Update On The Electromagnetism Module In LS-DYNA

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Abstract

An electromagnetism module is being developed in LS-DYNA version 980 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 and welding in different configurations, high pressure generation for equation of state studies and material characterization, induction heating, resistive heating, electromagnetic launchers, magnetic levitation and so forth.

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.

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 features of the solver with examples from real life experiments.

2- The Eddy Current Solver

2-1 Presentation of the physics

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 σ = 0 and μ = μ_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] :

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

And :

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

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

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

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

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

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 T [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".

2-4 Example: Magnetic metal forming

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].
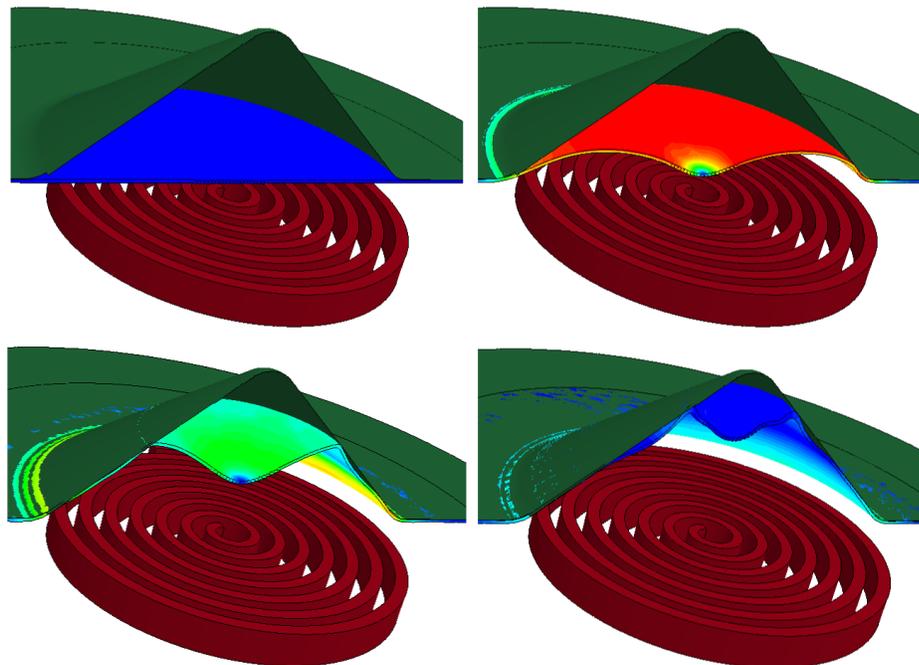

Figure 1 Magnetic metal forming example

3- Induction heating

3-1 Presentation of the model

Induction heating is the process of heating an electrically conducting workpiece (usually a metal) by electromagnetic induction (usually with a moving or non-moving coil), where eddy currents induced within the resistive workpiece generate Joule heating. The solution is computed in the time domain and not in the frequency domain, in order to easily take into account the coil versus workpiece motion as well as the time evolution of the EM parameters (and in particular the electrical conductivity which often is temperature dependent). We use the eddy current solver presented in the last section. However, the setups for induction heating usually see currents with very large frequencies (say in the order of 1MHz), which imposes a very small electromagnetism time step (say around 1.e-8 s). The total duration of the process being in the order of a few seconds, the eddy current solver cannot be used directly.

The induced heating solver thus works the following way: a full eddy-current problem is solved on one period with a "micro" EM time step. Averages of the EM fields, including the Joule heating power over this period are computed. It is then assumed that the properties of the material (and in particular the electrical conductivity which drives the flow of the current and the joule heating), as well as the relative coil/workpiece position do not change for the next periods of the current. The electrical conductivity depending mostly on the temperature, the assumption can therefore be considered accurate as long as the temperature does not change too much. During these periods, no EM computation is done, but the previously computed averaged joule heating power is passed to the thermal solver. As the temperature changes, and thus the electrical conductivity, the EM fields need to be updated accordingly, so another full eddy current resolution is computed for one period of the current giving new averaged EM fields and an updated Joule heating power. Figure 2 shows a schematic of the inductive heating solver (See [2] for more details).
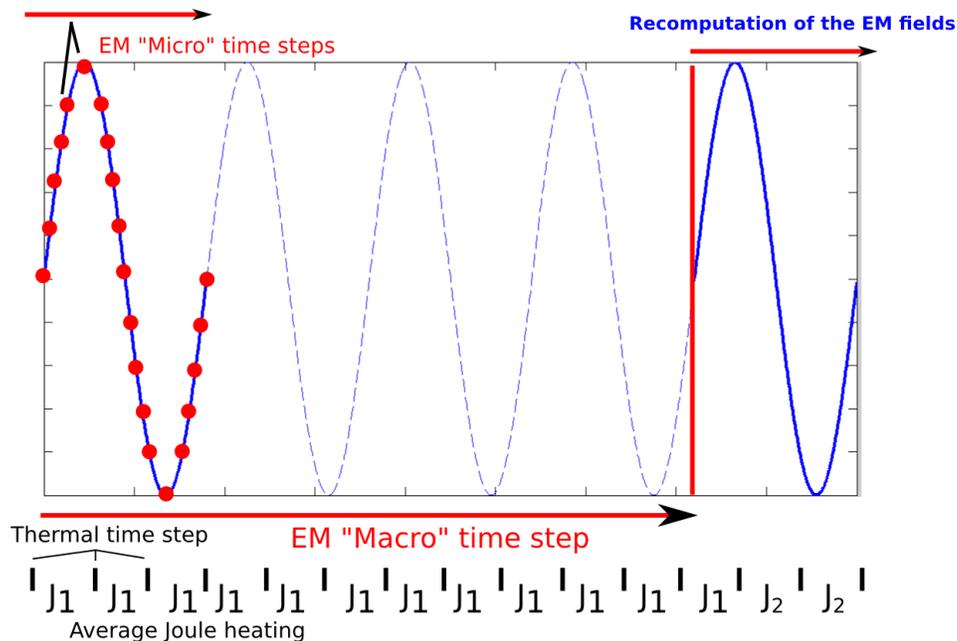

Figure 2 Inductive Joule heating solver handling

3-2 Example: plaque heating

Figure 3 features an example of an industrial application of the inductive heating solver. 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] .
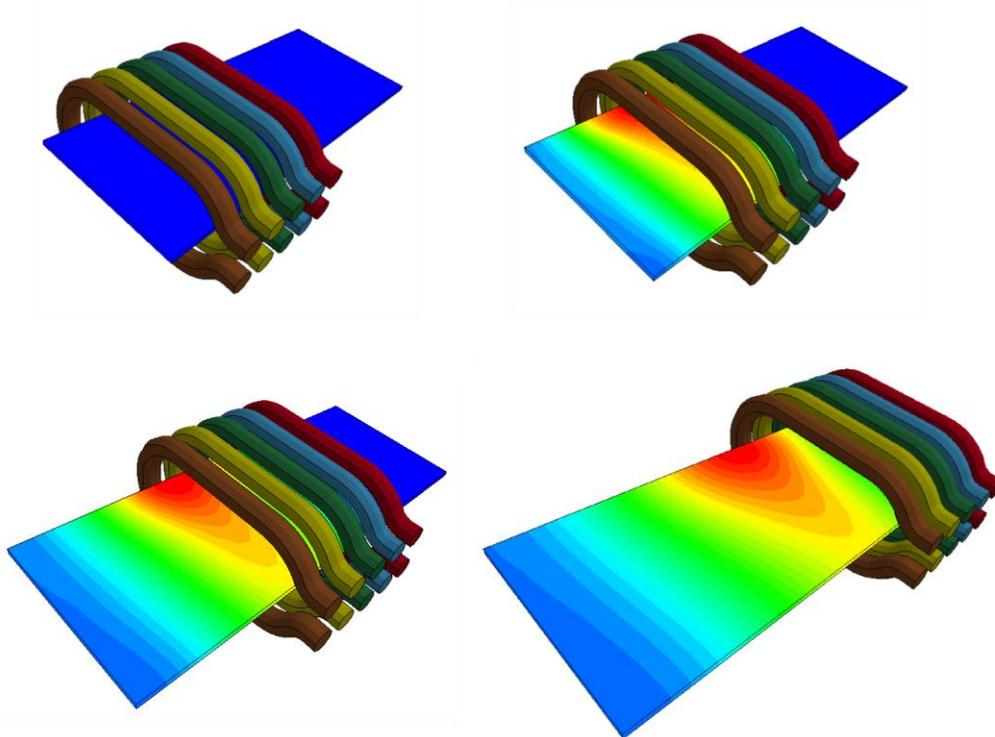

Figure 3 Temperature fringes of an inductive heating example

4- Resistive heating

4-1 Presentation of the physics

The resistive heating solver is a simplified version of the eddy-current solver for slow enough rising current; typically milliseconds to one second, where the inductive effects can be neglected, and the diffusion of the EM fields is considered as an infinitely fast process. This translates into setting $\vec{A} = 0$ in Equation (2) and just keeping the scalar potential Φ with Dirichlet conditions determined by the given voltage versus time. Since $\vec{A} = 0$, $\vec{B} = 0$ and so is the Lorentz force. There however still is some joule heating in the resistive conductor, which is added to the thermal solver. The time step are not limited by the diffusion condition ($t \leq \frac{(l_{element})^2}{2D}, D = \frac{1}{\mu_0 \sigma}$) anymore and no BEM is necessary which makes this solver much faster than the full eddy current one (See [2] for more details).

4-2 Contact resistance

As in the eddy current solver (see Section 5-1), the resistive heating solver can be used with electromagnetism contacts between two conductors, allowing the current to flow from one conductor to the other. A contact resistance has recently been introduced, based on Ragmar Holm's model [10]. This resistance is added to the corresponding electrical circuit.

4-3 Example

This example shows a potential application of the contact resistance feature using the resistive heating solver. In this test case, a conductor wheel rolls over a conductor plate with the current flowing from the wheel to the plate at the contact area between them.
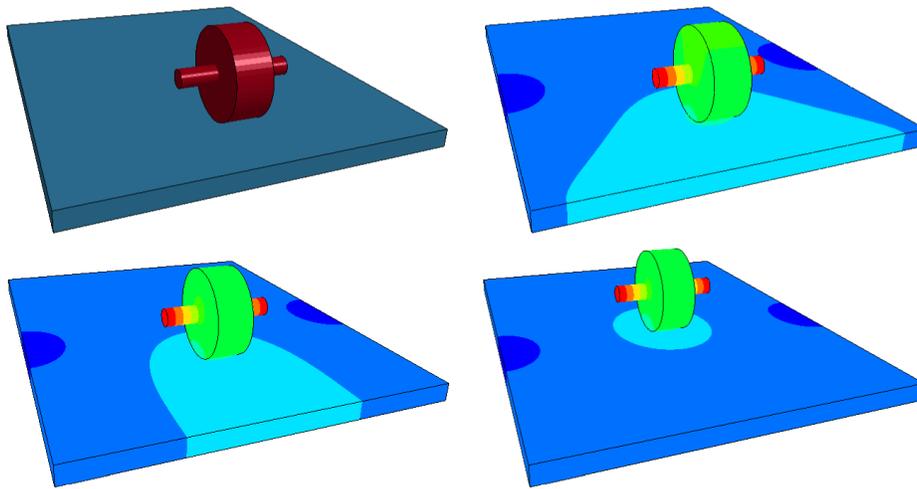

Figure 4 Scalar Potential fringes of conductive wheel in contact with conductive plate

5- Other features

5-1 Electromagnetic sliding contact

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].
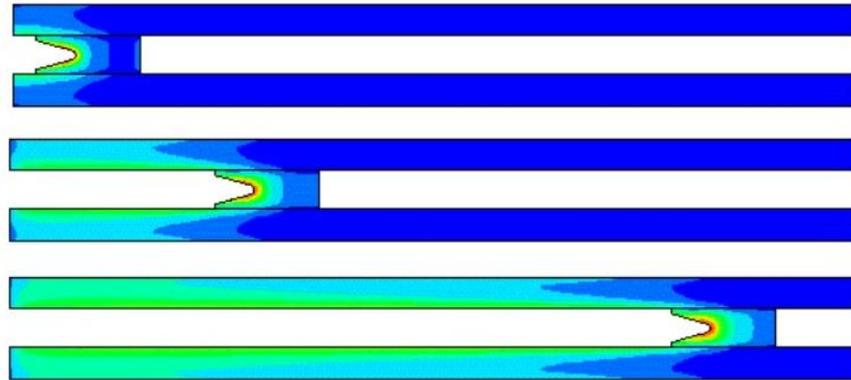
Figure 5 Rail gun model : Current flowing between rails and projectile generates magnetic field (fringes) and Lorentz forces that accelerate the projectile
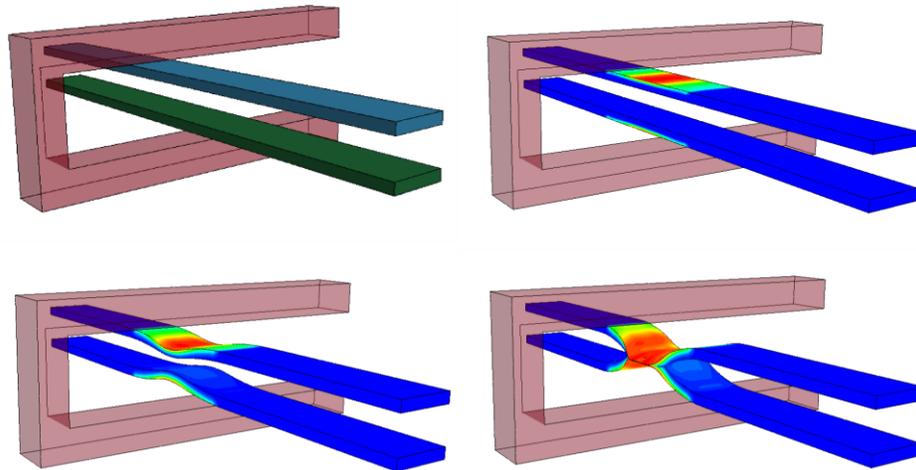

Figure 6 Current density fringes of a Welding test case between two metal pieces. Conducted in collaboration with the University of Waterloo, Canada

5-2 External field

The code allows coupling the model with time dependent external magnetic fields. These fields are uniform in space for now, but more complicated forms could be added. They can induce eddy currents in conductors such as shown in Figure 7 which features the deflection of a cantilevered beam by an external field. More details about this simulation can be found in [12].
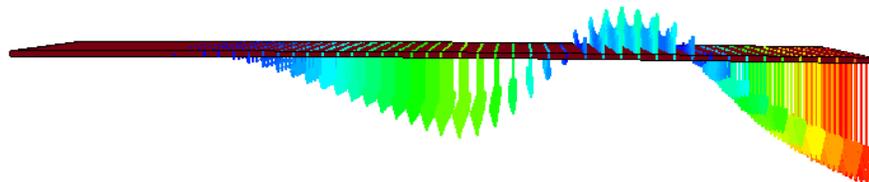

Figure 7 Cantilevered beam deflected by an exterior field

5-3 Conductors with uniform current

Some conducting parts can be defined as "stranded conductors" where the full eddy current problem is not solved, hence no diffusion happens, but instead, they see a uniform current flowing through them. This corresponds to actual stranded conductors composed of multiple wires, or to conductors with large enough skin depths compared to their cross section. These conductors do not participate to the BEM system and are coupled to other "eddy current" conductors by the Biot-Savart equations:

$$\overrightarrow{A_0}(\vec{r}) = \frac{\mu_0}{4\pi} \int \frac{\overrightarrow{J_s}(\overrightarrow{r'})}{|\vec{r} - \overrightarrow{r'}|} d\overrightarrow{r'} \tag{5}$$

$$\overrightarrow{B_0}(\vec{r}) = \frac{\mu_0}{4\pi} \int \frac{\overrightarrow{J_s}(\overrightarrow{r'}) \times (\vec{r} - \overrightarrow{r'})}{|\vec{r} - \overrightarrow{r'}|} d\overrightarrow{r'} \tag{6}$$

where $\overrightarrow{J_s}$ is the uniform source current in the stranded conductor and $\overrightarrow{A_0}$ and $\overrightarrow{B_0}$ are the potential vector and magnetic field created in the Eddy current conductors.

These conductors could be used as a cheap replacement of multi-turn coils in certain geometries such as in the Figure 8 example where a multiturn coil inducing current in a plaque is simply replaced by a cylinder-shaped coil very easy to model. More details about this simulation can be found in [12].
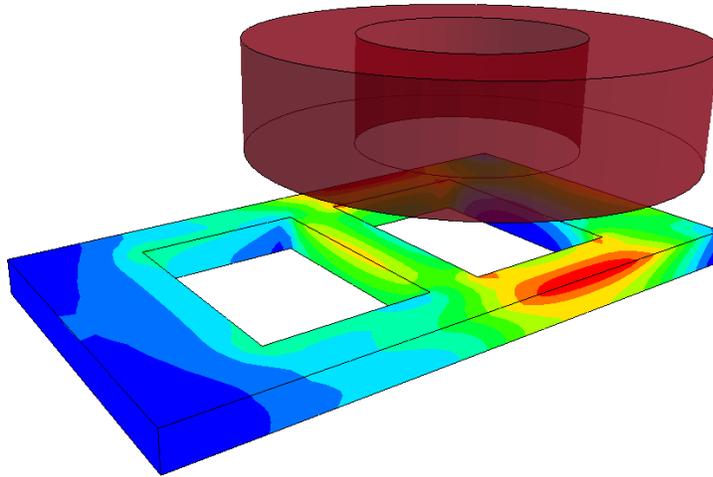

Figure 8 Uniform current in Multiturn Coil inducing current in a plaque

6- 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 the induced heating and resistive heating ones are derived.

Other capabilities have also been presented, like a sliding contact for the electromagnetic fields which allows the simulation of rail gun like experiments (See [11] for more details on the railgun in LS-DYNA), the introduction of external electromagnetic fields, and stranded conductors. The different capabilities have been benchmarked against experimental and numerical results on academic as well as industrial cases (See [12]).

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