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EXPERIMENTAL IDENTIFICATION OF A MAGNETORHEOLOGICAL SYSTEM

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Abstract. *The property of the magneto-rheological fluids (MRs) to have its viscosity changed in a reversible way, allows the construction of semi-active damping and vibration control systems with a high degree of applicability. MR dampers has been used in tactile feedback systems, automotive suspensions, seismic dampers, and even in transfemoral prosthesis. Considering the applicability of magneto-rheological dampers in different areas of engineering, this work aims to synthesize and analyze this system through a phenomenological approach, which consists in the analysis of experimental results obtained in three different workbench configurations. The damper model used in this work, based on the Bingham model for viscosity, and based on the behavior observed in each of the proposed experiments, was conducted to identify the model parameters for the system. To validate the obtained model, simulations were performed and the results were compared to the measured data from experiments.*

Keywords: *magneto-rheological fluids, MR dampers, experimental identification, Bingham model.*

1. INTRODUCTION

The controllable fluids present one or more mechanical properties that, under the influence of a certain physical greatness variation, like temperature, electric field, pressure, magnetic field, or the like, suffer reversible changes. (Yang *et. al.*, 2002). Among the controllable fluids, the ones employed in control devices are: magneto-rheological fluids and eletro-rheological fluids (ER). The most used intelligent materials are: the piezoelectrics, the electro-restrictive and those with shape memory. (Steffen *et. al.*, 2004, Pons, 2005, e Banks *et. al.*, 1996).

The magneto-rheological fluids (MRs) exist at about twenty years (Yao, 1999), being employed in automotive suspensions, damping in heavy vehicles seats, damping systems for seismic, intelligent prosthesis and tactile feedback systems. The magneto-rheological fluids (MRs) are fluids which present a reversible change in their rheology properties: viscosity, elasticity and plasticity, when exposed to a magnetic field. Under the presence of a magnetic field, the MR fluid varies its rheology together with the field intensity. However, the fluid behaves like a common Newtonian fluid under the absence of a magnetic field. The MR fluids are constituted of magnetically polarised particle (iron oxide), suspended in a fluid, like mineral oil, sintetic oil or silicon. The MR fluids have more advantages than the ER ones; that is why they are more employed.

The purpose of this article is studying the magneto-rheological damper, which consists basically of an absorber, which duty fluid presents an resistance against shearing that varies together with the magnetic field applied over it. (known as magneto-rheological fluid), allowing that, by the application of a controlled magnetic field, become possible to control its cushioning. As its mathematical formulation depends on phenomenological parameters, this article is composed by an experimental modelling, able to obtain the necessary parameters to build the mathematical model adopted, and a simulation comparing the mathematical model with results of MR damper, obtained experimentally.

2. THE MAGNETO-RHEOLOGICAL DAMPER

The magneto-rheological fluid, when are exposed to a magnetic field, shows that its particles own a paralell dipole momentun in relation to the direction of magnetic field. This way, particles, previously dispersal, align themselves along flow lines of the magnetic field, building an structure in the shape of a chain, like shown in Fig 1.

a) b)

Figure 1. a) The MR Fluid, in the absence of a magnetic field b) The MR Fluid, under the presence of a magnetic field (Stutz, 2005).

Each chain of particles formed along a line of flow presents a resistance to go out of this configurations, and the level of resistance presented is proportional to the intensity of the magnetic field under which the fluid is exposed. The Bingham visco-plasticity model (Shames *et. al.*, 1992) is applied to describe the MR fluids behavior as a function of the intensity of a magnetic field. In this model, a fluid behaves as a solid as far as the yield shear stress τ_0 be exceeded and the fluid ends up exhibiting a linear relationship between the tension τ and the shearing deformation rate $\dot{\gamma}$, as observed in the Eq. 1.

$$\tau = \tau_0(H)\,\mathrm{sgn}(\dot{\gamma}) + \eta\dot{\gamma} \quad (1)$$

where: sgn is the signal function and η is the plastic viscosity, defined as being the viscosity presented by the fluid, after occurring the yield. In the absence of a magnetic field, H = 0, the Bingham Model reduces itself to the Newton visco-elasticitys model and the MR fluid behaves like a common Newtonian fluid.

The most common usage of magneto-rheological fluids is in dampers. Their capability to alter their viscosity in a reversible manner provides a great potential in vibrations control applications. The typical scheme of a magneto-rheological damper is shown in Fig. 2.

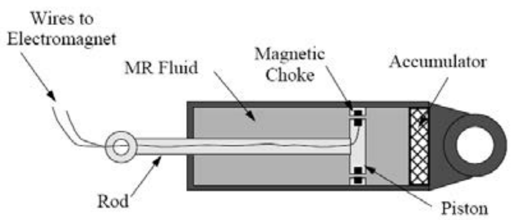

Figure 2. The magneto-rheological damper (Carlson, 2000)

The main cylinder of the damper contains the piston, the magnetic circuit (coil), an accumulator and the magneto-rheological fluid. As a matter of fact, a magneto-rheological shock absorber differs from a conventional one by the presence of a coil in its valve, having the purpose of generating the magnetic field that will modify the reologic properties of the fluid. By increasing the magnetic field intensity, the resistance to the fluid flow through the valve is also increased, resulting in the MR damper force. (Carlson, 2000).

3. THE MATHEMATICAL MODEL OF MR DAMPER

Both non-parametric (Burton *et. al.*, 1996, Ehrgott and Masri, 1992), and parametric models, (Gamota and Filisko, 1991, Spencer *et. al.*, 1996, Kamath and Wereley, 1997, Stanway *et. al.*, 1987), were considered to model the observed behavior in magnetic and eletro-rheological dampers. Ehrgott and Masri, 1994, presented a non-parametric view to model the ERs (eletro-rheological dampers), assuming that the damper force could be described in function of the speed and the acceleration, by Chebychev polynomials. McClamroch and Gavin, 1995, followed a similar methods, when they modelled an ER device. One of the difficulties of this assumption is that the resulting models are, frequently, too complex. Kamath and Wereley (1996) and Makris *et. al.*, (1996), developed parametric models to characterise ERs (eletro-rheological) fluids and the controllable fluid devices. Alternatively, the parametric models based in simple mechanical idealizations were considered by Stanway *et. al.*, (1985, 1987), and Gamota and Filisko, (1991), to describe the behavior of controllable fluids and the controllable fluids dampers .

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The parametric models are phenomenological models usually constituted by means of a combination of simple mechanical elements, like for instance, springs, dampers and friction elements. In this models, parameters are adjusted in a way to reproduce, in a convenient manner, results observed experimentally.

Due to its relative simplicity, the Bingham Model is largely used for the development of MR dampers (Yang, 2001, Poynor, 2001) because it provides an understanding of the influence of the damper geometrical parameters in its performance. The Bingham Model is used in the numerical analysis of a vibrations semi-active device (Johnson *et. al.*, 1998). For these reasons, the mathematical model chosen is the Bingham's.

3.1 The Bingham Model

The Bingham Model consists of a Coulomb friction element put in parallel with the viscous damper, as shown in Fig. 3.

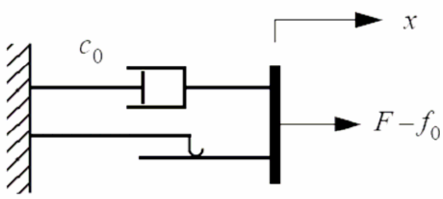

Figure 3. The Bingham Model (Spencer, *et. al.*, 1996)

In this model, for piston speeds different from zero ($\dot{x}$) the force generated by the mechanism is given in Eq. 2:

$$F = f_c \operatorname{sgn}(\dot{x}) + c_0 \dot{x} + f_0 \tag{2}$$

where $\dot{x}$ is the relative speed of the damper ends, sgn( ) is the signal function, c_0 is the constant of plastic damping, that is, the damping coefficient observed after the drainage of the fluid, and f_c is the force related to the drainage tension of the fluid.

4. THE EXPERIMENTAL MODELLING

The experimental formulation is necessary to obtain each one of the three parameters which describe the behavior of the damper through the Bingham model. The MR damper, object of this work, is the model MR RD 1005-3, produced by the Lord Corporation. Three experimental configurations were assembled with the purpose of finding each one of the parameters which compose the Bingham equation, as described below:

4.1 Obtaining the parameter f_0

The f_0 parameter in the Bingham modelling represents the force due to the presence of the internal accumulator of the magneto-rheological damper (Liao, 2011 e Lord, 2007). This value may be considered as an offset of the magneto-rheological system. To obtain this parameter, the experimental assembly shown in Fig. 4 is used.

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Figura 4. The experiment scheme to obtain the f_0 parameter

For each value of current (0A, 0.25A, 0.50A, 0.75A e 1A) a test is done and each measurement is repeated three times. The ideal result for the measured values in the presented experiment is a graph force versus displacement (Fig. 5) with perfect steps demonstrating the constant value of the force expressed by the f_0 parameter, since this value appears, no matter the damper rod has or not condition of displacement. Besides, the f_0 gets evident when speed is equal to zero, since all the other terms of Bingham equation get null, as demonstrated in Eq. 3.

$$F = F_c.\mathrm{sgn}(\cancelto{0}{\dot{x}}) + co.\cancelto{0}{\dot{x}} + fo = fo \qquad (3)$$

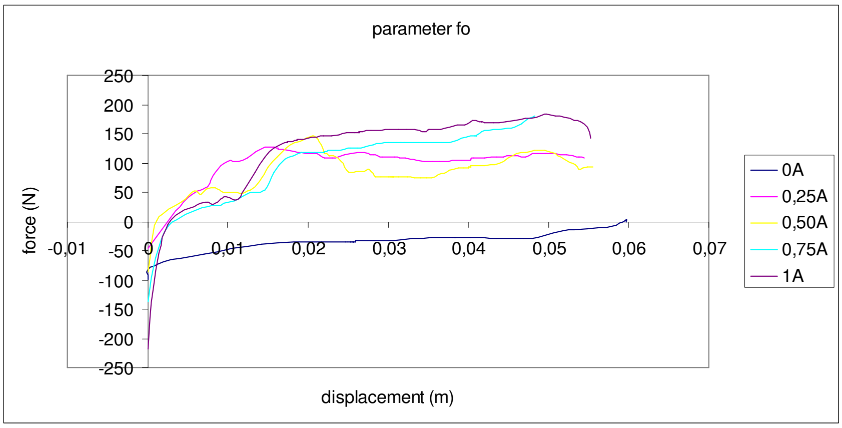

Figure 5. The graph Force x Displacement for the f_0 parameter

Due to the variation of f_0 with displacement, a procedure is adopted for its determination, in accord with two lanes of displacement. The first one at the initial region of the chart and the another in a second region where the value of the force tends to get stabilized. As a manner of getting the graph closer to the ideal condition, it was adopted a linearization in these two distinct patches of the graph. This way the f_0 may be determined for each considered patch of displacement, by the linear equation of each linearization.

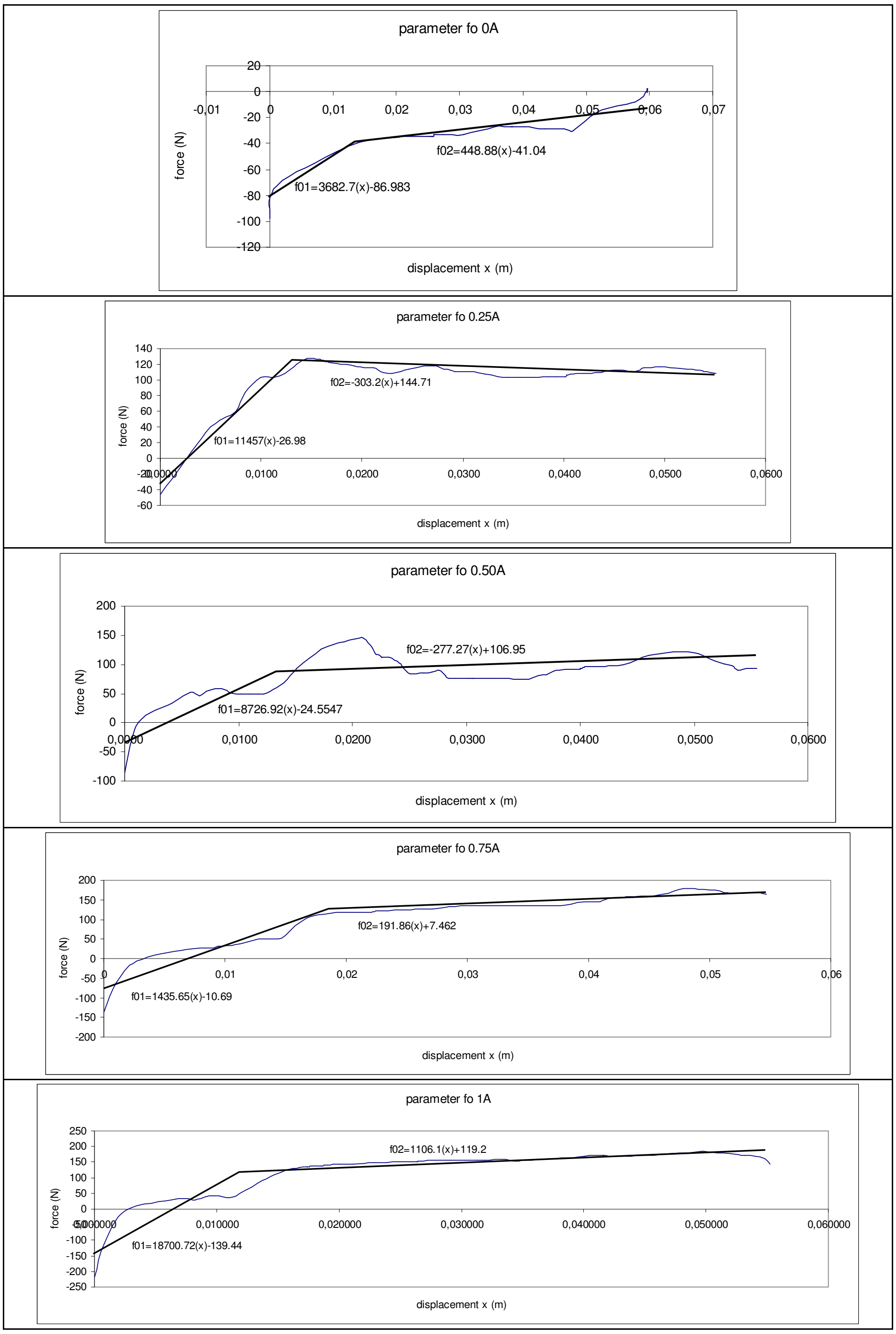

Figure 6. The obtaining f_0 parameter from the graphs Force x Deslocation obtained experimentally

4.2 Obtaining f_c and c_0 parameters

The obtaining experiment of the two parameters is similar to that one used for obtaining the f_0 parameter. From the damper position on, with its rod totally retreated (closed), known weights are hung and a certain value of current is applied. Afterwards, using the potentiometer the descent speed of the damper is measured due to the action of the weight. The Figure 7 shows this configuration.

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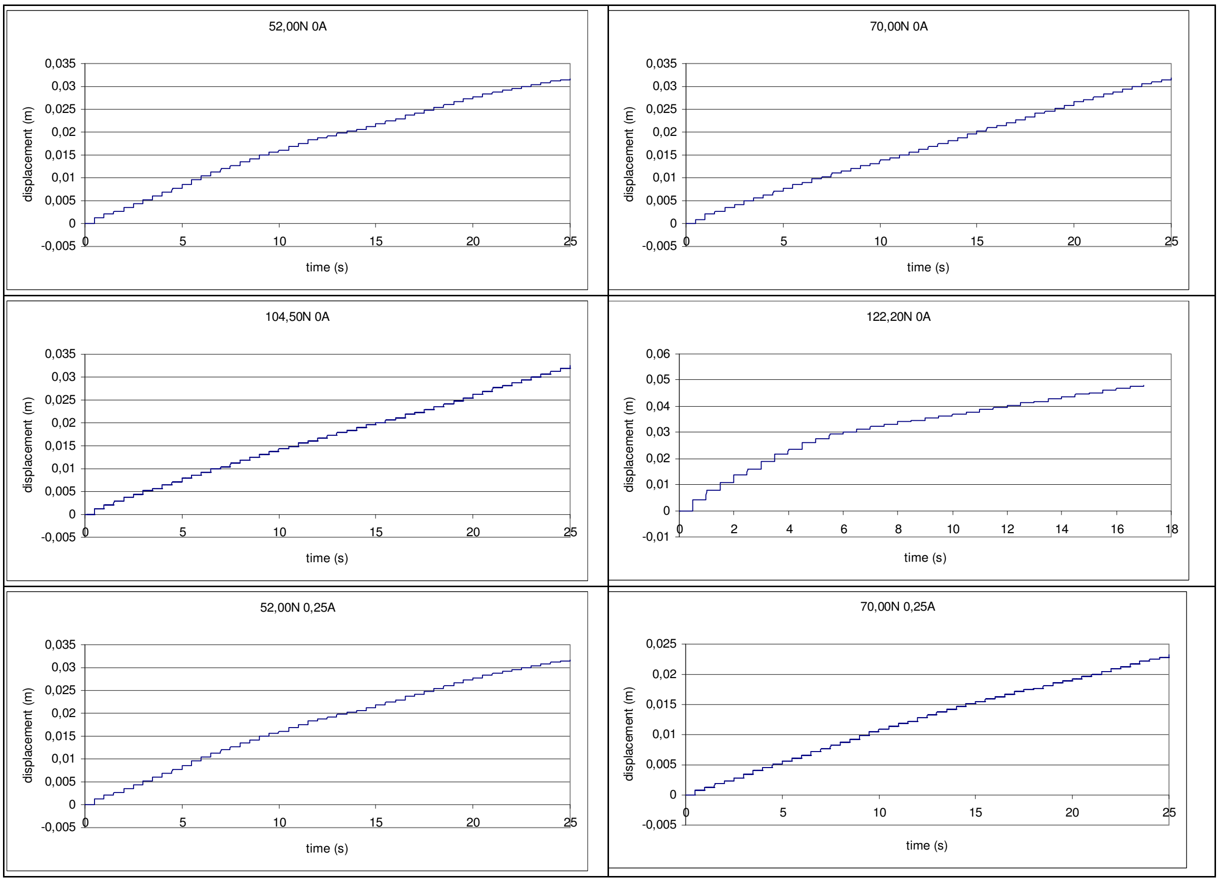
Figure 7. The experiment scheme for obtaining f_c and c_0 parameters

Therefore, once knowing the force, and having measured the speed, and determined the f_0, the Bingham equation turns into only two parameters to be determined: f_c e c_0. As the displacement per time graphs have a linear behavior, it is possible to extract the speed values in the graph by means of calculating its gradient. The speed per time graphs, for each control current value (0A, 0.25A, 0.50A, 0.75A e 1A) related to each value of weight (52.00 N, 70.00 N, 104.50 N e 122.20 N), are shown in Fig. 8.



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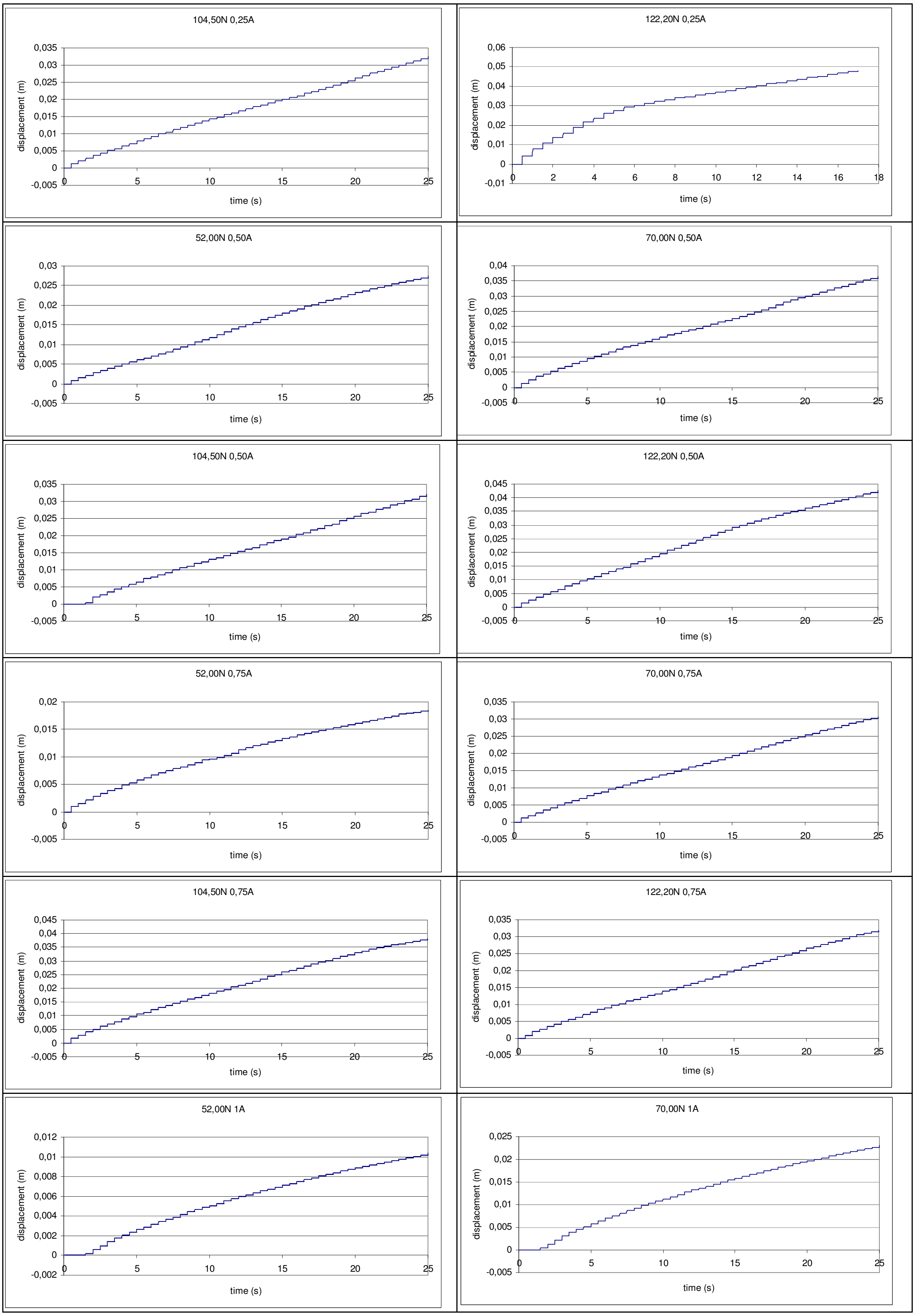

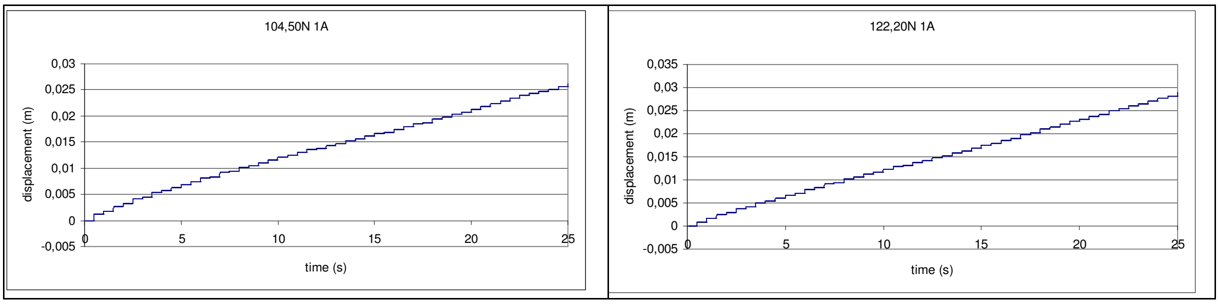

Figure 8. The graphs Displacement versus Time

With this, once knowing the value of the force (F), the value of speed ($\dot{x}$) and the value of f_0, one may build a linear equations system, from the manipulation of Bingham equation. For each patch of displacement and value of current, four equations are built as shown in Eqs. 4 e 5.

$$\begin{cases} F_1 - f_{01} = F_c.sign(\dot{x}_1) + C_0(\dot{x}_1) \\ F_2 - f_{01} = F_c.sign(\dot{x}_2) + C_0(\dot{x}_2) \\ F_3 - f_{01} = F_c.sign(\dot{x}_3) + C_0(\dot{x}_3) \\ F_4 - f_{01} = F_c.sign(\dot{x}_4) + C_0(\dot{x}_4) \end{cases} \tag{4}$$

$$\begin{cases} F_1 - f_{02} = F_c.sign(\dot{x}_1) + C_0(\dot{x}_1) \\ F_2 - f_{02} = F_c.sign(\dot{x}_2) + C_0(\dot{x}_2) \\ F_3 - f_{02} = F_c.sign(\dot{x}_3) + C_0(\dot{x}_3) \\ F_4 - f_{02} = F_c.sign(\dot{x}_4) + C_0(\dot{x}_4) \end{cases} \tag{5}$$

Where: F_1 = 52.00 N, F_2 = 70.00 N, F_3 = 104.50 N, F_4 = 122.20 N, $\dot{x}_1$, $\dot{x}_2$, $\dot{x}_3$ e $\dot{x}_4$ are the speeds related to the values of current and weight, obtained from the presented graphs, and f_{01} and f_{02} are the the extreme values in the patch of f_0 parameter, related to the value of current, and obtained in section 4.1. Substituting the values in Eqs. 4 e 5 and solving the equations systems using the Ordinary Least Squares Method, the values for f_c and c_0 related to the value of current and path of displacement are obtained.

The table 1 displays all the parameters from Bingham equation, obtained experimentally for the MR RD 1005-3 Damper.

Table 1. The values of the parameters obtained for MR RD 1005-3 Damper.

0A			
Displacement(m)	f_0 (N)	c_0 (N/m/s)	f_c (N)
0 ↔ 0.0146	-86.99 ↔ -34.68	118731.75	-182.26 ↔ -129.96
0.0146 ↔ 0.0577	-34.68 ↔ -15.13	118,731.75	-129.96 ↔ -110.41
0.25A			
Displacement (m)	f_0 (N)	c_0 (N/m/s)	f_c (N)
0 ↔ 0.0146	-26.98 ↔ 140.29	104694.00↔104709.30	-70,57 ↔ 96.68
0.0146 ↔ 0.5510	140.28 ↔ 128.00	104709.30	96,67 ↔ 84.39

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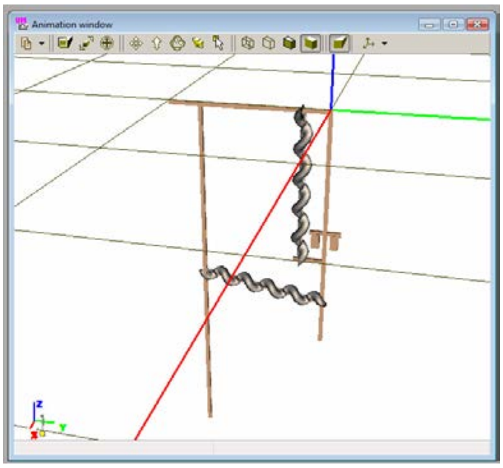
0.50A			
Displacement (m)	f_0 (N)	c_0 (N/m/s)	f_c (N)
0 ↔ 0.0146	-24.55 ↔ 102.85	115934.92	-68.95 ↔ 58.44
0.0146 ↔ 0.5510	102.90 ↔ 91.56	115934.92	58.49 ↔ 47.16
0.75A			
Displacement (m)	f_0 (N)	c_0 (N/m/s)	f_c (N)
0 ↔ 0.0146	-10.69 ↔ 10.26	108584.06↔108590.02	-20.70 ↔ 0.25
0.0146 ↔ 0.0547	10.26 ↔ 17.95	108449.80↔108584.06	0.45 ↔ 7.94
1A			
Displacement (m)	f_0 (N)	c_0 (N/m/s)	f_c (N)
0 ↔ 0.0146	-139.44 ↔ 135.46	118064.13	-146.34 ↔ 128.55
0.0146 ↔ 0.0552	135.46 ↔ 180.25	118063.48↔118064.13	128.55 ↔ 173.34

5. SIMULATION

The simulation is developed in the multibody system dynamics software called Universal Mechanism© (UM). This software is based on numerical methods and allows the generation of motion equations, numerical analysis and results treatment. In the Figure 9 shows the models referring to the two experimental configurations.

a)



b)

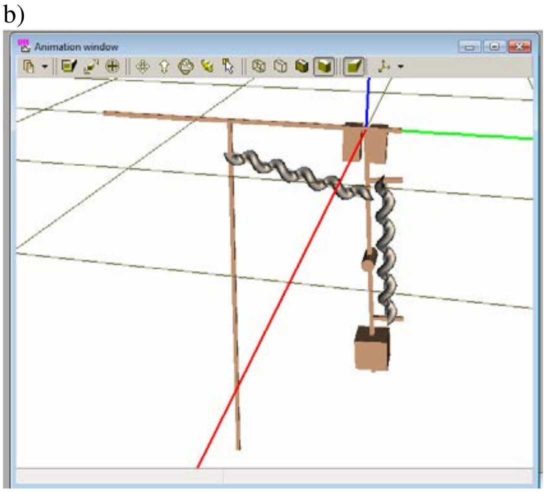


Figure 9. a) The model of experimental configuration for obtaining the parameter f_0, b) The model of experimental configuration for obtaining the parameters f_c e c_0

The elements in the form of spring are just visual elements and represent the pneumatic actuator and the MR damper, having no mechanical characteristic of the spring element. The actuator and the MR damper, are modeled through its mathematical equations, thus allowing their adjustment parameter for each simulation. In the simulation are used parameter values f_0, f_c and c_0 experimentally obtained. In the Figure 10 are presented the simulation results with the experimental modelling.

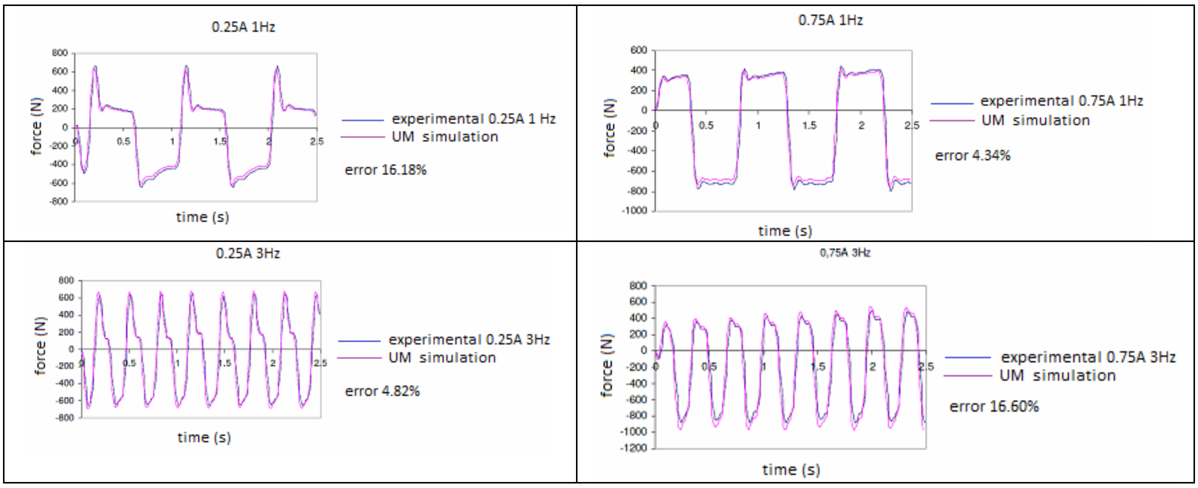


Figure 10. The graphs Simulation versus Experiment

6. CONCLUSION

The experimental results were compared with the curves generated by the simulation, and are satisfactory. The purpose of this study was to analyze and obtain the mathematical modelling, through an experimental analyzing its phenomenological behavior through experimental tests. As Bingham postulated the model for rheological fluids (non-Newtonian behavior), this was the primary reason for the use of his model for the damper. The second reason was due other models found in the literature (Filisko Gamota model, Bouc-Wen model and the model of Bouc-Wen Modified), all of them using modelling based on the Bingham model, but adding more parameters in order to better define the behavior of the damper. The inclusion of these additional parameters ends up increasing the complexity of the equation, which would be useful only for phenomenological approach of great difficulty. The experimental configurations were developed to test the damper in a case close to a real situation, in order to verify its behavior under these conditions. From the results obtained, it was observed that any backlash resulting from movement and vibration influences experimental measurements. Obtaining parameters under these conditions allows getting values in a real situation, subject to the influence of mechanical phenomena, such as vibrations and friction, present in any kind of mechanism.

It was discovered a variation of the parameter values f_c and f_0 related to the position of the damper rod. Moreover, there was not variation in parameter values with the change of excitation frequency, but with the current value of control. It can be seen that the experimental values are satisfactory, once they vary according to the damper operation. Furthermore, the values obtained experimentally by means of the simulation prove that theoretical and experimental graphs are, in fact, very similar. The presented experimental workbenches allow their use in most studies in this large area with the same model of the damper or with other models. The settings were designed aiming at a future work using a Magnetorheological Transfemoral Knee Prosthesis

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