situation for simulating the Induction Heating process is to model the full three-dimensional (3D) problem taking into account all nonlinearities with a small time step to deal with the transient behaviors. The ideal situation may include optimization to minimize cost. This is likely to be achieved, but not in the foreseeable future. The designer must then decide on simplifying assumptions to get timely results. One simplification resulting in a major time reduction is to reduce the problem's dimensionality. Thus a real problem (three dimensional) is reduced to two-dimensions or even one-dimension. Each reduction in dimensionality significantly reduces computation time and designer's modeling time. The trade-off is reduced model accuracy.

A further simplification is to assume certain material properties are temperature independent. This again may reduce computational times considerably. Finally, restricting the problem's geometry allows software algorithms to be created that efficiently solve a simple class of problems. When numerical techniques improve and computer speeds increase more complicated analysis will become possible reducing the need for problem simplification.

Example

Illustrated is a camshaft problem to be inductively heated. The figures show the magnetic field lines (Figure 2), eddy current density near the camshaft's corner (Figure 3), and an eddy current graph from the center to the outer surface of the camshaft (Figure 4).

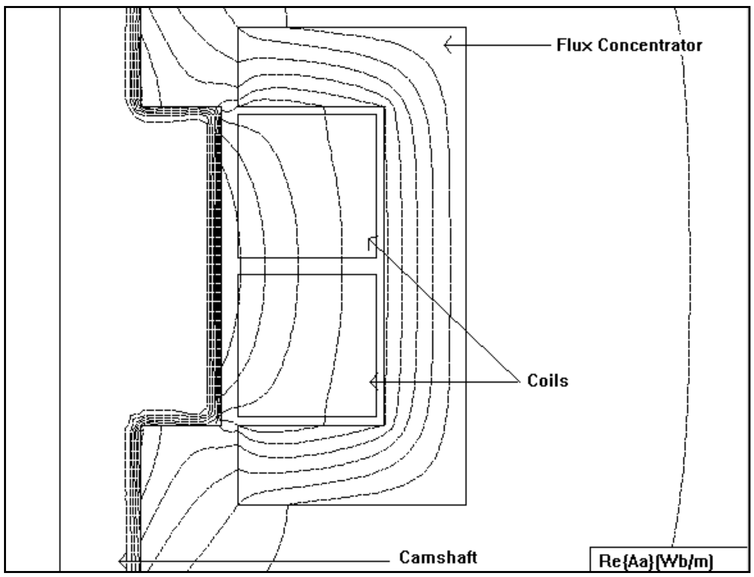

Figure 2: Field Lines in the Induction Heating System

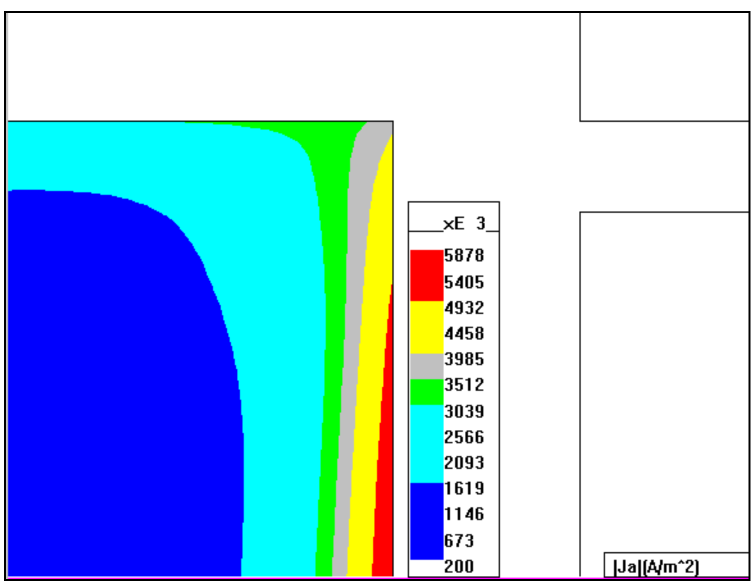

Figure 3: Eddy Current Density Near the Corner of the Camshaft

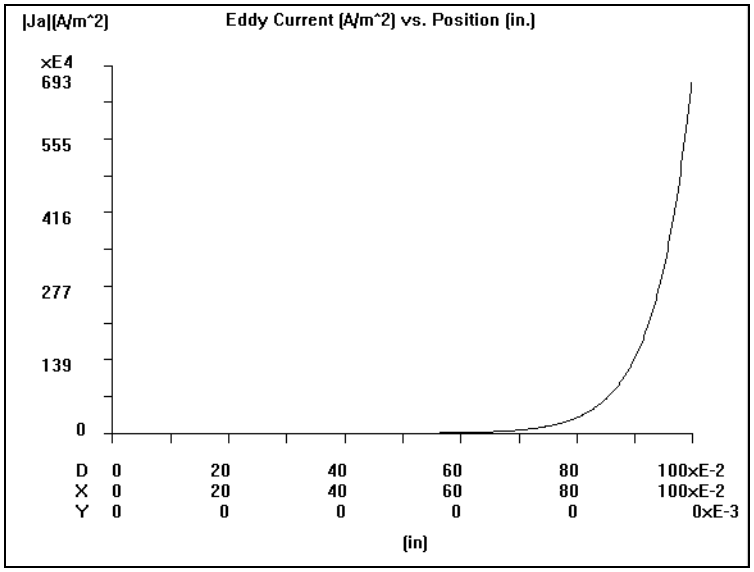

Figure 4: Eddy Current Magnitude From Camshaft's Center to Edge

Conclusion

For problems where the interior and exterior regions must be solved simultaneously the boundary element method (BEM) has some distinct advantages over the traditional finite element approach. As well, problems with small skin depths are easily handled using the boundary element approach as boundary element density is only weakly dependent on frequency. Some of the BEM simplicity is lost, however, when problems are non-linear. In such circumstances the nonlinear region must be divided into subareas.

Although simulating the complete Induction Heating process has not been attempted using just boundary elements a BEM approach can yield excellent Induction Heating CAE simulation results.