Design and analysis of a magneto-rheological damper for an all terrain vehicle

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Abstract- A shock absorber design intended to replace the existing conventional shock absorber with a controllable system using a Magneto-rheological damper is introduced for an All Terrain Vehicle (ATV) that was designed for Baja SAE competitions. Suspensions are a vital part of an All Terrain Vehicles as it endures various surfaces and requires utmost attention while designing. COMSOL multi-physics software is used for applications that have coupled physics problems and is a unique tool that is used for the designing and analysis phase of the Magneto-rheological damper for the considered application and the model is optimized based on Taguchi using DOE software. The magneto-rheological damper is designed to maximize the damping force with the measured geometric constraints for the All Terrain Vehicle.

Keywords- All Terrain Vehicle (ATV), COMSOL, Magneto-rheological damper, damping force, Smart-materials.

1. Introduction

The BAJA SAE Series® is an event which originated in the name of Mini - BAJA, in the year 1976 at University of Carolina, which then spread across various countries including India. This competition allows groups of college undergraduates to design, fabricate and validate an all terrain vehicle to be tested in a series of events that test the vehicle for its engineering aspects which includes gradability, speed, acceleration and maneuverability and a durability test [1]. The shock absorber plays a vital role in the various events conducted which tests the vehicle, making a better design absolutely necessary. Semi-active vibration control used in automotive suspensions has been accepted by researchers as a new era in design engineering. This is due to the presence of smart materials in these suspensions; these smart materials that are used have an important contribution to this due to its low response time for low powered actuation inputs. These actuation inputs may be in any of the various forms of energy which includes magnetic energy. Magneto-rheological fluids are one of such smart materials, whose elastic, plastic and viscous properties can be controlled using the magnetic energy as input for actuation. This change in properties which requires very less response time is considerable and reversible [2] making it highly reliable for control valve, brake, and damping applications. This makes it the best candidate for damping applications used in the all terrain vehicle. A magneto-rheological damper design requires three basic components, namely, a piston cylinder assembly, an electromagnetic coil, and magneto-rheological fluid flow volume [6, 7]. This paper, aims to design an innovative magneto-rheological damper model for an all terrain vehicle and conduct analysis based on finite element analysis. COMSOL Multi-physics is a finite element analysis software package used for a wide range of physics and engineering applications which allows for coupled physics analysis making it most suitable for the problem at hand [11]. Therefore, the best platform to model and analyze this design is COMSOL Multi-physics; moreover, FEA results are in par with the experimental results as per Ashwini Kumar and Mangal [4,5]. The analysis and design is done on COMSOL platform making it an innovative work with regards to the study conducted by Aswini Kumar and Mangal, moreover the simulation and analysis for optimization and design were conducted on Minitab® 17.1.0 and COMSOL Multi-physics 5.0 software respectively. L. Zheng and Y. Li also conducted an electromagnetic analysis without an experimental validation for an MR damper based model for an ATV in 2009, which focused on the static performance of an MR damper and intended to
improve upon that [8]. This paper focuses on considering and improving the damping force for the all terrain vehicle used in the BAJA SAE© competitions by the students of Amrita university in the year 2016.

1.1. Smart Materials.

Smart materials are specifically synthesized materials which have one or more properties that which exist as a direct or indirect output of an external stimulus. Piezoelectric, Shape memory alloys, Magnetostrictive, Ferro-fluids etc. are some of the few major types of smart materials that exist in the current scenario. Magneto-rheological fluids are an extension of the existing Ferro-fluids.

1.2. Magneto-rheological Fluids

A magneto-rheological fluid is a type of smart fluid which when subjected to a magnetic field greatly increases its apparent viscosity, to the point of becoming a visco-elastic solid. It was discovered by Jacob Rabinow at the US National Bureau of Standard in 1948. Magnetic field intensity controls the yield stress of this liquid in its visco-elastic solid state, which can be used then for various applications. The idea is to be able to manipulate the magnetic field intensity in order to obtain a required yield stress value; this is usually managed using an electromagnet making magneto-rheological fluids appropriate for control based application. The magnetic particles, which are typically micrometer or nanometer scale spheres or ellipsoids, are suspended within the carrier oil and distributed randomly in suspension under normal circumstances, however, when a magnetic field is applied, however, the microscopic particles align themselves along the lines of magnetic flux.

2. Methodology

All Terrain Vehicles (ATV), as the name suggests it denotes a vehicle which can be used in all terrains, namely, slopes hill climbs, bumps, rugged roads etc. Baja SAE is an event which allows students to design, build, and race an off-road style vehicle. The students compete against other engineering students from around the world. The vehicle must have 4 open wheels and must allow for a single driver to operate the vehicle safely. The ATV used for Baja SAE competitions are under strict scrutiny over the amount of money that can be spent on it. A suspension system on a vehicle separates the body of the car and the driver from the road or terrain on which the automobile runs on. The system is made up of springs and shocks which join the chassis and the tires in the automobile. The tire is joined to the automobile by using linkages which act as rigid body supports for this purpose. The purpose of such a system is to maintain the contact between the road and the wheel all the time and also intends to keep the tires contacted at an optimal position to avoid loses in traction and excessive wear on the tires. Considering various options it has become quite clear that the most important design and part goes to that which controls the vibrations caused by the irregular terrain on which the competitions take place. The heavy vibrations usually lead to eccentricities within the engine system, discomfort to the driver, instability of the vehicle, and may even cause engine failure. Therefore, it becomes quite clear that the suspensions play an integral role in the safe design of the ATV. In this the decisive factor lies in the damping effect induced by the damper placed alongside the spring. To design this required damping effect the most viable option would be to substitute an existing hydraulic damper with a magneto-rheological damper.

2.1. Dimensions

The geometry of the system is considered based on the constraints and dimensions are measured from an All Terrain Vehicle designed by the students of Amrita University which participated in the BAJA SAE competition in the year 2016. The fabricated automotive used the FOX FLOAT SERIES 3 suspension for the competition. Based on the dimensions measured from the automotive body, the design for a magneto-rheological damper was done as per the model depicted in figure 1 [4]. The design constraints measured from the ATV designed were done for the front suspension and the maximum distance between the chassis and wheel contact were measured as 470 mm, the design constraints were extended to identifying the maximum diameter for the cylinder outer casing calculated as 65mm. The dimensions regarding the coil diameter (D), cylinder wall thickness (t), Piston radius (r), Pole length (L), Coil length (l), fluid gap (h) and radial distance from rod to coil (H), are calculated and selected from previous literature and are depicted in Table 1. From the considered
constraints a new model for a MR damper to replace the conventional damper was mooted. Modeling of magneto-rheological damper depends mostly on the development of the piston head where the coil is placed, and damping is controlled.

Figure 1: Magneto-rheological damper schematic

The dimensions for the design of the magneto-rheological damper for the all terrain vehicle are as shown in table 1.

Table 1: Dimensions for design of Magneto-rheological damper

| SL. NO | NAME | EXPRESSION(mm) | DESCRIPTION                  |
|--------|------|----------------|-------------------------------|
| 1      | R    | 6              | piston rod radius            |
| 2      | H    | 10             | radial distance from piston rod to coil width |
| 3      | T    | 7              | thickness of cylinder        |
| 4      | R    | 23             | piston radius                |
| 5      | L    | 22             | distance between poles       |
| 6      | L    | 28             | pole length                  |
| 7      | H    | 0.7            | fluid gap                    |
| 8      | D    | 7              | Coil width                   |

2.2. Selection of material

Considering [4] the geometry defined the material assigned for the 2D model is mainly dependent on the magnetic relative permeability and permittivity values of the materials in close proximity with the fluid. The materials that have high relative permeability are required to generate a distributed flux range in order to generate a more uniform damping force. Considering this AISI 1010 is selected as the material which has a relative permeability of approximately 500. Copper is considered as a conductive material and is selected along the coil geometry. The analysis is dependant only on the gap of the fluid along the damper piston periphery and therefore the fluid is assigned to the geometry that lies in between the piston head and outer cylinder. The comparison for MRF 132 DG and MRF 122 EG is done so that the selection of fluid can be specialized. Materials assigned to each domain in the COMSOL software after strict and thorough literature study, as shown in figure 2.

Table 2: Material selection

| SL. NO | GEOMETRY SELECTED    | MATERIAL ASSIGNED      |
|--------|----------------------|------------------------|
| 1      | Piston Head          | AISI 1010              |
| 2      | Cylinder Casing      | AISI 1010              |
| 3      | Fluid Gap            | MRF 122 EG, MRF 132 DG |
| 4      | Coil                 | Copper coil            |
2.3. Mathematical Fluid Model

Bingham plastic model is considered as the most basic of models considered for a non-Newtonian fluid. The model approximates that, the viscosity of the fluid ($\mu$) is constant and remains so, and the threshold shear stress value $\tau_0$ has to be overcome in order to begin the flowing of the fluid.

$$\tau = \tau_0 + \mu \left( \frac{du}{dz} \right)$$  \hspace{1cm} (1.1)

Where, $\mu$ is the viscosity of the fluid, $\tau_0$ is the yields stress and $\frac{du}{dz}$ is the velocity gradient. The threshold yield stress and viscosity are the main values of consideration. Magneto-rheological fluid is a shear thinning fluid and the main disadvantage of the Bingham plastic fluid is that it does not account for this shear thinning property. Neglecting these effects will result in variation in the damping force calculated. Bingham Plastic model shows satisfactory results even though they omit the shear thinning considerations.

3. Optimization

For the optimization procedure, it is necessary to choose the parameters that are most influential for the required operation, and for maximizing the damping force for the designed model. Considering various studies and literatures it became evident that the four major parameters affect the damping force, which are, Pole length ($L_p$), Coil width ($D$), Fluid gap ($d$) and cylinder outer wall thickness ($t$). Following the optimization method conducted by Ashwini Kumar and Mangal [5], the array used to conduct optimization was selected as $L_{16}$ array from the Taguchi mixed level design as shown in Design of experiments. The FEM results obtained are in par with the experimental results obtained [5], and therefore experimentation is avoided considering the cost required for fabricating the models required for optimization. For this study of optimization, the maximum current considered from a battery source is restricted to 2A and sixteen models are designed using COMSOL Multiphysics platform. Table 1 depicts the damping force values for the designed models. The Signal to Noise ratio curve observed from the Taguchi analysis suggests modeling the optimized parameters based on the maximum values observed from the Figure 3.
Table 3: L16 array with input and response parameter.

| COIL WIDTH, (D), mm | FLUID GAP, (d), mm | THICKNESS, (t), mm | POLE LENGTH, (L), mm | DAMPING FORCE, (FD), mm |
|---------------------|-------------------|-------------------|-------------------|-------------------|
| 5                   | 0.7               | 5                 | 25                | 7965.8            |
| 5                   | 0.8               | 6                 | 26                | 7248.9            |
| 5                   | 0.9               | 7                 | 27                | 6691.4            |
| 5                   | 1.0               | 8                 | 28                | 6246.0            |
| 6                   | 0.7               | 6                 | 27                | 8603.0            |
| 6                   | 0.8               | 5                 | 28                | 7806.4            |
| 6                   | 0.9               | 8                 | 25                | 6195.8            |
| 6                   | 1.0               | 7                 | 26                | 5799.9            |
| 7                   | 0.7               | 7                 | 28                | 8921.6            |
| 7                   | 0.8               | 8                 | 27                | 7527.6            |
| 7                   | 0.9               | 5                 | 26                | 6444.3            |
| 7                   | 1.0               | 6                 | 25                | 5577.0            |
| 8                   | 0.7               | 8                 | 26                | 8283.3            |
| 8                   | 0.8               | 7                 | 25                | 6970.1            |
| 8                   | 0.9               | 6                 | 28                | 6936.9            |
| 8                   | 1.0               | 5                 | 27                | 6020.2            |

The optimized values came out as Fluid gap = 0.7mm, Pole length = 28mm, Coil width = 7mm, Cylinder thickness = 7mm. The model generated for the optimization process is as shown in Table 3. The variation of damping force with current is shown in Table 4.

Figure 3: Graph for Signal to Noise ratio for critical parameters.

4. Analysis

As per the proposed scheme, a 2D-axisymmetric model for the magneto-rheological damper is modeled using the software based on the dimensions from Table 1. Materials are assigned to each component designed to specify boundary and define properties. A MRF 132 DG is used as the electromagnetic fluids and properties are based on graphs and values selected from Lord Corporation.
These values are used to define the material characteristics and properties in order to introduce a new material. The problem uses multiphysics between the fluid layer interaction and electromagnetic behavior of the fluid. AC/DC and CFD modules are used to identify the viscous damping force and shear force due to energizing of the liquid. The Bingham plastic model of plates [3] divides the damping force $F_D$ into a yield stress, $F_Y$ and a viscosity induced component, $F_\eta$.

The equations used to calculate damping force which is used as an input to the software is as follows:

$$F_D = F_Y + F_\eta$$  \(1.2\)

$$F_Y = \left( 2.07 + \frac{12Q\eta}{(12Q\eta + 0.4wh^2\tau_Y)} \right) \frac{\tau_Y\ln\eta(v)A_p}{h}$$  \(1.3\)

$$F_\eta = \left( 1 + \frac{wh\nu}{2Q} \right) \frac{12Q\tau_A p}{wh^3}$$  \(1.4\)

Ampere circuital law is defined over the system and the fluid respectively as the fluid requires specific inputs including the H-B curve [16]. Yield stress depending on the magnetic field is defined as a variable using an interpolation curve generated from the MR fluid properties available from the Lord MR Data sheet. The damping force equation requires yield stress values and dynamic viscosity values. Magnetic insulation is defined around the periphery of the model defining the outer boundary of the system to be solved. A Multi-Turn coil is specified at the coil geometry with AWG 32 for 500 turns. CFD module provides an input for Laminar flow with a Non-Newtonian Carreau model which is defined over the fluid geometry. The shear rate- shear stress dependence graph available from the Lord MR Data sheet for 132 DG is also defined as an interpolation curve as shown in Figure 5 (a). Viscous and shear forces provide to the damping force making it necessary to identify both parameters to use them as inputs for the software.

![Figure 4: MR Fluid properties used as input for COMSOL Software (a) Shear stress vs Shear rate graph; (b) Yield stress vs Magnetic Field graph](image-url)
4.1. Modeling

Axial symmetry is provided along the axis of the system to define the total 3D geometry of the system. Physics controlled mesh is enabled to give a better meshing and convergence of the result. From the dimensions acquired and the data available from Lord MR Data sheet [9] the model is designed in the COMSOL platform and is meshed using extra fine meshing following the 2D model depicted in Figure 5. The whole meshed structure consists of 21181 elements which include both quadrilateral and triangular elements. Quadrilateral elements are observed over the multiphysics zone, that is, the fluid gap interface.

4.2. Analysis of designed model

Based on the designed model the analysis is conducted in the COMSOL interface using a stationary study as to evaluate the damping force corresponding to current input, as to identify the maximum value of damping force generated. The COMSOL software analyses the design and materials specified to the corresponding physics enabled to generate a series of outputs from which the magnetic flux and field densities are interpolated to identify required parametric variables [10]. The magnetic field value interpolates to give the yield stress value of the MR fluid. The force required for damping is calculated using the derived value of surface average along the fluid gap to give an average damping force along the piston periphery. The maximum Magnetic Flux density averaged along the fluid gap is determined to be 0.863 T. Maximum Magnetic Flux Density is observed at the coil metal interface; this is due to high permeability of the material used for the piston which has no influence on the damping force. A high permeability material is essential to attain maximum magnetic field, but the material should also be magnetized and demagnetized effectively without hysteresis losses. Magnetic Field generated for corresponding magnetic flux density is depicted in Figure 6. The magnetic field magnetizes the fluid along the gap and depicts maximum magnetic field at the coil fluid interface. The derived value for average magnetic field along the fluid gap is observed as $2.949 \times 10^8$ A/m. The magnetic field induced in the fluid converts the fluid into a visco-elastic state which damps the piston.
4.3. Fluid selection

The equation for Damping force calculation is adopted into the software as a variable with input parameters calculated from within the outputs generated by the software. The damping force equation (1.2 - 1.4) is calculated as variables by the software generating outputs required for varying inputs. The result extends to the comparison of MRF 122 EG (Case I) and MRF 132 DG (Case II) for the optimized model. The calculated values of damping force for the two fluids for 0.5 A input current is depicted in figure 7.

Table 4: Variation of damping force for different fluids.

| SL. NO. | INPUT CURRENT | FLUID SELECTED | DAMPING FORCE – COMSOL (N) |
|---------|---------------|----------------|-----------------------------|
| 1       | 0.5 A         | MRF 132 DG     | 5396.7                      |
| 2       | 0.5 A         | MRF 122 EG     | 4200.0                      |

Figure 7: Simulation results of damping force along the fluid gap for (a) MRF 122 EG (b) 132 DG

From the damping force identified at 0.5 Ampere, it is clear that MRF 132 DG is the better fluid for the specified application. The damping force is maximized over the surface of the fluid away from the periphery of the coil as magnetic field is greater along the specified region. MRF 122 EG shows a lower value of damping force compared to MRF 132 DG for the same model with geometry defined per table 1.

5. Result and discussion

The magneto-rheological damper designed is considered and proposed as a replacement for the Fox float 3 series suspension damper used as the conventional model for the All Terrain Vehicle [12]. The magnetization of the fluid converts the viscous fluid into a visco-elastic solid with a considerable yield stress. The condition for actual usage of this system depends on the type of condition required, necessitating the usage of either a semi active or active damping system consisting of sensory and feedback details. This paper considers the replacement of an actual existing conventional damper with a magneto-rheological damper refraining from the sensory and actuation details and is regarding only the geometrical parameters. The analysis provides the values for magnetic field and magnetic flux for maximum current input, which are then used as inputs for the damping equation for the model proposed. The fluid is selected as MRF 132 DG as it shows better performance for maximizing damping force for the valve mode that is considered [13]. The variables used in COMSOL allow in defining various parameters required for the damping force model input. The equations 1.2 – 1.4 are used to evaluate the damping force directly from the COMSOL software by defining variables as a combination of the outputs obtained from the software. The post processor section allows us to alter the existing data set and expression from which we are able to select the variable used for damping force to give us a graphical representation of the variation of damping force along the fluid gap. For varying inputs of currents a time dependant study is required in which we provide current as a function...
of time and interpret the results by analyzing the surface average value from derived values along the fluid gap interface. The variation in damping force for input currents are denoted in Table 6. The variation for input current is shown from 0 to 2 A on a step of 0.5 A. Table 5 Shows the various presets of damping force for the fox float 3 series suspension. Comparing the tables 5 and 6 we are able to see that up to a preset value of 80 psi can be set which would show an equivalent damping force of 6232 N which can be achieved using 1 A current for the proposed model.

Table 5: Conventional Damping force values for fox float 3 series

| SL. NO | FOX FLOAT 3 SERIES PRESET | EQUIVALENT DAMPING FORCE (N) |
|--------|----------------------------|-------------------------------|
| 1      | 50                         | 3896.36                      |
| 2      | 60                         | 4676.29                      |
| 3      | 70                         | 5455.68                      |
| 4      | 80                         | 6232.2                       |

Figure 8: Damping Force calculated along the Fluid Gap

Table 6: Variation of damping force with input current

| CURRENT (Amp) | DAMPING FORCE –COMSOL (N) |
|---------------|---------------------------|
| 0.1           | 910.57                    |
| 0.5           | 5953.4                    |
| 1             | 6798.0                    |
| 1.5           | 6946.1                    |
| 2             | 7047.6                    |

The designed model at 2 A, gives a maximum averaged damping force of 7047.6 N. The Figure 8 shows the variation of damping force along the fluid for 2 A current. The maximum value of damping force is derived at fluid interface; as the coil’s relative permeability is considered as 1 and magnetic insulation is provided at the outer boundaries of the system, the fluid interface along the periphery of the coil shows reduced damping force. The figure 9 shows linear variation of damping force with the input current which is expected from the study.

Figure 9: Damping force variation with input current
6. Conclusion

The Magneto-rheological damper as per the proposed model is advantageous over the conventional damper due to constant or partial response for required damping as to constantly redefine its damping characteristics to adapt to the required damping force depending on its actuation. MRF 132 DG is a better fluid for the specified application compared to MRF 122 EG which was observed from the analysis. Based on the COMSOL model it is evident that the magneto-rheological damper can be employed in the existing system with actuation current derived from any power source connected to the system that can generate 0-2 Amperes of DC current. The MR damper has been optimized using Taguchi L16 OA and 16 models were analyzed using the COMSOL software, followed by the optimization using DOE. The conventional model for the fox float 3 series can be replaced for the required presets up to 90 psi which can be used for an ATV. The proposed damper model can be employed for the All Terrain Vehicle application that requires damping forces for a maximum of 7047.6 N.

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