

Miniature Magneto Rheological Fluid Actuator for High Force Locking and Damping Application

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Abstract:

The MRF actuators are new electromechanical components using Magneto Rheological Fluids (MRF). These smart fluids are characterized by their ability to change their rheological properties versus applied magnetic field. They can switch from a liquid to an almost solid body. This effect is reversible and operates within a few milliseconds. MRF are used to create controllable dampers, smart shock absorbers or brakes. After having developed several MRF actuators with an original characteristic (presenting a blocking force at rest), Cedrat Technologies was asked to develop a very challenging new MRF damper which goal can be summed up with a few words: “small size and high force”. The customer’s specifications were as follows: locking-damping force at rest above 1kN, on 8mm stroke within a volume of about 50cm³. This paper explains the design methodology of MRF actuator to meet the customer’s requirements, from the architecture choice to technological aspects. Then, it describes the trials and gives the prototype test results, comparing these to the customer’s expectations.

Keywords: MRF, actuator, damping, high force

Introduction

The MRF actuators are new electromechanical components using Magneto Rheological Fluids (MRF) [1]. These smart fluids are characterized by their ability to change their rheological properties versus applied magnetic field. They can switch from a liquid to an almost solid body. This effect is reversible and operates within a few milliseconds. MRF are used to create controllable damper, smart shock absorber or brakes.

Most of MRF actuators (see for ex [2]) offer a controllable breaking force but not a blocking force at rest. This characteristic is for example very useful for self-locking operations.

For several years, Cedrat Technologies has been conceiving, manufacturing and testing MRF actuators targeting several aims:

- to offer a blocking force at rest, which can be nullified by applying a current,
- to provide an electrically- controllable resistive force,
- to perform the control of the force in a very short time, typically in a few ms.

CEDRAT TECHNOLOGIES MRF actuator can be used for two main applications: damper and latch - lock. Obviously, these two applications can be combined. For example in some embedded instruments, it is wise to damp vibrations when the lock / unlock operations occur.

The self-locking feature has been obtained in the developed actuator thanks to a particular magnetic circuit designed with FLUX software [2] and knowledge acquired on MRF fluid magnetic and rheological properties [3].

Application

The main application of CEDRAT TECHNOLOGIES MRF actuator is the optimization of the damping force. The optimization takes into account the travel speed of the damper rod and its position. A controller adjusts the energy dissipation in the damper by regulating its controllable damping force. The control of this force in real time is made by the current control. Within a few milliseconds, the energy dissipation can be adjusted by more than 1000%. A specific design of the magnetic circuit, which includes an appropriate magnet, offers a maximum damping without power supply and thus the fail safe operating can be guaranteed in several applications.

Here, a customer asked us to design and manufacture a damper with the requirements given in Fig 1.

Blocked force	>1000N at 0A
Free force	<100N
Stroke	>8mm
Shift Time @100N	<1s
Size	Length 66mm, diameter 32mm

Fig 1: Specifications

Other important points in this project are the reliability of the damper and its time to switch from blocked state to free state.

The main comments are that the damper has to be small, about 50 cm³, but with a significant blocked force.

Design phase: Fluid property

Well known magneto rheological fluids are made of a carrier fluid that can be oil, water and so on, and magnetic particles in suspension. These particles are mostly microscopic iron particles sizing from 0.1 micron to 10 microns.

Without magnetic field, MRF behaves like a Newtonian fluid. But when a magnetic field is applied, the particles align themselves along the flux lines. The result is that the fluid can become nearly solid under a high enough magnetic field. The effect is reversible and the time to switch between both states occurs within a few milliseconds. There is a change in the apparent viscosity of the fluid. This apparent viscosity can be freely controlled according to the value of the magnetic field.

Several models can be used to describe the MRF physical properties. The simplest and the most widely used is the Bingham model:

$$\tau = \tau_y(H) + \eta \frac{dv}{dz}$$

Where H is the magnetic field, τ the yield stress, η the Newtonian viscosity and $\frac{dv}{dz}$ the fluid velocity.

Architecture

Magneto-rheological fluids can be used using two main modes, the flow mode in which the fluid has to go through a fixed armature and the shear mode in which there is a displacement of one armature and no fluid flow. A third mode that is a combination of these first two modes is the squeeze mode [6].

The schemes give an overview of several architectures in the frame of a damper design:

The direct shear effect:

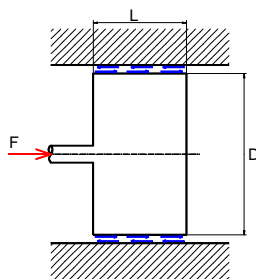


Fig 2: Direct shear effect

The force is directly coming from the shear stress that appears in the fluid when pushing on the piston. It is controlled by the maximal shear stress variation (τ_{max}) in the MRF.

$$F = \pi \cdot D \cdot L \cdot \tau_{max}$$

Numerical computation:

$$\left. \begin{array}{l} L = 10mm \\ D = 25mm \\ \tau_{max} = 40kPa \end{array} \right\} \Rightarrow F = 30N$$

The flow control in an external annular duct:

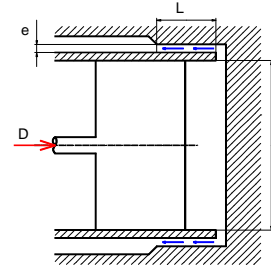


Fig 3: Flow control in an external annular duct

The force is coming from the pressure difference between both chambers. The piston is blocked until there is enough pressure to force the fluid to pass in the annular duct.

$$F = \pi \cdot D^2 \cdot \frac{L}{2e} \cdot \tau_{max}$$

Numerical computation:

$$\left. \begin{array}{l} L = 10mm \\ D = 25mm \\ \tau_{max} = 40kPa \\ e = 125\mu m \end{array} \right\} \Rightarrow F = 3000N$$

These calculations show that the direct shear mode is far from the customer's expectations, whereas using flow mode, it is possible to reach the requested amount of force if the duct clearance is small enough.

Flow control in annular external duct (twin tubes):

The main advantage is that the fluid control takes place in a static part. It is easier to have optimized magnetic and hydraulic circuits. And the piston is very simple. The main drawback is there is an increase of the moving fluid mass. This creates an inertia track for high frequency displacement damping.

Based on the customer's requirements, the twin tube architecture is the most appropriate. The next step is the electromagnetic design.

Electromagnetic design

The electromagnetic design was achieved using the finite element analysis. The damper has to have its

maximal damping force without power consumption. The solution is to add a permanent magnet in the circuit.

A Finite Element Model (FLUX) allows designing the magnetic structure.

The magnetic design is a trade off between the minimization of the damper volume and a significant controllability thanks to the coil supply.

In order to reduce the device volume, the magnetic material section must be minimized. However, the minimization of magnetic material section causes magnetic saturation which must be avoided in order to have a high control of the induction in the fluid gap. Indeed, the material saturation limits the efficiency of the current on the induction in the fluid gap.

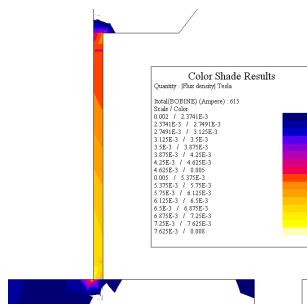


Fig 4: Induction at the center of the fluid gap (FLUX)

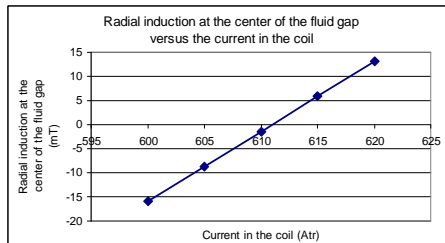


Fig 5: Induction in fluid gap versus current

The magnet size was chosen to reach the requested level of force without current. Then, the coil was designed to control the level of induction in the fluid gap. An optimized design allows decreasing by 99% the induction in the fluid gap when the coil is supplied.

Response time

The time to switch from the ON state to the OFF state is important for this project. The theoretical response time can be calculated in an analytical way.

The magnetic flux generated by the coil supply by 2.906A is computed to:

$$\Phi_{physical} (I = 2.906A) = 318 \times 10^{-6} Wb$$

$$N \times \Phi_{physical} = \Phi_{coil}$$

$$\Phi_{coil} (I = 2.906A) = 210 \times 318 \times 10^{-6} = 66.78 \times 10^{-3} Wb$$

The inductance is computed :

$$L = \frac{\Phi_{coil}}{I} \quad L = \frac{66.78 \times 10^{-3}}{2.906} = 23mH$$

The electrical time constant is so computed:

$$\tau = \frac{L}{R} \quad \tau = \frac{23 \times 10^{-3}}{5.94} = 3.9ms$$

The electrical time constant of the device without considering the eddy current effect is 3.9ms.

It is important to note that these computations do not consider the iron loss (and particularly the eddy current losses). The response times can not be directly deduced from this computation. A smarter model must be achieved in order to estimate the time needed to cancel the locking force.

A Finite Element Model in transient on FLUX CAD has been achieved. The eddy current effects during the current variation in the coil are modelled.

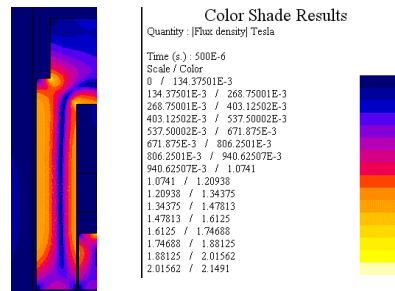


Fig 6: Induction @ t=30 ms (Tesla)

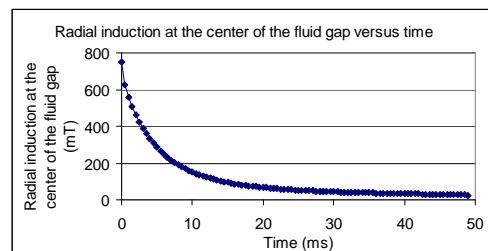


Fig 7: Induction in the fluid gap versus time

A non homogeneous induction is the result from the eddy current phenomenon.

The induction in the fluid gap decrease by 95% in 35ms. Thus the blocking force will decrease from 921N to 50N in 35ms.

The eddy currents increase by 3 the time needed to decrease the induction in the fluid gap by 95%. Therefore the eddy current phenomenon should not be neglected.

Mechanical design

The force capabilities of the damper are directly linked to the pressure in the device through the piston surface: $P = \frac{F}{S}$

In order to minimize the pressure in the damper, the piston surface is maximized. Therefore, the piston diameter impacts the diameter of the damper.

In spite of the maximisation of the piston surface, the pressure in the device is significant:

- $P^{\circ} = 21$ Bars for 1000N
- $P^{\circ} = 32$ Bars for 1500N

The material choice and the material section must be chosen in order to stand to the pressure.

The material thicknesses are validated by analytical computation:

The external tube must be able to resist to the pressure. A computation pressure of 30 Bars is considered (40% higher the nominal pressure)

If the following equation is respected, the tube will resist to the pressure.

$$P_{eff} \times \frac{Di^2 + De^2}{De^2 - Di^2} \leq Rpe \quad \text{With} \quad \frac{Di}{e} \leq 20$$

With :

P_{eff} : the differential between the internal and the external pressure of the tube

Di : internal diameter

De : external diameter

$$Rpe = \frac{Re}{s} = \frac{470}{5} = 94MPa, \quad \text{Re: tensile strength yield \& s: security coefficient}$$

$$P_{eff} \times \frac{Di^2 + De^2}{De^2 - Di^2} = 30 \times 10^5 \times \frac{29^2 + 32^2}{32^2 - 29^2} = 30MPa$$

The aluminium alloy 7075 tube is thick enough for the application.

Test results

A prototype was manufactured, and a test bench was set up. The test bench is made of a force sensor, an hydraulic cylinder to apply the force, and a linear potentiometer to measure the displacement.



Fig 8: MRF damper

The prototype's blocked force is 1500N, which is more than the minimum wanted by the customer.

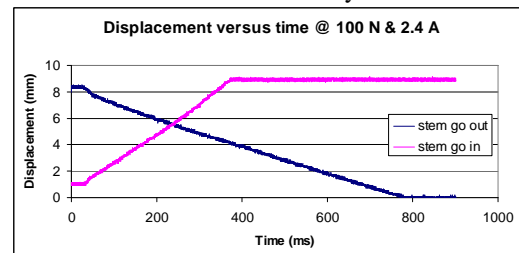


Fig 9: Displacement versus time

The free force of the actuator when it is supplied with a 2.4A current is lower than 100N as the figure 14 shows for both directions. And the time to reach the final position is below 1s.

The customer's requirements are reached and the results are close to the expectations. This is mainly the result of the electromagnetic design. Since the device has to work mainly at low speed, its behaviour is mostly linked to the induction in the fluid gap. The knowhow in this field and the use of finite element method enables to obtain accurate results.

References

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