MPS Analysis of Magneto-Rheological Fluid Magnetization Anisotropies

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Giovanni Imberti
DIMEAS
Politecnico di Torino
ITALY
giovanni.imberti@polito.it

Henrique de Carvalho Pinheiro
DIMEAS
Politecnico di Torino
ITALY
henrique.decarvalho@polito.it

Massimiliana Carello
DIMEAS
Politecnico di Torino
ITALY
massimiliana.carello@polito.it

***Abstract* — Magneto-Rheological Fluid (MRF) started to be used for industrial applications in the last 20 years, and, from that moment on, innovative uses have been evaluated for different applications to exploit its characteristic of changing yield stress as a function of the magnetic field applied. The interest of studying the fluid-dynamic behavior of the material and the different ways the fluid could be magnetized, bringing to anisotropy in its performance has led to looking for innovative simulation strategies and approach, for obtaining a more realistic result.**

The paper proposes an Electro-Thermal equivalence for performing a mapping of the Magneto-Rheological Fluid put in a gap. The model, developed with the software ParticleWoks, allows to visualize the effects of a non-uniform magnetization around the fluid and how much this affects the global performance of the application. The model also allows other simulations to analyze more realistic situations as having air bubbles inside the fluid and how much that affects the final global performance.

The model proposed has been applied to an innovative MRF based Zero-Emissions Braking System and the output to be evaluated is the peak braking torque available at the system once the magnetization is reached. The goal is to obtain a consistent Electro-Thermal Validation of the solution developed and the braking torque being compliant with a traditional disc brake.

Keywords—MPS, Electro-Thermal Equivalence, Magneto-Rheological Fluid, Zero-Emissions Braking.

I. Introduction

The automotive industry is going through a new era, in which it is fundamental to reduce the environmental impact of the vehicle using electric motors [1, 2], innovative materials [3] and alternative fuels [4, 5]. Although, another problem that is going to be discussed more soon regards the reduction of secondary pollutants. In particular, the new euro 7 normative underlines the effects on the emissions coming from some vehicles sub-components, as the tires and most importantly the brakes [6, 7]. For this reason innovative zero-emissions braking systems have been developing as presented in previous research work [8]. The solution proposed combines a MRF based braking system with an Electric Motor (EM) Regenerative Braking capability. MR braking seems to be the more suitable in terms of torque capabilities and geometrical limits for a vehicle and for this reason an innovative design has been developed and virtually validated.

The MRF is an innovative fluid capable of changing its yield characteristic according to the different magnetic field applied on it. For this reason, it is hard to simulate the behaviour of the fluid using directly a multi-physics software and although a strategy has been previously defined for obtaining a first preliminary design capable of reaching the project targets [9], it is important to evaluate some of the characteristics of the non-uniformity of the fluid, specifically the different magnetisation of it in different geometrical points.

In this article an anisotropic analysis has been performed, following the steps:

- Definition of the Geometrical Model to be analysed.
- Development of the Electro-Thermal (ET) Equivalence
- Validation of the Electro-Thermal Equivalence with a defined Model
- Analysis of a non-uniformly magnetised fluid
- Understanding of the effects of a non-ideal magnetisation.

The results of the model will be commented and also the effectiveness of the use of a Moving Particle Simulation Method (MPS) rather than a traditional Meshing model will be described.

II. Characteristics of an MPS Analysis

The software used during the analysis is ParticleWorks and is based on a MPS method. This method solves the Navier-Stokes Equations with a deterministic Lagrangian Approach

[10]. The governing equations are discretized by particle interaction models [11].

The characteristics of MPS based software is the capability of obtaining reliable results in a reduced time, because of the different approach in simulating the particles interaction, that is macroscopic and deterministic.

The model has to be defined introducing a domain area in which the fluid is limited to flow and all the boundaries are designed and imported from a CAD file. In fact, another characteristic of the MPS strategy is its connection on the geometry of the structures and their motion. It is preferrable to evaluate a defined portion of a fixed fluid, monitoring its behaviour interacting with the different components.

Another effect that should be taken into consideration is the particle density and dimension. The computational operation evaluates the neighbouring particles area around a point in order to compute the specific value of the point itself through a Kernel function. For this reason, the density discretization of the particle is a pivotal value for obtaining a sufficiently accurate result.

III. Model Description

A. *Geometrical Definition*

Once defined the way the simulation methodology has been introduced, it is possible to describe the geometry and the model that has been developed.

For the simulation of the fluid-dynamic behaviour of the solution chosen, starting from the geometry descripted in the previous works [9], it is fundamental to simulate the geometrical area around the fluid composed by, as it is possible to see in Fig. 1, the rotor and its protuberance (1-4), the braking system stator (3) and the magnetisation source that is the coil attached to the stator (5).

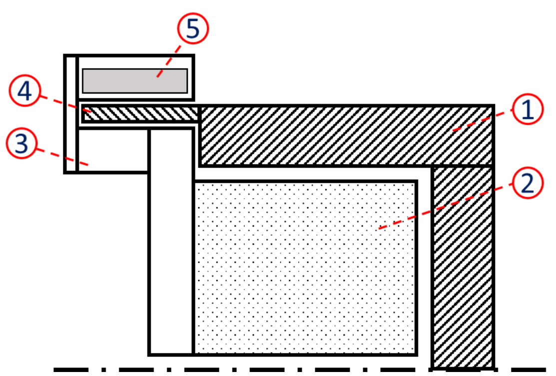

Fig. 1 Schematic Layout of the Innovative Braking Solution [9]

Starting from the geometry, it has been decided, for optimising the computation and reducing the simulation times, to perform a simulation of such a small section of the MR Brake proposed to be considered it linear rather than circular. In fact, because of the approach and the limitation of the motion of the fluid around a given domain, it is not needed to simulate more than that.

As it is possible to see in Fig. 2, for representing the behaviour of the rotor inside a fixed linear part of the stator it has been proposed a linear rotor part equal to the section of the rotor, long enough to simulate the behaviour of the real application. The stator, designed as the periodic linear section of the whole component with a width of 10mm, is fixed and the fluid – whose colour is magenta in Fig. 2 – is limited to the domain defined around the stator area.

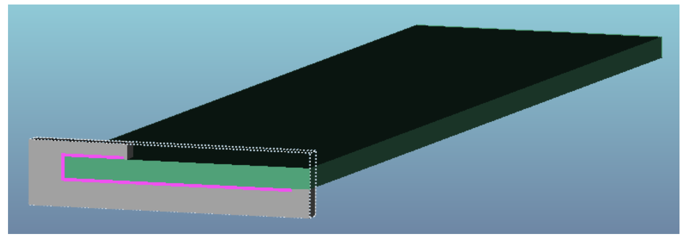

Fig. 2 Model Geometrical Layout

For defining the motion of the rotor, it has been decided to report a linear speed equal to a vehicle speed of 130 km/h, in order to simulate the behaviour of a limit braking manoeuvre. Once the computation is concluded, the results would be converted to evaluate the full braking system behaviour rather than the partial one.
The lateral walls around the fluid were defined as boundaries with "periodic" feature, meaning that the particles flowing outward of the control area are then reintroduced in the opposite boundary with the same physical characteristics.
It has also been important to generate virtual volumes around the MRF for representing a punctual thermal source capable of modifying the thermal behaviour of the fluid itself. The strategy has been implemented so that it will be possible to map the fluid and creating a similar thermal distribution to the one obtained through magnetization for obtaining a coherent Electro-Thermal equivalence.

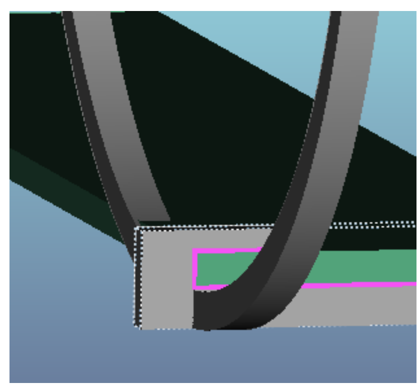

Fig. 3 Thermal Sources Added to the Model

In Fig. 3 is possible to visualize one of the thermal sources generated. The effects of the geometry shown is just focused on having a fixed value of temperature and heating the area around it. There is no interaction with the fluid unless a heat exchange. The capability of this strategy also allows to obtain a transient behaviour in which the variation of the fluid yield characteristic, connected to the thermal variation, changes because of the starting position of the thermal sources, that, at the beginning of the simulation are far from the fluid and then are attached to it, generating a heat exchange.

B. MRF Modelling

In order to obtain and validate a consistent electro-thermal equivalence, it is important to generate an equivalent model based just on the specific characteristics of the material and then make the equivalent thermal equation converge to the result.

1) Bingham Model

For defining the behaviour of the MRF and validating the Electro-Thermal Equivalence it is important to analyse at least two points around its Yield curve evaluated varying the Magnetic field applied, as shown in Fig. 4.

The points analysed are at the maximum magnetization, in order to evaluate the maximum braking strength of the braking solution, and in a condition of just rolling resistance, in which no magnetic field is applied.

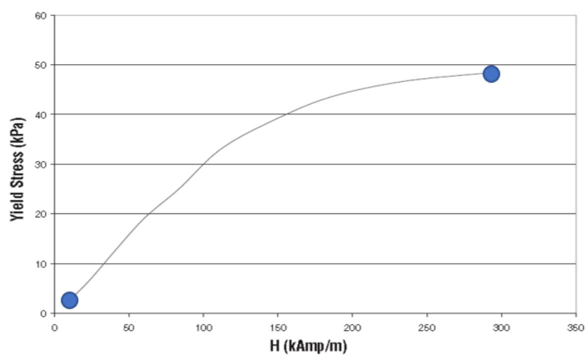

Fig. 4 Yield Stress vs. Magnetic Field - Points Analyzed MRF-132DG [12]

The two points on the diagram in Fig. 4 have been defined using a Bingham Model for Non-Newtonian Fluid inside the software ParticleWorks, using the parameters obtained by the datasheet of the MRF produced and sold by Lord ltd [12].

The results obtained using the MPS analysis have also been compared to the one obtained using a CFD analysis and reported in the previous work [9].

2) Equivalent Thermal Comparison

In order to represent the changes in the fluid behaviour varying the magnetic field applied, it has been decided to, using the software capabilities of defining a user-imposed function for the variation of the kinematic viscosity, iteratively generate a function capable of following the path of the MRF behaviour once that a magnetic field is applied.

After multiple iterations, the most suitable function chosen is reported in Eq. 1:

$$K_v = (0.00009T) + 3 \cdot 10^{-5} \tag{1}$$

Where:

- K_v is the kinematic viscosity.
- T is the Temperature in °C.

It is interesting to underline that, in order to maintaining the equation nearer to a real behaviour rather than just being a simulation trickery, it has been decided to use the real kinematic viscosity of the MRF as the added coefficient not function of the thermal parameter. In this way, since, at the beginning of the simulation the MRF temperature has been imposed as equal to 0°C at which no effects on the equation could be visible, the fluid would have been the real kinematic behaviour.

C. Thermal Model Peculiarities

Using an Electro-Thermal equivalence is a simulation strategy used to obtain a model capable of evaluating in a more realistic way the results coming off a simulation previously validated using a realer model just representing a steady-state behaviour of the fluid itself. From literature it is possible to find different examples of how a thermal equivalence is an interesting way to evaluate non-conventional characteristics to be exposed and analysed [13, 14].

From a pure physical point of view, although, the representation has some limits not to be forgotten that limits the way in which the results could be analysed. In particular:

- Using the Temperature as a Variable
- The Specific Heat of the Walls
- Using the Kinematic Viscosity as an equivalent behaviour

1) Using the Temperature as a Variable

Having the T as the variable of the function determines that the variation of it is not only coming from the external walls having fixed input, but also from physical parameters. For example, starting with a T=0°C at the beginning of the simulation, it happens that, because of rotation, the T reaches 40°C before activating the thermal walls. For this reason, it is important to create functions in which the Temperature needed for peaking the kinematic viscosity is 1000 times bigger than the working temperature, otherwise it will be impossible to visualise the effects of the defined function.

2) Specific Heat of the Walls

The time response of the electro-magnetic effects is immediate. For this reason, in order to consider the results obtained in a transient simulation, the specific heat should be lowered and put equal to 1 J/kgK. The interaction between the walls and the thermal volumes is something realistic also in terms of thermal distribution on the fluid, that has to be, once the model is validated, equal to the magnetisation map of the MRF itself. For maintaining limited the number of degree-of-freedom for modulating the behaviour of the fluid it has been decided to keep fixed to 1 J/kgK.

3) Use of the Kinematic Viscosity

It is fundamental to remember that the kinematic viscosity does not imply in the real behaviour of the magneto-rheological fluid, as its characteristics does not depend on the T, while the kinematic viscosity is a function of the thermal behaviour. As it has been described by Olabi [15] the resistance created on a MRF depends on the way the particles inside the fluid are magnetised and in which way the chains, that follow the magnetic fields line, are generated. The effects, furthermore, cannot be represented through a function of the kinematic viscosity. For this reason, the validation of the function has been done taking into analysis the effects of the function, as the force acting on the rotor, rather than the kinematic viscosity, which has zero variation during a steady-state.

IV. Results

The first model to be analysed is the one in which the MRF has been defined using the Bingham Model descripted in III.B.1), that has been also compared to the results obtained with the same material model using a CFD software and presented by [9]. The result obtained is very similar and the two different analyses converge to a value that satisfies the expectations of the design-phase.

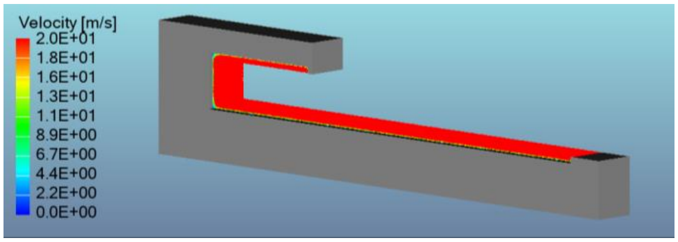

Fig. 5 Velocity Layout on the MRF - Bingham Model

In Fig. 5 it is possible to visualize the result obtained in term of speed in the steady-state analysis using the Bingham Model.

A. Particle Size Sensitivity Analysis

In an MPS simulation the particle dimension is an important aspect to be taken into consideration in order to evaluate the sensitivity of the results obtained. For this reason, because of the small gap in which the MRF is put, it has been decided to choose two particle measures of 0.15mm or 0.2mm. For computational reasons, it is impossible to visualise effects on the particles once that there are less than 7 layers of elements.

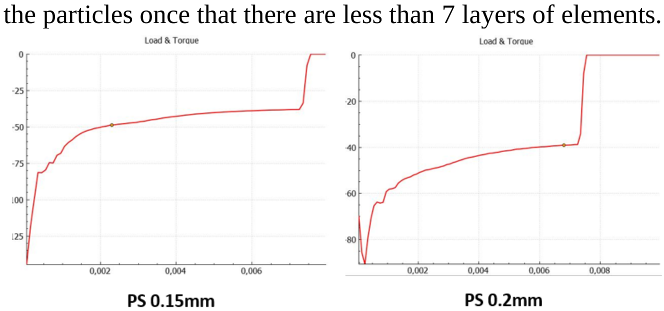

Fig. 6 Sensitivity Analysis on Particle Dimension

As it is possible to see in Fig. 6, there is not a real difference in results obtained between the two analyses. For this reason, the next simulations have been performed using a particle size equal to 0.2mm as the number of analysed elements is reduced, minimising the computational times, maintaining a consistent reliability of the result.

B. Electro-Thermal Validation

Once the Electro-Thermal Model for the fluid has been used, the validation phase of the kinematic viscosity equation with the Bingham model results is crucial for further analysing the fluid anisotropies.

The results shown in Fig. 7 describe as in terms of output forces, although the results converge in different ways, the steady-state result is very similar and reported in Tab. 1. The same has been done when no magnetic field is applied.

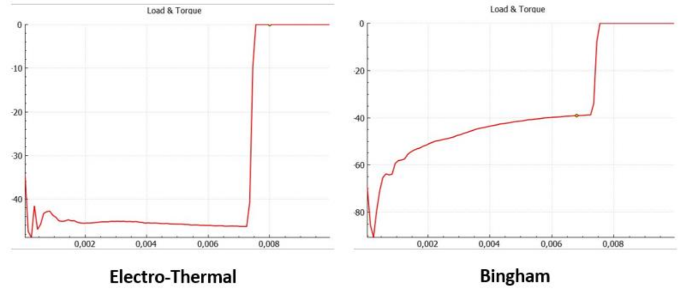

Fig. 7 Electro-Thermal vs Bingham Comparison – Max Strength

The comparison between the two models allows to ensure the consistency of the behaviour of the defined function. The force result obtained through the thermal validation reaches 43 N, rather than 41 N once the stabilisation is reached. The same equivalent validation has been done at an equivalent zero magnetic field applied to the fluid, obtaining 2.4 N for the Electro-Thermal comparison rather than 1.5 N for the modified Bingham.

Tab. 1 Electro-Thermal vs Bingham - Model Forces Validation

Condition	Bingham Force (N)	ET Force (N)
With magnetic field	41	43
Zero magnetic field	1.5	2.4

C. Electro-Thermal Model – Variable Magnetic Field

Once the Electro-Thermal Equivalence is confirmed in terms of output results, it is possible to customize the model in order to obtain a modulation of the temperatures inside the fluid, so that is possible to evaluate the different behaviours and results of the MRF with a non-uniform magnetization.

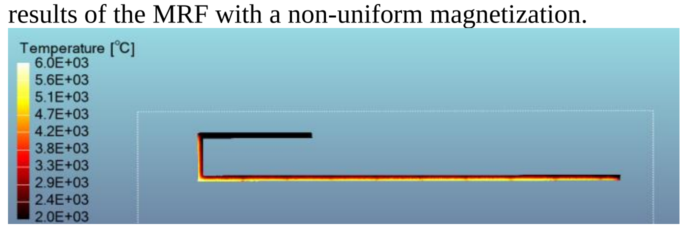

Fig. 8 Temperature Layout in the MRF

For doing so, multiple simulations have been developed for obtaining a thermal mapping coherent with the magnetic field acting on the fluid, obtained from Altair Flux and reported in previous analyses [9]. The temperature layout is then the one depicted in Fig. 8, where it is possible to see that the thermal values are coherent in scale to the values defined by the MRF producer in Fig. 4.

According to the results obtained in Fig. 9, the mapping is sufficiently coherent to the magnetization obtained during Electro-Magnetic Simulations

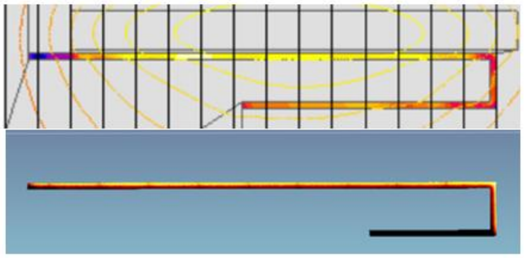

Fig. 9 Fluid Magnetization vs Temperature

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Using a transient simulation, for visualising the effects of the ET equivalence both at zero-magnetic field and when the strength is maximum.

The expected results regard the reduction of the available maximum resistive force once the model evaluates a non-homogeneous magnetization.

In fact, as it is possible to see from Fig. 10, the temperature varies as a function of time and once the temperature volumes have been attached to the stator (after 0.003s) the fluid temperature starts growing.

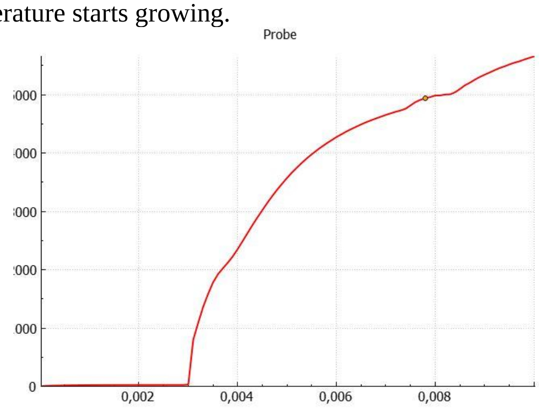

Fig. 10 MRF Temperature in transient non-uniform simulation

From the force curve depicted in Fig. 11, it is possible to underline the strong effect of the material characteristics variations once that the thermal model starts working (after 0.003s).

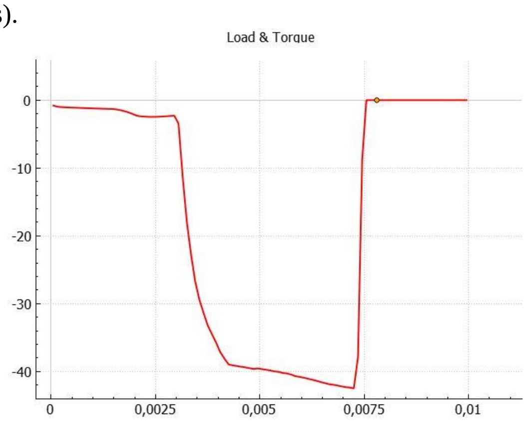

Fig. 11 Resistive Force on the Rotor in transient non-uniform simulation

It is possible to see in the first part of the simulation how the thermal model effect is negligible, while, running the simulation, the resistive force acting on the rotor starts growing as a function of the temperature growth, reaching, after 0.0035s its stabilization and a value equal to 38 N, representing a force reduction respect the state in which the MRF has been considered fully magnetized, in an ideal way.

After the first stabilization, it is possible to understand, comparing the two diagrams of Fig. 10 and Fig. 11 that the temperature does not stop growing inside the fluid. The reason is connected to the physical effect generated by the kinetic viscosity. In fact, K_C is a parameter varying with the temperature and able to generate more friction between the fluid when growing. The result is that the higher the generated force, the higher will be the energy dissipation due to frictional effects. For this reason, automatically in the simulation the force will continuously grow coupled with the T growth.

This effect is a limitation for the model, and it has been already introduced in paragraph III.C.3). It is pivotal not to forget this effect analyzing the results obtained in term of resistive force.

In fact, the resistive force tends to stabilize and then starts growing once the superposition effect of the growing of the K_C and T starts combining. The result is, for this reason, reliable only in the first ms after the forced thermal variation. The same behaviour, as the fluid characteristic is defined in the same way, is also visible at the beginning of the simulation, in which the force makes a sort of step after 0.002s of simulation.

Conclusions

In conclusion, the study proposes an Electro-Thermal Equivalence for simulating in a realer way the behaviour of a magnetized MRF, using a MPS analysis.

The obtained results are comparable to the ones obtained using a CFD analysis in a reduced amount of time.

The use of an Electro-Thermal Equivalence allows to perform interesting analysis and evaluates how much of reduction can be obtained with a not fully magnetized MRF, but there are important model potential issues to be taken into consideration:

- Temperature scale should be controlled for avoiding the superposition of natural temperature growth with the forced one used for evaluating the model.
- Thermal Conductivity of the walls around the fluid could be an issue if absorbs too much of the heat transmitted.
- The output of the simulation are reliable but only for a reduced amount of iteration because of the superposition between the growth of the temperature and of the kinematic coefficient.

The partial magnetization effect is visible and correspond to a reduction around 8% of the maximum available Force when the MRF is fully magnetized.

The MPS simulation strategy allows to reduce the simulation times respect a traditional CFD solver of about 75% and, in this way, it is possible to perform multiple simulations that allows to define a realistic correlation function between the T and K_C, but also to determine a more precise mapping of the fluid for obtaining a temperature around the fluid as similar as possible to the one defined during the Electro-Magnetic Simulations.

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