A Coupled 3D/2D Axisymmetric Method for Simulating Magnetic Metal Forming Processes in LS-DYNA

P. L'Eplattenier[*], I. Çaldichoury

Livermore Software Technology Corporation, Livermore, CA, USA
[*]Corresponding author. Email: pierre@lstc.com

Abstract

LS-DYNA is a general purpose explicit and implicit finite element program used to analyse the non-linear dynamic response of three-dimensional solids and fluids. It is developed by Livermore Software Technology Corporation (LSTC). An electromagnetism (EM) module has been added to LS-DYNA for coupled mechanical/thermal/electromagnetic simulations, which have been extensively performed and benchmarked against experimental results for Magnetic Metal Forming (MMF) and Welding (MMW) applications. These simulations are done using a Finite Element Method (FEM) for the conductors coupled with a Boundary Element Method (BEM) for the surrounding air, hence avoiding the need of an air mesh.

More recently, a 2D axisymmetric version of the electromagnetic solver was introduced for much faster simulations when the rotational invariance can be assumed.

In many MMF and MMW applications though, the rotational invariance exists only for part of the geometry (typically the coil), but other parts (typically the workpiece or the die) may not have this symmetry, or at least not for the whole simulation time.

In order to take advantage of the partial symmetry without limiting the geometry to fully symmetric cases, a coupling between 2D and 3D was introduced in the EM. The user can define the parts that can be solved in 2D and the ones which need to be solved in 3D and the solver will assume the rotational invariance only on the 2D parts, thus keeping the results accurate while significantly reducing the computation time.

In this paper, the coupling method will be presented along with benchmarks with fully 3D and fully 2D simulations, comparing the accuracy of the results and the simulation times.

Keywords

Simulation, Finite element method (FEM), Electroforming

1 Introduction

A 3D electromagnetism module has being developed in LS-DYNA for coupled mechanical/thermal/electromagnetic simulations (L'Eplattenier et al, 2008).

More recently, a new 2D axi-symmetric version of this solver was introduced, allowing much faster simulations (L'Eplattenier et al, 2015). In this 2D solver, the EM equations are solved in a 2D plane, and the 2D EM fields, Lorentz force and Joule heating are then expanded to 3D elements by rotations around the axis. This allows the coupling of the 2D EM with 3D mechanics and thermal, thus keeping all the LS-DYNA 3D capabilities available. The user needs to provide a 3D mesh with rotational symmetry, either on the full 360 degrees or a small slice.

Both the 3D and the 2D-EM eddy-current problems are solved using a coupled FEM-BEM method, based on differential forms. They can be coupled to different external circuits, including imposed currents, imposed voltage or (R,L,C) circuits. They both work in serial and MPP (L'Eplattenier et al, 2010) and allow contact between conductors (L'Eplattenier et al 2012).

Many applications show a partial rotational invariance. It would be interesting to take it into account to reduce the computation time while still solving the non-axisymmetric parts in 3D to keep a good accuracy. A coupling between 2D and 3D was thus introduced in the EM solver. The user can define the parts that can be solved in 2D and the ones which need to be solved in 3D and the solver will assume the rotational invariance only on the 2D parts.

In this paper, the coupling method will be presented along with benchmarks with fully 3D and fully 2D simulations, with comparisons on the accuracy of the results and the simulation times.

2 Presentation of the 3D/2D Coupled EM Model

2.1 The 3D Eddy Current Solver

The electromagnetic equations are solved using a coupled Finite Element Method (FEM) and Boundary Element Method (BEM). Note that the following demonstration is just a brief summary of what is presented in details in (L'Eplattenier et al, 2008).

In the eddy current approximation of the Maxwell equations, we can introduce a scalar potential φ and a vector potential $\vec{A}$ and get all the EM fields from the evolution of these potentials. They satisfy the following evolution equations:

$$\nabla . \sigma \vec{\nabla} \varphi = 0 \tag{1}$$

$$\sigma \frac{\partial \vec{A}}{\partial t} + \vec{\nabla} \times \frac{1}{\mu} \vec{\nabla} \times \vec{A} + \sigma \vec{\nabla} \varphi = \vec{j}_s \tag{2}$$

Where σ is the electrical conductivity, μ the permeability and $\vec{j}_s$ a source current. When projecting these equations against form based basis functions (Rieben et al, 2006), and integrating over a volume, we get the following finite element equations:

$$\int_{\Omega} \sigma \vec{\nabla}\varphi . \vec{\nabla} W^0 d\Omega = 0 \tag{3}$$

$$\int_{\Omega} \sigma \frac{\partial \vec{A}}{\partial t} . \overrightarrow{W}^1 d\Omega + \int_{\Omega} \frac{1}{\mu} \vec{\nabla} \times \vec{A} . \vec{\nabla} \times \overrightarrow{W}^1 \, d\Omega = -\int_{\Omega} \sigma \vec{\nabla}\varphi . \overrightarrow{W}^1 d\Omega + \int_{\Gamma} \frac{1}{\mu} \left[\vec{n} \times \left(\vec{\nabla} \times \vec{A}\right)\right] . \overrightarrow{W}^1 d\Gamma \tag{4}$$

Where W^0 are the so called 0-form basis function and $\overrightarrow{W}^1$ the 1-form (Rieben at al, 2006). The last term in this last equation is computed using a BEM (Ren et al, 1990):

$$\vec{A}(\vec{x}) = \frac{\mu_0}{4\pi} \int_{\Gamma} \frac{1}{|\vec{x} - \vec{y}|} \vec{k}\,(\vec{y}) dy \tag{5}$$

$$\left[\vec{n} \times \left(\vec{\nabla} \times \vec{A}\right)\right](\vec{x}) = \frac{\mu_0}{2} \vec{k} - \frac{\mu_0}{4\pi} \int_{\Gamma} \frac{1}{|\vec{x} - \vec{y}|^3} \vec{n} \times \left[(\vec{x} - \vec{y}) \times \vec{k}(\vec{y})\right] dy \tag{6}$$

We can notice in particular in Eq. 5 the 3D kernel:

$$G_{3d}^0(\vec{x}, \vec{x}') = \frac{1}{|\vec{x} - \vec{x}'|} \tag{7}$$

2.2 2D Eddy Current Solver

We now introduce a cylindrical system of coordinates (r,θ,z) and consider that we have some axi-symmetric conditions, i.e. that the fields depend only on r and z. We consider an axisymmetric situation where the currents are toroidal (along $\overrightarrow{e_\theta}$) and the B field poloidal (along $(\overrightarrow{e_r}, \overrightarrow{e_z})$). This corresponds to a purely azimuthal vector potential (L'Eplattenier et al, 2015):

$$\vec{A}(\vec{r}) = A(r, z) \overrightarrow{e_\theta} \tag{8}$$

Since $\vec{A}$ is homogeneous to $\vec{\nabla}\phi$ (see **Eq. 2**), we must also have $\vec{\nabla}\phi$ azimuthal and (axisymmetric). We thus have:

$$\phi(r,\theta,z) = \phi(\theta) \tag{9}$$

$$\vec{\nabla}\Phi = \frac{1}{r}\frac{\partial\phi}{\delta\theta}\overrightarrow{e_\theta} \tag{10}$$

The FEM part of the 2D is very similar to the FEM of the 3D part, except that the integration is over 2D faces compared to 3D solids. The BEM part, though, is quite different since one point in the (r,z) plane actually represents a whole circle around the axis. Eq. 5 for example reads:

$$\vec{A}(r,z) = \iiint r'dr'dz'd\theta' \frac{k(r',z')\overrightarrow{e_{\theta'}}}{|x(r,\theta,z) - x'(r',\theta',z')|} \tag{11}$$

And the integration over θ’ leads to:

$$\begin{aligned} A(r,z) &= \vec{A}(r,z).\overrightarrow{e_\theta} \\ &= \iiint r'dr'dz'd\theta' \frac{k(r',z')\overrightarrow{e_{\theta'}}.\overrightarrow{e_\theta}}{|x(r,\theta,z) - x'(r',\theta',z')|} \\ &= \iint dr'dz'k(r',z')G(r,z;r',z') \end{aligned} \tag{12}$$

Where $G(r,z;r',z')$ is the 2D kernel which involves elliptic integrals. These different kernels due to the extra integration over θ in 2D are the main differences between 3D and 2D.

2.3 3D/2D Eddy Current Solver

In the new coupled 3D/2D model, the user can choose which parts are to be handled in 3D and which are to be handled in 2D. Again, the FEM system is not very complicated, the 3D parts having their own FEM matrices and system, and same for the 2D. The real coupling between the 3D and 2D comes from the BEM equations, since all the parts interact with each other. A typical BEM matrix is thus composed of 4 blocks as represented below:

$$P = \begin{bmatrix} P_{3d-3d} & P_{3d-2d} \\ P_{2d-3d} & P_{2d-2d} \end{bmatrix} \tag{13}$$

Where P_{3d-3d} represents all the interactions between the 3D parts, and is computed the same way as in section 2.1, and similarly, P_{2d-2d} is computed as in section 2.2. The coupling parts, P_{3d-2d} and P_{2d-3d} are computed by projecting the 3D basis functions onto the local 2D plane (or its normal depending on the type of basis function) and using a kernel very similar to the 2D one – the only difference being only one integral over the angle θ of the 2D basis function, instead of 2, hence a factor 2π. In other words, the 3D bases see the 2D ones as if they were a sum of 3D basis function all around the axis, with a rotational invariance. The 2D basis functions on the other hand see the 3D ones as their "in plane only" (or "out of plane only" depending on the kind of basis function) components in the rotational plane used for the 2D.

3 Numerical Results

3.1 Turning 3D into 2D

The case presented here features a spiral type coil with imposed current and a 1 mm thick Aluminium sheet forming on a conical die as shown on Fig. 1. The experiment was performed at the Department of Mechanical Engineering, University of Waterloo, Ontario, Canada (L'Eplattenier et al, 2009). Fig. 2 shows a comparison between the numerical and experimental final shape of the sheet, which shows a very good agreement. More details on the experimental/simulation comparisons can be found in (L'Eplattenier et al, 2009).

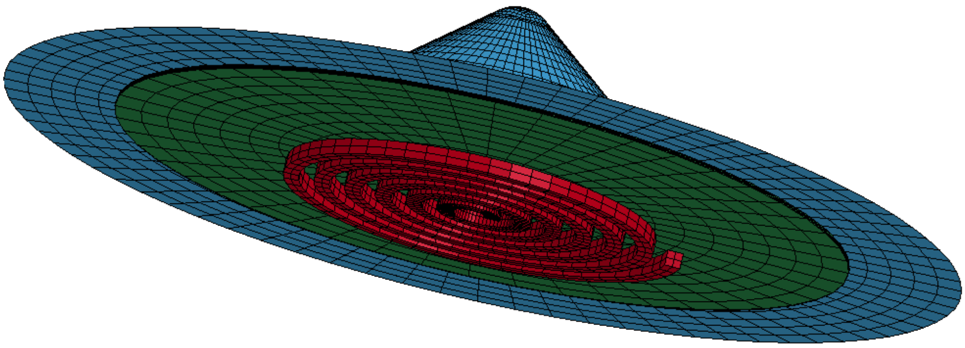

***Figure 1**: Magnetic metal forming with spiral coil. 3D setup*

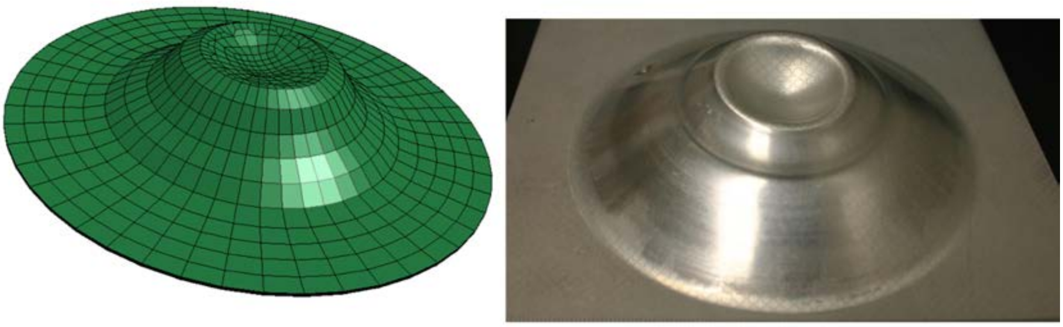

***Figure 2**: Magnetic Metal Forming: 3D numerical result (left) and experimental (right) final shape of the sheet*

This case has been chosen because it allows us to illustrate how the 2D axi-symmetric solver can be used in order to significantly reduce the calculation time. In order to transform a specific part in 2D, a 3D slice of the conductor must be provided along with some segment sets that define the plane where the EM-2D calculation is done as well as where the current flows in and out (See **Fig. 3**). **Fig. 4** and **Fig. 5** then offer some comparison of the results between the 2D setup and the 3D setup. The results appear to be very similar; the discrepancies may be explained by the 3D effects of the pitch in the spiral shaped coil. However, while the complete 3D run took about 20 minutes on 1 CPU, the 2D axi-symmetric problem only took 10 seconds.

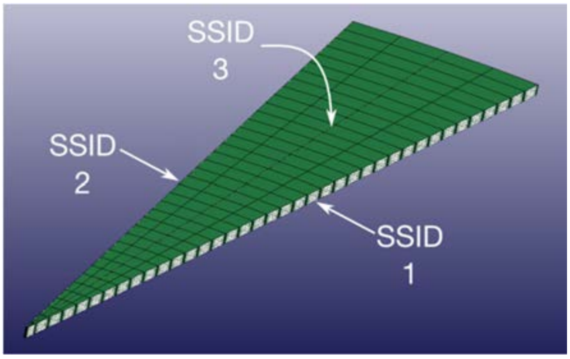

Figure 3*: Example of a 2D axisymmetric part made of 1/32th of the full cylinder*

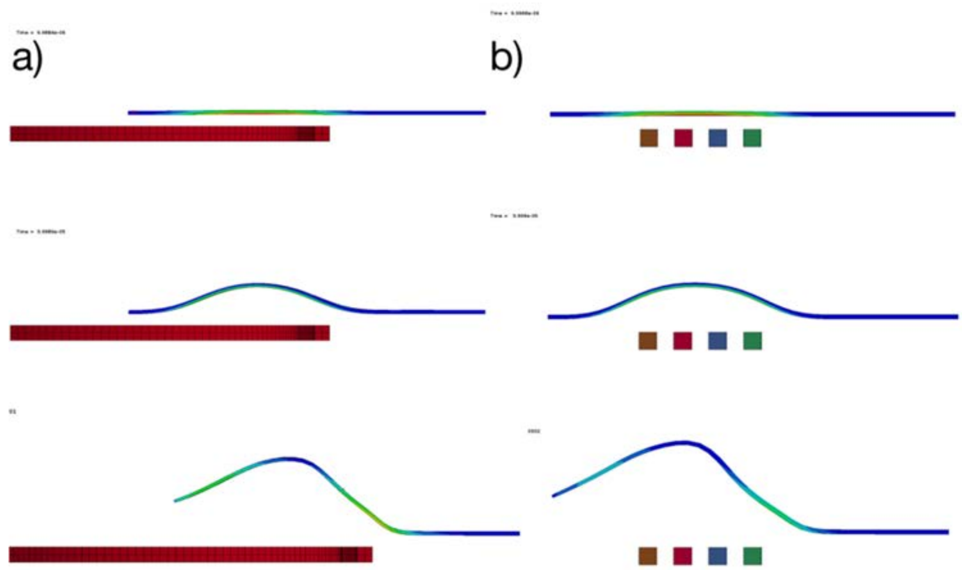

Figure 4*: Lorentz force fringes at different times in a cross section of the workpiece. Comparison of the displacements between 3D, a) and 2D b)*

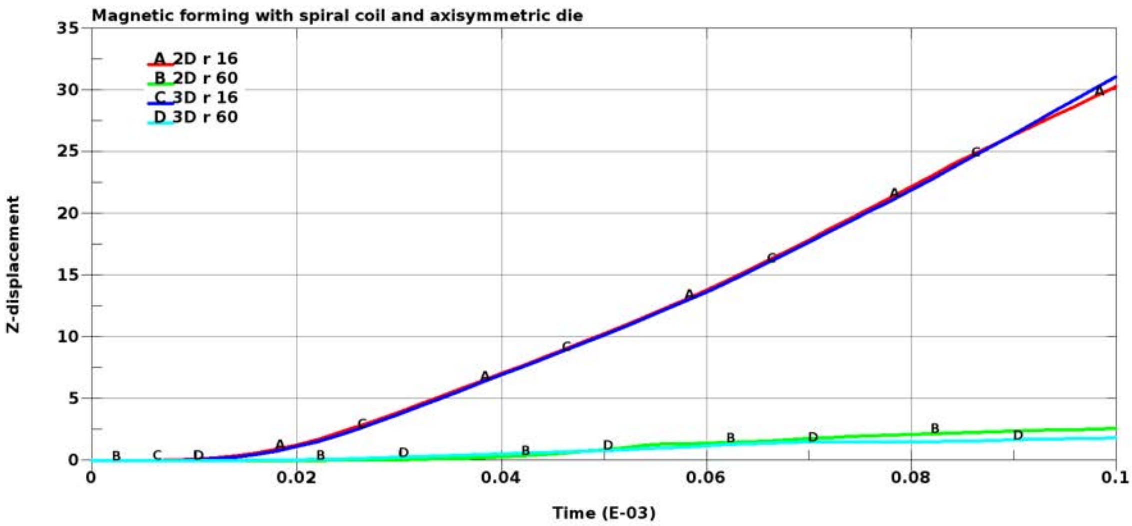

***Figure 5**: Comparison of displacements between 2D and 3D for two points along the workpiece's radius, one close to the center (radius = 16 mm), one further away (radius = 60 mm)*

3.2 Mixing 3D and 2D Parts

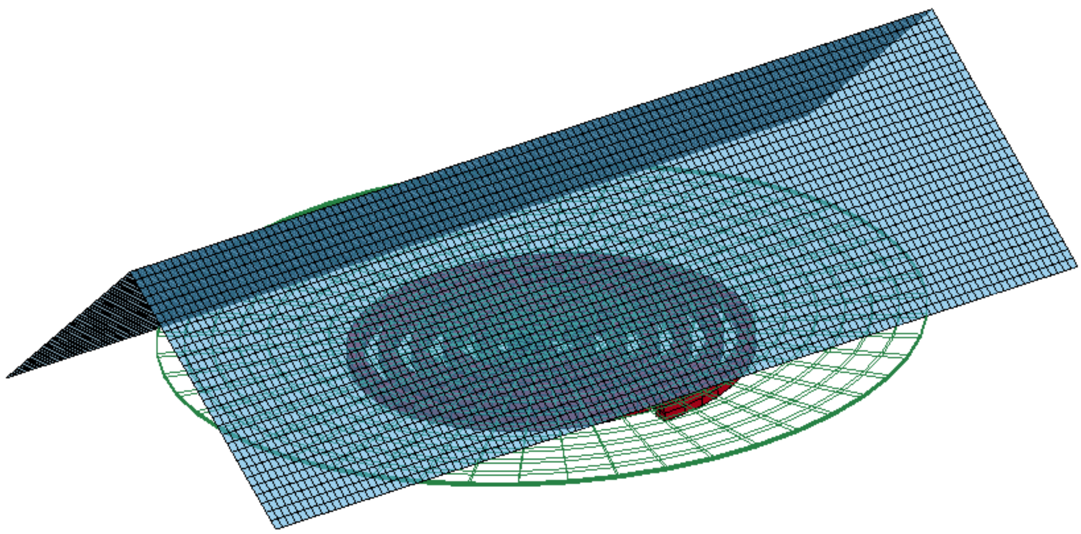

***Figure 6**: Magnetic metal forming with spiral coil and non-axisymmetric die. 3D setup.*

The previous case had the advantage of presenting an axi-symmetric coil, workpiece and die, thus allowing the problem to be fully reduced to 2D. However, it many instances, any of those parts could present some 3D features that cannot be reduced to a 2D equivalent. For this reason, the new method allows users to combine 2D parts with 3D parts. In this example, the previously described case has been slightly modified by using a different shape for the die as shown on **Fig. 6**. In such a configuration, the workpiece can no longer be reduced to an axi-symmetric part since it will not keep its rotational invariance during its deformation. However, it is still possible to use the 2D solver for the coil. **Fig. 7** offers a view of the final shape of the workpiece. The somewhat strange shape is due to the rebound of the sheet against the die. **Fig. 8** offers a comparison between displacements for the fully 3D and the 2D-3D mixed case. Again, good agreement between the results is found but with a significant reduction in the calculation times for the 2D-3D configuration which took about 7 minutes on 1 CPU compared to the 20 minutes for the 3D case.

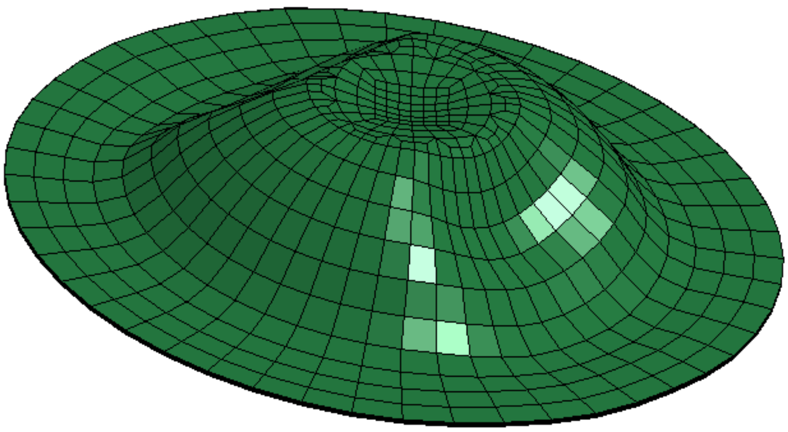

***Figure** 7: Final shape of the sheet after forming against the non-axisymmetric die*

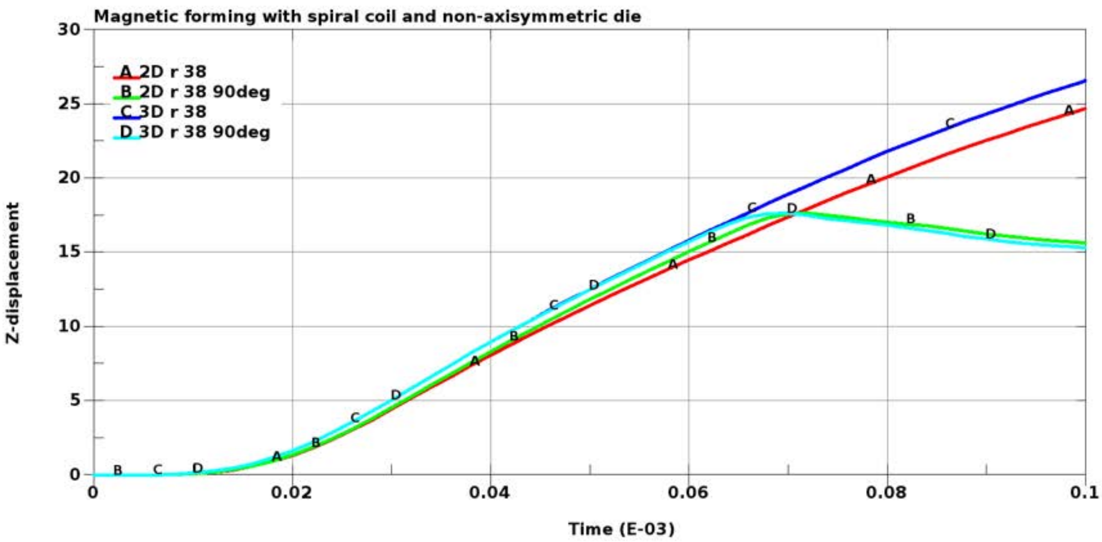

***Figure 8**: Comparison of displacements between 3D and 3D mixed with 2D for two points with the same radius but shifted by an angle of 90 degrees*

4 Conclusion

The development of the axi-symmetric solver arose from a need by users to reduce their calculation times in their EM metal forming and welding simulations. Indeed, in certain configurations, it was possible to accelerate the output of the desired result by a factor ten. However, it was so far limited to perfectly axi-symmetric cases. The newly developed extension that allows for mixing between 2D and 3D parts suddenly expands tremendously the range of application that the axi-symmetric solver can have. The signification reduction of calculations costs that it proposes will allow users to bring more flexibly in their setting up of model, give them more opportunities to conduct trial runs but also permit them to potentially couple the EM solver with LS-Opt for optimization purposes.

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