NUMERICAL MODELING OF MAGNETO-RHEOLOGICAL DAMPERS

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RESUMO

Entre as diferentes estratégias disponíveis para controlar vibrações em engenharia, o controlo semi-activo com base em amortecedores magnetoreológico (MR) tornaram-se uma tecnologia promissora para ser utilizada em estruturas de engenharia civil. A capacidade destes dispositivos para alterar o comportamento estrutural, sem a necessidade de alimentação por grandes fontes de energia, é uma grande vantagem que pode ser usada para justificar o seu potencial de aplicação para este ramo de engenharia. Este trabalho aborda o conceito básico de fluidos MR e fornece uma visão do comportamento dinâmico de amortecedores MR, bem como dos procedimentos numéricos disponíveis para descrever a resposta do amortecedor. A partir de uma visão geral das propriedades básicas dos fluidos MR, é apresentado o comportamento do fluido sob regimes diferentes de fluxos. Em seguida, com base na literatura disponível, detalha-se a seleção de modelos numéricos para simular o comportamento de amortecedores MR.

ABSTRACT

Among the different strategies available to control engineering vibrations, the semi-active control based on Magnetorheological (MR) dampers have become a promising technology to be used in civil engineering structures. The ability of these devices to change the structural behavior without the need of large power sources is a major advantage that can be used to justify their potential application to this engineering branch. This paper reviews the basic concept of MR fluids and provides an insight of MR dampers dynamic behavior and the available numerical procedures to describe the damper response. In the first section an overview of the basic properties of the MR fluids and the fluid behavior under different flow regimes are presented. Then, a selection of numerical models to simulate MR dampers behavior will be presented based on the available literature.

1. INTRODUCTION

In the last years engineers began to use and developed the so-called “smart materials”, i.e. materials in which at least one property can be changed in a controllable fashion by an external perturbation, in order to improve the behavior or to control the physical and mechanical properties of these materials. As is known, it is possible to obtain significant changes in some material properties like shape or viscosity when some external conditions like temperature or a magnetic field in order are changed. These properties allow the engineers to create “smart” devices some of them based on the use of fluids with controllable properties like Electrorheological (ER) and Magnetorheological (MR) fluids.

The initial discovery and development of MR fluids is credited to Jacob Rabinow at the US National Bureau of Standards in 1949 (Rabinow, 1948). Originally the research related with these fluids was focused in ER fluid, however in the last years MR fluids have been extensively studied due to their robustness for real-life engineering applications (Guglielmino et al., 2008).

The essential properties of typical ER fluids and MR fluids are summarized in Table 1 (Carlson and Spencer Jr., 1996). Basically, the main differences between ER and MR are related with operate temperature range, maximum yield stress and the sensitivity to impurities. The performance of MR fluids is less sensitive to temperature because the magnetic polarization mechanism remains unchanged over the operable temperature range. MR fluids can operate at temperatures from −40 to 150 ºC with only slight variations in yield stress (Carlson and Weiss, 1994). Also, MR fluids behaviour is not affected by impurities, which means that is insensitive to contamination, while ER fluids are highly sensitive to moisture or impurities as result of manufacture and usage process.

Table 1 - Typical ER and MR fluids properties (www.lord.com)

Property	ER fluid	MR fluid
Response time	Milliseconds	Milliseconds
Plastic viscosity, η (at 25°C)	0.2-0.3 Pa.s	0.2-0.3 Pa.s
Operable temperature range	+10 to +90°C (ionic, DC) -25 to +125°C (non-ionic, AC)	-40 to +150°C
Maximun yield stress, τ_y	2-5 kPa (at 3-5 kV/mm)	50-100 kPa (at 3-5 kV/mm)
Maximum field	4 kV/mm	250 kV/mm
Power supply (typical)	2-5 kV, 1-10 mA (2-50W)	2-25 kV, 1-2 mA (2-50W)
η/τ^2_y	10^{-7}-10^{-8} s/Pa	10^{-10}-10^{-11} s/Pa
Density	$1x10^3$-$2x10^3$ kg/m^3	$3x10^3$-$4x10^3$ kg/m^3
Maximum energy density	10^3 J/m^3	10^5 J/m^3
Stability	Cannot tolerate impurities	Can tolerate impurities

Magnetorheological (MR) fluids are non-Newtonian and rheologically stable suspensions with a shear yield strength, which can be controlled by a magnetic field. These fluids react promptly to the application of an external magnetic field (in a few milliseconds) exhibiting a reversible and adjustable transition from a free-flowing state to a semi-solid state. Due to this property these materials exhibit a significant change in their rheological behavior (viscosity and plasticity).

Fig 1 illustrates the variation of the shear stress and apparent viscosity with shear strain for an MR fluid under different magnetic field strengths (Li et al. 2000, Sapiński and Filuś, 2003).

In these plots is possible to verify the characteristic MR fluid behavior specially the critical yield stress that defines the transition between pre-yield and post-yield regions and the apparent increase of viscosity. The expression “apparent viscosity” is used because the carrier fluid viscosity does not change as the magnetic field intensity is modified.

The rheological behavior of MR fluids depends on the magnetic field strength, however it is possible to define a pre and post yield areas as shown in Fig. 1a.

The transition from pre-yield to the post-yield region occurs when the stress is greater than the shear stress. In this transition zone it is possible to identify the dynamic shear yield stress $\tau_{y,d}$ defined as the point of the zero-rate of the linear regression curve fit and the static shear yield stress $\tau_{y,s}$ defined as the shear stress necessary to initiate MR fluid flow (Ginder 1996; Sapiński and Filuś, 2003). These values allow defining the characteristic shear stresses of the MR fluid.

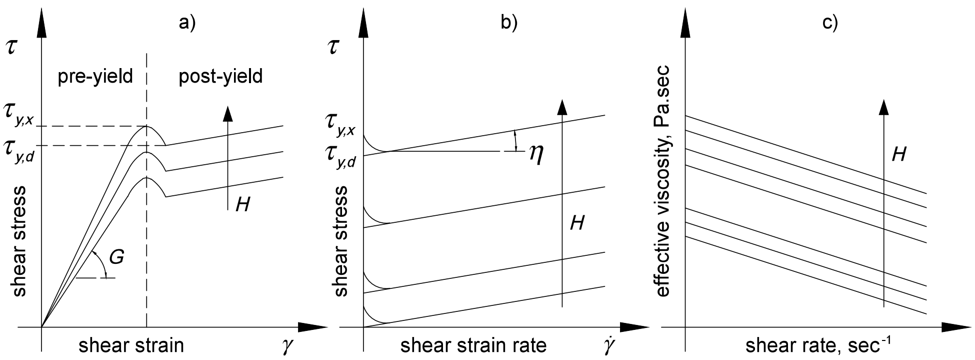

Fig.1 - Constitutive behavior of a MR fluid: a) pre-yield and post-yield regions, b) non-Newtonian post-yield behavior and c) apparent viscosity.

2. NUMERICAL MODELS

MR dampers are semi-active devices whose damping characteristics can be modified in real time due to the capability to adjust the resistance to flow of a MR fluid within the damper through the application of a magnetic field. The particular properties of the MR fluid allow variations in the damping force that can be controlled by varying an applied current. Thus, the hysteretic behaviour of a MR damper is current dependent but also function of the amplitude of the excitation. To predict the behaviour of MR dampers under certain magnetic fields or excitations, it is necessary to model the device with an appropriate approach. This becomes relevant aspect because before the production of a MR damper it is necessary to design and select the correct parameters that will define the behavior of the device.

Hence, a previous numerical simulation is needed to validate the design and since the MR damper is a semi-active device it is also necessary to verify if the proposed properties are suitable for the system in which is intended to apply the MR damper.

The main challenging problem regarding MR damper numerical modelling is the accurate inclusion of the characteristic nonlinear nature of these devices into the model. Due to the MR effect, this nonlinear behaviour is also current and excitation dependent, which increase the difficult task of develop a MR damper model. Consequently, in the last decade numerical modelling and validation of MR dampers have attracted significant attention by many researchers. The model must be able to simulate the nonlinear behaviour of the MR damper but at the same time it has to be simple as possible to allow their effective implementation in control systems. Therefore, an adequate modelling of these semi-active control devices must involve a simple, sufficiently accurate and robust numerical model. This is essential for the suitable prediction of the behaviour of the controlled system.

The relevance of MR damper behaviour modelling in the study of semi-active control systems led the development of various kinds of mathematical models that can be organized in different categories as shown in Table 2 based on the classification criteria defined by Wang and Liao (2011).

Table 2 - Classification criteria for MR dampers

Classification criteria	Category
Properties represented	- Quasi-static models - Dynamic models
Modelling methods	- Parametric models - Non-parametric models
Reversibility	- Dynamic models - Inverse dynamic models

The modeling techniques can be categorized in parametric and non-parametric models, according with the approach employed to assemble the model. The parametric models are obtained with an assemblage of linear and/or nonlinear springs, dashpots and other physical elements in order to define accurate device behavior. The non-parametric models are based on analytical expressions that describe the characteristics of the MR damper. Table 3 describes the available models for MR dampers numerical simulation (Braz-César and Barros, 2012).

To obtain the parameters that define the MR damper behavior in the parametric models it is necessary to have experimental data and afterward initiate an identifying procedure. However, the nonlinear nature and the elevated number of the parameters involved in the identification lead to a complex procedure based on assumptions that becomes the main disadvantage of these models. Since non-parametric methods depend on the performance of the MR device and are based on both testing

Table 3 - Classification MR dampers models

Modelling technique	MR damper Models
Bingham models	- Original Bingham model - Modified Bingham model - Gamota and Filisko model - Updated Bingham model by Occhiuzzi *et al*. - Three-element model by Powell - BingMax model by Makris *et al*.
Bi-viscous models	- Nonlinear bi-viscous model - Nonlinear hysteretic bi-viscous model - Nonlinear hysteretic arctangent model - Lumped parameter bi-viscous model
Visco-elastic-plastic models	- General visco-elastic-plastic models - Visco-elastic-plastic model by Li *et al*
Stiffness-viscosity-elasto-slide model	- Stiffness-viscosity-elasto-slide (SVES) model
Hydro-mechanical model	- Hydro-mechanical model
Bouc-Wen models	- Simple Bouc-Wen model - Modified Bouc-Wen model - Bouc-Wen model for shear mode dampers - Bouc-Wen model for large-scale dampers - Current dependent Bouc-Wen model - Current-frequency-amplitude dependent Bouc-Wen model - Non-symmetrical Bouc-Wen model
Dahl models	- Modified Dahl model - Viscous Dahl model
LuGre models	- Modified LuGre model by Jimenez and Alvarez - Modified LuGre model by Sakai et al
Hyperbolic tangent models	- Hyperbolic tangent model by Kwok *et al*
Sigmoid models	- Sigmoid model by Wang *et al* and Ma *et al*
Equivalent models	- Equivalent model by Oh and Onoda
Phase transition models	- Phase transition model

principles, they can overcome the disadvantages of the parametric model.

Parametric models assume that MR dampers can be characterized by a system of mechanical elements with linear or non-linear behavior including springs, dashpots and other elements in order to obtain a mathematical model that correctly incorporate the nonlinear behavior of these devices.

Up to now, several dynamic models for MR dampers have been developed and validated mainly to create a realistic model that simulate their inherent hysteretic behavior. The accuracy of the model becomes a very important factor to successfully achieve desirable control performance in order to easily integrate the device into a control system. To accomplish this objective many researchers presented a considerable amount of different parametric model that were proved by comparing the predicted hysteresis behavior with experimental results.

Among the large number of available parametric models, the Bingham and the Bouc-Wen based models are the most widely accepted phenomenological models adapted to study MR dampers and to develop semi-active control systems based on these so-called smart devices.

2.1. Bingham model

The Bingham plastic model has been used to characterize the rheological behaviour of smart fluids such as ER and MR fluids. This model assumes that a body behaves as a solid until a minimum yield stress is exceeded and then exhibits a linear relationship between the stress and the rate of shear or deformation. Stanway et al. (1987) proposed a mechanical model based on the Bingham plastic model to characterize the ER damping mechanism. This model is known as the Bingham model and combines a Coulomb friction element with a viscous dashpot as shown in Fig. 2.

From the equilibrium of the mechanical element configuration the force generated by the MR dampers can be expressed as

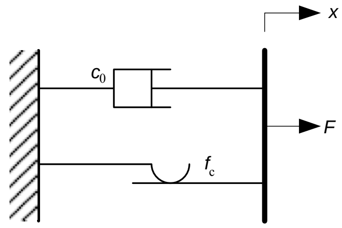

Fig.2 - Bingham model for MR dampers (Spencer *et al.*, 1997).

$$F(t) = c_0 \dot{x} + f_c \,\mathrm{sgn}(\dot{x}) + f_0 \qquad (1)$$

where $\dot{x}$ is the velocity of the external excitation, c_0 is the damping coefficient, f_c is the frictional force and f_0 is the force offset related with the presence of an accumulator assuming that this component has low stiffness and linear characteristics. It is also possible to derive the Bingham model from the mathematical expression proposed to study the flow of MR fluids

2.2. Bouc–Wen models

The Bouc–Wen hysteresis model is one of the most widely accepted approaches to simulate an extensive variety of softe-ning/hardening smoothly varying hysteretic behaviour that can also include hysteresis pinching and stiffness/strength degradation.

The model was introduced by Bouc (1971) and later generalized by Wen (1976) who demonstrated the versatility of this model to represent a large variety of hysteretic patterns. Due to this advantageous characteristic, the model was used to describe several nonlinear hysteretic sys-tems such as hysteretic isolators and MR dampers.

Although MR dampers exhibit a well-defined typical behaviour, the final hysteretic configuration depends on some particular behavioural features related with the damper geometry, presence of an accumulator, etc. Therefore, the model must be adapted to include the realistic MR damper behaviour and several variations of the Bouc-wen model were developed to correctly simulate MR dampers. According to the procedures proposed in the literature (Braz-César and Barros, 2012), the modifications of the Bouc-Wen model for MR dampers can be categorized as:

- Simple Bouc-Wen model;
- Modified Bouc–Wen model or Spencer model;
- Bouc–Wen model for shear mode dampers;
- Bouc–Wen model for large-scale MR damper.
- Current-dependent Bouc–Wen model;
- Current–frequency–amplitude-dependent Bouc–Wen model;
- Non-symmetrical Bouc–Wen model.

Among these models, the simple Bouc-Wen model will be used to simulate the hysteretic response of a MR damper. The simple Bouc-Wen model has three components: a spring, a dashpot and a Bouc-Wen block, in a parallel configuration as shown in Fig. 3. The non-linearity of the system is located in the Bouc-Wen block, which is capable of capturing the behavior of MR dampers.

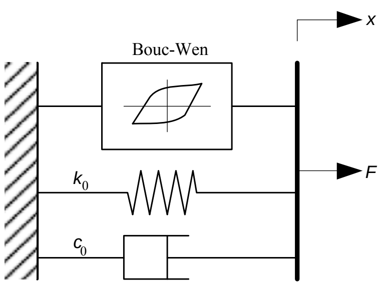

Fig.3 - Simple Bouc–Wen model (Spencer *et al.*, 1997).

This model was adopted by Spencer et al. (1997) to study the behaviour of a MR damper comparing the performance of this model with other parametric models. According to the mechanical configuration shown in Fig. 3, the damping force in this system is given by

$$F(t) = c_0\dot{x} + k_0(x\text{-}x_0) + \alpha z \qquad (2)$$

where c_0 is the viscous coefficient, k_0 the stiffness coefficient and z is an evolutionary variable associated with the Bouc-Wen block and governed by

$$\dot{z} = -\gamma\,|\,\dot{x}\,|\,z\,|\,z\,|^{n\text{-}1} - \beta\dot{x}\,|\,z\,|^{n} + A\dot{x} \qquad (3)$$

The initial displacement x_0 allow including the presence of an accumulator into the system. The parameters c_0, k_0, α, β, γ, n and A are usually called characteristic or shape parameters of the Bouc–Wen model and are functions of the current applied to the MR damper, the amplitude and frequency of vibration. The non-linear shape of the hysteretic curve can be adjusted by changing the values of the Bouc-Wen block parameters allowing controlling the linearity in the unloading and the smoothness of the transition from the pre-yield to the post-yield region.

Due to the capability to capture the hysteretic component of the MR damper behaviour, the simple Bouc–Wen model is assumed as a more reasonable MR damper model for numerical simulations when compared with the Bingham based models. However, the model is unable to reproduce the typical roll-off effect in the yield region that is observed in the experimental testing of a MR damper.

3. EXPERIMENTAL ANALYSIS

The Lord Corp. RD-1097-1 MR damper shown in Fig. 4 was tested in order to study its experimental response. This is a small sponge type MR damper with a conventional cylindrical body configuration and an absorbent matrix saturated with an MR fluid in the piston rod. The enclosing cylinder is 32.0 mm in diameter and the damper is 253 mm long in its extended position with ±2.5 cm stroke. The device can operate within a current range from 0.0 A up to 1.0 A with a recommended input value of 0.5 A for continuous operation and can deliver a peak force of 100 N at a velocity of 51 mm/s with a continuous operating current level of 1.0 A. Thus, this damper can be used to control very small structural systems.

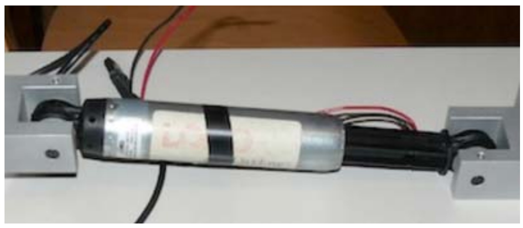

Fig. 4 - Sponge type RD-1097-1 MR damper from Lord Corp.

A parametric study was carried out: several combinations of amplitudes, frequencies and input current were studied in order to obtain the required data to characterize the damper response to further develop a numerical model based on the experimental data. Hence, the damper was subjected to a series of predefined sinusoidal displacement excitations through a MTS actuator system working in displacement control mode.

The excitation signals were automatically generated with the MTS controller and a regulated power supply unit was used to provide the constant current supply for each set of sinusoidal signals. The selected set of frequencies, amplitudes and current supplies involved in the experimental procedure the specified in Table 4.

Table 4 - Parameter variation for Lord RD-1097-1 MR damper experimental analysis

Parameter	Values
Frequencies (Hz)	(0.50, 1.00, 2.00)
Amplitudes (mm)	(2.5, 5.0, 7.5)
Current supplies (A)	(0.0, 0.1, 0.2, 0.3, 0.4, 0.5)

The testing procedure was carried out with a fixed frequency and amplitude sinusoidal displacement for a specific current supply repeating this process for every parameter combination. The experimental data of the parametric study were grouped into frequency-dependent tests, amplitude-dependent tests and variable input current tests. The responses of the MR damper for the variable input current tests are shown in Fig. 5. In this case, the MR damper response was obtained varying the input current while the amplitude and frequency are kept constant.

Different constant current levels were selected according with the values referred in Table 4 and different amplitudes and frequencies were applied for each current level. The maximum input current level was set to 0.5A since this is the recommended peak input value for continuous operation and the actual range level of this device. A thermocouple was used to monitor the damper temperature to avoid overheating that could damage the device.

The damping force increase along with the input current level and the hysteretic behavior is intensified. When the device is operating without input current, the damper response reveals a reduced hysteretic loop while operating with a non-zero constant input current level the damper exhibit a significantly larger hysteretic behavior.

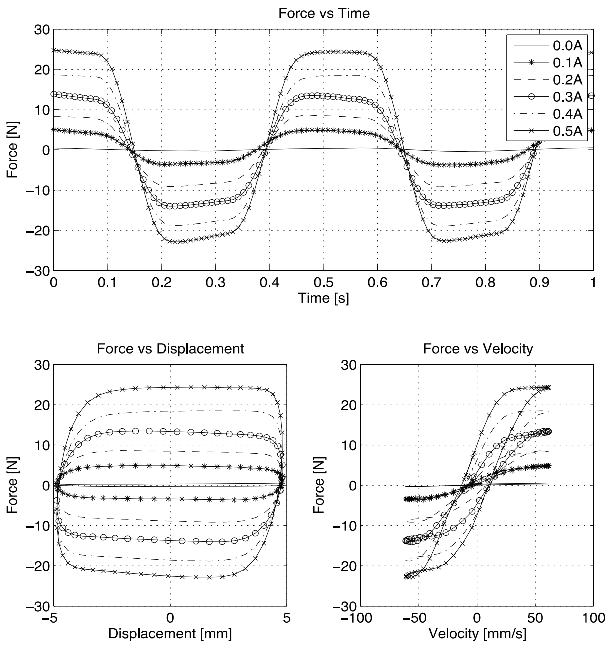

Fig. 5 - RD-1097-1 MR damper: Measured damping forces under a 2.00 Hz sinusoidal excitation with amplitude of 5.00 mm and variable input current.

An increase in the input current means that the magnetic field to which the MR fluid is exposed is also increasing and therefore the mechanical properties of the fluid are changed, specially the yield force that causes a plastic-like behavior in the hysteresis loops.

In the post-yield region is perceptible that the change rate of the damping force with respect to the velocity is moderately low while the damper presents substantial hysteresis characteristics in the pre-yield operation regime.

4. NUMERICAL ANALYSIS

The preceding experimental program was executed to obtain the MR damper response data required to develop an accurate numerical model to further design the appropriate semi-active control strategy for the MR actuators. The hysteresis behaviour of MR dampers becomes a particularly important characteristic when these devices are used for vibration suppression and control, however, the identification of the hysteresis response can be a complex procedure due to its strong non-linear hysteretic dynamics.

The parametric models are mathematical models that require the characterization of the parameters and consequently parameter identification is needed to determine the corresponding values of the parameters for a particular MR damper (Barros and César, 2012).

To implement the identification procedure, the model parameters can be defined as a vector of coefficients Θ that must be identified as

$$\Theta = [\Theta_1, \ldots, \Theta_n] \tag{4}$$

To compare the experimental response with the model-predicted response, the following performance criterion or objective function J can then be introduced

$$J(\Theta) = F_{mr}(\Theta) - F_e \tag{5}$$

where F_{mr} is the model-predicted force and F_e is the force obtained in the experimental procedure. Finally, an optimization algorithm can be used to adjust model parameters in order to minimize the objective function

$$\min_{\Theta} \sum_i^N J_i(\Theta)^2 = \min_{\Theta} \sum_i^N (F_{mr,i}(\Theta) - F_{e,i})^2 \tag{6}$$

where N is the number of points in the experimental data or experimental samples.

The least square method is a simple and standard approach to reduce the difference between an experimental value and the fitted value provided by a dynamic model and the application of this method is mostly appropriate for models that are linear in parameters. But dynamic models for MR dampers are nonlinear in the parameters, and a nonlinear approach should be considered to estimate model parameters.

In this study the lsqcurvefit MATLAB routine was used as the least-square solver because it provides a convenient interface for data-fitting problems. The routine finds coefficients x (related with Θ) that solve the problem expressed by the following equation (7):

$$\min_{\Theta} \sum_i^N (F(x, xdata_i) - ydata_i)^2 = \min_{\Theta} \sum_i^N (F_{mr,i}(\Theta) - F_{e,i})^2 \tag{7}$$

given input data xdata, and the observed output ydata, where xdata and ydata are matrices or vectors, and F (x, xdata) is a matrix-valued or vector-valued function of the same size as ydata.

In order to obtain a numerical model for the RD-1097-1 MR damper, the Bingham model and the Bouc-Wen model are considered. The Bingham model requires the optimization of three parameters that make this model a simple way to numerically reproduce the damper response while The Bouc-Wen model requires the optimization of seven parameters. Obviously, the Bingham model is the simpler numerical model and the Bouc-Wen model is a more complex and accurate approach.

4.1. Bingham model

The Bingham mechanical model consists of a Coulomb friction element placed in parallel with a viscous damper and comprises the identification of three parameters: the frictional force f_c, the viscous damping parameter c_0 and the force due to the presence of the accumulator f_0. Therefore, the identification procedure is related with an optimization problem involving the parameter vector

$$\Theta = \left[f_c, c_0, f_0 \right] \tag{8}$$

Since this device does not have an accumulator, the force f_0 can be considered as been close to zero (in fact there is a slight offset that is obviously not produced by the accumulator but due to expected asymmetries in the damper response produced by asymmetric friction, etc.).

The parameters f_c and c_0 are voltage/current dependent and their values were computed with the same parameter identification procedure as was used for the preceding MR damper.

Fig. 6 shows a comparison numerical and experimental of the results obtained with the parameter identification procedure for the Bingham model.

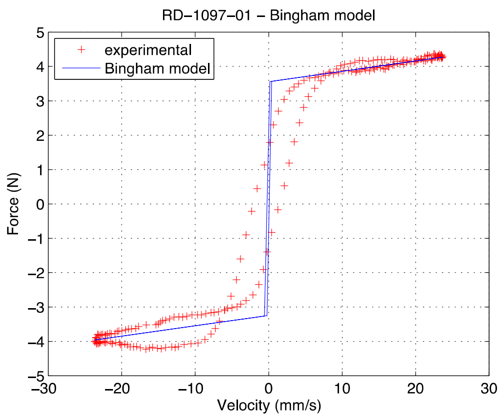

Fig. 6 - RD-1097-1 MR damper: Parameter identification of Bingham model under 1.50 Hz sinusoidal excitation, 4mm amplitude and 0.75A.

The values of the mechanical parameters f_c and c_0 of the Bingham model for each set of experimental tests were determined and a polynomial curve fitting was used to find the current dependent functions. The average values of each set of frequencies and amplitudes for a specific operating current were used to define the data points displayed. The relationship between the Bingham parameters and the operating current are defined by the polynomial functions described in Fig. 7 and 8.

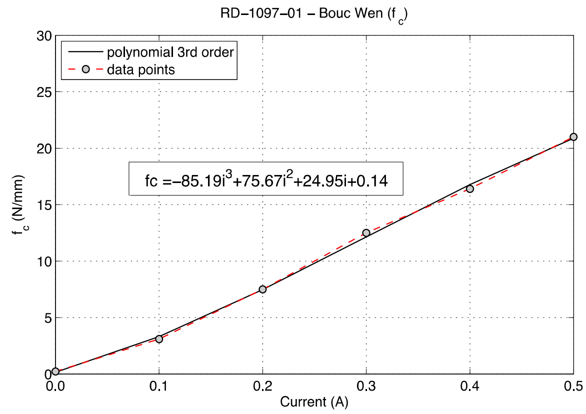

Fig. 7 - Curve fitting for the friction force $f_c(I)$ of the Bingham model.

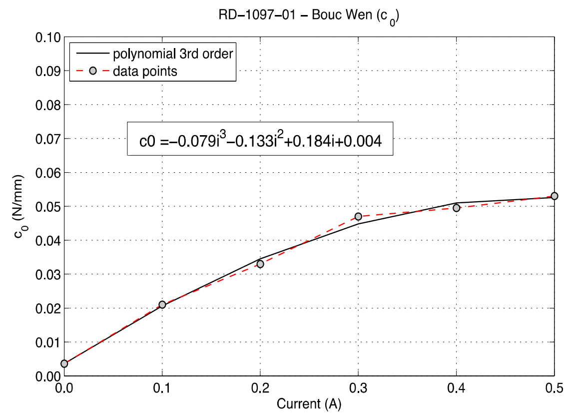

Fig. 8 - Curve fitting for viscous damping $c_0(I)$ of the Bingham model.

According with the linear fitting presented in Fig. 7, the polynomial function that defines the parameter f_c with respect to the operating current is given by

$$f_c(I) = -85.19I^3 + 75.67I^2 + 24.95I + 0.14 \quad \text{(N)} \tag{9}$$

Similarly, the variation of the parameter c_0 can be obtained with the curve fitting described in Fig. 8 and is given by

$$c_0(I) = -0.079I^3 - 0.133I^2 + 0.184I + 0.004 \quad \text{(N.s/mm)} \tag{10}$$

These functions were implemented in a MATLAB routine to obtain the predicted MR damper response.

Fig. 9 illustrates the numerical and experimental responses for a sinusoidal excitation with 1.00 Hz frequency, 5mm amplitude and 0.50A.

4.2. Bouc-Wen model

The sponge-type MR damper presents a well-defined hysteretic behaviour that can be easily simulated by the Bouc-Wen model. The device produces a smooth hysteretic loop and since it does not have an accumulator, the loading/unloading force oscillations caused by the accumulator are not present. Then, a precise hysteretic numerical response is expected.

A set of constrains for each model parameter were selected and implemented in the identification algorithm to accelerate the minimization procedure. The parameter n=1 was defined according with the results obtained in previous research work (Shen et al., 2007) and finally, the force offset $f_0 \approx 0$ has the same value of the Bingham model force offset.

Fig. 10 illustrates the result of the parameter identification for the Bouc-Wen model when the damper is driven with a sinusoidal excitation of 1.00 Hz with 5mm amplitude and an operating current of 0.50A. The identification procedure was repeated for each set of experimental data and the different values of the model parameters of the Bouc-Wen model were determined.

The parameters current independent A, β, γ are considered as constant values during the sinusoidal excitation and the average values A= 38.012, β=-1.401 mm^{-2}, γ=4.794 mm^{-2} and k_0 = 0.01 N/mm were estimated. The polynomial functions of the current/voltage dependent parameters α, and c_0 were obtained with a polynomial curve fitting of the average values of each set of frequencies and amplitudes for a specific operating current.

The resulting current dependent function for α is shown in Fig. 11 and this model parameter can be described by a third order polynomial function as

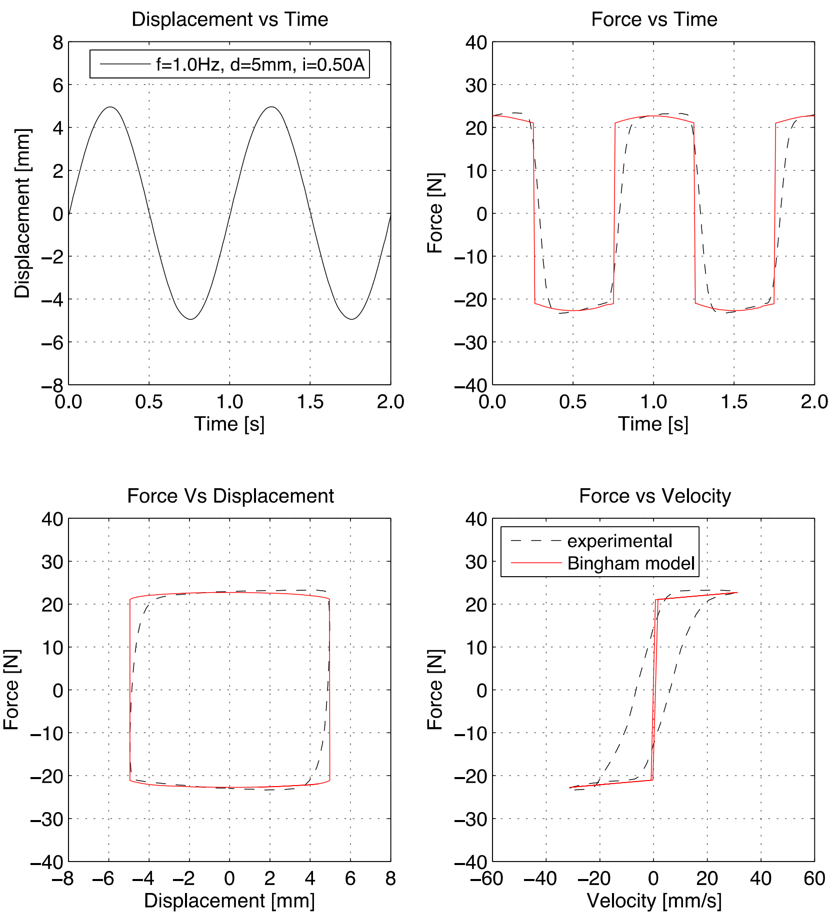

Fig. 9 - RD-1097-1 MR damper: Experimental vs. numerical response for the Bingham model (1.00 Hz sinusoidal excitation with 5mm amplitude and 0.50A).

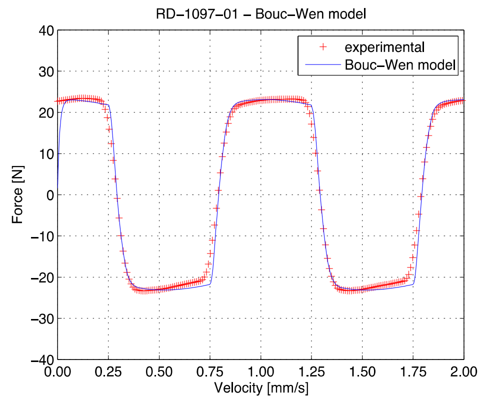

Fig. 10 - RD-1097-1 MR damper: Parameter identification of Bouc-Wen model under 1.50 Hz sinusoidal excitation, 5mm amplitude and 0.50A.

$$\alpha(I) = -9.66I^3 + 9.76I^2 + 1.12I + 0.10$$

(N/mm) (11)

A fourth order curve fitting was selected for the model parameter c_0 and the polynomial function is given (Fig. 12) by

$$c_0(I) = 4.48I^4 - 4.74I^3 + 1.35I^2 + 0.05I + 0.01$$

(N.s/mm) (12)

Comparison of computed predictions and experimental measurements over a 1.0Hz sinusoidal excitation with 5mm of amplitude and operating current I= 0.50A is presented in Fig. 13.

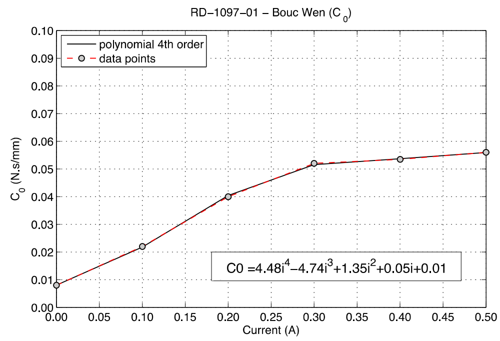

Fig.11 - Curve fitting for parameter *α*(*I*) of the Bouc-Wen model.

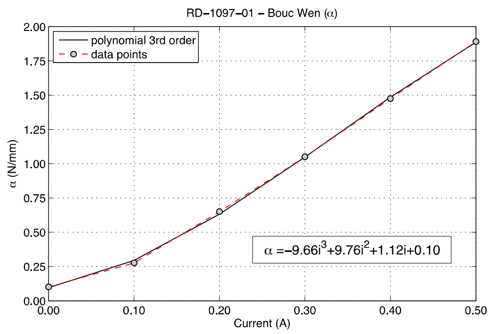

Fig. 12 – Curve fitting for parameter $c_0(I)$ of the Bouc-Wen model

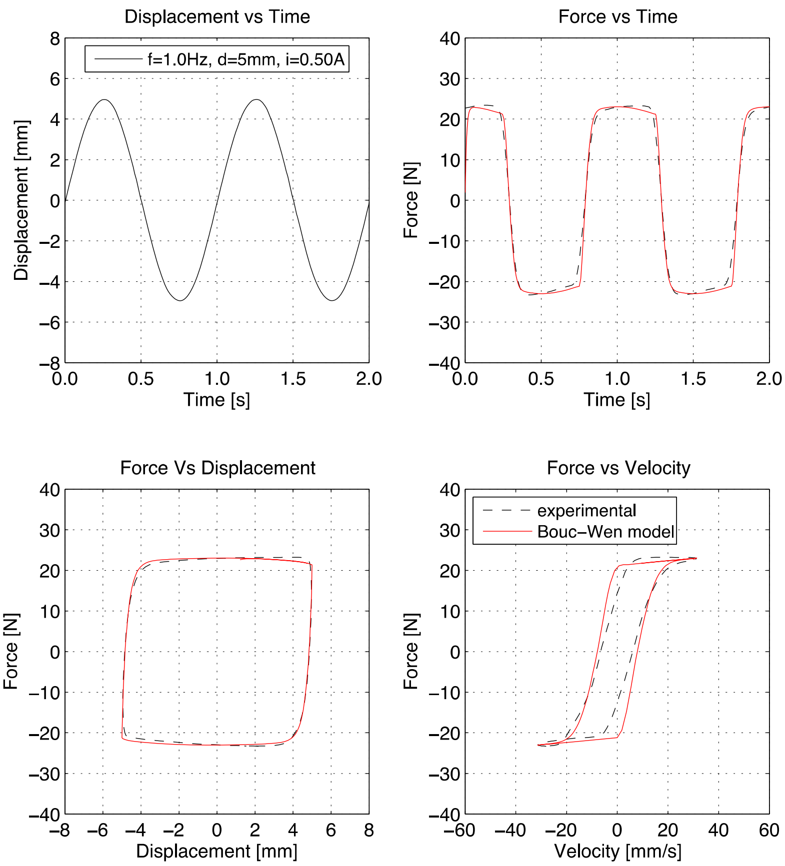

Fig. 13 - RD-1097-1 MR damper – Experimental vs. numerical response for the Bouc-Wen model (1.50 Hz sinusoidal excitation with 5mm amplitude and 0.50A).

In the previous study two commonly used parametric models were employed to simulate the response of a small sponge type MR damper. Although both models have been used as feasible modelling approaches, it becomes obvious that the Bouc-Wen model has the additional capability of being able to characterize the hysteretic behaviour of the device.

Fig. 14 displays the numerical response of the Bouc-Wen and of the Bingham models compared with the experimental data (1.50 Hz, 5mm and 0.50A).

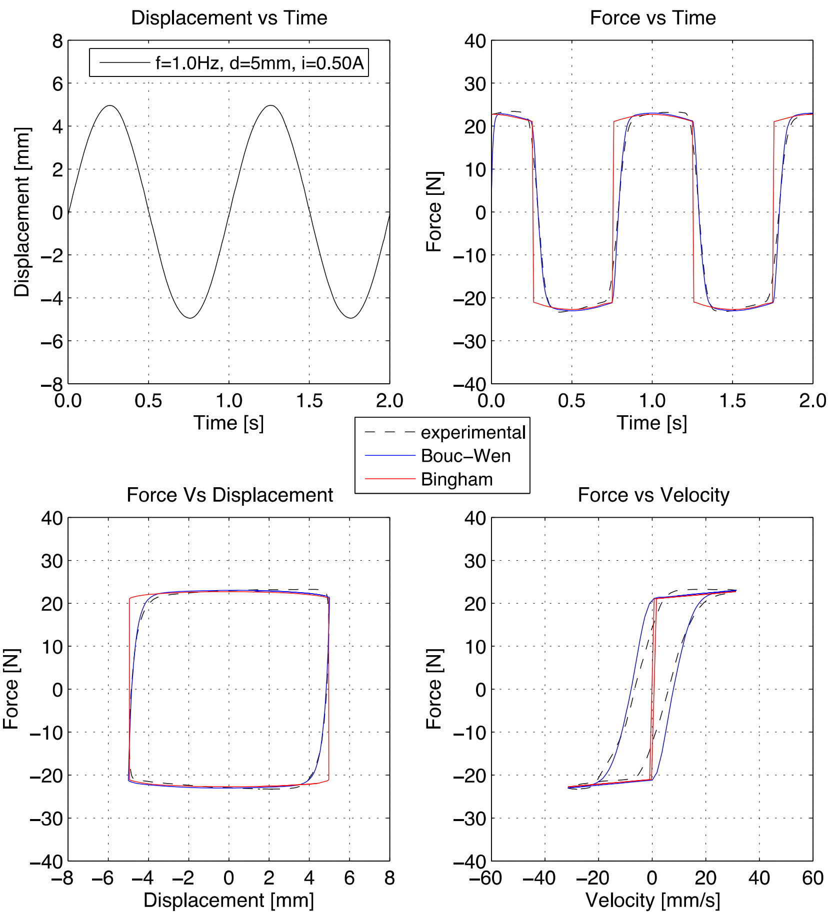

Fig. 14 - RD-1097-1 MR damper: Experimental vs. numerical response for the Bouc-Wen and Bingham models (1.50 Hz, 5mm and 0.50A).

The Bingham model is a simple approach that can simulate the MR damper response although without the typical hysteretic behaviour that is present in these devices. The damping force in the friction element is equal to the applied force since a non-zero damping force is produced for zero piston velocity and the damping force is not correctly described for null velocity excitation.

The Bouc-Wen model is a more accurate approach to predict the MR damper response than the Bingham model. It has the ability to model the hysteretic response but requires the identification of more model parameters than the Bingham model, which involves a more elaborated identification procedure.

5. CONCLUSION

This article addressed the experimental characterization and numerical analysis of a small MR damper. Initially, the general properties of MR fluids and their ability to develop smart controllable devices were presented. Then, a brief review of the available parametric models was addressed. The small MR damper was tested to find the dynamic properties and two parametric models were developed to simulate its behaviour. Finally, an identification procedure was carried out to find the model parameters and was verified the viability of these models to simulate the MR damper response.

6. ACKNOWLEDGMENTS

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