Update on the EM solver (R17)

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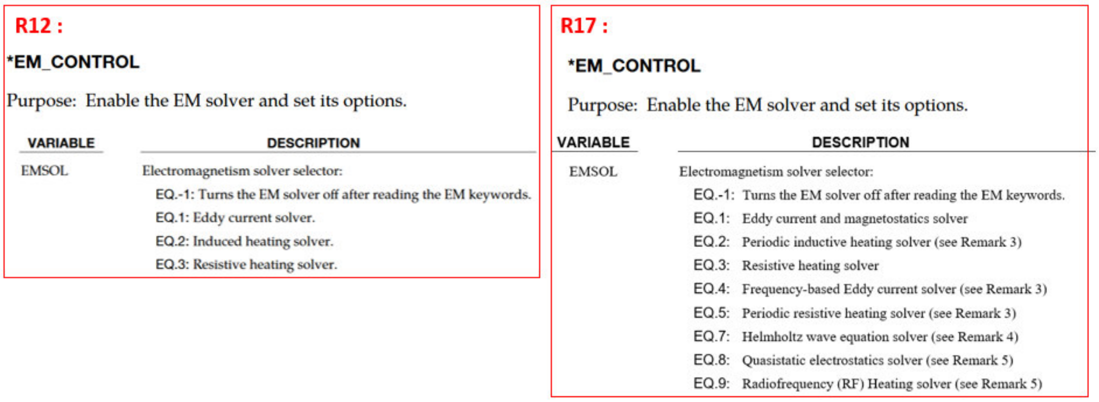
1 Introduction

1.1 Why the generic title?

The EM solver has been part of the LS-DYNA software package since its first official release in R7 [25] [26]. However, over the years, it has grown in terms of features but also simply in terms of physics covered and the number of applications. The R17 release further pushes those boundaries with the introduction of additional solvers. Fig. 1 shows how the keyword **`*EM_CONTROL`** which allows to select different EM solvers has grown and progressed between R12 and R17.

While this offers an ever-growing array of capabilities, it can also be overwhelming for the LS-DYNA user that wishes to get familiar with the EM solver but is unfamiliar with the exact physics. The objective of this paper is therefore to link those different solvers to the physics solved and offer an entry point to comprehend the capabilities, especially the ones recently introduced. It may also be of use to LS-DYNA users familiar with the EM solver and who have used it for specific applications (battery simulations, magnetic metal forming, magnets or electrophysiology) but who wish to learn more about the root equations being solved and broaden their understanding.


R12 :

***EM_CONTROL**

Purpose: Enable the EM solver and set its options.

VARIABLE	DESCRIPTION
EMSOL	Electromagnetism solver selector: EQ.-1: Turns the EM solver off after reading the EM keywords. EQ.1: Eddy current solver. EQ.2: Induced heating solver. EQ.3: Resistive heating solver.

R17 :

***EM_CONTROL**

Purpose: Enable the EM solver and set its options.

VARIABLE	DESCRIPTION
EMSOL	Electromagnetism solver selector: EQ.-1: Turns the EM solver off after reading the EM keywords. EQ.1: Eddy current and magnetostatics solver EQ.2: Periodic inductive heating solver (see Remark 3) EQ.3: Resistive heating solver EQ.4: Frequency-based Eddy current solver (see Remark 3) EQ.5: Periodic resistive heating solver (see Remark 3) EQ.7: Helmholtz wave equation solver (see Remark 4) EQ.8: Quasistatic electrostatics solver (see Remark 5) EQ.9: Radiofrequency (RF) Heating solver (see Remark 5)

Fig.1: Between R12 and R17, five new solvers have been added, without counting Electrophysiology (not shown here) and specific modules such as BatMac.

1.2 How the paper will be structured

This paper does not have the pretention of being a thorough "Theory Manual" but offer a good overview of root capabilities. Starting with the Maxwell equations, it will describe the hypotheses that lead to the formulations addressed by the different EM solvers and how they are connected to one another. New capabilities that are part of R17 will be highlighted and applications will be given as examples. In the interest of clarity, the numerical techniques that are implemented notably the unique and powerful FEM-BEM approach that allows to solve magnetic interactions without resorting to an Air mesh will be mentioned but not described in detail. We refer readers to other presentations that have covered those topics [3] [20] [21] [22] [25] [26] [27] [28] [40].

2 The Maxwell equations

The introduction offered a fair warning, and we will start with the Maxwell equations. The Maxwell equations are a set of four fundamental equations that describe how electric and magnetic fields are generated and interact with charges and currents. They form the foundation of classical (Newtonian) electromagnetism. They can be formulated in the time domain or in the frequency domain via the introduction of complex quantities (defined by a Real and Imaginary part or an Amplitude and Phase shift). Each domain offers specific advantages depending on whether the electromagnetic fields vary with time in a periodic or non periodic way. The time domain formulation will be useful to deal with transient time varying problems but also D.C or magnetostatic problems. The frequency domain formulation is used for problems that involve periodic or sinusoidal signals, usually at medium to high frequencies (from household 50Hz to the Ghz range).

2.1 In the time domain

2.1.1 Equation Set

Gauss's Law (Electric Field): $$\nabla.\boldsymbol{D} = \rho \tag{1}$$

Gauss's Law (Magnetism): $$\nabla.\boldsymbol{B} = 0 \tag{2}$$

Faraday's Law: $$\boldsymbol{\nabla} \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t} \tag{3}$$

Ampere-Maxwell's Law : $$\boldsymbol{\nabla} \times \boldsymbol{H} = \boldsymbol{J} + \frac{\partial \boldsymbol{D}}{\partial t} \tag{4}$$

2.1.2 Constitutive equations:

$$\boldsymbol{D} = \varepsilon\, \boldsymbol{E} \tag{5}$$
$$\boldsymbol{J} = \sigma\, \boldsymbol{E} \tag{6}$$
$$\boldsymbol{B} = \mu\, \boldsymbol{H} \tag{7}$$

Electromagnetic Fields :

E: Electric field (V/m)
D: Electric displacement field (C/m²)
B: Magnetic flux density (T)
H: Magnetic field intensity (A/m)

Material properties :

ε : **Permittivity** (F/m)
σ : **Electrical conductivity** (S/m)
μ : **Permeability** (H/m)

Sources :

ρ: **Free charge density** (C/m³)
J: **Current density** (A/m²)

2.2 In the frequency domain

2.2.1 Equation Set

Gauss's Law (Electric Field) : $$\nabla.\widehat{\boldsymbol{D}} = \hat{\rho} \tag{8}$$

Gauss's Law (Magnetism) : $$\nabla.\widehat{\boldsymbol{B}} = 0 \tag{9}$$

Faraday's Law : $$\boldsymbol{\nabla} \times \widehat{\boldsymbol{E}} = -j\,\omega\widehat{\boldsymbol{B}} \tag{10}$$

Ampere-Maxwell's Law : $$\boldsymbol{\nabla} \times \widehat{\boldsymbol{H}} = \widehat{\boldsymbol{J}} + \boldsymbol{j}\,\boldsymbol{\omega}\widehat{\boldsymbol{D}} + \widehat{\boldsymbol{J}}_{\boldsymbol{source}} \tag{11}$$

2.2.2 Constitutive equations:

$$\widehat{\boldsymbol{D}} = \boldsymbol{\varepsilon}\widehat{\boldsymbol{E}} \tag{12}$$
$$\widehat{\boldsymbol{J}} = \boldsymbol{\sigma}\widehat{\boldsymbol{E}} \tag{13}$$
$$\widehat{\boldsymbol{B}} = \boldsymbol{\mu}\widehat{\boldsymbol{H}} \tag{14}$$

2.2.3 Phasor Notations:

For a time-harmonic field, say the electric field:

$$\boldsymbol{E} = R\{\widehat{\boldsymbol{E}}e^{j\omega t}\}$$

$\widehat{\boldsymbol{E}}$ is the phasor representation of $\boldsymbol{E}$, $\boldsymbol{\omega} = \boldsymbol{2\pi F}$ is the angular frequency (rad/s) with F the frequency (Hz). All time derivatives become multiplications by $j\omega$. $\varepsilon = \varepsilon' - j\,\varepsilon''$ is the complex permittivity, $\mu = \mu' - j\,\mu''$ is the complex permeability, σ is real electric conductivity (inverse of electric resistivity).

3 Quasistatic approximation (Solver 8 and 9).

The **quasi-static electrostatic approximation** means that magnetic field variation in time is negligible (adjusts instantaneously over the domain of interest) but displacement currents are retained. Neglecting magnetic induction implies a change in Eq. (3) which leads to the introduction of the scalar potential φ (Volts):

$$\boldsymbol{\nabla} \times \boldsymbol{E} = 0. \;\rightarrow \boldsymbol{E} = -\boldsymbol{\nabla}\varphi$$

3.1 In the time domain (Solver 8)

Applying the Divergence operator on Eq. (4) to express the Continuity Equation (Charge Conservation) yields:

$$\nabla.(\boldsymbol{\nabla} \times \boldsymbol{H}) = 0. \ = \nabla.\boldsymbol{J} + \frac{\partial \nabla.\boldsymbol{D}}{\partial t} \ \rightarrow \nabla.\boldsymbol{J} + \frac{\partial \rho}{\partial t} = 0.$$

By considering Eq. (1), (5), (6) we get the final Quasi-static Electrostatics Equation in the time domain:

$$\boldsymbol{\nabla}.(\boldsymbol{\sigma\nabla\varphi}) + \frac{\boldsymbol{\partial}}{\boldsymbol{\partial t}}[\boldsymbol{\nabla}.(\boldsymbol{\varepsilon\nabla\varphi})] = \boldsymbol{0}$$

Which is the Equation solved by EM **solver 8**. It is the **quasi-static equation** for the scalar potential φ combining **resistive** (σ) and **capacitive** (ε) effects.

From this equation, the joule heating term (conductive losses) is calculated and fed to LS-DYNA's thermal solver as an external heat source:

$$P_j = \sigma(\boldsymbol{E})^2$$

Using **solver 8** is recommended for highly transient problems where **both conductive and dielectric properties** matter such as Electrical Insulation and **Dielectric Breakdown** present in **Power systems or cable manufacturing**. It is a purely FEM approach and only available in **R17** and onwards.

3.2 In the frequency domain (Solver 9)

When switching to the Frequency domain, the quasi-static approximation yields the following final equation:

$$\boldsymbol{\nabla}.((\boldsymbol{\sigma} + \boldsymbol{\omega\varepsilon j})\boldsymbol{\nabla\varphi}) = \boldsymbol{0}.$$

From which conductive (Joule) losses and dielectric heating terms can be extracted for coupling with the thermal solver:

$$P_j = 0.5\sigma(\boldsymbol{E})^2$$

$$P_d = 0.5\omega\varepsilon''(\boldsymbol{E})^2$$

In the **frequency domain**, we can model dielectric loss simply by defining a **complex permittivity.** Dielectric losses *can* be modeled in the time domain — but it's usually more difficult and less convenient. In our quasi-static Electrostatics equation, they are not modelled.

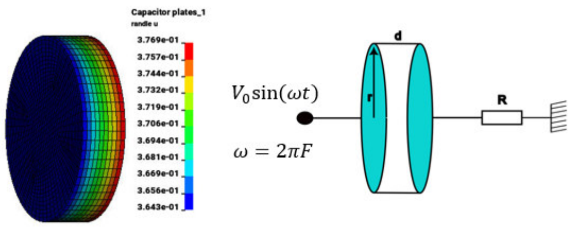
This version of the equation is commonly used in radiofrequency (RF) problems common for example in healthcare applications or microwave circuits. It is the equation solved by EM **solver 9.** Note that RF capabilities were present in previous versions [6] but have been reorganized in **solver 9** for **R17**.

3.3 Example

Here we give an illustration example comparing solver 8 and solver 9. We model a parallel plate capacitor characterized by relative permeability ε_r' and conductivity σ connected in series to an alternating voltage source and a resistor R (See Fig. (2)). The objective is to find the electric field and voltage at the outlet that in this case admits an analytical solution:

$$\alpha = \frac{1}{r_c C} + \frac{1}{RC} \quad \beta = \frac{V_0}{\omega^2 + \alpha^2}\left(\frac{\alpha}{r_c C} + \omega^2\right) \quad \gamma = \frac{1}{\omega}\left(\alpha\beta - \frac{V_0}{r_c C}\right) \quad C = \frac{\varepsilon_0 \varepsilon_r' S}{d} \quad r_c = \frac{d}{\sigma S} \quad S = \pi r^2$$

$$V_{out}(t) = \gamma\left(\cos(\omega t) - e^{-\frac{t}{\alpha}}\right) + \beta(\sin(\omega t)) \qquad E_{out}(t) = \frac{1}{d}(V_{out}(t) - V_0 \sin(\omega t))$$



var	value
V_0	12.
R	1000.
d	$5.0e^{-3}$
r	$1.0e^{-2}$
σ	$6.66e^{-4}$
ε'_r	260.
ε_0	$8.854e^{-12}$
F	$1.e^{6}$

Fig.2: Capacitor model showing input parameters and geometry.

Both solver 8 and 9 can solve this problem. If the initial transient effects need to be captured solver 8 will be favored, if the analysis covers an important number of periods, the Radiofrequency solver will be preferred. Fig. 3 illustrates the expected results:

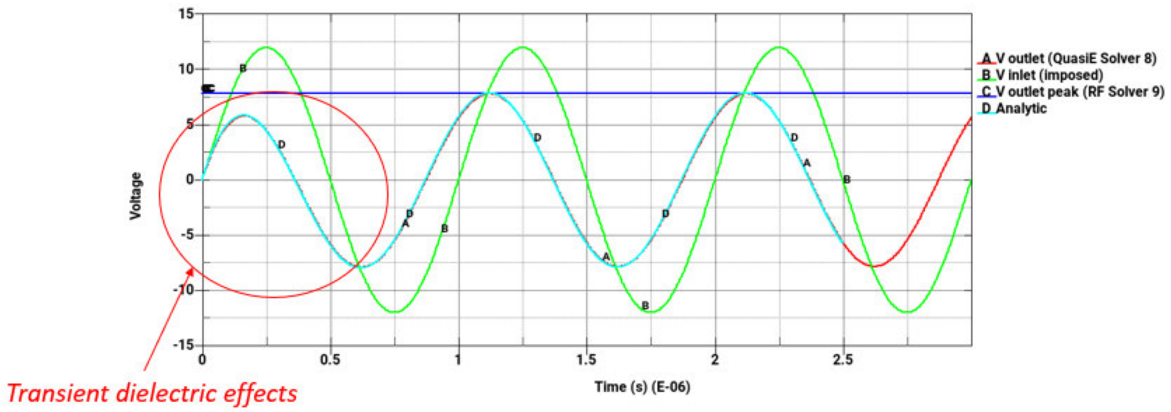


Fig.3: Results showing a transient effect until the fields adopt their final time shift and amplitude and follow a repeatable periodic behavior

3.4 Important Keywords

The choice of solver as well as the Frequency (for solver 9) is defined in `*EM_CONTROL`. Material properties (conductivity, permeability) are found in `*EM_MAT_001`. Boundary conditions such as imposing a voltage can be done via `*EM_CIRCUIT`, `*EM_BOUNDARY_PRESCRIBED`, `*EM_ISOPOTENTIAL/*EM_ISOPOTENTIAL_CONNECT`. Note that for frequency domain solver the imposed value represents peak amplitude.

4 Steady State Conductive limit or resistive heat (Solver 3 and 5).

4.1 Resistive heat (Solver 3)

If we take the previously defined quasi-static electrostatic equation and apply the steady-State conductive Limit:

- Long timescales or DC voltage conditions.
- Good conductive material $\sigma \gg \omega\varepsilon$

Then conduction current dominates, and displacement current becomes negligible i.e resistive behavior dominates. The equation becomes:

$$\boldsymbol{\nabla}.(\boldsymbol{\sigma}\boldsymbol{\nabla}\boldsymbol{\varphi}) = \mathbf{0}.$$

$$P_j = \sigma(\boldsymbol{E})^2$$

This is the equation that is solved by **solver 3** i.e the Resistive heat Solver and is typically used to calculate ohmic losses in good conductors (wires, metals). The resistive heat solver in LS-DYNA is also heavily used in **battery applications** [1] [7] [8] [9] [29] [30] [36] [38] [42] and by the **BatMac** module [31]

[32]. The introduction of Randles circuits that mimic the electrochemistry of batteries is an extension of **solver 3**. Solver 3 forms also the basis for the advanced Electrophysiology solvers used in healthcare applications [14] [16] [33] [35], where the equivalent of the "Randles circuits" are the so-called "ionic models".

4.2 Periodic solver (Solver 5)

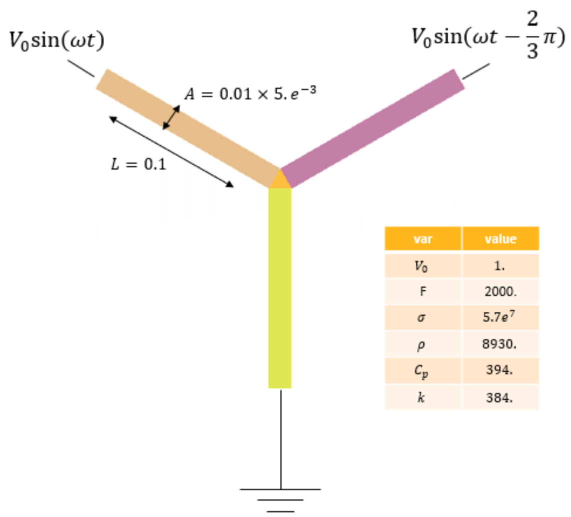
For problems that involve sinusoidal source currents, the periodic heat solver i.e **solver 5** is also available. It works the following way:

- After a sinusoidal current has been defined via **`*EM_CIRCUIT`**, a **full Resistive heat problem** is first solved on **one full period** using a **"micro" EM time step.** This micro timestep is defined by the circuit's frequency divided by a number of local steps *numls* in **`*EM_CONTROL`**.
- An **average of the EM fields and Joule heating** 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" EM timestep** (defined in **`*EM_CONTROL_TIMESTEP`**), **a new cycle is initiated** with a full resolution.
- Naturally, in cases of constant properties and static conductors, this EM timestep can be as large as the total run endtime.
- The thermal timestep also becomes independent of the EM frequency and can be chosen based on varying thermal quantities or boundary conditions. It is common to define it as equal to the circuit's period as a starting point.

For such problems switching to **solver 9** is also an adequate approach. Picking between solver 5 and 9 becomes essentially a user preference. **Solver 5** is essentially a modification of solver 3 while **solver 9** is a different approach (frequency domain) but both should yield similar results in terms of heat generated.

4.3 Example

To illustrate solver 3, 5 and 9, a simple Y-circuit branch is modelled. It is composed of three branches of Resistance R. Two branches have an imposed sinusoidal voltage while the third branch is grounded. The imposed Voltage is defined by its amplitude V_0 and frequency ($\omega = 2\pi F$). One branch voltage is shifted by $\frac{2}{3}\pi$.



var	value
V_0	1.
F	2000.
σ	$5.7e^7$
ρ	8930.
C_p	394.
k	384.

Fig.4: Y branch circuit. Input parameters and geometry.

The Current at the grounded branch can be analytically estimated as:

$$I(t) = -\frac{V_0}{R}\sin\left(\omega t - \frac{1}{3}\pi\right)$$

While the sum of all three currents must be 0.

When solving for an alternating current in the time domain, the EM solver timestep used must be small enough to properly capture the transient changes. It is considered good practise to have one hundred timesteps per period so $emdt = 5.e^{-6}$ (See ***EM_CONTROL_TIMESTEP**). Since the Power provided to the thermal solver will vary at each EM step, the thermal timestep will also be set to $thdt = 5.e^{-6}$. When using the frequency or periodic solvers, thermal timesteps can be much higher and only one single EM solving step is needed unless properties change (Amplitude of imposed boundary conditions, conductors deforming, conductivity changes etc).

Fig. 5 shows how the current behaves using solver 3 and how the temperature behaves when comparing the three approaches. Temperatures must match at each period between the time domain approach (solver 3) and the frequency or periodic approaches (solver 9 and 5 respectfully):

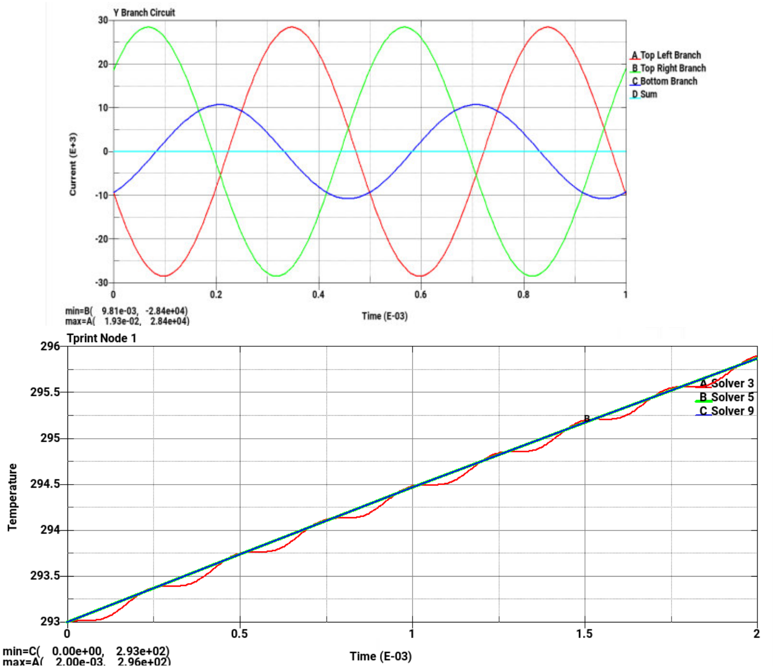


Fig.5: When coupled to the thermal solver, a frequency-based solver gives the averaged heat generated over one electromagnetic period. Therefore, whilst temperature behavior should follow the same trajectory, it can only match exactly at each period.

5 Eddy current approximation (Solver 1,2 and 4).

So far, the solvers described were all FEM based. For the rest of the paper, where the EM fields in the air have an influence on the solution in the solids, the solvers described all make use of a FEM-BEM approach to model the magnetic interactions between conductors. This uses numerical techniques that are uniquely advanced to provide robust and accurate results in coupled analysis (moving or deforming conductors). For users, the main advantage over traditional approaches is that the Air surrounding conductors and meshes does not need to be modelled which simplifies the model set up and allows to directly use mechanical models and add the electromagnetic solve via a few keywords.

Starting back from the Maxwell equations, the Eddy current approximation states that:

- Neglect displacement current: $\frac{\partial \boldsymbol{D}}{\partial t} \ll \boldsymbol{J}$
- Have a good conductive material: $\sigma \gg \omega\varepsilon$

Consequently, all terms involving displacement currents will disappear. However, compared to the quasi-static approximation, we no longer neglect **magnetic induction,** and Electric fields can be **induced by time-varying magnetic fields.** Magnetic induction can be produced by a time varying source (circuits, external fields) or a dynamically moving static source (permanent magnet, moving conductors in static field). The Eddy current approach is typically valid over a broad range of frequencies **(Hz to KHz – up to MHz** or until Displacement currents can no longer be neglected).

5.1 In the time domain (Solver 1)

Eq. (2) allows to introduce the intermediary vector Potential variable $\boldsymbol{A}$ such as:

$$\boldsymbol{B} = \boldsymbol{\nabla} \times \boldsymbol{A}$$

Which injected into Eq. (3) gives the relationship between $\boldsymbol{E}$ and $\boldsymbol{A}$:

$$\boldsymbol{E} = -\frac{\partial \boldsymbol{A}}{\partial t} - \boldsymbol{\nabla}\varphi$$

Injected into Eq.(4) yields the following system on the vector potential:

$$\boldsymbol{\nabla} \times \frac{1}{\mu}(\boldsymbol{\nabla} \times \boldsymbol{A}) + \sigma\frac{\partial \boldsymbol{A}}{\partial t} + \sigma\boldsymbol{\nabla}\varphi - \sigma\,\boldsymbol{V} \times (\boldsymbol{\nabla} \times \boldsymbol{A}) = J_{source}$$

Where we solve for $\boldsymbol{A}$. This equation must be supplemented by a **gauge condition**, typically the **Coulomb gauge is used:** $\boldsymbol{\nabla}.\boldsymbol{A} = \boldsymbol{0}$**.** The Eddy current velocity effect term $\sigma\,\boldsymbol{V} \times (\boldsymbol{\nabla} \times \boldsymbol{A})$ only appears in a Eulerian framework. If the conductors move function of each other and appropriate matrix reassemblies are triggered, this term is implicitly present. The Vector Potential equation is solved on conductor parts (FEM). The interaction between conductors is handled by a BEM approach. The BEM contributions can be viewed as part of the effective source term in the FEM domain J_{source}.

This equation is solved by **solver 1**. It is used in magnetic metal forming, welding and bending [3] [16] [17] [41] [43] [44] [47], in electromagnetic launchers (railguns) [18] [2], coil design [23] [24], inductive heating (ohmic losses are still present) [10] [11] [12] [13], eddy current brakes and many others [39] [45] [46].

5.2 In the frequency domain (Solver 4)

In the frequency domain, the vector potential equation reduces to:

$$\boldsymbol{\nabla} \times \frac{\boldsymbol{1}}{\boldsymbol{\mu}}(\boldsymbol{\nabla} \times \widehat{\boldsymbol{A}}) + \boldsymbol{\sigma\omega j}\widehat{\boldsymbol{A}} = \widehat{\boldsymbol{J}}_{\boldsymbol{s}}$$

This is solved by **solver 4**. It is the Eddy current equivalent of solver 9. It is typically used in **crack detection** (used by the **oil and gas industry** for example) and **inductive heating** (where periodic source currents are common). It can be used to retrieve **impedance matrices** and can also model some hysteresis losses.

5.3 Periodic solver (Solver 2)

Solver 2 is used for inductive heating problems and works in a similar way to solver 5 but applied to Eddy current problems. It is an alternative to solver 4 and can be used based on users' familiarity. It was introduced before the capabilities provided by solver 4 were available. Solver 4 may offer significant reduction in calculation times compared to solver 2 (one single solve in the frequency domain instead of multiple solves over a given period).

5.4 Example

This example is a modification of the standard T.E.A.M 7 problem to highlight the use of the three Eddy current solvers (See Fig 6). It features a stranded coil with an imposed Ampere-turn current and an asymmetric plate with a fixed conductivity that in this scenario heats up due to Eddy-current inductive heating. For the transient Eddy current solver, the EM timestep and thermal solver must be low enough to capture the current oscillations (typically 100 timesteps per period). All three solvers must give similar temperature results.

When checking for current density, solving in the time domain highlights the initial transient effects, where the periodic behavior takes roughly three periods to get established. Consequently '$nperio$' in **`*EM_CONTROL`** has been set to 3 for the solver 2 run. Therefore, the solution for solver 2 will take the third period to calculate its average quantities to pass to the thermal solver.

var	value
AT	$1.e^5$
σ	$3.526e^7$
F	200.
ρ	7000.
C_p	490.
k	15.

Fig.6: Modified T.E.A.M 7 input parameters

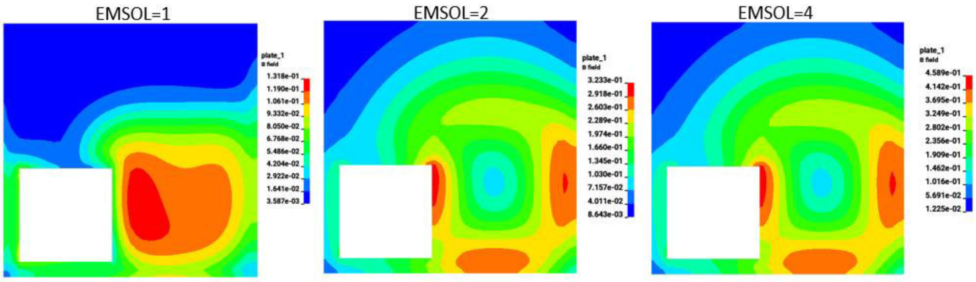


Fig.7: Magnetic flux density at time 0.1. EMSOL=1 gives instantaneous quantities while EMSOL=2 and EMSOL=4 give time averaged outputs.

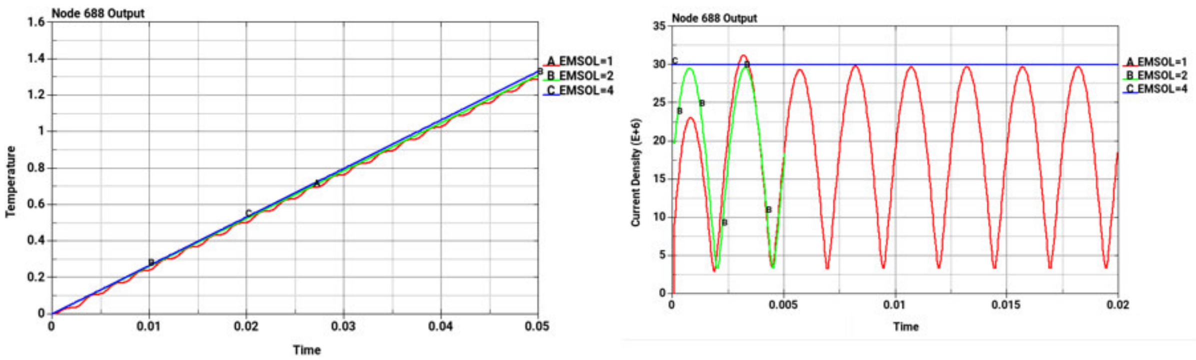


Fig.8: The current oscillations highlight the initial transient effects and establishment of periodic behavior. Temperatures follow the same trajectory.

5.5 Important keywords

Typically for Eddy current problems, **`*EM_CIRCUIT`**, **`*EM_EXTERNAL_FIELD`** or **`*EM_CIRCUIT_SOURCE`** (for stranded coils) are used to define a source magnetic field. One important aspect to note is that solver 4 is only available by using the monolithic solver, see **`*EM_SOLVER_FEMBEM_MONOLITHIC`** and LLT factorization is recommended for the BEM preconditioner (See **`EM_SOLVER_BEM`**). **`*EM_EXTERNAL_ECVEL`** is available as a new R17 development and allows the user to place the model in a Eulerian (i.e nonmoving) frame and apply Eddy current velocity effects (specifically useful in rotating problems or constant speed problems to avoid BEM matrix recomputations)

6 Magnetostatics (Solver 1 and 4).

In magnetostatic cases, $\sigma = 0$. which reduces accordingly the Vector Potential equation to:

$$\boldsymbol{\nabla} \times \frac{\mathbf{1}}{\boldsymbol{\mu}} (\boldsymbol{\nabla} \times \boldsymbol{A}) = \boldsymbol{J}_{\boldsymbol{source}}$$

Solver 1 in combination with the monolithic FEM-BEM solver can be used to solve magnetostatic problems. Since no time derivative is present, each new magnetostatic solution is independent from the previous solve (transient effects are only present if boundary conditions change function of time or conductors move or deform). Magnetostatic solves are typically used in permanent magnet simulations and applied on magnetic parts that exhibit low conductive effects either by being a poor conductor or by considering Eddy currents to be fully diffused and to have a low effect. Ferromagnetic materials are often part of a magnetostatic analysis and exhibit high or nonlinear permeability effects. Magnetostatic analysis if often used for **actuator, motor simulations, magnetic brakes** or for solving **magnet snapping** [37] problems present in **consumer electronic industries**. Note that no Joule heating can be present on $\sigma = 0$. materials.

6.1 Magnetization and force considerations

Two forces can be extracted from the Eddy-current and/or magnetostatic Vector Potential solve:

- The Lorentz force: the force on charges or currents in electromagnetic fields. It is the **direct force on free charges or currents**. It is a **fundamental electromagnetic force**. For it to occur, moving conductors or moving fields must be present.
- The forces that arise from **variations in magnetic permeability or from permanent magnets** - i.e., magnetization forces, sometimes called **material magnetic forces.** It's a force on bound magnetic dipoles and appears due to material properties **(spatially varying** μ or **permanent Magnetization** $\boldsymbol{M}$). For it to appear, fields may be static but ferromagnetic materials or permanent magnets must be present.

The general form of the Lorentz force is:

$$\boldsymbol{F}_{\boldsymbol{Lorentz}} = \rho \boldsymbol{E} + \boldsymbol{J} \times \boldsymbol{B}$$

This includes the Coulomb force i.e Electrostatic contribution $\rho \boldsymbol{E}$ which is removed in the Eddy Current approximation as well as the main magnetic field contribution $\boldsymbol{J} \times \boldsymbol{B}$.

For the Lorentz force to exist, the material must be defined as conductor ($\boldsymbol{J} = \sigma \boldsymbol{E}$), and either the magnetic field must vary in time or conductors must move when put a steady magnetic field.

Different formulations of the magnetization force exist. For the present description we consider:

$$\boldsymbol{F}_{\boldsymbol{mag}} = (\boldsymbol{M}.\boldsymbol{\nabla})\boldsymbol{B}$$

$\boldsymbol{M}$ is the magnetization vector. It represents the **magnetic dipole moment per unit volume** of the material. It describes the alignment of magnetic moments (such as atomic or molecular dipoles) within a material. The ability of a material to develop magnetization $\boldsymbol{M}$ under the influence of an external magnetic field is governed by its magnetic susceptibility χ_m, which is a material property (not given by user). In a linear material (uniform and constant $\mu = \mu_0$), $\boldsymbol{M}$ is directly proportional to $\boldsymbol{H}$ via $\boldsymbol{M}= \chi_m \boldsymbol{H}$. In such cases, the magnetization force is 0.

Magnetic force arises only when the relationship between $\boldsymbol{H}$ and $\boldsymbol{M}$ becomes complex. In **ferromagnetic materials or permanent magnets**, the magnetic flux density $\boldsymbol{B}$ is related to $\boldsymbol{M}$ and the applied magnetic field **H** via the relation:

$$\boldsymbol{B} = \mu_0 \boldsymbol{H} + \boldsymbol{M}$$

In non-linear materials, this relationship between $\boldsymbol{B}$, $\boldsymbol{H}$ and $\boldsymbol{M}$ is represented by the introduction of non-linear B-H curves ($\boldsymbol{B} = \mu \boldsymbol{H}$) as material properties that are provided by the user.

In a permanent magnet, $\boldsymbol{M}$ remains even in the case of no external source $\boldsymbol{H}$. Typically to define a magnet the **coercive force $\boldsymbol{H_c}$** is given as input which represents the external magnetic field strength that would be needed to reduce the magnetization M to zero.

On a practical level, LS-DYNA's EM solver can calculate both these forces for transient coupling with LS-DYNA's mechanical solvers (either explicit or implicit). The Lorentz force is a relative straightforward vector product operation that gives a volume force per element while the magnetic force is expressed as a surface force, and its evaluation requires more advanced numeric implementation but follows the description of [48]. Typically, for applications involving good conductors and where strong Eddy currents are present, the Lorentz force dominates (**magnetic metal forming, pulse welding, railguns** etc) while the magnetic force is the main driver behind **actuators, rotors, magnet latching** and **snapping** and so forth.

6.2 Hysteresis (Solver 4)

In our typical magnetostatic modelling approach, we define a $B-H$ curve to model the nonlinear behavior (optionally making it temperature or stress dependant). If we start from zero and increase H, B rises and eventually saturates. If H then decreases, the path that B takes is the same as when H increases. In paramagnetic materials, this is a broadly true assumption. However, for ferromagnetic materials this is only true if we neglect their hysteresis behavior. In reality, once saturation is reached, if we decrease H back to zero B, does not retrace the same path, instead it follows a different curve. This is because the magnetic domains don't instantly reorient, they lag behind the applied field. Fundamentally, hysteresis is the lag between magnetization (B) and applied field (H) due to the energy needed to reorient the magnetic domains.

The cost of hysteresis can be expressed in terms of energy loss. That energy loss corresponds to the Area of the hysteresis loop shown on Fig. 9 ($\int HdB$) and generates heat that can damage components especially at high frequencies.

It is currently not possible to model hysteresis losses with solver 1. However, **solver 4** allows to take those magnetic losses into account as a **new R17 development**. In the frequency domain, μ is expressed as a complex quantity (See Eq. 14) which means that if the imaginary part μ'' (or magnetic loss tangent: μ''/μ') is defined, B will lag behind H and losses will occur. The challenge is to define the material's loss tangent in such a way that the area and shape of Fig 10 matches as closely as possible the real hysteresis loop of Fig 9. Fortunately, this approach is relatively common and loss tangent properties for materials exist in the literature.

When magnetic losses are present in solver 4, they are automatically added to the thermal solver as:

$$P_m = 0.5\omega\mu''(\boldsymbol{H})^2$$

As can be observed from the formula, this term becomes more important at high frequencies.

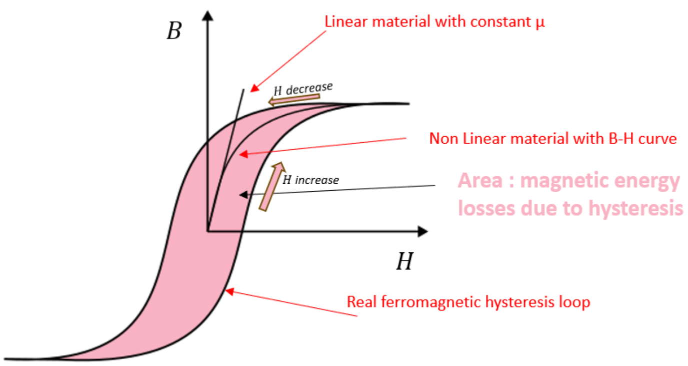


Fig.9: $B = \mu H$ *different behaviors*

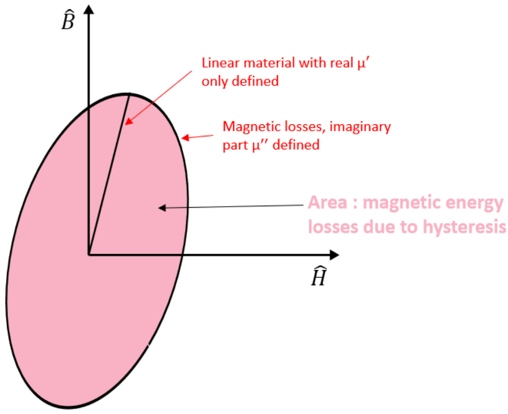


Fig.10: $\hat{\boldsymbol{B}} = \mu\hat{\boldsymbol{H}}$ *in phasor notation*

To quickly check our implementation, we consider the following simple case of an iron solid sphere of Radius $r = 1$. We consider the sphere without conductivity, $\sigma = 0.$, with a relative permeability $\mu_r{}' = 2.$ and apply a spatially uniform external magnetic flux with an Amplitude $B_0 = 1.T$ in the Z direction. We make the loss tangent term vary and check the resultant uniform magnetic flux and phase in the sphere as well as the magnetic heating term knowing that this problem admits an analytical solution:

$$|B_{sphere}| = B_0 \frac{3.}{(\mu_r{}' + 2.)^2 + \mu_r{}''^2} \sqrt{(2.\ \mu_r{}'')^2 + \left(\mu_r{}''^2 + \mu_r{}'^2 + 2.\ \mu_r{}'\right)^2}$$

$$\Phi = -tan^{-1}\left(\frac{2.\ \mu_r{}''}{\mu_r{}''^2 + \mu_r{}'^2 + 2.\ \mu_r{}'}\right)$$

$$P_m = \frac{\omega}{2.\mu_0}\mu_r{}'' \frac{|B_{sphere}|^2}{|\mu_r|^2} = \frac{\omega}{2.\mu_0}\mu_r{}'' \frac{|B_{sphere}|^2}{\mu_r{}''^2 + \mu_r{}'^2}$$

Fig. 11 shows the good agreement between the numerical and analytical results (minus some mesh effects since it is not a perfect sphere geometry).

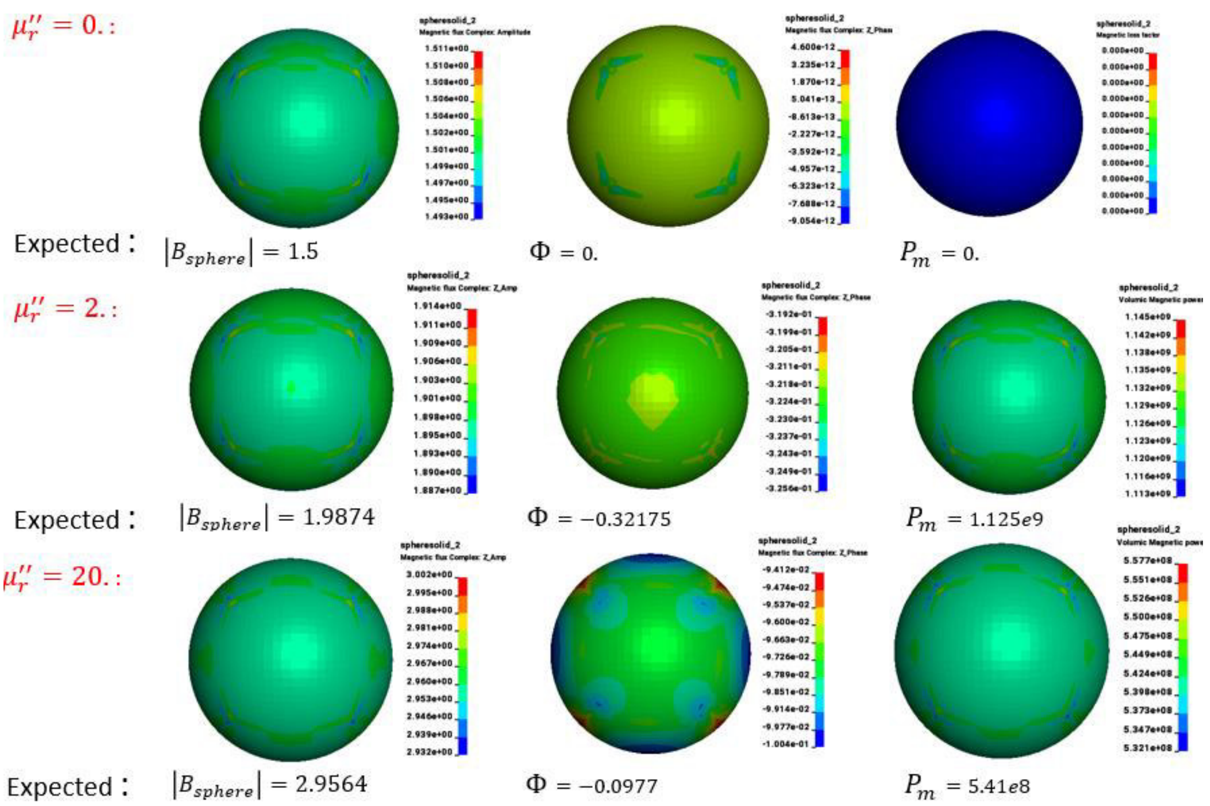


Fig.11: Iron sphere placed in external magnetic field along the Z direction defined by Amplitude and Frequency. Different loss values impact the Magnetic flux amplitude, phase and magnetic losses generated.

6.3 Important keywords

If a problem includes a part where $\sigma = 0.$ and falls under the considerations of solver 1, then ***EM_SOLVER_FEMBEM_MONOLITHIC** must be used. To turn on the magnetic force calculation, the second field of ***EM_CONTROL_COUPLING** must be used. Magnetic material properties, whether it is a constant $\mu \neq \mu_0$, or defined with nonlinear BH-curves ($\boldsymbol{B} = \mu \boldsymbol{H}$), can be done using ***EM_MAT_002**. Hysteresis losses can be defined on the second line of that same keyword. A magnet typically provided by a manufacturer is defined by giving a linear permeability in ***EM_MAT_002**, a north/south orientation and a coercive force value defined in ***EM_PERMANENT_MAGNET**. For nonlinear ferromagnetic materials the usage of LLT factorization for the BEM preconditioning in ***EM_SOLVER_BEM** is again recommended.

7 Wave propagation of Full Maxwell problem (Solver 7).

In cases of wave propagation, open-domain radiation or scattering problems (**Antenna – radar analysis- MRI**), displacement currents cannot be ignored, and the full set of Maxwell's equations must be employed. The very high frequency usually justifies the use of a complex formulation which allows to express the Maxwell equation function of the Electric field. Equations (8), (9), (10) and (11) combined with the constitutive equations can be rewritten as:

$$\frac{1}{\mu}\boldsymbol{\nabla} \times \widehat{\boldsymbol{E}} + j\,\omega\,\boldsymbol{\nabla} \times \widehat{\boldsymbol{H}} = 0$$
$$\boldsymbol{\nabla} \times \widehat{\boldsymbol{H}} - j\,\omega\,\varepsilon\widehat{\boldsymbol{E}} = \sigma\widehat{\boldsymbol{E}} + \widehat{\boldsymbol{J}}_{source}$$

This yields the final Wave equation on the Electric field:

$$\boldsymbol{\nabla} \times \left(\frac{1}{\mu}\boldsymbol{\nabla} \times \widehat{\boldsymbol{E}}\right) - \omega^2 \varepsilon \widehat{\boldsymbol{E}} = -j\omega\widehat{\boldsymbol{J}}_{source}$$

This is the equation solved by **solver 7** which is **newly introduced in R17**. This formulation is valid on conductor parts. BEM is again used for the far field domain. Note that permittivity and permeability are represented by complex numbers with a real and imaginary part. Excitation fields are typically Plane waves (Radar, scattering) i.e prescribed $\hat{\boldsymbol{E}}$ field or Current sources $\hat{\boldsymbol{J}}$ (Antennas, coils, wires). Three heating terms are generated with this solve:

- Conductive losses (joule heating-W): $P_j = 0.5\sigma(\boldsymbol{E})^2$
- Dielectric losses (dielectric heating-W): $P_d = 0.5\omega\varepsilon''(\boldsymbol{E})^2$
- Magnetic losses (magnetic heating-W): $P_m = 0.5\omega\mu''(\boldsymbol{H})^2$

7.1 Example

The author of those lines is getting tired and no longer has the energy to collect and set up a relevant example before the submission deadline has been reached. We ask for your indulgence and recommend contacting us for further information. Examples will be provided in the next iteration of this work.

7.2 Important keywords

The choice of solver 7 and the frequency is again done in **`*EM_CONTROL`**. Excitation fields can be defined using **`*EM_EXTERNAL_FIELD`** and current sources via **`*EM_CIRCUIT_SOURCE`**.

8 Conclusion

8.1 How to pick a solver?

As we have seen, EM solvers can broadly be divided into three categories. Time domain solvers, frequency domain solvers and periodic solvers, with periodic solvers acting in a similar way to frequency-domain solvers:

- Time domain solvers: Eddy current and magnetostatics (Solver 1) – Resistive heat (Solver 3) and Quasistatic electrostatics (Solver 8).
- Frequency domain solvers: Eddy current (Solver 4) – Helmholtz Wave equation (Solver 7) and RadioFrequency solver (Solver 9).
- Periodic solvers: Periodic resistive heat (Solver 5) and Periodic inductive heat (Solver 2).

The time scale of the problem will help to determine the choice of solver. Direct current (D.C), static source or non-periodic cases will use Time domain solvers. For problems involving alternating current, the time scale will give an indication on which solver to favor. Typically, for simulations involving more than ten periods, Frequency or Periodic solvers will be preferred over Time domain solvers.

The second indicator regarding the choice of solver will depend on which electromagnetic physics effect is dominant, and which electromagnetic material property (Conductivity, Permittivity and Permeability) is present. Again, the operating frequency can provide a useful guideline.

One final observation is that Time domain solvers are often used in transient coupled problems with LS-DYNA's mechanical solvers, with electromagnetic forces interpolated and passed at each step. In terms of coupling, frequency or periodic solvers on the other hand mostly concern themselves with passing heat terms to the thermal solver.

8.2 Capability summary

In terms of numerical methods, the EM solvers can broadly be classified into two categories:

- FEM solvers: Solver 3, Solver 5, Solver 8, Solver 9.
- FEM-BEM solvers: Solver 1, Solver 2, Solver 4, Solver 7.

In purely FEM methods, no electromagnetic interactions between two conductors can occur without providing a mesh. The resulting system and matrix assembly is usually much simpler and faster resulting in lower computation costs.

FEM-BEM solvers use advanced and sometimes proprietary techniques to solve the electric or magnetic interactions between conductors without needing to mesh the Air in between. Those models are usually more complex, require more care in their set up and have higher calculation times.

In terms of physics tackled, the Table below offers a summary of which quantities are present depending on the solver picked:

Solver	Ohmic losses (σ)	Eddy currents – current diffusion	Dielectric effects (ε)	Dielectric losses	Magnetic effects (linear μ)	Magnetization (permanent magnets, nonlinear μ)	Magnetic losses	Time Integration
[1]	Yes	Yes	No	No	Yes	Yes	No	Time
[2]	Yes	Yes	No	No	Yes	No	No	Time-Avg
[3]	Yes	No	No	No	No	No	No	Time
[4]	Yes	Yes	No	No	Yes	No	Yes*	Freq.
[5]	Yes	No	No	No	No	No	No	Time-Avg
[7]*	Yes	No	Yes	Yes	Yes	No	Yes	Freq.
[8]*	Yes	No	Yes	No	No	No	No	Time
[9]**	Yes	No	Yes	Yes	No	No	No	Freq.

*New R17 development
**Capability existed before (RF heating) but has been reorganized

8.3 Where next?

As mentioned in the introduction, Electromagnetic capabilities have been part of LS-DYNA for a long time and have had numerous applications and uses over the years. However, we feel that LS-DYNA R17 marks a new landmark since for the first time, all major possible physics are covered by the electromagnetic solver. We are also continuously updating and upgrading our existing solvers. For example, FEM and BEM matrix reassembly times are greatly improved in R17 with options available to users to skip some parts of the BEM reassembly in cases of nonmoving or rigid conductors. A new hybrid solving approach between a direct method and a conjugate gradient method for solving large battery module problems has also been introduced. Advanced features are also continuously added such as magnetostriction capabilities or coupling between EM and fluids (ICFD) [4] [5] and we are currently investigating whether the magnetic force results for interactions between magnets can be further improved at a higher level of accuracy. Astute users will also have noticed the absence of a “solver 6”. This would be part of our R&D efforts, and we hope to be able to say something about it in the next iteration of this paper.

Ultimately, what pushes the electromagnetic capabilities forward is our users that continuously send us their feedback and recommendations, and we commend them on their commitment and effort as we journey together in the magnificent world of FEA. Please continue to do great work and reach out, we always appreciate collaborative efforts.

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