LS-DYNA® R7: Update On The Electromagnetism Module (EM)

Pierre L'Eplattenier
Iñaki Çaldichoury
Julie Anton

Livermore Software Technology Corporation
7374 Las Positas Road
Livermore, CA 94551

Abstract

An electromagnetism module is being developed in LS-DYNA version R7 double precision for coupled mechanical/thermal/electromagnetic simulations. The physics, numerical methods and capabilities of this module will be introduced. Some examples of industrial applications will be presented. These include magnetic metal forming, bending and welding in different configurations, high pressure generation for equation of state studies and material characterization, induction heating, resistive heating, short circuits due to crashes, electromagnetic launchers, ring expansions, magnetic levitation and so forth. Additionally, magnetic material capabilities are currently available for beta testing and will also be discussed in this paper.

1- Introduction

An electromagnetism (EM) module is under development in LS-DYNA in order to perform coupled mechanical/thermal/electromagnetic simulations [1], [2].This module allows us to introduce some source electrical currents into solid conductors, and to compute the associated magnetic field, electric field, as well as induced currents. These fields are computed by solving the Maxwell equations in the eddy-current approximation. The Maxwell equations are solved using a Finite Element Method (FEM) [3], [4] for the solid conductors coupled with a Boundary Element Method (BEM) [5] for the surrounding air (or insulators). Both the FEM and the BEM are based on discrete differential forms (Nedelec-like elements [4], [6]). The solver exists in Serial and MPP versions and is available in the R7 double precision release.

Electromagnetic Metal Forming (EMF) has historically been the main application of this solver, but newer developments now allow other processes that could be simulated. These include induced heating, resistive heating with the possibility of added of contact resistances, the coupling of a time dependent external field with conductors and so forth.

This paper will describe the main physics of the solver along with application examples. It will then focus on the current state of development of magnetic material capabilities.

2- The Electromagnetics Solver

2-1 Presentation of the physics

The Electromagnetic solver focuses on the calculation and resolution of the so-called Eddy currents and their effects on conducting pieces. Eddy current solvers are also sometimes called induction-diffusion solvers in reference to the two combined phenomena that are being solved. In Electromechanics, induction is the property of an alternating of fast rising current in a conductor to generate or “induce” a voltage and a current in both the conductor itself (self-induction) and any nearby conductors (mutual or coupled induction). The self-induction in conductors is then responsible for a second phenomenon called diffusion or skin effect. The skin effect is the tendency of the fast-changing current to gradually diffuse through the conductor’s thickness such that the current density is largest near the surface of the conductor (at least during the current’s rise time). Solving those two coupled phenomena through the Maxwell equations allows calculating the electromechanic force called the Lorentz force and the Joule heating energy which are then used in forming, welding, bending and heating applications among many others.

Let Ω be a set of multiply connected conducting regions. The surrounding insulator exterior regions will be called Ω_e. The boundary between Ω and Ω_e is called Γ, and the (artificial) boundary on Ω at the end of the meshing region (hence where the conductors are connected to an external circuit) is called Γ_c. In the following, we will denote $\vec{n}$ as the outward normal to surfaces Γ or Γ_c. The electrical conductivity, permeability and permittivity are called σ, μ and ε respectively. In Ω_e, we have $\sigma = 0$ and $\mu = \mu_0$.

We solve the Maxwell equations in the so-called low frequency or “eddy-current” approximation, which is valid for good enough conductors with low frequency varying fields such that the condition $\varepsilon_0 \frac{\partial \vec{E}}{\partial t} \ll \sigma \vec{E}$, where $\vec{E}$ is the electric field, is satisfied [1]. When using a vector potential $\vec{A}$ and scalar potential Φ representation and using the Gauge condition $\nabla(\sigma \vec{A}) = 0$ [7], we end up with the following system to solve [1], [2] :

$$\nabla\left(\sigma \overrightarrow{\nabla \Phi}\right)=0 \tag{1}$$

And :

$$\sigma \frac{\partial \vec{A}}{\partial t} + \vec{\nabla} \times \left(\frac{1}{\mu} \vec{\nabla} \times \vec{A} \right) + \sigma \vec{\nabla} \Phi = \vec{J_s} \qquad (2)$$

where $\vec{J_s}$ is a divergence free source current density.

Equations (1) and (2) are projected over Nedelec-like basis functions, resulting in the linear systems:

$$\boldsymbol{S^0}(\boldsymbol{\sigma})\Phi = 0 \qquad (4)$$

$$\boldsymbol{M^1}(\boldsymbol{\sigma}) \frac{\partial a}{\partial t} + \boldsymbol{S^1}\left(\frac{1}{\mu}\right) a = -\boldsymbol{D^{01}}(\sigma)\Phi + \boldsymbol{S}a \qquad (5)$$

where $\vec{A}$ and Φ have been decomposed on their corresponding 1-for and 2-for basis functions a and Φ and $\boldsymbol{S^0}$, $\boldsymbol{S^1}$, $\boldsymbol{M^1}$ and $\boldsymbol{D^{01}}$ are FEM matrices (see [1], [6] and for details).

The outside term SA is solved using a BEM method [5], for which details can be found in [1].

2-2 Coupling with the mechanics and thermal

Once the EM fields have been computed, the Lorentz force $\vec{F} = \vec{j} \times \vec{B}$ is evaluated at the nodes and added to the mechanical solver [2]. The mechanical and electromagnetic solvers each have their own time step. For a typical EMF simulation, the mechanical time step is about 10 times smaller than the electromagnetic one. At this point, the explicit mechanical solver of LS-DYNA is used when coupled with electromagnetism. The mechanical module computes the deformation of the conductors and the new geometry is used to compute the evolution of the EM fields in a Lagrangian way.

The Joule heating power term $\frac{j^2}{\sigma\rho}$ is added to the thermal solver which uses its own time step to update the temperature. Several thermal models are available, isotropic, orthotropic, isotropic with phase change and so forth. The temperature can be used in turn in an electromagnetic equation of state to update the electromagnetic parameters, mainly the conductivity σ. At this time, a Burgess model [8] has been introduced, as well as a simpler Meadon model, and a tabular model where a load curve defines σ versus the temperature [2].

2-3 Coupling with external circuits

The eddy current solver can be coupled with one or several external circuits. At this point, each circuit can be either an imposed current through a segment set, where the current versus time is defined by a load curve; an imposed voltage drop between two segment sets, again with a load curve defining the voltage versus time; or an R, L, C circuit.

Imposed currents are dealt with global constraints on the BEM system, whereas imposed voltages or R, L, C are taken care of with Dirichlet constraints on the scalar potential Φ in the FEM system [1], [2].

Segment sets, through which the flux of the current density versus time is computed, can be used as "Rogowski coils".

It is also possible as an option, to apply an external field on a given conductor. This feature can for example be useful in cases where the user knows or has a good idea of the magnetic field generated by a coil on a workpiece. This way, the whole coil does not need to be modeled which can save a lot of calculation time.

2-4 Examples of applications

Figure 1 shows an example of an industrial application for metal forming. This study conducted in collaboration with M. Worswick and J. Imbert from the University of Waterloo, Ontario Canada, features a metal sheet undergoing plastic deformation and being forced on a conical die (only 1/2 of the die and the work piece are represented) by strong magnetic forces generated by the coil’s high density magnetic field and the induced currents of the workpiece. The main objective of this study was to predict the final shape of the metal sheet. Details on the experimental setup as well as experiment/simulations comparisons can be found in [1].

Figure 3features an example of an industrial application of the inductive heating solver. This solver is being used in induced heating problems involving larger time scales (typically a few seconds) and very high frequency currents. In this test case, a steel plate is moving at a constant velocity while being heated by a set of coils. More details about the inductive heating solver as well as industrial applications can be found in [9].

For cases where induction-diffusion effects can be neglected a special solver called the resistive heating solver can be used. Since no BEM effects need to be calculated, this solver is very fast and very high time steps can be used. In such cases, no Lorentz forces are computed but Joule heating is still taken into account. One application example would be the study of short-circuits in car batteries due to crash or impacts.

A contact capability has been introduced in the EM module to handle electromagnetism contact between two conductors. One on the applications of this new capability is rail-gun simulations. In a rail gun, the electromagnetic forces created by an electrical current are used to accelerate a projectile between two conductor rails at supersonic speeds, as shown on Figure 5. The contact capability allows simulating the sliding contact between the rails and the projectile. Other industrial applications for this feature include electromagnetic welding cases where two conductive metal pieces come into brutal contact with each other as shown in Figure 6. More details about rail gun simulations can be found in [11].

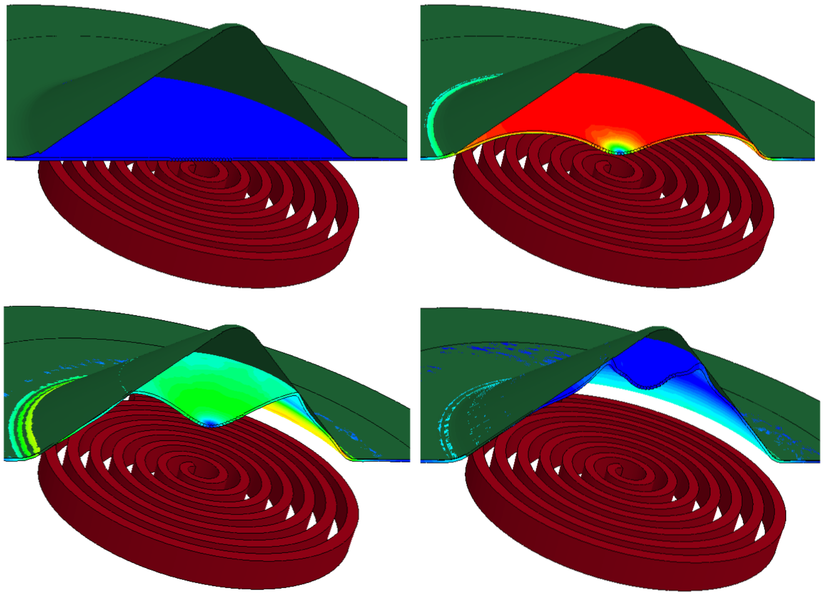

Figure 1 Magnetic metal forming example where an Al plate is formed against a conical die by EM forces

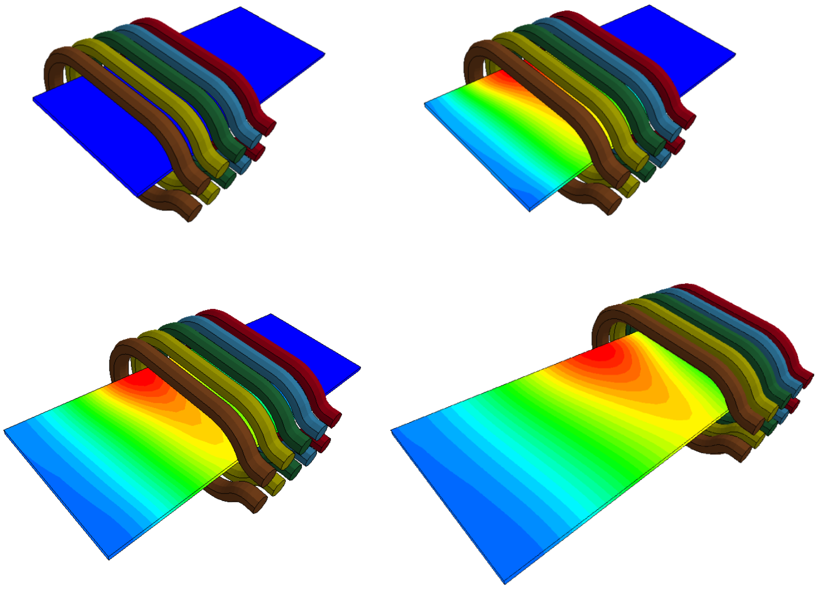

Figure 2 Temperature fringes of an inductive heating example where a plate moves through and is being heated by five coils

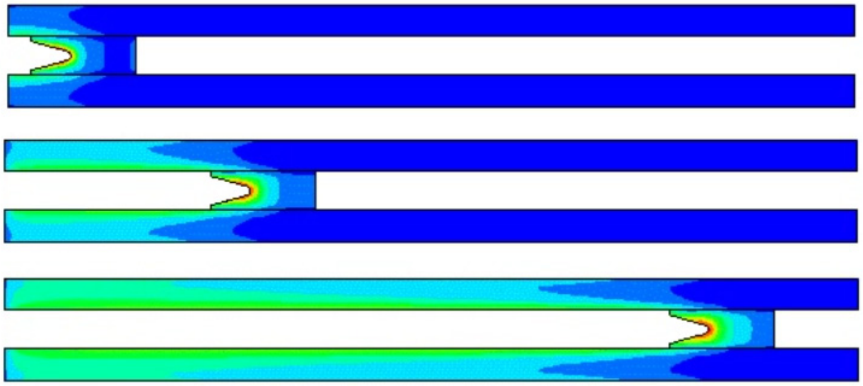

Figure 3 Rail gun model: Current flowing between rails and projectile generates magnetic field (fringes) and Lorentz forces that accelerate the projectile

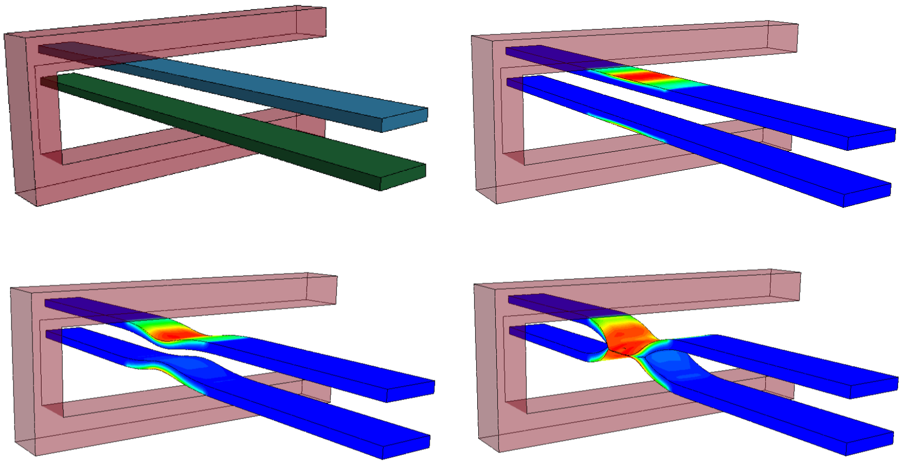

Figure 4 Current density fringes of a Welding test case between two metal pieces. Conducted in collaboration with the University of Waterloo, Canada

3- Magnetic material capabilities

3-1 Magnetic materials

So far all the conductors were considered nonmagnetic materials. This means that their permeability is considered equal to the vacuum permeability ($\mu_0 = \mu_{material}$). Certain type of conductors exhibit magnetization behavior in response to an applied magnetic field. Such materials are called magnetic materials. Magnets are a special case of magnetic materials where no source magnetic field is needed to reach a magnetized state. The degree of magnetization that a material obtains in response to an applied magnetic field is expressed represented by μ with: $B = \mu H$ where B is the magnetic flux density and H the magnetic field intensity. For nonmagnetic materials μ is equal to μ_0 which is the permeability of free space i.e a measure of the amount of resistance encountered when forming a magnetic field in a classical vacuum. For magnetic materials however, μ is different from the vacuum permeability μ_0. Magnetic materials can be further divided into linear magnetic materials (paramagnets, diamagnets) and nonlinear magnetic materials (ferromagnets) (See Figure 5).

In practice magnetic materials can be encountered in applications such as generators, motors or flux concentrators. In some cases, the magnetization process is very fast compared to the diffusion of the Eddy Currents. In order to save calculation time, it is therefore interesting to consider the solver in an already initially magnetized state or “steady state”. Consequently, there are currently two new features under development in the EM solver: the implementation of magnetic materials where the whole transient magnetization process is solved as well as a so called magneto-static solver where the magnetic materials would be directly considered in a magnetized state.

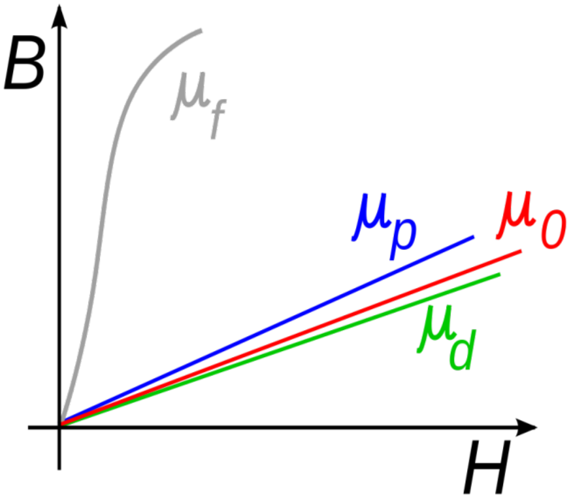

Figure 5 μ_p for paramagnetic materials, μ_d for diamagnetic material, _f for ferromagnetic material

3-2 Numerical issues

One difficulty with non-linear materials is that the numerical system becomes non-linear, i.e. the matrices in (5), namely $\boldsymbol{S}^{\mathbf{1}}\left(\frac{1}{\mu}\right)$, depends on the solution through μ. In an eddy current problem, if the time step is sufficiently small, one can build the matrices using the solution of the previous time step and solve a linear system. However, when the time step becomes too large, iterations on the non-linearity are needed.

Another difficulty which arises for eddy current problems with large time step and even more for magnetostatics is that the system (5) becomes singular which requires special treatment.

Finally, still for large time step eddy current or magnetostatic problems, the traditional method used by the EM solver with iterations between the FEM and BEM systems (so called preconditioned Richardson's iterations) does not converge anymore since the spectral radius of the global (FEM+BEM) matrix is larger than 1. We thus are developing a new method to solve the coupled system using the Generalized Minimal RESidual method (GMRES). The system we are dealing with is indeed non symmetric and GMRES, a Krylov's subspace based method, is suitable for such systems.

Using this method a larger range of problems involving magnetic problems has been solved and we are now working on improving its efficiency by adding preconditioners.

3-3 Availability in LS-DYNA R7

The GMRES method is already available as a beta version for linear and nonlinear eddy current as well as for linear magnetostatic problems. It should soon be available for nonlinear magnetostatic problems. Once it will have passed several internal validation tests, it will be released in the official R7 version. In the meantime, users are free to try it out as beta and send back feedback.

4- Conclusion

The Electromagnetism module of LS-DYNA was presented. The electromagnetic fields are computed by solving the Maxwell equations in the eddy-current approximation, using a FEM for the conductors coupled with a BEM for the surrounding air and insulators. The module can be used both in serial and in MPP [13]. The eddy-current solver is the main one, from which further solvers are derived for such as the induced heating and resistive heating solvers for special applications.

The next step would now be the implementation of magnetic material capabilities for even more applications. In order to meet this objective, new solving methods of the FEM-BEM system are currently under investigation (GMRES combined with Preconditionners). Magnetic material capabilities are available for beta testing.

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