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AN EXPERIMENTAL APPROACH OF ELECTRORHEOLOGICAL FLUID DAMPERS DESIGN

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Abstract. As far as nowadays the technology continues to advance, the need for vibration isolation becomes increasingly necessary. Electro-Rheological Fluid (ERF) dampers have been proposed for vibration control. This work presents an experimental study of Electro-Rheological (ER) dampers that could be used mainly in vehicle suspension systems. So far, an experimental setup of a double cylinder stroked by a single cross head is established, in order to investigate the vibration performance of an electrorheological fluid damper, under different electric fields. The electrorheological fluid used for the experiments is a mixture of SAE 10 oil and zeolite particles. The major findings are the hysteresis loops and the damping force that measured and presented for the various electric fields. It is clearly obtained that, as the electric field increases the capacity of the damping increases. Machine learning in terms of regression have been then applied for damping forces versus electric field yield further predictions.

Keywords. Electrorheological Fluids, Smart dampers, Smart materials

1. INTRODUCTION

Structures and mechanical systems should be designed to enable better performance under different types of loading, particularly dynamic and transient loads. ERFs are smart materials whose rheological properties (viscosity, yield stress, shear modulus, etc.) can be readily controlled using an external electric field. They can switch from a liquid-like material to a solid-like material within milliseconds with the aid of an electric field. Electro-rheological fluids have witnessed the rise in demand lately, due to high demand from sectors such as automotive and defence research & development. An ER suspension consists of an insulating liquid medium, which embodies either a semi conductive particulate or liquid material, and has the capability of responding to stimulation from an external electric field. ER fluids can be used in three distinct modes of operation or combination of these modes, namely, the shear mode, flow or pressure mode, and the squeeze mode. The most recently introduced mode is the squeeze flow. This operating mode involves electrode motion in the direction of the applied field therefore, the field strength continually varies according to the electrode distance [1]. The main segment of the recent works related with the electrorheological fluid dampers and its applications are presented below. A new type electrorheological fluid shock absorber was designed [2] and a fuzzy control electrorheological fluid shock absorber system was also designed. A new analytical approach for dynamic modelling of the Electrorheological (ER) damper for accurate prediction of the hysteresis behaviour presented in [3]. The design principle of an electrorheological isolator for adjustable hysteresis modelling is put forward with its basic performance analyzed [4]. A single-layer electrorheological device and electrorheological isolator for adjustable hysteresis were designed and four types of hysteretic damping force models of both dampers were developed through numerical simulations. The field-dependent yield stress of the ER fluid evaluated experimentally at various temperatures and the dynamic characteristics of the ER damper were investigated in order to obtain the time constant. The dynamic mechanical properties of conventional standard hydraulic oil-filled and an ERF filled shock absorber for automotive applications were characterized and their behaviours compared [5]. A numerical investigation of semi-active vehicle suspensions based upon smart fluid dampers was also reported [6]. After demonstrating the unsuitability

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of employing a smart damper in open loop, the advantages of linearizing the force/velocity response were demonstrated. It was shown, how a smart damper with force feedback can operate as a controllable viscous damper. The response analysis of a vibration system with ER dampers using the viscous and bilinear hysteresis damping model was discussed in [7]. The reduction of vibrations using electrorheological fluids by controlled damping was presented in [8]. The result shows a good agreement and an effective isolation ability. A giant ERF was developed in [9] with a binary liquid phase by the addition of alkane to the silicone oil continuous phase. The rheological characteristics of the suspension composed of PDPA/Fe_3O_4 particles suspended in silicone oil were investigated by a rotation rheometer [10], demonstrating standard electrorheological (ER) characteristics with a dramatic increase in shear stress and dynamic moduli under the application of an electrical field strength.The purpose of this work was to develop an experimental model for predicting the behaviour of the force and the damping produced by electrorheological dampers. An ER double concentric tube with single cross head model was designed and manufactured in order to perform the experiments. The Scotch Yoke mechanism is used as an autonomous vibrator. An ER fluid based on the SAE 10 lubrication oil mixture with zeolite particles is prepared and used. The hysteresis loops and the damping force under the various electrical fields are measured and presented. The effect of the ERF that increases the damper capacity is clearly observed. Machine learning techniques are also used in order to predict the damping force as a function of the electric field. The proposed design of the ER damper can be used for testing shock absorbers for several technologies, setting up the soft and the hard requirements which is essential for the implementation of new control strategies for semi-active suspension systems.

2. MODELING ER FLUID FLOW IN VIBRATION DAMPERS

It is well established that the electrorheological fluids provide the basis for the controllable vibration damping devices. The most popular of ER damper device is one applied on the automotive shock absorbers. For ride comfort, shock absorbers with a soft setting are required to dissipate shock energy from the road; on the contrary a hard set up is required for a good vehicle handling. The damper consists of an external cylinder and it has a big enough surface for the ER effect. Their disadvantages are the relative big volume and the manufacturing cost. However, the easy access of the oil filling, as well as the assembly and disassembly of its components, are some of its advantages. The proposed damper consists of two tubes as shown in Fig. 1. The gap between the tubes is 1mm. Inside the internal tube a number of holes have been manufactured, which facilitates the flow of the ERF from the internal to external cylinder. The electrorheological phenomenon is developed between the gap of the two cylinders. The volume regarding the developed ER phenomenon is big enough and it is a function of the cylinder's height. Insulating seals are also used between the two cylinders.

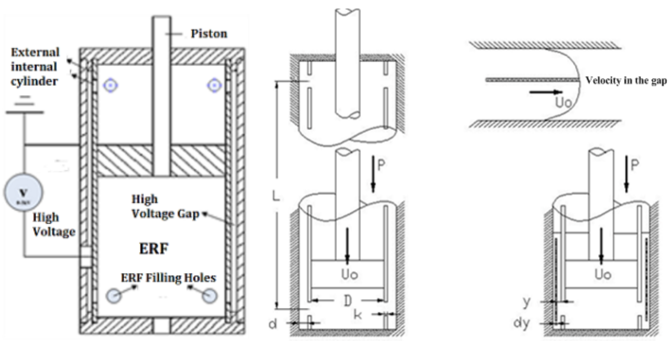

Figure 1. The basic operation principle.

According to theoretical model, the viscous force, and the shear stress is given by the expressions (1) and (2)

$$F = \pi DLd\tau = \pi DL\frac{d\tau}{dy}dy \tag{1}$$

$$\tau = -\mu \frac{d\upsilon}{dy} \tag{2}$$

From the expressions (1) and (2) it is obtained:

$$F = -\pi DLdy\mu \frac{d^2\upsilon}{dy^2} \tag{3}$$

The viscous force produces pressure on the piston given by expression (4):

$$p = \frac{F}{\pi D^2/4} = \frac{4F}{\pi D^2} \Rightarrow p(\pi Ddy) = \frac{4F}{D}dy \tag{4}$$

The term πDdy denotes the lubricant area between y and $(y+dy)$. By supposing that the medium piston velocity is the same throughout the fluid flow, it is obtained from expressions (3) and (4):

$$\frac{d^2\upsilon}{dy^2} = -\frac{4F}{\pi D^2 l\mu} \tag{5}$$

Using the following boundary conditions: $\upsilon = 0$ for $y = 0$, $\upsilon = \upsilon_0$ for $y=d/2, \upsilon = 0$ for $y = d$

and by integrating the Eq. (5) the Eq. (6) is obtained:

$$\upsilon = \frac{2F}{\pi D^2 L\mu}(yd - y^2) \tag{6}$$

The lubricant oil flow can be given by the expression (7):

$$Q = \int_0^d \upsilon\pi Ddy = \frac{1}{6}\frac{2F}{Dl\mu}d^3 \tag{7}$$

The oil flow rate in the piston gap must be equal to the piston rate movement:

$$\upsilon_0 = \frac{Q}{\pi D^2/4} \tag{8}$$

From the combination of Eq.s (7) and (8) and for $F = c\upsilon_0$ it is obtained the damping coefficient as:

$$c = \frac{3}{4}\mu\left[\frac{\pi D^3 L}{d^3}\right] \tag{9}$$

In the performed experiments, the ER fluid behaves as Bingham fluid. The Bingham model in one dimensional flow can be written:

$$\tau = \tau_0 + \mu_0 \dot{\gamma} \tag{10}$$

where τ is the shear stress, τ_0 is the dynamic shear stress, μ_0 is the plastic viscosity and $\dot{\gamma}$ is the shear rate. In order to determine the ER fluid material behavior, the ER damper setup has been modified operating as rotary viscometer (Fig 3). The shear rate can be given by the expression $\dot{\gamma}$, where ω is the angular viscosity of the internal cylinder of the viscometer. The shear stress is related with torque by the expressions:

$$\tau = \frac{T}{2\pi L r_1^2} \tag{11}$$

where $r_1=(R+r)/2$, r is the internal viscometer diameter and R is the external cylinder diameter, and L is the external viscometer cylinder length. The dynamic yield stress at zero speeds can be calculated as, [11]:

$$\tau_0 = \tau_1 \frac{1-1/s^2}{2\ln(s)} \tag{12}$$

where $s=R/r$, $\tau_1=T_0/(2\pi l r^2)$ and T_0 is the dynamic yield torque, which can be computed for the extrapolation of linear relation of the experimental data (torque versus speed). The apparent viscosity can be calculated by the following relation:

$$\mu_\alpha = \frac{\tau_\tau - \tau_R - 2\tau_0 \ln(s)}{2\omega} \tag{13}$$

where, $\tau_r / \tau_R = (R/r)^2 = s^2$, or using the Petroff's equation [12], the eq. (14) is obtained:

$$\mu_\alpha(\dot{\gamma}) = \frac{Tc}{\pi^2 D^3 LN} \tag{14}$$

where c is the gap between the viscometer cylinders and N is the internal viscometer cylinder revolutions and T is the viscometer Torque. The variation of the shear stress as a function to shear rate, for several electric fields, is depicted in figure 2a. It is obvious that the proposed ERF behaves clearly as a Bingham fluid. For the dynamic yield stress a polynomial approximation is used. The dynamic yield stress is obtained (Fig.2b) as:

$$\tau_0 = \alpha_0 + \alpha_1 E + \alpha_2 E^2 \tag{15}$$

Where, $a_0 = 120.54109$, $a_1 = 216.52739$, $a_2 = -36.55134$, E is the electric field density.

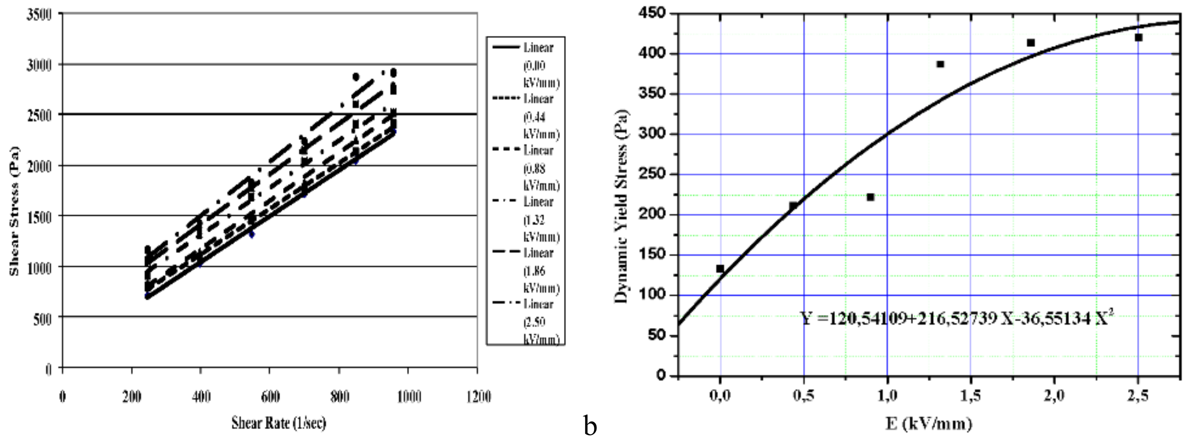

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Figure 2. a) Shear stress as a function of shear rate for the ERF fluid used for several electric fields, b) Dynamic yield stress as a function of the electric field.

3. EXPERIMENTAL PROCEDURE

The ERF damper is shown in Fig. 3. The damper is a single cross head with double cylinder. It consists of a metallic cylinder, a metallic cross head, two covers up and down, and the seal gaskets. The external and internal cylinder is made by copper while the piston and the cross head are made by stainless steel. The top and bottom cover of the damper have been made by Plexiglas, which insulates electrically the internal and the external cylinder. The metallic frame has been constructed by a steel sheet with 5 mm thickness. This means that the support structures are stiff enough in order its dynamic performance not to influence the damper dynamic behavior. Furthermore, the stroke length is 190mm, the diameter of the piston is 19.8mm while the diametral gap between the piston and the internal cylinder is 2.2 mm. The experimental ring consists of the electrorheological damper, the Scotch Yoke mechanism, an oscilloscope by a labview setup, a charge amplifier of Brüel and Kjaer, type 2635, a Nickel – Constantan thermocouple in order to monitor the temperature of the damper oil.

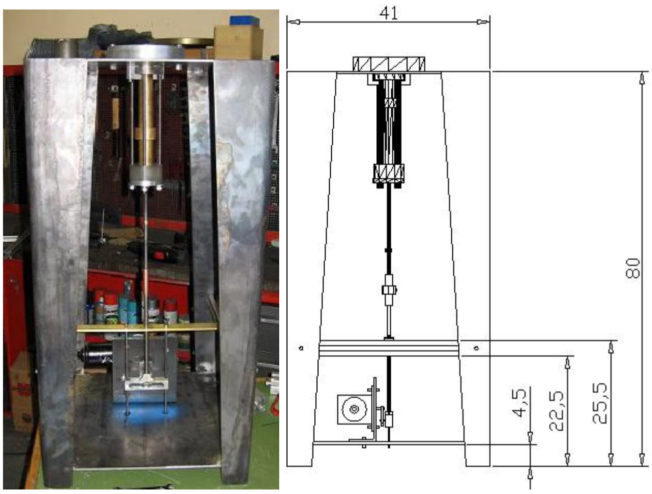

Figure 3. Basic dimensions of the experimental ring.

In order to apply the various electric fields on the electrorheological fluid, a power amplifier with range 0–24 V, DC and a voltage multiplier with range from 0 to 3.5 kV are used. The experiment is monitored by a PCMCIA computer card of National Instruments and the Lab View software. The force transducer used in order to measure the forces produced by the electro rheological damper is the 8200 of Bruel&Kjaer. A series of tests have been performed in order to calibrate the Scotch Yoke Mechanism. They are transformed in sinusoidal loading conditions regarding the acceleration components. Displacements and velocity diagrams have been also obtained.

4. RESULTS

4.1. Damping measurements.

A series of tests is conducted to measure the response of the damper under various sinusoidal loading conditions. A performance test consists of frequency sweep held at constant displacement input. The variation of the damping force of the ERF damper versus the electric field, for several rotational speeds is presented in Figure 4. The indicated temperatures correspond to the equilibrium temperature state where the response measurements have been taken. It is clearly observed that, as the electric field increases the damping force also increases for any rotational speed. From figure 4 also, it can be seen that the ER damper is asymmetrical; the maximum force in extension (positive velocity) is greater than the force generated in compression (negative velocity).

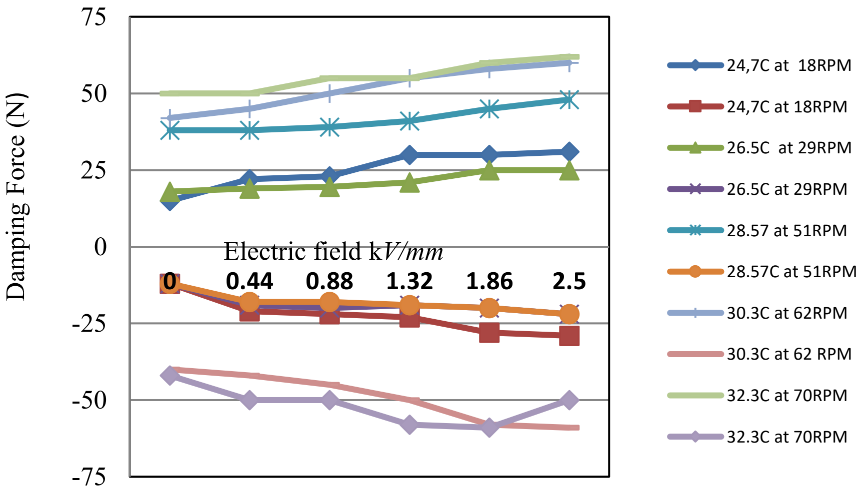

Figure 4. Damping force variation as a function of the electric field, for various motor speeds: a) 28 rpm, b) 29 rpm, c) 51 rpm, d) 62 rpm, e) 70 rpm.

The force consists of a velocity dependent component, which is also different in the extension and compression stages. The damper presents hysteresis in all of its operational range, being more notorious at low and positive velocities. The electrorheological mixture is prepared using a zeolite solids with Oil SAE–10, a common oil for lubrication and zeolite particles Z3125, by Sigma Chemical Co. with Chemical formula $Na[(AlO_2)86(SiO_2)106]{\times}H_2O$, nominal pore diameter 9–10 Å and particle diameter 10µm. For the present work one mixture were prepared, with 26.3% the percentage by weight of zeolite. Before the mixture, the zeolite particles were subjected to a drying process for 5 h in order to reduce the humidity of the particles, doing the electrorheological phenomenon more effectively. The apparent viscosity of the ERF was measured by a commercial viscometer Ferranti type VL and found to be 0.175 Pa·s at 30.90 °C. The gap between the two cylinders (external and internal) was 1 mm.

4.2. Machine learning.

For the purpose of this study simple and multi-variable data models were built in order to describe relationships between predictor and response values. The models discussed in this study are simple and multi variable, linear and polynomial regression all based on the least-squares fit methodology in which the sum of the squares of the residuals needs to be minimized. As discussed [14] these regression models are widely used in machine learning applications mainly due to their simplicity and accuracy to predict the corresponding response values. To increase the applicability of the model, regression of the parameters is necessary. The maximum excitation velocity and the applied electric field have been taken into consideration to regress the identified parameters. The simple linear regression model describes the relation between one dependent variable y and one or more in this case independent variables: x_1, x_2. The equation that describes this relation is a simple line with slope β_1 and y-intercept β_0:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \varepsilon \tag{12}$$

Where, ε represents the prediction error.

For the current study y represents the damping force values [N/s], while x_1 and x_2 represent the corresponding electric field [KV/mm] and rotating velocity [rpm]. With the data obtained a set of n-observation leads to a system of n-equations that is generated in matrix form:

$$Y = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix} = \begin{bmatrix} 1 & x_{11} & x_{21} \\ 1 & x_{12} & x_{22} \\ \vdots & \vdots & \vdots \\ 1 & x_{1n} & x_{2n} \end{bmatrix} \begin{bmatrix} \beta_0 \\ \beta_1 \\ \beta_2 \end{bmatrix} \tag{13}$$

or

$$Y = XB \tag{14}$$

The solution of this system generates the values needed for the regression line: β_0, β_1, β_2. The difference in the case of the polynomial regression line is that the X matrix has to be adapted to represent the corresponding polynomial. For the current study a 2nd degree polynomial for both independent variables is discussed and the X matrix is formed accordingly:

$$X = \begin{bmatrix} 1 & x_{11} & x_{21} & {x_{11}}^2 & x_{11}x_{21} & {x_{21}}^2 \\ 1 & x_{12} & x_{22} & {x_{12}}^2 & x_{12}x_{22} & {x_{22}}^2 \\ \vdots & \vdots & & \vdots \quad \vdots & \vdots & \vdots \\ 1 & x_{1n} & x_{2n} & {x_{1n}}^2 & x_{1nx_{2n}} & {x_{2n}}^2 \end{bmatrix} \tag{15}$$

In order to measure the goodness of fit for the generated lines the coefficient of determination, or R^2 is calculated for both models. This coefficient indicates the difference between the values dependent variable y_{fit} calculated from the model and the observations y_{exp} obtained from the relevant experimental simulations.

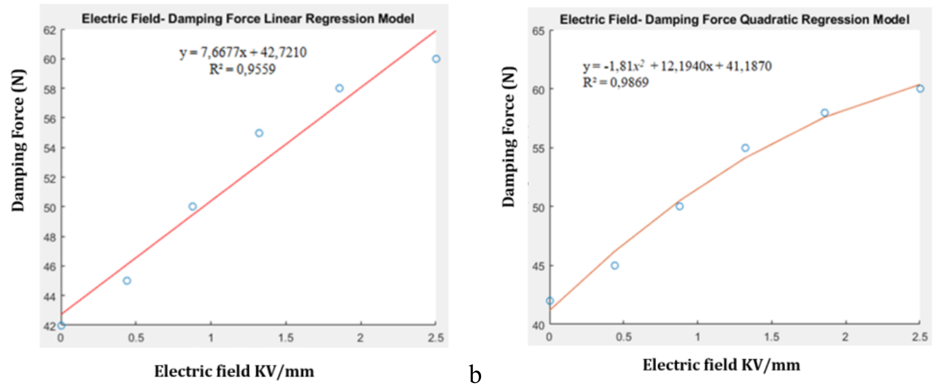

Figure 5. Damping force variation as a function of the electric field, for 62 rpm and down stroke: a) linear regression model, b) quadratic regression model**.**

To begin with, the data obtained by the figure 5 were used in order to train a model that predicts the damping force versus electric field. This is an initial approach with a simple linear regression model based on one independent value. Running the algorithm a trend line was generated with a slope of 7.66 and a y-intercept of 42.77 for down stroke of 62 rpm, and respectively 8.52 and 38.99 for upstroke condition. This regression model has a coefficient of determination of 0.9559 which can be translated to a 95.59% accuracy for the model to predict the relation between damping force and electric field for downstroke and 95.29% for the upstroke design damping force for the case studied. For the second approach, a 2nd-order polynomial regression line was generated for the same case studies. The line is described by the constants [–1.81, 12.89, –41.18], for the downstroke, and has a coefficient of determination 0.9869. This model has the ability to predict the force with a 98.6% accuracy and since it was built based on the same data pool it is considered to be of preference for the current study. The case of the upstroke, the line is described in its turn by the constants [0.1047, –0.8340, –38.019], for the downstroke, and has a coefficient of determination 0.9519. This model has the ability to predict the damping force with a 95.2% accuracy.

4.3. Electrorheological fluid damper hysteresis measurements.

The force velocity and force displacements experimental results, (figures 6–7) are analyzed and the following characteristics can be identified: (i) hysteresis: the observed hysteresis is considered significant, based on the dispersion of the force measurements; (ii) static friction and (iii) viscous damping. Here it is presented the occurred hysteresis response diagrams for 62rpm motor revolutions, with the electric field variation (figures 5 – 6). The area of the certain diagrams that present the variation of the force versus the displacement and the velocity of the piston corresponds to the needed work and power for one completed piston cycle. Using the simple Simpson's rule, as below, the enclosed area can easily be calculated, Eq. 16:

$$I = \int_{x_0}^{x_2} f(x)dx \approx \frac{h}{3}(f(x_0) + 4f(x_1) + f(x_2)) \tag{16}$$

where $h=(x_0+x_2)/2$ and $x_1=(x_0+x_2)/2$. So, using the limits which are written in the figures 6–7 and for E=0 kV/m, the calculated work is 3.20 Joule and the respective power is 5.30 Watt. Respectively, for E=2.6 kV/m the calculated work is 4.60 Joule and the corresponding power is 7.35 Watt. The work increment in this case is 28.50% while the increment in the power is 27.40%.

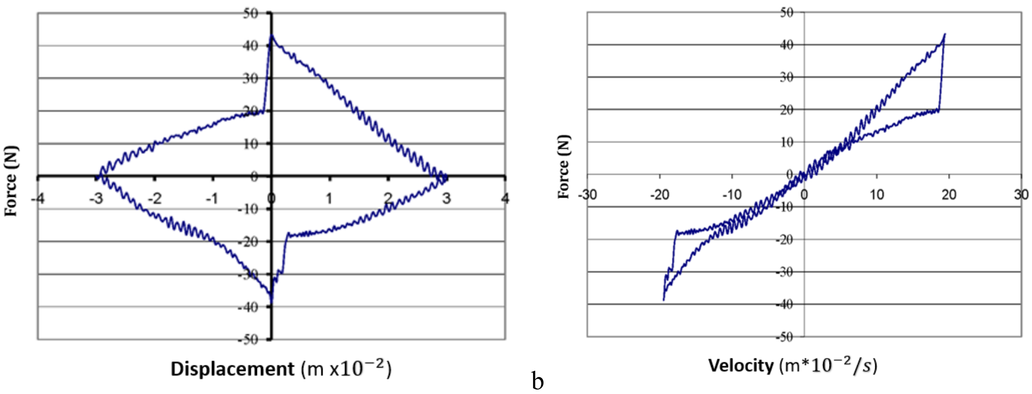

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Figure 6. Hysteresis loop of ERF damper: a) force vs. displacement, b) force vs. velocity, for *E* = 0 kV/mm.

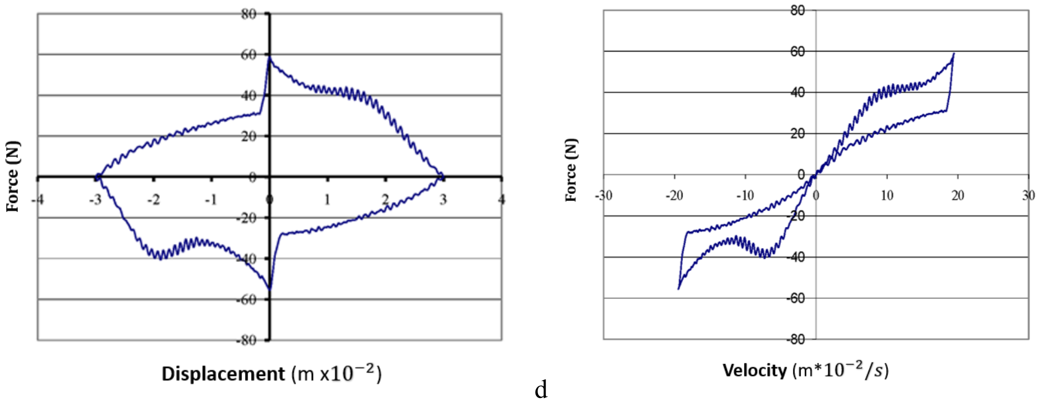

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Figure 7. Hysteresis loop of ERF damper: a) force vs. displacement, b) force vs. velocity, for *E* = 2.6 kV/mm.

5. CONCLUSIONS

In this paper an experimental study and a simplified mathematical model is presented, for the characterization of a controllable ER fluid damper. With the developed ER damper the response under dynamic conditions can be characterized in a form that could be suitable for control simulations. The experimental observations of the hysteresis loops indicates that the electrorheological damping force has a significant increment by increasing the applied electric field. The experiments resulted that the work and the power needed for one complete cycle are both increased by increasing the electric field. Regression models were used as machine learning application, mainly due to their simplicity and accuracy, in order to predict the corresponding response values of the damping force and the electric field. All in all, the proposed experimental and simple mathematical procedure is a quick and reliable methodology to evaluate smart dampers behavior, offering inputs for its detail design and control strategies.

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