Inductive and Radiofrequency (RF) heating in LS-DYNA for medical and other industrial applications

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1 Abstract

Inductive and radiofrequency heating both rely on an electromagnetic power source to generate heat. However, they are based on different frequency scales that trigger different electromagnetic behavior and make some terms predominant over others. Inductive heating can be viewed as a "contactless" form of heating where a current source (typically a copper coil) with a frequency in the range of KHz or *MHz* approaches another conductor thus triggering induced currents (Eddy currents) in nearby conductors which can generate heat, depending on the material's properties (resistivity, permeability). In this paper, radiofrequency heating can be viewed as an extension of traditional Resistive heating where an electrode is plugged between two ends of a specific material. Contrary to resistive heating, the material's electrical conductivity is usually very low, or the material can be an insulator, but the input source is in a high frequency range (GHz or higher) which triggers molecular displacements that generate heat via friction. This dielectric heat source term becomes the dominant factor rather than the Ohmic losses term.

Inductive and Radiofrequency heating are both present in medical applications and other industrial applications. For example, RF heating of body tissues is used for muscle therapy and at higher temperature to kill tumors and cancer cells. On the other hand, inductive heating is present in various domains, from sterilization procedures (Needle and surgical instruments heat treating) to induction casting of dentures and medical implants.

This talk will give an overview of LS-DYNA's capabilities, describe existing features as well as introduce the recent advancements that extend the scope of applications. It will also focus on specific items and keywords to keep an eye on.

2 Introduction

The EM solver incorporated within LSDYNA has been first introduced in 2008 and released in 2012 [1]. Its focus is to bring powerful and easy to use numerical tools to users that wish to simulate coupled problems involving mechanical displacements or deformations, as well as thermal effects. Its capabilities can generally be described as either involving Eddy currents or resistive heating. Eddy current problems are solved using state of the art coupled FEM/BEM methods where no air mesh is necessary to calculate the magnetic interactions between conductors [2]. Applications involve magnetic metal forming and welding [3], [4], magnet snapping or latching [5], [6], [7], haptic devices, electromagnetic launchers [8], magnetic gears [9] as well as inductive heating [10], [11], [12], [13]. For that latter application, several new developments have been introduced that will be discussed in Section 4.

The so-called resistive heating solver on the other hand originally consists of a FEM Laplace equation solve. However, over the years, several specific capabilities have been added to this base, making it the background solver used in a diversity of applications such as battery simulations, resistance spot welding as well as Electrophysiology (EP). Radiofrequency can be viewed as a similar extension of the resistive heating solver and its capabilities will be described in Section 3.

3 RF Module extension

3.1 Introduction

In typical Joule heating applications, current flows through a conductor which produces heat. The importance of Joule heating effects is dependent on the material's electrical conductivity properties as well as on the amount of current flowing through it.

If the frequency of the current becomes high enough, typically in the range of $MHz \sim GHz$, molecular dipole rotation causes an additional heating term to appear and potentially become predominant: dielectric heating. Contrary to Joule heating, dielectric heating is not dependent on the material's conductivity (the material can be nonconductor) but rather, on its dielectric properties (dielectric constant and dielectric losses).

To solve such problems, the complex frequency domain form of the electric field's equation is adopted:

Vacuum Permittivity Imaginary number

Scalar Potential (unknown)

$$\nabla.\left(\left(\sigma + 2.\pi.F\varepsilon_0(\varepsilon_r' + \varepsilon_r'' j)\, j\right)\nabla\varphi\right) = 0.$$

Electric Conductivity

Radio Frequency Dielectric constant Dielectric losses

From the scalar potential solution, an electric field can be calculated from which two heating terms are extracted, Dielectric Heating Power (P_d, in W) and Joule Heating Power (P_j, in W):

$$E = -\nabla\varphi$$

$$P_d = 2.\pi.F\varepsilon_0\varepsilon_r''(\boldsymbol{E})^2 \quad P_j = \sigma(\boldsymbol{E})^2$$

$$\rho C_p \frac{\partial T}{\partial t} - \nabla.k(\nabla T) = P_d + P_j$$

As typically done with other similar applications within LS-DYNA, those heating terms can automatically be passed to the thermal solver to solve coupled EM-thermal applications. In turn, the thermal solver temperature results can be used to update the dielectric constants, electrical conductivities, and dielectric losses if temperature dependent laws are defined. It is important to note that contrarily to pure resistive heating applications, the conductivity of the material needn't be present ($\sigma = 0.$), if the material is a nonconductor and only possesses dielectric properties.

3.2 Capabilities and Keywords

The following boundary conditions and contacts are available for the EM RF heating solver:

- Imposed Voltage (Dirichlet)
- Imposed Current (Neumann)
- Imposed Resistance (Robin)
- Imposed Impedance (Complex Robin)
- Imposed Power (non-linear Dirichlet)
- Periodic/Sliding
- Contact (constraint or penalty based)

The imposed voltage/current/resistance/impedance/power conditions can be found in the following keywords:

***EM_ISOPOTENTIAL_CONNECT**

CONID	CONTYPE	ISOID1	ISOID2	VAL	LCID		

CONTYPE = 1: Short (Dirichlet b.c)
= 2: Imposed Resistance (Robin b.c)
= 3: Imposed Voltage (Dirichlet b.c)
= 4: Imposed Current (Neumann b.c)
= 7: Imposed Power (Dirichlet b.c)

When a Power boundary condition is present, the solver will solve the resistive heating or radiofrequency heating problem in two steps per timestep. In the first step, it will apply a Dirichlet boundary condition with an imposed voltage of 1 to each power boundary condition. Once the first solve is complete it will retrieve the current on the boundary to update the voltage boundary condition to the value corresponding to the user defined expected value for Power and solve again.

In classic resistive heating application, the classic Ohm's law is used to determine the relationship between Power, voltage and current:

$$P = V\ I$$

However, in radiofrequency applications, i.e when complex numbers are present, Power is calculated with the sum of the real and imaginary parts:

$$P = V_r I_r + V_i I_i$$

***EM_BOUNDARY_PRESCRIBED**

BPID	BPTYPE	SETTYPE	SETID	VAL	LCID		

				VAL2	LCID2		

BPTYPE = 1: Short (Dirichlet b.c)
= 2: Imposed Resistance (defined by val or lcid) or Impedance (defined by val2 or lcid2) (Robin b.c)
= 3: Imposed Voltage (Dirichlet b.c)
= 4: Imposed Current density (Neumann b.c)

The impedance boundary condition, defined in the second line of the keyword, when val2 or lcid2 is used in conjunction with BPTYPE=2 is the only complex boundary condition and only available in the radiofrequency heating module.

Material properties for the dielectric parts can be defined in:

***EM_MAT_001**

MID	MTYPE	SIGMA	EOSID				

	FREQ	EPSRR	EOSID2	EPSRI	EOSID3		

SIGMA and EOSID: conductivity and optional equation of state ID allowing users to define conductivity function of temperature.

FREQ: Radiofrequency.

EPSRR and EOSID2: dielectric constant and optional equation of state ID allowing users to define dielectric constant function of temperature.

EPSRI and EOSID3: dielectric losses and optional equation of state ID allowing users to define dielectric losses function of temperature.

3D, 2D planar and 2D axisymmetric capabilities are present. The choice of dimension can be done in ***EM_CONTROL.** Finally, it is worth noting that coupling with the ICFD solver is present. The keywords ***EM_MAT,** ***EM_ISOPOTENTIAL_CONNECT** as well as

`*EM_BOUNDARY_PRESCRIBED` allow the definition of properties and boundary conditions on ICFD Parts. The dielectric domains can be made continuous between the fluid and the structure by using the keywords **`*ICFD_BOUNDARY_FSI`** and the appropriate option in **`*EM_CONTROL_COUPLING`** (Extra constraints between the fluid domain dofs and the structure dofs will be added to the system).

3.3 Example

To test the module, a simple test representative of a typical application has been setup. The model consists of two materials (fat and a blood vessel wall). Default properties are listed in Table 1 (in S.I. Units), and default boundary conditions consist of a terminal boundary condition with an imposed voltage and a grounded face of the fat material. Figure 1 shows a sketch of the mesh and geometry. The Terminal has an imposed Voltage of 100V and a linear rising time of two seconds. Figure 2 shows the rising temperature at two reference points.

	Fat	Blood Vessel
Density	911.	1102.
Electrical conductivity	0.044	0.325
Dielectric constant	60.	325.
Dielectric losses	0.	0.
Thermal conductivity	0.21	0.46
Thermal heat capacity	2350.	3300.
Radio frequency	450.e3	450.e3

Table 1: Properties for the two domains in the Radiofrequency example.

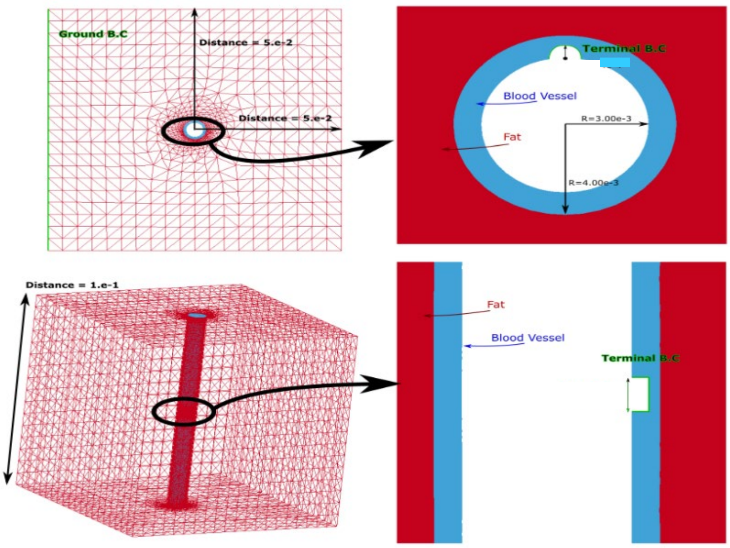


Fig.1: Mesh and Geometry of Model. Number of elements. Approx 350k for Blood Vessel, 950k for Fat.

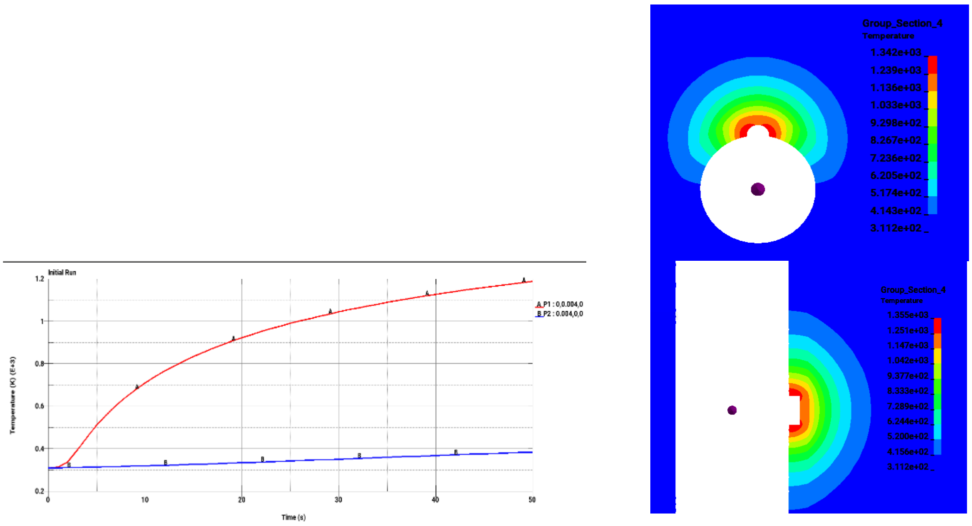


Fig.2: Temperature measured at two points at mid plane (Z=0) at the Blood/Fat intersection: P1 (0,0.004,0) P2(0.004,0,0).

4 Inductive heating extension

4.1 Principle

Induction heating is the process of heating an electrically conducting object (usually a metal) by electromagnetic induction, through heat generated in the object by eddy currents. Compared to Radiofrequency heating, the inductive heating process involves lower frequencies and relies on joule heating as the heat source. The typical application involves AC current with frequency in the $kHz{\sim}Mhz$ range and a total application time of several seconds.

The way the traditional heating solver works in LS-DYNA has been described on numerous occasions [2], [10], [11], [13] but will be summed up here. After a sinusoidal current has been defined, a full Eddy Current problem is first solved on one full period using a “micro” EM time step. An average of the EM fields and Joule heating energy during this period is computed. It is then assumed that the properties of the material (heat capacity, thermal conductivity as well as electrical conductivity) do not significantly change over a certain number of oscillation periods delimited by a “macro” time step. No further EM calculation is done over the macro time step and the Joule heating is simply added to the thermal solver at each thermal time step. After reaching a “macro” timestep, a new cycle is initiated with a full Eddy Current resolution.
This way, the solver can efficiently solve inductive heating problems involving a big amount of current oscillation periods. Figure 3 offers a summary of the process.

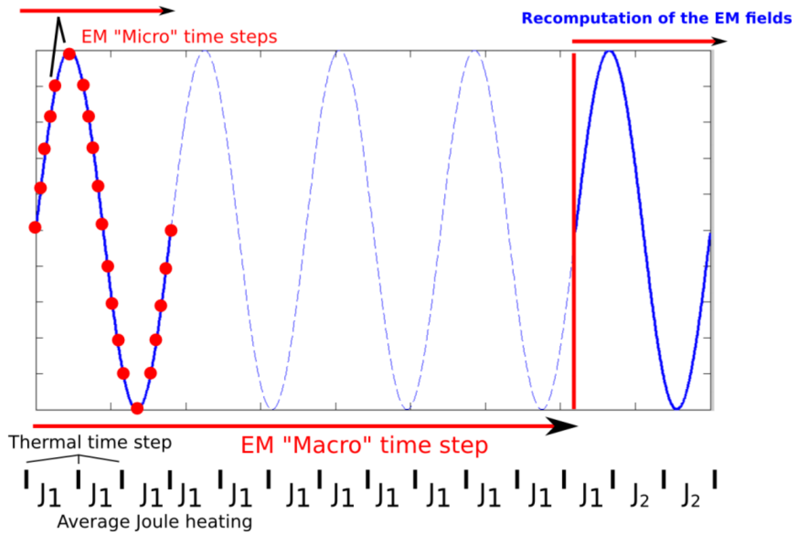


Fig.3: Principle of the LS-DYNA time based inductive heating solver.

4.2 Temperature (or stress) dependent BH curves

4.2.1 Modelling techniques

Previous recent developments have added the support of nonlinear materials for inductive heating [13]. These capabilities are further extended by allowing users to consider the temperature dependency of the material's relative permeabilities. Several approaches have been made available to the user based on the complexity of the model or the amount of existing experimental or reference data.

Approach 1: Using an analytical law for BH curves and temperature dependency.

LS-DYNA allows the user to define an analytical law to characterize the nonlinear magnetic permeabilities. These analytical laws can be extended in order to take into account the temperature dependency, either by using an exponential decay law (defined by an austenitization temperature and an exponential decay constant) or a general user defined criterion:

Analytical arctan law:

$$B(H,T) = \mu_0 H + \frac{2B_s}{\pi}\mathrm{atan}\left(\frac{\pi}{2B_s}H\mu_0(\mu_{r0} - 1.)\right)F(TEMP)SF$$

Analytical Froelich law:

$$B(H,T) = \mu_0 H + H\frac{B_s}{1.+\mu_{r0}H}F(TEMP)\,SF$$

F(TEMP) and SF are optional scaling factors (=1. If not defined). SF is a general law that can be defined by the user (not limited to temperature) and F(TEMP) is defined as:

$$F(TEMP) = \max(0.,1.-exp^{\left(\frac{T-T_s}{C}\right)})$$

With T_s the austenitization temperature and C the exponential decay constant.

Approach 2: Using a discrete BH curve at a reference temperature and include a temperature dependency law.

A second approach, when an analytical formulation for the nonlinear behaviour is not known, is to provide a discrete BH curve and add a user defined law that accounts for the temperature dependent behaviour.

When defined, the scale factor will be taken into account the following way:

$$B(H,T) = \mu_0 H + G(H)\,SF$$

In other words, the nonlinear behaviour of $B(H,T)$ will be decomposed into a linear part $\mu_0 H$ and a nonlinear part $G(H)\,SF$ with $G(H)$ determined by the reference load curve given by the user and SF the scale factor as defined by the user. Thus, the physical behaviour of B function of H will be retained when saturation occurs ($B(H,T) \to \mu_0\, H + M_s$ with M_s the saturation magnetization for very high H values).

If the user has access to lots of experimental data for H and B field pairs at different temperatures, he can calibrate SF based on the formula described above. SF will typically adopt an exponential type of behaviour as defined in the first approach or a polynomial law.

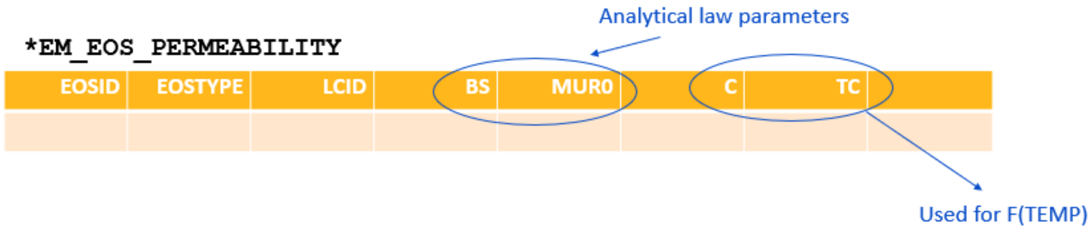
Approach 3: Using several discrete BH curves for different temperatures.

If the user does not know or cannot calibrate his temperature dependency law, a third approach is to directly input several temperature dependant BH curves. Then the solver will reconstruct a fictitious BH curve at any given temperature by interpolating linearly between the curves given by user at the different temperatures.

4.2.2 Keywords

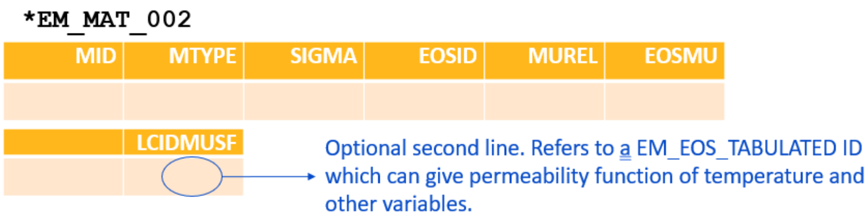
Approach 1:

The selection and definition of the parameters for the analytical law formulations can all be found in:



Approach 2:

The SF scaling factor is defined in the second line of ***EM_MAT_002**. It is a more general approach where the user can define his own temperature dependent law or even include different parameters e.g stress/strain (See ***EM_EOS_TABULATED** and ***DEFINE_FUNCTION**):

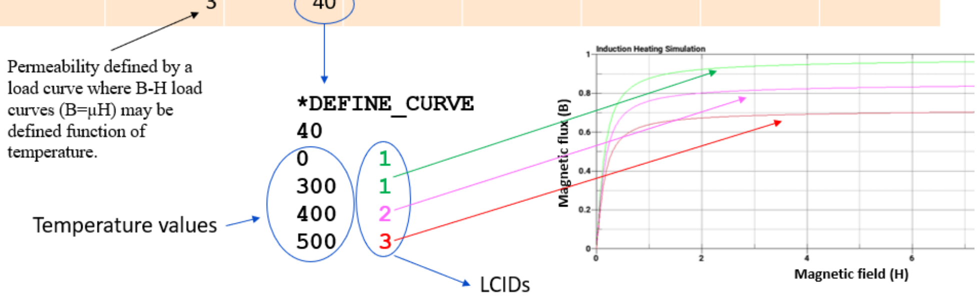


Approach 3:

The multiple temperature dependant BH curve approach is also defined through the ***EM_EOS_PERMEABILITY** keyword.

***EM_EOS_PERMEABILITY**

EOSID	EOSTYPE	LCID	BS	MURO	C	TC	
	3	40					



4.3 Frequency domain solver

4.3.1 Introduction

As mentioned in the previous section the inductive heating solver is a time-based solver, where the EM fields are solved per small steps over one or several periods before an average can be calculated (and passed to the thermal solver in the case of Joule heating). For nonlinear magnetic materials such as previously described, this remains the unique way of solving. However, for materials that adopt a linear permeability (or simply use $\mu_r = 1.$), it can be convenient to adopt a frequency-based solver for Eddy currents. In this approach, the entire Eddy current problem is solved in one single step for a whole given period and averaged fields over the period can be directly retrived for coupling with the mechanical or thermal solvers. This can allow users to save important amounts of calculation times, especially in problems with moving coils where the EM fields need to be updated and recomputed several times at different locations or at different material properties.

4.3.2 Keywords

The frequency-based Eddy current solver can be selected and turned on using the keyword ***EM_CONTROL** and setting the first field EMSOL to 4. The second field NUMLS, traditionally used to define the number of micro steps in the time-based inductive heating solver (EMSOL=2), now represents the frequency (negative values point to a load curve ID allowing user to have varying frequency function of the problem total time).

***EM_CONTROL**

EMSOL	NUMLS						
4	50.						

The keywords that define source terms (***EM_CIRCUIT, *EM_CIRCUIT_SOURCE, *EM_EXTERNAL_FIELD)** remain the same. However, load curve values now represent Amplitudes and consequently, only CIRCTYPE=1 or 2 are supported for ***EM_CIRCUIT** and ***EM_CIRCUIT_SOURCE.**

One final remark is that the EM timestep defined in ***EM_CONTROL_TIMESTEP** again represents a “macro” timestep. The EM fields should only be updated if material properties have changed, displacement or deformation of conductors have occurred, or source terms have changed (varying amplitude or frequency). Otherwise, the EM timestep can be as long as the total length of the run.

4.3.3 Example

To validate the solver, we consider the TEAM 7 benchmark example "Asymmetrical Conductor with a Hole" [14] (www.compumag.org). It consists of a source coil with uniform current over a conductor plate (See Figure 4). The current oscillates at a given and constant amplitude and frequency. The objective is to retrieve the magnetic flux values along several lines between the coil and the workpiece at two different frequencies (50 Hz and 200 Hz). Figure 5 shows the good agreement between the numerical results and the reference results.

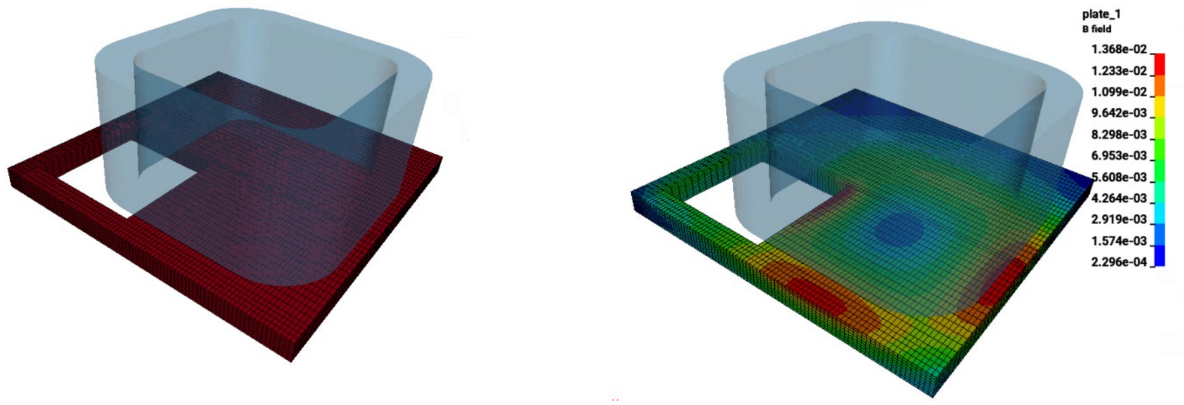


Fig.4: T.E.A.M 7: Geometry and result (B field).

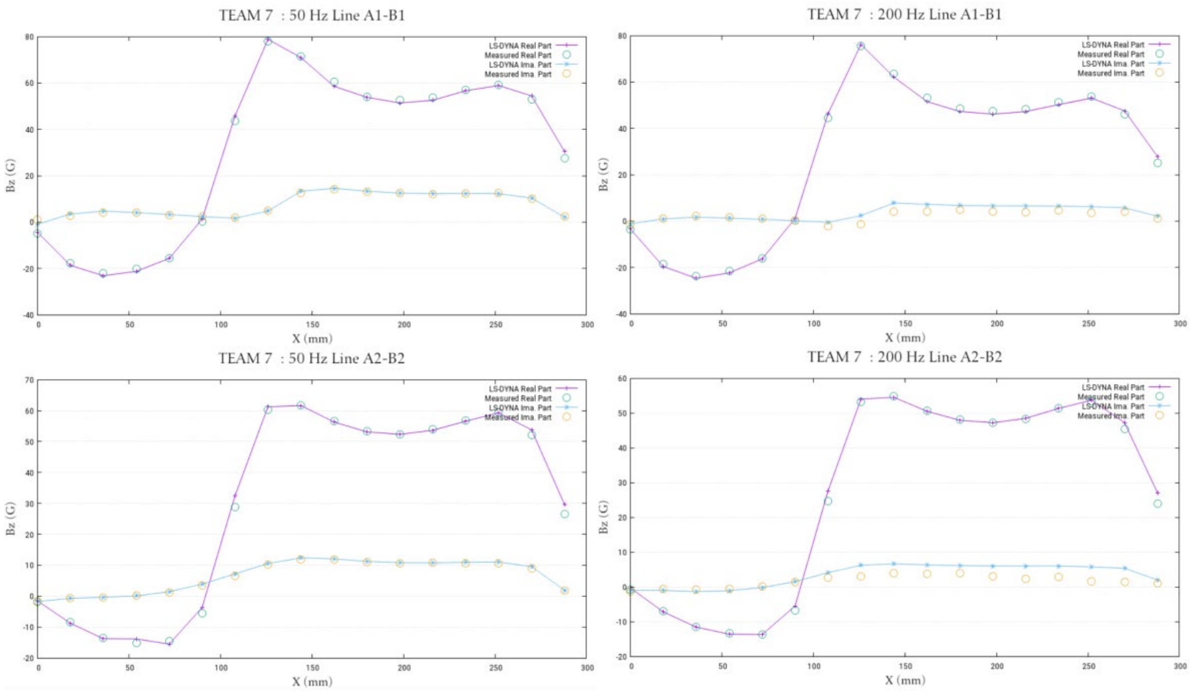


Fig.5: T.E.A.M 7: Result and comparison with literature results for the B field along two different lines between the coil and workpiece at two different source frequencies.

5 Conclusion

Since it was first introduced in LS-DYNA release 7 (R7), developments and enhancements to the EM solver have been continuous and numerous. LS-DYNA R12 for instance introduced the battery module to the EM solver. LS-DYNA R13 brought capabilities for magnets simulations as well as nonlinear magnetic materials. LS-DYNA R14 then expended those capabilities by introducing magnetostatic solver capabilities and advanced preconditioners. Similarly, LS-DYNA R15 can be viewed as specially focusing and expending capabilities related to heating and coupling with the thermal solver. The radiofrequency module is an enhancement of the resistive heating module and broadens the range of physics covered by the EM solver. On the other hand, temperature dependant nonlinear magnetic materials as well as the introduction of a frequency-based Eddy current solver give users even more flexibility and capabilities in addressing their inductive heating and Eddy currents needs.

6 Acknowledgements

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7 Literature

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