Magnetorheological Fluid Application to Smart Helmet Project

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Analytical Analysis

Team: C4
Name: Smart Helmet

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1 BACKGROUND

1.1 Introduction

One aspect of the smart helmet project consists of improving the safety of football helmets by changing the padding that is currently used. One way to improve the protection of the padding is to absorb more forces on impact by increasing the time of impact. Magnetorheological (MR) fluid is being considered to use as a padding for the project due to its controllable yield stress. A magnetic field is used to increase or decrease the yield stress of the fluid. The magnetic field is able to control the yield stress because this MR fluid is a mixture of particles of iron in a carrier fluid. MR fluids are applied in three different modes, valve mode, shear mode, and squeeze mode. Valve mode is used for applications where there is a pressure applied on the one end of the MR fluid and the variable yield stress is used to resist the flow of the MR fluid. Shear mode is when the MR fluid is placed between a fixed surface and a moving surface and the variable yield stress is used to resist the force applied to the moveable surface. The least researched mode is the squeeze mode where the layout is similar to shear except the force is applied perpendicular to the moveable surface.

1.2 Problem Definition

This analytical analysis communicates the research done on applications of the MR fluid to the project. It will also be analyzing the feasibility to the project based on the customer requirement relating to keeping the weight of the helmet similar to the weight of the current helmets which are around four pounds. The feasibility will be analyzed by the calculation of the factor of safety of implementing this fluid into the design.

2 ASSUMPTIONS

2.1 Values

This analytical report will use equations researched to evaluate the feasibility of implementing the fluid to the project. Due to the inability to analyze all the variables of the MR fluid there are assumptions that are made to simplify calculations and be able to focus on the variables being analyzed. Due to wanting to minimize the weight addition to the helmet, MRX-126PD is the commercial MR fluid being analyzed for its properties since it had the lowest densities of the commercial fluids while maintaining its controllability. The density of this fluid is 2.66 g/mL which is 2660 kg/m^3, the percent Iron by volume is 26%, and the carrier fluid used is Hydrocarbon oil. A typical football helmet weighs around four to six pounds which is about one and a half to three kilograms. Carbon Kevlar is the material used for the shell of current helmets to reduce the chances of the brain hitting the skull and causing a concussion while also reducing the weight of the helmet. A mass of half a kilogram is assumed for the calculations for the volume based on mass of current carbon Kevlar shells. Other electronics are being implemented into the project for the sensors and magnetic field generation, a mass of 0.3 kilograms is assumed for those electronics.

2.2 Equations and Variables

The first equation used to analyze the MR fluid is equation 1 which is calculating the volume of MR fluid that can be applied to the helmet based on the assumed variables above.

$$V=m/\rho \tag{1}$$

The volume of MR fluid is V, the mass of fluid available is m, and the density of the MR fluid is ρ. Pictured below in figure 1.3 is the plot of the range of volumes of fluid based on the range of helmet masses wanted. The plot is useful for the client to choose a desired mass for the helmet and get a volume of fluid to apply to the project. The equations below are used to analyze the feasibility and factor of safety of implementing MR fluid into the project. Bingham's plastic equation 2 of materials that behave like a rigid body for low stresses but flows as a fluid for high stresses help in understanding the behavior of MR fluids [1].

$$\tau = \tau y(H) + \eta\gamma \tag{2}$$

The stresses that are being applied to the fluid is τ, the yield stress of the fluid is τy, H is the magnetic field applied to the fluid, $\eta$is the viscosity of the fluid with no applied field, γ is the fluid shear rate. A plot of the yield stress vs. the applied magnetic field is shown below in figure 1.2. The volume of MR fluid needed for the application can be calculated with equation 3.

$$V=k(\eta/(\tau\text{^}2))\lambda W_m \tag{3}$$

The active volume V can be calculated using the above equation where λ is the desired control ratio, k is a constant that is equal to one for direct shear, W_m is the controllable mechanical power. The gap between the surfaces that border the MR fluid can be calculated with equation 4 below [2].

$$g=(\eta/\tau)\lambda S \tag{4}$$

The gap is noted by the variable g, S is the speed of the moveable surface. To apply this equation to the smart helmet project, the speed of the surface will need to be measured using sensors on the surface. The speed of the moveable surface is also used to calculate the controllable mechanical work in equation 5.

$$W_m=F\tau S \tag{5}$$

Mechanical power is a function of the force due to shear $F\tau$. The factor of safety of implementing MR fluid into the design can be calculated using the force of failure F_f divided by the force allowed F_a shown in equation 6.

$$FOS=F_f/F_a \tag{6}$$

The maximum threshold force before the player experiences brain injury is about 490 N. Using the force from the maximum yield stress of the MR fluid as about 4545 N, the FOS value is about 9.

3 PHYSICAL MODELING

Using the equations above, the physical model can be generated with dimensions of volume and the distance between the surfaces bordering the MR fluid. Due to there being numerous dependent variables and little independent variables it is difficult to isolate the exact dimensions needed to construct a model for the desired design of implementing the MR fluid. Figure 1.1 is a model depicting the known modeling factors that are necessary based on research found in [3]. The black portions in the model below represent the current foam used in helmet padding, the hatched grey portion represent the surfaces bounding the MR fluid, and the MR fluid is the light gray section. This model represents the squeeze mode application of the fluid where the surfaces bound the top and bottom of the fluid and the foam surrounding the fluid allows for the fluid to deform to the sides during impact. More research is necessary for calculating the exact dimensions of the model but this model contains the characteristics needed to apply the MR fluid.

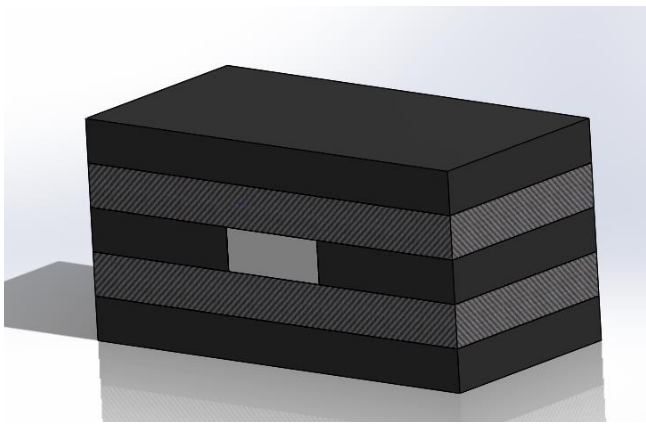

Figure 1.1: Cross Section of MR Fluid Implemented in Padding

4 DIAGRAMS

A plot of the yield stress of the MR fluid vs the applied magnetic field in figure 1.2 was constructed by [4] and is useful for understanding the magnetic field that needs to be generated in order to get the yield stress necessary for an incoming collision between players. The top line represents the MRX-126PD commercial fluid chosen for the analysis.

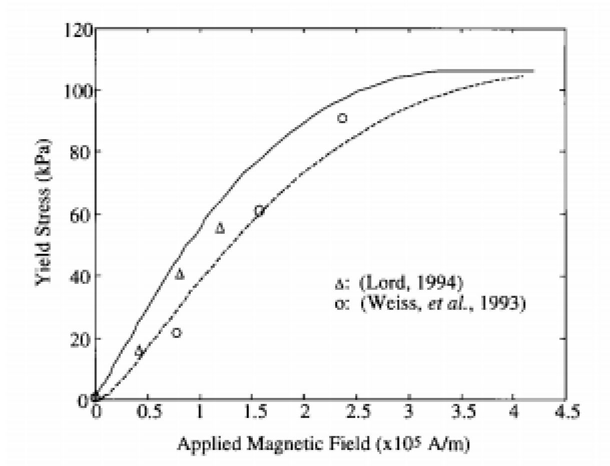

Figure 1.2: Yield Stress vs. Applied Field

The volume allowed for the project based off the customer requirement values of weight is depicted below in figure 1.3. This plot was requested from the client to gain a better understanding of the constraints of the project in implementing MR fluid into the design.

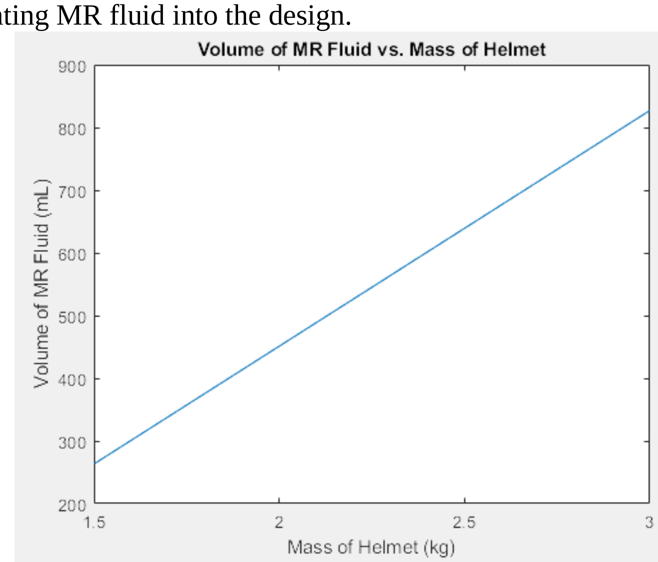

Figure 1.3: Volume of MR Fluid vs. Mass of Helmet

Three different modes of application of the MR fluid are shown in figures 1.4-1.6. These diagrams show that the mode that is similar to the smart helmet project is the squeeze mode because the forces exerted on the helmet are perpendicular to the surface of the helmet.

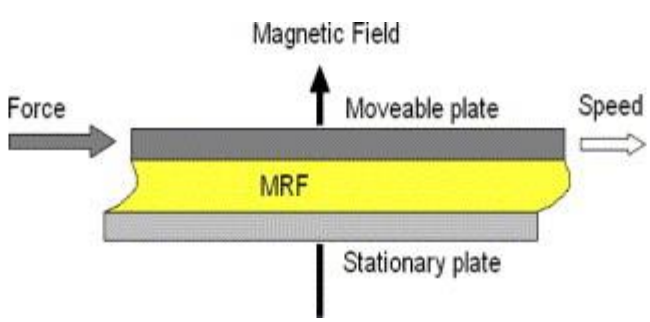

Figure 1.4: Shear Mode Diagram

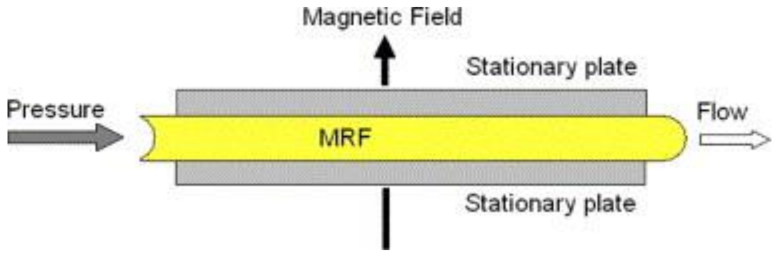

Figure 1.5: Valve Mode Diagram

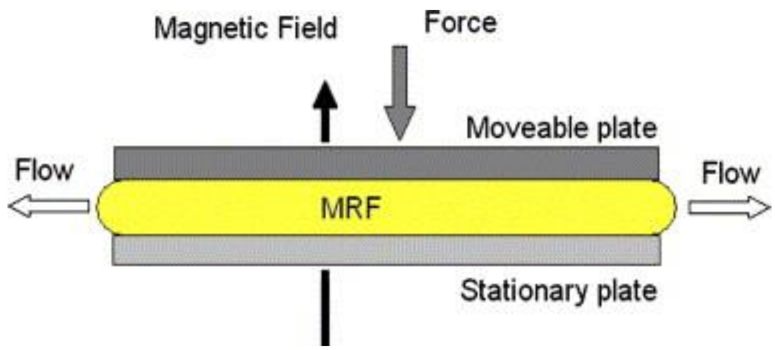

Figure 1.6: Squeeze Mode Diagram

5 CONCLUSIONS

This analysis is applicable to the smart helmet project because it evaluates the feasibility of implementing MR fluid as a smart padding for football helmets. The volume allowed was calculated based off of requirements of the client. Research on ways to apply the MR fluid was found in the analysis but exact dimensions weren't able to be calculated due to the numerous dependent variables in the equations found. In order to get exact dimensions for the MR fluid application, more research and testing would need to be performed to define some of the variables and isolate the dimensional variables. The factor of safety was estimated and although it is higher than most engineering factors of safety for machines and other designs, a higher factor of safety is needed for this project due to the fact that a parameter for the project is to protect the human brain. To implement MR fluid into the smart helmet project, testing would need to be done for the control ratio and mechanical power in order to be able to calculate dimensions. After analyzing the MR fluid and judging by the time constraint of the project, this material doesn't seem feasible for the smart helmet capstone project but could possibly be useful for other dampening applications where weight and time of the project isn't a constraint.

6 REFERENCES

[1] J. D. Carlson, "Magnelok technology: a complement to magnetorheological fluids," *Smart Structures and Materials 2004: Industrial and Commercial Applications of Smart Structures Technologies*, 2004.

[2] R. Stanway, J. L. Sproston, and A. K. El-Wahed, "Applications of electro-rheological fluids in vibration control: a survey," Smart Materials and Structures, vol. 5, no. 4, pp. 464–482, Jan. 1996.

[3] E. Nowiński, "The Lubricity and Rheological Properties of Magnetorheological Fluids," *Journal of KONBiN*, vol. 39, no. 1, pp. 141–158, Jan. 2016.

[4] J. Carlson and M. R. Jolly, "MR fluid, foam and elastomer devices," *Mechatronics*, vol. 10, no. 4-5, pp. 555–569, 2000.

[5] Jolly, M., Carlson, J. and Muñoz, B. (1996). A model of the behavior of magnetorheological materials. *Smart Materials and Structures*, 5(5), pp.607-614.

7 APPENDICES

7.1 Appendix A: Matlab Code

```
%Race Oshiro
clear; clc; close all;

%Calculations
rho_MR=2660;   %kg/m^3
max_mass=1.5:0.1:3;  %kg
shell_mass=0.5; %kg
electronics_mass=0.3; %kg
mass_available=max_mass-(shell_mass+electronics_mass);
vmax=(mass_available/rho_MR)*1000000; %mL

%plot
plot(max_mass,vmax)
grid on;
xlabel('Mass of Helmet (kg)')
ylabel('Volume of MR Fluid (mL)')
title('Volume of MR Fluid vs. Mass of Helmet')
```