Finite Element Analysis of Magneto-Rheological Damper

Ashwani Kumar[1] and S. K. Mangal[2*]
[1]Research Scholar, [2]Associate Professor,
Mechanical Engineering Department, PEC University of Technology, Chandigarh - 160 012, India
*Corresponding author e-mail: skmangal_pec@rediffmail.com

Abstract- In this paper, a finite element analysis of magneto-rheological fluid (mr) damper is presented. It is necessary to develop a fem model for calculation of damping force of a given mr damper. An axi-symmetric fem model is thus built on ansys platform to analyze and examine a prototype of the mr damper. In this paper, geometrical parameters and magnetic flux density at the clearance space of the damper are studied. The study has indicated that the fem modeling is effectively portraying the behavior of a mr damper and is adequate enough for estimation of the damping force, its control and design. The results obtained in this paper will be helpful to the future designers to predict the damping force of a given damper.

Keywords: Finite Element Model; MR damper; Axi-symmetric; Magnetic flux density.

I. INTRODUCTION

Magneto-rheological (MR) Damper is the most promising and up-coming area in automobile suspension protection field. These dampers normally use MR fluids to produce controllable damping coefficient [1]. The MR fluids are one of the smart materials which react to applied magnetic fields and undergo drastic & reversible changes in its rheological characteristics. The most interesting feature of the MR fluids, over the conventional fluids as used in hydraulic dampers, is its ability to change its viscosity (several orders of its magnitude) in a fraction of millisecond which mainly depends upon the applied magnetic field intensity. The discovery of the MR fluids is credited to Jacob Rabinow at the US National Bureau of Standard in 1948 [2]. A typical MR fluid is the suspension of micron sized ferromagnetic particles suspended in an appropriate carrier liquid such as mineral oil, synthetic oil etc, which when subjected to electric or magnetic fields, undergo changes in their mechanical characteristics, viscosity and stiffness most importantly. A variety of additives (stabilizers and surfactants) are also added in the MR fluid to prevent gravitational settling problem and also to promote a stable particles suspension which in-turn will enhance lubricity [3].

ANSYS is general purpose software which is universally accepted for Finite Element Analysis (FEA). The ANSYS is used to simulate interactions of all disciplines *i.e.* physics, structural, vibration, fluid dynamics, heat transfer and electromagnetic problems for engineer/scientist community. It also provides an access to virtually any field of engineering simulation that is mandatory in any design process. The ANSYS can also import data from other software *e.g.* Pro/Engineer, NASTRAN, IDEAS, AutoCAD etc. It also enables designers to build geometry with its preprocessing abilities. After defining the boundary conditions of a problem in terms of loads & displacement and carrying out the analysis, the ANSYS results can be viewed either in numerical or graphical form.

The main objective of this paper is to develop an FEA model of the MR damper while maintaining the maximum performance of the MR effect. The MR fluid dampers are semi-active control devices which can operate from the power of batteries alone [4]. These MR dampers are capable of generating the magnitude of damping force sufficient for large-scale applications, *e.g.* vehicle suspension systems, vehicle seat suspension, vibration control of railway bridges, seismic response, and landing gear. The performance of the MR damper is limited by the magnetic flux saturation phenomenon occurring in the magnetic circuit as well as the saturation yield shear stress of the MR fluid.

II. MODELING OF MR DAMPER

The primary thing in designing the MR damper is to decide the desired range of the damping force. Accordingly, the material for the various parts of the MR damper *e.g.* piston, cylinder, piston rod and MR fluid is selected. As the damping force in the device depends upon the magnetic field induced so the MR circuit must have a good magnetic performance. To achieve this, the cylinder and piston are preferably be made of magnetically soft materials. The meticulous literature survey has suggested that the low-carbon steel [5] works well for the good magnetic performance.

A. *Magnetic circuit design of the MR damper*

Based on the critical literature survey, the dimensions of the MR prototype damper, as listed in Table 1, are selected. The typical magnetic loop is shown in Fig. 1. In this Figure, h denotes the working clearance space between the piston & the cylinder and it is also known as MR fluid working gap. The R denotes the radius of the piston, L denotes the pole length, t denotes the thickness of the cylinder and r denotes the piston rod radius.

TABLE I DIMENSIONS OF PROTOTYPE MR DAMPER

No.	Parameter	Dimensions (mm)
1	Pole length(L)	23
2	Distance between the poles (ℓ)	22
3	Radius of the piston(R)	23
4	Piston rod radius(r)	06
5	Radial distance from piston rod to coil width (H)	07
6	Clearance space between piston and cylinder (h)	01
7	Thickness of the cylinder(t)	08

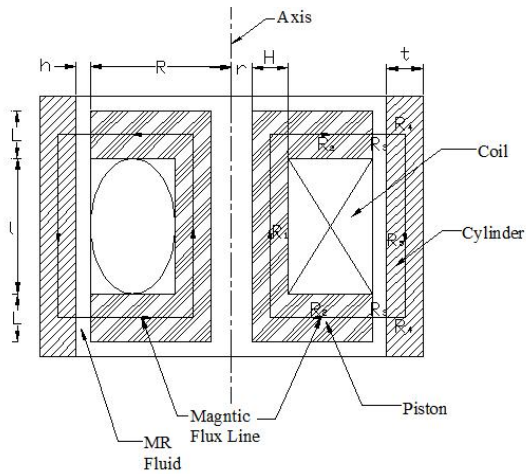

Fig. 1 Typical Magnetic circuit Loop of the designed MR damper

B. FEA Modeling of the MR Damper

Study of MR damping is a promising topic for the automotive industry particularly in the field of automobile suspension. A large number of researchers have begun their research activity on this topic with the help of Finite Element Method (FEM) as a tool for its modeling and designing of MR dampers. They have explored its modeling from different aspects of design. This has resulted different MR dampers designed in a variety of shapes, effective damping force range and working principles. The quasi-static laminar flow of the MR fluid is assumed inside the damper while designing the damper and also to determine the pressure gradient of the flow through it. The purpose of the Finite Element Analysis is to identify the saturation phenomenon occurring in the magnetic circuit. The damping force produced by the MR damper mainly depends on the magnetic field induced in the working fluid clearance space. The MR damper is a class of problem of an axi-symmetric solid subjected to an axi-symmetric loading and thus a 2-D FEM modeling is sufficient enough to analyze it (Fig. 2).

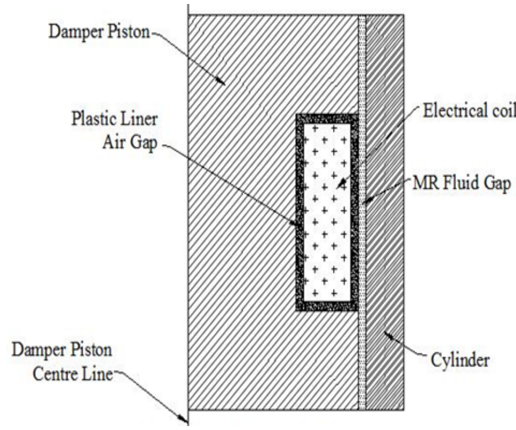

Fig. 2 2-D Axi-Symmetric Model of MR Damper in ANSYS

Following steps are generally used in the ANSYS for a static magnetic analysis of the MR damper:-

- Create the physics environment
- Build & mesh the model and assign physics attributes to each region within the model
- Apply boundary conditions and loads (excitation)
- Obtain the solution
- Review the results

C. Assumptions and Restrictions

In the 2-D axis-symmetric model, there are assumptions and restrictions which are used to create the model. The assumptions made for this study are as under:-

- The area of the element must be positive
- The element must lie in a global X-Y plane
- Y-axis must be the axis of symmetry for axis symmetric analysis
- An axi-symmetric structure should be modeled in the +X quadrants
- The element used in the model has only magnetic and electric field capability
- The element does not have structural, thermal or piezoelectric capability
- The only allowable material properties are the magnetic and electric properties (μ_o, μ_x)

The piston, MR fluid in the clearance space and the cylinder are assumed to be stationary component and completes the magnetic circuit. In the ANSYS modeling, 350 turns (Fig. 3) for the electromagnetic coil are used to calculate the magnetic flux density. The electrical current is varied, in the coil, to get the corresponding value of the magnetic flux density. In this modeling, the piston and cylinder material is taken as steel having relative permeability 2000 while the relative permeability of electromagnetic coil is taken as 1. The relative permeability of the MR fluid is taken as 6. The Magnetic permeability of free space (μ_o) is taken as $4\pi \times 10^{-7}$ H/m.

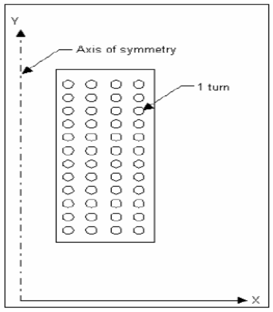

Fig. 3 Electrical Coil Cross Section

D.Element description

The ANSYS software includes a variety of elements in its library and one can choose any one of these elements to model the electromagnetic phenomena of a MR damper. From literature survey, it is decided to use PLANE13 element which is a 2-D quadrilateral coupled-field-solid element containing four nodes. It is shown in Fig. 4. The PLANE13 element has 2-D magnetic, thermal, electrical and piezoelectric field capability with limited coupling between the fields. The element also has nonlinear magnetic capability for modeling of the B-H curves

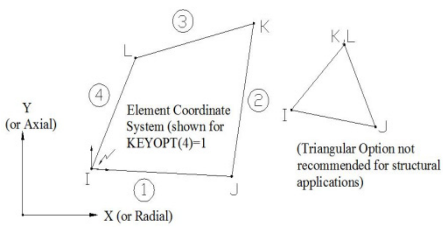

Fig. 4 PLANE13 Element description

E. Input Data

The geometry, node locations and the coordinate system for the Plane 13 element are shown in Fig. 4. The element input includes coordinates of four nodes, magnetic and electrical properties wherever required. The metric units are used in the analysis. The relative permeability for each material is also specified by the μ_x. For an electromagnetic static analysis through ANSYS, one needs to give DC current as an input to the software. This is given in the form of current density (J) which can be given as:

$$J = \frac{NI}{A_e} \qquad (1)$$

Where J is the current density, N is numbers of turns, I is the applied current and A_e is the electrical coil cross-sectional area.

F.Output Data

The output solution associated with the problem is in the following forms:

- Nodal degrees of freedom included in the overall nodal solution.
- Additional element output *e.g.* electromagnetic components.

The element output directions are parallel to the element coordinate system. In the ANSYS, one defines the magnetic flux density as B_x and B_y along the x and y axes respectively. The term B_{sum} is the vector sum of these magnetic flux densities and is given as

$$B_{SUM} = \sqrt{B_X^2 + B_Y^2} \qquad (2)$$

G.Element Solution

Figure 5 shows the results of ANSYS analysis in the form of 2-D flux lines around the electromagnetic coil.

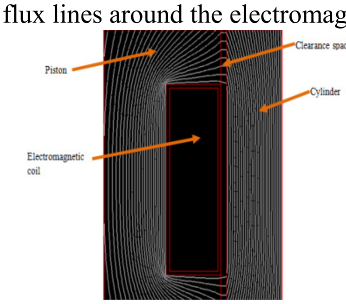

Fig. 5 2-D flux lines around the electromagnetic coil of MR damper prototype

Figure 6 (a) shows an axi-symmetric 2-D elemental solution of the magnetic induction distribution while the Fig. 6 (b) shows the spatial view of the same. The flux density around the electromagnetic coil as vectors is shown in Fig. 7.

The magnetic flux density data at various nodes of the proposed model are thus obtained by the ANSYS software. From the data, magnetic flux densities *i.e.* B_{SUM} values at the nodes lying at the clearance space of the piston and cylinder are noted down. The overall average values of the magnetic flux densities are taken at 0.1 – 0.7 A current in a step of 0.1 A current which are shown in Table 2.

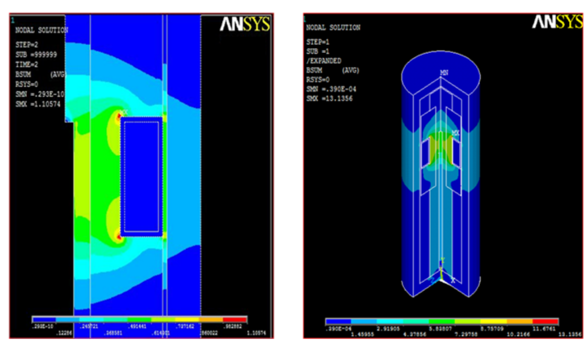

Fig. 6 Elemental solution of the magnetic induction distribution (a) 2-D solution and (b) A spatial view

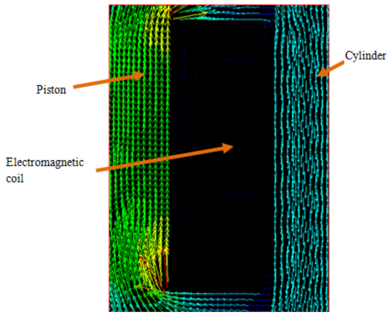

Fig. 7 Flux Density shown around electromagnetic coil as vectors

TABLE II MAGNETIC FLUX DENSITY OF FEM MODEL OF MR DAMPER PROTOTYPE

Current (A)	Magnetic Flux Density- FEM Model (Tesla)
0.1	0.053
0.2	0.106
0.3	0.158
0.4	0.211
0.5	0.264
0.6	0.317
0.7	0.370

III. CALCULATION OF THE TOTAL DAMPING FORCE

The damping force for the FEM modeling is calculated using the magnetic flux density as determined at different current levels (Table 2). The yield shear stress (τ_y) relationship with the magnetic flux density (B) for MR fluid MRF-122EG of Lord Corp. [6] is shown in Fig. 10. For the magnetic flux densities computed in the previous section, the corresponding yield shear stress is found by using Fig. 10. This can then be substituted in the following equations to get the total damping force.

According to the plate model of Bingham plastic model, [7 & 8], the damping force, F_D, can be divided into an induced yield stress F_τ and viscous F_η components *i.e.*:

$$F_D = F_\tau + F_\eta$$

$$= \left(2.07 + \frac{12Q\eta}{12Q\eta + 0.4wh^2\tau_y}\right)\frac{\tau_y L A_p}{h}\mathrm{sgn}(v) + \left(1 + \frac{whv}{2Q}\right)\frac{12\eta Q L_t A_p}{wh^3} \quad (3)$$

Where $Q = A_p \times v$ (4)

$$A_p = \frac{\pi}{4}\left(D^2 - d_o^2\right) \quad (5)$$

where Q is the volumetric flow rate, A_p is the effective cross-sectional area of piston, D is the diameter of the piston, d_0 is the diameter of the piston rod, v is the piston velocity, τ_y is the yield shear strength of the MR fluid, η is the off-state (no magnetic field) viscosity of the MR fluid, L is the effective axial pole length, h is the gap between piston and cylinder, L_t is the total axial pole length, w is the mean circumference of the damper's annular flow path, *sgn(v)* is used to consider the reciprocating motion of the piston.

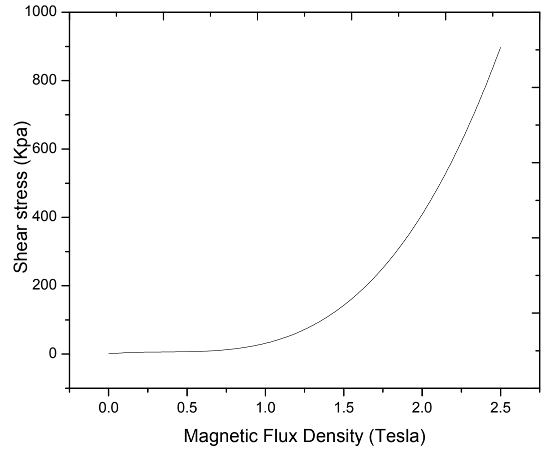

Fig. 8 Shear stress vs Magnetic Flux Density

The literature [9 & 10] states that some frictional force (F_f) exists in the MR devices when in operation and thus it need to be accounted for the analysis. Thus, the total damping force is the sum of F_τ, F_η and F_f and is given as

$$F_D = F_\tau + F_\eta + F_f \quad (6)$$

where F_τ is the force component due to induced yield stress, F_η is the viscous force component and F_f is the friction force component. The total damping force is then calculated by using Eq. (6) for the model and its computed values are shown in Table 4 while the Fig. 11 shows the damping force qualitatively at various current levels.

TABLE IV DAMPING FORCES FOR THE ANALYTICAL MODELING

Current (A)	Damping force (N)
0.10	206.38
0.20	303.20
0.30	371.95
0.40	418.33
0.50	448.02
0.60	466.67
0.70	480.06

The Table 4 shows that the damping force increases from 200 N to 480 N with the increase in the magnetic field strength which is achieved by changing the current in the electromagnetic coil. This shows that the damping force can be controlled according to the need/practical problem by just varying the current.

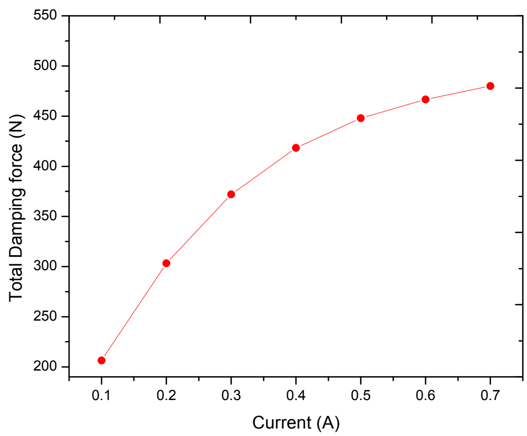

Fig. 9 Damping Force of FEM modeling

IV. CONCLUSION

In this study axi-symmetric model of the MR is developed using ANSYS. Due to the high cost of MR dampers prototyping, the simulation methodology like FEM can be a critical alternative. A numerical modeling via FEM makes us to see the performance variation by changing various parameters of a design at a very easy manner. Thus, one can improve the performance of process *i.e.* MR damper.

In this paper, FEM modeling of the MR damper is done to calculate its damping force. In this an axi-symmetric model of a MR damper is prepared and the magnetic flux density is generated along the MR fluid gap. This allows the designer to obtain the desired force range and is able to predict the maximum damping force for the damper. In the damper, the fluid is forced to flow through a magnetically clearance space between the cylinder and piston. This forced flow of the fluid generates the more damping force, which can be controlled by varying the strength of the applied magnetic field. Thus, an FEM model is developed based on the various geometrical parameters of the MR dampers.

As the magnetic field can be generated with relatively low voltages, the MR dampers are most promising devices for automobiles vibration control. The results obtained in this paper will help the designers to create more efficient & reliable MR dampers. It will also help the designer to predict the damping force within the permissible error of engineering analysis with an ease.

REFERENCES

[1] M.M. Rashid, M.A. Hussain and N. Abd. Rahim, "Application of Magnetorheological damper for Car Suspension Control," Journal of Applied Sciences, Vol. 6, No.4, 2006,pp.933-938.

[2] J. Rabinow, The Magnetic Fluid Clutch, Transactions of the AIEEE, 67, 1948, pp.1308-1315.

[3] Ashwani Kumar & S.K. Mangal, Properties and Applications of Controllable Fluids: A Review, Int J of Mechanical Engineering Research,Vol. 2, No.1, 2012, pp.57-66.

[4] D. H. Wang and W. H. Liao, "Semiactive controllers for magnetorheological fluid dampers," Journal of Intelligent Material Systems and Structures, Vol. 16, pp. 983–993, November/December 2005.

[5] Rupam Singla, Design of a Mixed-Mode MR Damper with Reduced Off-State Damping, MS Thesis, The Ohio State University, USA, 2005.

[6] www.lord.com

[7] Zhao-Dong Xu, Da-Huan Jia & Xiang-Cheng Zhang, Performance tests and mathematical model considering magnetic saturation for magnetorheological damper, J of Intelligent Material Systems and structures, 23(12), 2012, pp.1331–1349.

[8] Engineering Note- Designing with MR Fluids, Lord Corporation-Thomas Lord Research Center.

[9] Xiaojie Wang and Faramarz Gordaninejad, Dynamic Modeling of Semi-Active ER/MR Fluid Dampers, in Proceedings of SPIE Conference on Smart Materials and Structures, 2001, pp.82-91.

[10] Xuezheng Jiang, Jiong Wang, and Hongsheng Hu, Designing and Modeling of a Novel Magneto-rheological Fluid Damper Under Impact Load, in Int Conf on Mechanical Engineering and Mechanics, Beijing, 2009, pp.203-207.