Design and Modelling of a Semi-active Helicopter Seat Cushion

Nicole Tiago da Cruz
nicole.cruz@tecnico.ulisboa.pt

Instituto Superior Técnico, Lisboa, Portugal

November 2016

Abstract

Helicopters are susceptible to excessive vibratory loads that lead to poor flight ride quality. The main goal is to help mitigate structural vibration through the performance evaluation of a novel seat cushion. Magnetorheological materials present a promising approach for this purpose. The unique properties of MR materials - their ability to mechanically respond to magnetic fields and their characteristic material non-linearity - make designing these applications a challenge. The MR seat cushion consists of a distributed magnetic material embedded in elastomers and various electromagnetic coils. Two commercial software(COMSOL® and FEMM), capable of modelling complex electromagnetic problems and non-linear materials, have been 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. Based on all results, a conceptual final design configuration is proposed as well as a 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 seat cushion design proposed has been performed in collaboration with the National Research Council Canada and it is going to be manufactured and tested.
Keywords: helicopter seat cushion, magnetorheological materials, finite element modelling, magnetic circuit, design, control

1. Introduction

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, due to its unique capability to take-off and land vertically as well as its ability to hover, there have been increasing complaints of fatigue, discomfort and pain during prolonged exposures to this vibration. This type of exposure interferes with the operational performance by degrading situational awareness that may affect decision making.

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. Due to the complex coupling between the rotor system, airframe, transmission system and engine, the vibratory loads and noise energy are transmitted throughout the helicopter structure and contribute to poor ride quality for passengers and crew. 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 [8]. Since there is nothing the pilot could do in flight to minimize the pain, it becomes a distraction that could jeopardize the security of the flight, mission or passengers.

Considerable efforts have been undertaken to reduce helicopter vibration. 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 helicopter vibration. In order to successfully reduce vibration level, vibration cancellation on seats technologies and techniques (locally) has attracted significant interest in recent years, since they have been considered a low-cost strategy for improving comfort and mitigating certain vibration.

This research focuses on the use of magnetorheological materials for enhanced occupant protection and comfort in order to present a semi-active seat cushion system, 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.

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. The term "magnetorheological" comes from a combination of *magneto*, meaning magnetic, and *rheo*, the prefix for the study of deformation of matter under applied stress.

This 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.

The proposed seat cushion design, in the end, is going to be manufactured experimentally tested.

2. Background and Preliminary Design

The author gives a review on magnetorheological materials (MRE - magnetorheological elastomer or MRF - magnetorheological fluid) and the techniques used to control vibrations. Preliminary design is concerned with the initial development of the project; what means and what is involved in a seat cushion; the first calculations performed in order to help on chosing a viable material to produce and evaluate if the first configuration thought is the best one or not for this purpose.

2.1. Magnetorheological Materials

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. One great supplier and widely requested company is LORD Corporation. In recent years, there has been a renewed interest in MR fluid devices, for example, to use in cycling, dampers, seat suspensions and prostheses or even polishing optical lenses [9]. 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 of the device. The most common model used to describe these materials is the Bingham plastic model:

$$\tau = \tau_y(H) + \eta\dot{\gamma} \quad (1)$$

There are several more complex non-linear parametric models that are used to describe these materials such as Bouc-Wen model. When applying a magnetic field, the material changes from a fluid state to a semi-solid state. The fluids particles align with the direction of the field, as shown in figure 1.

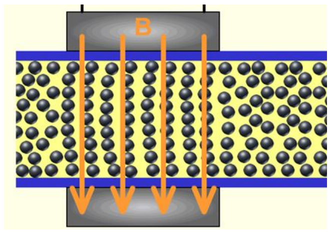

Figure 1: MR Fluid solidifying in response to magnetic field

Magnetorheological elastomers are, like the MR fluids, a kind of smart material, which usually has three different components: a rubber or polymeric matrix (non-magnetic); magnetically polarizable particles and few additives. 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). One usual supplier of this material is Ioniqa Technologies. The MRE has also three operation modes: shear mode; squeeze mode and field active mode. Applications for MRE include adaptive tuned vibration absorbers, shock isolators, papermaking machine and engine mounts [5].

It has also been investigated a new design concept, using a magnetorheological fluid encapsulated in a passive elastomer matrix. 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. One can conclude that MRE and MRF complement each other.

2.2. Vibration Control

Vibration control is categorized as: active, passive, or semi-active, based on the power consumption of the control system. 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. The main function of a passive system is dissipating energy and primarily consists of springs and dampers. 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. 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. This technique can usually achieve a high performance for eliminating vibration, but it is too expensive, design intensive, require a great deal of power to operate, and adding energy to a system can sometimes cause instability. Semi-active solution (in which the mechanical properties can be adjusted in real time) possesses the advantages of both passive and active solutions. The purpose of semi-active systems is to dissipate energy while increasing the durability of a system. In semi-active control, the properties of the actuators are dynamically modified, in order to optimally damp the vibration of the system.

The control system consists of a structure employing devices and sensors which is exposed to disturbances. Concerning to the area of seat suspensions, a number of control approaches have also been proposed and developed to improve the seat suspension performance. It was brought in a simple, yet effective vibration isolation strategy that is fulfilled by connecting a fictitious damper between the mass and the stationary sky, named Skyhook Control.

2.3. 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.

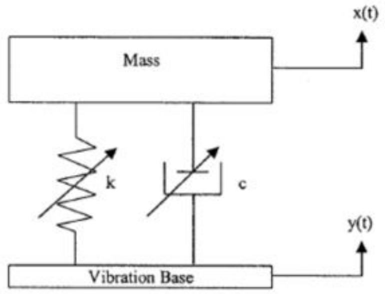

Figure 2: Semi-active vibration system

Natural vibration analysis of a system provides its dynamic characteristics. Based on figure 2, 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. The equation of motion of this system can be represented as:

$$x_r = (x - y) \tag{2a}$$

$$m\ddot{x}_r + c\dot{x}_r + kx_r = -m\ddot{y} \tag{2b}$$

Further assuming the pilot to be a rigid body, the natural frequency f of the pilot-cushion system can be expressed as:

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \tag{3}$$

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 initial configuration proposed, in the beginning of this work, has a layer with two samples of MRF and three of MRE (with an angled trapezoidal shape) and two coils in each part surronded by magnetic material. One of the proposed challenges was to estimate the stiffness generated from the MRE in this kind of configuration. The angled trapezoids assumed in the calculations act in shear and also in compression due to a vertical load. Therefore, one should resolve each angled face into two equivalent springs.

To achieve the proposed frequency ($5.4Hz$), it requires a very soft elastomer (much less than $100kPa$ as Young's modulus), which is impractical. Some compromises (dimensions and feasability of the sample) were made and it ended up being assumed a desired resonant frequency of $8.1Hz$. It has resulted in a range of desired sitffness between $123kN/m$ and $255kN/m$. The magnetic particles used for both materials should be soft particles (like carbonyl iron) due to high permeability and high saturation magnetization.

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 (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 project 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. 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. Only for the magnetic circuit analysis it will be also used as well 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.

3. Finite Element Modelling

The finite element method is a numerical method for solving problems that involve complex physics, geometry or boundary conditions. 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.

3.1. Magnetic Circuit Design

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 basic theory in the software is based on Maxwell's equations [2] and its relations were employed:

$$\nabla \cdot B = 0 \tag{4}$$

And Ampère's law:

$$\nabla \times H = J \tag{5}$$

Where, H is the magnetic field intensity and J the current density. 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.

The main procedure in FEMM 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. After that the mesh is generated and the problem is solved quite quickly. 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. Then deal with the mesh processing, define the input current and other magnetic field features and, solve the problem.

The electromagnetic coil is an important design parameter, as it is the source of the magnetic circuit. It was based on the Multi-Turn Coil domain inside the software and the coil wire cross-section area could be defined for its dimension, for the SWG (Standard Wire Gauge) number or for the AWG (American Wire Gauge) number. 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 electromagnet coil is limited, which depends on the cross-sectional area of the wire and its material. In the end, a 15 AWG size copper wire is used to wind the coil of the cushions electromagnet with 600 turns.

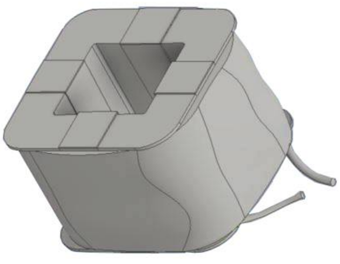

Figure 3: CAD model of the coil used for the project

One important factor to be considered 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. The magnetorheological materials, used in this work, have almost non-hysteresis effect so that they can be easily demagnetized.

Another main parameter that defines a material's magnetic characteristics is its permeability μ, which is the ratio between the applied magnetic field intensity H and magnetic flux density B. Permeability can be thought as being the magnetic conductivity of a material. For design purposes, only the average $B-H$ curve, which incorporates magnetic saturation effects, but not hysteresis, is needed or accepted inside COMSOL.

3.2. Materials Design

The materials used in the cushion have a crucial influence on the magnetic circuit. The fast and reversible reaction of MR fluids offers them to be a suitable candidate to interface between these systems. Two types of hydrocarbon-based magnetorheological fluid will be tested during this work: MRF-132DG and MRF-140CG. Material properties for the MR fluid were chosen based on typical values reported in the manufacturer's provided literature by LORD Corporation. When encapsulated in a regular elastomer, the matrix material can be, for example, silicon to avoid the fluid leakage.

There are almost none suppliers of magnetorheological elastomers. The supplier *Ioniqa Technologies* only provided a rough magnetization curve in imperial units and from that, 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.

In order to intensify the field generated by the electromagnets, high permeability and high saturation magnetic material needs to be utilized. Based on this criterion the AISI 1010 and AISI 1018 will be tested.

3.3. Mesh Generation

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 geometrys domain. The free triangular and the quad elements were tested, in order to prove that this is a mesh independent problem. The example of the finer mesh, with $0.2cm$ element size will have 224605 degrees of freedom solved and the other with $1cm$ will have 153537 degrees of freedom. One of the key concepts in this section is the idea of mesh convergence as one refines the mesh, the solution will become more accurate. Analyses were conducted with different meshes to determine the ideal element size.

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

3.4. Validation

To validate the method and software used during the research, the author tried to reproduce a couple of previous works ([7] and [10]) 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.

3.5. Experimental Rigs

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 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.

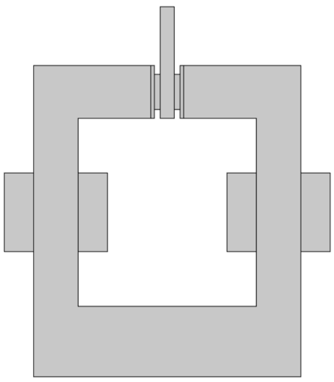

Figure 4: 2-D model created for shear rig concept

The model was tested to an applied current from 0 until $5A$ and the maximum magnetic flux density value was registered. The output results fluctuated between $50T$ and $470T$.

In the compression rig 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 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 calculations.

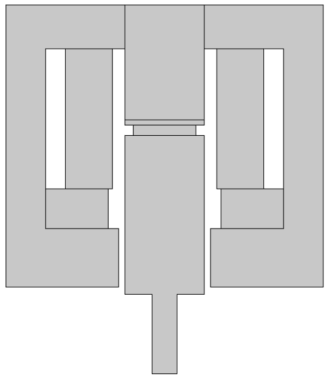

Figure 5: 2-D model created for compression rig concept

The model was tested for the same applied current and the obtained results are from $80T$ to $680T$. An extremely important conclusion, based on these results, is that it was decided for now, the cushion would benefit the most only with MR samples in compression because it presents the higher obtained values and are less costly to manufacture. So the angled trapezoidal shape will not be adopted from now on.

There is no analytical solution that fully reflects the actual problem but some approximations can be made. For these calculations, the models were divided into differents parts and it was calculated the length, the cross-section area and the relative permeability value for each one. Based on *Hopkinson's Law* it is possible to have the total reluctance of the circuit and with that one has the magnetic flux, from magnetostatics.

$$\Phi = B{\cdot}A_{MRE} \tag{6}$$

$$N{\cdot}I = \Phi{\cdot}\mathcal{R}_{total} \tag{7}$$

$$\mathcal{R} = \frac{l}{\mu_0 \mu_r A} \tag{8}$$

Where Φ is the magnetic flux; $\mathcal{R}$ is the magnetic reluctance, l is the mean flux path length, μ is the magnetic permeability and A is the cross-sectional area of each part. Based on this information and the geometry divisions, the calculations were performed knowing that for the compression rig there is only one coil and for the shear rig there are two coils.

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.

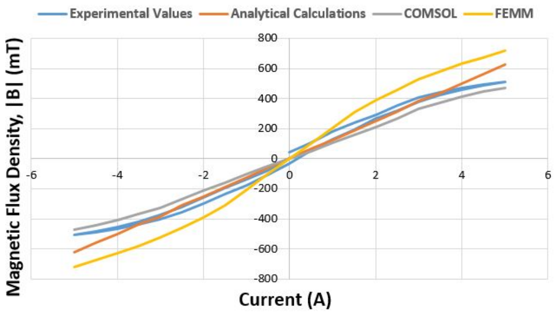

Figure 6: Shear Rig final results

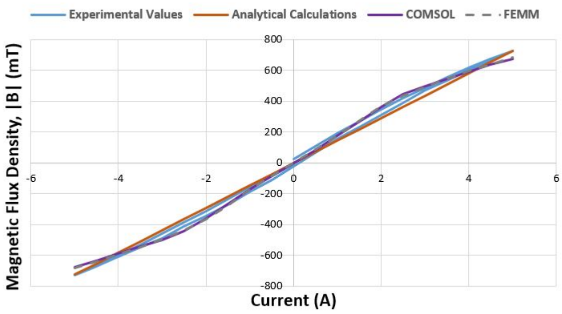

Figure 7: Compression Rig final results

All options produced consistent and almost the same final results, which means that both models were successfully developed and represent indeed the behavior of the experimental rigs.

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. 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. In order to analytically calculate the same results, it was used a method of force calculation based on reluctance.

$$F = \frac{B^2 \cdot A}{2\mu_0 \mu_r} \tag{9}$$

A comparison between COMSOL values and analytical calculations was made and the obtained results are extremely consistent and, as expected, the magnetic force increases with the magnetic field.

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.

4. Parametric Studies and Optimization

Different configurations of MR material cushion sections are used, to identify the parameters that affect the most the design and shape of the device, in order to maximize the magnetic field intensity within the gap. After a short optimization example application and obtaining the final dimensions of the geometry, the final design configuration of the seat cushion is presented.

4.1. Candidate Configurations

The general concept leaves room for a variety of different configurations depending on the choices made regarding aspects such as the number of coils; the number of MR samples; MRF or MRE to be used; the thickness of the gap; magnetic material to be used; size and location of the components and dimensions of the overall geometry. Four different configurations will be described throughout this section. The available parameters to test and the advantages or disadvantages of each configuration are mentioned as well.

The first chosen design is the simplest one possible, having the MR Fluid or MR Elastomer below the coil and a small layer of magnetic material. The second configuration adopted is the one that reproduces the initial conceptual design. 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 surrond that with magnetic material. The fourth configuration was thought in order to have just one MR material sample, placed in the best possible location (serving partly as magnetic core). All the dimensions were tested with different values and 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.

4.2. Optimization

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. Dimensional optimization is used as the final step in the design process and is carried out once the design is more or less 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 [4]) with the aid of the COMSOL Multiphysics® Optimization module. With this, the final values were used to built the final configuration.

4.3. Final Design

The CAD drawing and cross-sections of the final configuration are presented, based on the obtained dimensions.

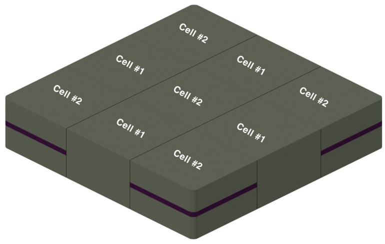

Figure 8: Final Cushion

The cell 1 is for the MR Fluid and the cell 2 is for the MR Elastomer.

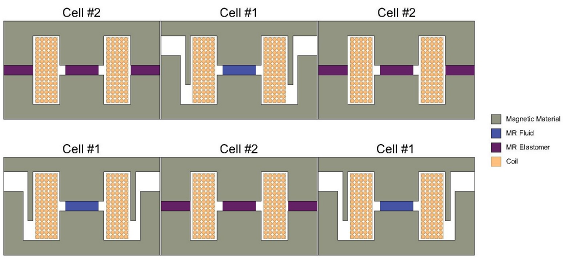

Figure 9: The two different cross-sections of the cushion

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 and the magnetic flux density distribution plots are shown.

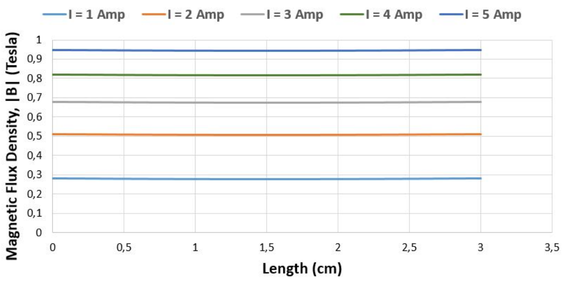

Figure 10: MRF cell 1 final results

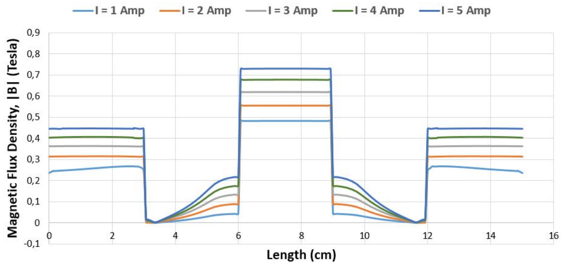

Figure 11: MRE cell 2 final results

Now the seat cushion design is going to be experimentally tested.

5. 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 MRF performance.

5.1. Mathematical models and validation

The dynamic model of the materials are extremely difficult to develop due to their non-linear behavior and the internal damping. For the MRE there are no equations or models to represent its behavior. There is only a finite-column model proposed to calculate the field induced shear modulus [1]. For the MRF, it is used a MRF-E pouch and the equation representing the squeeze mode is based on [3]. Squeeze mode arises from vertical motion, which creates a pressure in the thin film of material between the two layers. The model is based on the integration of the total pressure on the surface, and the final total force equation accounts for the inertia effects:

$$F_{total} = \begin{cases} \pi R^2 \tau_0 \left(\frac{-1}{K_H} + \frac{1}{2} \frac{h^2 e^{\frac{2K_H R}{h}}}{K_H{}^3 R^2} - \frac{3}{2} \frac{R^2 \eta \dot{h}}{h^3 \tau_0} - \frac{1}{2} \frac{h^2}{K_H^3 R^2} - \frac{h}{K_H{}^2 R} \right) - \frac{\pi R^4 \rho \ddot{h}}{8h} + (4925.2h - 45.1) & \text{if } \dot{h} < 0 \\ -\frac{\pi R^4 \rho \ddot{h}}{8h} + (4925.2h - 45.1) & \text{if } \dot{h} \geq 0 \end{cases}$$

Where h is the gap size, $\dot{h}$ the velocity of the layers and the right term on both equations is the initial fixed spring force due to the initial stiffness MR pouch has, that depends on the membrane material type.

It is also possible to differentiate this equation, in order to obtain the stiffness of the material, for different magnetic fields.

Figure 12 and 13 show the force response, using the final geometry and the MRF-140CG properties.

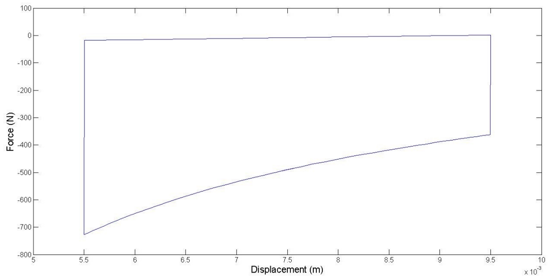

Figure 12: Force versus displacement MR Fluid final model

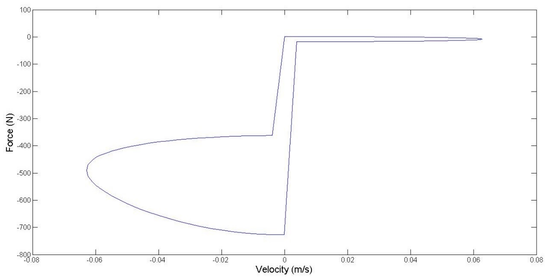

Figure 13: Force versus velocity MR Fluid final model

As seen in Fig.5.1 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.

5.2. 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.

5.2.1 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 $60s$ flight test. The input signal has a maximum value of $21.87m/s^2$ 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.

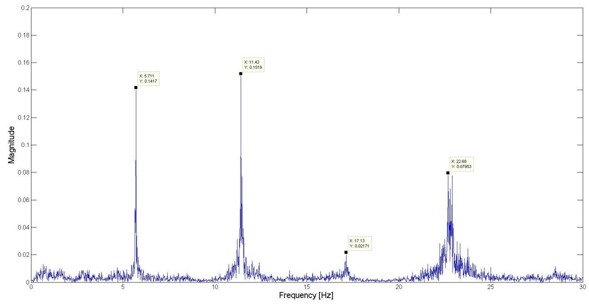

Figure 14: Input acceleration signal in frquency domain

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.

5.2.2 Simulink® System

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. Since the force model represents the total force, it was created a unique block with both together, having as input the yield stress τ , the relative displacement, velocity and acceleration. The data from MRF-140CG yield strength versus applied magnetic field intensity is available from LORD Corporation [6]. 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 parameters used were the initial gap size h of $7.5mm$ that represents the thickness of the MR Fluid; the slope K_H that is 0.07; the radius R is $2cm$; the viscosity is $0.28Pa/s$; the density of the material is $3640kg/m^3$ and the mass of the system (pilot+cushion) is $85kg$. The only variable is the magnetic field, represented by the yield stress. Based on the curve of the material from the data sheet and the COMSOL values, that parameter can vary between 5500 and 58000 Pa.

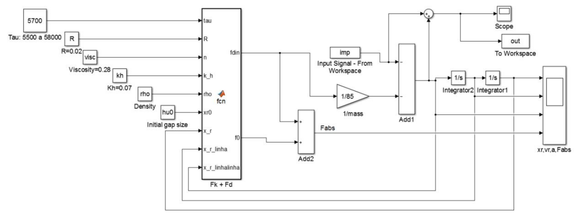

Figure 15: Final Simulink model

The acceleration felt by the aircrew, after applying the system for example with an input current of 0.5A (yield stress of 5500 Pa) is shown in figure 16.

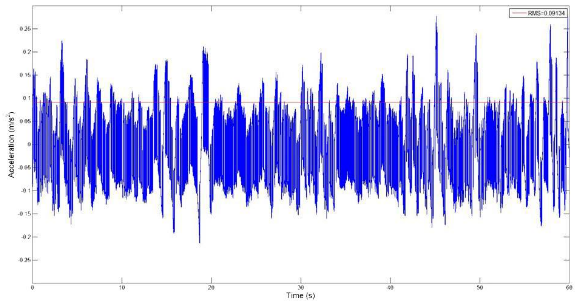

Figure 16: Output acceleration example, for 0.5A current

It can be seen that the output is extremely reduced when compared with the helicopter input, having a reduction of around 97%.

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

5.3.1 Skyhook Control

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, τ is given as output and reintroduced again in the system. The schematic of this system is reproduced in figure 17.

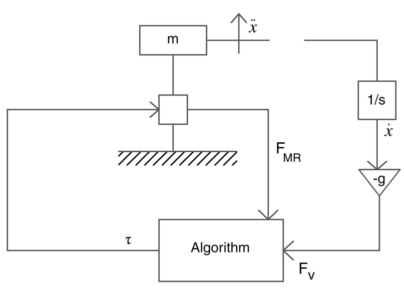

Figure 17: Schematic of the skyhook control system

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.

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.

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.

6. Conclusions

This project has a couple of original contributions and a relevant development regarding MR materials. A magnetorheological seat cushion is proposed as a possible solution for the conventional one. These magnetorheological materials can, in fact, mitigate vibrations and are considered a viable solution for vibration suppression and control. The 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 the presence of a magnetic field (stiffness and damping control).

A magnetic field analysis was conducted and an electromagnetic circuit design for a MR cushion was 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. The definition of the winding in the coil is of extreme importance, so that the software may clearly understand how many coils are in each design. Regarding the finite element software, 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.

After validating the mathematical models, this was used to reproduce the response of MR Fluid. With that, a Simulink block diagram model was developed. The maximum possible displacement is 2mm and if the applied current increases, that displacement reduces. 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 system seems to be almost unnecessary since high reductions are obtained only with the passive system.

This project 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 comfort; 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.

Future work should start with the optimization of the model for the MRF material response; then the development of a material response model and respective performance for the MRE and the definition of more adequate and multi-degree of freedom control strategies and comparison with test experiments. The implementation of the final solution to check the integrability of the semi-active cushion is required.

This technology holds great promise for potential applications to other vehicle seats.

Acknowledgements
The author would like to thank to the supervisors, Professor Afzal Suleman, who provided the opportunity to work in Centre for Aerospace Research and Eng.Amin Fereidooni, for their assistance and support; to NRC and University of Victoria - Canada, for having welcomed me and allowing me to perform this research; to all the members of CfAR, colleagues and professors who helped me to surpass my limits. A special word to Dr. Luis Falcão da Luz for all his knowledge and guidance and, last but not least, I would like to thank all friends and family for the unconditional support throughout this journey.

References

[1] L. Chen, X. Gong, and W. Li. Microstructures and viscoelastic properties of anisotropic magnetorheological elastomers. *Smart Materials and Structures*, 16(6):2645, 2007.

[2] COMSOL. AC/DC Module–user's guide. *COMSOL*, 5:300, 2014.

[3] M. J. Craft, M. Ahmadian, A. Farjoud, W. C. Burke, and C. Nagode. Force characteristics of a modular squeeze mode magneto-rheological element. Active and passive smart structures and integrated systems 2010. In *Proceedings of the SPIE*, volume 7643, page 13, 2010.

[4] K. Deb. *Optimization for engineering design: Algorithms and examples.* PHI Learning Pvt. Ltd., 2012. ISBN 978-8120309432.

[5] W. Li and X. Zhang. Research and applications of MR elastomers. *Recent Patents on Mechanical Engineering*, 1(3):161–166, 2008.

[6] LORD. Technical data - MRF-140CG. *LORD Corporation*, 2008.

[7] B. Mazlan and S. Amri. *The behaviour of magnetorheological fluids in squeeze mode.* PhD thesis, Dublin City University, 2008.

[8] D. F. Shanahan and T. Reading. Helicopter pilot back pain: a preliminary study. *Aviation, space, and environmental medicine*, 55(2):117–121, 1984.

[9] J. Wang and G. Meng. Magnetorheological fluid devices: principles, characteristics and applications in mechanical engineering. *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials Design and Applications*, 215(3):165–174, 2001.

[10] X.-J. Zhang, A. Farjoud, M. Ahmadian, K.-H. Guo, and M. Craft. Dynamic testing and modeling of an mr squeeze mount. *Journal of Intelligent Material Systems and Structures*, 22:1717–1728, 2011.