Study of the Attenuation Force Generated by a Magnetorheological Fluid in Industrial Robot Grippers Shock Absorbers

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Abstract. The attenuation force generated by the use of magnetorheological fluid (FMR) during the expansion and compression of the shock absorber in robot grippers has been studied. The shock absorber has a stroke of 25 mm and a volume of 4,071.50 mm³ in which the FMR made up of ferric micro-particles and nanoparticles is housed; this fluid modifies its rheological properties when exposed to a magnetic field of variable intensity generated by an electromagnet. The intensity of the magnetic field is gradually varied in order to obtain an attenuated and controlled dynamic force in the dissipation of energy. The research includes an analysis of magnetic field generation with the purpose that the particles of the fluid are aligned according to the polarity of the flow lines, thus forming a fibrillary structure chained in a few milliseconds. This magnetic field modifies the viscosity of the fluid, taking it from a low viscosity to a higher density state without altering its chemical composition and shape. The results are reflected in the direct correlation and in the obtaining of data where the saturation of the fluid is given to a maximum intensity of magnetic flux (B) of 0.01 Tesla; and a damping force of 6.12 Newtons. This concludes that the theoretical and experimental analysis of attenuation in FMR based buffers serve to mitigate impact excitations, in order to provide a buffered velocity of motion.

1. Introduction
The application of FMR in the industrial field has been advancing with the passing of the years, today many investigations are carried out as in ascent valves, control pumps, brakes, assembly claws, among others [1]. The study of magnetorheological fluids is based on the ability to change instantly from a viscous fluid state to a semi-solid state in the presence of a magnetic field. FMR fluids have iron microparticles that are held together by the magnetic field forming a kind of chain that is resistant to a certain level of shear stress by behaving like a semi-solid material [2]. The function of a shock absorber starts when it receives a series of oscillations produced by irregularities in the medium, then the energy received by the shock absorber is dissipated when the shear stress exceeds a critical value, being beneficial to design a magnetorheological shock absorber FMR to control the attenuation when operating a gripper coupled to an industrial robotic arm [3].

2. Experimentation
2.1. *Power supply*
The shock absorber required a source that provides 3 independent outputs with ranges of 0-30 volts and 0-3 amps, a serial output was configured to obtain the value of 12 volts and 0.92 Amps of current [4].

2.2. *Magnetic Field Sensor*
The measurement of the magnetic field is possible thanks to the magnetic field sensor Xplorer Glx of the brand Pasco, this magnetic sensor offers sensitivity in a single range of -1000 to +1000 gauss with an accuracy of ± 3 gauss [5].

2.3. *Dynamometer*
The response to attenuation is reflected thanks to the Hoosiwee Weighing Machine, which has a large capacity of electronic scales, has a high precision sensor system that allows you to measure a maximum capacity of 50 kg to ensure a precise weighing session [3].

2.4. *Magnetoreological fluid*
The LORD MRF-140CG brand magnetorheological fluid is used with a density of \( \rho = 3740 \text{ kg m}^{-3} \) and viscosity of \( \mu = 0.28 \text{ Pa s} \) [6].

2.5. *Methodology*
The investigation included a design stage of the shock absorber and winding, then the acquisition of a commercial FMR and finally the application in grippers for the subsequent study of the attenuation force results.

2.6. *Shock absorber design*
The mechanical design of the shock absorber was oriented towards a short-stroke suspension system where a maximum range value of 0.025 m was established for the piston rod in expansion or compression. The body of the shock absorber was constructed of 6061 T6 aluminum, (see figure 1) [3].

![Figure 1. Diagram of the components constituting the shock absorber](image)

The static structural analysis of the shock absorber is done by Computer Aided Engineering (CAE) and Finite Element Analysis (FEA). The maximum deformation of the shock absorber cylinder shown in the figure 2; and piston rod shown in the figure 3 are very low, considered as negligible and acceptable. The resulting stress of Von Mises is relatively low compared to the yield strength of 6061-T6 aluminum, which has a value equal to 315 [MPa], so it is concluded that the design is safe. To consider an acceptance of the design we note that the critical safety factor of the design is greater than the permissible safety factor of \( N = 2 \), the design being considered as safe.
2.7. Winding
The technique of indirect-external winding was used as can be seen in figure 4, the length of the coil Ls=0.036 m, with 6 layers and a number of coils N=56, using AWG 22 copper wire of diameter Dal=6.44 ×10^{-4} m and resistivity 5.6/100 m, as in equation (1) [4].

\[
N = \frac{L_s}{D_{al}} \quad (1)
\]
2.8. Behaviour of the FMR in the shock absorber

The flow rate (Q) generated by the fluid passing from one chamber to another within the internal cavity of the shock according to equation (2) was determined as a function of the speed of the shock absorber; the transverse area of the Aa shock absorber is obtained from the following equation (3); and the piston diameter Dp of 0.012 m are established according to the conditions of the internal structure of the gripper according to its dimensions, (see figure 5) [5].

\[
A_a = \frac{\pi (D_p)^2}{4} = \frac{\pi (0.012 m)^2}{4} = 1.13 \times 10^{-4} [m^2] \tag{2}
\]

\[
Q = (1.13 \times 10^{-4} m^2) (0.0295 \frac{m}{s}) = 3.336 \times 10^{-6} [\frac{m^3}{s}] \tag{3}
\]

2.9. Magnetic permeability

Ability of a material to attract or allow the passage through itself of a magnetic field equation (4), \(\mu_0\) is the vacuum magnetic permeability equal to \(4\pi \times 10^{-7}\) NA\(^{-2}\) and \(\mu_r\) represents the relative magnetic permeability of the 100 NA\(^{-2}\) core as in (see figure 5) [7].

\[
\mu = \frac{B}{H} \tag{4}
\]

\[
B = \frac{\mu_0 \mu_r N_i}{L_s} \times N_c \tag{5}
\]

\[
B_x = \frac{\mu_0 \mu_r N_i}{2\pi z} \times N_c \tag{6}
\]

2.10. Magnetic hysteresis curve

It shows the relationship between the induced magnetic flux intensity (B) and the magnetization force (H), resulting in a magnetic field of 0.938 Tesla inside the cylinder, equation (5); and a smaller magnetic field in the periphery \(B_x\) of 0.0192 Tesla, as in equation (6) [8].

![Figure 4. Indirect-External Rewind](image)

![Figure 5. Fibrillar arrangement of the FMR in the shock absorber](image)
2.11. Testing and Simulation

Five cushioning trials were conducted, in each of which values were taken for subsequent data tabulation and evaluation of averages. A simulation of the magnetic hysteresis was also performed in the Comsol Multiphysics software, entering the design parameters of the coil and the density of the fluid equal to 3.15 g cm\(^{-3}\) at a temperature of 130 °C according to the data of the fluid manufacturer, to analyze the behavior of the magnetic field of the coil [9].

3. Results

The values obtained in the Tests are reflected in the following tables, where the magnetic flux intensity \(B\) and the attenuation force \(F\) of the shock absorber have very high values as it rises to a maximum peak current reaching 0.7 amps supplied in steps of 0.1 amps. Table 1 represents the values obtained in the ascent, descent with north polarity at the top and south at the bottom of the coil. Meanwhile in table 2 it represents values at the moment of reversing the polarity, these are affected in the orientation of the magnetic field lines, numerically they change of negative sign in relation to table 1, with the permeability the intensity of magnetic field \(H\) is calculated.

Figure 6 shows the FMR magnetic hysteresis curve \(B-H\), which starts from a demagnetized state, where the current starts from zero in the center of the graph. As the magnetic force \(H\) increases positively, the flux density \(B\) follows the curve from the origin to (point 1) where \(+B\) is maximum and saturation is met; while \(H\) decreases, the flux follows the curve from (point 1) to (point 2) through \(Br\), which is the residual induction, this (point 2) represents the amount of flux remaining during the falling edge as the magnetizing force decreases; in the third and fourth quadrant the magnetizing force -\(H\) where the electromagnet begins to lose its magnetism, as shown by following the curve from (point 2) to (point 3). This point is known as coercive force -\(Hc\) where the coil will be completely demagnetized; the curve corresponding to (point 3) and (points 4) is known as -\(Bmax\) which represents the saturation peak in the opposite direction to \(B\) max; from (point 4) to (point 5) the value -\(H\) decreases, this point is known as Flux -\(Br\) which represents a magnetization force equal to zero with less magnetic flux; lastly from (point 5) to (point 6) is known as coercive force + \(Hc\) reducing the magnetization of the electromagnet to zero and the magnetic force continues to increase until completing the curve from the final point to the initial one [8].

![Figure 6. Magnetic Hysteresis Curve](image-url)
### Table 1. Direct Polarization

| I [A] | Test # 1 B Gauss | Test # 2 B Gauss | Test # 3 B Gauss | Test # 4 B Gauss | Test # 5 B Gauss | Average B Gauss | F Kgf | N Gauss |
|-------|-----------------|-----------------|-----------------|-----------------|-----------------|----------------|-------|--------|
| 0.0   | -5.14           | -5.21           | -5.09           | -5.22           | -5.12           | -5.16          | -5.16 | 2.000005566 | 3.22E-08 |
| 0.1   | 19.13           | 19.81           | 17.59           | 25.55           | 17.59           | 19.934         | 0.002 | 2.804701 | 1.245E-07 |
| 0.2   | 37.82           | 38.13           | 37.81           | 40.45           | 37.79           | 40.45          | 0.0052 | 4.4129922 | 3.325E-07 |
| 0.3   | 52.61           | 53.64           | 51.98           | 55.39           | 52.42           | 53.208         | 0.0053 | 4.4129922 | 3.325E-07 |
| 0.4   | 72.51           | 73.28           | 68.76           | 73.72           | 69.7           | 71.594         | 0.0072 | 5.413270 | 4.474E-07 |
| 0.5   | 76.53           | 79.42           | 75.73           | 80.89           | 76.49          | 77.812         | 0.0078 | 5.707470 | 4.863E-07 |
| 0.6   | 91.81           | 93.21           | 89.98           | 95.83           | 90.56          | 92.276         | 0.0092 | 6.4527755 | 5.767E-07 |

### Table 2. Inverse Polarization

| I [A] | Test # 1 F Gauss | Test # 2 F Gauss | Test # 3 F Gauss | Test # 4 F Gauss | Test # 5 F Gauss | Average F Gauss | F Kgf | N Gauss |
|-------|-----------------|-----------------|-----------------|-----------------|-----------------|----------------|-------|--------|
| 0.0   | 10.5            | 10.49           | 11.42           | 9.98            | 10.56           | 10.59          | 0.0105 | 1.824036 | 1.207E-05 |
| 0.1   | -12.3           | -12.3           | -14.05          | -11.47          | -12.5           | -12.52         | 0.00125 | 2.432049 | 2.85E-05 |
| 0.2   | -32.84          | -31.64          | -38.14          | -29.72          | -33.56          | -33.56         | 0.00331 | 3.5992734 | 3.0000052 |
| 0.3   | -49.62          | -49.22          | -51.86          | -48.33          | -50.98          | -50.98         | 0.00500 | 3.733487 | 3.175E-07 |
| 0.4   | -63.29          | -62.41          | -68.89          | -62.21          | -64.78          | -64.78         | 0.006643 | 4.0403399 | -0.001173 |
| 0.5   | -72.08          | -71.93          | -73.81          | -69.44          | -73.27          | -72.10         | 0.007214 | 4.452215 | -0.002630 |
| 0.6   | -79.42          | -77.65          | -82.63          | -73.96          | -75.99          | -77.99         | 0.007790 | 5.491778 | -0.005685 |

The analysis of the attenuation force generated in the damper is reflected in the graph corresponding to the fluence stress as shown in figure 7, representing the gradual increase of the numerical value with respect to the magnetic flux intensity, obtaining the maximum attenuation value of the damper of F equal to 6.1193496 N, with a flux density of B equal to 0.01 T. The analysis of the attenuation force generated in the damper is reflected in the graph corresponding to the fluence stress, representing the gradual increase of the numerical value with respect to the magnetic flux intensity, obtaining the maximum attenuation value of the damper of F equal to 6.1193496 N, with a flux density of B equal to 0.01 T.
When comparing the curve of the magnetic hysteresis obtained with the tabulated data with respect to the curve obtained by simulation, it is observed that the periodic increase of the force of magnetization \( H \) causes that the magnetic flux that circulates through the nucleus is greater than the remaining flux of the exterior during the rising and falling flanks forming this way the hysteresis loop. Finally, we can conclude that we have an FMR hysteresis curve with high permeability, low residual magnetic flux, and low coercive force (Figure 8 [9]).

**Figure 7.** Performance Yield Stress Curve vs. Flux Density

**Figure 8.** Magnetic field simulation in COMSOL Multiphysics Software
4. Conclusion
Research indicates that the magnetorheological fluid produced by LORD MRF-140CG series can be used in the design of industrial shock absorbers, because the maximum attenuation force obtained is 6.6 Newtons, at a current of 0.7 amps applied to the winding, which demonstrates the applicability of the shock absorber in industrial grippers. The innovation of this work is reflected in the design and development of a damping system, based on magnetorheological fluids for grippers or tweezers, which, when installed in industrial robotic arms, will allow safer and more reliable handling of fragile objects such as glass, ceramics and containers of dangerous products, which may otherwise be harmful to the operator. The gripper model with this damping system is not available in the national market, figure 9.

5. References
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