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The Modeling and Utilization of MagnetoRheological Fluids to Virtual Reality

THESIS

submitted in partial satisfaction of the requirements for the degree of

MASTER OF SCIENCE

in Mechanical and Aerospace Engineering

by

Josep Maria Serrahima de Cambra

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2017
Als meus pares i al meu germà,
per ser sempre allà
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ABSTRACT OF THE THESIS

The Modeling and Utilization of MagnetoRheological Fluids to Virtual Reality

By

Josep Maria Serrahima

Master of Science in Mechanical and Aerospace Engineering

University of California, Irvine, 2017

Dean Gregory Washington, Chair

Smart materials are materials that can significantly vary one or more of their properties when an external input is applied. Magnetorheological (MR) fluids are one of these materials as they change their apparent yield stress, which exhibits the behavior of changing from a fluid to a semi-solid as the magnetic field is increased. The fluid is made from ferrous (magnetizable) microparticles suspended in a carrier fluid (usually oil). When a magnetic field is applied, the particles align with the field. Using this phenomenon, linear dampers have been studied and developed. This thesis has two different parts. On the first part a MR fluid sponge-based damper is designed, built and tested. The results of the tests are discussed in detail, focusing on the forces needed to move the damper for different electrical currents applied: the higher the electric current is, the larger the force needed to move the damper. The second part of the thesis involves the use of this damper as a controller to a Virtual Reality game. The game is created using the programming environment Unity, and controlled using a hardware in the loop system employing data acquisition boards, sensors and a Simulink model. The damper works as controller for the
game, since the user receives a force feedback, as the force needed to move the damper depends on the position of the player on the game.
INTRODUCTION

The evolution of the human race is without any doubt tied to the application of different materials to the tools used. The different eras that humanity has gone through are usually defined using the material that made a breakthrough on the daily life. Stone, Bronze and Iron are usually the steps to define the kind of technology of humanity, which would allow them to create tools and solve day to day problems.

During the twentieth century a new revolution happened due to new technology, the synthesis and improvement of materials, the improvement on sensing devices and processors and miniaturization of systems. All these entities have enabled the creation of the so-called smart materials and structures, which are materials and systems that can change their behavior depending on the environment, adapt and monitor their actual condition.

Magnetorheological fluids are one of these smart materials. The word magnetorheological (MR) comes from its behavior: this fluid changes its viscosity when a magnetic field is applied, and it changes its properties from those of a fluid to a semi-solid. This change in properties has been studied and applied to different kinds of dampers, brakes, rotors and other types of devices. Magnetorheological fluid dampers use this characteristic to control the damping effect or the resistance to the movement for many different applications.

One example of an application of MR dampers is the control of vibration. However, this kind of damper is used now as force feedback systems, or haptic devices. Due to the fluid, MR dampers can change its behavior: if no magnetic field is present they can be moved easily, but when a field is present, a stronger force is needed to move the damper. An
emerging field for this material is the field of haptics (utilization as a system that gives a force feedback) so the user can apply these materials in a broad range of fields, from remote surgeries to game systems. The main benefit here is that the materials only add damping and as such dramatically reduce the possibility of system instability. This thesis adds to the state of the art by introducing virtual reality (VR) concepts in that the dampers can now be used to provide force feedback in a VR based game.

This thesis has two different parts. First one involves all the steps of the engineering design: after doing research about how MR fluid and MR dampers work, a theoretical design of one damper has been completed. Then, this damper was constructed, assembled and tested for different magnetic fields until the results were aligned with theoretical values.

The second part of this thesis uses the designed damper as a controller for a game. Virtual reality (VR) is a concept that involves the creation of games that make the player immerse into the digital environment of the game. This environment can be created with headsets, directly on the screen and/or using different types of controllers. For this thesis a game that will be played directly on the screen of the computer has been created. Then, the virtual reality environment is created with the controller. The designed damper works as a controller, which creates a force feedback system to the user, who will feel different response on the damper depending on what is happening on the game.

The first part of the thesis is formed by Chapters 1 to 3, where the description, design, construction, assembly and testing of the Magnetorheological fluid damper are explained; the second part is exposed on Chapter 4, where the different software to create the game
and the control system are explained, finishing up with the discussion of the results obtained.
CHAPTER 1. Smart materials and structures

Historians classically define a three-age system to explain the stages that the civilization took from the beginning of the human race to the modern day history.

One million years ago the first of these eras started, and it is called the Stone Age, which is defined by the usage of stones to create tools. Then, civilization evolved when the metals started to be used. The Bronze Age is characterized by the first alloys of copper and tin to create bronze, which is stronger than both of them, and could be used for more complex and durable tools and weapons. This second age spans around 3500BC and 1000BC, when a new material was discovered. The Iron Age followed and was characterized by the first iron metallurgy. Iron could be found easily as a mineral, it was cheap but required higher temperatures to be processed. Thanks to this material the human race was able to continue its evolution, to develop scientific tools, and the Industrial revolution was the result.

Historians know the approximate beginning of the Iron Age, but there is discussion regarding the end of it. Iron, and mostly steel, is still used nowadays for most of the industrial applications, construction, transportation systems... so basically, it is still the most used hard metal in modern civilization. This being said, it is difficult to define a new era that defines our current times. However, during the twentieth century many different materials were discovered, and man-made synthetic materials and tools created a new dimension of technological advance, as these could apply to all different brands of high performance engineering products, from aerospace to computer science or medical systems. These more sophisticated materials, some of them inspired on nature, could be discovered and improved due the technological advances. These materials can change their
behavior depending of the surroundings or the environment, allowing them to have different responses to the inputs that they can receive. These materials are defined as smart materials.

Smart materials are materials that can significantly vary one or more of their properties when an external input is applied [1]. External inputs can be changes in the environment, such as light, temperature, electric or magnetic field, among others. The changes that these materials may exhibit when the stimuli are applied can be on the shape, viscosity, stiffness, etc. All these changes are reversible; that is, when the input is no longer present, the material comes back to its initial characteristics. Moreover, the process can be repeated many times without a deterioration of the material.

There are many types of smart materials, the most common being the piezoelectric. This kind of material can be used as sensors or actuators due to the reversibility of their properties. Piezoelectric materials suffer a deformation (mechanical strain) when an electric field is applied, and when a strain is applied they produce voltage. Another type of smart materials is the shape memory alloys (SMA). These alloys change its shape with a certain temperature. They can be plastically deformed at low temperature, but when the transformation temperature is achieved they recover their original undeformed shape. Electrorheological fluids change their viscosity when an electric field is applied; magnetorheological fluids change their viscosity when a magnetic field is applied.

Smart structures are a combination of actuators, sensors and control units that are able to act in a certain way depending of the environment. They form a system that incorporates its sensing devices, which collect data, a processor or microprocessor that analyzes the
data from the sensors and, using integrated control theory, they instruct the actuator to work in a certain way.

Smart structures are becoming more and more used in today's world as the research in smart materials has increased a lot since the 1950s, hence making them available commercially; advances in the construction and assembly of all the components, and the advances in microelectronics: processors, sensors and information transmission devices have made them more usable and wanted in today's world.

**1.1. Magnetorheological fluids**

The most important smart materials that are in the form of fluids are electrorheological (ER) and magnetorheological (MR) fluids. Their main characteristic, which makes them part of the smart materials’ group, is that they drastically change their apparent viscosity with the application of an electric or magnetic field, respectively. Both of them are formed by a suspension of particles in a carrier fluid, and when the field is applied the particles become polarized and align themselves in branch chains increasing the apparent viscosity.

They were discovered and became a field of study around the 1940s and 1950s [2]. At the beginning ER were more used as they could be used more easily in the laboratories, but since the 1990s MR fluids have increased their importance in research as the maximum yield stress that they are capable of producing can be twenty times larger than those of ER fluids, and also maintain their properties in a broader range of temperatures.

For the last couple of reasons, this thesis focuses on Magnetorheological fluids and its applications.
Magnetorheological fluids are suspensions of magnetizable microparticles in a carrier fluid. These particles are randomly dispersed throughout the fluid that is usually some kind of oil. MR fluid is a free moving fluid until a magnetic field is present. When it is applied, the particles, which are responsive to the field, align themselves with it creating thus a semi-solid state.

Before looking at what is exactly happening microscopically, the concept of viscosity must be well defined. The dynamic viscosity of a Newtonian fluid is defined as the ratio between the shear stress and the shear strain of the fluid. That is:

\[ \tau = \mu \frac{\partial u}{\partial y} = \mu \dot{\gamma} \]  \hspace{1cm} (1)

In this equation \( u \) is the velocity of the fluid and \( y \) is the spatial coordinate perpendicular to the velocity of the fluid; the shear stress is represented by \( \tau \), and \( \dot{\gamma} \) is the shear strain. The general definition for viscosity is:

\[ \mu = \frac{\partial \tau}{\partial \dot{\gamma}} \]  \hspace{1cm} (2)

The plot of the shear stress versus the shear strain for a given Newtonian fluid should be linear with its slope equal to the viscosity of the fluid.

One of the ways to measure the viscosity of a fluid is by the idealized situation of the Couette flow [3]. In this situation, the fluid is situated between two semi-infinite horizontal parallel plates that are separated by a distance \( h \). One of these is fixed and the other moves constant speed \( U \). The moving plate generates a shear stress to the fluid. By the non-slip
condition, the fluid in contact with the moving plate has its velocity equal to that of the plate; meanwhile, the fluid in contact with the static plate has 0 velocity.

Using Navier-Stokes equations, neglecting pressure and gravitational terms, we obtain a differential equation such as:

$$\mu \frac{\partial^2 u}{\partial y^2} = 0$$

Using as boundary conditions the velocity of both plates: $u(y = h) = U$ and $u(y = 0) = 0$, the equation can be solved and the velocity profile can be obtained:

$$u(y) = U \frac{y}{h}$$

The velocity depends only on the vertical position, and it has a linear profile.

To sum up, the term viscosity refers to the resistance of the fluid to movement. The definition that has just been exposed is usually referred as the Newton’s Law of Viscosity. Therefore, all Newtonian fluids follow this behavior, which is that they flow as soon as a
shear stress is applied and the shear rate is directly proportional to the applied shear stress (by the viscosity).

Additionally, rheology is the study of the flow of matter, and it is used in this thesis to explain the behavior of fluids. Newtonian fluids can define their rheology by their viscosity for a specific temperature.

However, after this theoretical explanation of how Newtonian fluids work, a statement must be made: Magnetorheological fluids are non-Newtonian fluids. MR fluids vary their rheological properties with the application of a magnetic field: they suffer a rapid increase in their apparent viscosity [4].

This behavior can be explained by the components that form the MR fluid. As said before, MR fluids are made by a carrier fluid, which is usually some kind of oil, and suspended magnetizable particles of the size of microns. MR fluids have a regular viscosity when no magnetic field is applied, which depends solely on the viscosity of the original carrier fluid, and the concentration of suspended particles.

Everything changes when a magnetic field is applied. The application of the magnetic field forces the particles to align with the direction of the field. Hence, chains of particles are formed by magnetic attraction. As one would expect, the yield stress of the fluid where the magnetic field is applied is much higher than the fluid in the off-state.
Looking microscopically, it is possible to see how the magnetizable particles form a chain that is aligned with the magnetic field (Figure 3).

So, what is the actual behavior of the flow of MR fluids? We can define three different stages [1], [3]:

- When there is no magnetic field applied, the fluid behaves like a Newtonian fluid, with a constant viscosity $\mu$, which can be found as explained in Equation 2.
• When a magnetic field is present, the alignment of the micron-sized particles limits the movement of the fluid. The applied shear stress can be supported by the chains, which do not allow the fluid to move. As shear stresses in the fluid increase the chains start deforming, until they arrive at a certain value when they break. The yield stress ($\tau_y$) of the fluid is this threshold value in which the chains break. While they remain unbroken, that is, for shear stresses lower than the yield stress, there is no flow of the fluid. In this stage, the fluid behaves as a semi-solid.

• When the shear stress is increased above the value of the yield stress ($\tau > \tau_y$), the chains start to break, so the fluid starts flowing. The slope of the curve after this point is called the plastic viscosity ($\eta$).

Figure 4 Simplified yield behavior: no field and pre and post-yield

The yield stress is highly dependent on the applied magnetic field. This fact explains the main fact about MR fluids: the higher the strength of the magnetic field, the higher the yield stress is. Therefore, the shear stress needed to overcome the resistance must be higher.
There is one idealized model that explains this behavior for the MR fluids: the Bingham model. This model explains its field-dependent characteristics:

\[ \tau_{tot} = \tau_y(H) + \eta \cdot \dot{\gamma} = \tau_y(H) + \eta \cdot \frac{\partial u}{\partial y} \]  \hspace{1cm} (5)

This model states that the fluid behaves as a solid until the value for the yield stress of the fluid is overcome. Then, it behaves as a Newtonian fluid with its plastic viscosity (\( \eta \)). Above the yield point, the total shear stress (\( \tau_{tot} \)) needed to make the fluid flow is equal to the yield stress (\( \tau_y \)), that depends on the magnetic field strength (\( H \)), and the viscosity and the shear strain rate (\( \dot{\gamma} \)).

The plastic viscosity is slightly dependent on the magnetic field, but many references assume that it is constant and equal to the Newtonian viscosity. The Bingham model is then usually expressed as:

\[ \tau_{tot} = \tau_y(H) + \mu \cdot \dot{\gamma} \]  \hspace{1cm} (6)

This idealized model explains correctly the rheology of MR fluids even though the actual behavior is slightly different for low strain rates. Figure 5 compares the Bingham model with actual behavior.
In the literature one can find a number of models that describe the effect of the magnetic field in MR fluids, like the Herschel-Bulkley model [6] and [7], which adds to the Bingham model the effects of shear thinning and thickening of the fluid; Biviscous Model, Extended Bingham Model and others try to explain the hysteresis effect and the pre-yield behavior [1].

1.2. Basic work modes of MR fluid devices

Even though there are different applications for MR fluids, the working principle of these devices can be summarized with the following operational modes.

There are basically three operational modes:

a) Valve mode: It is also referred as flow mode or fixed plate mode. The working principle is the Poiseulle flow, that is, the two plates are static, and a pressure
gradient guides the fluid. It is the most common method used to create MR valves or dampers.

b) Direct shear mode: uses the theory behind the Couette flow. There is relative motion between the two plates, which are the electrodes or magnetic poles. One of the two plates is static, while the other moves parallel, keeping the gap between the two constant. There is relative displacement between the two, creating a shear stress on the fluid. This mode is used in sponge-based MRF dampers or brakes.

c) Squeeze mode: direction of the movement of the electrodes or plates is parallel to the direction of the magnetic field. The gap between the plates therefore changes.

![Operational modes](image)

Figure 6 Operational modes (Source: [4])

The majority of applications of MRF base their working principle on one of these three operational modes. In this thesis the focus is on MRF dampers, so let's explain how they work.

### 1.3. MR fluid dampers

A damper is a mechanism that is designated to reduce oscillation on vibratory systems or absorb or damp shock impulses. They convert kinetic energy into another form of energy, usually heat that is then dissipated. They are usually a cylinder filled with some kind of
viscous fluid interacting with a piston. Dampers are used in many different applications, such as automobile suspensions, aircraft landing gear, doors, etc.

The basic main components that make up the dampers that use magnetorheological fluids as main working principle are the cylinder, piston, electric coil and, of course, the fluid. Two different types of dampers can be easily distinguished by its main operational principle [8]. Basically, they are the dampers that use the flow mode and the shear mode.

1.3.1. Flow mode damper

These dampers are the most common type of linear dampers, not only for MRF. They have a cylinder filled with fluid, a piston and usually a gas accumulator.

The most basic flow damper is the so-called monotube damper. These dampers are simply a single cylinder, with one piston and rod, one reservoir that contains the fluid and the accumulator with high pressure gas. The piston has a hole that works as connector of the two sides of the reservoir.

![Diagram of monotube damper](image)

During the usage of the damper, the piston moves in any of the two directions. The fluid goes through the annular orifice from one side of the piston to the other. The accumulator
of gas, which is enclosed by a floating piston or diaphragm, helps with the effects that the moving piston has on the incompressible MRF, while at the same time gives an extra damping to the system.

The additional improvement that the MR fluids give to a conventional damper is the following. As it has already been mentioned, the piston movement makes the MRF flow through the annular orifice from one side of the cylinder. Now is when the smart material is used.

When the MR fluid is in contact with a magnetic field, the particles inside it align with the field and thus creating a semi-solid behavior. Now, how can a variable magnetic field be created? Basic electromagnetism explains that when a coil of conducting wire is surrounding a ferromagnetic core, and a current (or intensity) is applied to the wire, a magnetic field is created around it. Therefore, controlling the applied current a magnetic field of the strength we want is created. A further explanation on this topic is done in Chapter 2.

In the following Figure 8 a drawing of a MRF damper is represented. The black arrow represents the direction of the movement of the piston. As explained before, this movement forces the fluid to go through the annular channel. When there is no magnetic field present, the force needed to move the shaft is due only to the viscosity of the fluid when going through the orifice.

The coil consists of electrically conducting wire surrounding the piston where a current is applied. When this current is on, a magnetic field (represented by a red dotted line) is
created. Due to the particles on the MR fluid, when a magnetic field is present, magnetizable particles align with the direction of the flux.

As it can be understood with the theory behind MRF, the increase in electric current that is applied to the wire is directly proportional to the resistance to movement that the damper feels. This effect is furtherly described in Section 2.2.

![Figure 8 MRF flow damper (Source: [8])](image)

Flow mode dampers can have a more complicated geometry: twin tube system, double-ended damper, and mixed-mode, among others. A good summary can be found in Reference [8].
However, this type of damper has a high cost and requires maintenance. This is due mainly to the following: the cylinder is full of fluid, so it needs high quality sealing in order to avoid leaks; and this, added to the weight of the main parts (steel cylinder, steel piston, etc.), makes them a really heavy and expensive system. For this reasons, simplicity and cost, the damper designed, built and used in this thesis is a sponge-based damper.

1.3.2. **Sponge-based damper**

Using the same principle, the magnetic behavior of the particles inside of the fluid, sponge-based dampers offer a cheaper, lasting and easier to manufacture system compared to the flow dampers.

This type of dampers uses an absorbent sponge or foam saturated with the fluid, thus avoiding the need for seals and bearings, as the cylinder is not filled with fluid. They differ from the other type as they consist of a hollow tube, with a piston inside wrapped with the sponge and saturated with the fluid.

Figure 9 is an example of sponge-based damper [9]. The housing is made by a hollow steel cylinder; inside, a shaft, usually made of a non-magnetic material, sustains a steel piston that has a coil made of electrically conductive wire, and wrapping all of it there is the sponge. The sponge is glued to the piston and is saturated by the MR fluid.

Comparing to the previous example of linear damper, it can be clearly seen that this type is easier to build and assemble, requires less maintenance, an inferior number of components, and uses a much smaller quantity of fluid.
The present thesis uses this kind of damper, and in the following chapter there is a further detailed explanation on how to design, build and assemble the parts, and its exact functioning.

*Figure 9 MR fluid sponge-based damper (Source: [9])*
CHAPTER 2. Design of a MRF sponge-based damper

The first step towards the design of the damper is to decide its purpose. The damper in this project will be used as a game controller (or joystick) by a user or player, therefore the size must be one that is comfortable to use with one hand. As the damper will be used as a controller, one should be able to use it without problems.

Also, the average human hand must be able to move the piston without making a big effort while the damper is in the off-state; however, the maximum yield stress that the damper can handle must be so that it gets stuck even with high force from the user.

So, in order to start, there must be an assumption of the maximum force that the user can do. The damper is linear, grabbed with one hand and doing horizontal movement.

![Diagram of movement of the damper](image)

*Figure 10 Simple diagram of movement of the damper*

After assuming the maximum force that the damper will exert, we must check the available commercial MR fluids. For this thesis the MR fluid is made manually, not purchased to one of the producers. In order to start with the design, we can assume that the properties of the handmade fluid done for this thesis will only be as good as the worst commercial one available. The optimum shape must then be found, so that later we can calculate the number of turns needed for the coil that will create the magnetic field.
Prior to the start of the steps of the design, it is good to make a quick review of the main terms that are going to be used in this thesis about electromagnetism, of how the electric current creates a magnetic field, its most important magnitudes and how they relate.

2.1. Brief summary on electromagnetism

Before continuing with the design it is necessary to understand what is exactly happening to create the magnetic field [10].

Ampere’s Law explains that when an electric current goes through any conductor a magnetic field is created around it. A single conducting wire creates a low magnetic field; when the wire is winded creating a coil, the created magnetic field has much more strength with the same applied current. In a coil, every single turn of the wire creates its own magnetic field, and they superpose altogether to create a much stronger magnetic field. Coils have a hole in the middle, which is called magnetic axis. When a ferromagnetic material is placed inside this axis the magnetic field magnetizes the material, which then creates its own magnetic field that adds up to the one from the coil, thus creating an even stronger magnetic field.

![Figure 11 Magnetic field created by an electric coil](image)

*Figure 11 Magnetic field created by an electric coil*
Now, how is a magnetic field measured? There are different magnitudes that define magnetic field.

- **Magnetic field (or magnetic flux density):** it is defined as the vector field that makes a charged moving particle correctly follow the Lorentz force law. It is designated as $B$, and it has as units the Tesla ($T$).

- **Magnetic flux:** it is defined as the product of the average magnetic field times the perpendicular area that it penetrates. It is denoted with the Greek letter $\phi$, and the SI unit of the magnetic flux is the Weber ($Wb$). The equation that defines it is:

$$\phi = B \cdot A \quad (7)$$

- **Magnetic field strength:** it designates the influence of an external magnetic field in a material. Therefore, it is closely related to the magnetic field. It is designated by $H$ and it has Ampere over meter as unit ($A/m$).

$$H = B_0/\mu_0 \quad (8)$$

This last equation adds another magnetic term that is of the utmost importance. In a vacuum, the magnetic field and the magnetic field strength are directly related with a constant, called the magnetic permeability of free space that has an exact value of $\mu_0 = 4\pi \cdot 10^{-7} \ H/A$ (henries over meter, or also Newton over Ampere squared). When a material has a magnetic field applied, the permeability ($\mu$) measures the ability of this material to support the creation of a magnetic field within itself. Therefore, when the
magnetic coil is not placed in vacuum the relation between magnetic field and the strength is:

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

(9)

Furthermore, we can also define a relative permeability (it has no units) of a certain material by doing the ratio of the permeability of this material to the constant in vacuum:

\[ \mu_r = \frac{\mu}{\mu_0} \]  

(10)

Last but not least, the term magnetic reluctance defines the magnetic energy stored in the material. It has a meaning when a magnetic circuit is analyzed, as the magnetic field makes the magnetic flux follow the path of minimum reluctance. It is analogous to the electric resistance and the electric current in circuits. The reluctance has units of inverse Henry \((H^{-1})\) and it can be calculated with the following equation, where the length of the circuit is divided by the magnetic permeability and the cross-sectional area:

\[ \mathcal{R} = \frac{l}{\mu A} \]  

(11)

The last equation that is used for the design of the coil relates the magnetic flux and the total reluctance with the electrical current and the number of turns of the coil:

\[ NI = \phi \mathcal{R} \]  

(12)
After this brief summary of electromagnetism and the equations that relate the different terms, the design of the MR sponge-based damper can start.

So, let’s start with the design.

### 2.2. Theoretical design

As said before, we are going to start with an assumption of the maximum force that an average person can do laterally. Following Reference [11] for a sponge-based MR fluid damper, the usual range of currents is between 0 and 2 Amperes. However, as it will be explained on the next section, the wire that is used in the damper for this thesis has a maximum flowing current before being damaged. That current is set to be 1A for short periods of time; however, as the damper can be used for longer periods of time, the maximum will be set at 0.8A. Therefore, following the charts of force and current for the mentioned article, for 1 Ampere the force that the damper exerts is around 60N, and for 0.5A the force needed to move it, around 40N. Averaging, the assumed starting force for this project will be set to be 50N.

Thus, when the current is at its peak, the force needed to move it will be:

\[
F_{\text{max}} = 50N
\]  

As it has already been explained, the magnetorheological fluid has been made by the author for this thesis, instead of being purchased to one of the main producers. However, before creating the actual damper, for the design there must be an assumption of the properties of the fluid that has to be used. In order to obtain this information, the main producer of MR fluids has been checked for its different varieties.
The largest company that produces magnetorheological fluids is the Lord Corporation. Checking their database the MRF that they sell that has a lowest yield stress (on its peak point) is the Lord MRF-122-2ED. Then, the properties that are going to be used for the design of our fluid are the same ones of this commercial fluid: our MRF will have the same properties as the commercial MRF by Lord Corporation that has a lowest yield (Figure 12):

![Figure 12 Lord MRF 122-2ED](image)

So, the properties that are going to be used for the design are those of its saturation point (that is, even if a larger magnetic field is applied, the resulting yield stress is the same); according to the graphs they will be:

\[ \tau_y (H = 400 \text{ kAmp/m}) = 28 \text{ kPa}, \quad B(H = 400 \text{ kAmp/m}) = 0.8 \text{ T} \quad (14) \]

As it is known, the maximum force is exerted when the maximum yield is present (as explained in Section 1.2, in order to start movement the chains of the MRF must break, and that happens when the value for the yield stress is overcome).

Shear stress can be defined as the force per unit area. Using the maximum force and the yield stress, we can find the area needed:
\[ \tau = \frac{F}{A} \rightarrow A = \frac{F_{\text{max}}}{\tau_y} \] 

The area where the shear stress is applied is where the sponge, saturated with MRF, is situated. As the piston has a cylindrical shape, and the sponge is wrapping it, the area that is experiencing the shear stress is:

\[ A = 2\pi r \cdot L \] 

The total area of the sponge needed is \( A \). However, due to practical reasons, the sponge has to be divided in two parts, so that the coil is placed in the middle and the magnetic circuit uses the entire area of the sponge. That is so because in order to feel a shear stress, the sponge has to be attached to the piston and in contact to the housing, while the magnetic field is applied on the entire area of the sponge.

A cross section of the damper is showed in Figure 13, where the piston, sponge saturated with the fluid, the housing and the coil are represented. In the same figure the position of the coil is represented, as well as the theoretical magnetic field created due to it in the ferromagnetic piston and housing.
Figure 13 Cross section of a sponge damper

This drawing shows how the sponge is divided into two equal parts, each of them having an area of \( A/2 \) respect to the one calculated with the force and the shear stress. Also, the coil is represented, as well as the direction of the magnetic field. The direction of the arrow of the magnetic field can be easily found with the right hand grip rule, which accounts the direction of the current to fiend the magnetic field.

Now that the direction of the magnetic field is clear, it is important to find all the dimensions of the piston. If we recall Equation 11, in order to calculate the reluctance of a magnetic circuit the type of material, the shape and the dimensions are important. When
calculating the reluctance it must not be forgotten that we are actually dealing with a
cylindrical piston, so the cross section areas must take this into account.

The shaft where the piston is placed must be made from a different material with a really
high magnetic reluctance, so that the magnetic circuit is the one shown. It must be able to
support forces and have the shape that we want.

After the reluctances of each individual segment of the circuit, an equivalent total
reluctance $R_T$ can be found by adding up the different parts, as the reluctances are situated
in series.

Simultaneously, as the area of the sponge has been computed before, and the magnetic field
is obtained from the plots of the commercial MR fluid, the magnetic flux can be computed,
using Equation 7.

The next stage is to figure out how many turns of wire will be forming the coil. In order to
do that, the following equation has to be used:

$$NI = \phi R_T$$

(17)

In this equation, as explained in the electromagnetism review, we have the number of turns
of coil, that is our desired number, the flux and reluctance that were previously calculated,
and the current. However, picking the last term, the current, is not an easy part.

There is a limiting factor on each type of gauge of wire, and that is the maximum current
that this wire can support without losing its properties or getting damaged. So, after
deciding which type of gauge of wire we are choosing, we can proceed to calculate the
number of turns that must be used to get the magnetic flux we need for the given reluctance.

There is one last step: having the gauge of the wire and the number of turns, it must be checked if the coil fits on the space designed to do so on the piston.

As it can be seen, there are many steps, and varying one of them may change all of the other results, and therefore the final design. Thus, the design of our damper has been an iterative process, of checking properties and types of materials, different shapes to minimize the reluctance and the size while having good forces; the limiting current on the gauge of the wire chosen, and then if the amount of turns needed for the coil fit in the desired space.

However, the design does not finish here. When the sizes are calculated, the shape and the number of turns of wire are decided, there must be checked if the desired materials and shapes are available in the market.

After the theoretical design, the damper in this project has been 3D designed with the software SolidWorks, in order to have the 3D parts and its drawings. When the damper and its pieces looked good and there were no design problems, the next step is to purchase, machine the parts and assemble them.

2.3. Designed damper

After an iterative process with the equations mentioned above, a final shape and size was calculated to be good for the purpose of the damper. The materials had to be available on the dimensions and the qualities expected, so that the real parts were the same as the designed.
The main parts have the following drawings and measures:

**Figure 14 Piston**

The exact measures of the piston are slightly different due to the machining of the piece; however, they differ only on small error. All the dimensions are in millimeters.

**Figure 15 Housing**

The length of the housing has been left untouched: it is one foot long (304.8 mm). This decision has been done because with this length there is more range of movement of the piston inside of the housing, so the user can have a broader range of movement.
Figure 16 Shaft

The shaft has the maximum length, in order to be able to hold the piston and work as handle at the same time.

The total number of turns in each coil is $N = 400$.

After the iterative process explained in Section 2.2, the previous dimensions have been calculated and fixed as final. Then, the theoretical forces can be calculated. Using all the equations defined above we can get the following:

$$\phi = \frac{NI}{R_T} = \frac{400 \text{turns} \cdot 0.8A}{R_T} = 5.4743 \cdot 10^{-5} Wb \quad (18)$$

The total reluctance can be calculated from the geometry and the properties of the materials. Then the magnetic field is:

$$B = \frac{\phi}{A} = 0.1867 \, T \quad (19)$$

Using Figure 12 we can find the yield stress for this magnetic field (for $B = 0.1867 \, T$ the yield stress is approximately $\tau_y = 15000 \, kPa$), and therefore we can find the force:

$$F_{max} = A \cdot \tau_y = A \cdot 15000 = 43.988 \, N$$
Prior to the start of the iterative process, it has been explained that, following the literature, a force around 50N would be good for this purpose. Then, the calculated theoretical maximum force just stated, around 44N, is set to be acceptable for this damper. Hence, the damper is finally designed and the next step is to find the correct materials and pieces to machine, assembly and test.

For the mechanical parts made from metals, three different pieces were purchased to create the main parts. They were rods, with a length of one foot (30.48cm) and as sizes as follow:

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Material</th>
<th>ID</th>
<th>OD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Piston</td>
<td>1018 steel rod</td>
<td>----</td>
<td>1.25 in (31.75 mm)</td>
</tr>
<tr>
<td>Housing</td>
<td>1018 steel tube</td>
<td>1.35 in (34.7 mm)</td>
<td>1.75 in (44.45 mm)</td>
</tr>
<tr>
<td>Shaft</td>
<td>Aluminum tube</td>
<td>0.185 in(4.69 mm)</td>
<td>0.375 in(9.53 mm)</td>
</tr>
</tbody>
</table>

However, these materials are just rods or tubes of the materials selected. In order to maximize the magnetic properties, the outside diameter (OD) of the piston has been left without being decreased, same as the interior (ID) and OD of the housing.

The next step after purchasing these pieces was to machine them in the machine shop. Here I need to thank my lab mates, who have the Machining Certificate and helped and taught me how to do them. Then, the final parts are shown on the next following images, where both the 3D part made with Solidworks and the final piece are shown together.
As it can be seen in Figure 17, the piston has space for two coils instead of only one. This decision was taken for different reasons. The most important one is that keeping a small dimension for its diameter, with two different coils we can have both of them acting at the same time, which means that they will create double magnetic field, and therefore the force needed to move it will be higher.

The piston has a hole that goes all the way through it, where the shaft is placed. The shaft is made from the aluminum tube, where the diameter of some part has been decreased so that the piston fits is with exactly the same diameter of hole.

The outside diameter of the part of the shaft that has been decreased fits exactly to the interior diameter of the hole of the piston. By doing this, the change of section of the shaft fixes the piston, as it cannot move to the direction where the diameter is higher; it needs an extra piece to completely fix it. On part B of the figure there is a detail of the drawing of the
shaft. The change of section is clearly shown, and pointed by a black arrow. Also, another
detail is pointed in the drawing. That is a small drilled hole that goes through the shaft, and
that is where the wire will go in order to be able to start wiring the coil. This hole is
matched by a hole in the piston, of the exact same size. The next figure shows this hole, and
the incision that the outer part of the piston has, that will be used to take the wire out after
the coil is done.

![Figure 19 Detail of the hole and incision on piston](image)

With these three main metallic parts, however, the damper is not completed. There are
some parts missing. In the following table all the other components are exposed, together
with their purpose.

<table>
<thead>
<tr>
<th>Part</th>
<th>Where is placed</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collar</td>
<td>Shaft</td>
<td>It fixes the piston to its position, does not allow axial movement</td>
</tr>
<tr>
<td>Copper wire</td>
<td>Piston</td>
<td>The coil is wired on each of the two spaces for this purpose</td>
</tr>
<tr>
<td>Sponge</td>
<td>Piston</td>
<td>Wrapped around the piston</td>
</tr>
<tr>
<td>Glue</td>
<td>Piston</td>
<td>Fixes the sponge to the piston</td>
</tr>
</tbody>
</table>

A further explanation is necessary on these components.
The shaft collar is a mechanical component that fixes or stops the components around. In this damper the collar, that has as inner diameter the same one as the outer diameter of the shaft, is used to fix the piston between the change of section and the collar itself. Then, the axial movement of the piston is not allowed, even with the forces that rise when the magnetic field is applied and the stresses increase.

The copper wire is of the utmost importance. It allows the electrical current to flow around the metallic core, and by the number of turns calculated, it allows a magnetic field to be created around it. For this thesis, two different wires were tested. The first kind failed in creating the magnetic field. This first wiring was directly made from copper, with no protection around it of any kind, just bare copper. After wiring the coil and applying current, no magnetic field was created, and that was so because the copper itself is conductive in all the coil, so the current did not follow the number of turns and therefore did not create the magnetic field.

The second and final type of wire used was an enameled copper wire. This wire has an isolating surrounding, and therefore the current must follow the path of the wire, that is, the coiling. Thus, with this new wire when applying the current is able to create a magnetic field of the calculated strength. The chosen wire, for its dimension and the limiting factor of the maximum current, is a 28 AWG (American wire gauge), which has a diameter of 0.0135 in (0.343 mm). For this dimension of wire, the maximum current that can flow through it is approximately 1A, however, using this current for a long period of time could damage the wire, so for this thesis the maximum current to be used will be limited to 0.8A.
The selection of the sponge was a critical point. First of all, the type of sponge used is really important. Recalling the function of the sponge, it is saturated with the MR fluid. Therefore, it must be able to hold it without leaking, and more importantly, it must be able to hold the maximum amount possible. In order to do that and following the literature ([8], [9]), the type of sponge selected is an open-celled polyurethane foam. By being open-celled, the sponge can absorb more quantity of fluid for the same space compared to the closed-celled ones.

Once selected the type of sponge, the next important factor is its thickness. As it has been explained, the sponge is wrapped around the piston, and both of them must be able to fit inside of the housing. Then, the thickness of the sponge cannot be bigger that the space that there is between the piston and the housing. Also, it cannot be too thin to allow having air in between them, because if they are not in contact the effect of the fluid is worthless, as the yield can only happen if the fluid is in contact with both steel parts through the sponge. For the damper on this thesis, many companies were contacted, and thanks the company William T. Burnett & Co we were able to build the damper, as they sent several different samples of sponges, with one of open-celled polyurethane foam with good qualities and very high open volume that has been the used one.

Regarding the glue to fix the foam to the steel piston, many different ones were tested. To start with, the glue must be capable of keeping the sponge when high shear stresses are applied. Also, the glue has to keep the sponge stuck but without being absorbed by it, that is, leaving the cells of the sponge empty so that it can be saturated with fluid. After different tries, the selected glue is Foam Fast by 3m, glue in spray that has worked correctly and has been capable to fix the sponge after repetitive uses of the damper.
The following image shows the piston after being wrapped by the sponge, together with the coils already prepared and the shaft collar.

![Image of piston with sponge, coils, and shaft collar]

*Figure 20 Piston with sponge*

So far we have explained all the main components of the damper but one, which is the most important one: the magnetorheological fluid. As explained on the theoretical explanation, for this project the MR fluid has been created only for this purpose, instead of buying one. For this purpose the literature has been followed. Reference [11] tested different samples of MR fluids with different concentrations. The MR fluid obtaining best result in such paper has been used in our project.

There are two components to create the MR fluid. Additives are not used, as there is no sedimentation of the metallic particles due to gravity, since the presence of the fluid within the sponge prevents this from happening.

The first component is the metallic micro particles. These are the ones that will align with the magnetic field. The particles used in this thesis are: carbonyl iron powder: particles with a size between \(2 - 7 \mu\).

The second component is the carrier fluid. The chosen fluid is pure silicon oil. This oil has a viscosity of 5 cSt.
With these two components a broad range of MR fluids can be done depending on the weight ratio used. Following Reference [11], the weight ratio used has been that the weight of the iron powder is five times the one of the fluid. For example, the next table represents the actual weight used for the MR fluid on this project:

<table>
<thead>
<tr>
<th>Carbonyl iron powder</th>
<th>Silicon oil (carrier fluid)</th>
<th>Weight ratio of iron powder to oil</th>
</tr>
</thead>
<tbody>
<tr>
<td>80.002 grams</td>
<td>16.133 grams</td>
<td>4.958 ≈ 5</td>
</tr>
</tbody>
</table>

For the preparation of the fluid, some measures were taken. The micro particles of iron can spontaneously burn due to fast oxidation compared to their size. Then, when this fluid was being prepared there could not be any electronic machine around that could cause a spark. Also, due to their small size, the particles can be absorbed with the breath, so the usage a mask was mandatory, together with an extractor to take away the flying particles.

![Handmade MR fluid](image)

*Figure 21 Handmade MR fluid*

The resulting fluid is a dark, very viscous fluid, as it can be seen in the previous Figure. The particles are fully dissolved in the carrier oil, making up this dense liquid. As it has been clearly explained, MR fluid behaves as a liquid normally, except when a magnetic field is applied. Using this handmade fluid, the effects can be clearly seen. When a magnet gets
close to it, the shape of the fluid changes and it can be seen how it shows a solid-like behavior, as it does not even fall due to gravity when it is facing down.

When the fluid is prepared, and the damper is built, the next step is to prepare the entire system. The saturation of the sponge with the fluid is a meticulous process, as the entire sponge needs to be wet from the fluid, without spots with less quantity of it. In order to have the entire sponge saturated the process had to be repeated three times so that the sponge arrives to its absorption limit, hence all of its pores are full of fluid. Then, the entire surface of contact between the piston and the housing has a layer of fluid, which is hold by the sponge, and when magnetic flux crosses this layer the iron particles will align with it and the lubrication of the fluid will yield to friction.

The last component needed to make the system work is a power supply. This power supply can provide an electric circuit with a certain current and voltage. For this project, the purpose of the power supply is to give a certain amount of current that can be kept constant for the time needed. The power supply XFR 150-8, from Xantrex, can give direct current with a maximum voltage of 150V and 8A.
It has different modes of operation. For the initial tests of the damper, the local or manual mode has been used. For this, there are two knobs that control the output current and voltage that it supplies. As the magnetic field is due to the flow of current, the used knob is the one that controls the current. Turning up and down the current can be set to a fixed value, for example in the figure, $I=0.8\, \text{A}$, and the power supply fixes the output voltage that it needs to supply to maintain the flow of current through the circuit.

With all the mentioned parts, the system is fully functional and can be tested, to see how the damper is behaving for different currents, the forces exerted and the yield stresses acting.
CHAPTER 3. Testing

The damper needs to be tested to know for sure its response to the different applied currents. As it has been explained, the electrical current creates a magnetic field, which aligns the particles of the magnetorheological fluid that creates a stress and therefore hinders the movement. Then, there needs to be a test that assesses the force needed to move the damper for a certain amount of electrical current.

For these tests, our laboratory has the perfect machine. It is a MTS 858 Table Top System. It allows static and dynamic tests, using a servo hydraulic power system. With this machine static tests to check the resistance of materials can be done, as well as fatigue tests, and of course the one that will be used for the damper.

Figure 23 MTS 858 Table Top System
This MTS machine has two different parts. The clamp at the bottom is fixed, while the upper clamp can be moved vertically via the hydraulic system. The mode that is used moves the top at the selected frequency, and the sensors gather data about the position at each instant of time and the force that the system needs to do to move. Then, the data collected will be stored for each test. It must be outlined that the power supply for the damper is completely independent from the MTS testing machine. Then, using the exact same test conditions with the MTS machine but varying the current on the power supply changes completely the results of the test, and that is what we are interested into.

There was an added difficulty before starting the tests. The usually used clamps for the MTS machine are flat and the damper consists of a cylinder and the shaft, which have both of them a circular shape. There is another type of clamps that are the ones that are used for the tests: chucks. Using a chuck solved the problem of holding the shaft to the moving part of the machine; however, the bottom could not hold the cylinder with the chuck, as the housing is too big. A holding device had to be designed and implemented.

Different options have been considered. An important factor must be taken into account: the bottom of the cylinder needs air to be able to go inside of the cylinder, otherwise the piston will create a closed section with air, that will need to be compressed when moved downwards, or will have suction when moved upwards, which will add non-desired forces to the system. Then, the holding system must allow airflow to the inside of the cylinder.

The solution chosen consists on using two L-shaped brackets, bolts, washers and nuts. The lower part of the housing was drilled through, and there is one hole on each side where the screws that hold the brackets will be placed. Using all the components mentioned above,
Figure 24 shows the assembly of all of them to achieve the purpose of holding the damper attached to the chuck.

With this new configuration, the fixed chuck of the MTS can hold the bigger bolt, and therefore keeps the housing of the damper fixed, while the upper chuck holds the shaft, and moves it up and down. The damper is now ready to be tested.

The following parameters will be fixed for all the tests: frequency, amplitude of movement and data acquisition interval. These fixed values are shown in the next Table.

<table>
<thead>
<tr>
<th>Table 4 Fixed parameters of the MTS machine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
</tr>
<tr>
<td>0.25 Hz</td>
</tr>
<tr>
<td>Amplitude</td>
</tr>
<tr>
<td>60 mm</td>
</tr>
<tr>
<td>Data acquisition time (∆t)</td>
</tr>
<tr>
<td>0.00993 seconds</td>
</tr>
</tbody>
</table>

Therefore, the test consists on the piston moving with a sinusoidal pattern, with the parameters of the previous table. The following Figure 25 plots the displacement versus
time, and this sinusoidal movement can be clearly seen. The piston starts centered at its origin position, the cycle starts when the MTS machine moves it up to its higher position that is set to 30mm up, and then descents to its minimum position, that is -30mm. Thus, the amplitude of movement is 60mm.

*Figure 25 Movement of the damper vs. time*

The testing system can be seen in the next image, Figure 26, where one can see the damper attached to the chucks via the support system, and also, the computer which controls the machine and the power supply connections.
Now, after the detailed explanation of the testing assembly, let’s start with the results of the tests.

As it has been described before, on the damper there are two different coils. Then, the first test will be done with both coils inactive. This way we can find the force needed to move the damper when no current is applied, and only friction affects. Afterwards, a current will be supplied to one of the coils, and while performing the same test, we will be able to see the effect of the current on the damper.

Figure 27 represents the force needed to move the piston when no current is applied to any of the two coils.
Figure 27 Displacement and force with no current applied

The previous plot shows the displacement of the piston, which moves as explained before with an amplitude of 60mm, in orange, and the forces that the MTS machine does in blue. All this data is gathered by the sensors in the very machine.

Different things can be appreciated when looking at the plot. First of all, the forces are symmetric but not with respect the zero force. That is so because, even when the machine is not moving some force needs to be done to compensate the weight of the piston, that is, the force acting needs to compensate the effect of the gravity. Checking the average of the forces at the top and at the bottom, it can clearly be seen:

\[ F_{av}^{top} = 6.75N \text{ and } F_{av}^{bottom} = -4.16N \]  

\[ \text{(21)} \]
Due to gravity then, a bigger force is needed to lift the piston up compared to the force needed to push the piston down.

Also, the shape of the forces compared to the movement shows clearly how the MTS needs to create forces to move the piston: the force remains approximately constant from the start of the cycle until the piston reaches its maximum point, then the force switches direction and goes to its maximum force on the other direction until the piston arrives to its desired bottom position. Then the cycle starts again, with the force back to its maximum positive value.

The next step is to test the piston with different currents applied to each coil. Tests are going to be done with increases of $\Delta I = 0.1A$, from the minimum to a maximum of $I_{\text{max}} = 0.8A$, as it has been explained before, in order not to damage the wire.

Let’s start with only one coil active.

3.1. Coil 1

For differentiation purposes we will call the coils “Coil 1” and “Coil 2”. With the so-called Coil 1 active we obtain the results shown in the following Figure 28. Every test has been repeated three times, the results have been averaged and we obtain the following plot.
Some different details can be appreciated on this plot. Four different lines are represented here: when no current is applied, and when the currents are $I_1 = 0.2A$, $I_2 = 0.4A$ and $I_3 = 0.6A$. In order to make a clear plot only this four representative currents are shown.

The line in blue represents the forces when no current is applied, that is, the force needed to just move the piston, the same that it is represented on Figure 27. The other three lines represent the forces when current flows on the coil, therefore creating a magnetic field and aligning the micro particles in the fluid. Recalling Equation 6:
\[
\tau_{tot} = \tau_y(H) + \mu \cdot \dot{\gamma}
\]  \hspace{1cm} (22)

This model expresses that the total yield stress on the fluid depends on the magnetic field that is applied \((H)\). Hence, the force, which is directly proportional to the stress through the equation \(F = \tau_{tot} \cdot A\), will also depend on the applied current. Looking at the test results on Figure 28, we can see that there are a few peaks on the yellow line \((I_2 = 0.4A)\). Those picks can be due to many different factors, since it is an averaged result between three different tests, each test has different results, or minor problems on the sponge or the amount of fluid that is on the sponge can occur. However, the results are still very clear to be studied and follow the model.

We can study the increase on the forces by averaging the maximum force, that is, the forces on the top that make the piston to move up, to obtain a representative figure for each current.

<table>
<thead>
<tr>
<th>Current</th>
<th>Average force</th>
</tr>
</thead>
<tbody>
<tr>
<td>(I_0 = 0A)</td>
<td>(F_0 = 6.75N)</td>
</tr>
<tr>
<td>(I_1 = 0.2A)</td>
<td>(F_1 = 19.29N)</td>
</tr>
<tr>
<td>(I_2 = 0.4A)</td>
<td>(F_2 = 30.38N)</td>
</tr>
<tr>
<td>(I_3 = 0.6A)</td>
<td>(F_3 = 44.91N)</td>
</tr>
</tbody>
</table>

As it can be clearly seen, the pattern is that the force needed to move the piston increases as the current goes up on the coil. Therefore, the results agree with the theoretical model, which states that the more magnetic field strength is applied to the fluid, the higher the force will be needed to move it.
Furthermore, we can see that the average force needed to move the damper when the current on the Coil 1 is $I_3 = 0.6A$ is $F_3 = 44.91N$. Recalling the theoretical calculations for the design of the damper on Section 2.2, the maximum force to design the damper was set to $F_{\text{max}} = 44N$ when $I_{\text{max}} = 0.8A$. However, on the test results we can see that using a lower current we can actually obtain the same force. Therefore, the first coil improves the designed damper, as it can give the same force with a lower current, which means that the power used is lower and the damper can be used for longer without an increase on the temperature of the coil due to the current.

Another way to study the effect of the MR fluid and how it works on the damper is to study the shear stress. As explained before, the MR fluids behave as a semisolid when a magnetic field is applied, until the shear stress overcomes a value, the yield stress, when the chains of particles break and the fluid starts to flow. In this type of plot, Figure 29, the shear rate is plotted against the shear rate, which represents the speed of the movement compared to the thickness of the space where the fluid is placed, the sponge, and the effect of the different magnetic fields applied should be appreciated. If we study this plot for the first coil we obtain the following result.
On Figure 29 we can see that as the current increases, making then a stronger magnetic field, the shear stresses are higher. For a current of $I_3 = 0.6A$ we can see that the shear stress needed to move the damper is close to 15kPa, which is higher than the one for $I_2 = 0.4A$ (which is 10kPa) and the shear stress for the lowest current plotted. For the current of $I_2 = 0.4A$, however, it can be seen that following the experimental data, the line is not as constant as the others, but it still follows the increase of shear for the current.

3.2. Coil 2

The results for Coil 2 being active differ a little bit from those obtained with the first coil and are already shown in Section 3.1.
Activating the only second coil, and leaving the first one off-state, we obtain the following results. As done before, for each current the test has been repeated at least three times. The plotted results on the next figures are the average between the data of each of these tests.

To make a comparable plot with the previous coil, the next Figure 30 also shows the results for $I_0 = 0A$, $I_1 = 0.2A$, $I_2 = 0.4A$ and $I_3 = 0.6A$. Then, the data collected from the MTS can be plotter as shown in the next Figure.

![Figure 30 Coil 2 active](image)

*Figure 30 Coil 2 active*

Figure 30 shows clearly the effect of the current on the damper. Following the same pattern as with the first coil, when the current increases the force needed to move increases too.
Theory explains this behavior as the magnetic field aligns the particles and makes the damper harder to move.

However, looking exactly at the actual forces that the MTS machine needs to do with Coil 2, we can see that they are a little lower compared to those of Coil 1. Table 6 compares them:

<table>
<thead>
<tr>
<th>Current</th>
<th>Coil 1</th>
<th>Coil 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_0 = 0A$</td>
<td>$F_0 = 6.75N$</td>
<td>$F_0 = 6.75N$</td>
</tr>
<tr>
<td>$I_1 = 0.2A$</td>
<td>$F_1 = 19.29N$</td>
<td>$F_1 = 11.67N$</td>
</tr>
<tr>
<td>$I_2 = 0.4A$</td>
<td>$F_2 = 30.38N$</td>
<td>$F_2 = 25.26N$</td>
</tr>
<tr>
<td>$I_3 = 0.6A$</td>
<td>$F_3 = 44.91N$</td>
<td>$F_3 = 35.18N$</td>
</tr>
</tbody>
</table>

It can be seen that the second coil does not increase the friction that much, compared with the first one. It may be due to many different reasons. First of all, the sponge that wraps the piston may be less attached to the piston closer to the second piston. Also, another possible reason could be that the saturation of the sponge is not fully, which would mean that less fluid is available on the sponge, and thus a minor number of particles of iron would be aligning with the magnetic field and therefore the force needed to move is lower. Other possibilities may occur. However, if we recall the theoretical design, the maximum current that the damper is designed for is 0.8A. Then, for this second coil a broader study has been done.

In order to know exactly the effect of the current, more tests has been done on this second coil. For these tests, the current step is set to be $\Delta I = 0.1A$, as mentioned previously. The results of these tests can be seen on the next plot, Figure 31, which is more saturated than the previous ones, but we have considered that it is important to show it. This figure shows
two tests for each current, that is, two lines for $I = 0.1A$, two other for $I = 0.2A$ and so on, up to $I = 0.8A$.

If one looks at it closely, it can be seen that for each current the two tests overlap completely, thus showing that the effect of the current on the damper is repeatable for many different tests. The only ones that slightly differ are the tests for $I = 0.2A$, but the magnitude of the force needed is almost the same. For all the others, the increase on the force is almost constant as we increase the current, arriving to a maximum of $I = 0.8A$. If we study the maximum value for the second coil we obtain the following result:

$$I = 0.8A \rightarrow F_{\text{max}} = 47.18N$$  \hspace{1cm} (23)

As the data from the tests shows, the maximum force that the damper needs to be moved is, when the current is set to $I = 0.8A$, $F_{\text{max}} = 47.18N$. Comparing with the theoretical calculation we can get the actual improvement of the built damper compared with the theoretical calculation:

$$F^{\text{theo}}_{\text{max}} = 44N \text{ and } F^{C2}_{\text{max}} = 47.18N \Rightarrow$$

$$\varepsilon(\%) = \frac{F^{C2}_{\text{max}} - F^{\text{theo}}_{\text{max}}}{F^{\text{theo}}_{\text{max}}} \cdot 100 = 7.27\%$$  \hspace{1cm} (24)

Therefore, we can see that even with the second coil being less powerful than the first one, it still improves the theoretical calculations by a 7%, as the force needed to move the damper for the designed current is higher than the calculated.
As it has been done for the first coil, the shear stresses for the damper when the second coil is active can be studied too. Figure 32 shows the shear stresses versus the shear rates for the same currents as Figure 30 for the second coil. Compared with the resulting plot for the first coil, Coil 2 shows much clearer results. The shear stresses increase as the current gets higher, which follows the theory. The highest the current applied is, the bigger the shear stress is, as the yield stress value needs to be overcome.

Figure 31 Tests for Coil 2
After testing both coils separately, it is time to test them altogether. To assemble the electric circuit, both coils are placed in series, as we want the same current in both coils. Then, using the power supply to give them a certain current, the power supply adjusts to supply the proper voltage for the given resistance of the circuit.

The forces that the MTS machine needs to move the damper when both coils are activated is shown in the following Figure 33. In it, it can be appreciated the difference between the blue line, when no current is applied, and the other lines after the application of the current. When a current of $I = 0.2A$ is applied, the data collected, the red line, shows some
error, since the results do not follow exactly the path that they are supposed to, like the other two lines that represent the average of three tests of the indicated currents. It can be seen that the force that the MTS machine needs to do is higher as the current increases.

Figure 33 Forces when both coils are active
However, there is a clearer way to see the effect of both coils working at the same time compared to the effect of each of them individually, and that is to plot them in one single figure. It can be seen on Figure 34.
Comparing each single coil active, and both of them acting together, we can see the expected results: when both coils are active, forces are much higher than when only one coil is active. Forces for Coil 1 are represented as dashed yellow and red lines; forces for the second coil are represented with dotted lines, and when both coils are active we can see lines. Comparing up to $I = 0.6A$, it can be seen that the forces for both coils acting together are much higher than any of the single coils using the same magnitude of current. If we compute the average force for each current and compare them on a table, Table 7, we obtain the following:
Table 7 Forces on the damper

<table>
<thead>
<tr>
<th>Current</th>
<th>Coil 1</th>
<th>Coil 2</th>
<th>Both coils</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_0 = 0A$</td>
<td>$F_0 = 6.75N$</td>
<td>$F_0 = 6.75N$</td>
<td>$F_0 = 6.75N$</td>
</tr>
<tr>
<td>$I_2 = 0.4A$</td>
<td>$F_2 = 30.38N$</td>
<td>$F_2 = 25.26N$</td>
<td>$F_2 = 46.77N$</td>
</tr>
<tr>
<td>$I_3 = 0.6A$</td>
<td>$F_3 = 44.91N$</td>
<td>$F_3 = 35.18N$</td>
<td>$F_3 = 56.17N$</td>
</tr>
</tbody>
</table>

The results clearly show the improvement on the force when both coils are used at the same time, as for the same current applied the force is much higher. It can be seen that the force that the machine has to do is not the direct addition of the two separate coils; however, it can also be seen that, using the first and best coil to a current of $I_3 = 0.6A$, the maximum force is $F_3 = 44.91N$, which is lower than the force needed to move the damper when both coils are active and with a current of $I_2 = 0.4A$:

$$F_{I=0.6}^{Cl} = 44.91N < F_{I=0.4}^{both} = 46.77N$$  \hspace{1cm} (25)$$

Then, using less amount of current ($I_2 = 0.4A$) we can obtain a higher force when using both coils at the same time.

### 3.4. Discussion of results

After all this section where the different results for the tests have been explained, it is a good idea to summarize them in here.

The first clear result that can be appreciated is that with a lower electric current applied the first of the two coils studied can give a bigger force than the one that the damper has been designed for. This implies that, using less electric power, the damper needs the same force to be moved than the theoretical design.
The second coil gives slightly different results. The forces obtained are lower than the ones for the first coil, but they are still equal to the theoretical ones. Also, for the second coil the resulting plots are nicer and clearer than the ones for those ones first one.

It can be seen that both coils and its resulting forces follow the Bingham model, as the force needed to move the damper increases with the applied current. Thus, the higher the current is, the more force needs to be done to move the damper.

When using both coils at the same time it can be seen that the resulting forces are higher than when using each one of the separately, and what is more, with a lower current the forces required are higher than any single coil. Then, using a lower current we can obtain a higher force, which can be used in order to reduce the current and therefore the heating of the system.

Results of the tests agree with the references on the literature [9], [11] – [14].

This analysis, however, is purely quantitative. The forces are just figures on the plots that come from the data of the MTS machine. But the damper is going to be used by a user, which will be using with his or her hand it as controller for a game. Then, the forces need to be explained comparing them with an average user.

After some tests with several people using the damper with different ranges of current flowing through the coils, it is necessary to expose the results that they felt.

When no current is applied to any of the coils, everyone could move the damper easily in both directions. When the current is increased approximately to $I = 0.3A$ the movement of the damper could be done, but more force was needed, as the friction felt is much higher. When current on one of the coils is increased up to $I = 0.6A$, things change. The yield stress
is high, so the beginning of the movement is complicated. Thus, most of the people who tested the damper could not make a smooth movement of the shaft, but they felt that it got stuck, until they could force to move it for a short while and then it would get stuck again. Then, the movement is just intermittent, when the force is higher enough to overcome the yield stress, the damper moves until the magnetic field aligns the micro-particles again and stopping the movement again. Lastly, when the current is set to the maximum, $I_{\text{max}} = 0.8A$, the damper gets stuck and the user, any of them, cannot move it even with their maximum force.

Then, after the design, assembly and tests of the damper, the range of currents to be used is known, as well as the forces needed for each of these currents. Hence, the damper can be used as a controller from now on.
CHAPTER 4. Virtual Reality application

The introduction of this thesis exposed the main idea behind this project. Using a damper that can give a variable force feedback (that is, the amount of force needed to move it is variable) as a controller for a game will make the user immerse much more into the game.

As it has been exposed in all the previous sections, a magnetorheological fluid uses electrical current to create a magnetic field that aligns the iron microparticles on the fluid, and therefore create a yield stress that needs to be overcome, or in other words, higher force needs to be exerted to make a movement on the damper when there is a current applied. This process has been quantified on the Sections 3.1 to 3.3 with several different tests. Then, the next step is to develop a system in which the damper will be the controller that the player will use.

Before explaining all the components and programs used to control the system, it is necessary to define what a game in virtual reality is. Virtual reality is a concept that is expanding a lot on the videogame industry. Its purpose is to create an immersive environment to the player so that he feels that he is in the center of the game. Virtual reality (VR) can be generated by a number of different components. Its most used component is a headset that covers the user's eyes while working as a “screen” where the users view the action as if they were living it. Sometimes the headset is accompanied with other components, like physical controllers.
The main idea of the headset is to create an imaginary world where the user is set, with the combination of images and sounds that surround him. However, in this project there has not been enough time to apply the game to the headset, so the screen of the computer will be working as the “VR” environment.

There are many different controllers for videogames and applications of VR. Some of them have buttons to control the game, knobs, others are haptic devices; there are some that have accelerometers to detect movement and/or position, and many others. Some of them can vibrate, which is an input for the user, as it makes them feel that they may be in a dangerous position, for example. However, the majority do not have a component that can be a key on the near future: force feedback to the user.

A controller that can give a force feedback to the user is a controller that, depending on the situation is easier or more difficult to move or to be controlled. Then, the players actually believe that what they are doing resembles to the game. This effect can be used to create a VR environment to the user, as they will believe that what they are seeing corresponds to what they are doing. Therefore, the player can have force feedback if a MR fluid damper is used as controller. This system has actually been used and right now is being developed for different applications. One example of the application of VR and a MR fluid damper is on
training for surgeries. For example, Reference [15] exposes a system to use the damper for practice for vascular interventional surgeries.

In order to create this game and use the damper as a controller an entire system must be created, with different components and a control system for all of them. The following sections explain the different components, how they work, the interconnections between all of them and the different software that have been used. The components are: data acquisition boards, power supply, sensor, connection wires and computers with different software.

The first section on this Chapter will be the explanation of the software used to create the games used for this project: Unity.

4.1. Unity

Unity is a game engine that allows the creation of games in 2D and 3D for many different platforms, such as Xbox, Android, Linux, MacOS and Windows. It is a program that works with a visual interface, which allows the creation of simple games using drag and drop functionality, and more complex games through the use of scripts in C# programming language.

Unity allows the creation of games with the application of real physics simulator, effects, and animations for many different platforms. Thus, the application of the controller with one game created with this engine would allow using the damper in many different ways.

For this thesis, the first step is to test the damper with a simple game. Then, it can be tried and made sure that it can work as a controller for it. For this purpose, the starting game is described now. Unity allows the creation of games in 2D or 3D. For the simplest case, as the
damper has one degree of freedom, it is not necessary to create a game in three dimensions. Therefore we are going to start with the software and create a game in 2D.

On the initial screen of the program it can be seen that there are different sections. On the top left there is a screen where the figures or players created are shown; on the bottom left there is an image of the actual gameplay where the action figures, terrain and other elements of the game are shown. On the center there is a section where the creator can define objects, the direction of lights, cameras, define materials for the objects, and create scripts to attach to objects. The section on the right is the Inspector, where the properties of each of the objects can be changed.

To start to develop a simple game for the damper, it is necessary to think about how to make it work. The simplest scenario is the following: the player is a simple object, for example a cube, which can move on the X-axis, that is horizontal movement. This movement is guided by the actual movement of the damper, as it will work as a controller. Then, a 2D game can be created, with a cube as the player, as it can be seen on the Figure 36.
The more objects are created, the more options are there on the menu of the center. As the cube is selected, the Inspector allows us to change many properties: starting position, Rigidbody properties, attach a script and many others.

To make it simple, on the bottom left of the screen, where the actual gameplay is shown, we can see the different areas for the starting game. First, on the center we can see a black cube: this is the player, the object that will be controlled by the damper. The blue terrain is the "normal ground", where the damper is moved easily; however, the pink section of the ground is the "high friction ground", that is, when the player is on this section of the terrain the user has more difficulty to move the player. Then, what the game does is showing that the cube can be moved easily when the player is on the blue ground, but when the player is
on the pink terrain the user will have more trouble moving the damper, that is, he is having a force feedback, as it will be more difficult to control the position.

In order to be able to control the cube with the damper many different things are needed. First, on the same program the cube must be defined as a Rigid Body: then, it will have a physical component that will detect the collision with other objects, even though this collision will just have triggering effects, not an actual collision.

Also, Unity needs to receive data to move the player: as previously explained, the damper works as a controller, so the program needs to receive the data from the actual position and movement of the piston inside of the damper. Thus, a system to allow Unity to read the position needs to be established.

Then, as soon as the player enters the “high friction ground” a trigger signal needs to be sent to the power supply connected to the coils of the damper to activate it and make the movement more difficult to happen. So there is also a need of a way to send this information to the power supply.

In order to make these connections, we will need sensors and data acquisition boards, interconnections between them and coding in different programming languages. The following Figure 37 exposes how the entire system works, while showing the communication links between them. Then, the next sections will explain each and every one of the components and how they are connected.
As it can be seen, there are two data acquisition boards (Arduino and Quanser), a displacement sensor and the power supply. The different types of connections are going to be explained on the next sections.

The game needs to gather information from a sensor that will describe its movement, so the first step of the control process will be to use a sensor and connect it to the game through an Arduino board.

**4.2. Arduino and sensor**

The sensor selected for tracking the position of the damper is an Ultrasonic Ranging Module HC – SR04. It is a sensor that measures distances without contact, its range is from 2 to 400cm and the accuracy is 3mm. Figure 38 shows the sensor.
Figure 38 HC-SR04 sensor and its timing diagram

The triggering signal is a pulse of 10\(\mu\)s, which works as an input to the sensor. Then, the sensor sends out an 8 cycle burst of ultrasound at 40 kHz and waits for the echo. With the reception of the echo the distance can be calculated using a simple equation with the speed of sound in air at room temperature, the time that it takes the echo to travel back, and divided by two as the signal goes, rebounds to the object and comes back to the sensor:

\[
x(m) = \frac{v_{\text{sound}} \cdot t(\mu s)}{2} \quad \rightarrow \quad x(mm) = \frac{343 \cdot t(\mu s)}{20000}
\]

With this sensor and its associated Equation a distance to the object can be found. However, there is a need of a board that allows the adequate connection of the sensor so that it can be controlled from a computer. The chosen board is an Arduino Uno microcontroller. Arduino Uno board has analog and digital inputs and outputs pins, a 16 MHz quartz crystal, a USB connection, a power jack, an ICSP header and a reset button. This board can easily connect to any computer through the USB connection, which transfers the code to the controller to work on a certain way.
The software used to control the Arduino board is its own Arduino Software IDE, which is coded in C/C++. When a program is finished it is compiled and uploaded to the Arduino, which will be then functioning until the Arduino is disconnected from the power (by unplugging it from the computer or from the power jack).

For this part of the thesis, the Arduino board has two different purposes that are working simultaneously. First, the sensor is giving information that the Arduino needs to process, so that the distance of the object can be detected; then this data needs to be transmitted to the Unity game to control the position of the player. The second is that, depending on the position of the player on the game, a signal will be send to the Arduino from Unity, which will work as a trigger to Arduino to send an output signal.

The data process of the system works as follows: the Arduino triggers the sensor to send the ultrasonic signal and waits until it receives the eco. Then, the code in Arduino calculates the distance using Equation 26. This value is transmitted using Serial Port communication between the Arduino and Unity. The script written in C# is attached to the player in Unity, which reads the data sent from the Arduino; then, it uses this data to position of the player on the game. Then, the position is checked to see if the player is on the “high friction ground”. A byte with information is sent from Unity to Arduino, depending on the position of the player. Lastly, Arduino reads this byte and sends a voltage output related to its position.

The code for both Arduino and Unity can be found on Annex 1 and 2, respectively.
Figure 39 Arduino circuit

Figure 39 shows the circuit that connects the ultrasonic sensor to the Arduino using jumpers, the Arduino connected to the laptop using a USB cable, and two alligator connectors being the ground and the positive voltage outputs.

The output voltage that an Arduino can supply is analogic from 0 to 5V. However, it is not completely analog; it has a range value from 0 to 255, setting the output to 0 the voltage is 0V, and the maximum is 255, with the voltage being then 5V. Then, the step that the Arduino can supply is \( \Delta V = 0.0196V \). However, as it is going to be explained later, the power supply needs small values for the input voltage, so we need a way to decrease this output voltage that comes from the Arduino before it is set as input to the power supply.
Then, there is a need for another system that can receive and supply voltage as input and output, respectively. That is why we are going to use a Quanser data acquisition board.

4.3. Quanser Data Acquisition System

An Arduino board can supply an analog voltage output; however, it is not completely analogic as it has a $\Delta V$ step. Thus, as the voltage needs to be exact for our application, another additionally data acquisition system is needed.

In order to use Quanser data acquisition board we need another computer, a tabletop computer which has all the necessary components preinstalled: a MultiQ-PCI board that is installed on the computer, where the Quanser terminal board is connected. Using this MultiQ board the computer is equipped with the data acquisition terminal board, and can use all the software needed to run code to control real-time problems. The MultiQ board contains the necessary drivers to use the terminal board, which has analog inputs and outputs and encoders, as shown in Figure 40.

![Figure 40 Quanser terminal board and MultiQ](image)
In order to control the MultiQ board, there are two different types of software used. WinCon is a real-time Windows application, which allows the control of systems and plants. This program allows plotting data from the real time problem, data which can come from the inputs or from the calculations on the control algorithm.

The control algorithm to be used is defined in Simulink, where one can build models to be simulated or, in this case, to be controlled in real time. Then, the process to create the model and to be able to control it through the Quanser is the following: after having installed on the computer the MultiQ board and its software, open Matlab and proceed to create a new Simulink file. The Quanser MultiQ toolbox should be installed in Simulink, and then the necessary boxes that control the model can be created. Then, if everything is correct, the WinCon model is created and the real-time process can be controlled.

Now, it is necessary to recall why we need this board. The game in Unity sends a signal to the Arduino board when the player has entered the high friction ground. Then, the Arduino sends a voltage output signaling that there is contact and therefore the damper should be set to on-state. However, the output sent from the Arduino cannot have the exact values that will be needed for the power supply; also, as the output is not constant due to the noise that the sensor has, it must be smoothed and the maximum value should be limited. These are the reasons to use the Data Acquisition System by Quanser.

The next Figure 41 shows the actual connections to the terminal board: the analog voltage input that comes from the Arduino; the output analog voltage output that will be connected to the power supply, and lastly the ribbon cables connect the terminal board to the MultiQ data board on the computer.
Figure 41 Connections on the terminal board

The physical connections of the terminal board are known, so let’s show the actual model to control the system. The Simulink model is shown in Figure 42:

Figure 42 Simulink model

Relating the two previous images, we can see that the first box in our model is the Analog Input. The voltage sent from the Arduino is read through this input. Then, this input follows two different directions: the first one is a scope that plots on real time the signal that the
board is receiving; the second is a low pass filter that softens the noise that comes from the signal sent by the Arduino. The filtered signal can also be plotted on real time; and it passes through a gain.

This gain is the most important part of the entire model. Finding this value was capital, as it sets the output that will be sent from the Quanser board towards the power supply. Then, the data after applying the gain goes to a saturation box, which sets the maximum value that the data can have (it limits the range of the output signal). Then, the output value has been filtered, a gain has been applied and a limiting maximum has been set, and it is ready to be sent as an output voltage to the power supply using the Analog Output box.

4.4. Power supply

The power supply used for the second part of the thesis is the same that was used for all the previous Sections (3.1 to 3.3). There is, however, a big difference on the way it has been used. For all Chapter 3 the power supply was used on a Manual mode, that is, in order to change the output current the knobs were used to increase or decrease the current. As it can be expected, if the damper is going to be used as a controller for a game, it makes no sense to have a manual control of the output current.

The power supply XFR 150-8, from Xantrex, has a remote operation mode, which is the one that is going to be used for this part of the project. As the power supply is programmable, the output voltage and current can be controlled remotely through an input. Following Section 4 from the Operating Manual for the XFR 1200 Watt Series Programmable DC Power Supply, the Remote Analog Programming of the Output Voltage and Current Limit is used to control the output current supplied.
In order to have a remote control of the power supply there is a need of a voltage input supplied to the back of the power supply, with some jumpers and alligator connectors as shown, and the correct position of the switches.

![Remote programming of the power supply](image)

Setting the switches as shown in Figure 43, the power supply is expecting an analog input in volts with a range of 0 to 10V. As this input is varied, the power supply's output varies proportionally over its output range. That is, if the input is maximum (10V), the output of the power supply will be maximum too (150V). Thus, the power supply has a factor by which multiplies the input to obtain an output. As it is explained in the previous sections, the damper designed for this project needs a low current (0.8A) and low voltage (7V) as a maximum, so the range of inputs will be really small. Thus, there is the need of an analog supply of voltage that will remotely control the power supply, and this is the voltage that the Quanser board is giving as output.
4.5. Application of an MR fluid damper to Virtual Reality

This last Section summarizes all the previous work done on this thesis. Here, the implementation of the entire system is defined, tested and the results are explained. The general working principle of the entire system is explained, together with the actual details for the correct development of the game.

The game, created with Unity, is played on the HP laptop, which has connected the Arduino board with the Ultrasonic distance sensor. Using serial communication between the Unity and the Arduino software, data regarding the position of the damper is sent to Unity in order to place the position of the player in the game, and a signal is then delivered from Unity to the Arduino regarding the actual position on the game and if it is necessary to activate the damper to its on-state. Then, the Arduino sends an analog voltage output towards the Quanser terminal board.

The Quanser terminal board reads the voltage that is sent from the Arduino using one of its analog input ports. This signal is filtered to avoid having too much noise; then a gain is applied to the filtered signal, the gain in our case reduces the magnitude of the signal, and lastly the signal goes through a saturation process, where the maximum value for the signal is limited. After these processes, the signal is sent as output from one of the analog output ports on the terminal board towards the power supply. Then, the power supply is remotely activated through this input and supplies a current to the coils of the damper to activate it.

These last paragraphs explain the working principle of the entire system, so let’s now state the actual details of the chosen control process. As the connection between the game and
Arduino has just been explained, and the signal sent is just a byte, the first important output signal that we need to explain is the output signal from the Arduino.

Two different tests have been done on this part of the thesis. The first one is done to check that the limits of the control model work properly and the damper cannot be damaged; the second one, for the actual gameplay.

### 4.5.1. Maximum current test

In this test a high current will be tested to set the parameters to avoid possible damage on the coils. The characteristics for each of the devices involved on the control of the system are as follow:

- Arduino: when the triggering signal from Unity is sent, the program sends an output voltage. Two different values can be sent:
  
  - When the player is on the “high friction ground”: Arduino sends the maximum output voltage. The maximum output voltage of the analog ports of the Arduino board is 5V; however, due to the board being connected just to the laptop through the USB port and not connected to the current, the actual maximum voltage is a curve with an average of approximately:
    
    $$V_{\text{Ard max}} \approx 4.4V$$  \hspace{1cm} (27)
    
  - When the player is on the “normal ground”: Arduino sends the minimum output voltage, which is approximately zero volts.
    
    $$V_{\text{Ard min}} \approx 0V$$  \hspace{1cm} (28)
• This voltage is read on the Quanser terminal board, and the value goes on the Simulink model. In order to find the Gain on the model, we must know the output that the board needs to send to the power supply in order that it gives the necessary current to the coil. To find this value, the circuit was tested with different resistors, in order not to damage the coil of the damper if a current supplied by the power supply was higher than the maximum allowed by the wire. The last resistor tested had a resistance of 10Ω, which was really close to the total resistance of the coil (R≈8 Ω). Then, the value for the Gain was found:

\[ K = 0.034 \]  \hspace{1cm} (29)

Applying this gain to the input voltage we obtain a much lower value, which will be sent as output:

\[ V_{out} = K \cdot V_{in} \rightarrow V_{out} = 0.034 \cdot 4.4V = 0.15V \]  \hspace{1cm} (30)

This output value, however, is not fixed, as it has been explained before. It is varying as the input is not constant. As we don’t want a value higher than \( V_{out} = 0.15V \), the saturation on Simulink will prevent this from happening as it is fixed to \( V_{sat} = 0.15V \). This effect can be seen in the next Figure 44.
Figure 44 Screenshot of Wincon with saturation of output voltage

- The power supply will receive a voltage of $V_{in} = 0.15V$ as input to activate the remote control. After the tests with different resistors, this is the maximum value for the input, as using this value as an input the output voltage and current are:

$$V_{in} = 0.15V \Rightarrow \begin{cases} V_{coil} = 5.2V \\ I_{coil} = 0.60A \end{cases}$$

Using all the values that have been explained when the player enters the high friction ground the maximum current that will be supplied to the coil will never exceed $I_{coil} = 0.60A$, therefore the coil will never be damaged.

Figure 45 shows the entire functioning system: the player is on the “high friction ground”, the Arduino sends a voltage that is plotted, filtered and after the gain is applied on the
Quanser system, a new signal is sent to the power supply, which supplies the maximum current.

Figure 45 shows the entire system: the game is being played, with the player (black cube) on the “high friction ground”, as the damper has been moved to that position, the signal being read by the Quanser board and the output sent to the power supply, which sets the damper to on-state. As it is the test to see the maximum current on the system, if one tries to move the damper will have problems to be able to move it. However, this is just the testing to keep the damper safe. Next Section shows the actual gameplay with the regulated current to be played.
4.5.2. Gameplay

For the actual gameplay, the Simulink model is the same one as for the previous Section; the connections between the different components are equal, but the output sent from the Arduino differs. For this case the output sent from the Arduino will be lower when there is contact (Y) and still zero when the player is on the normal ground (N), that is:

\[
\begin{align*}
V_{out}^Y &\approx 1.5V \\
V_{out}^N &\approx 0V 
\end{align*}
\]  

(32)

With this voltage, when the Gain is applied on the Simulink model the output voltage that the terminal board from Quanser will be:

\[
V_{out} = K \cdot V_{in} \rightarrow V_{out} = 0.034 \cdot 1.5V = 0.051V 
\]

(33)

The output voltage given by the Quanser board is the one on Equation 33, and when this voltage works as input on the power supply, the resulting current and voltage given by it are:

\[
V_{in} = 0.051V \Rightarrow \begin{cases} 
V_{coil} = 2.2V \\
I_{coil} = 0.25A 
\end{cases}
\]

(34)

Comparing this value to the values obtained experimentally, for example the values on Table 6 on Section 3.2, we can see that, for both the first and the second coil, for a current of \(I_{coil} = 0.25A\) the resulting forces needed are between 15.07N and 22.06N, after linear interpolation. After the different tests that have studied the behavior of the damper, for a force like this the user can move the shaft, therefore controlling the movement, but the
force that must be done is higher than the normal case when the current is zero. Then, a force feedback controller has been created.

**Figure 46 Gameplay system, "high friction ground"**

Figure 46 shows the entire system working when the player is on the area where the user will feel resistance to move the damper. For a general user, the force needed to move the damper until the normal ground is not too much, therefore the user will be able to leave this area and continue using the damper without a significant amount of force, as it is shown in Figure 47.

When the damper has been moved and the player is outside of the higher friction area, the user can move it easily. However, as it can be seen in Figure 47, the remote control of the power supply does not exactly give a zero current output to the damper. If one checks the
output voltage value from the Quanser board, plotted on the monitor through the WinCon application, the value, even really close to zero, is not zero exactly. The power supply's input is a really small value ($V = 0.051V$) to give the current that we want. Then, when the Quanser board gives as an output a value that is of the scale of $V = 10^{-5}V$, that is, almost zero, the power supply stills consider this as input and supplies a really small current. However, for a normal user the force needed is really low, so the working principle is still the same.

Figure 47 Gameplay, off-state damper
4.6. Discussion of results

All the previous Sections explain the working principles, components and connections used to make the entire system work.

It was not an easy path, though. Each of the components gave challenges when trying to create the entire system: the power supply’s remote connection mode had problems that had to be solved before it could be used; the Quanser terminal board can only be used on the tabletop computer that has been used, and it is a Windows XP computer, therefore its programs are out of date, and also the generation of the WinCon application had problems; lastly, the connection between the Arduino and Unity was not easy as it had to go both ways simultaneously. However, due to patience, work and some help from the schoolmates from the ISSL lab, they were solved.

The entire system works: using the damper as a controller the black cube that works as a player moves on the game. When the player enters the “high friction ground” the system activates the coils of the damper and the user feels a difficulty to move it, thus a higher force is needed to continue moving until the player exits this area and gets to the normal one.

There are a few things to be improved, however. Due to lack of time to continue working on the game, it suffers of lag. Lag is defined as comparative slowness or retardation, but when talking about games, it is defined as noticeable delay between the action of the player and the actual movement on the game. On the game prepared for this thesis, this problem occurs. Due to the noise on the data read by the ultrasonic sensor the position of the player on the game is not clear or constant, and then it suffers some lag when it is moved. The
change on the behavior of the damper is instantaneous when the position changes from the normal ground to the high friction one, so the problem is not on the data, as the triggering still occurs when it has to. The problem can be on the amount of data read from the sensor and the impossibility to show all that on the actual game, or the noise of the data read. A low pass filter was tried to be applied on the Arduino, but then the communication between it and Unity did not happen correctly. Probably with more time working on this it could have been solved, but due to the limited amount of time for this thesis, this can be left as a future work.

The game designed for this thesis, although simple, was enough to test the correct behavior of the system. Consequently, the expansion of the game can be considered after this thesis. Another more complete game was planned to be created on Unity for this thesis, but as it was to be more complex the use of the damper as the controller could not be achieved. For example, Figure 48 shows a possible game on which the damper could be used as controller.
On this Figure a new and more complete version of a game is shown. This game is more complicated to code as it is a 3D game; the yellow arrow shows the direction that the player follows automatically, with a constant speed that is not controlled by the user. The blue arrow shows the direction on which the user can move the player through the damper. When the player collides with a wall, the damper should not allow more movement on that direction but getting far from the wall should be permitted and done easily; different surfaces with different frictions are also shown, so that the same controller used in this thesis can be applied to solve this problem. Moreover, collectables can reward prizes or higher punctuation to the player on the game. Obviously, much more complicated games can be designed using the damper as a controller, but they are out of the scope of this thesis.
The design of a new damper with two degrees of freedom, that is, that could allow linear and rotational movement, with the same principle using MR fluids, could be used as controller for more complicated games or other alternative applications.
CONCLUSIONS AND FUTURE WORKS

This thesis had two clear and different goals. These goals were to study a smart material, the Magnetorheological fluid, and to create a damper that can be used afterwards as a controller for a Virtual Reality game.

After studying how the MR fluids work and the different dampers that are nowadays more used on the literature, a decision was made to build a sponge-based damper. On this type of damper the assembly and maintenance is simpler and cheaper than other types, mostly due to the fact that there is no need for sealing and bearings, since the damper is not filled with fluid. Instead, a sponge is placed wrapping the piston, and the MR fluid is saturating this sponge. As it has been explained, the working principle of the damper is that when a magnetic field is present, the iron micro particles on the MR fluid align and the fluid changes its viscosity and behaves like a semi-solid. Then, as the fluid is on the sponge that is placed between the piston and the housing of the damper, more force is needed to move the damper when a magnetic field is present. Additionally, in order to have a variable magnetic field the damper has two independent coils, which create magnetic field when a current flows through them. Therefore, the damper can be controlled and the magnetic field can be increased or decreased using the electric current supplied.

A damper like the one just described has been designed and built for this thesis. Different parts were purchased and machined to have the dimensions that followed the theoretical calculations. Then, when the damper was ready, it has been tested using a tensile test MTS machine, which is able to move up and down, making the perfect testing conditions for the designed damper. The tests have been done under different conditions: first when no current is applied on the damper, that is, when there is no magnetic field and therefore the
MR fluid behaves as a fluid; and afterwards with different currents applied to the coils, which create the magnetic field. The data collected from the tests has been studied afterwards.

The tests show good results: both coils give better results than the initial design hypothesis. During the theoretical design, a maximum force was assumed and the optimal dimension for a damper able to work under those strengths was designed. Then, the tests showed that for a given electric current, the actual force needed to move the damper is higher than the forces needed on the theoretical design. Also, the behavior of the damper follows the theoretical model: the higher the electric current applied is, the more strength that the magnetic field has, and thus the force needed to move the damper is higher.

Once the behavior of the damper was quantified, the second part of the thesis could start. The damper was designed so that it could be used as a controller for a game in a Virtual Reality environment. Using the working principle that had been tested, the range of currents that could be used to make the damper a force feedback controller were known.

In order to use the damper as a controller for a game a complex system had to be created. First of all, a game had to be created, in this case using the program Unity, which is a game engine developer. The game created was simple, as the main purpose of this thesis was to make a system that could use the damper as a controller, not to create a complex game.

Using a system that involved two computers, two different data acquisition systems, a sensor and a power supply, the damper works as a controller for this game. The game is simple but clear enough to show the change of behavior of the damper: there are two different regions, when the player is on the normal region the user can easily move the
damper, but when the player is on the high friction area, the damper goes on-state and thus the user needs to do a larger force to move it, until it leaves this area and goes back to the normal one again.

This thesis had two different goals, and the results show that both of them have been satisfied. A damper that carries a smart material, MR fluid, can change its behavior to make a force feedback system, and this effect has been used in a virtual reality environment successfully.

Regarding future works that follow this thesis, different paths can be followed. First, even though the game created is simple, it shows how the behavior of increasing the apparent viscosity of the MR fluid can make the damper work as a force feedback controller. However, the game can be improved, so a way to continue this thesis would be increase the complexity of the game, with more possibilities and maybe rewards towards the gamer. Also, next stage can be the application of this game to a Virtual Reality headset, thus making the player feel even more inverse in this environment, while using the damper as controller.

Another direction that a future work can follow is the improvement of the damper: the damper created here has one degree of freedom, that is, it only allows linear movement. Thus, another damper with two degrees of freedom, for example linear movement and rotation, would allow the creation of a more difficult and entertaining game. A joystick with two degrees of freedom can also be created with two rotation dampers, which would use the same working principle and can add a new dimension on the control of the game.
REFERENCES


Other bibliography:


ANNEX 1

Arduino code that reads distance from the sensor, then sends this data to Unity and reads back its feedback to send output voltage

```c
//define output and input pins
const int TRIG = 9;
const int ECHO = 10;
const int voltageout=3;
char myCol[20];

void setup (){ 
    //start the program
    Serial.begin(9600);
    pinMode(TRIG, OUTPUT);
    pinMode(ECHO, INPUT);
}

void loop (){ 
    //start the ultrasonic sensor's function
    int data = GetUltra(TRIG,ECHO);
    Serial.write( data ); //send data to Unity
    delay(20);

    int If = 10;
    //reads the Byte sent from Unity
    Serial.readBytesUntil(If, myCol, 1);
    if(strcmp(myCol,"y")==0){
        //if player ("yes") is on the high friction ground
        //send voltage output=80
        analogWrite (voltageout, 80);
    }
    // else {
    if (strcmp(myCol,"n")==0){
        //player is on the normal ground
        analogWrite (voltageout, 0);
    }
    }
}

//GetUltra is the function that calculates the distance of the damper
double GetUltra ( int trig , int echo){

digitalWrite(trig , LOW);
delayMicroseconds(2);
digitalWrite(trig, HIGH);
delayMicroseconds(8);
digitalWrite(trig, LOW);
```
//Equation 26 to calculate distance
double distance = ( pulseIn(echo, HIGH) )* 343.2 / 20000;

return distance;
}
ANNEX 2

Script attached to the player in Unity:

```csharp
using System.Collections;
//Start the solver engine
using UnityEngine;
using System.IO.Ports;
using System.Threading;

public class code : MonoBehaviour
{
    //define variables
    public float distance;
    private Rigidbody rb;

    //Open serial port communication to be able to read the information sent from Arduino
    SerialPort stream = new SerialPort("COM5", 9600);

    // Use this for initialization
    void Start()
    {
        //Open the communication channel
        stream.Open();
        stream.ReadTimeout = 30;
        //Define as rigid body
        rb = GetComponent<Rigidbody>();
    }

    // Update is called once per frame
    void Update()
    {
        Vector2 temp = transform.position;
        if (stream.IsOpen)
        {
            try
            {
                float data = stream.ReadByte();
                data = Mathf.Clamp(data, 3, 18);
                //to normalize the data, we substract 10 to get the minimum value to -15
                data -= 10;
                //the data now goes from -7 to 8 as the playing field that goes from -7
                //x position of the player is the value read from the sensor normalized
                //to the screen of the
                temp.x = data;
            }
            catch (System.Exception)
            {
            }
        }
    }
}
```
```csharp
{
    Debug.Log("timeout");
}

transform.position = temp;

//Trigger is the function that detects collision between rigid body objects
void OnTriggerEnter()
{
    //first contact between the two objects, sends message of contact
    print("Collision detected with a trigger object");
}

void OnTriggerStay(Collider other)
{
    //if the player goes inside the "high friction area", a message is sent
    print("Still colliding.");
    //Send the byte with "y" (yes) to Arduino about the position
    stream.Write("y");
}

void OnTriggerExit(Collider other)
{
    print("Keep moving");
    //When there is no contact a byte with "n" (no contact) is sent to Arduino
    stream.Write("n");
}

```