Whisker sensor based on magnetostrictive material modeling in dyna

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1 Introduction

Magnetostrictive whisker sensors have received increased attention. Compared to other types of whisker sensors, magnetostrictive whisker sensors have the advantage of working under static or low frequency conditions [1]. Thanks to these characteristics, whisker sensors have been used widely for tactile sensing in bionic robots, automatic vehicles and so forth [2].
The working principle of magnetostrictive whisker sensors relies on the modification of material permeability with an external applied stress. The permeability changes induce different values of linkage flux which can be measured by conventional magnetic field sensors like Hall sensors. The measured voltage gives information on the deflection due to the external applied stress.
In this paper, a whisker sensor is simulated using LS-DYNA implicit mechanical [3] and EM [4] solvers, with "magnetostrictive" non-linear B-H curves depending on the stress tensor. In the first part of the analysis an external load is considered as an initial condition in the implicit mechanical simulation. Once the resolution is done, the elemental stress tensor, the structure deformation and the final mesh position are compacted as an input and sent to the EM solver for a second analysis.
In the EM solver, to estimate the relative permeability function of stress, two methods are employed: firstly, from a given stress tensor, the equivalent Von Mises stress is used to estimate the relative permeability based on B-H experimental curves for different stress levels. This method does not consider the deflection direction and the mulitiaxial effect. To consider the deflection direction, another method is proposed based on state-of-the-art literature. It consists of transforming the stress tensor into an alternative expression that includes the magnetic field direction [5].

2 Sensor structure

A magnetostrictive whisker sensor [6] consists of four parts. The first part is a very thin and long cantilever subjected to a force causing a deflection. Magnetostrictive beams are bonded to the cantilever beam. A magnet provides a magnetic source and magnetic Hall sensors measuring the flux linkage.

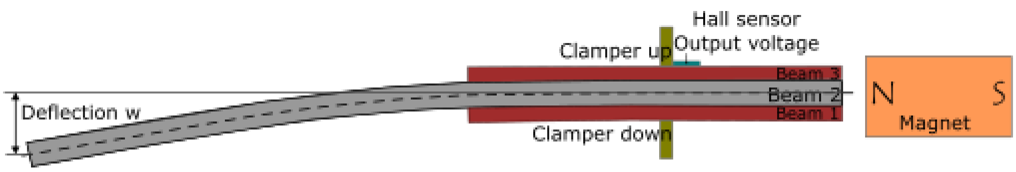

Fig. 1: Structure of magnetostrictive whisker sensor

2.1 Sensor geometry in LS-DYNA

The list of components of the whisker sensor is detailed in Table 1. As the structure is a thin beam, in the first test, a mesh with 5 layers for each cantilever has been used. The results obtained are close to another mesh with only 1 layer by considering **ELFORM**=-2 in **SECTION_SOLID**. As the computation time is 5 times faster with the second option, the mesh with one layer has been used for further tests.
Whisker sensors work under static and low frequency; to avoid dynamic noise, the LS-DYNA implicit solver is a better choice to simulate the deformation and obtain the stress tensor resulting from external loads. A data file (**dynain** file) containing this information can be inserted into an input deck in EM solver in the next simulation step.
In the implicit run, the two clampers up and down are considered, but in the second run, as no movement is considered, the two clampers are removed. Magnetic sensors are added in the mesh file to make the magnetic field measurement.

Component	Material	Modeling Approach	Dimensions (mm)
Magnetostrictive layer 1	Galfenol	Elastic body	30x4x0.2
Copper layer	Beryllium_bronze	Elastic body	80x4x0.3
Magnetostrictive layer 2	Galfenol	Elastic body	30x4x0.2
Magnet	NdFeB	Rigid body	8x4x3
Clampers	Steel	Rigid Body	4x4x2
Hall sensors		Rigid body	

Table 1: Whisker sensor model Components

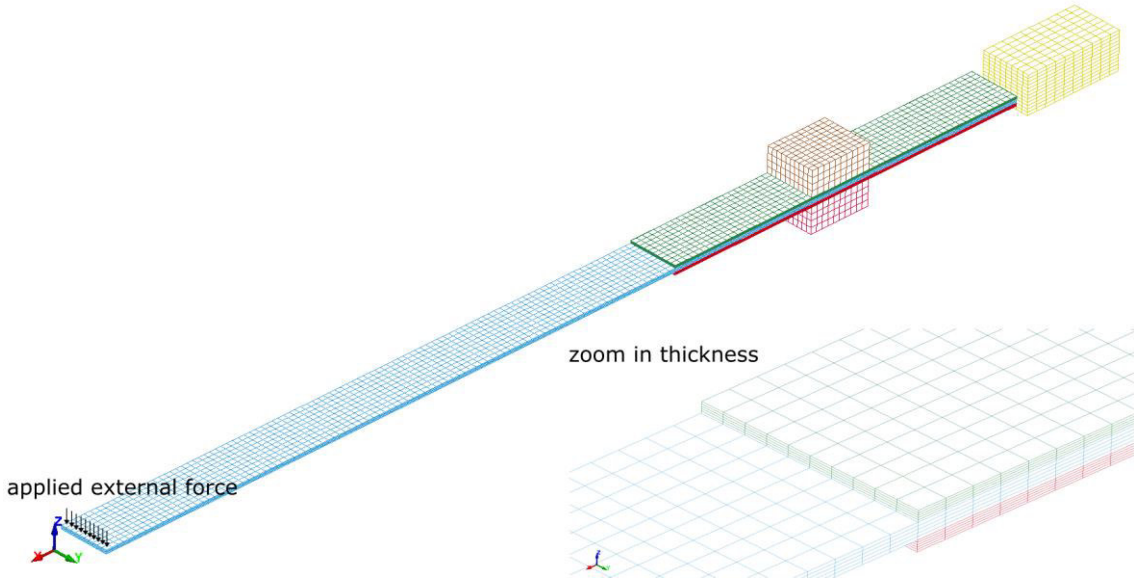

Fig. 2: Mesh of magnetostrictive whisker sensor in implicit run

2.2 Magnetostrictive modeling

The magnetostriction effect is defined as a change in shape subjected to the application of a magnetic field. The whisker sensors use the inverse magnetostrictive effect, also known as the Villari effect which implies change in the magnetic permeability of the material subjected to mechanical stress.

Various models have been proposed in the literature to investigate the coupled magneto-mechanical effects: strong coupling models consider the constitutive laws with magnetic field and stress, or with magnetic flux density and strain as state variables. Such methods are computationally expensive and complex in their implementation. In this work, a one-way decoupled approach is considered. Magnetic permeability modification and deformation due to external loads are not solved simultaneously but rather a twostep approach is considered with the mechanical analysis done in a first step, and the magneto strictive analysis done in a second step using the deformations obtained in the first part. Both steps use the same hexahedral mesh which avoids numerical errors that come from the projection of one field to another field.

In LS-DYNA, BH data curve given by users is interpolated by piecewise cubic function [7], which must retain continuous first-order derivation over the whole data set. The interpolated curve is smoother than the initial curve, giving a better convergence in BH non-linear characteristic cases. To assimilate the Villari effect, a family of experimental BH curves of magnetostrictive material subjected to different stresses is imported into LS-DYNA. With a given stress, the permeability is calculated in proportion between two closest stresses BH curve.

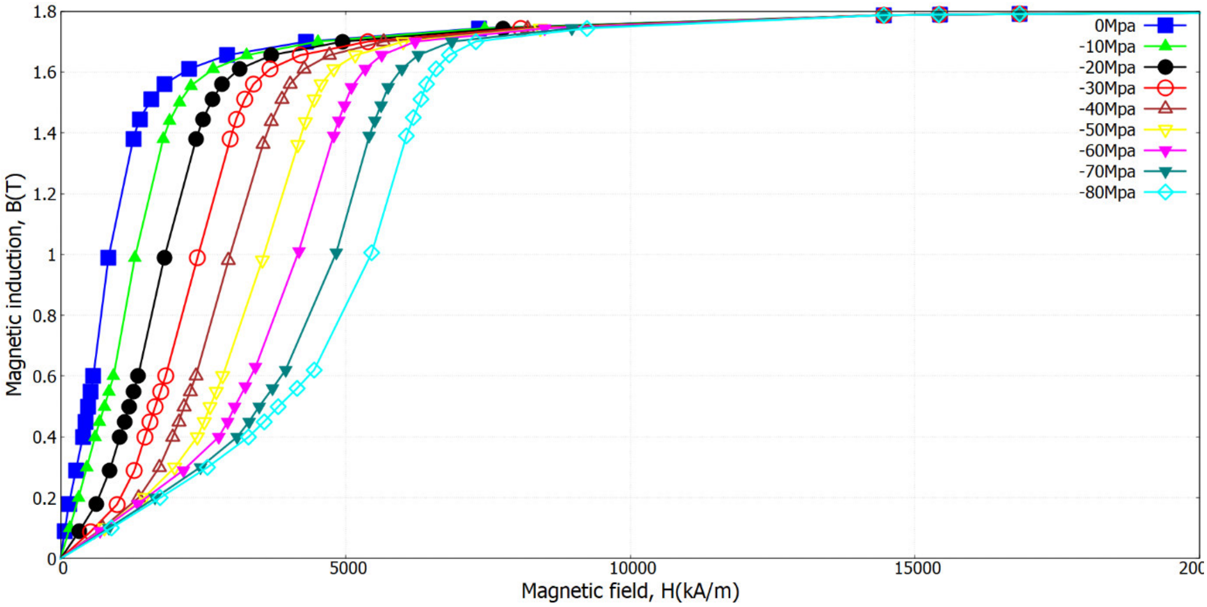

Fig. 3: Structure of magnetostrictive whisker sensor

Fig 3. shows the initial BH curve of Galfenol extracted from experimental points curves at different points [8]. In the LS-DYNA EM solver, the assimilated smoother curves will be created from the experimental curves with prolongation to saturation. These BH curves are utilized for our first simple approach whisker sensor case in which only Von Mises stress is considered, the multiaxial effect is neglected. The Von Mises stress is defined as following:

$$\sigma_{VM} = \sqrt{\left(\frac{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2}{2}\right)} \quad (1)$$

where σ_1, σ_2, σ_3 are the stress components following *x*, *y*, *z* direction respectively. From this formula, the multiaxial and shear effects are completely neglected. The sign of σ has no impact on σ_{VM}, using the formula (1), the magnetic permeability will be the same in both cases of compressive and tensile stress on bronze layer.

The second approach, more sophisticated, considers the multiaxial stress effects [9].

The flux density **B** is written as **B**=*B***b** where B is the magnitude and **b** is a unit vector. The stress tensor is transformed into an equivalent uniaxial stress which is parallel to the flux density $\boldsymbol{\sigma}_{eq} = \sigma_{\mathrm{eq}}\mathbf{b}\mathbf{b}^t$

The deviatoric part of stress is defined as: $\boldsymbol{d} = \boldsymbol{\sigma} - (1/3)(tr\ \boldsymbol{\sigma})\boldsymbol{I}$ (2)

From a family of experimental BH curves dependence on stress, at an arbitrary position, the permeability can be plotted as a function of stress. The parameter r is defined as the equivalent stress at which the permeability is at maximum. In the case of non-defined r, r is supposed to be +∞, the equivalent stress is simplified as:

$$\sigma_{eq} = \frac{3}{2}\mathbf{b}^t\boldsymbol{d}\mathbf{b} \quad (3)$$

In other cases, the equivalent stress is calculated as

$$\sigma_{eq} = \begin{cases} r - \sqrt{\left(\boldsymbol{b}^t\left(r\boldsymbol{I} - \frac{3}{2}\boldsymbol{d}\right)^2\boldsymbol{b}\right)}, \text{if } \boldsymbol{b}^t\boldsymbol{d}\boldsymbol{b} \le \frac{2r}{3} \\ r + \sqrt{\left(\boldsymbol{b}^t\left(r\boldsymbol{I} - \frac{3}{2}\boldsymbol{d}\right)^2\boldsymbol{b}\right)}, \text{otherwise.} \end{cases} \quad (4)$$

In this approach, we use the family of BH curves obtained from experimental measurement, which is presented in two figures, one corresponds to tensile stress, and another to compressive stress. The stress varies from -70MPa up to 45MPa, the slope of corresponding BH curve increases, therefore, the value of r should be more than 45 MPa, therefore r supposed to be +∞. It means that the equivalent stress will be calculated as in (4).

The width of the hysteresis loops in original curves [10] is very thin; in this work, we neglect the dissipative loss due to the hysteresis effect. Only one branch of the hysteresis cycle is considered. Like the last cases, all extracted point-to-point curves are approximated by splines curves to get smoother and saturation prolongation.

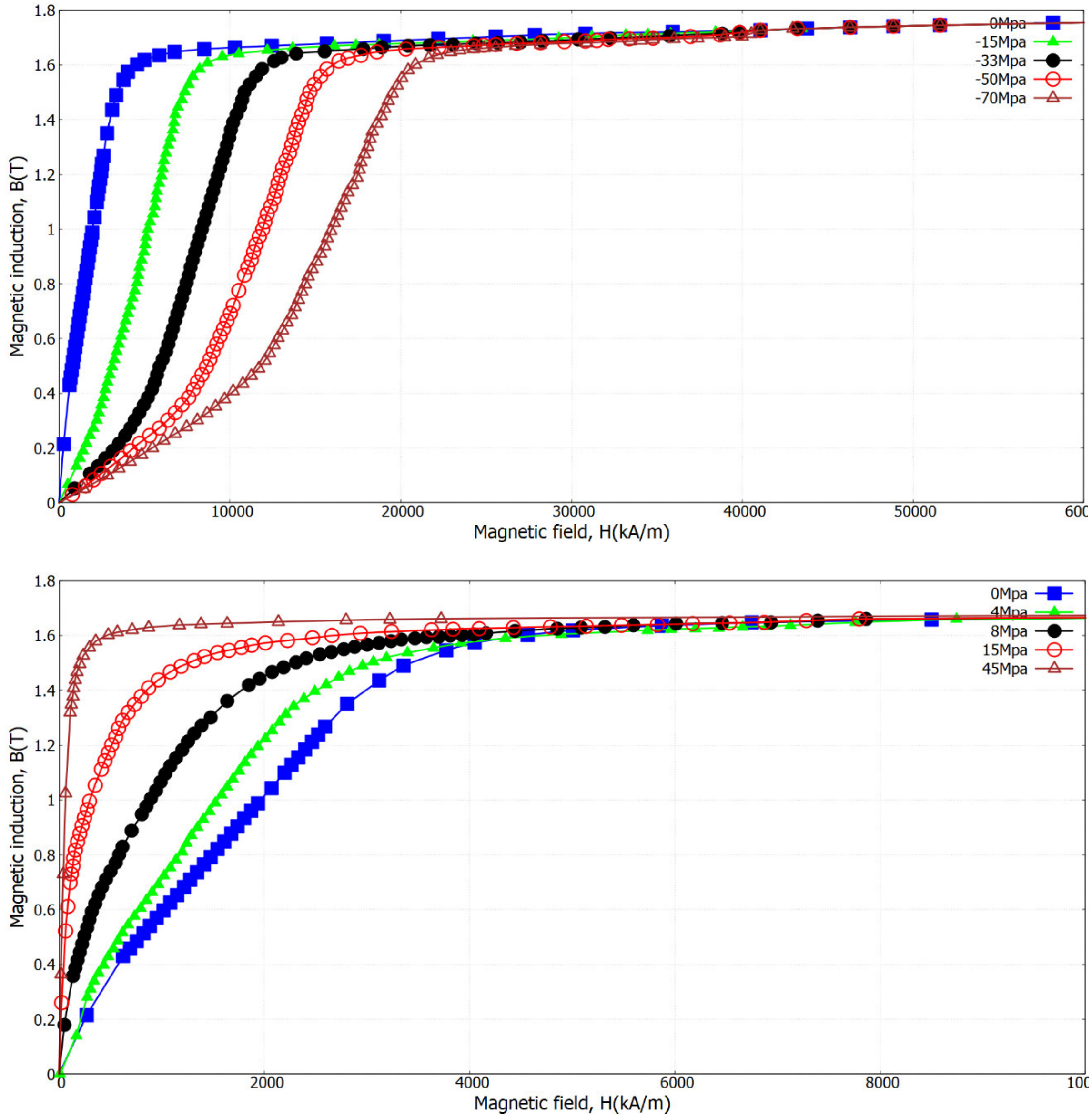

Fig. 4: Structure of magnetostrictive whisker sensor

Magnetostrictive behavior of Galfenol responds differently to the effect of uniaxial stress under compressive and tensile stress. As a result, the permeability modification in these two cases is expected to be different. Taking advantage of this difference, the whisker sensor could detect the two directions of deflection up and down.

3 Implicit Mechanical Solver

To estimate the permeability of each element of the Galfenol beam, the stress tensor must be calculated thanks to the mechanical solver. The two clamps up and down allow to guide the structure deformation only in deflection mode. A linear loading force curve is applied at the extremity of the berrylium-bronze beam. The final deformation is measured at 0.01s.

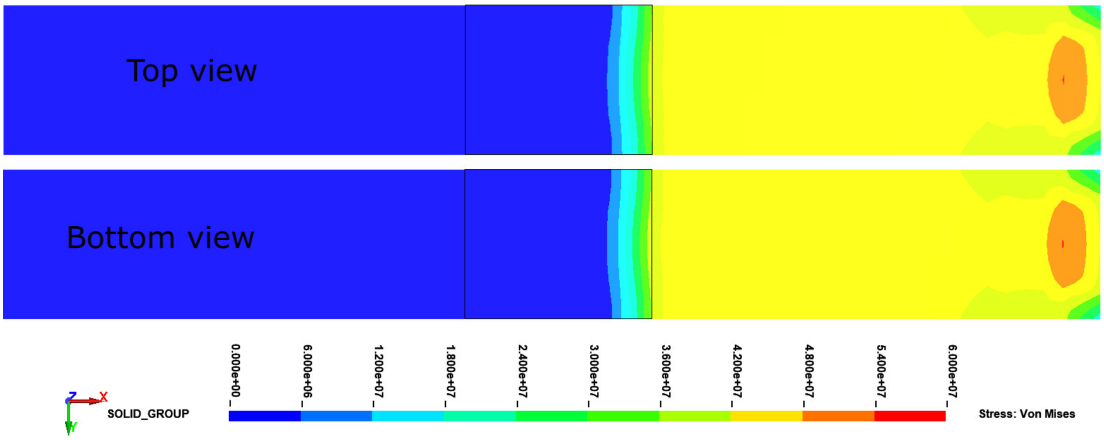

Fig. 5: Von Mises stress on the top and bottom layers

In the first approach, the Von Mises stress is considered. Fig. 5 shows the Von Mises stresses on the galfenol up and down layers. The stress distribution on the top and bottom layers is symmetrical in the first approach using Von Mises stress, but not in the second stress using equivalent stress formula.

4 Result

By adding a magnetic source, the two galfenol beams are subjected to a magnetic field. The magnet is polarized in *x*-direction; therefore, the magnetic field is principally along the *x*-direction. To detect the modification of the magnetic field due to the deflection, the Hall sensors must be put on the boundary between the clamps and the galfenol layers. This zone is the most sensitive to permeability modification, and therefore to the deflection. The Hall sensors measure the *z* component of the magnetic field in the galfenol layers.

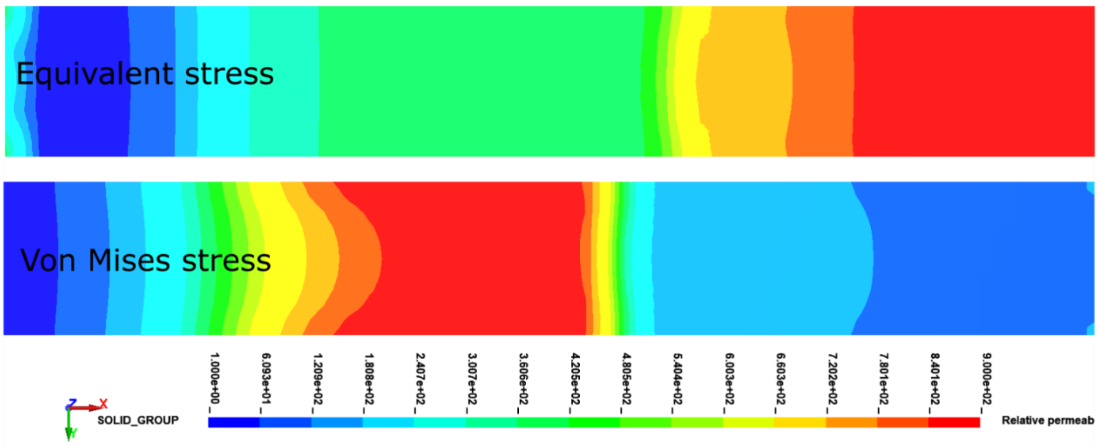

Fig. 6: Relative permeability in bottom layer with 2 approaches: Up: equivalent stress. Down: Von Mises stress.

The permeability in the Von Mises stress approach is symmetric between the two galfenol layers. Using the equivalent stress, the permeability is different from one layer to another layer, since it depends on the projection of the stress on the magnetic field direction. As the principal direction of the magnetic field is along *x*, the *x*-direction of the stress is similar to the permeability distribution. As the permeabilities in the two approches are quite different, the flux density distributions are not the same.
Fig. 7 and Fig. 8 shows the *x*-component of the flux density distribution of the top and bottom galfenol layers using Von Mises stress and equivalent stress. Using the equivalent stress, the response of the magnetic flux density is more accurate as the upper and down layers do not have the same stress due to the bronze layer deflection.

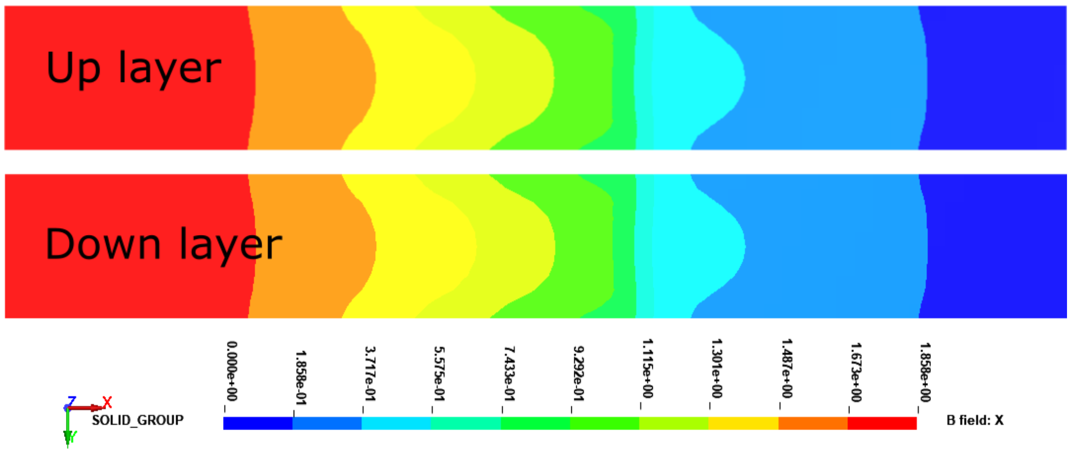

Fig. 7: X-component of flux density with Von Mises formula in up and down layer.

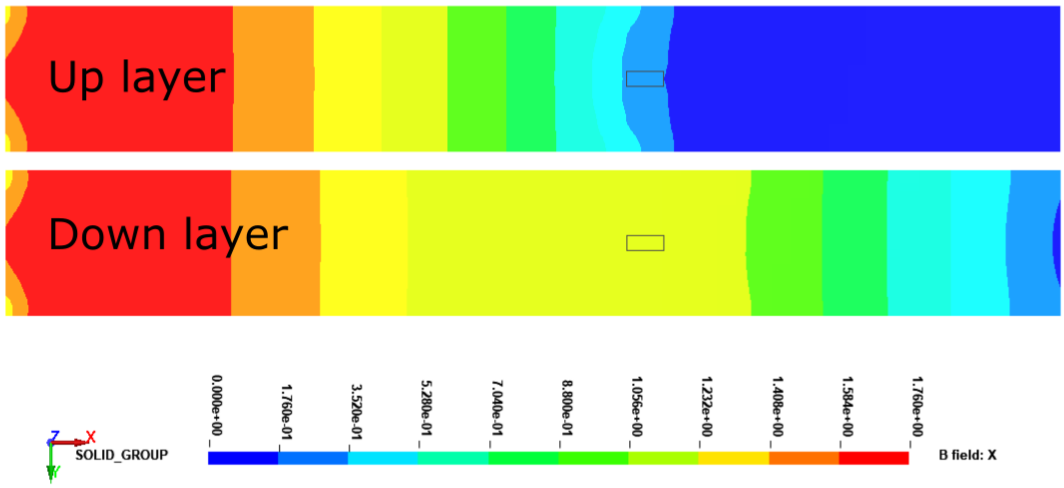

Fig. 8: X-component of flux density with equivalent stress formula in up and down layer.

Fig. 9 and Fig. 10 shows the *z*-component of the flux density. The *z*-component is lower than the *x*-component, but thanks to the *z*-component, the magnetic sensors can detect the permeability modification due to the deflection. Using Von Mises formula, the flux density value is expected to be the same at the top layer as at the bottom layer. Using the equivalent stress, the flux density is different between layers, as presented in Fig. 10

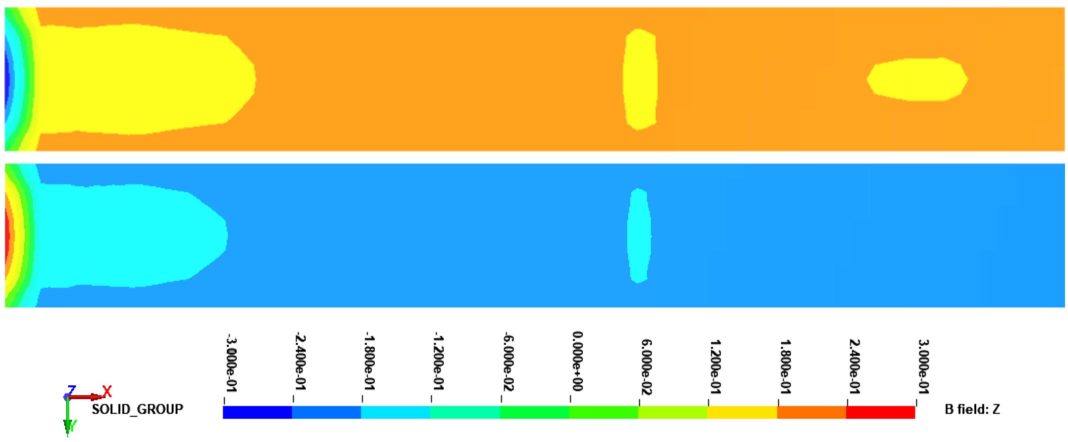

Fig. 9: Z-component of flux density with Von Mises formula in up and down layer.

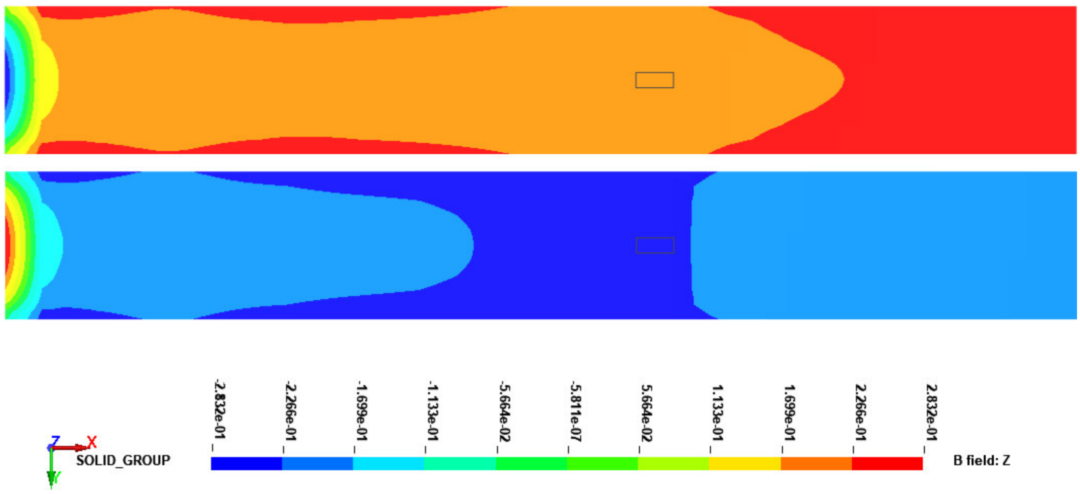

Fig. 10: Z-component of flux density with equivalent stress formula in up and down layer.

The deflection of the structure was observed to vary linearly with the magnitude of the externally applied forces. For each deflection value, magnetic sensors were used to measure the z-component of the magnetic flux density on both the upper and lower layers of the specimen.
The results obtained from the Von Mises stress formula are presented in Fig. 11. In this case, the z-magnetic flux density values on the upper and lower layers were found to be identical; therefore, only the data corresponding to the upper layer are shown. These findings confirm the linear dependence of the z-component of magnetic flux density on structural deflection. The application of the Von Mises stress formulation enabled effective characterization and simplification of the observed behavior.

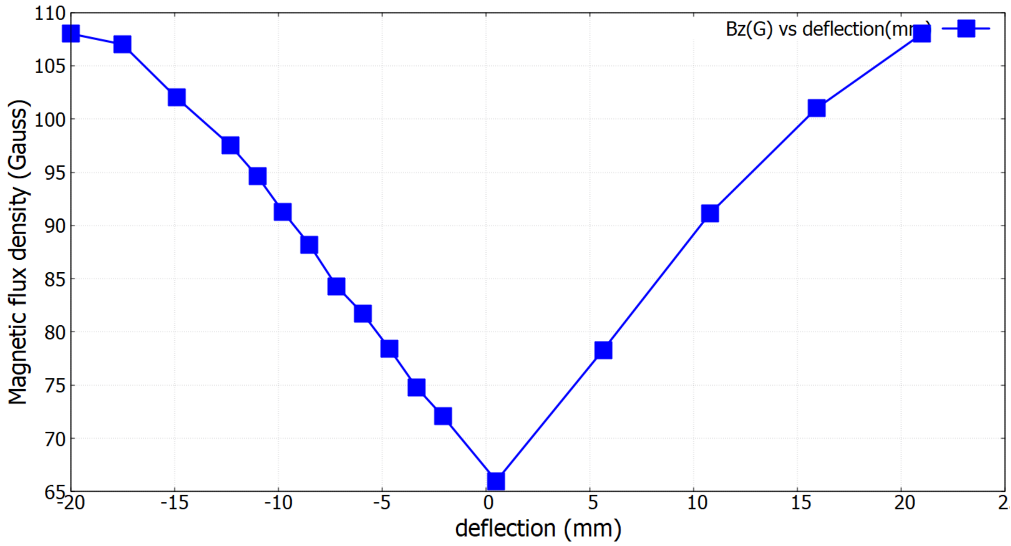

Fig. 11: Z-component of flux density as a function of bronze layer deflection.

We define $\Delta = B_z^1 - B_z^2$ where B_z^1, B_z^2 the z component of up and down layers respectively. Fig. 12 plot Δ as a function of the deflection, using Δ can detect if the external force is compressive of tensile. The simulation result is in good agreement with the experiment measurement in [5].

The equivalent stress is physically more accurate than the Von Mises stress, but it is more time consuming to obtain convergence. The final stiffness matrix is less symmetrical in the cases of the equivalent stress than the Von Mises stress. A non-physical test has been introduced by presenting the value of parameter r, the solution still achieves convergence with more iterations.

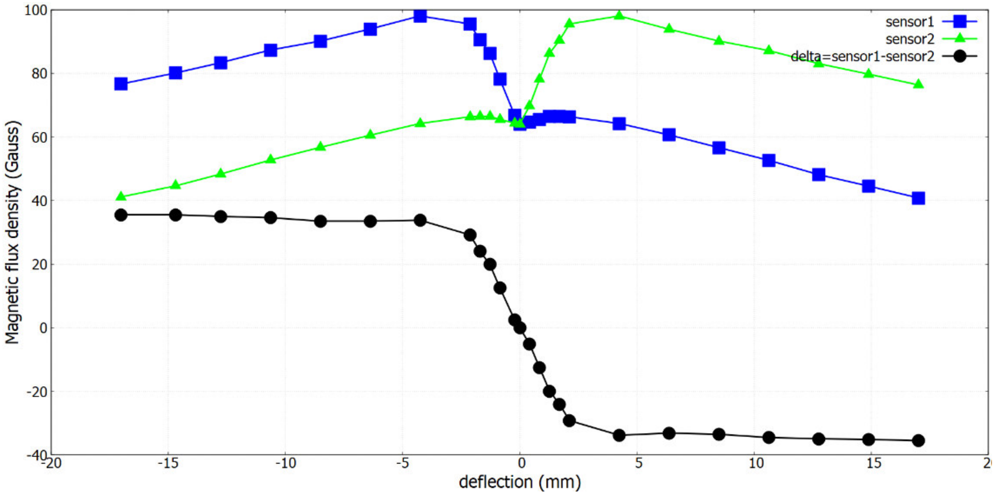

Fig. 12: Z-component of flux density in up and down layers as a function of bronze layer deflection.

5 Summary

A new possibility of magnetostrictive modeling is proposed in LS-DYNA. In this new development, with a very simplified assumption, a Von Mises stress is used, this approach can firstly detect the impact of magnetostrictive phenomenon. The second approach is more accurate using equivalent stress. Magnetic field prediction is feasible using uniaxial measurements but requires data under both compressive and tensile stress conditions. However, this method is more time-consuming than the initial approach and poses greater challenges in achieving convergence.

The first perspective of this work is testing another device based on inverse magnetostrictive phenomenon with another family of BH curves which introduce the parameter r. The computational cost, the complexity of the solver must be checked.

6 Literature

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