A Magneto-Rheological Brake Excited by Permanent Magnets

Antonino Musolino [1], Marco Raugi [1], Rocco Rizzo [1], Luca Sani [1], and Efrén Diez-Jimenez [2]

[1] Department of Energy and Systems Engineering
University of Pisa, Pisa, 56122, Italy
antonino.musolino@unipi.it, marco.raugi@unipi.it, rocco.rizzo@unipi.it, luca.sani@dsea.unipi.it

[2] Mechanical Engineering Area
University of Alcalá, Alcalà de Henares, 28801, Spain
Efren.diez@uah.es

Abstract **─** In this paper an innovative brake, based on magneto-rheological fluids, is described. A system of Permanent Magnets, properly arranged in the device, has been designed to maximize the excitation field inside the fluid. The system has been analyzed by means of a 3D FEM code. The results in terms of magnetic flux density inside the fluid and the braking torque have been discussed. Furthermore, the magnetic torque necessary to perform the brake actuation has been calculated. Finally, some preliminary measurements on a prototype have been performed.

Index Terms **─** FEM, Magneto-Rheological Brake, Permanent Magnets.

I. INTRODUCTION

Magneto-Rheological Fluids (MRFs) are synthetic oil-based or water-based suspensions of magnetically polarizable micro-particles, capable of changing their rheological behavior as a function of the intensity of an external magnetic field [1]. In fact, the micro-sized ferromagnetic particles, dispersed inside the MRF, align themselves along the direction of the magnetic field, allowing a rapid and reversible transition from a liquid to a near-solid state. By removing the magnetic field, these fluids can return to their liquid state in a very short time (15-20 *ms*), being the phenomenon perfectly reversible [2]. MRF-based devices have been developed since the end of 1940s [3], when the first MRF actuator was presented. The main applications are in dampers in the automotive and aerospace industry [4]. Also, they can be found in finishing processes for optical lens, waveguides, hard disk, and so forth [5, 6].

As for magneto-rheological brakes, many solutions have been presented in past years [7-11]. The use of MRF in such devices w.r.t. conventional mechanical or electrodynamic brake, allows smooth and steady transmissible/braking torque with many applications like in space, automotive industry, robotics, industrial machines or gym/fitness equipment. Furthermore, the MRF-based brakes do not exert axial load and they can be easily controlled by tuning the magnetic field in the fluid.

Currently, most of the solutions use conventional wired electromagnets to activate the fluid. Other designs use permanent magnets (PMs) as excitation source, but very few of them have been developed till now [12-14]. There are also solutions that combines PM-coil exciter in order to control the magnetic field inside the fluid. Purely PM-based devices can be found in [15, 16]; while in [17, 18], a hybrid Electrodynamic/MRF based clutch has been described.

In the present paper, a new MRF-based brake is proposed. It uses a system of Permanent Magnets to excite the fluid. The braking torque can be controlled by rotating the PMs in the circumferential direction by an angle of 90°. The device has been analyzed by using a 3D magnetic FEM code [19]. The results in terms of magnetic flux density inside the fluid and braking torque have been discussed. Furthermore, the magnetic torque necessary to perform the brake activation has been calculated. Finally, some very preliminary measurements on a prototype have been performed.

II. THE PROPOSED BRAKE

A. The fluid characteristics

In the proposed device, the magnetorheological fluid MRF140CG has been used. It is produced by Lord Corporation, Cary NC, USA [20], and the main magnetic and mechanical characteristics are synthesized by the *B-H* curve and the *τ-H* curve (Yield/Shear stress τ vs magnetic field H), obtained by the producer.

When an external magnetic field is applied in a gap filled by the MRF, the polarizable particles align themselves along the flux lines, allowing to create particle chains that prevent the movement of the particles themselves in the fluid. Once the magnetic field is removed, the fluid come back in a liquid state.

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Although many mathematical models have been developed, a very simplified equation can be used to describe the shear stress as a function of the applied magnetic field. In particular, combining the *B-H* curve and the *τ-H* curve of the fluid, the following relationship between shear stress τ and magnetic induction *B* can be used [7, 21]:

$$\tau_0(B) = 67\,B^4 - 222\,B^3 + 200\,B^2 + 17\,\mathrm{B} + 0.18. \quad (1)$$

In (1), the unit of the yield stress τ_0 is *kPa* while that of the magnetic flux density *B* is Tesla.

B. The brake characteristics

The design requirements for the brake are the following: the braking torque > 5 *Nm*; the ratio between the maximum and minimum torque > 8; maximum diameter < 100 *mm*; maximum axial length < 40 *mm*; maximum relative angular speed between the two shafts < 1500 *rpm*.

Figure 1 shows a schematic view of the proposed device with the main dimensions and materials, capable to fulfill the design requirements. It is composed of two coaxial shafts, input and output shafts of the brake, the magneto-rheological fluid inserted between the two coaxial shafts, and a third inner element carrying the permanent magnets.

The shaft number 1 is a hollowed cylindrical element made completely of ferromagnetic material.

The shaft number 2 is composed of four 90°-sections of ferromagnetic materials; in two of these sections, a certain number of non-ferromagnetic plates are inserted allowing the magnetic flux to pass through and thus, affecting the MR fluid. In the other 90º two sections, there are not non-ferromagnetic plates; therefore, any magnetic field externally applied is shielded. The number and dimensions of these non-ferromagnetic plates have been chosen by using a multi-objective optimization procedure, capable to maximize the performance of the device.

The MRF excitation system consists of four pie-shaped rare-earth NdFeB magnets, with a remanence field *Br* = 1.36 *T* and a coercivity field *Hc* = −1020 *kA/m*. They are positioned inside the two shafts, coaxially. Each of the PM occupies an angle of 45° along the circumferential direction and is magnetized along the radial direction.

As shown in Figs. 2 (a-b), the brake operates as follows: let's assume that initially the PMs are in the OFF state; the magnetic field does not pass through the fluid since the flux lines close themselves in the solid ferromagnetic sectors which act as a shunt for the flux lines just below the MRF. In this condition, the shaft number 1 rotates at a given speed and the shaft number 2 is not drag by shaft 1. Once the decision to brake the shaft number 1 has been taken, the PMs system must be rotated (by an auxiliary mechanism) along its circumferential direction (indifferently in clockwise or counter clockwise) with respect to the shaft 2. While the PMs rotate by moving away from the OFF state, the presence of non-ferromagnetic plates progressively forces the magnetic field to cross the fluid and to close its flux lines, following the path of least magnetic reluctance. The highest values of the field inside the MRF and, consequently, of the braking torque are obtained when the permanent magnets system rotates by an angle of 90°, working in the ON state.

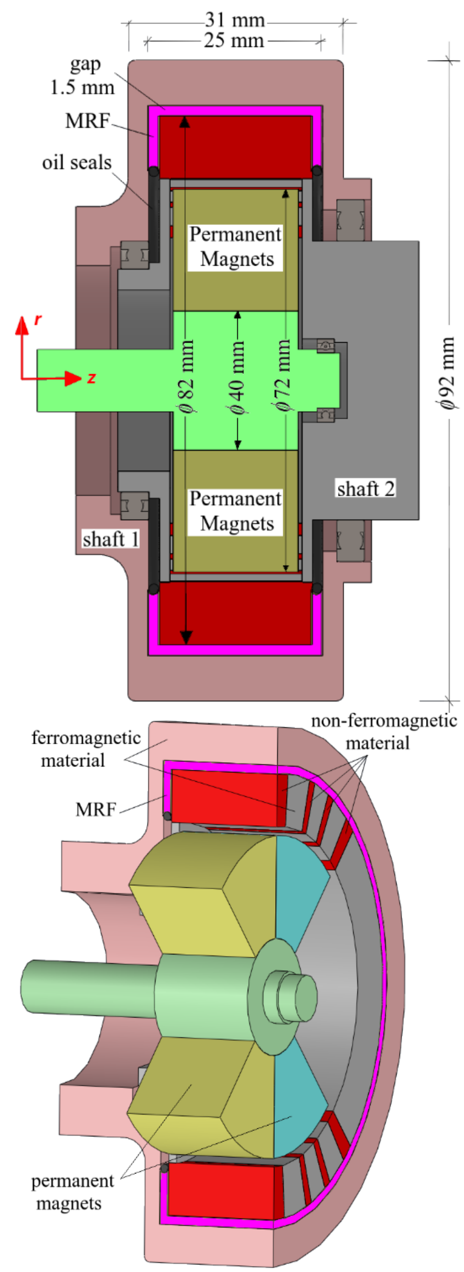
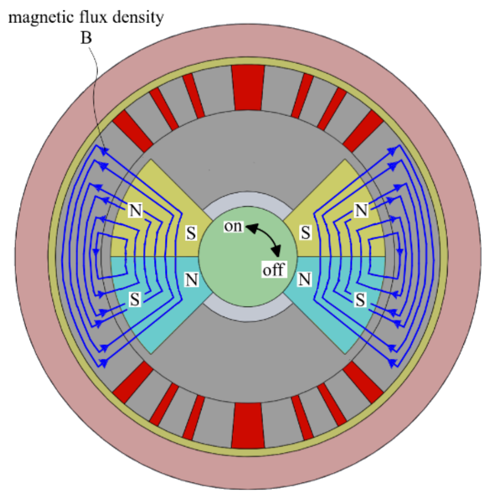
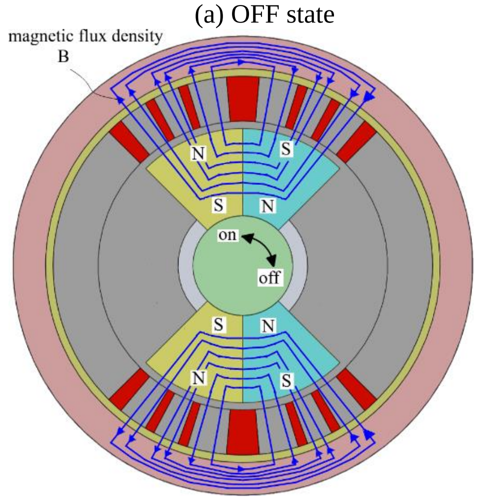


Fig. 1. The proposed brake with the main dimensions and materials.



(a) OFF state



(b) ON state

Fig. 2. The operation principle of the proposed brake.

In order to actuate the brake, an auxiliary mechanism (not shown in figure) capable to produce a proper activation torque that perform the rotation of the permanent magnets from the ON to the OFF state position is used. Considering that this activation torque (see Fig. 8) is quite low, the auxiliary mechanism can be composed of a preload torsion spring, which at rest keeps the PMs in the OFF state. Then, by manually or automatically twisting the spring along its axis by a proper angle (in the range 0° to 90°), the PMs can be rotated towards the ON state, so controlling the braking torque.

C. The FE model

The device has been analyzed by using a 3D model based on a Finite Elements code [19]. The FE mesh is shown in Fig. 3, while in Table 1, the main simulation parameters and materials have been reported. The geometric dimensions of the model are shown in Fig. 1.

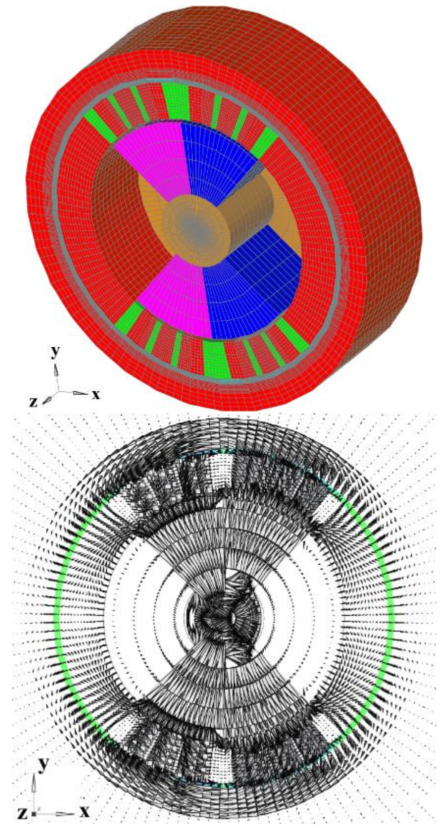


Fig. 3. The FE model and the magnetic flux density vectors in the ON state.

Table 1: Simulation parameters and data

Number of mesh elements	$7x10^5$
Ferromagnetic material	AISI 1018
Non-ferromagnetic material	AISI 316
Permanent Magnets: NdFeB	Br = 1.36 T; Hc = 1020 kA/m.
Magneto-rheological fluid	MRF140CG

All the simulations have been performed considering the *B-H* functions of the nonlinear materials (MRF, Permanent Magnets, ferromagnetic material).

The hysteretic behavior of these materials has been neglected, although several accurate and efficient models have been recently proposed [22-24].

As an example of simulation results, the Fig. 3 shows also the distribution of the magnetic flux density in the device when the system is in the ON state.

The performance of the device can be obtained by analyzing the magnetic flux density distribution in the MRF as produced by the permanent magnets.

Figure 4 shows the magnetic flux density on a cross-section on the x-y plane of the device, respectively when the PM system is in the OFF state (0°), in the intermediate position (45°) and in the ON state (90°).

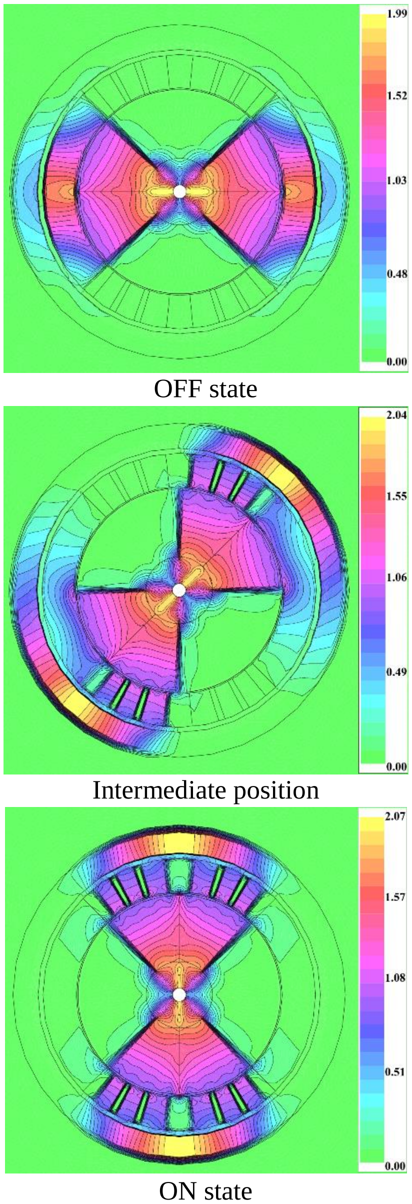


Fig. 4. The map of *B* (in [*T*]) on a middle cross-section of the x-y plane of the device at different conditions.

Figure 5 shows the radial component of the magnetic flux density along a circumference inside the MR fluid, in the same conditions of the previous figure.

The simulation results show that the magnetic induction in the MRF when the PMs system is in the ON state reaches up to 1 T, which is high enough to produce a high shear-stress and consequently a high level of braking torque. On the contrary, the OFF state is characterized by a very low magnetic flux density, not higher than 0.1 T and therefore low shear stress in the fluid.

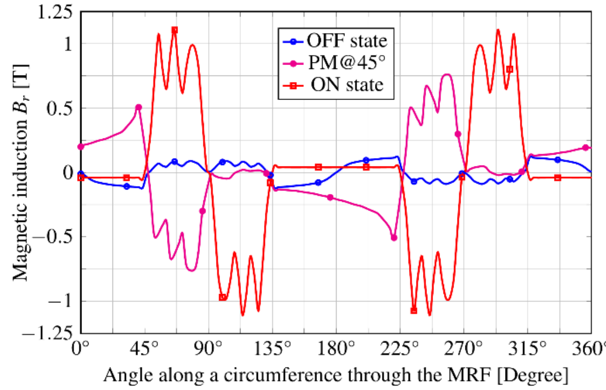


Fig. 5. The radial component of *B* along a circumference inside the MRF.

III. THE RESULTS

A. The braking torque

The braking torque has been calculated in a post-processing from the magnetic simulation as follows. The torque developed by a single volume element of MRF, centered at a generic *r* distance from the axis of the device and positioned between the two lateral surfaces of the cylindrical structure:

$$\Delta T_b = \tau_0(B) \cdot r^2 \cdot \Delta\theta \cdot \Delta z. \qquad (2)$$

Neglecting the edge effects along the z-direction and using the value of τ_0(B) calculated numerically from (1) in the center of the MR fluid, each cell of MR fluid produces the following contribution:

$$\Delta T_b = \tau_0(B) \cdot \left[\frac{r_{inn_{MRF}} + r_{out_{MRF}}}{2}\right]^2 \cdot \Delta\theta_c \cdot l_z\,. \qquad (3)$$

Then, taking into account the number of cells of the FE mesh and their azimuthal dimension, the total torque developed by the proposed brake can be approximated by a summation:

$$T_b = \sum_{n=1}^{N_c} \Delta T_b. \qquad (4)$$

Using the simulation results in terms of magnetic induction and shear stress, the braking torque developed by the proposed device has been calculated by using (4). Figure 6 shows its value as a function of the position of the permanent magnets system along the circumferential direction. When the PMs are in the ON state (angular-displacement = 90°), the braking torque is about 5.5 *Nm*, while in the OFF state (angular-displacement = 0°) the torque is about 0.65 *Nm*. This latter value is mainly due to the fluid natural viscosity. Anyhow, the ratio between the maximum and minimum torque, that is between the torque in the ON and OFF state, for the proposed brake is about 8.5, a satisfactory value in this kind of device.

In the same figure, experimental data are shown. They have been obtained by using the test bench (see Fig. 7) composed of a controlled brushless motor, two elastic couplings and a torque meter. During the tests, the relative angular speed between the two shafts has been kept constant at 100 *rpm*. The braking torque has been measured respectively when the PM system was in the OFF state, in the intermediate position (45°) and in the ON state. As for the maximum relative angular speed between the two shafts, some tests have shown that the device operate quite well up to 1000 *rpm*.

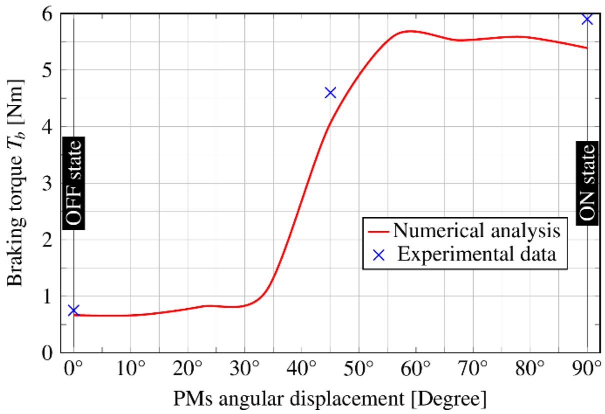


Fig. 6. The braking torque as a function of the angular displacement of the PMs.

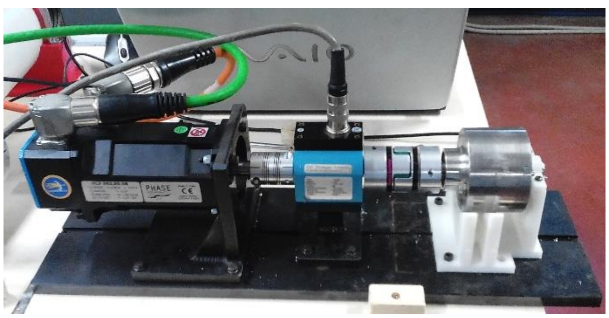


Fig. 7. The test bench.

As can be seen, the maximum deviation between the calculated torque and the measured one is about 15%. This deviation is explained because the simulation results neglect the contribution to the braking torque of the MRF that fills the gaps axially at the two bases of the cylindrical structure.

B. The brake actuation

As described in previous sections, the brake activation can be obtained by rotating the PMs system along its circumferential direction (indifferently in clockwise or counter clockwise). However, during the rotation, there is a magnetic torque that hinders the PMs motion from the OFF to the ON state and vice-versa. This activation torque is due to the natural magnetic interaction between magnets and ferromagnetic materials which constitute the shaft 2.

Figure 8 shows the activation magnetic torque value as a function of the PMs angular displacement, obtained by using the 3D FE model. As expected, the maximum value occurs when the PMs displacement is 45°, that is when the permanent magnets system is in the midway between the ON and OFF state.

An auxiliary mechanism (not shown in figure) can be exploited to move the permanent magnets from the ON to the OFF state. In this experiment a preloaded torsional spring have been used to overcome the magnetic torque and to rotate directly the PMs from OFF to ON state. By controlling more accurately the angular displacement of the PMs, using for example a stepper motor, the braking torque could be precisely modulated. Anyhow, the power required to activate/deactivate the proposed brake is a very low fraction of the braking power.

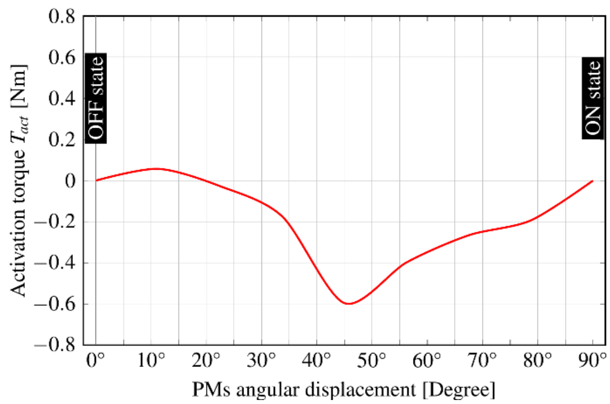


Fig. 8. The activation torque as a function of the angular position of the PMs.

VI. CONCLUSION

The authors have presented a Magneto-rheological brake excited by a system of permanent magnets. The brake is activated by rotating the PMs system along its circumferential direction (indifferently in clockwise or counter clockwise) by an angle of 90°. The proposed brake is characterized experimentally by a maximum braking torque of about 5.5 *Nm* and the ratio between the maximum and minimum torque is about 8.5, a satisfactory value in this kind of device. Finally, the results show that the actuation of the brake requires a very low power.

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