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Characterization of the magnetorheological fluid MRF-140 CG for applications in robotic prosthesis

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Abstract. The present article shows the different results of the rheological properties of the magneto-rheological fluid (MRF-140CG; LORD Co. (USA), focused on predicting its behavior in devices that use these materials, to characterize the fluid MRF-140CG several tests were performed using a rotational rheometer Anton Paar Physica MRC-501 equipped with a magnetic rheological cell MRD-70/1Text, according to DIN-53018, the tests were performed with magnetic fields from 0 T to a maximum of 800mT with increments of 200mT and temperatures from 20 to 50°C with increments of 10°C in each test. In addition, in order to determine the dynamic model, a shock absorber designed by the authors was tested in accordance with ISO 2954 standards on the Dyno-Shock 11 test bench. To determine which of the models precisely predicts the behavior of the magnetic rheological fluid, a comparison was made between Experimental model, Bingham plastic model, the Bi-Viscose model and the Herschel-Buckley model. This contributed to the design of increasingly sophisticated, reliable and efficient intelligent mechanical devices according to each need.

1. Introduction

Nowadays the technological advance in the field of intelligent materials, among others can be transformed by external agents, such as a magnetic field, which applied to an MRF fluid changes its behavior being non-Newtonian in the presence of the field and Newtonian in the absence of the field, in other words, its state changes from a fluid with low viscosity, to a fluid with high stress with high presence of viscosity. Due to the change in their properties in a controlled way, they are of great interest for applications in engineering fields such as: biomechanical devices, robotic exoskeletons, intelligent prosthesis, etc. [1,2], in suspensions, damping systems, anti-seismic systems, valve control, etc. [3,4] with the purpose of guarantee a technological development innovating with intelligent devices that help to improve people's quality of life.

2. Characterization

In order to characterize the magnetorheological fluids, the parameters are: the type of particle, geometry, size, distribution, and quantity of particles used [5], as far as the carrier fluid is involved, the characteristics of interest are the dynamic behavior of the viscosity and the different additives for the variables of response velocity, deposition and stability. [6] Being necessary for applications with magneto rheological fluids a deep knowledge of their properties and how they are performed at external stimuli to predict the behavior of these parameters and adjust them for application in



technological designs that take advantage of these characteristics.; With a focus on these parameters, the characterization of the fluid was carried out by means of two normalized tests, first in a sample, to measure the rheological properties, which are altered under the action of magnetic fields at different intensities and temperatures, followed by a test to determine the dynamic model, which predicts the performance of the fluid, in a magneto-rheological shock absorber, the following models were considered: Empirical model Bingham Plastic model, Bi-Viscose model and the Herschel-Bulkley model.

3. Test apparent viscosity

Realized in rheometer MCR-501, with magnetorheological cell MRD-70/1Text in combination with a measurement system with parallel plates of 20mm diameter of non-magnetizable metal, to avoid radial magnetic forces on the measurement axis, in addition to the thermostatic bath system Julabo F-25 for the application and temperature control with a stability less than $\pm 0.1^\circ\text{C}$. Considering the non-Newtonian behavior and the non-constant stress state in the whole sample for the conversion of the parameters of the rheometer rotation angle, rotation speed and torque, and the rheological parameters strain, strain rate and stress the Rabinowitsch conversion was used. [7]

3.1. Test conditions

Fluid tests were performed under the following initial conditions: Temperatures of 20, 30, 40, and 50°C , Heating rate of 0 to 350 rad/s and magnetic field from 0mT to 800mT with 200mT increments in each test.

3.2. Test Results

The processing of the data, as well as their interpretation, is the key to accurately provide all the variables involved in the research, in order to describe the characteristics of the test data, these are processed using descriptive statistical techniques and are presented in graphs of curves to compare and analyze the results.

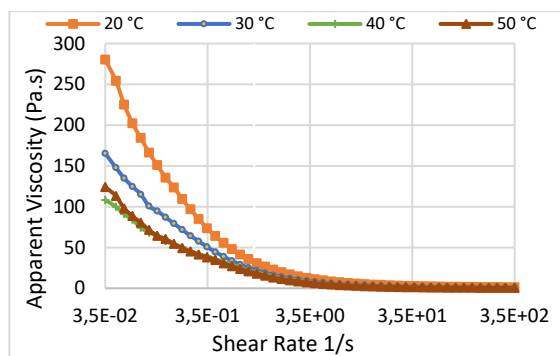


Figure 1. Apparent Viscosity vs Shear Rate 0T.

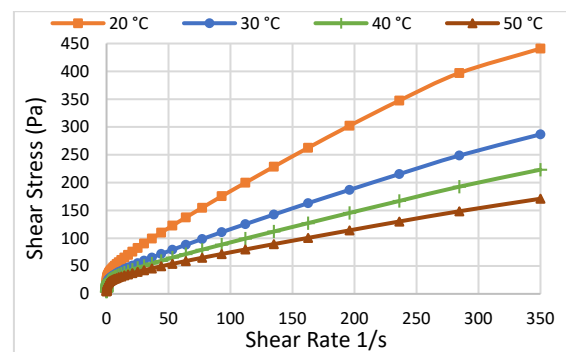


Figure 2. Shear stress vs Shear rate 0T.

From the previous results it is concluded that temperature has an effect on viscosity at 0T figure 1 however it does not have an important effect on the apparent viscosity of the fluid MRF-140CG once the magnetic field is applied figure 2. In figures 3,4,5 and 6 the shear stress vs. shear rate is shown for all tests from 0 to 800mT with increments of 200mT.

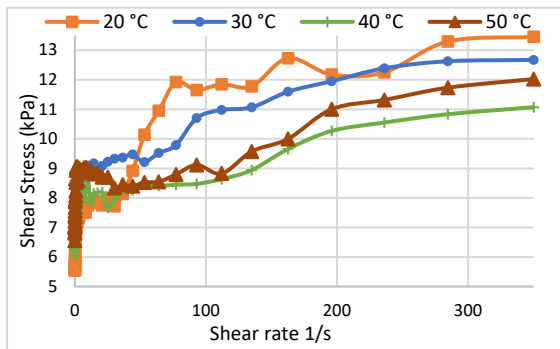


Figure 3. Shear Stress vs Shear Rate with 200 mT.

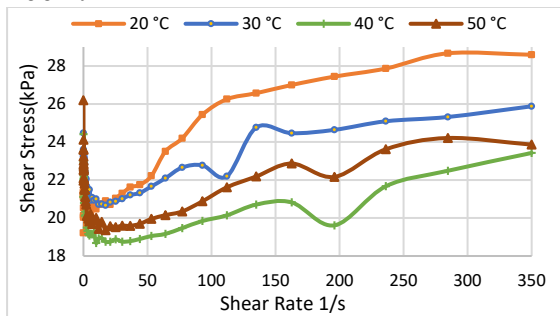


Figure 4. Shear Stress vs Shear Rate with 400 mT.

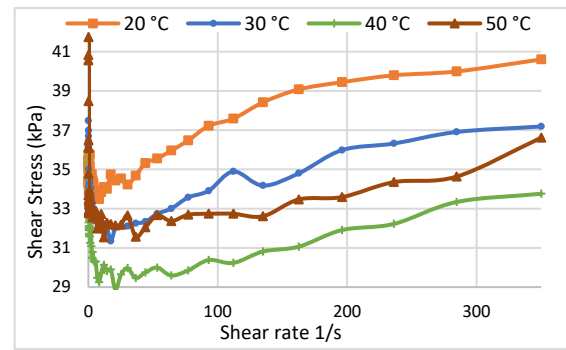


Figure 5. Shear Stress vs Shear Rate with 600 mT.

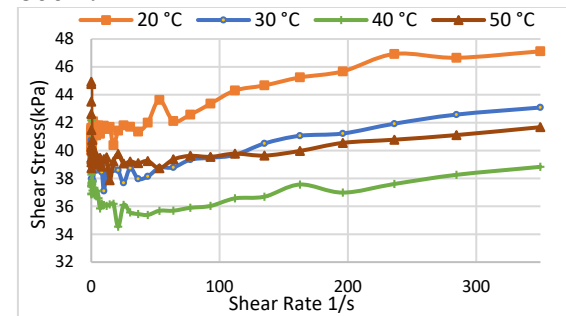


Figure 6. Shear Stress vs Shear Rate with 800 mT.

From these results it is determined that, compared to the off state i.e. in the absence of magnetic field the viscosity increases a percentage of 65631.74% with a field of 200mT figure 3, an increase of 228.26% for 400mT figure 4, then with 600mT it decreases to 58.63% figure 5, and finally at 800mT it falls to 14.02% figure 6, i.e. the fluid begins to saturate until it reaches full saturation at approximately 1.7T, from which the apparent viscosity remains constant.

4. Test comportment dynamic model

Different theoretical models have been proposed to predict the dynamic behavior of the MRF and each one of these can be more specific than the other depending on the application and the type of device in which it is wanted to use. In the case of robotic and exoskeletal prostheses the loads are small compared to applications in suspensions and automotive shock absorbers for this reason, it is important to select the model that best adapts to our specific application.

In order to validate the accuracy of each model, a total of 10 laboratory tests were carried out on the magneto-rheological shock absorber, according to ISO 2954, on the Dyno-Shock 11 test bench, under the following conditions: Displacement of 40mm with frequencies of 1.59; 3.18; 4.77 and 6.37 Hz and speeds of 125; 200; 400; 600 and 800 mm/s at a temperature of 25°C with a heating speed of 200mm/s.

4.1. Empirical model.

For the empirical model by means of equation (1), can obtain the magnitude of the total resistance to yield [8],

$$\tau_{T(H)} = C 271.700 \phi^{1,5239} \tanh(6,33 \cdot 10^6 H) \quad (1)$$

Where:

$\tau_{T(H)}$ = Magnitude of total resistance yield

H = External magnetic field

4.2. Bingham Model

For the Bingham plastic model, it is considered that the plastic viscosity of the fluid remains approximately constant and the shear stress that must be exceeded to initiate the flow is equal to total resistance yield. Is given by equation (2)[9].

$$\tau_{T(H)} = \tau_{y(H)} + \eta_p \dot{\gamma} \quad (2)$$

Where:

$\tau_{y(H)}$ = Shear stress of the fluid controlled by the magnetic field and defined by the intercept point of the linear regression line.

η_p = Plastic viscosity obtained from the slope of the linear regression line of the shear stress as a function of the Shear rate.

$\dot{\gamma}$ = Shear Rate.

4.3. Bi-viscous Model

For the Bi-viscous model, especially in devices working in squeeze mode, equation (3) and equation (4) govern the total resistance yield.

$$\tau_{T(H)} = \begin{cases} \tau_{y(H)} + \eta_p \dot{\gamma} & |\tau| > \tau_1 \\ \eta_r \dot{\gamma} & |\tau| < \tau_1 \end{cases} \quad (3)$$

$$\tau_{y(H)} = \tau_1 \left(1 - \frac{\eta_p}{\eta_r}\right) \quad (4)$$

Where:

η_r y η_p = Viscosities related to the properties of the fluid in the elastic zone and in the viscous zone respectively.

τ_1 = Shear stress of fluid before yield.

4.4. Herschel-Bulkley Model

For the Herschel-Bulkley model, in which the fluid is subjected to thickening or thinning by cutting after the yield point, particularly when subjected to high shear rate, the model is expressed in the equation (5) [10].

$$\tau_{T(H)} = \tau_{y(H)} + K \dot{\gamma}^n \quad (5)$$

Where:

K = Consistency factor

n = Index of flow behavior and is defined by the exponent of the potential trend curve, for $n > 1$, represents a cutting thinning fluid, cutting thickening fluids are described with $n < 1$, for $n = 1$, the model is reduced to Bingham Plastic Model. Si $\tau_T > \tau_{y(H)}$ the fluid behaves like a fluid, otherwise like a solid.

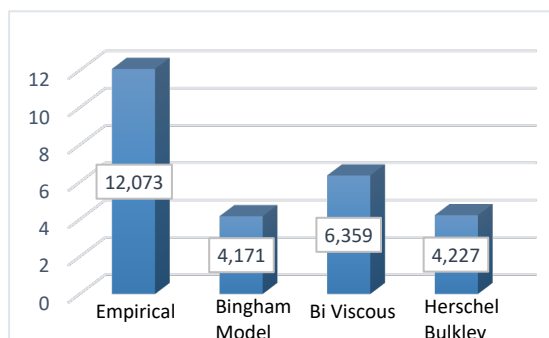


Figure 7. Average error ratio of each model

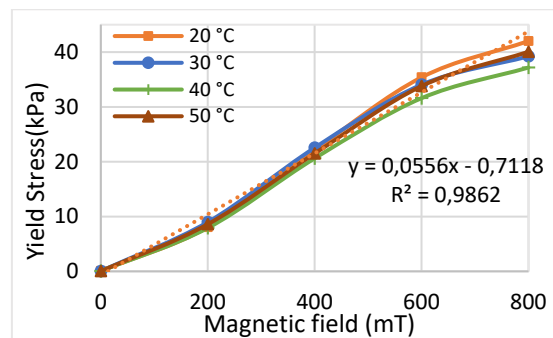


Figure 8. Shear yield stress of MRF-140CG as a function of the magnetic field.

4.5. Test Results

Based on these results from the four models analyzed, the percentage of average error is determined for each one of them figure 7, because Bingham's plastic model has the lowest average error is the best one to predict the behavior of MRF-140CG fluids, this model is used to find the equation of flow resistance as a function of a magnetic field of specific intensity. Then the results are plotted to obtain the regression equation that defines the relationship between the flow resistance and the magnetic field. In Figure 8, it can be appreciated that the yield stress increases as the magnetic field stress increases. By means of linear regression the equation 6 of the curve is obtained, with the square of the relation of person equal to 0,9862 which indicates a positive correlation.

$$y = 0,0556x - 0,7118 \quad (6)$$

Where:

y magnitude of total resistance yield ($\tau_{T(H)}$) en kPa.

x magnetic flux density (B) en mT.

5. Conclusions

Bingham's plastic model is the one that most accurately predicts the dynamic behavior of the MRF-140CG fluid under the influence of a magnetic field, with an error of only 4.171%. Therefore, it is safe to use this model for the design of any device that optimally exploits the mechanical properties of the magneto-rheological fluid studied.

For magnetic fields below 200mT, the flow resistance of the fluid is linearly proportional to the field intensity and reaches a value of 8,035 kPa. However, for magnetic fields greater than 200mT, a shear stress of 54,896 kPa is obtained in the case of the design of a prosthesis with a magnetic field of 1T by means of equation 6.

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