Magnet dynamics using LS-DYNA®

Trang Nguyen[1], Iñaki Çaldichoury[1], Pierre L'Eplattenier[1], Lars Kielhorn[2], Thomas Rüberg[2], Jürgen Zechner[2]
[1]Ansys - Livermore Software Technology LLC, 7374 Las Positas Road, Livermore, CA 94551, USA
[2]Tailsit, Nikolaipl. 4, 8020 Graz, Austria

1 Abstract

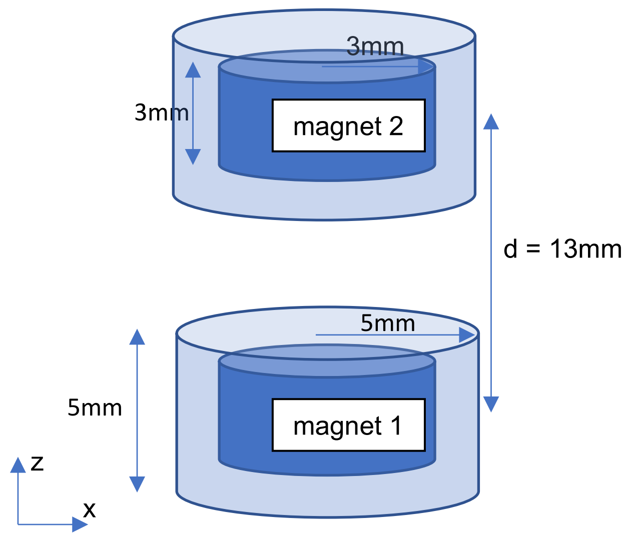
The LS-DYNA® Electromagnetic solver (EM) has recently integrated a new monolithic FEM (Finite Element Method) – BEM (Boundary Element Method) solver along with an AMS (Auxiliary Maxwell Space) preconditioner. Eddy-Current and Magnetostatic - including linear or non-linear magnetic materials - analysis can be done thanks to these new implementations [1]. On top of this, the capability to have permanent magnets has been introduced. We will start by showing a benchmark between LS-DYNA® and ANSYS Maxwell on the force calculation between two magnets in different conditions.
The first model consists of two-cylinder magnets at a distance d. The magnet is a Neodymium Iron Boron magnet with a magnetic coercivity of -900 kA/m. In the first comparison, a linear magnetic characteristic of the magnet is considered. Then a non-linear BH curve is introduced in the next comparison. The insulator is a linear material with no conductivity.
In the second model, we added a steel plate with high permeability between the 2 magnets to see its influence on the force on each magnet.
The benchmark gives a good agreement between Ansys-Maxwell and LS-DYNA® in terms of results and computational cost in both linear and nonlinear case.

2 Introduction

One of the strengths of the LS-DYNA EM solver is its FEM+BEM coupling where the air mesh is not needed [2]. It allows easy simulations of moving and deforming conductors as well as conductors coming in contact with each other. The R13 release introduces the simulation of moving magnets due to magnet-magnet or magnet-steel plate interactions. This opens a wide range of new applications involving magnet latching, snapping or interacting with other conductors. An important step to validate this approach is to make sure that the magnetic force is computed correctly. To that effect, in this paper, we establish some benchmarks and compare this new capability to other available electromagnetic software.
In section 2, the model with permanent magnets will be introduced. In section 3, a comparison between the new LS-DYNA solver and ANSYS-Maxwell will be made. Section 4 compares the magnetic force on magnet in presence of steel plate. Section 5 presents the movement of magnets in LS-DYNA in the case of 2 magnets.

2.1 The 2 magnets model

The benchmark consists of 2 cylindrical magnets separated by a distance d. Each magnet is surrounded by an insulator. These 2 cylindrical magnets are put into an airbox in the ANSYS-Maxwell solver since it uses a pure FEM method. No air mesh in needed in LS-DYNA's FEM-BEM electromagnetic solver [2]. The magnets are made of Neodymium Iron Boron with a magnetic coercivity of -900 kA/m. The magnetic poles are such that the 2 magnets are pulled towards each other.



The ANSYS Maxwell solver generates a tetrahedral mesh (for the magnets and the surrounding air) while LS-DYNA generates a hexahedral mesh (of the magnets only). In the next section of comparison, one magnet will be moved along the z-axis, x-axis, or rotated around an axis.

2.2 Force calculation

In ANSYS Maxwell, the principe virtual work method is used to calculate the global force applied on the magnets.

$$F_{magnet} = \left.\frac{dW(s,i)}{ds}\right|_{i=const} = \frac{\partial}{\partial s}\left[\int_V \left(\int_0^H B.dH\right) dV\right]$$

Where W(s,i) is the magnetic coenergy of the system at a current i constant, s the virtual displacement of the system.

In LS-DYNA, to calculate the magnetic global force on the magnet, the Maxwell stress tensor is used. The Maxwell stress tensor in a constant permeability region such as air is written as following:

$$\boldsymbol{\sigma} = \boldsymbol{B} \otimes \boldsymbol{H} - \frac{1}{2}\boldsymbol{B}.\boldsymbol{H}$$

where $\boldsymbol{\sigma}$ is the Maxwell stress tensor, $\otimes$ the tensor product.
The volume and surface force density is the divergence of the Maxwell stress tensor

$$\boldsymbol{f}_\Omega = div\,\boldsymbol{\sigma} = \boldsymbol{j} \times \boldsymbol{B}$$

$$\boldsymbol{f}_\Gamma^+ = -\boldsymbol{\sigma}\boldsymbol{n} = -\frac{1}{2\mu_0}B_n^2\boldsymbol{n} + \frac{\mu_0}{2}|\boldsymbol{H}_t|^2\boldsymbol{n} - B_n\boldsymbol{H}_t$$

where $\boldsymbol{f}_\Omega$ is the volume force density, $\boldsymbol{f}_\Gamma^+$ the surface force density of the exterior force.
The global force is obtained by integrating the surface force density over the surface.

2.3 Mesh quality

In this first calculation, the material is linear, the poles of magnets 1 and 2 are in opposite. Therefore, the force exerted on magnet 1 is positive, while the one on magnet 2 is negative. Tables 1 and 2 present the global force on magnet 1 (force 1) in LS-DYNA and Maxwell versus the number of degrees of freedom (dofs).

LS-DYNA	Mesh 1	Mesh 2	Mesh 3	Mesh 4
Number of dofs	500	4600	5000	10000
Force on magnet 1 (mN)	110.14	112.3	112.8	112.6
Computational time	17s	2 mins 12s	4 mins36s	6 mins 54s

Table 1: Force 1 versus Dofs in LS-DYNA

Maxwell	Mesh 1	Mesh 2	Mesh 3	Mesh 4
Number of dofs	96822	120460	153306	227166
Force on magnet 1 (mN)	113.02	107.46	108.43	116.9
Computational time	5 min 3s	6 min 47s	8 mins 02s	8 mins 36s

Table 2: Force 1 versus Dofs in Maxwell.

The computational time is given for 1CPU for each solver. Note that in Maxwell, the initial mesh size given by the user can have an impact on the computational time. Sometimes, an initial fine mesh takes less time to reach the convergence criteria than the one with coarser mesh. In the subsequent simulations, LS-DYNA uses mesh 2 with 4600 dofs, Maxwell uses mesh 4 with 35000 dofs.

3 Comparison between LS-DYNA and Maxwell

Most permanent magnets in a numerical model are defined by these two characteristics: the value of coercivity field (H_c) and the magnetic properties (B-H curve). The magnetic constitutive law in a permanent magnet is written as follows $B = \mu_0 \mu_r H + H_c$. In this study, the coercivity field is supposed to be constant. The BH curve can be linear or nonlinear.

3.1 Linear case

In this part, the magnetic properties of magnets are considered isotropic and linear, with a relative permeability $\mu_r = 1.09$. Magnet 2 is moved along z-axis while magnet 1 does not move. The magnetic force is calculated on magnet 1 depending on the distance between the 2 magnets.

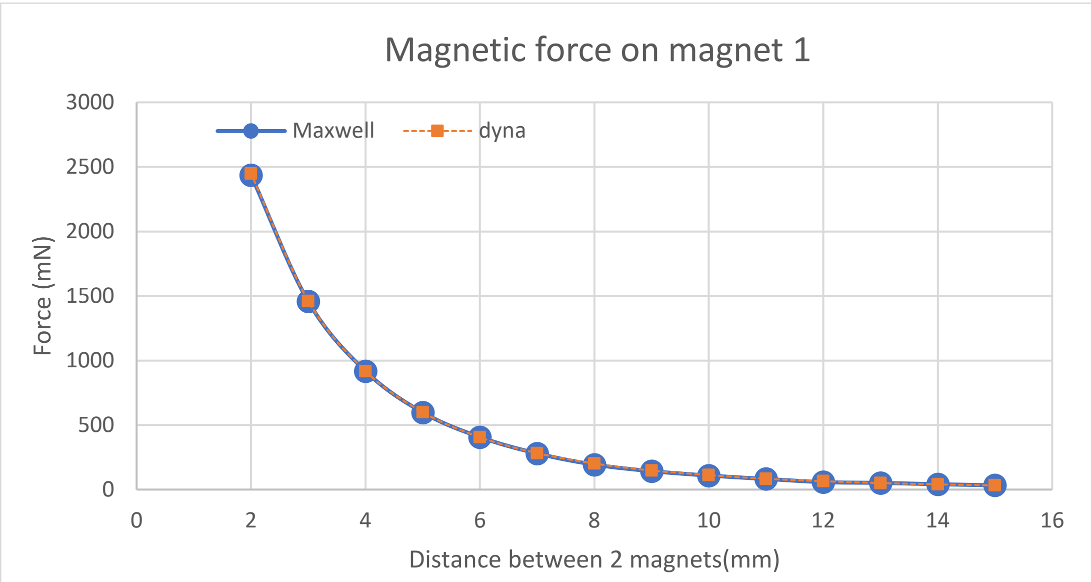


Fig. 1 Magnetic force versus distance between 2 magnets in linear case

As the distance between the 2 magnets decreases, the magnetic force becomes bigger. The magnetic force results between Maxwell and LS-DYNA are very similar, even with a small distance. In this paper, the contact between 2 magnets is not considered.

3.2 Nonlinear case

The magnetic constitutive law is supposed to be nonlinear. The relative permeability is not a constant value, the B-H curve is a nonlinear curve. The figure 2 (left) presents the BH curve shifted to the left due to the coercive field in the magnet.
For the LS-DYNA model, to fit the experimental BH curve, the Fröhlich-Kennelly model is applied:

$$B(H) = \left(\mu_0 + \frac{\alpha}{1+\beta H}\right) H$$

where the two coefficients (α, β) have to be calculated.

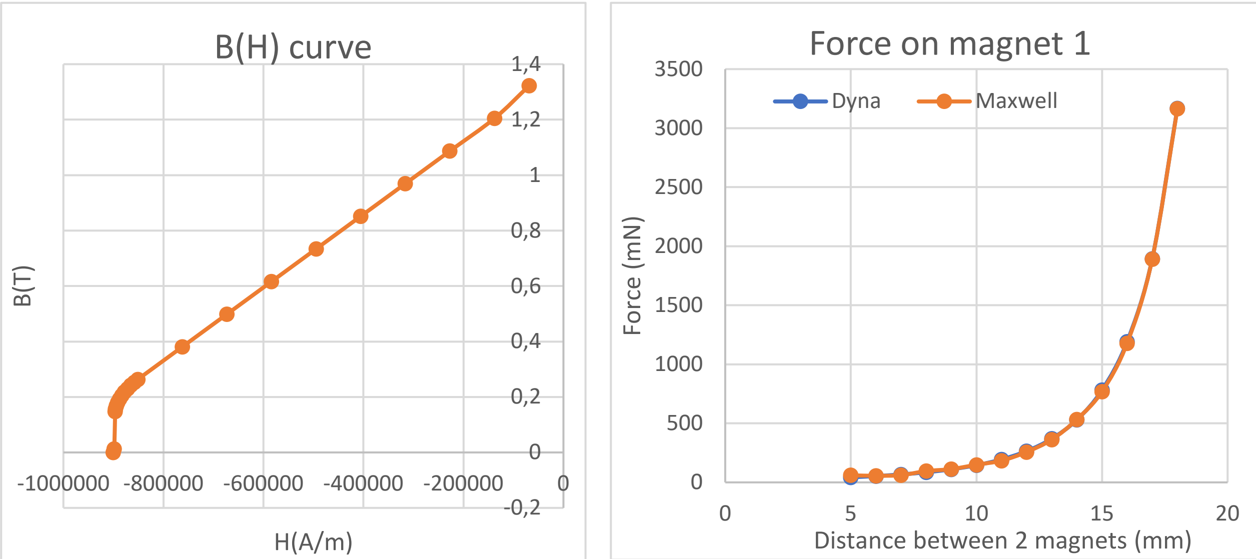


Fig. 2 BH curve (left) and magnetic force versus distance between 2 magnets (right)

In the nonlinear case, the magnetic force results in Maxwell and LS-DYNA are very similar. At a given distance between the two magnets, the magnetic force in nonlinear cases is bigger than the one in linear cases. This difference can be explained by the permeability of the 2 magnets which increases in the nonlinear case (the slope of the first part of BH curve is more than 1).

3.3 Rotation of a magnet

In this situation, magnet 2 is rotated around the x-axis with an angle θ. Magnet 1 is subject to a magnetic force which now has 2 components, along the z-axis and the y-axis.

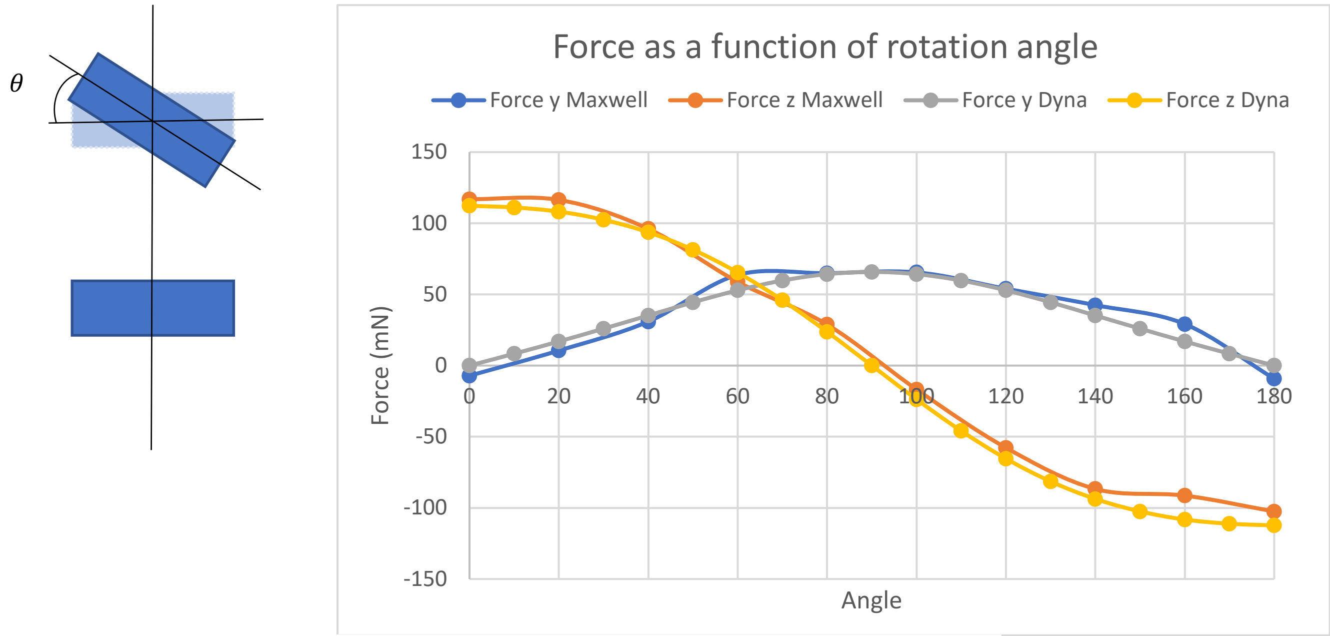


Fig. 3 Magnetic force versus rotation angle in linear case

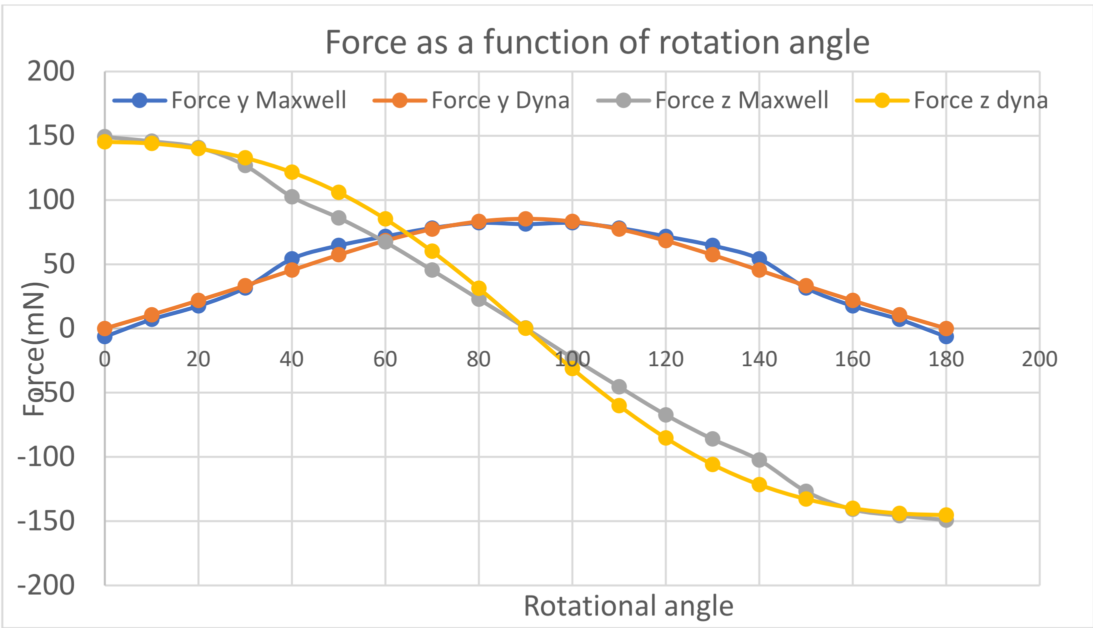


Fig. 4 Magnetic force versus rotation angle in nonlinear case

The results between LS-DYNA and Maxwell show a good agreement for both the y-force and the z-force. But in this comparison, the result obtained by Maxwell is not as smooth as the one obtained by LS-DYNA. This may be because in Maxwell, for each rotation of the magnet, a new adaptative mesh is created, therefore the mesh is not the same for each simulation. Results are expected to be smoother when using a finer mesh.

In Figures 3 and 4, the z-component of the magnetic force is at its peak when the two magnets are face to face, and almost zero when the 2 magnets are perpendicular. Conversely, the y-component is almost zero at 0 degree rotation and reaches the maximum at 90 degrees.

3.4 Displacement following x-axis of a magnet

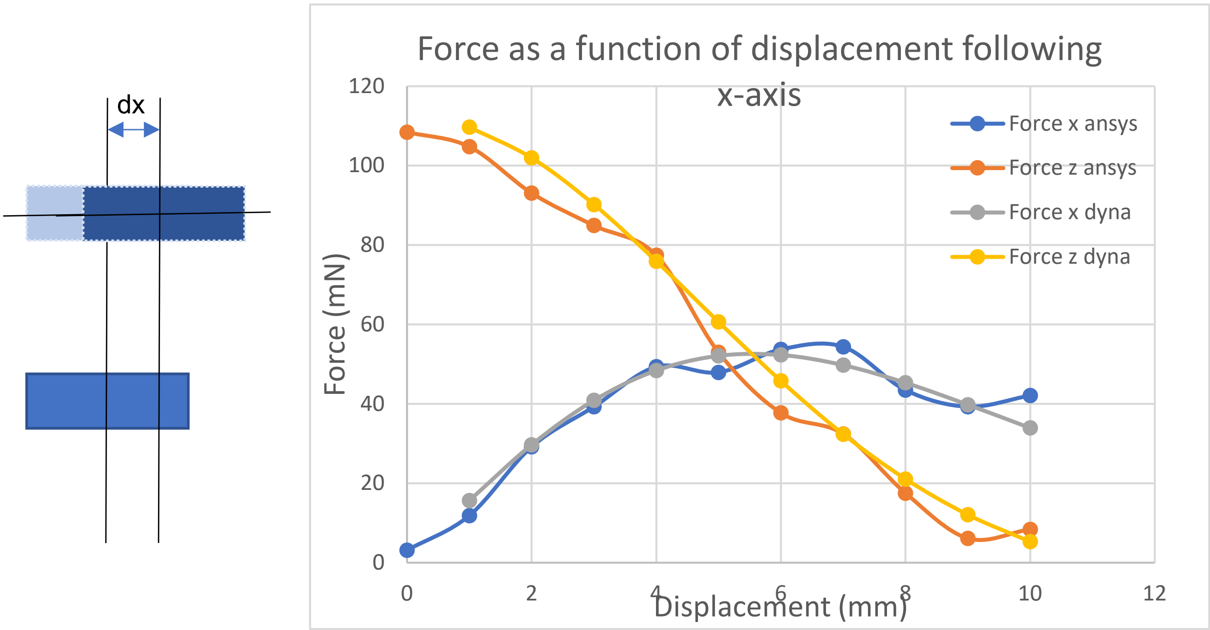


Fig. 5 Magnetic force versus displacement following x-axis

Magnet 2 is now moved along the x-axis. This movement creates a x-component on the magnetic force while the z-component is decreased and reaches zero. The x-component of the magnetic force increases initially but decreases when the 2 magnets are far from each other.

4 Magnetic force in presence of steel plates

4.1 One steel plate between 2 magnets

In this study, a steel sheet in inserted between the 2 magnets. The permeability of the steel is 1000. Magnet 2 is moved along z-axis whereas magnet 1 is kept at the same position.

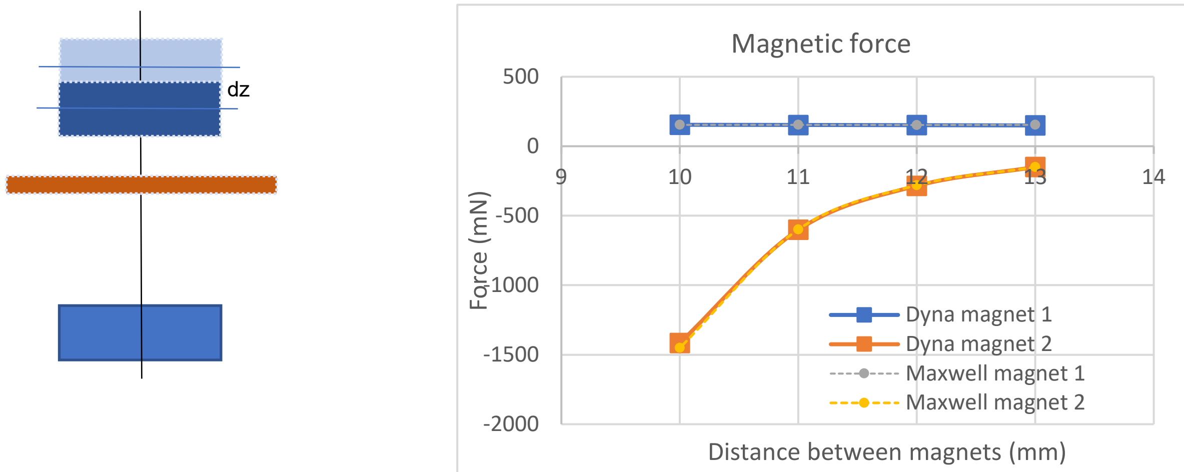


Fig. 6 Magnetic force in magnet 1 and 2 obtained by Dyna and Maxwell

As presented in Figure 6, the magnetic force on magnet 1 is quite stable, independent of the position of magnet 2. As the steel plate has a higher permeability, the field lines do not go much across the plate. Therefore, the steel sheet acts as a shield to the magnetic field between the 2 magnets. The influence of the steel plate on the B-field lines can be seen in figure 7. The results obtained by Maxwell and LS-DYNA are almost the same.

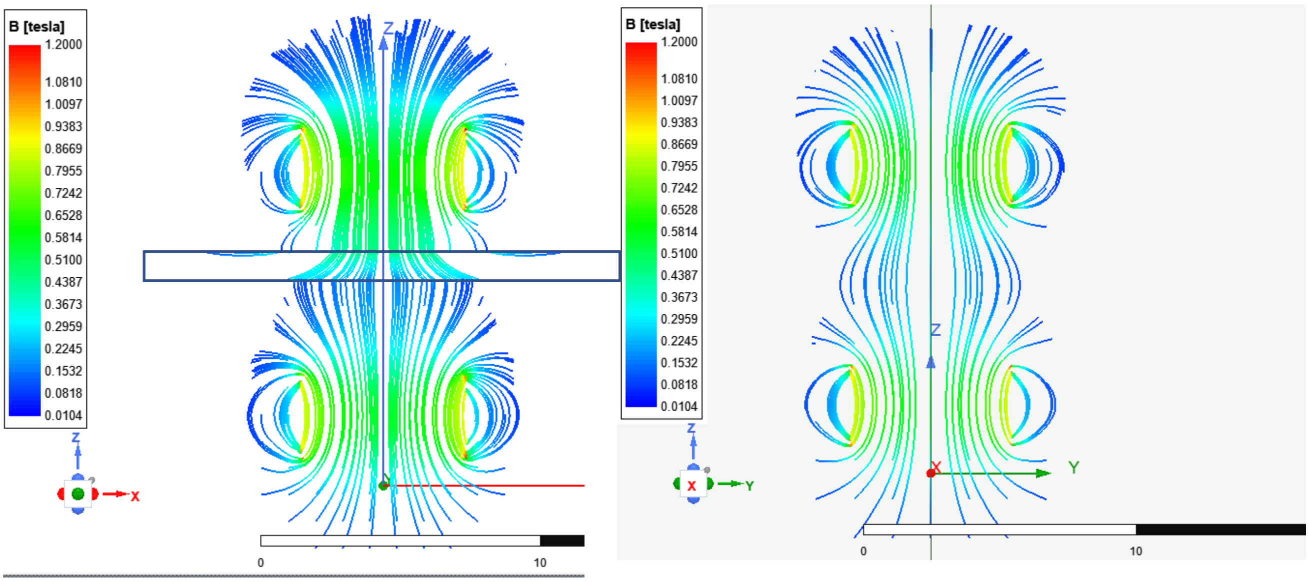
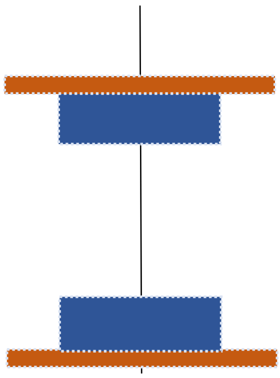


Fig. 7 Magnetic field streamline with (left) and without (right) steel plate

4.2 2 steel plate under 2 magnets

The permeability of the steel plates is 1000. Each steel plate is connected to a magnet (the nodes are merged). As they have a higher permeability than the magnets, the field lines are attracted to them. Therefore, the force between the 2 magnets is decreased. There are no insulators around the magnets in this configuration.



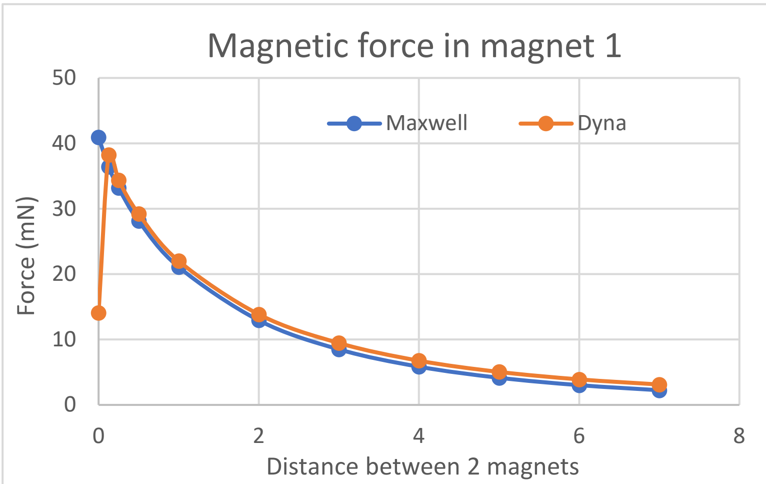


Fig. 8 Magnetic force in magnet 1 as a function of distance between 2 magnets

The magnetic force is increased as the distance between 2 magnets is decreased. The results obtained by Maxwell and LS-DYNA are in accordance, except when the distance is zero. The force in LS-DYNA is dramatically decreased while still increasing in Maxwell. This is due to the BEM faces which come in contact with one another and are therefore removed from the force computation (in effect, removing almost all interaction between the two magnets). The contact between magnets unprotected by a layer of insulator material will be the focus of future developments.

5 Movement of magnet

In LS-DYNA, the coupling between the electromagnetic and mechanical solvers is realized automatically via the magnetic forces. Figure 10 shows an example of the dynamics between 2 magnets attracting each other and coming in contact.

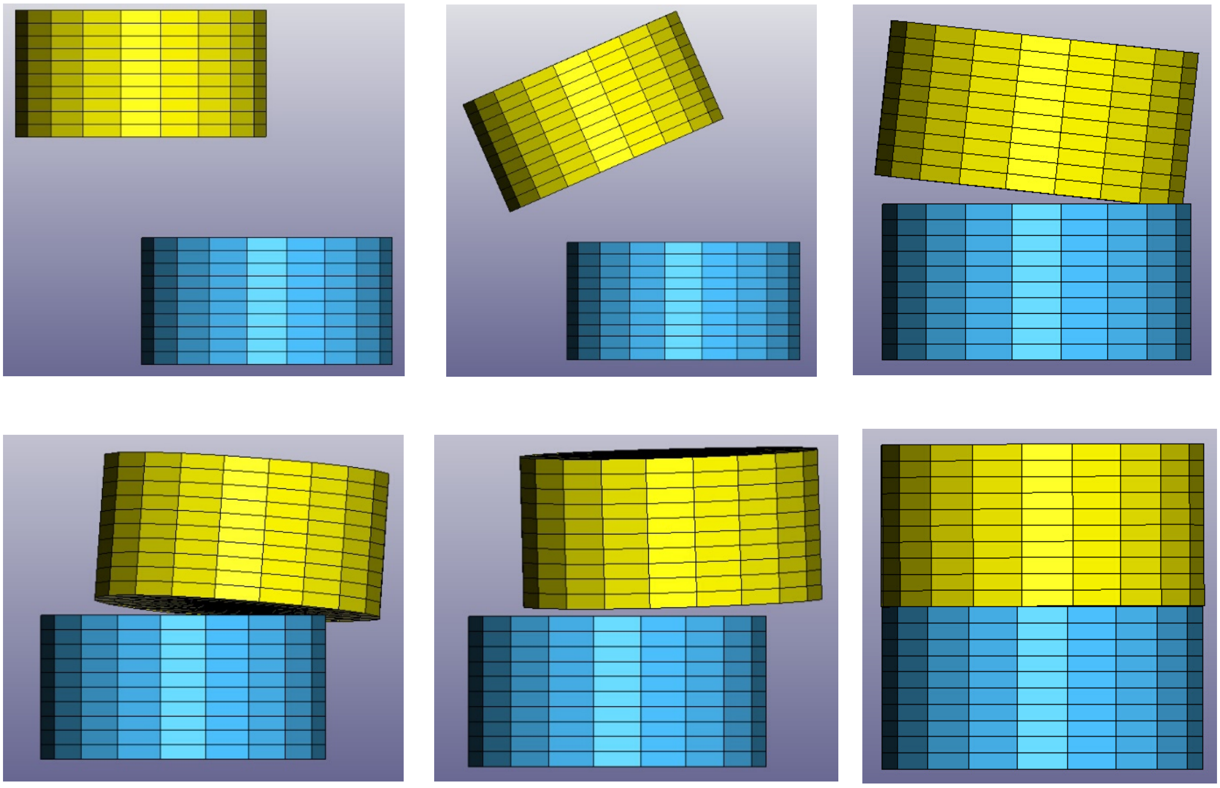


Fig. 9 Movement of 2 magnets. From left to right, up to down:

(a): Initial position	*(b): t=0.00379s*	*(c): t=0.00779s*
(d): t=0.01179s	*(e): t=0.01219s*	*(f): t=0.03999s*

As the two poles are in opposite position, the two magnets attract each other. When the 2 objects in contact, the magnetic force try to attempt the equilibrium position.

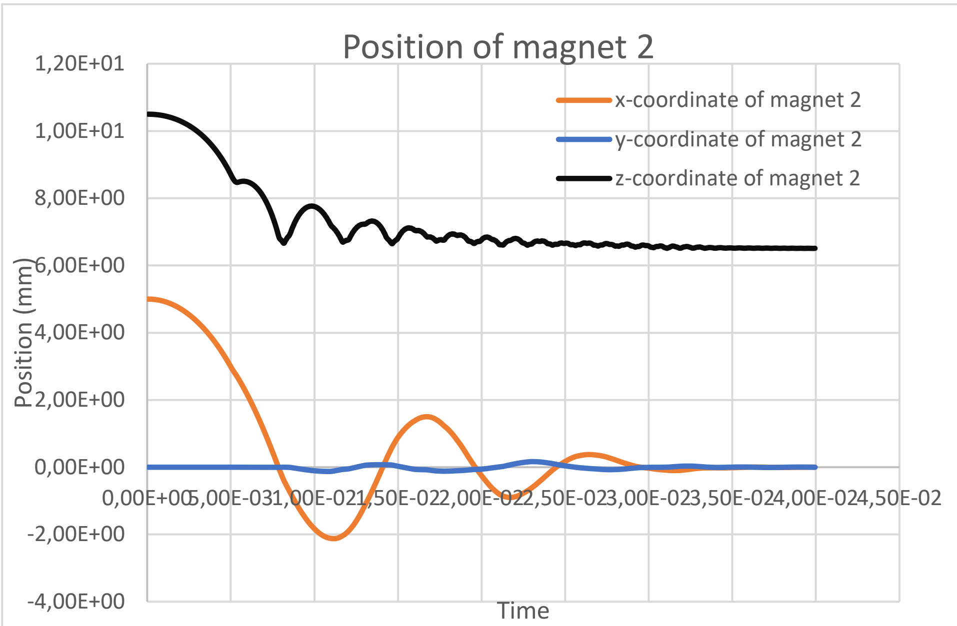


Fig. 10 Position of magnet 2

Figure 10 shows the absolute position of magnet 2. The position along z-axis and x-axis oscillates until the equilibrium position is reached. The magnetic force generating the dynamic of the magnet is presented in Figure 11. At equilibrium position, the force on x and y-axis is zero, the force on z-axis is almost constant.

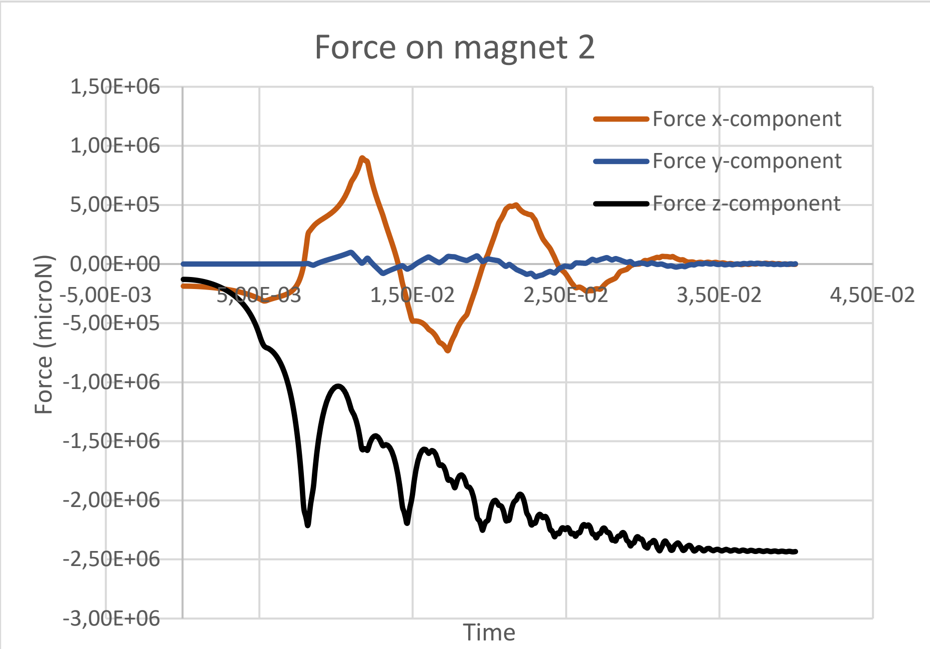


Fig. 11 Magnetic force on magnet 2

6 Summary

In this benchmark, the magnetic force calculation in LS-DYNA is compared to Maxwell in different configurations, giving comparable results with Maxwell in term of value and computational time. The configurations mentioned in this benchmark are: the two magnets at different distances, one magnet is rotated around an axis, a steel plate in the middle of the 2 magnets, and each magnet is associated with a steel plate. To calculate the magnetic force, LS-DYNA uses the Maxwell stress tensor while Maxwell uses the virtual work method. The two methods give very satisfying results even in the presence of a high permeability plate. LS-DYNA's unique capability of offering a fully coupled approach while removing the need to model the air is a powerful proposition to solve challenging problems involving electric motors, magnet clamps, moving coil meters, magnetic suspension devices and other similar applications involving moving permanent magnets.

7 Literature

[1] Thomas Rüberg, Lars Kielhorn, Jürgen Zechner, “FEM-BEM Coupling with Ferromagnetic Materials “, 12th European LS-DYNA Conference 2019, Koblenz, Germany

[2] Pierre L'Eplattenier, Iñaki Çaldichoury, “A BEM method for Electromagnetics in complex 3D geometries “, 38th International Conference on Boundary Elements and Other Mesh Reduction Methods Conference 21st to 23rd September 2015 New Forest, United Kingdom.

[3] ANSYS Maxwell 3D, Release 2021 R1, User's Guide, ANSYS Inc., 2021.

[4] François Henrotte and Kay Hameyer “A theory for Electromagnetic Force Formulas in Continuous Media”, IEEE Transactions on Magnetics, Vol 43, No. 4, 04/2007.