Design and Modelling of a Semi-active Helicopter Seat Cushion

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Aerospace Engineering

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To my parents, for the unconditional support...
Acknowledgments

The conclusion of a university master degree is a long commitment involving many obstacles and challenges and, its accomplishment involves the help of many different people that I want to mention and to whom I need to extend my gratitude.

This research work was accomplished at University of Victoria, in Canada, in collaboration with NRC Canada, in Ottawa.

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Without their valuable participation and input, this research thesis would have not been successfully concluded.

Lisbon, Portugal

15/10/2016
Resumo

Os helicópteros estão sujeitos a elevadas cargas vibratórias, o que leva à redução da qualidade do voo. Tem havido um crescente número de queixas de fadiga, desconforto e dor por parte da tripulação durante exposições prolongadas à vibração neste aparelho.

O principal objectivo é ajudar a atenuar este tipo de vibração através da avaliação de um novo assento.

Esta investigação centra-se na utilização de materiais magnetoreológicos para uma melhor protecção e conforto dos ocupantes, a fim de apresentar um sistema de assento semi-activo.

Os materiais magnetoreológicos são uma das estratégias mais promissoras para esta finalidade. As propriedades únicas destes materiais - a sua capacidade de responder mecanicamente a campos magnéticos e a sua não-linearidade característica - fazem do desenvolvimento destas aplicações um desafio.

A almofada do assento magnetoreológico consiste na utilização de material magnético, várias bobinas electromagnéticas e diferentes amostras de fluido ou elastómero magnetoreológico.

Dois software comerciais (COMSOL® e FEMM), capazes de modelar problemas complexos em matéria de análise electromagnética e materiais não-lineares, foram analisados e utilizados. Um estudo detalhado de cada material é levado a cabo, em termos de design e das suas aplicações, bem como a definição da geometria, propriedades, condições de fronteira e geração da malha.

O sistema da almofada do assento demonstrou ser eficaz, após o estudo de modelos teóricos do desempenho do material magnetoreológico e a criação de modelos de elementos finitos bem como através da resposta do material, em reduzir as vibrações sentidas pela tripulação.

Para concluir, é proposta uma configuração final do design a produzir, assim como um diagrama de blocos do Simulink® para representar a resposta da almofada e uma primeira proposta de controlo. É expectável que, no futuro, esta seja a solução a implementar nesta problemática.

O design proposto do assento vai ser fabricado pelo National Research Council Canada, com o qual foi possível esta colaboração.

Palavras-chave: assento de helicóptero, materiais magnetoreológicos, elementos finitos, circuito magnético, design, controlo
Abstract

Helicopters are susceptible to excessive vibratory loads that lead to poor flight ride quality. There have been increasing complaints of fatigue, discomfort and pain by crew, during extended exposures to this vibration.

The main goal of the thesis is to help mitigate structural vibration by designing and evaluating the structural performance of a novel seat cushion.

This solution focuses on the use of magnetorheological (MR) fluids and elastomers to dampen the structural response of the semi-active seat system, to enhance occupant protection and comfort.

Magnetorheological materials present a promising approach for this purpose. The MR seat cushion consists of a distributed magnetic material embedded in elastomers and various electromagnetic coils. The unique properties of magnetorheological materials - their ability to mechanically respond to magnetic fields and their characteristic material non-linearity - make designing these applications a challenge.

Two commercial software (COMSOL® and FEMM), capable of modelling complex electromagnetic problems and non-linear materials, have been evaluated and used. A detailed study of each material is carried out, in terms of design and response as well as the definition of the geometry, properties, boundary conditions and mesh convergence.

The study of analytical and computational models to quantify the performance of the MR material (response output) has demonstrated that the proposed helicopter seat cushion system is effective in reducing the vibration felt by the pilots.

To conclude, a conceptual final design configuration is proposed as well as Simulink® block diagram to represent the cushion response and a one-degree of freedom control model. This is expected to be the main solution adopted in the future.

The thesis has been performed in collaboration with the National Research Council Canada and the seat cushion design proposed is going to be manufactured and tested.

Keywords: helicopter seat cushion, magnetorheological material, finite element method, magnetic circuit, design, control
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<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>ACSR</td>
<td>Active Control of Structural Response</td>
</tr>
<tr>
<td>AC</td>
<td>Alternate Current</td>
</tr>
<tr>
<td>AISI</td>
<td>American Iron and Steel Institute</td>
</tr>
<tr>
<td>ARC</td>
<td>Active Rotor Control</td>
</tr>
<tr>
<td>AWG</td>
<td>American Wire Gauge</td>
</tr>
<tr>
<td>BVI</td>
<td>Blade Vortex Interaction</td>
</tr>
<tr>
<td>CAD</td>
<td>Computer Aided Design</td>
</tr>
<tr>
<td>CCL</td>
<td>Controllable Cushion Layer</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>ER</td>
<td>Electrorheological</td>
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<tr>
<td>FEA</td>
<td>Finite Element Analysis</td>
</tr>
<tr>
<td>FEMM</td>
<td>Finite Element Modelling Magnetics</td>
</tr>
<tr>
<td>FEM</td>
<td>Finite Element Method</td>
</tr>
<tr>
<td>FFT</td>
<td>Fast Fourier Transform</td>
</tr>
<tr>
<td>GA</td>
<td>Genetic Algorithm</td>
</tr>
<tr>
<td>HACS</td>
<td>Hybrid Air Cushioning System</td>
</tr>
<tr>
<td>MRE</td>
<td>Magnetorheological Elastomer</td>
</tr>
<tr>
<td>MRF-E</td>
<td>Magnetorheological Fluid-Elastomer</td>
</tr>
<tr>
<td>MRF</td>
<td>Magnetorheological Fluid</td>
</tr>
<tr>
<td>MR</td>
<td>Magnetorheological</td>
</tr>
<tr>
<td>NRC</td>
<td>National Research Council</td>
</tr>
<tr>
<td>PSD</td>
<td>Power Spectral Density</td>
</tr>
<tr>
<td>RMS</td>
<td>Root Mean Square</td>
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<tr>
<td>SDOF</td>
<td>Single Degree of Freedom</td>
</tr>
<tr>
<td>SWG</td>
<td>Standard Wire Gauge</td>
</tr>
<tr>
<td>TF</td>
<td>Transfer Function</td>
</tr>
<tr>
<td>VAD</td>
<td>Vibro-Acoustic Disease</td>
</tr>
<tr>
<td>WBV</td>
<td>Whole-Body Vibration</td>
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</table>
Nomenclature

Greek symbols
\[ \delta \quad \text{Volume fraction.} \]
\[ \dot{\gamma} \quad \text{Shear rate.} \]
\[ \eta \quad \text{Viscosity.} \]
\[ \mu \quad \text{Permeability.} \]
\[ \Phi \quad \text{Magnetic flux.} \]
\[ \rho \quad \text{Density.} \]
\[ \sigma \quad \text{Electrical conductivity.} \]
\[ \tau \quad \text{Shear stress.} \]
\[ \theta \quad \text{Shear strain.} \]
\[ \mu_0 \quad \text{Vacuum permeability.} \]
\[ \mu_r \quad \text{Relative permeability.} \]
\[ \tau_0 \quad \text{Yield stress.} \]

Roman symbols
\[ \mathcal{R} \quad \text{Reluctance.} \]
\[ A \quad \text{Cross-section area.} \]
\[ B \quad \text{Magnetic flux density.} \]
\[ c \quad \text{Damping coefficient.} \]
\[ E \quad \text{Young's modulus.} \]
\[ F \quad \text{Force.} \]
\[ f \quad \text{Frequency.} \]
\[ F_d \quad \text{Damping force.} \]
\[ F_k \quad \text{Spring force.} \]
$G$  Shear modulus.
$g$  Gain.
$h$  Gap size.
$I$  Current.
$J$  Current Density.
$k$  Stiffness.
$l$  Magnetic flux path.
$M$  Magnetization.
$m$  Mass.
$N$  Number of turns.
$q$  Laminar flow.
$R$  Radius.
$S$  Saturation.
$x_r$  Relative displacement.
$p_\eta$  Viscous pressure.
$p$  Pressure.
$H$  Magnetic field intensity.
$u$  Velocity.

Subscripts
$c$  Coercivity index.
$e$  External condition.

Superscripts
$n$  Flow Index.
$T$  Transpose.
Chapter 1

Introduction

1.1 Motivation

Nowadays, the harmful effects on human performance and health issues caused by undesired vibration transmitted through vehicle seats have been of increasing concern.

Even though the helicopter has became a versatile mode of aerial transportation, high vibration levels transmitted through the helicopter seats lead to poor ride quality for its aircrew. Unpleasant vibration has been known to cause physiological damage such as fatigue and discomfort to the aircrew in a short-term exposure as well as neck strain and back pain injuries due to long-term exposure, particularly in military pilots. This type of exposure interferes with the operational performance by degrading situational awareness, which may affect decision making.

In order to counteract these effects, the proposed solution is a new seat cushion, which is expected to be the least costly change with the least impact in certification and the most effective, rather than modify or replace something in the structure itself. The target point and the impact it will have is to provide more comfort to the helicopter crew and probably to extend this type of seat cushion model to all the fleet. The major benefit is the no structural modification to crashworthy seat frame.

Thus, solutions that would deal with the above issues have interested the research community, such as the development of a seat cushion whose system takes advantage of magnetorheological materials properties. Huge efforts have been made in this research field and the biggest incentive is that this is a quite innovative idea, fairly recent and a lot can be done in the future.

This research project falls within the framework of the National Research Council Canada and is going to be a contribution of the University of Victoria, in Canada that will investigate the use of novel semi-active methodologies integrated in helicopter seats to mitigate the aircrew exposure to high vibration levels. This thesis provided the opportunity to be part of the development project of a new helicopter seat and to be in contact with the technical challenges inherent to this area.
1.2 Objectives

The target of this project is to investigate a novel design of a smart material cushion that seeks to reduce the vibration in the human body.

The project is addressed as semi-active control of a helicopter seat cushion - controllable cushion layer (CCL) - and its main purpose is to develop a seat cushion that incorporates two types of materials to mitigate the vibration felt by the crew in various flight envelopes.

Although such a project covers numerous areas of expertise such as structures, vibrations, materials, health care, electromagnetics, control, design and optimization, the main objective of this thesis is to have a new design of the novel cushion, to create a new magnetic circuit design and to evaluate the effects of seat cushions on mitigating the higher frequency, by reducing the acceleration felt by the aircrew, through the application of new materials and associated settings.

As it is a very recent topic, a further investigation and research on semi-active seat cushions and magnetorheological materials have been proposed, in order to get an overall understanding on their behavior, theoretical background and possible applications. So the author is going to provide a detailed finite element analysis tool for modelling magnetorheological materials and an accurate electromagnetic circuit design that is one of the main focus from NRC. Also, it presents a system for seat cushion to reduce the vibration levels transmitted to the body, through a numerical model and a single degree of freedom system that will reproduce the material response.

The main objective is to combine such different areas and explore its advantages and limitations. The steps previously mentioned, characterize the original contribution that the author is giving to the field.

By the end, the pilot should be isolated from the helicopter vibration coming through the seat.

1.3 Thesis Overview

This thesis focus on starting with the definition of the parameters, materials and models used; then some preliminary design considerations; a thorough magnetic circuit design investigation; different possible configurations and an optimization study to perform the best solution in order to be able to do the CAD design of the final seat cushion and the analysis of the influence of magnetic fields in mitigating the vibration from the helicopter on reproducing the material response. It is presented in figure 1.1, a schematic of the methodology used (the open loop is the first part of the work and in the end, with the control proposal, the loop is closed).

This thesis is divided into seven chapters and it is organized as follows:

**Chapter 1** provides an introduction and motivation for the main topics discussed within this work.

**Chapter 2** has the information regarding the state of the art and the theoretical background related to the work that has already been developed, so that the readers are able to understand what is analyzed in the following chapters and what has already been done in this area, as well as an introduction to all topics involved in this work. There is also a small reference to explain what is NRC and what they have developed.
Chapter 3 introduces the project, the cushion concept and some preliminary calculations and considerations based on the information provided from NRC (that by the end will be completely modified). Based on an existing biomechanical model, a small example of a base motion excitement and results obtained in terms of transmissibility and frequencies are, then, showed. At the end of the chapter, there is a description of the design and simulation procedure. Two FEA software packages, COMSOL Multiphysics and FEMM have been used for this purpose.

Chapter 4 explains the design process of the magnetic circuit and materials design in detail. In order to obtain a complete understanding of the MR material magnetic behavior, finite element models were built to simulate it. Then the mesh generation with associated convergence study and boundary condition notes are presented. After that, one has the first studies, which were done by the author, in order to validate both software using previous works and reproduce the experimental rigs used in the laboratory, comparing with analytical calculations and presenting a magnetic force study. Finally, a few design conclusions and extremely important steps are discussed.

Chapter 5 describes a variety of parametric studies in order to evaluate all the possibilities for each defined configuration. Different configurations that might be used are presented as well as the advantages and disadvantages. Then some of the studies and respective conclusions are presented. With the objective of exploring the capacities of COMSOL® software, a simple optimization example is addressed. In the last section the final configuration of the cushion with the respective CAD and cut sections detail is displayed.

Chapter 6 characterizes the response of the material, the final system representation of the cushion and an example of a possible control proposal. A numerical model, based on previous studies, is presented and discussed if it is able to reproduce MR Fluid squeeze behavior. This model has been validated and then used in a Simulink® application to reproduce the entire single degree of freedom approximation of the cushion model and check for the output acceleration felt by the aircrew. For the MR Elastomer just a little note is shown since there is no information yet about the models to be utilized. As a closure topic, to perform the closed loop of the project, a simple control example is discussed.

Chapter 7 presents general conclusions of the project, work achievements and suggestions for further work and improvements.

![Diagram of Methodology of the project](image1)

Figure 1.1: Methodology of the project
Chapter 2

Background

In this chapter, a detailed historical and theoretical background and state of the art on helicopter vibrations, magnetorheological materials and the techniques used to control vibrations are presented.

2.1 State of the art

The helicopter has turned into a versatile mode of transportation due to its unique ability to take-off and land vertically as well as its ability to hover, fly forward, backward and laterally. These peculiarities allow helicopters to be used in congested or isolated areas where other aircrafts cannot be used, in particular in military operations. Despite these unique capabilities, helicopter flights, due to high levels of structural vibrations caused by cyclic variation of inertial and aerodynamic loads, are generally unpleasant for aircrew and passengers due to their exposure to high vibration levels in the cabin.

The sources of this vibration, among all others, are the main hub reactions to the blade passage frequency; blade vortex interaction (BVI); gusts and blade stall.

![Figure 2.1: Sources of the Helicopter Rotor Vibration [1]](image)

The helicopter’s main natural frequency comes from the rotor hub and is usually constant under normal flight operations (between 4 to 5 Hz). The resulting vibrations lead to fatigue damage which results in higher maintenance costs and can cause health problems to aircrew and the passengers. This
has been a major topic of concern for the helicopter industry, in order to reduce or mitigate the undesired vibrations.

Due to the complex coupling between the rotor system, airframe, transmission and engine, the vibratory loads and noise energy are transmitted throughout the helicopter structure and contribute to poor ride quality for passengers and crew, low fatigue life of structural components, high maintenance costs and confined flight envelope of the vehicle.

Considerable efforts have been undertaken to reduce helicopter vibration levels. Many new devices and design modifications have been implemented on in-service helicopters, and achieved a few performance improvements. However, revolutionary approaches have to be developed to mitigate uncomfortable helicopter vibration transmission to the crew and passengers [1].

### 2.2 Health Concerns

Exposure to high intensity, low frequency - 4 to 80 Hz - noise can cause Whole-Body Vibration (WBV), which has become an increasingly significant area of concern in helicopter seat design. Such exposures to aerial vibration reach the limits of human tolerance and have been correlated with physiological disorders. Back pain in crew members has been documented in both rotary and fixed-wing aircraft, particularly in helicopters [2]. These symptoms have been associated with increased aircraft vibration, so it interferes with effective performance, and diminishes operational safety [3]. Short-term exposure causes several issues, the coordination and speech are affected and it may also cause some trouble in activities that require a certain degree of dexterity, mainly because the 4-5 Hz frequency is also one of the dominant resonance frequencies in the human body, thus producing diaphragmatic fluctuation causing a vibrating effect [4]. Long term exposure may lead to chronic pain, spinal misalignment, spine strain injuries and, also Vibro-Acoustic disease (VAD) [5, 6] that is shown through the thickening of pericardial walls, cardiac valves and arterial walls.

One particular case involves the U.S. Navy E-2C Hawkeye, a crew seat that was used in the laboratory during exposure to a selected operational signal, to evaluate those effects [7]. A vibration survey was conducted by the Air Force research laboratory to measure the seat accelerations. The study confirmed that the vibration associated to the propulsion system in this aircraft consistently occurred at about 18.5 Hz (rotor speed) and 73.5 Hz (blade passage frequency). Vibration at these frequencies can be felt by the aircrew [8]. The cushion was approximately 5.5 cm thickness, weighed 1.74 kg, and was covered with fabric. Similar flying related pain has also been reported in Swedish (57%) and Australian (29%) militaries [9].

Since there is nothing the pilot can do in flight to minimize the pain, it becomes a distraction that can jeopardize the security of the flight, mission or passengers. All these issues can be further complicated when the crew uses any kind of heads-up device (helmet, vision goggles and so on) which increase the weight and shifts the center of gravity and vibration may cause increased strain in neck muscles [10].
2.3 Development

In order to successfully reduce vibration level, vibration cancellation on seats technologies and techniques (locally) has attracted significant interest in recent years [11].

Seat cushions have been considered a low-cost solution for improving comfort and mitigating vibration. Conventional cushions typically increase the transmission of vertical vibration at low frequencies in the vicinity of the primary human whole-body resonance (4-8 Hz) and attenuate the transmission of vibration at higher frequencies [12, 13]. New seat designs, including active or semi-active vibration isolation of the seating system, could potentially mitigate the higher frequency vibration and improve comfort. An immediate and viable approach to control the whole body vibration (WBV) exposure that is being implemented in current helicopters is through the use of passive control systems, by using passive seat cushions.

Due to the significantly less certification effort needed to change the helicopter seat structure, the application of innovative technologies to the seat is more practical in order to reduce aircrew vibration, compared to flight critical components such as the main rotor [14].

2.4 Smart Materials

Magnetorheological Fluid and Elastomer belong to a class of materials that are known as "smart materials". The physical attributes of smart materials can be altered through the application of an external stimuli such as stress, electric, magnetic, or thermal stimulation. Some smart materials, known as piezo ceramics, exhibit a change in physical size when an electric current is passed through them [15]. Other materials, known as Shape Memory Alloys, can be deformed and then returned to their original state through the application of heat. Also active fiber composites and macro fiber composites [16] have been developed in this area. In general, smart materials can be divided into many categories based on their stimulus and response. There is a class of materials that responds structurally to changes in the surrounding magnetic field. These magnetorheological materials can be fluid, gel or even solid. The magnetorheological phenomenon was first discovered and developed by Jacob Rabinow in the late fifties.

The term Magneto-Rheological (MR) comes from a combination of *magne*to, meaning magnetic, and *rheo*, the prefix for the deformation of matter's study under applied stress.

2.4.1 Magnetorheological Fluid

Magnetorheological Fluids are comparable to the electro-rheological (ER) fluids that are another class of materials that exhibit rheological changes when an electric field is applied [17]. There are many drawbacks to ER fluids, including small rheological changes and large property changes with temperature and they also require very large voltages and very small currents and generate lower yield stress. For these reasons, MR fluids have recently become a widely studied smart fluid. There was a flurry of interest in these fluids in the beginning, but this interest quickly waned, probably due to difficulties in
preventing abrasion and particle sedimentation within the fluid [18]. Figure 2.2 presents an overview of the properties of both type of materials, providing a basis of comparison.

![Figure 2.2: Comparison between ER and MR Fluids [19]](image)

<table>
<thead>
<tr>
<th>Property</th>
<th>ER fluids</th>
<th>MR fluids</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield stress</td>
<td>2–5 kPa</td>
<td>50–100 kPa</td>
</tr>
<tr>
<td>Operating environment</td>
<td>−25 °C to +125 °C</td>
<td>−40 °C to +150 °C</td>
</tr>
<tr>
<td>Density</td>
<td>1–2 g/cm³</td>
<td>3–4 g/cm³</td>
</tr>
<tr>
<td>Energy density</td>
<td>0.001 J/cm³</td>
<td>0.1 J/cm³</td>
</tr>
<tr>
<td>Power supply</td>
<td>2–5 kV, 1–10 mA</td>
<td>2–25 V, 1–2 A</td>
</tr>
</tbody>
</table>

The magnetorheological fluids are a type of smart fluid, which change elasticity, plasticity and viscosity properties in the presence of a magnetic field, that are composed by ferromagnetic particles (usually iron powder – typically 3 to 5 microns) suspended in a non-magnetic carrier medium (oil or water) and a few additives [20]. The carrier fluid must be compatible with the particular application without suffering irreversible property changes [21].

They are water, oil, silicon or hydrocarbon-based magnetorheological fluids formulated for general use in controllable, energy-dissipating applications such as shock absorbers, dampers, clutches and brakes. They are of great commercial interest for many engineering applications, especially in aerospace, and others like human body prostheses [22]; gym equipment; bicycles and stabilization of buildings during earthquakes – base isolation [23]. Also, they have been used in the automobile industry as semi-active seat suspension, to reduce or mitigate the vibrations of road irregularities.

MR Fluids are a suspension of micron-sized, magnetizable particles in a carrier fluid. When exposed to a magnetic field, the rheology of the MR Fluid reversibly and instantaneously changes from a free flowing liquid to a semi-solid with controllable yield strength (exhibits high yield strength in the presence of a magnetic field and very low yield strength in the absence of the magnetic field) allowing for a wide range of controllability. Changing the strength of the applied magnetic field precisely controls the consistency or yield strength of the fluid. There are many aspects that influence the rheological properties of controllable MR Fluids such as concentration and density of particles; particle size and shape distribution; properties of the carrier fluid; additional additives; applied field and temperature. Besides this, there still are concerns regarding the achievable yield stress, the stability and durability of the fluid [24]. Well-known suppliers and widely requested companies include the LORD Corporation and Liquid Research Limited.

In recent years, there has been a renewed interest in MR fluid devices. LORD Corporation has been developing MR fluids and devices since the early 1990’s. In the mid 1990’s, LORD Corporation began manufacturing a rotary break that has been mainly used for cycling [25] and a MR damper line that have found their way into seat suspensions and prostheses [26]. Biederman Motech GmbH produced a variation of the LORD Corporation damper, only to build prosthetic legs [27]. Even the military area has most recently shown interest in using MR dampers to control gun recoil.

Recently, innovative applications with MR fluids have been implemented like polishing optical lenses as the magnetorheological material is able to overcome some technical limitations (when using traditional techniques) due to its ability to adapt to different situations: correct figure errors and smooth-scale micro
MR Fluids can be used in flow mode, known as valve mode (fluid flowing through an orifice) or in shear mode (fluid shearing between two surfaces), depending on the function used by the device. Also they can be working in squeeze mode.

When in the valve mode, the fluid flows between two plates that are not moving and the magnetic field produces changes in the viscosity of the fluid. In shear mode, the fluid passes through two plates – one fixed and a moving one. In the squeeze mode, which has not been widely investigated yet, force is applied in the direction of the magnetic field, perpendicularly to the plates, to expand or reduce the distance between them. In this mode the MR fluid can be subjected to dynamic or static loadings and is normally used when there are small displacements that require large forces [28]. The yield stress produced by the squeeze mode is several times greater than the yield stress produced by any other mode, and that is why it will be the mode used during this research.

These three modes, as shown in figure 2.4, can be used in several applications, like dampers and shock absorbers; clutches and brakes, and mitigate vibrations, respectively.

The dominant operational region in many applications is the post-yield region. Several attempts were done in order to characterize the complex shear modulus of the MR Fluid, as a function of the magnetic flux density and excitation frequency [30]. Due to their quickly varying and reversible rheological properties under an external magnetic field, MR fluids have been widely explored for active vibration control [21]. MR Fluids have a yield stress of an order of magnitude 50-100 kPa. This operational region can be
modelled as the Kelvin-Voigt chain element which can be represented by a viscous damper and elastic spring connected in parallel [31].

![Figure 2.5: Rheological Kelvin-Voigt Structure [31]](image)

The MR fluids have a lot of advantages such as fast response time, high yield stress, low off-state viscosity, high resistance to hard settling, easy remixing and they are non-abrasive [19].

The magnetorheological response of MR Fluid results from the polarization induced in the particles by application of a magnetic field. The most common model used to describe these materials is the Bingham plastic model that uses the fluid like a solid when the shear stress is lower than the yield stress. This is a very simplistic model so in the majority of the cases it is inaccurate (particularly in squeeze mode) and one should use a more generalized model like Herschel-Bulkley [32].

![Figure 2.6: Rheological models used for MR Fluid [33]](image)

For the first one, a simple parametric model is described (the parameter values are adjusted until the quantitative results of the model closely match the experimental data), where fluid flow is governed by Bingham's equation, having a variable yield strength:

\[
\tau = \tau_y(H) + \eta\dot{\gamma}
\]  

(2.1)

Below the fluid's yield stress (pre-yield state), the fluid displays viscoelastic behaviour, which can be represented by:

\[
\tau = G\gamma , \quad \tau < \tau_y
\]  

(2.2)

Where \( G \) is the shear modulus (complex material modulus), which has been observed in the literature that it is also field dependent [34]. This model demonstrates remarkable performance in predicting the damping force in the post yield region; however, it lacks a bit of precision in the pre-yield region. For the second model, the constitutive equation is commonly written as:

\[
\tau = \tau_0 + k\dot{\gamma}^n
\]  

(2.3)
Where $\tau$ is the shear stress, $\dot{\gamma}$ the shear rate, $\tau_0$ the yield stress, $k$ the consistency index (fluid parameter), $\eta$ the viscosity and $n$ the flow index. If $\tau < \tau_0$ the Herschel-Bulkley fluid behaves as a solid, otherwise it behaves as a fluid; and if $n = 1$ the model reduces to the Newtonian fluid, so the Bingham plastic model can be applied. The shear-thinning is obtained when $n > 1$ and shear-thickening when $n < 1$.

![Figure 2.7: Shear Thinning vs Shear Thickening [34]](image)

The bi-viscosity model, which is the only model that allows mathematical manipulation, and the three-element model (consisting of a viscous damper, a nonlinear spring and a frictional element in parallel) are used as well to describe the squeeze flow in MR material.

![Figure 2.8: MR Fluid Models](image)

There are several more complex non-linear parametric models (just briefly mentioned) that are used to describe these materials such as Bouc-Wen model (an analytical description of a hysteretic model) [35], Kwok (tangent function-based model for predicting the damping force) [36] and Gu Huo (that also considers velocity and acceleration) algebraic models [37].

The Bouc-Wen model was created as an analytical description of a hysteretic model and it is more appropriate for shear mode. The damping force estimated by this model is given by the following equation:

$$ F(t) = c_0 \dot{x} + k_0 (x - x_0) + \alpha z - f_0 $$

(2.4)

Where $z$ is a hysteresis component and $\alpha$ a scaling factor.
The squeeze behavior is still in constant development since there is not many information and detailed research in these models. The MRF stability is one of the areas that is receiving significant attention.

In the absence of a magnetic field, the MR fluid may be seen as a Newtonian fluid (the shear stress is a linear function of shear strain rate), the ferromagnetic particles move freely or allow free movement in the carrier fluid, and it exhibits a linear relationship between the stress and the strain rate at any point. When applying a magnetic field, the material changes from a fluid state to a semi-solid state. The fluid's particles align with the direction of the field (forming columnar parallel structures), thereby restricting the fluid's movement within the gap in proportion to the strength of the magnetic field, making the fluid more or less thicken. These magnetic dipoles align themselves along lines of magnetic flux. The MR fluids are assumed to be viscoelastic materials.

A recent application of MR fluid that has been investigated is a fixturing device for holding turbine engine blades while they are being manufactured. According to Kevin Rong and Rongjia Tao, the part to be held is partially submersed in MR fluid that is in a water-cooled electromagnet surrounded housing. When the fluid is activated, the sides of the housing are moved inward and for that reason, compressing the activated MR fluid around the work piece. When compressed, the activated MR fluid can be several times stronger than uncompressed activated MR fluid [40].

The development and success of MR fluids in recent years are mainly due to the rapid research devoted to improving the technology into one that is commercially viable. It is expected that due to the unique rheological properties of MR fluids, it will make them suitable for many other future applications, beyond what has been envisioned so far.
2.4.2 Magnetorheological Elastomer

Magnetorheological elastomers are, like MR fluids, a kind of smart material that change their properties rapidly, continuously, and reversibly when in presence of a magnetic field. These composites have sensitive mechanical and electrical properties, which can be changed under external stimuli, such as magnetic field, mechanical pressure, and temperature. These materials usually have three different components: a rubber or polymeric matrix (non-magnetic); magnetically polarizable particles and few additives. All the components are mixed together to form a compound with random particle distribution. There are two possible types: isotropic MRE (unstructured, cured without the presence of an imposed magnetic field) or anisotropic MRE (pre-structured, cured by applying a magnetic field), which is harder to manufacture than the isotropic one, however it shows a larger field-dependent modulus and a higher magnetorheological effect, that can be more useful in some applications. One usual supplier of this material is Ioniqia Technologies, but the data sheets are not always reliable.

![Figure 2.11: Isotropic (left) and Anisotropic (right) MRE](image)

Using the variation of magnetic field, the MR Elastomer will present different elastic and shear modulus, so it is possible to change from a soft elastomer to a semi-solid elastomer, which is the reason for their use in vibration attenuation. The MR Elastomer presents a linear viscoelastic region which demonstrates that they operate in the pre-yield region (when the strain is below 10% [42]) of the stress-strain curve. Having this in mind, the main property that can be controlled is the stiffness (elastic and shear modulus) and these modulus increase as the magnetic field increases and when removed the field, the material returns to its original status. The maximum magnetic field induced change in stress (and modulus) happens when the aligned magnetizable particles become saturated. This observation supports the use of a material for the particles with high magnetization saturation.

One can conclude that MRE and MRF complement each other, due to the fact that they work in different regions of the stress-strain curve and they have advantages that complement each other in order to mitigate vibrations. For example, with MRF it is possible to dampen vibrations and with MRE it is possible to change the natural frequency of the system.

There are a few studies that suggest the damping can also be controlled. In this particular case, damping usually comes from the frictional sliding between the matrix and magnetic particles so, concerning this, damping is not considered a controllable property of the MR Elastomers.

The MRE has also three operation modes: shear mode; squeeze mode and field active mode. The first ones have already been introduced, since they work in the same way as for MR Fluids. But it is important to notice the difference that the magnetic particles are locked in place, so the direction of the chain structure will not be the same as the magnetic field. Regarding the field active mode, the elastomer can change its shape (to be stretched by the magnetic field) during a process called magnetostriction.
that is a change of deformation and resistance in all magnetic materials due to magnetic field [43, 44].
Both magnetostriction and magneto-resistance are characteristics of MRE which make them sense and actuate.

![Figure 2.12: Basic operation modes for MR Elastomers: shear; squeeze and field-active mode [41]](image)

In shear mode, the stiffness is dependent on the shear modulus \( G \) and in squeeze mode, the MRE acts like a compression spring where its stiffness depends on the Young’s modulus \( E \).

There is a growing need to understand and model their behavior by using optimal components and production methods. Despite the lack of research in a specific model for the MR Elastomer (in particular for the squeeze mode), a few models (parametric and non-parametric) have been developed to describe the behavior of the MRE under the influence of an external magnetic field. Those are based on magnetic dipole interactions between two adjacent particles which are measured as an average over the entire sample to come up with the entire MRE behavior. Jolly et al. [45] developed a quasi-static model based on those dipole interactions where the effect is studied as a function of particle magnetization. Among all the other models available and based on the three-parametric model, conventionally used to describe the viscoelastic behavior of a rubber material, Li et al. [46] developed a four-parameter viscoelastic model, which was proven to be effective to describe the MR Elastomer behavior.

In order to simulate the magneto-elastic behavior, the Ogden model is the most suitable. Also important to note that Eern et al. proposed recently a dynamic model using a combination of the Ramberg-Osgood (to describe the nonlinearity) and Maxwell model (to introduce a viscoelastic element), which also represents a good agreement with the experimental data [47, 41].

![Figure 2.13: MR Elastomer models](image)

Applications for Magnetorheological Elastomers include adaptive tuned vibration absorbers (automotive bushings), shock isolators, papermaking machine and engine mounts.
A more recent and new design concept has also been investigated, using a magnetorheological fluid encapsulated in a passive elastomer matrix [47].

This new design offers the combined effects of MRF controllability and elastomer flexibility so that both the damping and stiffness properties of the MRF-E alter with the change in the magnetic field strength. It was also created to avoid the sealing effect (the fluid being squeezed out during compression), so there is no possible leakage. One important aspect to take into consideration is that both materials (magnetorheological fluid and regular elastomer) do not react with each other.

To explore the MR Fluid-Elastomer (MRF-E) a characterization device was built, where each sample was experimentally tested, under harmonic oscillatory vibrations for a wide range of frequencies and different applied magnetic fields. In the MRF-E the magnetisable particles are enclosed within a void inside the elastomer casing and do not need alignment during the curing process before the matrices solidification, like with typical MR elastomers.

This type has recently aroused extensive interest because of its quick response, reversible behavioral changes when subjected to magnetic fields. It can be represented as well by a variety of models such as the Maxwell model, Bingham viscoplastic model or viscoelastic-plastic model.

A new model has been proposed in order to comprise all the challenges and elements of this material. It was developed a three-element viscoelastic-plastic phenomenological model containing a non-linear spring, a viscous dashpot, and a Coulomb friction element, as shown in figure 2.15.
2.5 Vibration Control

Various different fields, such as civil, mechanical and aerospace engineering, make use of vibration control to manage the oscillatory behavior of their systems. Vibration control is categorized as: active, passive, or semi-active, based on the power consumption of the control system.

Vibratory control over a system is achieved by using one, or a combination, of these elements: passive, active, or semi-active. In the past few years, thorough research efforts have been performed in order to reduce and control vibration transmission levels of helicopters on the rotor system. Recent research efforts in helicopter vibration control has not only been focused on the global vibration reduction but also on the local vibration reduction that targets specific locations in the structure.

2.5.1 Passive Solution

Passive systems, a type of solution that provides a moderate reduction in vibration, comprise a range of materials and devices placed at specific points on the structure or equipment for enhancing damping, stiffness, and strength. A passive system consists of springs and dampers, which are the most conventional elements used to avoid unwanted vibrations [48].

The main function of a passive system is dissipating energy and primarily consists of springs and dampers. They have been implemented to reduce the whole body vibration (WBV) on a helicopter. Passive elements are widely used in industry because of their low cost, simplicity of design, ease of manufacturing, and the ability to operate the system without control.

One of its major disadvantages is the lack of adaptability, which means they only work for a specific frequency and cannot be adapted to different environments; also sometimes they provide weight penalties. The impedance properties of the traditional passive systems are difficult to optimize without compromising pilot handling quality.

Passive systems can be used in a helicopter as seat cushions; trim panels; blade mounted absorbers or isolation systems between the fuselage and the rotor.

2.5.2 Active Solution

Active systems comprise force devices and sensors attached at specific points in the structure or equipment together with controllers to improve the overall system performance.

The primary function of an active element is to add energy that is equal in force (magnitude) but opposite in phase (counteract the forces), to the vibration input of a system, which can be used to lower the WBV. In a helicopter, active systems can be adapted to different flight envelopes. Systems that contain pneumatic, hydraulic or piezoelectric elements are considered active systems as well. This technique usually accomplishes a high performance for mitigating vibration, and it has been used in different fields, such as industrial applications [18], but they are too expensive, design intensive, require a great deal of power to operate, and adding energy to a system can sometimes cause instability.
They can be classified into two groups [49, 50]:

- Active Rotor Control (ARC) – divided into two sub-concepts, the higher harmonic control (HHC) where the control inputs are applied to the rotor as a whole (all blades) and, Individual Blade Control (IBC) where a control input is applied directly to each blade to control its response. The main purpose is to mitigate the global vibrations of the helicopter.

- Active Control of Structural Response (ACSR) – concept for local vibration control where actuators are placed in specific points of the helicopter to try to mitigate the vibration close to those points. More commonly, this is used in helicopter fuselage and seat mounts. The implementation of this type of advanced active system has been restricted, despite its low certification requirements, to newly designed helicopters, such as EH-101.

Maciejewski et al. [51] presented an active seat suspension system consisting of a controlled pneumatic spring and a hydraulic shock-absorber. In a very recent study by Chen et al. [52], it has been developed an adaptive helicopter seat mount using stacked piezoelectric actuators, which has been retrofitted on a Bell-412 helicopter co-pilot seat.

### 2.5.3 Semi-active Solution

Semi-active solution (in which the mechanical properties can be adjusted in real time) possesses the advantages of both passive and active solutions [53]. Semi-active systems also require some force devices and actuators attached.

The purpose of semi-active systems is to dissipate energy while increasing the durability of a system. Semi-active elements implement the best qualities of both active and passive systems. Semi-active systems have the ability to change one or more properties, to obtain the desired stiffness or damping in order to dissipate a vibratory input.

Usually, it is used the magnetorheological materials and electromagnetic materials that are sensible to controllable parameters and they have been considered to develop seat mounts. In semi-active control, the properties of the actuators are dynamically modified, in order to optimally damp the vibration of the system.

An advantage of semi-active systems is that they require less power when compared to active systems. In addition, they are relatively reliable and fail-safe for practical implementation.

One of the most basic and widely control algorithm strategy used is the skyhook, where essentially the damper is adjusted to the desired force. Wu and Griffin [55] developed a semi-active seat suspension using an electro-rheological fluid damper, in order to reduce the seat impact caused by shocks or high amplitude vibration. Hiemenz et al. [54] investigated the use of a magnetorheological damper in a semi-active seat suspension structure for helicopter crew seats to enhance pilot comfort. Semi-active systems provide some desirable benefits, such as being easy to implement and control; however, the force range of semi-active system is limited.

Semi-active vibration control might be the most feasible solution for the cushion project.
2.6 Control Strategies

The control system consists of a structure employing devices and sensors which is exposed to disturbances. Based on the sensors' information (measurements of disturbances/vibrations, responses and inputs) control variables are generated by the controller, such that the responses provide good performances. The non-linear behavior of smart materials makes the objective of achieving a desired response very difficult.

A number of control approaches for active and passive system have been already developed, like open loop (a well-known model of the system is appropriate to synthesize the controller); feedback control schemes (only the signals from sensors are used to compute the control variable); feedforward control and feedback plus feedforward [56, 57].

For controlling semi-active systems in general, some control strategies have been considered to improve the system performance [58] such as: Lyapunov based methods; fuzzy logic [53]; maximum energy dissipation algorithm; sliding mode control [59]; feedback theory and backstepping control technique [60].

2.6.1 Skyhook Control

Concerning to the area of seat suspensions, a number of control approaches have also been proposed and developed to improve the seat suspension performance. In 1974, Karnopp et al. brought in a simple, yet effective vibration isolation strategy that is fulfilled by connecting a fictitious damper between the mass and the stationary sky [61]. The skyhook algorithm, efficiently achieves a combination of resonance damping and high frequency isolation.

Several adaptive seat frames that employ semi-active approaches such as magnetorheological dampers have been examined for heavy industrial vehicles. Choi et al. investigated seat vibration reduction systems using skyhook control algorithms with both electro and magnetorheological dampers for a commercial vehicle [62].
2.7 The National Research Council Project

The National Research Council is the primary national research and technology organization of the Government of Canada and in particular the Institute of Aerospace Research have been developing projects related to aerospace topics (Acoustics and Vibration; Avionics and Flight Control; Structures and materials and human-machine interface) in particular inside the Comfortable Aircraft and cabin environmental subject.

This project - Development of Smart Seat Cushion to Mitigate Aircrew Whole-Body Vibration Exposure - already has some previous work done such as comparing different control strategies (passive or active); test and explore what kind of semi-active materials could be used (magnetorheological elastomers and fluids) and the modes in which they should operate on, concerning the project goal.

In late 2007, it started a more detailed research about helicopter vibration and noise control. Several active suspension systems for seat vibration isolation devices have been explored [1] based on arising active material actuators. However, the vibration isolation performance in the low frequency range can be put in jeopardy, which is commonly known to have harmful effects on human body in a helicopter vibration environment. And it has been studied an adaptive seat mount interface concept that uses piezoelectric actuators to counteract vibratory loads directly to reduce vibration transmitted from the fuselage to the crew.

Flight tests on a Bell-412 were conducted and the measured acceleration data were used to characterize the vibration transmissibility from the helicopter to the aircrew body through the seat. The flight plan covered major flight conditions which include grounding, translational lift, hover and cruise. The worst vibration scenario in accordance to the aircrew's perception [1] was the translational lift. The flight tests also confirmed that the currently used seat cushions did not provide sufficient vibration isolation. Effective reductions of the vibration magnitude on all crucial locations have been obtained when using active suspension system.

Some conclusions already drawn show that classical passive vibration isolation techniques based on transmissibility plots indicate the resonance frequency of the mechanical system as required to be 4 to 5 times lower than the lowest harmonic frequency of the excitation input to achieve effective isolation. Such a design requires the Bell-412 helicopter seat cushion to have a rather difficult to achieve low stiffness that generates a large displacement to isolate the $\frac{1}{700}$ rotor excitation frequency at 5.4 Hz. Some design requirements (displacement and the cushion should not be separated from the seat and should be free
of resonance) must be considered in choosing novel cushion materials for the Bell-412 helicopter seat.

It is important to note that all the effort that was done in the past years was not to develop new cushion materials (even if that is a possibility that one could explore and mention) but to investigate the use of commercially available novel cushion materials as a low cost strategy for the helicopter seat project. There have already been some tests with Hybrid Air Cushioning System, known as mitigator which is designed to mitigate vertical impact energy through a set of internal bleed ports [63] and also viscoelastic polyurethanes, known as Sorbothane. A lot more is being done at present even with the contribution of this thesis.
Chapter 3

Preliminary Design

In this chapter, the cushion concept is presented and some considerations and requirements are outlined. Then it is presented the initial configuration proposed for the cushion layer with associated calculations in order to help on choosing a viable MRE material to produce. In the end, the design outline and the utilized software are described and an example of a biomechanical model is shown.

3.1 Seat Cushion

As a rule, helicopter seats are designed to meet crashworthy criteria [64] and to be fairly firm, to avoid excessive displacement during flight manoeuvres. Vibration isolation is relatively achieved through passive seat cushions. Recently, it was demonstrated that the semi-active MR damper based system for helicopter seat had significantly better vibration attenuation performance than passive seat suspensions [54].

For the Bell-412 helicopter, which has a 4 bladed rotor system, the $\frac{1}{rev}$ frequency is approximately 21.6 Hz and the $\frac{1}{rev}$ frequency is approximately 5.4 Hz. In general, the vibration levels increase with flight speed. Suppression of these vibration magnitudes (particularly the first natural frequency) could contribute to relief of the back and neck injury issues for the helicopter crew.

The seat is composed of a pan made of stiff composite material that slips on guide rails of the L shaped frame fixed to the helicopter floor. The cushions at the bottom and the back, that are in contact with the aircrew, are set up on the seat pan. Each seat weighed approximately 22.5 kg [1].

![Figure 3.1: Bell-412 helicopter aircrew seat from NRC [1]](image)
3.1.1 Design Considerations

In a project like this, there are always a few considerations and details to take into account. Some of the general suggestions which are directly related to the current thesis are:

- Interference with other cushion layers – any other cushion layer to be used at the top or bottom of the cushion will interfere with its functionality and that needs to be taken into account;

- Magnetic saturation of the MR Elastomer and Fluid – one important factor to consider when designing the magnetic circuit is that the operating points for the MR material have to be selected in order not to fall into the magnetic saturation region of the material, where it reaches a steady state condition;

- Weight constraint – since adding any additional weight to the helicopter will directly result in higher level of fuel consumption, optimizing the weight of the cushion is one of the objectives in the design process;

- Magnetic field for both MR materials – in order to control the MR Fluid and Elastomer independently, in the current design of the cushion, two isolated magnetic circuits are suggested to be implemented;

- The only fixed parameter is the outer dimension of the cushion: 50 × 50 cm.

3.2 Conceptual Design

The human body in a seated posture along with the seat structure were modelled in the vertical direction as a mechanical system composed of rigid bodies linked by springs and dampers. A practical approach is to consider a Single Degree of Freedom (SDOF) system and to evaluate the stiffness of the system and the overall dimensions.

Considering the SDOF system based on figure 2.16, it is the stiffness of the MR Elastomer that determines the natural frequency of the system. Natural vibration analysis of a system provides its dynamic characteristics. The equation of motion of this system can be represented as follows [65]:

\[ m\ddot{x} + F_d + F_k = 0 \] (3.1)

Based on that system from figure 2.16, there is the concept of relative motion that means the movement of the mass relative to the base, when this last one is excited by support motion. Having this in mind, a different equation is used to define the behavior of the SDOF system:

\[ x_r = (x - y) \] (3.2a)

\[ m\ddot{x}_r + c\dot{x}_r + kx_r = -m\ddot{y} \] (3.2b)

Assuming a representative range for relevant group of pilots, the weights to be adopted must be between 49 kg and 100 kg. Further assuming the pilot to be a rigid body, the natural frequency \( f \) of the pilot-
cushion system can be expressed as:

\[ f = \frac{1}{2\pi} \sqrt{\frac{k}{m}} \]  

(3.3)

If the system was linear (constant values of \( c \) and \( k \)), one could use the Transfer Function of the system to represent it and, the calculations and future Simulink model would be easier to solve.

In the situation of this project, one has a forced vibration system, where there is a spring with a non-linear stiffness \( k \) and a non-linear viscous damping \( c \), which is the reason why it dissipates energy and that is what turns this thesis in a different and innovative work, on dealing with that non-linearity and the non-existence of an analytical solution.

### 3.2.1 Stiffness Calculation

While not mentioned as a requirement, there is a particular consideration that has to be taken into account as well during this preliminary design of the cushion: minimum required stiffness change – the actual requirements towards the minimum range in available stiffness are dependent on the control algorithm that will be implemented in the future. But in this case, a simple estimation can easily be done based on the data available.

The initial configuration proposed, in the beginning of this work, is presented on figure 3.2, having a layer with two samples of MRF and three of MRE and two coils in each part surrounded by magnetic material. As said before, this is a conceptual design, no one knows if it is feasible or efficient for the goal of the project. Everything (despite the outer dimensions) can and will be changed in the final design.

![Figure 3.2: Initial Conceptual Design from NRC](image)

One of the proposed challenges was to estimate the stiffness generated from the MRE in this kind of configuration. The first attempt was to calculate that analytically, with well known formulas and to do a simple example in a software. In order to verify what has been said, a finite element model with NX Siemens was created in order to draw the trapezoidal geometry of the MRE, a force was applied and the displacement checked. The material used as an approximation was the PU 70/30 polyurethane with density 1.04 g/cm\(^3\). For different cases (different pilot's weights), it is possible to obtain different points and then the slope of the fitted line is the stiffness. The idea is to achieve a softer elastomer because if
the base is already inherently stiff, it is difficult for the MRE to change its elastic and shear modulus.

![MRE trapezoidal shape](image1)

![NX-Siemens MRE initial configuration](image2)

Figure 3.3: MRE initial configuration

The angled trapezoids assumed in the calculations (based on the geometry and on figure 3.3) act in shear and also in compression due to a vertical load. Therefore, one should solve each angled face into two equivalent springs. The trapezoidal shape will have two sections: 1 and 2, and the stiffness will be calculated such as:

$$k_{MRE} = k_1 + 4 \cdot k_2$$  \hspace{2cm} (3.4)

In section 1, it is pure compression based on its cross-section area and thickness. In section 2, there is an equal combination of shear and compression due to the vertical force applied (that will be decomposed into two components represented together by $\Delta y$), based on its own thickness, trapezium cross-section area, shear and elasticity modulus.

$$k_1 = \frac{A_1 E}{h_1}$$  \hspace{2cm} (3.5a)

$$k_2 = \frac{F_y}{\Delta y} = \frac{A_2 E}{h_2} \left( \frac{\cos^2 \theta \sin^2 \theta}{E} \right)^{-1}$$  \hspace{2cm} (3.5b)

To achieve the proposed frequency (5.4 Hz), it requires a very soft elastomer (much less than 100 kPa as Young’s modulus), which is impractical. Some compromises (dimensions and feasibility of the sample) were made and it ended up being assumed a desired resonant frequency of 8.1 Hz. It has resulted in a range of desired stiffness between 123 kN m$^{-1}$ and 255 kN m$^{-1}$.

The magnetic particles used for both materials should be soft particles (like carbonyl iron) due to high permeability and high saturation magnetization, in order to have any influence on the system.

### 3.3 Design and Simulation Procedure

In design challenges, the goal is to conceive a system capable of achieving a predefined performance.

To design the different components, it is necessary to take into account some details. The conceptual design of the cushion was proposed by the NRC but the only constraint indeed is the total size of the seat - 50 x 50 cm - that has to fit in that helicopter fleet (Bell-412); which means that one is allowed to explore different inside configurations, dimensions, placements, results and by the end try to contribute to a better and new cushion.
This section also addresses to the software selection process and scripting design methodologies when developing the seat cushion. COMSOL Multiphysics® is a well-known commercial program and it is a powerful tool regarding the couplings and non-linear analysis that one can do to simulate any engineering application.

This thesis takes part in the design, evaluation and optimization processes of several seat cushions configurations, and as a consequence it is of the utmost importance to use a CAD and FEA software that allows the easy and swift modelling and assembly of general configurations and also, in this case, to be able to make different study simulations regarding the physics module that one wants. The goal when dealing with the geometric design and assembly of different components is to render this phase as user independent as possible.

COMSOL Multiphysics® (released in 2000) is the interactive software for modelling and solving scientific and engineering problems based on partial differential equations. This environment runs finite element analysis together with adaptive meshing. The software includes many built-in application modes which can be combined into a single multiphysics model capable of simultaneous solving of the coupled physical problem.

Only for the magnetic circuit analysis it will be also used the freeware software FEMM, which is a package for solving problems in 2-D, planar or axial symmetric that allows quicker simulations, a much user friendly interface and material definition way and it is the best solution as a beginner.

First, the details and description of each designed part will be described, then validation examples are presented, in order to assure the efficiency of the software. In the end the simulation of the experimental laboratory rigs and the different configurations for the cushion layer are exhibited.

### 3.3.1 COMSOL

This software was developed from a multiphysical point of view. In COMSOL the geometry is built with defining different blocks of the model. Instead of defining coordinates for the geometry it is built by uniting rectangles and circles and other geometrical parts to complete a design. Meshing and solving is defined by default but the user is able to define customized size of the mesh.

In the post processing mode, by default, the magnetic field density will be plotted. It is also possible to plot each subdomain with the different areas of interest the user chooses.

The user will be able to model the geometry in 2-D and 3-D, though the 3-D simulation is very memory-intensive since the calculations might be very complex and not all the versions have the entire features.

To achieve the objectives of this thesis, an MR Fluid and Elastomer are to be analyzed as a 2-D model using COMSOL software. For a given current, one can determine the magnetic flux density. After these tests, it will be possible to connect all the information and analyze the cushion response.

### Biomechanical Model

After describing the software, in order to show its capabilities, and based on a human body in a seated position already drawn inside COMSOL, the idea was to seat the model and excite it with a base motion
example input, to show the reaction of the body and the higher frequencies towards that input. Just as an example to check the transmissibility graph and the peak frequency, a biomechanical model and an acceleration type excitement was added to model the effects of vibrating seat.

![Figure 3.4: COMSOL Biomechanical model](image)

(a) Total displacement response for a chosen frequency  
(b) Transmissibility graph of the system

In figure 3.4, it is exhibited an example (from different possible ones) of one frequency tested and the body reaction as well as the vertical transmissibility response of the whole system. It is evident that the behavior is quite similar to what was described before and the two peak frequencies are the expected ones (around 5 Hz and 10 Hz).

### 3.3.2 FEMM

This software was developed from a perspective of the electromagnetic problems. It is very straightforward when defining the problem and design the geometry of the intended problem.

To define a geometry in FEMM the user states the coordinates of a cross-section of the model intended to be simulated. This is done by using the point mode and segment/arc mode.

FEMM carries a small material library with the most common material constants and it is easy to define a new material by applying the $B-H$ curve. FEMM has a built-in mesh tool that will mesh the geometry automatically. Then it solves the problem with a predefined model and for the user it is very simple, just to press the solve button in the user field.
Chapter 4

Finite Element Modelling

The finite element method is a numerical method for solving problems that involve complex physics, geometry or boundary conditions. This is a technique analysis that replaces the exact differential equations of the problem with a system of simultaneous algebraic equations. Various commercial and research codes have been developed and are available such as ANSYS (1970), ABAQUS (1978) and COMSOL® (1986).

In this chapter, the FEM generated for the system is presented. This was carried out using COMSOL Electromagnetic (AC/DC) Module and FEMM (Finite Element Modelling Magnetics) since it is essential that the software is able to calculate problems within the electromagnetic field.

Through this chapter, in addition to the generation of the FEM, the finite element software used is also described in detail for each part of the geometry. Then a validation example is presented and the development of the models for the experimental test rigs and its results are exhibited.

4.1 Magnetic Circuit Design

One important aspect of the seat cushion design is the magnetic circuit. An optimal magnetic circuit design demands maximizing magnetic field energy in the fluid gap while minimizing the energy losses in the steel flux path. The main purpose of this topic is to relate the magnetic field intensity in the MR material active gap to the applied current and number of turns in the electromagnet coil. The first part will be connected to the description design of the coil, materials and mesh; then the software will be validated and 2-D models of the experimental test rigs, that are being used in the NRC laboratory, will be reproduced.

Finite element simulations were performed using COMSOL Multiphysics® and FEMM. The Magnetic Field module (mf) of COMSOL software (AC/DC module [66]) is selected to simulate the proposed system. The module also takes into consideration if the problem is linear or non-linear. The basic theory in the software is based on Maxwell's equations, that can be seen with more detail, in Appendix A. As a basis for a stationary or time-dependent solver, the relations defined by Maxwell's equations were
employed:
\[ \nabla \cdot B = 0 \]  \hspace{1cm} (4.1)

And Ampere's law:
\[ \nabla \times H = J \]  \hspace{1cm} (4.2)

Where, \( H \) is the magnetic field intensity and \( J \) the current density. Presenting the relation between current density and electric field intensity, \( E \):
\[ J = \sigma E + J_e \]  \hspace{1cm} (4.3)

Finally, the \( J_e \) term was generated with COMSOL's Multi-Turn Coil Domain interface, the value representing the external contribution of the electromagnetic coil to the applied current density, in A/mm²:
\[ J_e = \frac{N_{\text{coil}} I_{\text{coil}}}{A} \]  \hspace{1cm} (4.4)

Here, \( N \) is the number of turns in the electromagnetic coil, \( I \) is the applied current and \( A \) is the total area.

Through experience, one can notice that magnet wire should never be wound directly into a machined groove. Instead, additional insulation should separate the magnet wire from contact with the walls in the cushion design, as seen in figure 4.1.

A crucial topic of magnetic circuit design is that the region of highest reluctance is the region where the MR material will be activated and to get the most efficient magnetic circuit, the fluid or elastomer gap should be minimized.

Despite that each object in the universe is three-dimensional, many aspects can be studied using one or two-dimensional models (in this case it is also the most suitable due to the limitations of the computer). The three dimensional geometries are only advisable for experts since it takes a long time to understand the software, domains and conditions when working in 3-D. The main suggestions given in all the software technical forums are the reduction of the size of the model, if possible create a 2-D problem and when applicable, make use of any existant symmetry. Throughout this thesis, all the presented models were created in the 2-D domain.

For the analysis of the magnetic field distribution, it is prudent to also model the air around the component so that any leakage of magnetic flux is taken into account. This air domain usually is three times bigger than the entire geometry in order not to influence the geometry's magnetic field.

FEMM is a package that focuses on a few limiting cases of Maxwell's equations but it is extremely user friendly. The main procedure is to first define the type of problem (2-D; planar or axisymmetric), then create the geometry point by point, using coordinates and after that assign the different materials to be used. If the material is not inside the library, it is possible to add a new material with less mandatory properties than in COMSOL. After that the mesh is generated and the problem is solved quite quickly.

The only disadvantage of this software is that there is no possibility to rearrange or resize the geometry, if one wants to change something, it needs to be done from the beginning.

The main procedure with COMSOL is to set up the model (and select the physics one wants inside the
software), create the geometry (based on geometric shapes) and add the materials. When the material is not in the library, one can create a new one (with the respective properties) and add it to the library for the future. Then deal with the mesh processing, define the input current and other magnetic field features and, solve the problem.

An important detail is that COMSOL automatically converts units since they are written between brackets ([unit]).

4.1.1 Coil

The electromagnetic coil is an important design parameter, as it is the source of the magnetic circuit. As mentioned, it was based on the Multi-Turn Coil domain inside the software, which models a current carrying region to compute magnitude and direction of current flow and, the first thing to take into account is to have a closed current loop (with a closed geometry or with appropriate boundary conditions). With this option it is needed, as mentioned, to model an air domain around the conductor.

The coil can be linear (multiple parallel straight wires) or circular (multiple wires arranged as a circular coil) and the last one is the most suitable option for this system. The coil wire conductivity is defined as $S\ m^{-1}$ and the coil wire cross-section area could be defined for its dimension (in $mm^2$), for the SWG (Standard Wire Gauge) number or for the AWG (American Wire Gauge) number.

The AWG represents a standardized wire gauge, which is a classification of the wire in terms of its diameter and its cross-sectional area. Increasing gauge numbers denote decreasing wire diameters and they vary from 0000 until 40, which have a maximum possible applied current as well. The choice of the wire to use in the construction of the coil is related to the definition of the current at which the material will be operating and the number of turns in the coil.

The SWG represents exactly the same concept but it is used in the imperial unit system and the number classification goes until 50.

In a perfect scenario, higher values for the applied current in the coil will result in a high magnetic flux on the MR material gap. However, the current that can be applied to the coil is limited, which depends on the wire cross-sectional area, its material and its insulation. The wire material is usually copper.

For example, a 24 AWG has a maximum current of 3 A and a 21 AWG has a maximum of 9 A which means that if a higher current needs to be applied, another wire has to be selected. Thicker wires are capable of conducting greater currents but take more space and hence a fewer number of turns can be wound in the same area.

Another important aspect that was tested is the difference between using an air core or a magnetic material core in the coil. Due to its higher magnetic permeability, inserting a magnetic material (low carbon steel) core will give a magnetic field several times more than that of the equivalent air core.

Therefore, in this work, a couple of different coils configurations were tested but, in the end, a 15 AWG size copper wire is used to wind the coil of the cushion's electromagnet with 600 turns, because NRC also agreed it would be the best design. In figure 4.1 it is shown the model of the coil that is going to be used in the laboratory experimental rigs and will be, hereafter, adapted as the coil for the cushion layer.
Afterwards, one just defines the input (excitation source) coil current that one wants to test. First, in FEMM it is just to find the proper AWG wire wanted and select the part of the geometry where the coil is, and the software assumes it immediately. Regarding COMSOL, one has to add the copper material and then allocate that to respective part of the geometry. Thereafter, one has to add a domain to define a Multi-Turn Coil and there define the coil type, the cross-section area definition, the number of turns and the simulated current. In this case it is extremely easy to change the dimensions or any of these parameters (for example, the current).

4.1.2 Hysteresis Loop (B-H curve) and Permeability

One important factor to be considered when designing the magnetic circuit is that the operating point for the MR material has to be selected so that it does not fall into the magnetic saturation region of each material.

A hysteresis loop gives a lot of information on the magnetic properties of a material and it can be represented by the relationship between magnetic flux density $B$ and magnetic field intensity $H$ and is normally called the $B-H$ curve. For example, a material with a wide hysteresis loop has low permeability. The shape and size of the hysteresis loop greatly depends on the type of the material. The loop will be narrow if the material is easily magnetized, known as soft magnetic material such as soft iron. This type of curve is complex and expensive to measure inside a laboratory.

As one can check in figure 4.2, initially, magnetization for an unmagnetized ferromagnetic material will follow the dashed line, until it reaches magnetic saturation. Points $S$ and $S'$ represent the saturation values at positive and negative sides, respectively. When a magnetic material is magnetized in one direction, it does not return back to its initial point after the magnetizing field is removed.

When the value of $H$ is reduced to zero, the curve moves from point $S$ to point $B_r$, instead of returning back to its original point. At this point, some of the magnetic flux density still exists and this residual field $B_r$ is called the magnetic remanence. When the value of $H$ is placed in the negative side or as $H$ is reversed, the curve further moves to point $-H_c$ (coercivity or coercive force) at zero value of $B$ [19].

Coercivity which is described as the resistance of the material to the magnetization reversal, is the most important criterion for differentiating a soft from a hard magnetic material.

The magnetorheological materials, used in this thesis, have almost non hysteresis effect so that they
can be easily demagnetized; when the magnetic field is removed, the material returns to its initial state.

Another main parameter that defines a material’s magnetic characteristics is its permeability $\mu$, which is the ratio between the applied magnetic field intensity $H$ and magnetic flux density $B$, as can be seen in equation 4.5. It represents the capacity of the material to transfer magnetic flux over itself. Relative permeability $\mu_r$, which is the ratio between the material’s permeability and vacuum’s permeability $\mu_0$, is frequently used in the literature. Permeability can be thought as being the magnetic conductivity of a material.

$$B = \mu_0 \mu_r H$$

In this type of materials, permeability is not a constant for the entire domain of operation of the material but a function of the magnetic field.

For design purposes, only the average $B – H$ curve, which incorporates magnetic saturation effects, but not hysteresis, is needed or accepted inside COMSOL. In FEMM it is the same criterion but the curve has to be defined by hand, with a set of points.

It will not be possible to simulate the hysteresis effect in this version of COMSOL since it is not possible to reproduce a time dependent analysis (evolution of the current with time) in a non-linear problem.

### 4.2 Materials Design

The materials used in the cushion have a crucial influence on the magnetic circuit. In both software some material properties have to be defined. For the common materials such as air, aluminum and copper the software’s material library usually has predefined values on these material properties. For the magnetic materials it is essential to provide the correct $B – H$ relationship, for example. All the important aspects on their design is described in the next sections.
4.2.1 MR Fluid Characterization

The fast and reversible reaction of these fluids offers them to be a suitable candidate to interface between these systems. LORD Corporation is the exclusive supplier of the MRF and, two types of hydrocarbon-based magnetorheological fluid will be tested during this work: MRF-132DG and MRF-140CG. For the first one, the viscosity is $0.112 \text{ Pa} \cdot \text{s}$ and density is $2.95 \text{ g/cm}^3$. The other one has a viscosity of $0.28 \text{ Pa} \cdot \text{s}$ and density of $3.54 \text{ g/cm}^3$. The volume fraction of particles is estimated to be $84\%$ of weight. It was performed, in the very beginning, an analytical calculation study to test how much could a sample of material weight and based on the density values and the volume from its geometry, one could conclude that the weight would be from $175\text{g}$ to $300\text{g}$.

There have already been few studies made with COMSOL (simple tasks) concerning the MRF modelling, in engineering industry and also health and medical care (because the MR Fluid characteristics allows them to be tuned to the individual needs of a patient [67]) but there is not much information on this topic due to the fact that this subject is recent and still under investigation. Usually the dynamics of a magnetorheological fluid are modeled using multiphysics commercial finite element software that allows one to couple electromagnetic field distribution with non-Newtonian fluid optionally. This is achieved through a modified Bingham plastic definition, relating the dynamic viscosity of the fluid to the intensity of the magnetic field. Design and evaluation of such materials prior to their construction requires a high fidelity model with wide scope.

Material properties for the MR fluid were chosen based on typical values reported in the manufacturer’s provided literature by LORD Corporation. In Figure 4.3 it is shown the data for MRF-140CG and in Appendix B one may found the data for MRF-132DG.

![Figure 4.3: MRF-140CG](image)

(a) Typical Magnetic Properties - $B - H$ curve [68]  
(b) Yield Stress vs Magnetic Field Strength [68]

It is possible to define these material properties using an interpolation function from a data file, since the software library does not include these type of materials.

The dynamic model was implemented using COMSOL’s 2-D axisymmetric space (or later one can try to do in 3-D but the software is really sensitive for that) with the dimensions similar to the samples NRC predicts to have in the lab. It will be created a circular sample of MR Fluid encapsulated in a regular elastomer with $3 \text{ cm}$ diameter, approximately.

The MR Fluid has a lower coercivity value [39, 69] that is why they almost have no hysteresis and that is
desirable so that they can return to the demagnetized state when there is no magnetic field applied.

When encapsulated in a regular elastomer, the matrix material can be for example silicon or as it is going to be used in this case, TPU 70/30 polyurethane, to avoid the fluid leakage.

In COMSOL, for the magnetic circuit analysis, one just has to define that part as a non-solid material with the respective $B - H$ curve points, and then assign inside the software that curve as the constitutive relation. In FEMM, it is only necessary to add a new material type, define the $B - H$ curve and the electrical conductivity value (zero in this case).

### 4.2.2 MR Elastomer Characterization

The elastomer (anisotropic one) is going to be manufactured by another student in a project that is also underway in NRC. For that we had to find the elasticity modulus (and hence the stiffness of the device) that the elastomer should have to work in the target frequency and in order to choose a material that could in fact be manufacturable and best suits the requirements. The volume of the magnetic particles should never exceed 30%.

The first step was to calculate the equivalent stiffness of the system which was obtained with equation 3.4 and based on the conceptual design it is possible to conclude that there are parts of the elastomer acting in pure compression and others in a combination of compression and shear strain, which influences the final result.

Once a magnetisable elastic solid is settled in a magnetic field, magnetic moments are induced in the material. The magnetic moment per unit volume of the deformed body is called the magnetization and it is denoted by $M$ with units $[\text{A} \cdot \text{m}^{-1}]$. Inside the deformed body, the magnetic flux density vector is $B$ with units $[\text{T}]$ or $[\text{Wb/m}^2]$. The induced magnetization is related to $B$ by the relation:

$$B = \mu_0 (H + M)$$

Where $\mu_0$ is the permeability of vacuum. The $B$ field satisfies Gauss' law for magnetism and is a solenoidal vector field. The field $H$ is governed by Ampère's law.

There are almost no suppliers of magnetorheological elastomers. It is easier to buy separately the required elastomer and the magnetic particles and if the company has a material department, it is worthy trying to manufacture that inside the company. *Ioniqa Technologies* is the best known one in this field, despite that material technical data sheets sometimes are not that accurate or the samples of the material do not match with the technical properties.

Due to the lack of data on the $B - H$ curve of a MR elastomer, numerical analysis cannot be accurately conducted. The supplier *Ioniqa Technologies* only provided a rough magnetization curve in imperial units.

From the magnetization curve provided by *Ioniqa*, the author had to convert the units of the graph and then calculate the value of $H$ because both software only accept the $B - H$ curve of the material. It is not so common but in this data sheet, when one talks about magnetic induction, one is referring the magnetic flux density, the $B$ field.
In the technical data document, the magnetization $M$ unit is in the imperial system. So in order to have the SI unit to be able to perform the calculations, it was necessary to multiply by the density of the material, being in this case, around 3 g/cm$^3$. After having the values of $B$ and $M$ in the correct units, the equation 4.6 is used to get the $H$ values and then the curve in figure 4.5 is obtained. Despite not being so accurate, it was the best option procedure to have at least some properties to test the MRE.

In COMSOL this can be simulated using AC/DC modules and Solid Mechanics optionally. The procedure to create and design them in both software is exactly the same as for the MR Fluid.

### 4.2.3 Magnetic Material

The first aspect to consider in the choice of materials for each component, in particular for magnetic materials, is the desired magnetic behavior.

In order to intensify the field generated by the electromagnets, high permeability magnetic material needs to be utilized. There exist various magnetic materials with high relative permeability values, but some of them are not a good option because they saturate at very low field strength. So, for selecting the appropriate magnetic material, both factors have to be considered: high saturation and high permeability. Low carbon steel is one of such materials and in order to design a low reluctance flux conduit, the amount
of carbon should, ideally, not exceed the 15%. Based on this criterion the AISI 1010 and AISI 1018 will be tested and compared.

With the information provided on section 4.1.2 rather than defining a constant magnetic permeability for steel, the actual $B - H$ curve for AISI 1010 and AISI 1018 steel, supplied just in this version on COMSOL with the software’s material library, was used. These materials have no hysteresis and their curves are quite similar which predicts almost the same behavior for both.

![AISI 1010 $B - H$ curve](image1)
![AISI 1018 $B - H$ curve](image2)

Figure 4.6: Magnetic Material Properties

Aluminum-6061 was chosen for the non-magnetic parts since it combines good mechanical and thermal properties with low density.

As mentioned, for both software these two materials are already created inside the library so it is just a direct use from there.

When in COMSOL, one has to define an extra *Ampère’s Law condition* for the magnetic material to connect it to the respective $B - H$ curve, so the software can assume a non-linear relative permeability.

### 4.3 Mesh Generation

One of the central aspects of the finite element model is the discretization of the domain into finite elements, the process known as meshing and the first step is the selection of the finite elements to use.

When creating the mesh for the geometry, default free triangular mesh is suitable for the problem, but the important topic is the refinement of each geometry’s domain. There is the chance to let the software do the meshing process automatically (like FEMM where there is no choice) but in COMSOL it is possible to customize it, changing the maximum or minimum element size that limits how big or small each element can be.

The 2-D elements that can be used to mesh the geometry are Triangular and Quad. Each node has 6 degrees of freedom, 3 translational and 3 rotational.

The triangular and the quad elements were tested, in order to prove that this is a mesh independent
problem. The procedure, in COMSOL is to select the mesh creation node, in the model builder, and define if it is *Physics-controlled mesh* (automatically) or *User-controlled mesh* where one can edit the most adequate refinement type and the element size. In FEMM, it is just to click a button and the mesh is generated automatically and in accordance with the geometry.

![Figure 4.7: Different mesh elements and size](image)

In the figure 4.7, it is presented the two types of mesh that are possible to create in 2-D. On the left, the example with a so not refined mesh with quad elements, that seems to be suitable for this kind of geometry and the example with triangular elements with one of the most refined mesh possible.

The example of the finer mesh, with 0.2 cm element size will have 224605 degrees of freedom solved and the other with 1 cm will have 153537 degrees of freedom.

Due to the computer operation system and memory limitation, the mesh had a minimum limit of element size in order to simulate it. Below the 1.5 mm it is hard to get a solution or it will take a long time.

The main goal is to find the smallness of the elements in order to ensure that the results of an analysis are not affected by modifying the size of the mesh so, the problem is mesh independent.

### 4.3.1 Convergence Study

One of the key concepts in this section is the mesh convergence — as one refines the mesh, the solution will become more accurate.

Large elements produce a coarser mesh with lower computational requirements and faster solution time but may entrain important errors in the determination of the unknowns. The definition of the quality of the mesh is a delicate problem of compromise between conflicting interests. It is often a trial and error process until the ideal dimensions are found. There is always the need to perform a mesh refinement study and compare results on different sized meshes.

A useful feature is the ability to locally refine the mesh. Within the geometry, the elements in the end, are constrained to be 2 mm to get accurate results, while the air around the device is allowed to range from
2 to 20 mm. This allows the results around the device to be more accurate. The farther the elements are from the device, the bigger they get, which allows a shorter run time. The element size for the air was adjusted until the best size was found, which gives consistent results. The main basic steps are, firstly, to create a mesh using the fewest, reasonable number of elements and analyze the model and secondly, to recreate the mesh and keep increasing the mesh density and re-analyze the model until the results converge satisfactorily.

The established method of showing mesh convergence requires a curve of a critical result parameter, such as the maximum, the average or a result in a specific location, to be plotted against some measure of mesh density (number of elements or element size). However this method was not successfully accomplished due to the fact that sometimes in the same location of the maximum or minimum value, for every used mesh, it was the same (what would already mean a convergence, but that is not true). So the author has decided to perform different simulations with several meshes and take the overall result of a parameter (in this case, the magnetic flux density) and check the behavior graph. It was assumed to converge when those trend lines were exactly the same, like in the example of figure 4.8.

Analyses were conducted with different meshes to determine the ideal element size. The coarser mesh has a 3 cm element size, the coarse mesh has 1 cm, the fine mesh has 0.4 cm and the finer mesh has 0.2 cm which is the lowest possible value to indeed simulate.

![Mesh Convergence Study](image)

As it is seen from the given example, the fine and finer mesh produce exactly the same result (they even are overlapped) which means one has reached convergence, for both triangular and quad elements. In the other cases, the result presents a couple of irregularities, which shows that the mesh is not perfectly converged.

In the beginning there was an error stating that the maximum number of Newton iterations (process used to converge the solution) was reached and the returned solution was not converged. The problem was in the solver configurations, one has to change the iterations' tolerance to a higher value, in the fully coupled solver, inside the method and termination. Doing so, the simulations were successfully accomplished.
4.3.2 Boundary Conditions

In the mathematical approach of partial differential equations, one will find boundary conditions of the Dirichlet, Neumann, and Robin types. With a Dirichlet condition, one prescribes the variable for which one is solving. A Neumann condition, meanwhile, is used to prescribe a flux, which is a gradient of the dependent variable. A Robin condition is a mixture of the two previous boundary condition types.

In COMSOL and in particular in AC/DC module, all exterior boundaries are magnetically insulated by default. The main idea is to force the vector field component normal to the border to be zero.

A traditional approach is just to extend the simulation domain far enough (that will create a large amount of unnecessary mesh elements). If necessary, it would be applicable a Dirichlet condition/constraint, in order not to let the magnetic flux step out from the geometry. When using axisymmetric models, the boundary conditions topic needs a lot more of attention so that the software knows how to reproduce well the behavior.

Otherwise, like in FEMM, a perimeter boundary condition is applied in order to let the software understand the geometry's limits.

After the mesh had been generated, the FEM was solved using a parametric non-linear solver and the magnetic field distribution was obtained.

4.4 Performed Studies and Simulations

In this section the simulations made with the different software available are described as well as a validation of both. A brief description how the models were built and solved is included too.

4.4.1 Validation of the procedure

To validate the method and software used during the research, the author tried to reproduce a couple of previous works in order to get familiar with the software and verify that the models, units and results were coincident and correct for this kind of application, so that the readers may rely on the final results.

Based on a recent attempt [71], the magnetic field for the electromagnetic circuit design in squeeze mode MR damper was analyzed. In this study, only the FEMM software package was used to simulate it. This software package, as previously mentioned, covers the geometrical dimensions input including components' materials, coil turns and type, and applied current. To calculate the magnetic field intensity \( H \) across the surfaces, the line and area integrations available in the post-processor were used.

From a software tool GetData Graph Digitizer, the graph original data from the article were obtained (as much approximate as possible) so that the author is able to compare it with the personal simulations.

In this example, reproduced in figure 4.9, it was studied an MR mount for different applied currents, with an initial gap of 2 mm.
The compared results are the magnetic flux density $B$ and the magnetic field intensity $H$. Those values were obtained, from the middle line of the MR material (MRF-132DG), for the currents tested on the paper.

![Magnetic flux density validation comparison](image1.png)

![Magnetic field intensity validation comparison](image2.png)

Figure 4.10: Validation Procedure

The FEMM software is, then, validated and produced consistent results as shown in figure 4.10.

Also, based on [72], it was developed a MR mount to be used in experimental tests and it was simulated the magnetic field inside the air gap of the mount. This previous work was done in FEMM but the author also tried to reproduce it in COMSOL, to compare the obtained results.

The only graph presented in figure 4.11, relates the magnetic flux density value with the length of the gap (in this case 35 mm) and the applied current is 0.8 A. The values show that both software are reliable and they will be used throughout the thesis.

When reproducing the same problem inside COMSOL or FEMM, the obtained results and values are quite the same, being the small differences probably based on the solver, mesh fixed type in FEMM and the material definitions.
Other examples, like a MR fluid brake and a MR elastomer test apparatus were performed but they were not considered as relevant as the ones presented.

### 4.4.2 Experimental Rigs

This present work has been done in parallel with an experimental and material characterization one. There were two rigs to test and identify properties of the materials, both in shear or compression mode. The objective from the computational point of view is to develop models that would represent these rigs and evaluate the magnetic circuit behavior in order to verify and validate the experimental procedure.

The construction of the finite element model begins with the definition of the geometry and this task is generally the most time-consuming due to the challenge posed by the need to create a model that accurately represents the real system. The results shown in this topic are just for the MRE because experimentally there were no tests performed with MRF.

#### Shear Concept

This test rig is designed to determine the mechanical properties of the MR Elastomer, in particular the storage and loss modulus. It was developed a 2-D model that reproduces as well as possible the rig used in the lab, based on the geometric details of the CAD file and technical designs provided. The developed model is the cross-section of the rig that contains the magnetic field path.

The materials are copper for the coil wire, a 15 AWG; low carbon steel AISI 1018 for the magnetic parts;
aluminum for the spacer (placed besides the sample to put the Hall sensor to measure the field) and the MR Elastomer sample.

(a) Experimental Test Rig from NRC lab

(b) 2-D model created in COMSOL

Figure 4.12: Shear Rig Concept

The shear rig test consists of two samples of MRE, a circuit of magnetically conducting material and two coils to provide the required magnetic flux. Then it was performed a magnetic field simulation on COMSOL and FEMM to check for the magnetic flux density response.

The model was tested to an applied current from 0.5 A until 5 A and the maximum magnetic flux density value was registered. The output results fluctuated between 50 T and 470 T, which is highly consistent with the experimental ones.

Figure 4.13: COMSOL simulation on the shear rig model
Compression Concept

In this concept, the 3-D geometry is much more complex, so the author has decided to reproduce one of the cross-sections of the apparatus that would be the most representative. The lab rig has one coil and the sample apparatus built-in the outer magnetic material, so the MR material when in compression would benefit the most from the generated magnetic field.

The test rig consists of one MR Elastomer test specimen in a circuit of magnetically conducting material. The magnetic circuit contains an air gap to separate moving and non-moving parts, which presents a disadvantage to this particular rig because it adds a magnetic resistance to the circuit which has to be considered in dimensioning and calculations. It is also used an aluminum coil spacer, placed below the coil, to avoid its movement inside the rig. The spacer where the Hall sensor is placed, has 0.3 cm.

After this, it was performed as well a magnetic field simulation on COMSOL and FEMM to check for the magnetic flux density response and it can be seen that the MR material is placed as the core of the coil in order to have the higher values of magnetic field.

The model was tested for the same applied current and the obtained results are from 80 T to 680 T, which are higher than the shear ones.

An extremely important conclusion, based on these results, is that it was decided for now, that the cushion would benefit the most only with MR samples in compression because it presents the higher obtained values and they are less costly to manufacture. So the angled trapezoidal shape will not be adopted from now on.
Analytical Calculations

There is no analytical solution that fully reflects the actual problem but some approximations can be made. The goal is to calculate the required magnetic field, having the number of wire turns and the current.

For these calculations, the models were divided into different parts (with the respective material and magnetic field path) and it was calculated the length, the cross-section area and the relative permeability value for each one.

First, one needs to get approximate values for the relative permeability of the magnetic material and the elastomer, since they are non-linear. For the MRE, the relative permeability is estimated (in order to be able to perform the calculations) with Maxwell-Garnett equation, assuming relative permeability of 1 for the silicon matrix material and 1000 for the carbonyl iron magnetic particles. The volume fraction, \( \delta \), for the carbonyl iron particles is 0.3, representing 30% of the total volume. Of course, when changing a bit the relative permeability of the materials, the analytical values will change as well.

\[
\mu_{\text{MRE}} = \mu_{r,\text{sil}} \frac{2\delta_{\text{iron}} (\mu_{r,\text{iron}} - \mu_{r,\text{sil}}) + \mu_{r,\text{iron}} + 2\mu_{r,\text{sil}}}{\delta_{\text{iron}} (\mu_{r,\text{sil}} - \mu_{r,\text{iron}}) + \mu_{r,\text{iron}} + 2\mu_{r,\text{sil}}}
\] (4.7)

In the end a value of 2 was assumed. For the magnetic material, the value was approximated from the \( B - H \) curve of the AISI 1018 material and it is dependent on the range of magnetic field values that the magnetic material is exposed to in each circuit.

After that, it is possible to relate the magnetic field intensity \( H \) with the current \( I \), from the equations of magnetostatics [73]:

\[
F = N \cdot I = \oint H \cdot dl = H_{MR} \cdot L_{MR} + H_{\text{AISI1018}} \cdot L_{\text{AISI1018}}
\] (4.8)

\[
\Phi = B \cdot A_{\text{MRE}}
\] (4.9)

Where \( F \) is the magnetomotive force, \( L \) is the length of the path travelled by the magnetic flux in each
material, \( \Phi \) is the total magnetic flux, \( B \) is the magnetic flux density and \( A \) is the cross sectional area of the MR material.

The magnetic material used was AISI 1018 and the thickness of MR material was 5\text{mm}. The number of turns is always 600.

Based on Hopkinson’s Law it is possible to have the total reluctance of the circuit and with that one has the magnetic flux. Then, with equation 4.9 and knowing the cross-section area of the MR sample, one is able to obtain the magnetic flux density value to compare. It uses a satisfactory mathematical approximation and can be applied in case of homogeneously distributed magnetic flux density.

\[
N \cdot I = \Phi \cdot R_{\text{total}}
\]  

(4.10)

There is a magnetomotive force \( F \) (generated by the number of turns multiplied by the applied current) that is equal to the magnetic flux times the total reluctance of the circuit.

The magnetic reluctance is similar to the “resistance” of the circuit and is inversely related to permeability. The equation is given by:

\[
R = \frac{l}{\mu_0 \mu_r A}
\]

(4.11)

Where \( R \) is the magnetic reluctance, \( l \) is the mean flux path length, \( \mu \) is the magnetic permeability and \( A \) is the cross-sectional area of each part. Hopkinson’s law is the basis of magnetic circuit modelling and the convenience of this method is that the reluctance of each part in the magnetic circuit can be computed separately. The divisions made and the different resultant parts for each model are shown in figure 4.16.

![Figure 4.16: Analytical Calculations](image_url)

(a) Magnetic Field path for compression rig calculation  
(b) Magnetic Field path for shear rig calculation

Where \( A \) is the electromagnetic coil and \( B \) the magnetic material. In the compression rig model, the sample of MR material is represented by 7, the aluminum spacer is the 8 and the air gap is represent by 4. In the shear rig test, the samples of MRE are represented by 5 and the spacer for the Hall sensor is the 4. The one not mentioned numbers are magnetic material.
In the compression rig, the sample used is a circular shape with 3 cm diameter, where the cross-section area is given by \( A = \pi r^2 \). In the shear rig, it is used a square sample with 3 cm side. The cross-section areas for the remaining parts were based on the dimensions from the CAD file.

Based on this information, the calculations were performed and for the compression rig there is only one coil, so \( N = 600 \) and the total reluctance ended in:

\[
R_{\text{total}} = 2R_1 + 2R_2 + 2R_3 + 2R_4 + 2R_5 + R_6 + R_7 + R_8 + R_9 \quad (4.12)
\]

With this value and varying the applied current from 1 to 5 A, one obtains the different magnetic flux results.

For the shear rig there are two coils, so \( N = 1200 \) and the total reluctance, with the aid of equation 4.11, is given by:

\[
R_{\text{total}} = (R_1 + 2R_2 + 2R_3 + 2R_4 + 2R_5 + R_6) \quad (4.13)
\]

Just to note that the cross-section used for part 6 is the same as for part 3 and 4, due to the real contribution of the magnetic flux there.

In the future, these calculations could be performed for the 3-D model in order to check if the approximation is valid and if one gets more accurate results.

By the end of this procedure, the author asked for the experimental values and plotted a comparison graph between those results, the COMSOL and FEMM simulation and, the analytical calculations.

![Comparison Graph](image)

(a) Shear Rig final results

(b) Compression Rig final results

**Figure 4.17: Comparisons**

Just a note to say that the analytical calculations were being made in a linear way not taking into account the non-linear effects or hysteresis and that is why in both plots it appears a straight line and not a curve.

For the shear results, the plot shows the values obtained with the four manners and they were taken all from the same location (where the spacer is placed). All options produced consistent and almost the same final results.

For the compression results, the obtained plot gives a pretty well consistency between all the different ways of obtaining the magnetic flux values, which means that both models were successfully developed and represent indeed the behavior of the experimental rigs.
Magnetic Force

The magnetic force is a consequence of the electromagnetic force, one of the four fundamental forces of nature and it is highly dependent on the magnitude of the magnetic flux density $B$.

Inside COMSOL, the Maxwell stress tensor is used to calculate magnetic forces on objects. The total magnetic force on an object is given by a surface integral of the force density over its area [74].

To use this method, one simply has to add a **Force Calculation** node to the COMSOL model. After solving the model, forces can be evaluated with **Global Evaluation** node. These simulations have only been performed for the compression rig because it is the only one that matters for NRC and the cushion project, so far.

The force is calculated internally as an integral of the surface stress tensor over all boundaries. The expression for the shear tensor reads:

$$n_1 T_2 = -\frac{1}{2}(H \cdot B)n_1 + (n_1 \cdot H)B^T$$

(4.14)

Where $n_1$ is the boundary normal pointing out from the object and $T_2$ is the stress tensor of air. The obtained values come in Newton.

In order to analytically calculate the same results, it was used a method of force calculation based on reluctance. It uses a very good mathematical approximation and can be applied in case of homogeneously distributed magnetic flux density. This method of force calculation accounts for magnetic flux density, $B$ passing through a cross-section area $A$ according to the following formula:

$$F = \frac{B^2 A}{2 \mu_0 \mu_r}$$

(4.15)

When there is no sample in the rig (air) the formula is the same one with $\mu_r = 1$.

In this topic, it can be seen the influence of the magnetic force on the compression rig and it is shown, in the graphs in figure 4.18, a comparison between the computational and analytical results with air and MR material.

![Comparison between COMSOL and analytical values with air](image-a)
![Comparison between COMSOL and analytical values with MRE sample](image-b)

**Figure 4.18: Magnetic Force comparison**

In conclusion, the obtained results are extremely consistent and coincident with the analytical prediction.
and, as expected from the theory, when there is no magnetic field, there is no force and the magnetic force increases with the magnetic field. The results when the MRE sample is placed in the rig are lower than with air, because its relative permeability is higher than 1.

### 4.4.3 Trial Designs

Based on the initial conceptual configuration, presented on chapter 3, a few attempts were made with COMSOL and FEMM in order to get more familiar with the software and the configuration. Different configurations were tested, with different coils and wires. It was tested different magnetic materials and an air and steel core.

![Magnetic Flux Density contour plots](image)

**Figure 4.19: Magnetic Flux Density contour plots**

Where the geometry has 10 cm width; 15 cm height; two coils; the MR material has 1 cm thickness and the current is 5 A. Before the decision to use the coil already bought for the cushion design, there were some studies performed and presented that discussed the best parameters of it.

The graphs to achieve the magnetic flux density were obtained in the middle line of the magnetorheological material in every geometry. The option of using opposite direction current was tested as well but it is definitely not a good option, since it will have almost no magnetic flux density in the MR material. Another important conclusion is that the coil must be as close as possible to the MR material in order to have the most magnetic field lines as possible crossing the material and ideally the MR material should have the less thickness possible.
4.5 Design Conclusions

Although most of the COMSOL functions have worked well and could be employed in the design of the seat cushion parts, sometimes there were some minor issues that had to be addressed. Examples of such occurrences were that COMSOL is not a software for CAD modelling and the simulation is hard to setup and, it also was found that 3-D models are fairly complicated and do not run well in the software. One solution could be to perform 2-D axisymmetric simulation and then try to sweep into a 3-D simulation. Also, it is a hard software to learn by oneself, the way one has to define the geometry is not user-friendly.

One of the advantages of COMSOL is the use of material definition which gives the flexibility to define non-linear relationships.

Regarding some COMSOL tips, one needs to set up material cards for each specific part by using material properties from the manufacturers or experimental data when needed. Also, when there is a mix of MR Elastomer and MR Fluid in the same file, one has to tell COMSOL which one is specific for each part.

The FEA modelling process described in this section was deemed suitable for the prediction of MR Fluid and MR Elastomer behavior concerning magnetic field.

One of the lessons learned during this research was that having a large number of turns in an electromagnetic coil does not necessarily guarantee a powerful magnetic circuit (high flux density). The designer must attempt to achieve a compromise between the number of turns and the amount of current that can be achieved by a power source. And, of course, when there is no current, no magnetic field will be produced.

One of the major obstacles regarding this design and COMSOL was the amount of computer RAM because this software requires a huge computer power (and much time for the simulations) and the model here presented is considered to be a large model (due to the non-linearities) so it will not converge easily or it will not solve at all.

Sometimes, the convergence for nonlinear (magnetic, in this case) analysis is difficult. The reason seems to be in the $B(H)$ function for magnetorheological materials, probably it should have more points and, also, any sharp edge in the geometry.

To work properly, the magnetic field lines should be perpendicular to the direction of motion of the fluid, and the field intensity must be as high as possible in the working fluid gaps.

There is no need in using a permanent magnet because the magnetic field does need to be increased and if there is no power energy or a shutdown, the cushion will return to its original state (without the magnetic field) and that is not a critical situation.

Overall, the FEMM software is easy to work with, has a straight forward approach to define the problems and has a short training curve for a new user. Perhaps the main disadvantage is that the mesh is fixed and adapts itself to every geometry.

Regarding the coil definitions, in both software, it is extremely important the definition of the winding (the direction of each side) so that the software can recognize it as a unique coil.
In the end, in fact there are small differences in the values obtained with FEMM and COMSOL, but the trend and behavior as well as the range of values are the same.

COMSOL Multiphysics is a highly qualified work tool but it will need a long period of training for the user to be able to use all the included features efficiently.

One future option for the experimental rigs simulation, to get even more precise results, could be to create the 3-D finite element model of the rigs, in order to consider the tridimensional effects.

Based on the first trial designs made, the final considered design configurations and parametric studies are presented in the following chapter. It was decided that the angled trapezoidal shape for the MR Elastomer (from the initial conceptual design) will not be adopted because the magnetic field results obtained in shear configuration are lower than in compression.
Chapter 5

Parametric Studies and Optimization

In this chapter, several different configurations of MR material cushion sections are considered for analysis to identify the design parameters that are critical and most relevant in the design and shape of the device, with the objective of maximizing the magnetic field intensity within the gap. The resulting magnetic flux density and magnetic field intensity distribution plots for the selected designs are illustrated. On the last section, the final design configuration of the seat cushion is presented.

5.1 Definition of Candidate Configurations

It has been seen in the previous sections that the cushion is formed by magnetic material layers within magnetorheological material and coils enclosed. However, this general concept leaves room for a variety of different configurations depending on the choices made regarding the following aspects:

- Number of coils;
- Number of MR material samples;
- MR Fluid or MR Elastomer to be used;
- Thickness of the gap and location of the MR material;
- Magnetic material to be used;
- Size and location of the magnetic material;
- Dimensions of the components and overall geometry.

The proposed configurations will be considered from here on. For the different tested parameters, the result is obtained from the middle line of the MR material and the plots present the relation between the magnetic flux density and the length of the MR material.

In COMSOL, in order to visualize the field distribution and direction, one uses arrow plots as a post processing tool.
5.1.1 Design Issues

The following issues are important points to take into consideration when designing the possible configurations:

**Applied Current** - applying Ampere’s circuital law for magnetic circuits, the number of turns \( N \) (in a coil) and the applied current \( I \) determine the magnitude of the magnetic field strength \( H \) as depicted by equation 4.8, where \( l \) refers to the total length of the whole magnetic circuit. Therefore, \( l \) was also larger if the gap size was large. For the same number of turns, a higher electrical current or a small gap size would result in a greater magnetic field strength, but in some cases there is a current limit due to the possible heating or saturation;

**Gap Size** - the equation 4.8 shows that for a fixed number of turns and applied current, a small gap size would result in a greater magnetic field strength. On one hand, a narrower gap will have the MR material subject to a higher magnetic field intensity and will reduce the volume of the material but on the other hand, a too narrow gap will increase the production cost as it will require tighter tolerances;

**Coil** - if the coil is too far away from the MR material, the magnetic field will not go through the material.

5.1.2 Design and Results

Four different configurations are described throughout this section. The available parameters to test and the advantages or disadvantages of each configuration are mentioned as well. The coil geometry is now fixed so the objective is to vary the outer dimensions and thickness of the MR material, as well as the current and magnetic material. Those dimensions were taken from the CAD file provided. The magnetorheological fluid used in most of the studies is MRF-140CG.

**Design 1**

The first proposed design is the simplest one possible, having the MR Fluid or MR Elastomer below the coil and a small layer of magnetic material. This idea is based on the initial conceptual design (in compression) and tries to simplify the geometry to understand what are the results and advantages.

The dimensions of the geometry are identified with letters and just one parameter varies, the others being fixed, the purpose of which is to show the magnetic flux density, \( B \) for different values of that parameter.
Figure 5.1: Geometry created and parameters dimensions for design 1

Where 1 is the magnetic material, 2 the coil, 3 the core made of magnetic material, 4 the MR material sample and 5 the magnetic material layer.

The fixed dimensions correspond to the coil size and the others correspond to admissible values that were chosen for each parameter, based on the overall size of the cushion. Some of the results of magnetic field simulations will be shown, and some more extensive results are included in Appendix C.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>10 ; 15 or 20</td>
</tr>
<tr>
<td>B</td>
<td>7 ; 8 ; 10 or 12</td>
</tr>
<tr>
<td>C</td>
<td>4.5</td>
</tr>
<tr>
<td>D</td>
<td>2.25</td>
</tr>
<tr>
<td>E</td>
<td>6.7</td>
</tr>
<tr>
<td>F</td>
<td>0.5 ; 1 or 1.5</td>
</tr>
<tr>
<td>G</td>
<td>0.5 ; 1 ; 2 or 5</td>
</tr>
</tbody>
</table>

Figure 5.2: Parametric study results for the length and width of design 1

On the left of figure 5.2, the length corresponds exactly to the parameter under consideration, so the final graph presents different final lengths. In order to avoid that, it was decided to show the dimensionless value, dividing each value by the respective maximum length.

On the right, it can be observed that in the situation with 10 cm or 12 cm (or even a higher value) the magnetic field result is the same, so there is no influence and no advantage on increasing this parameter. Between the two types of MR material, it is shown that the MR Fluid is able to provide higher values than the MR Elastomer.

Another comment is that if the magnetic material layer is too small, it will produce in COMSOL simulation a higher concentration of magnetic field there and not in the MR material. The magnetic flux density
Figure 5.3: Parametric study results for the thickness of MR material and comparison between MRF and MRE distribution follows the intended path around the coil, crossing the MR material gap, but not in a uniform way. The parts of MR material directly below the coil are almost not affected by the magnetic field.

With just one coil and the MR material located at the bottom, the active area is smaller and the obtained magnetic field values are lower.

Design 2

Now the second configuration adopted is the one that reproduces the initial conceptual design.

![Geometry created and parameters dimensions for design 2](image)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>10; 15 or 20</td>
</tr>
<tr>
<td>B</td>
<td>7; 8; 10 or 12</td>
</tr>
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<td>C</td>
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<td>E</td>
<td>6.7</td>
</tr>
<tr>
<td>F</td>
<td>0.5; 1 or 1.5</td>
</tr>
</tbody>
</table>

Where 1 is the magnetic material, 2 the coil, 3 the core made of magnetic material and 4 the MR material sample, as mentioned in the previous design. The same type of simulations were performed and the conclusions are presented.
In this case, the same situation as mentioned in the previous design happens, regarding the A parameter (the length fraction) and the behavior of parameter B is also the same.

It is shown that the magnetic field distribution in the configuration with MRF-140CG is more intense than in the system with MRF-132DG. In order to have that high magnetic field output, although the difference is almost negligible, the low carbon steel AISI 1010 should be the option.

This configuration is much heavier than the previous one and in terms of production it is more difficult to manufacture and it does not have that much benefit, which is why it will not be chosen for the final configuration.

Design 3

After the conclusions from the previous designs, it was decided to try to place the MR material sample in the middle of the coil and surround that with magnetic material, which led us to this new configuration.
With 1 being the magnetic material (top), 2 the coil, 3 the MR material sample and 4 the magnetic material (bottom).

The parameter A has the same procedure and conclusion as previously mentioned. The parameter C also presents the same variation, which is the smallest possible thickness that will have the highest magnetic values.

In this case, it is again shown that the $B$ value reaches a 'stationary state', where no matter the increase in this parameter, the result will be the same. When using MRF or MRE sample, the fluid produces higher values but when using a mix combination (MRE on the side and MRF in the middle) a good compromise can be achieved.

This particular arrangement provides a larger active area and it is the best configuration since the MR material is placed in the area of higher uniformity and intensity of the magnetic flux.

**Design 4**

This configuration was thought in order to have just one MR material sample, placed in the best possible location (serving partly as magnetic core). But, in order not to have friction between magnetic material or not to break it, it is necessary to have a couple of air gaps.
With 1 being the magnetic material (top), 2 the coil, 3 the MR material sample, 4 the magnetic material (bottom) and 5 the air gap.

This configuration design was the most important in terms of parametric studies since it has a lot of different dimensions that may influence the result. The first one studied was the thickness of the material and as already mentioned when that value is the lowest possible, the results increase. Regarding E and G, it influences the total length of the configuration and it is known from previous conclusions that this value has a limit from which the magnetic field does not increase. About parameter F, despite the dimension zero not being that much realistic, it was done in order to show that one should avoid the air areas or at least make them as small as possible. The parameters I and J influence the height of the configuration, which has also a maximum value where the magnetic field is the highest possible.

The study of the parameter H showed that when the air gap is too large, there will be a reduction on the magnetic field result since it provides a flux leakage that one wants to avoid. The dimension’s value being zero is not feasible, so the suggestion is to have the lowest possible value without compromising the desired result. In parameter K, the value zero was not even tested because it is not possible due to the magnetic material friction.

The magnetic field inside the material is the strongest and that is the major advantage. The main disadvantage is the air gaps on the geometry because they will reduce the flux in the MR material and concentrate it on the magnetic material on both sides.
Afterwards, having in mind the pros and cons of each configuration, it was decided that design 3 and 4 would be used for the final configuration of the cushion, since they benefit from having the MR material in the middle of the coil. With those two configurations, the idea is to perform a simple optimization study just to refine the geometry and to find the best values to be able to develop the CAD drawing, in the following sections.

5.2 Optimization

An optimization problem consists of finding the values of the design variables (like the dimensions of a component) for achieving the best values of an objective function. The first step in this process is the definition of the actual problem, that is, to find the best geometry dimensions (design variables) in order to achieve the highest magnetic flux density.

In this case, dimensional optimization involves specifying design variables that can be directly adapted to manufacturing. Typical design variables may be width, length and height of structural parts. Dimensional optimization is used as the final step in the design process and it is carried out once the design is almost fixed in terms of the overall shape.

In this case it is a maximization problem, which is solved by using the Nelder-Mead method (simplex method) with the aid of the COMSOL Multiphysics® Optimization module. There are three other possible methods that can be used for dimensional optimization: coordinate search, Monte Carlo, and BOBYQA (Bound Optimization by Quadratic Approximation) [75].

The objective function is given as input in the optimization module and the optimization is performed. Nelder-Mead optimization, which is a first order approximate gradient method and usually the most robust, has a reduced number of function evaluations in each iteration. For \( N \) variables, \( (N + 1) \) points are used in initial simplex. In every iteration, the worst point in the simplex is found first. The centroid of all but the worst point is set. The worst point in the simplex is reflected about the centroid and a new point \( X_r \) is determined. If the functional value at this point is better than the best point in the simplex, expansion ahead the direction from the centroid to the reflected point is carried out. If the functional value is worse than the worst point in the simplex, then contraction in the direction from the centroid is performed [75]. The process persists until the end criterion is satisfied. One can also define the limits (maximum or minimum) and the initial values of each dimension, since one already has a general idea of the configuration and dimension parameters, based on the parametric studies.

The main tip is to always start (as in this situation) from a feasible design.

So the procedure was, having both configurations of the design 3 and 4, to define the objective function as being the magnetic flux density value and select and constrain each dimension (except the fixed ones, for the coil) between reasonable values and solve the simulation.
The final values and results were used to build the final configuration in Section 5.3. The obtained dimensions are given in table 5.1 for both designs:

<table>
<thead>
<tr>
<th>Dimension (cm)</th>
<th>A</th>
<th>B</th>
<th>C</th>
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<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
<th>J</th>
<th>K</th>
</tr>
</thead>
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<tr>
<td><strong>Design 4</strong></td>
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<td>2</td>
<td>1.5</td>
<td>1.5</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Table 5.1: Final geometrical values for the cushion

5.3 Final Configuration

In this section, the CAD drawing and cross-sections of the final configuration are presented, based on the obtained dimensions on table 5.1. It is a square shape cushion with $50 \text{ cm} \times 50 \text{ cm}$ and it has 9 separate and independent cells.
The cell 1 is for the MR Fluid and the cell 2 is for the MR Elastomer. In the MR Elastomer cell, the thickness of the material is a bit higher because one has to take into account the static deflection (that depends on the material area) which is the deflection that happens only because the pilot is seated on the cushion. The MR Fluid will be produced in a way that will prevent this effect from happening. The coil used is the one shown in figure 4.1 and the magnetic material is the low carbon steel AISI 1010.

Figure 5.13: The two different cross-section of the cushion

Having the final dimensions and parameters, a COMSOL magnetic simulation was performed, in order to check the behavior of the MR material in each cell with the applied current. An example of that is shown in figure 5.14.

Figure 5.14: COMSOL final design of each cell, for 5 A current

In figure 5.15 the magnetic flux density distribution plots are shown, for the MRF and MRE cell. As expected, the $B$ value increases with the current and it is almost uniform along the length of the MR material. Due to its properties, the MRF presents higher values than the MRE but the range is almost the same.

This seat cushion design is going to be manufactured and experimentally tested.
Figure 5.15: Final design results
Chapter 6

Material Response and Control System

It is fundamental to assure that the cushion is able to withstand external disturbances such as vibrations. In order to verify that, vibration simulations were performed using Simulink to evaluate the system response. This chapter outlines the development of a dynamic model for a seat cushion used to simulate and evaluate the MRF’s performance.

6.1 Mathematical Models

Dynamical systems are subjected to base excitations. The dynamic model of the material is extremely difficult to develop due to its non-linear behavior and the internal damping.

A vibration analysis was conducted to study the response of the system to a base excitation.

6.1.1 MR Elastomer

The magnetic-elastic coupling, which is extensively used for simulations, means the reciprocal effect between the magnetic and the elastic field [76]. In order to formulate a tractable problem, previous theoretical modelling have addressed the issue using simplified assumptions of material composition and structure. The constitutive equations are based on generalized forms of Hooke’s law and Maxwell’s equations for anisotropic materials.

When applying a constant magnetic field, the overall shape and elastic properties (like stiffness which is the resistance to deformation), of a MR material are altered rapidly and reversibly. This bulk effect is responsibility of the induced magnetic interaction between the ferromagnetic particles in the sample.

There are not many models, equations or studies reporting the physics of the problem. There is only one study that reports a relation between shear modulus and magnetic field [77]. A finite-column model
is used to calculate the field-induced shear modulus:

$$G = \frac{(\mu_\parallel - \mu_\perp)H^2 \sin \theta \cos \theta}{\theta}$$  \hspace{1cm} (6.1)

Where $\mu_\parallel$ and $\mu_\perp$ are the parallel and perpendicular permeability depending on the magnetic particles, respectively; $H$ is the magnetic field intensity and $\theta$ is the shear strain.

Some additional work needs to be done to find a model, more accurate, like the following one for the MR Fluid, that is able to reproduce the force (total or elastic one) to implement in the same way, in the final system of the cushion to evaluate the MR Elastomer material response.

### 6.1.2 MR Fluid

The main demanding problem regarding MR Fluid numerical modelling is the accurate inclusion of its characteristic non-linear nature into the model.

In squeeze mode, a material is deformed between two parallel boundaries approaching each other. Squeeze mode arises from vertical motion, which creates a pressure in the thin film of material between the two layers. This geometrical arrangement can produce compression and tensile stresses which are much higher than in the other modes.

As mentioned, a sample of MRF-E is used, named MR pouch. The equation, based on a model that has been developed in recent years [78], for the total force produced by the MR pouch is demonstrated.

A vertical compression force, $F$, was applied that enforces the pouch to compress and the MR fluid will escape from between the two layers of magnetic material into the flexible membrane, from the center towards it, as shown in figure 6.1.

![Figure 6.1: Drawing of the MR pouch [78]](image)

Where $h$ is the gap between the layers and $R$ is the radius. First, to model this squeeze mode, it is assumed the fluid radial flow will be approximated by the equation for laminar flow in a wide channel given by:

$$q = \frac{2b \left( \frac{h}{2} \right)^3}{3\eta} \left( -\frac{\partial p_a}{\partial r} \right)$$ \hspace{1cm} (6.2)

Knowing the geometry of the MR pouch, from figure 6.1, one has the following dimensions (being $b$ the
wet perimeter of the MR fluid):

\[ b = 2\pi r \]  \hspace{1cm} (6.3a)

\[ q = \pi r^2 \dot{h} \]  \hspace{1cm} (6.3b)

Substituting this in equation 6.2 and integrating the viscous pressure in the pouch with respect to \( r \), it would become:

\[ p_\eta(r) = \frac{-3\eta\dot{h}}{h^3} (r^2 - R^2) \]  \hspace{1cm} (6.4)

The MR fluid properties were considered as those of a Bingham fluid and the radial pressure gradient is given by:

\[ \frac{\partial p_{MR}}{\partial r} = \frac{\partial \tau}{\partial z} \]  \hspace{1cm} (6.5)

Integrating with respect to \( z \) (vertical coordinate of the system) and assuming that the shear stress \( \tau \) is just the yield stress, it follows that:

\[ \frac{\partial p_{MR}}{\partial r} = \frac{-2\tau_y}{h} \]  \hspace{1cm} (6.6)

The yield stress of the MR fluid is a function of the magnetic flux density and the amount of compression pressure and its relationship can be represented as:

\[ \tau_y = \tau_0 + K_H p_{MR} \]  \hspace{1cm} (6.7)

The value \( K_h \) (dimensionless) is the slope of the graph stress vs. pressure and an approximate value of 0.07 is assumed. It is known that this slope presents slight variations with the magnetic field but there are no specific details or information about that variation, but it is assumed that it can be neglected. Therefore the most usual value was chosen.

The total force on the MR element is reached by integrating the total pressure \((p_\eta + p_{MR})\) on the surface:

\[ F = -\pi R^2 \tau_0 \left( \frac{-1}{K_H} + \frac{1}{2} \frac{h^2 \dot{e} e^{2KH}}{K_H R^2} - \frac{3}{2} \frac{R^2 \eta \dot{h}}{h^3 \tau_0} - \frac{1}{2} \frac{h^2}{K_H R^2} - \frac{h}{K_H^2 R} \right) = \left( -26h + 9 \right) \]  \hspace{1cm} (6.8)

Where the term on the right side of the equation 6.8 is the initial fixed spring force (in imperial units) due to the initial stiffness MR pouch has, that depends on the membrane material type used and thickness. It can be determined when the MR Fluid is not activated (no magnetic field).

In this equation, there is a fixed spring force that comes from the elastomer surrounding and there is another spring force contribution that depends on the magnetic field. The damping force is essentially due to the viscosity of the fluid.

The force has a negative sign due to the compression (squeezing) mode.

While this model accounts for the viscous and MR effect as related to the height of the gap, it is necessary to consider the inertial effect due to the oscillatory flow. With this new expression it will be possible to verify the dynamic response of the system.
A standard theory of lubrication is applied to the equations governing fluid flow, being:

\[ \rho \frac{\partial u}{\partial t} + \frac{\partial p}{\partial r} = \frac{\partial \tau}{\partial z} \]  

(6.9)

Integrating equation 6.9 across the gap, then applying the condition of global conservation of mass in order to differentiate with respect to time and integrating again, results in equation 6.10:

\[ F_{\text{inertia}} = -\frac{\pi R^4 \rho \dot{h}}{8h} \]  

(6.10)

Considering all the mentioned effects, the total dynamic compression force is given by the following equation, in SI units:

\[
\begin{align*}
F_{\text{total}} &= \pi R^2 \tau_0 \left( \frac{1}{K_H} + \frac{1}{2} \frac{h^2}{R^2} \frac{2K_HH}{R} - \frac{3}{2} \frac{R^2 \rho h}{K_H} - \frac{1}{2} \frac{h^2}{R} - \frac{h}{K_H} \frac{R}{R} \right) - \frac{\pi R^4 \rho \dot{h}}{8h} + (4925.2h - 45.1) \quad \text{if } \dot{h} < 0 \\
&= -\frac{\pi R^4 \rho \dot{h}}{8h} + (4925.2h - 45.1) \quad \text{if } \dot{h} \geq 0
\end{align*}
\]

Where \( \dot{h} \) is the velocity of the layers when the cushion is set in motion.

### 6.2 Model Validation

It is of the utmost importance to confirm the validity of the model and for that, a MATLAB script was developed, based on equation 6.8 and with the available data from the paper [78], the comparison was made. The main idea is to describe the evolution of the force with the gap size (displacement) changing, for different applied currents. It starts with a 0 A current and ends with 1.5 A which presumes different values of yield stress, \( \tau \). The input is a sinusoidal signal with frequency 5 Hz (used in the paper data) and the material is MRF-120RD (not available or produced anymore).

![Figure 6.2: Comparison between the paper data and the model based on equation 6.8](image)
Based on figure 6.2 it is proved that the model is well designed since the model matches the data from the paper. And it is also shown that the compressive force increases with the magnetic field and with the less possible gap size.

Another calculation that is possible to perform is, to derive the force equation with respect to the displacement, to obtain the stiffness $k$.

$$\frac{\partial F}{\partial h} = k = -\pi R^2 \tau_0 \left( \frac{h e^{2K_H R}}{K_H^3 R^2} - \frac{9 R^2 \eta h}{2 K_H^2 R} - \frac{h}{K_H^3 R^2} - \frac{1}{K_H^2 R} \right) - 4925.2 \quad (6.11)$$

Using this equation and having in mind the final geometry of the MRF sample used in the project, MRF-140CG and cushion, another script was developed to show the influence of magnetic field in the stiffness.

Looking at the figure 6.3 it is possible to conclude, as predicted, that the stiffness increases with the magnetic field and with a lower displacement. The values of the stiffness between $5000 \text{ N m}^{-1}$ and $110\,000 \text{ N m}^{-1}$ are in accordance to what is expected for this type of materials. If the gap size is too big, the magnetic field has almost no influence, since the active area will be decreased and the stiffness is lower.

The presented results show briefly how the squeeze mode works and what is expected from a MRF sample on being compressed. The only missing detail with this equation is that it does not predict well the dynamic response and it does not show any dissipative component. This is addressed in the following section.

### 6.3 Force Response

Predicting the dynamic response of the material is not simple. It requires the introduction of the inertia effect and consequently, the acceleration experienced when in motion. The implementation of equation
6.8 in the Simulink diagram was not successful, since it did not attenuate the vibrations as it was expected. One can see that there is no area in the graph of force versus displacement, in figure 6.2, so the dynamic part was not considered here.

With the equation of $F_{total}$ and using the geometry of the final configuration and the material MRF-140CG with its properties (density and viscosity), being the radius $R$ equal to 2 cm and the initial gap size is 7.5 mm.

![Graphs](image)

**Figure 6.4: MR Fluid final model (SI units)**

The goal is to exhibit how the fluid reacts to an input of a sinusoidal function with an amplitude of 2 mm and a frequency of 5 Hz to predict what could be expectable when the input is the acceleration signal coming from the bottom of the helicopter. These graphs were obtained with 1 A current, which means 22100 Pa of yield stress and the final geometry of the MR Fluid. For the same current, the effect of the frequency (at least until 50 Hz) is not significant, but for the same frequency and different values of current (that means different values of magnetic field and consequently of yield stress), the force increases with the current.

The area on the graph force versus velocity means the MR Fluid dissipated energy, which means that the system is attenuating the effect of the input, from where it is possible to extract the damping coefficient.

The chosen model, based on $F_{total}$, predicts the response in the expected way, since it presents the same behavior and shape as other few experimental tests in squeeze mode [79]. This could be improved in order not to have such an abrupt step in the force response, from one sub-function to the other.

### 6.4 Performed Simulations

Based on all the previous information and understanding better how the model works, it is possible to use it into a Simulink model, based on the SDOF principle, to study the pilot reaction and response to an acceleration input.

#### 6.4.1 Acceleration Input

The complete vertical (z-axis) acceleration data for an helicopter flight test has been provided by NRC, through an Excel data file. This data is shown in a time-basis and represents what happens for an interval of 60 s flight test.
If one wants to obtain the velocity values from this acceleration input, numerical methods can be used, in order to integrate the acceleration in time and get an approximation of the velocity values.

The input signal, in figure 6.5, has a maximum value of $21.87 \text{ m/s}^2$ and a RMS value of 4.77.

One useful analysis of the data is to view the input signal in terms of frequency and for that we need a FFT - *Fast Fourier Transform*, in order to transform the time domain into frequency domain. It gives the input signal frequency spectrum.

Doing that in MATLAB, there is a built-in function done for that case that gives the PSD – *Power Spectral Density* – of the signal and in the vertical axis one has the amplitude/magnitude in the same units as the original one, as presented in figure 6.6.
It is possible to verify that the main frequencies are within the range predicted. There are four major frequencies (already mentioned) that influence and represent the system.

### 6.4.2 Simulink® System

Simulink® (*Simulation* and *Link*) is an extension of MATLAB® that offers modelling, simulating and analyzing of dynamical systems under a graphical user interface [80].

The first attempt was to analyze a simple mass-spring-damper system, which resembles a one-degree of freedom (SDOF) system, with relative motion, which means the displacement of the mass is relative to the support. With different kinds of input (step, sinusoidal or the acceleration signal) and changing the values of stiffness and damping, it was possible to check how the software works. But this means a linear system and that is not the case. So, the author developed a new block diagram model to incorporate the force equation and the non-linearities.

The measured acceleration data were used to characterize the vibration input from the helicopter floor to the aircrew body through the seat.

In order to import the acceleration data to the system, a “From Workspace” block was used, to read from the document and save the full signal. The sampling time is also important, so that the system knows how often the output is needed. The simulation time is also changed to 60 seconds in order to visualize the entire signal.

Then, instead of having two separate blocks for stiffness and damping, respectively, since the force model represents the total force, a unique combined block was used, having as input the yield stress $\tau$, the relative displacement, velocity and acceleration. Since the force is highly non-linear, there was the need to define a MATLAB function block with specific inputs to be able to integrate that easily in the general system.

The data from MRF-140CG’s yield strength versus applied magnetic field intensity is available from LORD Corporation, in figure 4.3 and the relation between them can be reached by curve fitting the data and use that as a function to relate the magnetic field $H$ (values from COMSOL for the final configuration) with $\tau$.

The viscosity of the fluid is taken from the data sheet as well and it shows the slope of the graph shear stress versus shear rate. The mass of the system is the average pilot’s mass plus the upper part of the cushion corresponding mass.

To get the output results, a “To Workspace” block was used, in order to plot the graphs.

In figure 6.7, the initial system developed is illustrated. This system has worked well and has reduced the acceleration, despite it presented a problem with initial conditions (an abruptly initial variation) that needed to be solved. So the force block was separated into two outputs (the initial force and then the dynamic part) and the final diagram that represents the cushion system is shown in figure 6.8.

The parameters used were the initial gap size $h$ of 7.5 mm that represents the thickness of the MR Fluid; the slope $K_H$ that is 0.07; the radius $R$ is 2 cm; the viscosity is 0.28 Pa · s; the density of the material is 3640 kg/m³ and the mass of the system (pilot+ cush ion) is 85 kg.
With all these results, the only variable is the magnetic field, represented by the yield stress. Based on the curve of the material and the COMSOL values, that parameter can vary between 5500 and 58000 Pa. Depending on the input current, the magnetic field produced will change, which correspond to a yield stress value that generates the output acceleration and relative displacement.

The acceleration felt by the aircrew, after applying the system for example with an input current of 0.5 A (yield stress of 5500 Pa) is shown in figure 6.9.
It can be seen that the output is extremely reduced when compared with the helicopter input, having a reduction of around 97%.

Varying the input current from 0 to 5 A, all the obtained values, with the same mentioned procedure, are presented in table 6.1, where it can be checked that the acceleration output is more reduced when one has a magnetic field intensity around 7570 A/m. When no current is applied, there is still present a residual yield stress value, relative to the force versus velocity behavior.

<table>
<thead>
<tr>
<th>Current (A)</th>
<th>Magnetic field, $H$ (A/m)</th>
<th>Yield Stress, $\tau$ (Pa)</th>
<th>Maximum (m/s$^2$)</th>
<th>RMS (m/s$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>180700</td>
<td>58000</td>
<td>0.89</td>
<td>0.83</td>
</tr>
<tr>
<td>4</td>
<td>135200</td>
<td>51700</td>
<td>0.8</td>
<td>0.743</td>
</tr>
<tr>
<td>3</td>
<td>92140</td>
<td>41700</td>
<td>0.672</td>
<td>0.599</td>
</tr>
<tr>
<td>2</td>
<td>52290</td>
<td>26750</td>
<td>0.477</td>
<td>0.38</td>
</tr>
<tr>
<td>1</td>
<td>22375</td>
<td>12470</td>
<td>0.303</td>
<td>0.179</td>
</tr>
<tr>
<td>0.5</td>
<td>7570</td>
<td>5500</td>
<td>0.28</td>
<td>0.09</td>
</tr>
<tr>
<td>0.3</td>
<td>1745</td>
<td>2790</td>
<td>0.29</td>
<td>0.089</td>
</tr>
<tr>
<td>0.1</td>
<td>270</td>
<td>2140</td>
<td>0.33</td>
<td>0.095</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>1700</td>
<td>0.4</td>
<td>0.11</td>
</tr>
</tbody>
</table>

Table 6.1: Results for simulations performed for different input currents

And the relation between the output-input acceleration ratio and the yield stress is described in the plot on figure 6.10.

![Figure 6.10: Acceleration output and input ratio vs. Yield Stress](image_url)

The main purpose is to achieve an output as low as possible, which means the highest signal attenuation. So the best solution is when the ratio is the lowest possible.

It is shown, in figure 6.11, all the possible obtained results (relative displacement, relative acceleration and velocity and total force) for the example of an input current of 0.5 A, from the Simulink model.
Figure 6.11: Output results example, for an applied current of 0.5 A

### 6.5 COMSOL Future Application

It was not possible to complete the study due to the lack of properties and parameters of the materials. However, the procedure and instructions are explained.

The physics applied in this section would be Magnetic Field, Solid Mechanics and Moving Mesh mode. The Magnetic Field and the Solid Mechanics are connected to represent the material’s ability to change its properties. The moving mesh is necessary due to the displacement of the system during the simulations. It could be done a time dependent analysis that measures effects on a time scale (like Simulink) or a frequency domain analysis which is a global study of the system; it takes time based data and fourier transform to convert into a a frequency dependent data.

With the same geometry used for the magnetic circuit analysis, one just adds the structural module, define the material properties or models/equations to represent it and then with a sinusoidal input or an acceleration data file on the bottom of the geometry it is possible to evaluate the output on the top of the geometry, where the pilot is seated.

### 6.6 Control

After having the entire system model working well, it is needed to add the controller. A challenge for the potential applications of MR materials devices is the development of an appropriate control strategy.

This is particularly attractive for vibration mitigation applications, since the main objective for designing a control algorithm is to shift the natural frequency as far as possible from the excitation frequency.

In theory, high damping is great to isolate the main resonance frequency but it is quite hard to stabilize the system because any small perturbation turns the system almost impossible to return to equilibrium.
and it just works well at higher velocities.

The main idea is to have a closed-loop control system so that the output has an impact in the controller action.

## 6.6.1 Skyhook Control

The presented block diagram model already represents the physics of the problem so in this topic it is necessary to add the controller part and check for the response, to evaluate its efficiency.

The skyhook is based on the mass related to the absolute velocity value of the output response. Then the signal is affected by a gain value and produces the desired force for this purpose, $F_v$. After that, and inside an algorithm (on-off condition) block, it is made a comparison between the desired force and the force coming from the MR model (dynamic force) and based on that, a value of yield stress, $\tau$ is given as output and reintroduced again in the system. The schematic of this system is reproduced in figure 6.12.

The desired force that one should obtain is given by $F_v = -g \cdot v$, where $g$ is the controller gain and $v$ is the absolute output velocity.

The algorithm is based on the two-position or on-off control action, where the control law is dependent on the actuating error signal (difference between the desired and the model force, represented by a Heaviside function). The control variable should be selected by the following procedure: if the cushion system is providing the desired force ($F = F_v$), the control variable should remain at the present level; on the other hand, if the magnitude of the force produced by the cushion is smaller than the magnitude of the desired force and the two forces have the same sign, the control variable is increased to the maximum level $\tau_{\text{max}}$, so as to increase the force produced by the cushion to track the desired one. Otherwise, the control variable is set to the minimum value $\tau_{\text{min}}$.

The clipped on-off algorithm is implemented in line with a controller which results in a force feedback tracking scheme, as mentioned, and is considered here for semi-active control. This algorithm can be stated as:

$$
\tau = \tau_{\text{max}} \cdot H[(F_v - F_{\text{MR}})F_{\text{MR}}], \quad \tau_{\text{min}} \leq \tau \leq \tau_{\text{max}}
$$

(6.12)
The goal is to understand if this type of control, for this particular purpose and configuration, is appropriate and necessary.

Based on different values for the gain, several simulations were performed in order to compare the final obtained result.

This semi-active solution would be, ideally, much more effective for reduced damping values. With high damping results, as in this case, the use of this system is almost unnecessary.

With this present situation, the only values of gain that could give the best result (just a bit lower from the more reduced previous one) are \( g \) between \(-0.09\) and \(-0.1\) that produces a maximum value for the acceleration of \(0.27 \, \text{m/s}^2\), but the model must be optimized since it presents a couple of irregularities that should not be present.

One important note is that all these results must be tested experimentally, since in theory the reduction seems to be extremely high but in reality it might not happen.

### 6.7 General Conclusions

Using a single degree of freedom seat model design strategy, a MR material cushion can be designed to reduce the vibration transmitted to the pilot. While the dynamics of a vehicle seat may be complex, a SDOF model can be a valuable tool for MR material cushion design and performance predictions.

There is a significant response reduction seen with the final Simulink model. The acceleration felt by the aircrew reduces around 97% when compared to the input signal, and it shows that the design achieves the goal of the project. It produced a low displacement value and the total force of the MR Fluid helps to mitigate the intensity of the input acceleration.

The adopted control strategy just for this particular purpose, proved to be a scenario to consider in this type of problem, but the force model must be refined, maybe the final configuration needs to be adjusted (change the radius or initial thickness) in order not to have so high damping values, so the skyhook control could be more effective.

The multiphysics FEA modelling process described in section 6.5 is applicable for the prediction of MR Fluid and MR Elastomer behavior when all the material data is available.
Chapter 7

Conclusions

A magnetorheological seat cushion is proposed as a potential solution (compared with the conventional one), to attenuate structural vibrations in helicopter seats. A study of magnetorheological materials was conducted and they present an adequate material for an application in seat cushion to mitigate vibrations and increase pilot comfort. In this chapter, a few considerations and comments are presented describing the overall process of the current thesis research.

7.1 Achievements

Magnetorheological materials can, in fact, mitigate vibrations and are considered a viable solution for vibration suppression and control. The thesis research presents a succinct theoretical background. The key throughout this process is to magnetize them in the right direction and depending on the particles, the behavior is different. The main goal was to evaluate the mechanical response of the magnetorheological material in the presence of a magnetic field (stiffness and damping control). If hard magnetic particles are used (like Barium Ferrite, used for permanent magnets) to create the system, they just become more stiffer and do not exhibit any influence on the system. If one would like to use them to create any mitigation, then soft particles (for example carbonyl iron) must be used, which present a desirable behavior as they lose their magnetization immediately when removed from the field. The volume fraction is also an important factor since as the volume increases, the magnetic field strength increases too.

The initial conceptual design and the software used in the simulations were introduced as well as simple analytical calculations were carried out. It was found that to achieve a lower than 5.4 Hz frequency, a soft elastomer is needed, which is not possible to manufacture and that is why some compromises have to be made.

A magnetic field analysis was conducted and an electromagnetic circuit design and geometry parameters for a MR cushion have been proposed in this study. Finite element models were created and their results prompted important design changes to improve the overall performance of the MR material. Different possibilities and arrangements were tested and studied to optimize the final design.

The coil wire is an important design parameter to support the input current. Important design parameters
include the thickness of the material, the length of magnetic material and the input current. There is no
need to have an extensive magnetic material layer since the magnetic field has a defined and restrict
path. It is also worth noting that one should avoid air areas because it reduces the magnetic flux density.
The definition of the winding of the coil is of extreme importance, so that the software may clearly
understand how many coils are in each design.
The finite element software used, has proved the flexibility and ability of an easy implementation of a
fairly complicated and complex coupled problem despite the fact that COMSOL takes a long time to
get familiar with, and to understand, all its capabilities and functions, since it is not as user-friendly as
FEMM.

By the end of this part of the project, a CAD of the final configuration is presented as well as its cross-
sections.
The behavior of MR fluids under squeeze mode has been researched and evaluated, since there is not
much information regarding this mode of operation, particularly using hydrocarbon-based MR fluids.
After validating the mathematical model, this was used to reproduce the response of MR Fluid. With that,
a Simulink block diagram model was developed and with the characteristics of the final configuration,
the acceleration output on the aircrew was proved to be reduced considerably when compared to the
input. The maximum possible displacement is $2 \text{ mm}$ and if the applied current increases, that displace-
ment reduces as well. The acceleration output maximum reduction is around 97%, which confirms the
suitability of the proposed design for vibration attenuation (main goal of the project).

The proposed controller is based on the skyhook algorithm, and it needs to be tested experimentally
in order to validate the obtained results and verify if this reduction is observable in practice. Since the
values of reduction are already quite high, the only possible values for the gain $g$ are between $-0.09$ and
$-0.1$ that produces an output acceleration peak of $0.27 \text{ m/s}^2$.

Summarizing, a new conceptual design of an adaptive seat cushion has been proposed, the model to
predict the material behavior has been validated and successfully implemented. It has been shown that
force and stiffness increase with the magnetic field. The acceleration is considerably attenuated when
felt by the aircrew and the controller appears to be unnecessary since high reductions in vibrations are
obtained, when using only the ‘passive’ system.

7.1.1 Contributions

This thesis presents the following contributions: a relevant development regarding MR materials; the
design of an innovative helicopter cushion seat to attenuate vibrations for increased pilot and crew com-
fort; and the development of “building blocks” (like the finite element models, the non-linear analysis and
simulations and, material response with Simulink implementation) to achieve the proposed conceptual
design such as the development of a non-linear material model to simulate the MR elastomer.

With respect to the MR Fluid material response, a simple one-degree-of-freedom dynamical model (with
MATLAB® and Simulink®) and associated control strategy are presented to evaluate the performance
of the proposed design. Even for the experimental test rigs used in the lab, computational models were
first created by the author and their behavior was studied. In the end, this thesis provides a new seat
cushion conceptual design that exhibits the required attenuation levels of vibration in the adaptive seat cushion.

7.2 Future Work

For future development, the following aspects should be considered:

- The optimization of the model for the material response of MRF, to improve the response of the seat cushion in terms of dimensions of the various segments of the design;

- The development of a material response model and respective performance for the MRE;

- The development of more adequate and multi-degree of freedom control strategies (algorithms). The use of a fully adaptive control strategy is required to maintain optimum isolation performance and associated experimental evaluation and verification;

- The implementation of the optimal solution experimentally in order to check the integrability of the semi-active cushion embedded on the existing seat structure. This is a crucial point when certification of the new design is required.

Finally, while this thesis research project has focused on helicopter seats, the proposed technology holds great promise for potential applications to other vehicle seats.
Bibliography


Appendix A

Maxwell Equations

In this appendix, the objective is to present a recap on the equations that are mainly used in electromagnetics. Secondly, it intends to familiarize the reader with the notation adopted in this thesis.

Maxwell's equations are defined by four partial differential equations that define the entire field of electromagnetics.

A.1 Electromagnetic Analysis

This set of equations are written in differential or integral form, explaining the relationships between the fundamental electromagnetic quantities [81]. Here the differential form is shown because it leads to differential equations that the finite element method can deal with.

\[
\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} \quad \text{(A.1)}
\]

\[
\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad \text{(A.2)}
\]

\[
\nabla \cdot \mathbf{D} = \rho \quad \text{(A.3)}
\]

\[
\nabla \cdot \mathbf{B} = 0 \quad \text{(A.4)}
\]

Where \( \mathbf{B} \) is the magnetic flux density; \( \mathbf{D} \) is the electric displacement or electric flux density; \( \mathbf{E} \) is the electric field intensity; \( \mathbf{H} \) is the magnetic field intensity; \( \mathbf{J} \) is the current density and \( \rho \) is the electric charge density.

Equation A.2 is known as Faraday’s Law of Induction which states that any change in the magnetic field results in the flow of charges in a conductive medium. Equation A.1 is the Maxwell-Ampere’s Law which states that electric current flowing through a closed loop results in magnetic field generation. Eqs. A.3 and A.4 are known as Gauss Law. Equation A.3 states that the divergence of electrical flux density is equal to the charge density and Equation A.4 states that the divergence of magnetic flux density is always zero for a closed surface defined.
Another fundamental equation is the equation of continuity:

\[ \nabla \cdot J = -\frac{\partial \rho}{\partial t} \tag{A.5} \]

To obtain a closed system, the equations include constitutive relations that describe properties of the medium, such as:

\[ B = \mu_0 (H + M) \tag{A.6} \]

Where \( \mu_0 \) is the permeability of vacuum, which in the SI system is \( 4\pi \cdot 10^{-7} \text{H/m} \) and this constant is available in COMSOL as predefined physical constants.
Appendix B

Technical Data

In this appendix, the properties of the magnetorheological fluid MRF-132DG are presented. Since in Section 4.2 only the properties for MRF-140CG are included, the author gives here the possibility to find the behavior of MRF-132DG, due to the fact that it is not so used for the project and simulations.

B.1 LORD Corporation Data

Based on the technical data provided and available, it is possible to characterize the MRF-132DG’s properties, which is the other possible MR Fluid to use.

(a) Typical Magnetic Properties - $B - H$ curve [82]

(b) Yield Stress vs Magnetic Field Strength [82]

Figure B.1: MRF-132DG
Appendix C

Parametric Studies Results

In this appendix, the remaining parametric studies done in all the configurations are presented, in order to clarify any missing information.

C.1 Design 1

One observes that using the parameter $G$ as $2 \text{ cm}$ or higher for the magnetic material layer, the output result is the same. Between the two types of fluid, it is worth using the MRF-140CG.

Figure C.1: Parametric study results for the length of magnetic material layer and comparison between MRF-140CG and MRF-132DG

C.2 Design 2

In the design with two coils, the parameter $B$, which will give the total height of the configuration, has a limit value. Above $10 \text{ cm}$ there is no need to increase this dimension because the final result will be the same.
C.3 Design 3

The parameter A, in this configuration, is represented by a length fraction in order to be able to check all the curves in the same window of the graph. And the parameter C is, preferably, the lowest possible.

C.4 Design 4

In this design, the parameter E and G represent the total length of the configuration; the parameter F shows one of the air gaps and the parameter I is connected to the height of the configuration.
(a) Results for parameter E variation

(b) Results for parameter G variation

Figure C.4: Parametric study results for the sides dimensions in design 4

(a) Results for parameter F variation

(b) Results for parameter I variation

Figure C.5: Parametric study results for one air gap size and the height of design 4