Validation Process of the Electromagnetism (EM) solver in LS-DYNA® v980: The TEAM problems

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Abstract

LS-DYNA version 980 includes an electromagnetic (EM) solver that can be coupled to the solid mechanics and thermal solvers of LS-DYNA to take full advantage of its capabilities to successfully solve complex industrial applications such as magnetic metal forming or welding, induced heating, and so forth. This paper will provide some insight on the validation process that is currently under way and focus on the so-called TEAM (Testing Electromagnetic Analysis Methods) problems.

TEAM Workshops are meetings of an open international working group aiming to compare electromagnetic analysis computer codes. A series of TEAM Workshops was started in 1986 and has been organized in two-year rounds, each comprising a series of "Regional" workshops and a "Final" Workshop, as a satellite event of the COMPAQ Conference.

The TEAM problems consist in a set of test-problems, with precisely defined dimensions, constitutive laws of materials, excitations, etc., each backed by a real laboratory device, on which measurements can be made. The range of the TEAM problems cover a wide area of applications and features such as moving or non-moving conductor parts, magnetic elements, conductors in time dependent magnetic fields and so forth.

Several TEAM test cases and their simulation results that are part of the global validation process of the solver will therefore be presented highlighting some features and application domains of the solver.

1- Introduction

LS-DYNA version 980 aims to solve complex multi-physics problems involving electromagnetism, fluids or chemistry interacting with the solid mechanics and thermal solvers of LS-DYNA. As the development of these solvers progresses, several verification, validation and benchmarking tests have been conducted both internally at LSTC and externally by beta testing users in order to track bugs and improve numerical accuracy. This paper will focus on the electromagnetism solver (EM) and present some of the test cases studied internally that have been used in order to validate some newly implemented features. These test cases are all part of the so-called TEAM problems.

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The TEAM problems consist in a list of test-problems, with precisely defined dimensions, constitutive laws of materials, excitations, etc., and each backed by a real laboratory device, on which measurements can be made. Some of these TEAM problems have been reproduced and studied in order to validate some of the new features of the electromagnetism solver.

After briefly presenting the solver's main applications, this paper will focus on the new features that have been implemented and use some TEAM problems results for illustration. A brief description of each model will be given as well as some of the main results obtained. In the future, a more complete description of these test cases will be made available for users who would wish to try and reproduce them.

2- Summary of the solver's main applications

The Electromagnetism solver solves the Maxwell equations in the Eddy current (induction-diffusion) approximation. This is suitable for cases where the propagation of electromagnetic waves in air (or vacuum) can be considered as instantaneous. Therefore, this wave propagation is not solved. The Maxwell equations are solved using a Finite Element Method (FEM) for the solid conductors coupled with a Boundary Element Method (BEM) for the surrounding air (or insulators). Thus, no air mesh is necessary (See [2], [3], [4] for more details).

The solver is also coupled with the solid mechanics solver in LS-DYNA and has been successfully used in order to solve complex problems involving magnetic forces and structural deformations such as in metal forming, metal cutting, metal welding or bending or high magnetic pressure generation.

Furthermore, the Joule heating is also taken into account for coupling with the LS-DYNA thermal solver thus allowing solving induced heating problems such as for instance, a coil moving over a conductive plate and heating it.

3- External magnetic field

3-1 Description

It is now possible to set up a uniform external magnetic field. The time dependency of each component in space can be set up through a load curve. This external magnetic field is then applied on the conductor parts where induced currents are generated and the classic Eddy current problem is solved [2], [3]. This feature can be useful in cases, where the user knows or has a good idea of the magnetic field generated by the coil on the workpiece. This way, he doesn't have to build to whole coil which can save a lot of calculation time.

3-2 The TEAM 4 problem

The TEAM 4 problem [1] is a simple test case which consists of a rectangular aluminum brick of conductivity $\sigma = 25.38\, e^{6} \Omega^{-1} m^{-1}$ with a rectangular hole placed in a time varying, space uniform magnetic field (See Figure 1 for the brick and hole dimensions). The magnetic field is perpendicular to the faces with the hole, and decays exponentially with time ($B_z = B_0 e^{-\frac{t}{\tau}}, B_0 = 0.1\, T,\ \tau = 0.0119\, s$). The main objective of the problem is to calculate the total circulating current density in the brick. Figure 2 shows the induced current vectors flowing around the hole and the magnetic field vectors oriented in the z-direction which get stronger closer to the hole. Figure 3 offers a superposition between the historical results [1] [5] obtained for the FELIX brick experiment and the LS-DYNA simulation. A good agreement can be observed despite the rather coarse mesh employed.

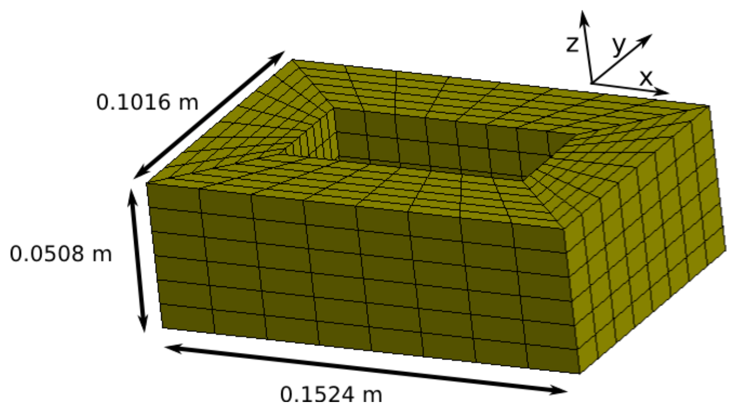

Figure 1 TEAM 4 Geometry and Mesh. Central hole: $0.0889\ m \times 0.0381\ m$

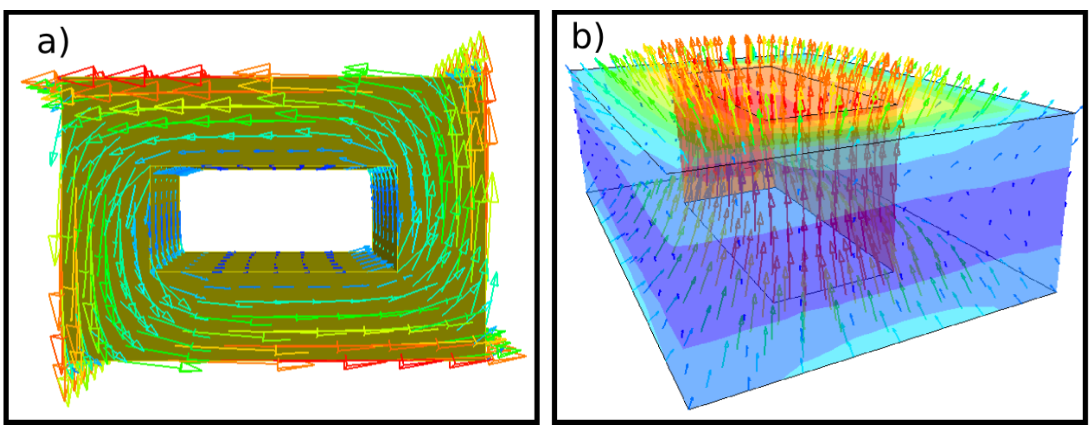

Figure 2 a) Current density vectors, b) Magnetic field vectors

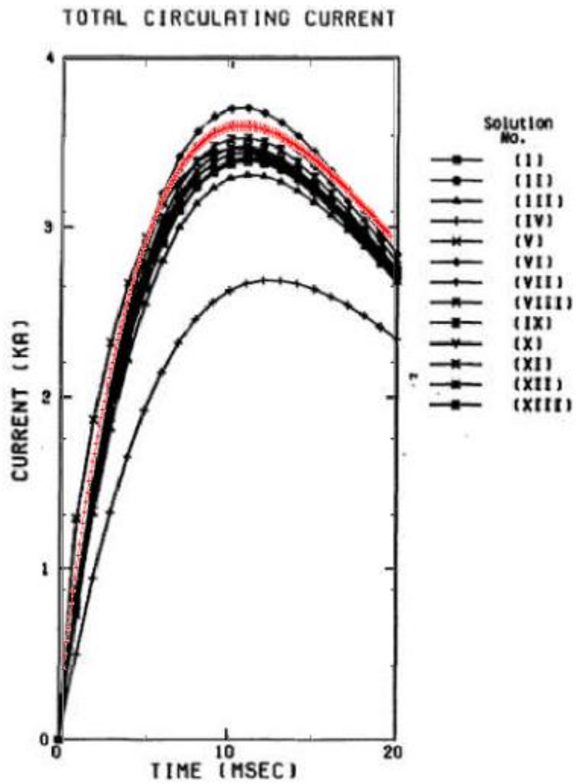

Figure 3 Comparison of the time variation of the circulating current in the FELIX brick between the reference results given by different codes (in black & white) and the LS-DYNA simulation (in red).

3-3 The TEAM 12 problem

The TEAM 12 problem is a more complex problem since it is a coupled problem with moving conductor. A clamped beam is placed in a uniform magnetic field (see Figure 4). The magnetic field has a first component exponentially decaying with time that generates an induced current in the beam that in turn, interacts with the second constant component of the field and create a Lorentz force which causes the beam's movement. The motion of the beam causes the current and deflection to be very different from what they would be if coupling were not present. The experimental results are based on a FELIX experiment [5].

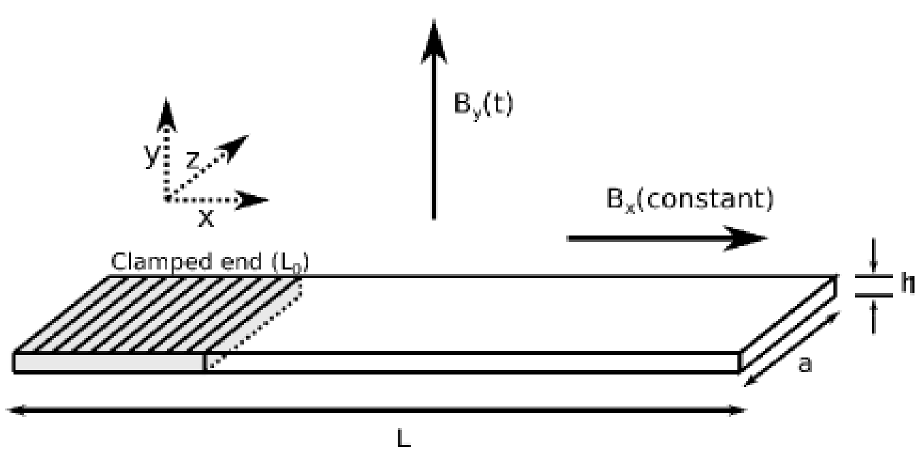

Figure 4 TEAM 12 sketch: L=487 mm, a=100 mm, h=3.175 mm, Lo=76 mm

A preliminary set of testing consists in only applying the orthogonal exponentially decaying component of the magnetic field ($B_y = B_0 e^{-\frac{t}{\tau}}$). In this case, the Lorentz force is parallel to the main direction of the beam and no movement is generated. Several conductivities corresponding to different materials will be chosen. For each material, the induced current will be compared to the experimental results of [5].

The second set of testing consists in adding the constant component of the magnetic field parallel to the main direction of the beam (B_x). Several values of B_x will be chosen and at each time the induced current as well as the beam's movement will be studied and compared to the experimental results. Table 1 and Table 2 give the parameters for the preliminary and the fully coupled tests. Five elements are used for the mesh in the z-direction.

Model Physical Parameters. Preliminary Tests	
B_0	$0.055\ T$
τ	$6.6\ ms$
$Copper\ conductivity$	$58.141\ e^6\ \Omega^{-1}m^{-1}$
$Aluminum\ conductivity$	$25.321\ e^6\ \Omega^{-1}m^{-1}$
$Brass\ conductivity$	$16.391\ e^6\ \Omega^{-1}m^{-1}$

Table 1

Model Physical Parameters. Coupled Tests	
B_0	$0.055\ T$
τ	$6.6\ ms$
B_x	$0.2, 0.5, 0.7, 0.9\ T$
$Aluminum\ conductivity$	$25.321\ e^6\ \Omega^{-1}m^{-1}$
$Aluminum\ density$	$2713\ kg.m^{-3}$
$Aluminum\ Young's\ Modulus$	$6.891\ e^{10}\ Pa$

Table 2

For the preliminary tests, Figure 5 offers a view of the current density vectors and the magnetic field vectors. As expected, the induced currents flow around in the orthogonal direction of the uniform imposed magnetic flow B_y. The field is stronger at the center of the beam due to boundary effects. As can be seen on Figure 6 the numerical results capture very well the behavior of the induced current with only slight differences for the peak current value.

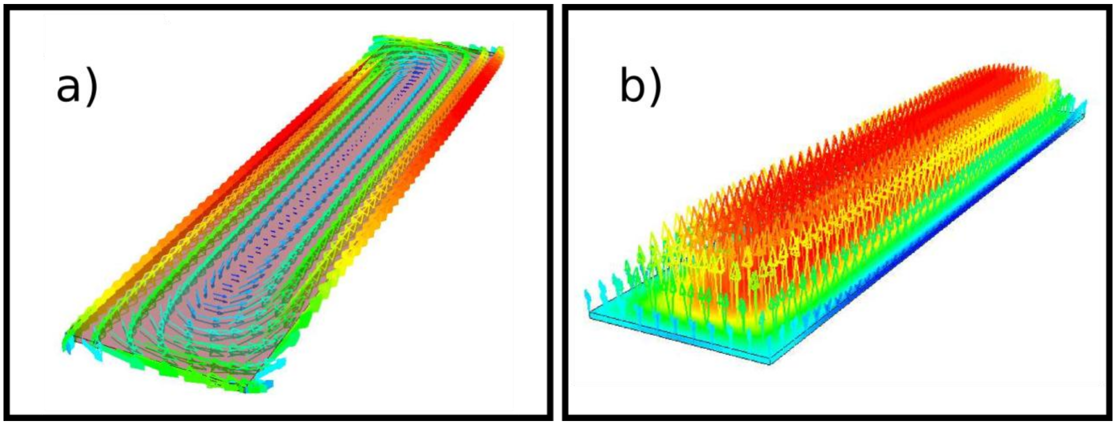

Figure 5 a) Current density vectors, b) Magnetic field vectors

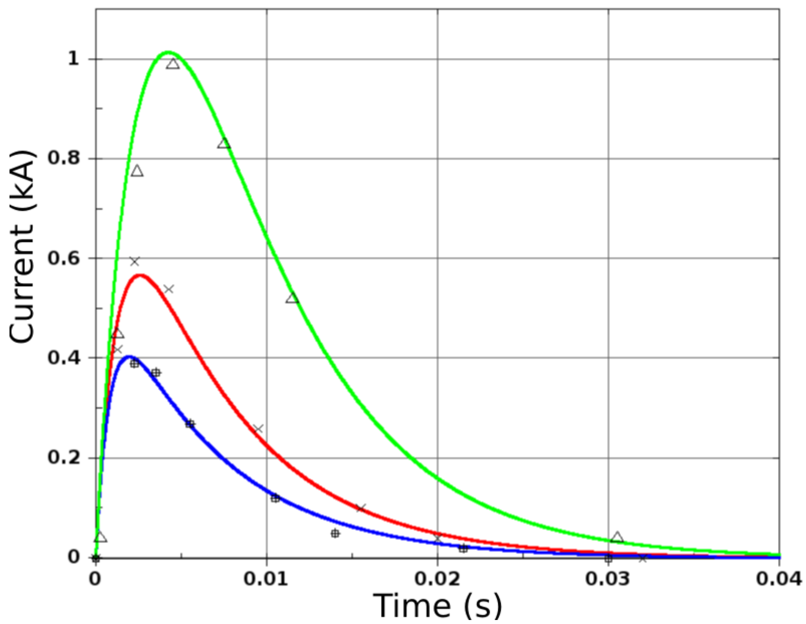

Figure 6 Preliminary comparison for the induce current between LS-DYNA results (full line) and experimental points. From top to bottom: Copper (in Green), Aluminum (in Red), and Brass (in Blue)

For the fully coupled tests, Figure 7 shows the acceleration vectors that are in this case directly proportional to the Lorentz force (Now $F_y^{Lorentz} = j_z \times B_x \neq 0$). Four modes of vibration can be identified. Figure 8 and Figure 9 show the deflection of the beam for various B_x values. It can be observed that for $B_x = 0.2$, the beam oscillates at its natural vibration frequency, the current decays quite smoothly with only small perturbation due to deflection. For $B_x = 0.5$, the damping becomes obvious as the displacement peak is significantly less marked than the first one. For higher values of B_x , after a first swing, the beam slowly returns to rest at the equilibrium position. Figure 8 and Figure 9 also show the excellent agreement between these observations and the experimental results which can be found in [5].

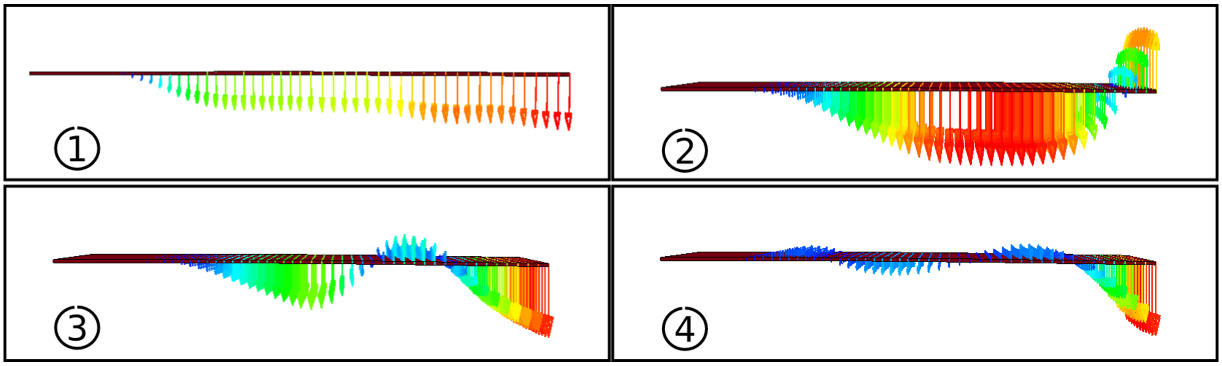

Figure 7 Characteristic Four Modes of Vibration. Acceleration Vectors

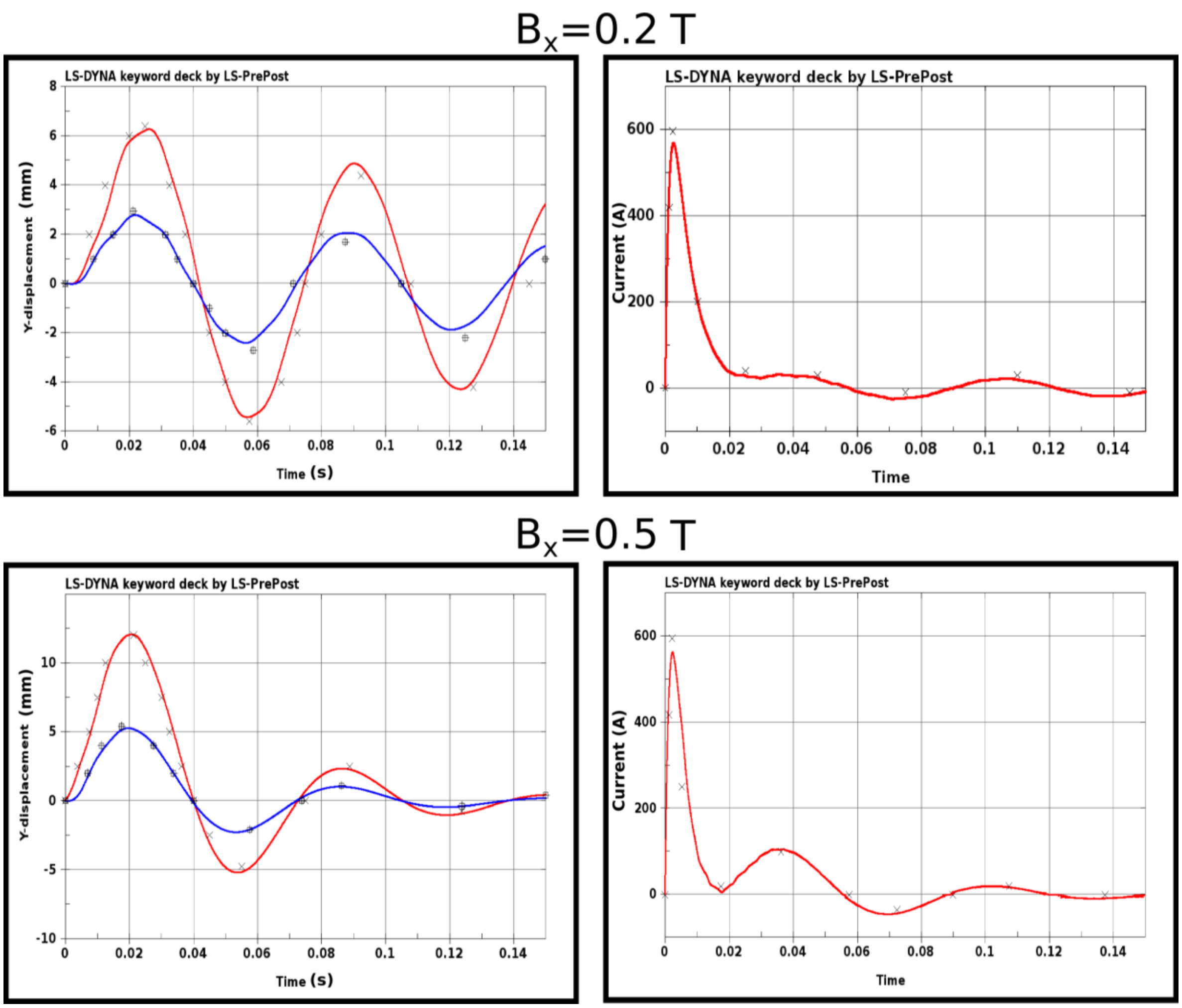

Figure 8 Current and Deflection at the free end (in Red) and 167 mm from the free end (in Blue). Comparison between LS-DYNA results (full line) and experimental results (points).

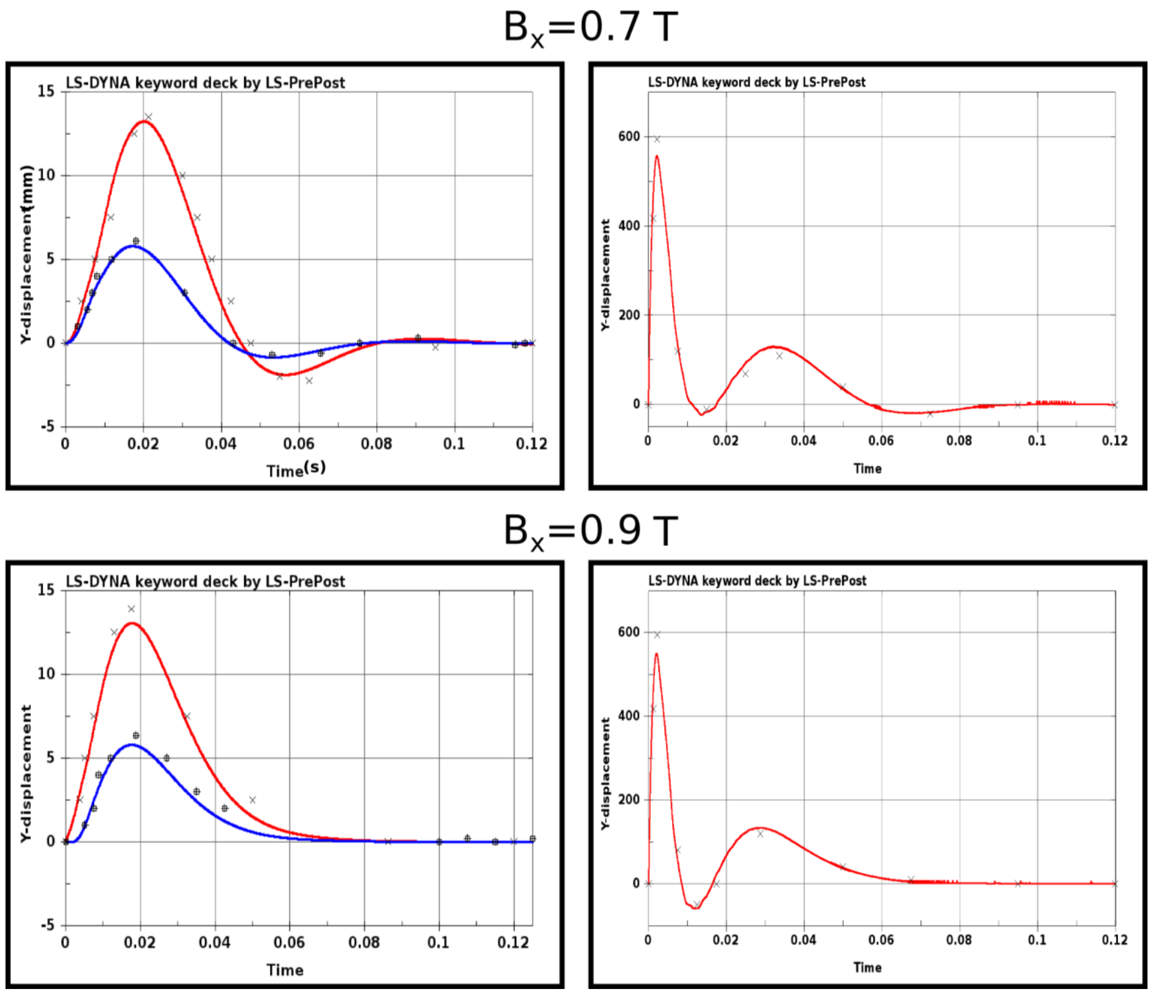

Figure 9 Current and Deflection at the free end (in Red) and 167 mm from the free end (in Blue). Comparison between LS-DYNA results (full line) and experimental results (points).

4- Uniform Current in Conductors

4-1 Description

So far, while using the classic Eddy Current solver, the full Eddy current problem was solved in every conducting piece (typically Coil+Workpiece). This implied that the coil's geometry had to be fully described which could prove to be tedious and computer costly in cases where the coil had a lot of turns. The solver now offers the possibility to use a uniform current in specific conducting parts (typically in the coil), and to limit the solving of the Eddy currents in certain parts (typically the workpieces) [3]. The geometry can therefore be greatly simplified by modeling the coil as a simple tore rather than model all the turns. In some cases, it can also save some computation time as no BEM will need to be built on the coils. The approximation induced by such modeling is all the more true when the coil's current oscillates at a low frequency (50 Hz) and the diffusion of the EM fields can be neglected. A Biot-Savart law is then used to compute the resultant magnetic field $\vec{B}$ and potential vector $\vec{A}$ at position $\vec{r}$ generated by the steady current I of the coil [3]. This magnetic field will induce current on the workpiece where the full Eddy current problem will be solved (diffusion of the current through thickness, Lorentz forces, Joules heating etc.) [3].

4-2 The TEAM 3 problem

The TEAM 3 problem is a classic validation test case often studied ([6], [7]) and consists of a conducting ladder, with two holes placed below a coil above carrying a sinusoidal current [1]. The coil is made of multiple turns strongly stranded together and thus the current in the coil is considered uniform (no eddy currents) while the ladder's induced current diffuses through its thickness (full eddy current problem is solved). Several positions of the coil were originally studied and for this test case, we are going to focus on the case where the coil is located directly above one of the holes. Figure 10 shows the geometry of the problem. Eight elements were used through the ladder's thickness. The coil sees a 1260 Ampere Turns current and oscillates at a frequency of 50 Hz while the ladder has a conductivity of $32.78\ e^{6}\ \Omega^{-1}m^{-1}$. The main objective of this test case is to study the behavior of the magnetic field along a line A-B that goes from (x=0, y=-55, z=0.5) mm to (x=0, y=55, z=0.5) mm (i.e along the symmetrical axis of the problem in the (x,y) plane, and between the coil and the ladder in the z direction). On Figure 11, it can be observed that the biggest part of the current flows around the hole directly located under the coil. On Figure 11, the good agreement between the present simulation and the reference experimental results from [1] can also be noted.

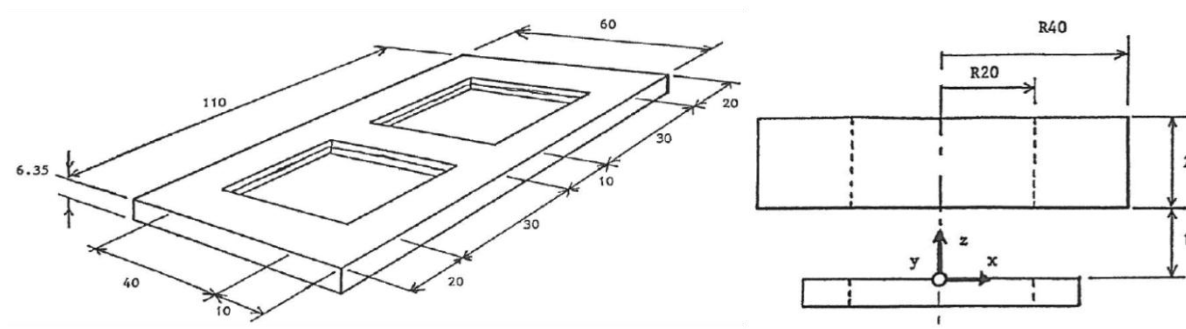

Figure 10 TEAM 3 problem sketch and dimensions

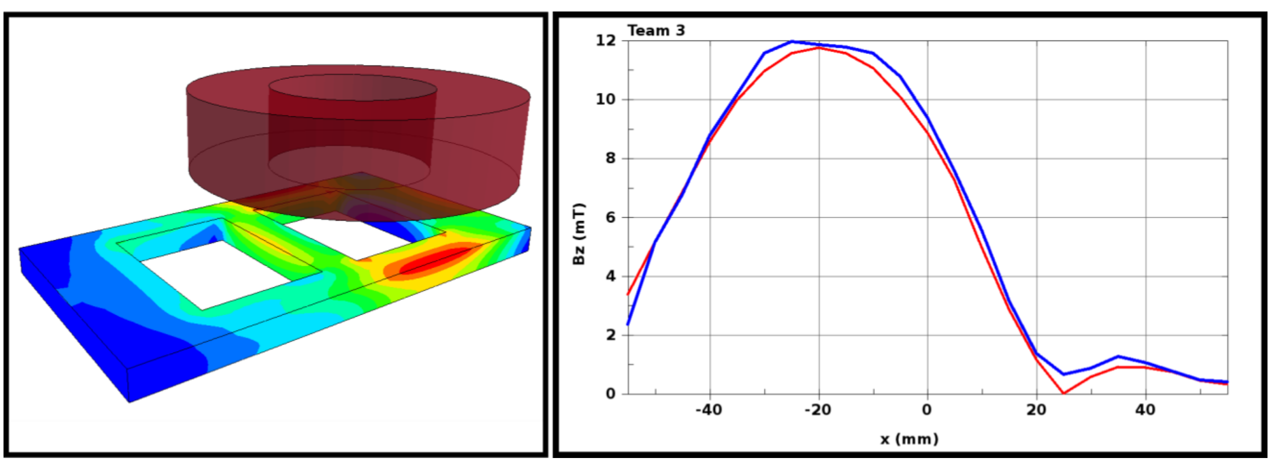

Figure 11 Current Density Fringes and Bz magnitude variation along the A-B line. Comparison between LS-DYNA (in Red) and reference experimental (in Blue) results.

4-3 The TEAM 7 problem

The TEAM 7 problem very similar to the TEAM 3 problem (Coil+ Workpiece) but offers a little more challenge since the geometry is asymmetric (See Figure 12). It consists of a thick aluminum plate with a hole which is placed eccentrically, and a coil that generates non-uniform magnetic fields which vary sinusoidally with time. The conductivity of the plate is $35.26\ e^{6}\ \Omega^{-1}m^{-1}$. The frequencies of the current in the coil are 50 Hz and 200 Hz respectively. To examine the accuracy of the results, the z-components B_z of the flux densities along the line A1-B1 (y=72 mm, z=34 mm) and A2-B2 (y=144 mm, z=34 mm) are studied at $wt = 0$ (i.e when the coil's current value is 0). The results are in good agreement compared to the experimental results at 50 Hz and 200 Hz [8] (See Figure 13). Ten elements will be used in the thickness of the ladder.

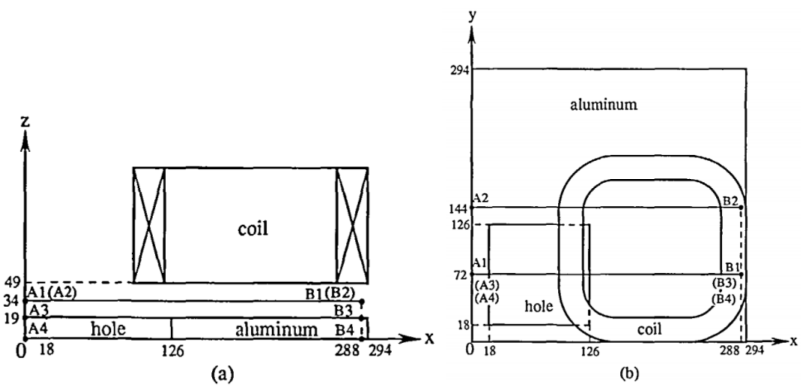

Figure 12 TEAM 7 problem sketch and dimensions

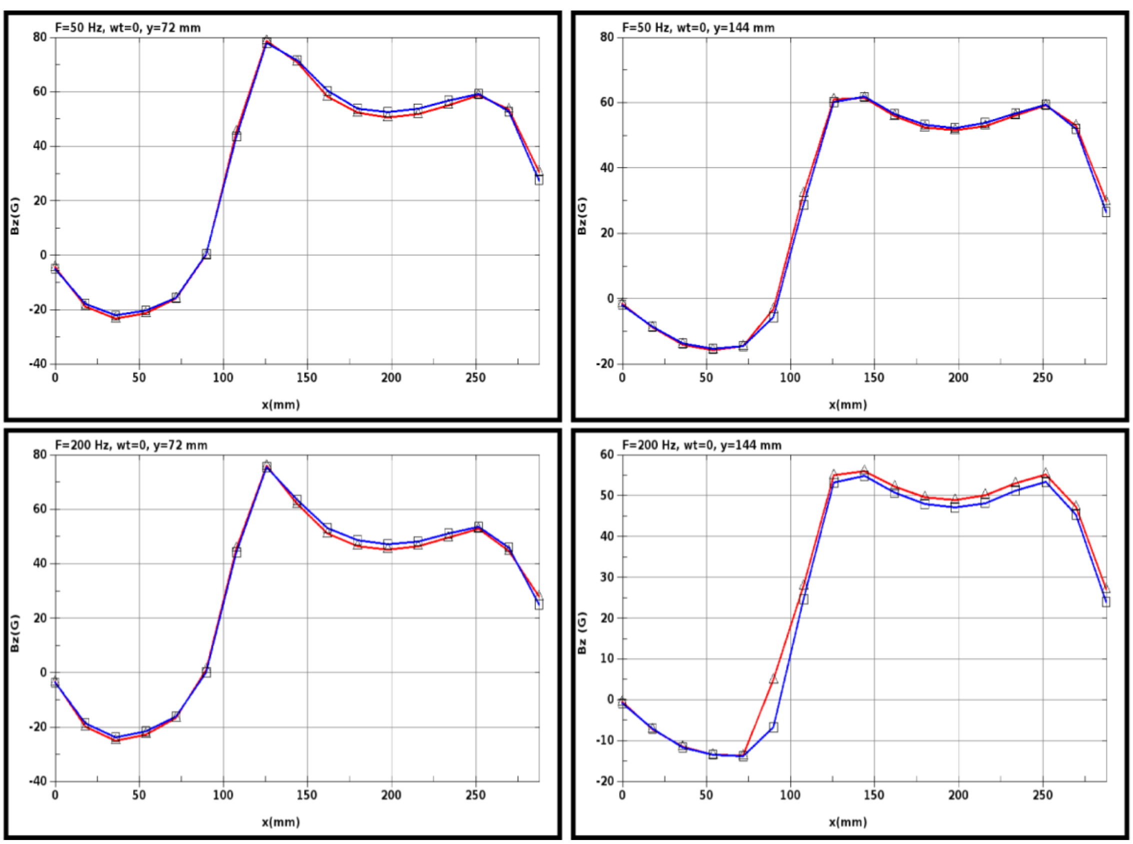

Figure 13 Bz (G=10e-4 T) variation along the A1-B1 (y=72mm) and A2-B2 (y=144 mm) line at time wt=0. Comparison between LS-DYNA (in Red) and reference experimental (in Blue) results.

4-4 The TEAM 28 problem

Finally the TEAM 28 is a coupled problem with the solid mechanics solver and consists of an electrodynamic levitation device with a conducting plate which levitates over two exciting coils. The aim is to determine the dynamic characteristics of the levitating plate (after some damped oscillations, the plate attains a stationary levitation height). Several work groups have tackled this problem (see [9], [10], [11]). Figure 14 offers a picture and a sketch of the problem. The two coils both have 20 turns; the interior coil has current amplitude of $960\ A$, the second of $576\ A$ and both have a current frequency of 50 Hz. The plate has a conductivity of $34.00\ e^{6}\ \Omega^{-1}m^{-1}$and a density of $2687\ kg.m^{-3}$. Since the problem is axisymmetric; it is possible to use the axisymmetric feature of the Electromagnetism solver for this test case. Three elements have been used for the plate's thickness. Figure 15 shows the Lorentz force fringes acting on the plaque. Figure 15 also shows the good agreement between the obtained results and some reference experimental results by [11] with the error on the frequency of the oscillation below 3%. As explained in [11], the discrepancy of the maximum levitation height during the first half period might be traced back to the modeling of the coils.

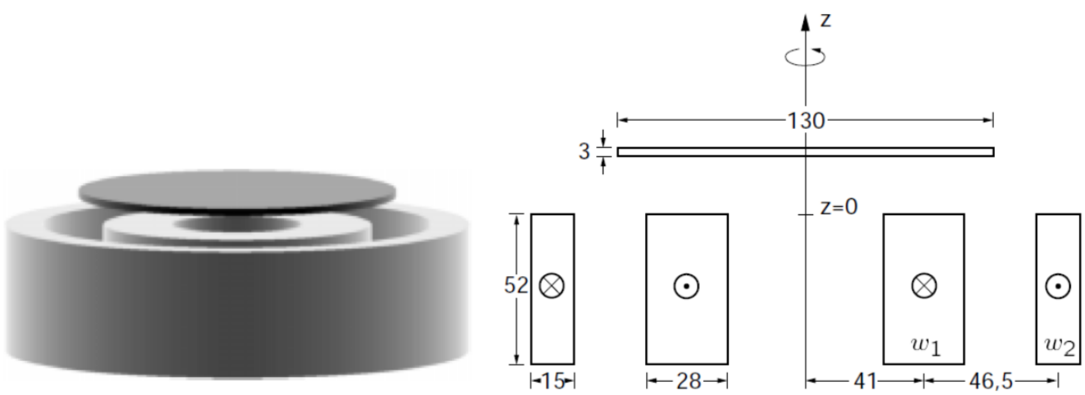

Figure 14 TEAM 28 problem sketch and dimensions

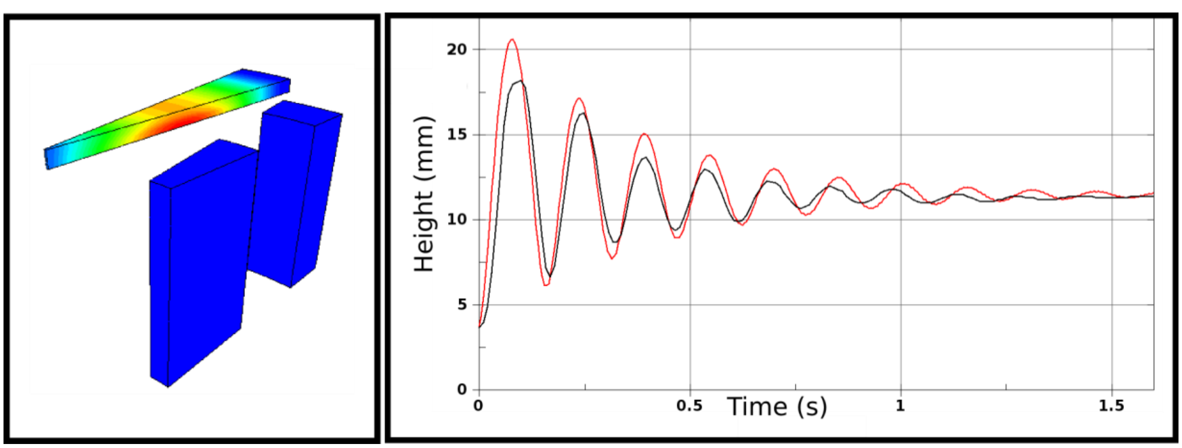

Figure 15 Lorentz Force fringes and Comparison between the experimental results (in Black) and the LS-DYNA numerical results (in Red).

5- Conclusion

In this paper, several validation test cases have been presented. For each test case, some results have been extracted and compared to references. These test cases are all part of the TEAM workshops and have been used to validate some of the newly implemented features in the electromagnetism solver. These new features are now available in the latest versions of the EM solver in LS-DYNA 980.

Validation is an ongoing process, in the future, new features will be implemented and further TEAM problems could be used through the validation process. For instance, magnetic materials with non-uniform permeability could one day be implemented. In that case, TEAM problem 10 and 13 may assist us through the debugging and benchmarking process.

References

[1] L. R. Turner, «Proceedings of the Vancouver TEAM Workshop at the University of British Columbia,» Argonne, Illinois, 1988.

[2] I. Çaldichoury et P. L'Eplattenier, «Update On The Electromagnetism Module In LS-DYNA,» chez *12th LS-DYNA Users Conference* , Detroit, 2012.

[3] I. Çaldichoury et P. L'Eplattenier, «EM theory manual,» LSTC, Livermore, 2012.

[4] P. L'Eplattenier, G. Cook, C. Ashcraft, M. Burger, J. Imbert and M. Worswick, "Introduction of an Electromagnetism Module in LS-DYNA for Couple Mechanical-Thermal-Electromagnetic Simulations," *Steel Research Int.,* vol. 80, no. 5, 2009.

[5] L. Turner, T. Hua et S. Lee, «Analysis of the FELIX experiments with cantilevered beams and hollow cylinders,» chez *Fourth Eddy Current Seminar Rutherford Appleton Laboratory*, Argonne, Illinois, 1986.

[6] Z. Razek, «New Technique for solving three dimensional multiply connected eddy-currents problems,» *IEE Proceedings,* vol. 137, 1990.

[7] D. Zheng, «Three dimensional eddy current analysis by the boundary element method,» *IEE Transaction on Magnetics,* 1997.

[8] K. Fujiwara and T. Nakata, "Results for Benchmark Problem 7 (Asymmetrical Conductor with a Hole)," *COMPEL-The International Journal for Computation and Mathematics in Electrical and Electronic Engineering,* vol. 9, no. 3, pp. 137-154, 1990.

[9] J. Stefan, Kurz et G. Lehner, «Three dimensional transient fem-bem coupled analysis of electrdynamic levitation problems,» *IEE Transactions on magnetics,* vol. 32, 1996.

[10] F. Rapetti, «An overlapping mortar element approach to coupled magneto-mechanical problems,» *Mathematics and Computers in Simulation,* 2008.

[11] H. Karl, J. Fetzer, S. Kurz, G. Lehner et W. Rucker, «Description of TEAM Workshop Problem 28 : An electrodynamic levitation device,» Stuttgard.