Analysis and Design of an Electromagnetic System for the Characterization of Magneto-Rheological Fluids for Haptic Interfaces

A. Bicchi[1], *Senior Member, IEEE*, M. Raugi[2], R. Rizzo[2], and N. Sgambelluri[1]

[1]Interdepartmental Research Centre "E. Piaggio," University of Pisa, 56100 Pisa, Italy
[2]Department of Electrical Systems and Automation, University of Pisa, 56100 Pisa, Italy

In this paper, the synthesis and design of a new device for the energization and characterization of magneto-rheological fluids (MRF) for haptic interfaces are presented. Due to the core structure and feeding conditions, only a three-dimensional numerical analysis provides an accurate prediction of the electromagnetic quantities and the rheological behavior of an excited specimen. The design constraints are shown in details and the results in terms of magnetic field inside the fluid and its spatial resolution are discussed.

***Index Terms*—Electromagnetic (EM) device, haptic interfaces, magneto-rheological fluid (MRF).**

I. Introduction

In many haptic applications, the ideal device would allow a user to feel virtual objects by freely moving his/her hand without mechanical constraints. Accordingly, in order to design an innovative haptic interface for whole-hand immersive exploration, we consider the possibility of using magneto-rheological fluids (MRFs). As shown in Fig. 1, these noncolloidal suspensions of micron-sized magnetizable particles respond to an external magnetic field turning near-solid in few milliseconds with a change in rheological behavior. Just as quickly, MRFs can be returned to their liquid state by the removal of the field [1]. Typically, the rheological change is manifested by the development of a yield stress that monotonically increases with magnitude of applied field. Usage of MRFs suggests the possibility to mimic rheology of biological tissue in order to realize haptic displays for surgical training useful in biomedical applications. This approach is justified by the observation that biological tissues viscoelastic properties could be mimicked by magnetically tuning the rheology of an MRF. An interesting application of MRF in haptic technology could be implemented in open surgery simulators, whereby the operator would interact with his/her free hand with virtual replicas of whole organs or complex surgical environments [2].

In this paper, we propose and design a new electromagnetic (EM) haptic system able to simulate both shapes and softness of virtual objects reproduced by means of the MRF contained in a plastic box, and excited through a suitable magnetic field.

An achievement was made in terms of magnetic field intensity and spatial resolution and finally in terms of rheological responses of the MRF has been obtained.

II. Device Synthesis

The MRF used to develop the proposed haptic interface is the *MRF132LD* produced by Lord Corporation, Cary, NC. It approximately exhibits dynamic yield strength in the range of 0–45 KPa for a magnetic field B between 0 and 0.5 T, and has a relative permeability μ_r between 3 and 7. The maximum strength in near-solid state (45 KPa) is limited by magnetic saturation; the magneto-rheological response time of the fluid is less than 10 ms.

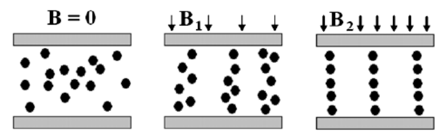

Fig. 1. Operation of a MRF under the effect of an increasing field B.

Accordingly, a suitable EM system for a proper energization of the MRF, should present the following characteristics:

- range of magnetic field in the MRF between 0 and 0.5 T;
- magnetic field inside a specified portion of the MRF as uniform as possible in order to discriminate different levels of compliance in a single region;
- controllability of the modulus of the magnetic field in a region that is as small as possible, in order to create tactile images of different shapes;
- accessibility of the MR specimen to facilitate free movements of the hand.

The ability of a device to satisfy these characteristics allows to obtain a functional MRF-based haptic display.

A. Preliminary Analysis

To test the magneto-rheological characteristics of the fluid, a first laboratory-operating device has been built. Such a prototype, the so-called *HBB-Haptic Black Box display* and presented by the authors in [2] and [4], has been developed as a system with a plastic box containing the MRF and a series of electrical coils to magnetically excite the fluid. As shown in Fig. 2, it consists of 16 cylindrical ferromagnetic cores, arranged in a matrix form of 4 × 4 and placed below a plastic box with a square base of 18 cm × 18 cm and a height of 4 cm. Each ferromagnetic core is equipped with a coil of 305 turns of enameled copper wire that supports a maximum dc current of about 10 A. The

Digital Object Identifier 10.1109/TMAG.2005.846280

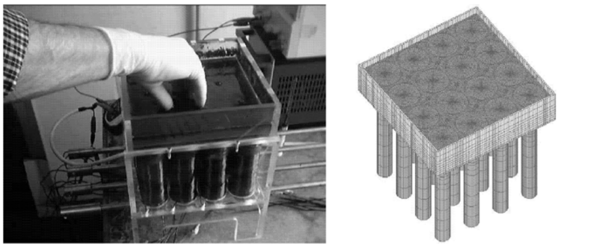

Fig. 2. (Left) First operating haptic device. (Right) FE model of the simulated system.

magnetic field necessary to excite a specified region of MRF is properly obtained by feeding the coil below the corresponding portion of fluid.

1) Three-Dimensional Finite Elements Analysis: Since the behavior of both MRF and ferromagnetic cores is highly nonlinear, an analytical method cannot carry out an accurate investigation of the proposed system. In order to take into account the B-H function for nonlinear materials, the leakage flux due to different magnetic paths in air, as well as the presence of different feeding coils, the simulations in the present work have been carried out by the use of a three-dimensional finite elements package developed at University of Bath (U.K.) [3].

a) Field Formulation: For regions with no source current, the field formulation in the used FE code is expressed in terms of total magnetic scalar potential ψ

$$\mathbf{H} = -\nabla\psi \Rightarrow \nabla \cdot (\mu\nabla\psi) = 0.$$

Using the "reduced scalar potential" formulation for the regions containing source current, it is possible to write

$$\mathbf{H} = -\nabla\phi + \mathbf{H}_s$$

and consequently: $-\nabla \cdot (\mu\nabla\phi) + \nabla \cdot (\mu\mathbf{H}_s) = 0$ where μ is the nonlinear function of the $\mathbf{B} - \mathbf{H}$ characteristics and $\mathbf{H}_s$ is the field due to the source current calculated using Biot–Savart law: $\mathbf{H}_s = (1/4\pi)\int \mathbf{J} \times \nabla((1/\mathbf{r}))dV$.

2) Simulation Results and Experimental Measurements: Due to the presence of two symmetry planes, only one quarter of the problem can be modeled. Fig. 2 shows the finite elements model of the simulated device. In this case, the simulations have been carried out supposing linear B-H curves for both of the carbon steel core and of the MRF. Hence, in order to easily validate the numerical model by experimental measurements, a first simulation has been performed setting the relative permeability of the MRF to 1, that is, supposing that the box empty. The system has been excited feeding the eight centered coils with a constant current of 10 A, for a total number of about 24 000 Ampere turns and the flux density B has been evaluated along the axis of a fixed coil as shown in Fig. 3. Then, by using a portable gaussmeter F.W. Bell/4048, equipped with accurate Hall sensor, some measurements have been obtained, and the results are reported in Table I. It can be seen that the maximum percentage error is about 8%, showing a good agreement between the simulated field and measured one.

After the validation of the FE model, a second simulation with the presence of MRF in the plastic box has been performed in order to analyze the behavior of the system. The results, reported in Fig. 3, show that the magnitude of flux density B, just outside the coils base, immediately decreases at very low values and at 1 cm distance from the box base the field is reduced to about 55%. Regarding rheological behavior of the MRF, this gradient of magnetic field induces a proportional decrease of the yield strength smoothing the softness of the virtual object perceived.

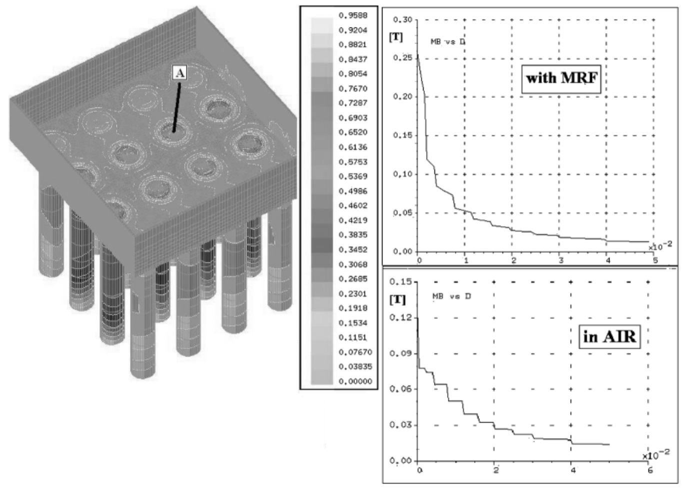

Fig. 3. Simulation results.

TABLE I
COMPARISON BETWEEN NUMERICAL AND EXPERIMENTAL RESULTS

Distance from the coil	Estimated **B**	Measured **B**	Error %
0 mm	0.15 T	0.146 T	3 %
2 mm	0.13 T	0.120 T	8 %
10 mm	0.06 T	0.057 T	5 %

The next sections will provide the design of a new device able to excite the MRF with improved performance with respect to the previous one.

B. Design Criteria

As a result of the FEM simulations, it is possible to report some general considerations on the main problems that have to be addressed in the design of a new EM device capable of properly exciting a specified volume of MRF. A critical point regards the paths of the magnetic flux that, as clearly shown in the device [2], close themselves in air increasing the magnetic reluctance and, consequently, decreasing the magnetic field inside the MRF. However, some possible solutions to increase the performance of the whole system are as follows:

- reduction of the reluctance of the magnetic paths by the introduction of ferromagnetic yokes and cores, properly positioned in the system, to close the magnetic flux path;
- increase of the number of ferromagnetic cores below the box to achieve a suitable spatial resolution.

Furthermore, another design criterion deals with the dimensions of the MRF volume to be energized. As discussed above, the relative permeability of such fluids, compared to that of air, leads to a huge magnetic reluctance with a decrease of magnetic field in the MRF. However, a compromise between an easy accessibility to the fluid, and the reduction of magnetic reluctance, allows to identify the proper height of the box. Then, it is possible to excite a parallelepiped of MRF with a two-dimensional spatial resolution related to the x-y axes of the plastic box, maintaining a constant height along the z direction; the height of the excited fluid could be modified varying its volume in the box.

Finally, we have to take into account the saturation of the used ferromagnetic materials whose nonlinearity compromises the performance of the whole system. However, the choice of special materials and the possibility to increase the transversal section of the ferromagnetic yokes and columns could attenuate this problem.

III. New MRF-Based Haptic Display

According to the simulation results obtained with the previous prototype and taking into account the general considerations reported in the previous section, a new device for the excitation of MRFs is proposed. The main points include: 1) the plastic box containing the MRF that is in a closed cubic shape and internally equipped with a latex glove able to handle the magnetically-excited fluid; and 2) a series of ferromagnetic cores, properly positioned in the system, to close the magnetic flux path allowing a reduction of the reluctance of the magnetic paths.

In such way, the operator can move his/her hand in a poking motion in order to discriminate shapes and compliance of the virtual objects, materialized adequately controlling the magnetic field.

All the used cores are composed of ferromagnetic material (carbon steel AISI 1015) with a high magnetic permeability and with a high saturation threshold in order to reduce the transversal sections. Finally, the whole system is completed by the insertion of a ferromagnetic sheet around the plastic box at a distance of about 4–5 cm. Due to the ability of this sheet to collect a part of the leakage flux, the field spatial resolution inside the fluid is increased by a factor of about 3.

A. Description of the Device

Fig. 4 shows a schematic view of the new device with its dimensions. It presents a system of external ferromagnetic cores (structures 1, 2, and 3) used as a base for the main coils and to close the magnetic flux path, and two subsystems (structure 4 with its twin 4'), symmetrically positioned with respect to the center of the plastic box, and capable of dynamically addressing the magnetic flux in different regions of the the MRF. Such subsystems, as shown in Fig. 5, are composed of two hollow ferromagnetic parallelepiped boxes with a series of 25 ferromagnetic "pistons," 17.5 cm long, and with a base area of about 3 cm^2, arranged in a matrix form of 5×5 below and over the plastic box containing the fluid. Each piston is winded by a coil of about 2500 Ampere turns for a fine control field resolution. Above each parallelepiped box is mounted an auxiliary system (not shown in the figures) able to move each piston along its axial direction; when all the pistons are at rest (inside the box), the reluctance of the magnetic path, closed along the line B-B', is very high and the value of flux in the fluid is neglectable; on the contrary, when two opposed pistons are "in action," the airgap along the magnetic path A-A' is reduced and it results

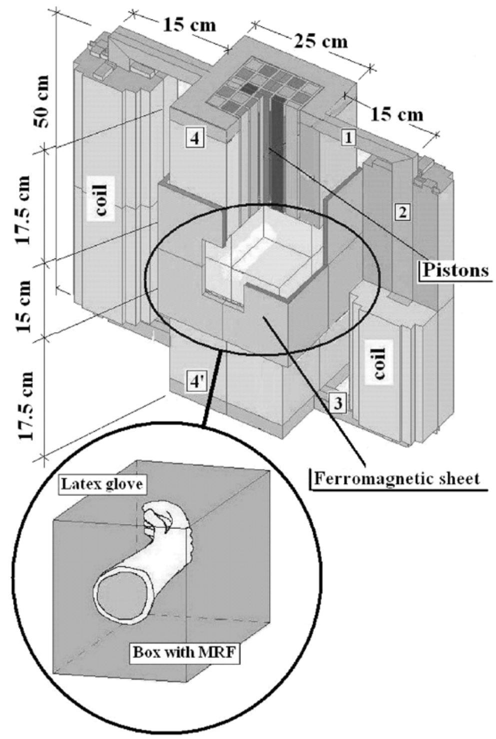

Fig. 4. Schematic representation of the new device with the main dimensions.

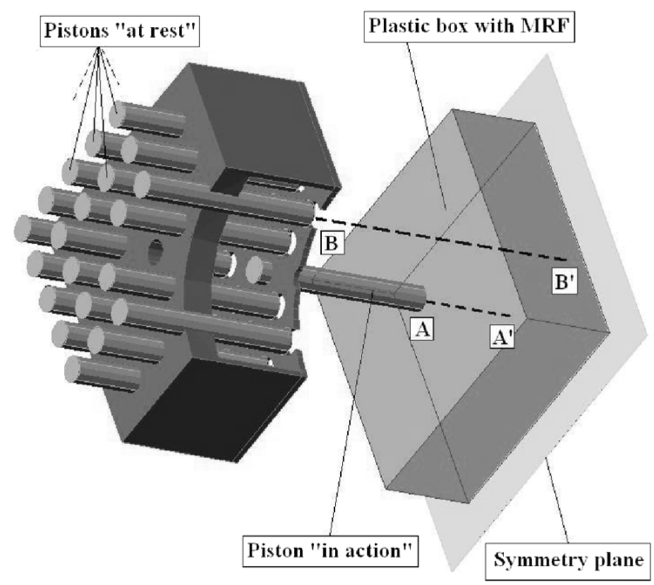

Fig. 5. System of ferromagnetic pistons to address the flux in the MRF.

in an increase of magnetic flux in a specified volume of fluid corresponding to the x-y position of the pistons. The controllability of the modulus of the magnetic field in a specified portion of the MRF and its spatial resolution is obtained acting both electrically, varying the value of the current in some coils, and mechanically, moving the pistons. In such way, it is possible to reconstruct many objects of different shapes in different zones inside the box containing the fluid.

1) Simulation Results: In order to analyze the values of magnetic field inside the MRF, several simulations have been carried out by means of the numerical code [3]. The knowledge

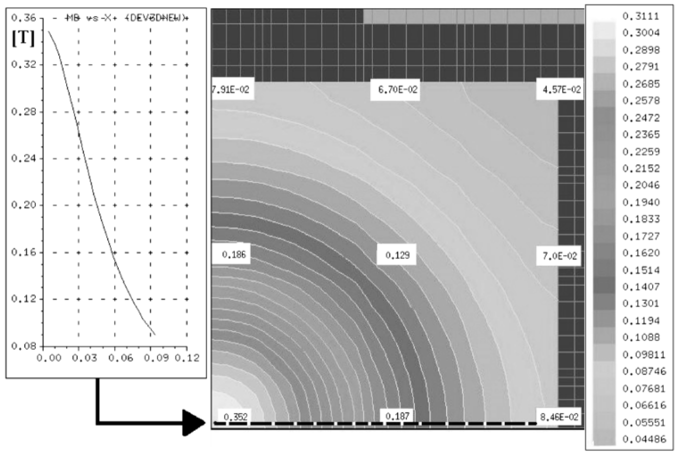

Fig. 6. Flux density in the fluid at $z = 0$.

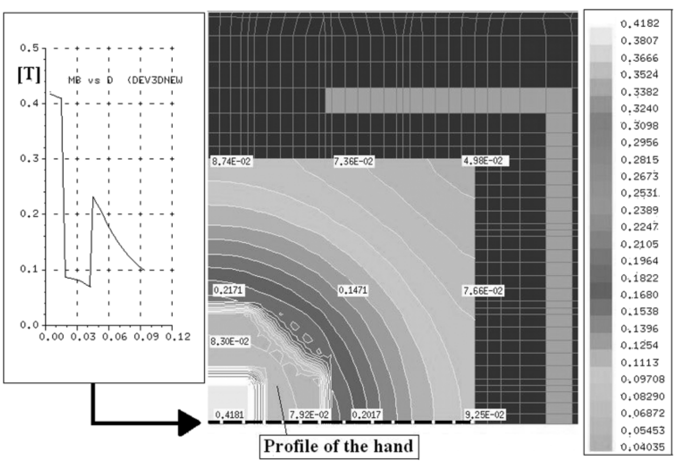

Fig. 7. Flux density in the fluid at $z = 0$ with a hand inside it.

of the field allows to characterize the rheological behavior of the fluid and to mimic different biological tissues.

The simulation results have been obtained using different values of dc current both in the main coils positioned around the external structure 2 and its twin 2' and in the coils around each ferromagnetic piston, for a total number of about 25 000 Ampere turns. Due to the symmetry of the system, only one eighth of the problem can be modeled.

Fig. 6 shows the flux density B along the indicated line in the fluid at $z = 0$, that is, at the intersection of the MRF with a plane orthogonal to the box's height in the center zone of the fluid, when only one couple of pistons are in action (central piston and its opposite) and with the coils feed in their maximum permissible current. It can be seen that the maximum value of the field in the fluid is about eight times that of the minimum: $B_{\max}/B_{\min} \approx 8$.

Fig. 7 shows the flux density B in same condition as in Fig. 6 but with a hand inside the fluid (modeled setting to 1 the relative permeability of that volume). In this case, the ratio between the maximum and minimum value of the field in the fluid is about 10, with a higher value of field magnitude and a better spatial resolution.

Furthermore, due to the presence of the MRF, when a couple of pistons is "in action," an attractive magnetic force acts between the pistons and the MRF. Such magnetic force has been simulated and its value is approximately $2.8N$ for each active piston. Accordingly, this force should be taken into account in the design of the EM actuator system necessary to move each piston along its axial direction in order to reach an active position (near the fluid) or a rest position (far from the fluid).

IV. Conclusion

This paper dealt with the analysis and design of an electromagnetic system for the characterization of magneto-rheological materials for haptic interfaces. Taking into account the simulation results obtained from a first operating device, some design criteria have been derived and a new system for the energization of MRFs has been developed and simulated by means of a finite elements code. The obtained results on this new device have shown good performance in terms of field intensity and its spatial resolution inside the MRF. Work is in progress to realize a prototype of the proposed device and to perform some psychophysical tests on the excited MRF in terms of softness and/or shape reconstruction.

Acknowledgment

This work was supported in part by the EU Commission under Contract IST-2001-38040 Touch-Hapsys.

References

[1] M. Jolly, J. Bender, and J. D. Carlson, "Properties and application of commercial magnetorheological fluids," in *Proc. SPIE 5th Annu. Int. Symp. Smart Structures and Materials*, San Diego, CA, Mar. 15, 1998.
[2] E. P. Scilingo, N. Sgambelluri, D. De Rossi, and A. Bicchi, "Toward a haptic black box: Magnetorheological fluid based display for softness and shape exploration," in *Proc. IEEE Int. Conf. on Robotics and Automation*, Taipei, Taiwan, R.O.C., Sep. 2003, pp. 2412–2417.
[3] MEGA, *User Manual*. Bath, U.K.: MEGA, Bath Univ., Nov. 2000.
[4] A. Bicchi, E. P. Scilingo, N. Sgambelluri, and D. De Rossi, "Haptic interfaces based on magnetorheological fluids," in *Proc. 2nd Int. Conf. Eurohaptics*, Edinburgh, U.K., July 2002, pp. 6–11.

Manuscript received June 8, 2004.