# Modeling and simulation of magnetorheological damper through bond graph

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Abstract— Magnetorheological (MR) dampers have received great deal of attention in recent years as they are one of the most promising control devices. The MR damper is a class of semi-active devices that uses MR fluid to control damping. The MR fluids consist of micron-sized, magnetically polarizable particles dispersed in a carrier medium such as mineral or silicone oil. When a magnetic field is applied to the MR fluids, the particles form chains, resulting in fluid becoming semi-solid that exhibits viscoplastic behavior. This ability of MR fluid to reversibly change from a free-flowing, linear viscous fluid to a semisolid with controllable yield strength on exposure to magnetic field is used to control the damping force. The MR damper involves interaction between different energy domains. Bond graph is a unified approach to modeling, simulation and synthesis of physical systems in different energy domains. This paper presents the modeling and simulation of MR damper through bond graph using Symbols Sonata software.

### Keywords— Magnetorheological damper; MR fluids; semiactive device; bond graph.

# I. INTRODUCTION

Passive and active devices are the two ends of the strategies used for reduction of response of a system. Semi-active device possesses the best features of the two strategies, the reliability of passive devices, and the versatility and adaptability of fully active devices. Semiactive device properties can be adjusted in real time but it cannot input energy into the system being controlled. Various semi-active devices have been proposed, two devices are Electrorheological (ER) such and Magnetorheological (MR) dampers. The main advantages of these devices are that they need very less control power, have simple construction, fast response to control signal. The ER and MR dampers falls under the classification of semi-active devices that uses controllable fluids. The controllable fluids have ability to reversibly change from a free-flowing, linear viscous fluid to a semisolid with controllable yield strength on exposure to an electric or magnetic field. Two fluids used for semi-active devices are electro-rheological (ER) fluids and magnetorheological (MR) fluids. The initial discovery and early development of the MR fluid was done by Jacob Rabinow at the U.S. National Bureau of Standards (now the National Institute of Standards and Technology) [9]. Amalendu Mukherjee Department of Mechanical Engineering IIT Kharagpur Kharagpur, West Bengal amalendu@mech.iitkgp.ernet.in

There was a brief period of interest in MR fluids in the 1950s and early 1960s. The interest in MR fluid research diminished in the late 1960s. The researchers pursued research in ER fluids by late 1980 primarily in automobile applications such as real-time controllable shock absorbers and torque transfer devices [6]. However, ER fluid devices failed to emerge in a big way in practical applications. The maximum yield strengths of the ER fluids remain low and it require power supplies capable of many kilovolt. The phenomenon is temperature dependent and has strong sensitivity to moisture and contamination, making their use difficult and costly.

As a result of limitations in use of ER fluids, there was again interest in MR fluids in the 1990s [6]. The MR fluids are suspensions of micron-sized, magnetically responsive particles in a liquid carrier such as mineral or silicone oil. When an external magnetic field is applied to the MR fluid, the suspended particles form chains along the magnetic field lines, resulting in fluid becoming a semi-solid that exhibits viscoplastic behaviour. This transition is reversible and can be achieved in a few milliseconds. The MR fluids can achieve yield strength higher than the ER fluids and can be operated in higher temperature range (-40 to 150°C) with slight variation in yield strength [8]. Additives (dispersants, friction modifiers, anti-wear agents etc.) can generally be used with MR fluids to enhance the properties of the fluid such as stability, anti-friction, seal life, bearing life, etc. The MR fluid devices require low voltage (e.g., 12-24V), current-driven power supply (1-2 A) [2]. The MR fluid automotive shock absorber system was finally realized in early 2002 on a Cadillac automobile which made use of a real-time controlled suspension system.

The existing MR damper models can be grouped into two main categories as parametric and non-parametric. The non-parametric models have parameters that do not necessarily have physical meanings. However, they are able to model the MR damper behaviour effectively but these models are very complicated. On the other hand the parametric models have parameters that have some physical meaning. These models are combinations of mechanical elements such as spring, linear viscous, friction etc. The earliest parametric model for MR damper was developed by Stanway et al [11] and is known as Bingham viscoplastic model. This model could reasonably

describe the force-displacement behaviour of the MR damper. Some other models proposed for modeling the behaviour of MR damper are visco-elastic-plastic model, nonlinear hysteretic biviscous model, hyperbolic tangent function model, Bouc–Wen model, modified Bouc–Wen model etc. [5].

The MR damper involves interaction between different energy domains. Bond graph is a unified approach to modeling, simulation and synthesis of physical systems in different energy domains. This paper presents the modeling and simulation of MR damper through bond graph using Symbols Sonata software.

# II. MR DAMPER CONFIGURATION

The schematic of the MR damper is shown in Fig 1. The MR damper has three chambers namely accumulator chamber, compression chamber and rod end chamber.

The compression chamber and the rod end chamber are filled with MR fluid. The accumulator chamber is filled with inert gas. Floating piston is used to separate the gas and the MR fluid. The accumulator chamber accommodates change in fluid chamber volume caused due to movement of piston rod into or out of the housing. The magnetic coils are wound in the machined groove on the periphery of the piston. The electromagnetic circuit of the system consists of the steel piston, a part of system housing and magnetic coils. The magnetic flux path is as shown in Fig 1. As can be seen in the figure the system housing becomes a part of the magnetic flux path and the gap between the housing and the piston acts as an annular fluid gap. The guide ring portion of the piston keeps the housing and piston concentric.



#### III. MATHEMATICAL MODELING

The main mechanism for dissipation of energy in MR damper is by damping on account of shearing of MR fluid as it flows through the annular gap between housing and piston. The MR fluid behaves as a newtonian fluid in off state mode. In the activated state the MR fluid behaves as a bingham plastic with variable yield strength.

MR fluid is modeled as a Bingham plastic that has variable yield strength. For this model, fluid flow is governed by Bingham's equations [6,7], given by

$$\tau = \tau_{v}(H) + \eta \dot{\gamma}, \tau > \tau_{v} \tag{1}$$

In the above equations , $\tau$  represents the fluid shear stress,  $\tau_y$  represents the magnetic field dependent yield stress, *H* represents the magnetic field,  $\dot{\gamma}$  represents the fluid shear rate, and  $\eta$  represents the plastic viscosity of the base hydraulic oil (viscosity when H = 0).

$$\tau = G\dot{\gamma}, \tau < \tau_{\gamma} \tag{2}$$

The fluid exhibits viscoelastic behavior below yield stress, given by equation (2), where G represents the complex material modulus.

The total pressure drop ( $\Delta P$ ) in MR fluid device in valve mode is sum of the pressure drop due to viscous resistance ( $\Delta P_{\eta}$ ) and the pressure drop due to yield stress

 $(\Delta P_{\tau})$  developed due to magnetic field [6,7].

$$\Delta P = \Delta P_{\eta} + \Delta P_{\tau} = \frac{12\eta QL}{{g'}^3 w} + \frac{c\tau_y L}{g'}$$
(3)

Q is the pressure driven fluid flow, and L, g', and w are the length, fluid gap, and width of fluid flow passage that exist between the piston and the housing.

The value of constant c, varies from 2 to 3 depending on the ratio  $\Delta P_{\tau} / \Delta P_{\eta}$ . If  $\Delta P_{\tau} / \Delta P_{\eta}$  is unity or smaller, the value for c is taken as 2. If the ratio  $\Delta P_{\tau} / \Delta P_{\eta}$  is around 100 or larger, the value for c is taken as 3.



Fig. 2. Valve mode operation of MR fluid

Fig. 1. Magnetorheological (MR) damper

# IV. MR DAMPER MODELING

The performance of the MR damper depends on many factors like fluid properties (particle density, base oil, plastic viscosity, yield strength due to magnetic field), dimensions of housing, piston rod, fluid flow passage, gas in accumulator chamber and friction between moving parts.

Following assumptions are made for modeling of the MR damper:

- There is no leakage of oil between housing piston and housing floating piston.
- The oil is assumed to be incompressible. This approach simplifies the model as the changes of oil volume in different chambers are determined from the piston and cylinder movement only.
- The housing of the system is considered to be rigid, i.e. no compliance in the walls.
- Friction effects between seal and corresponding mating surface wall is considered as tanh(\_) function.
- MR fluid is modeled as Bingham plastic.

The word bond graph model of the MR damper is shown in Fig 3. The velocities of the housing, floating piston and piston are represented by  $X\dot{I}$ ,  $X\dot{2}$  and  $X\dot{p}$  respectively.

Some capsules of 'SYMBOLS Sonata' software are used for modeling of the system. The Gas field with properties capsule is used for modeling gas in the accumulator chamber. The heat transfer between the gas accumulator and environment is modeled using thermal resistance (cylinder) capsule.



Fig. 3. Word bond graph of MR damper

A. Gas field with properties capsule



Fig. 4. Basic C-field for volume of gas

The cylindrical gas chamber of volume V, allows thermal interaction through the walls of the chamber and mass interaction through a material port. The internal energy (U) of gas contained in the chamber is expressed as a function of volume of the chamber (V), total entropy (S) and total mass (m) of the gas inside the chamber. The gas is assumed to be an ideal gas.

$$U = U(V, S, m) \tag{4}$$

The rate of change of internal energy is given as

$$\dot{U} = \frac{\partial U}{\partial V} \dot{V} + \frac{\partial U}{\partial S} \dot{S} + \frac{\partial U}{\partial m} \dot{m}$$
(5)

 $\frac{\partial U}{\partial V} = -P, \text{ thermodynamic pressure}$  $\frac{\partial U}{\partial S} = T, \text{ thermodynamic temperature}$  $\frac{\partial U}{\partial m} = \mu_{ch}, \text{ chemical potential}$  $\frac{\dot{U}}{\partial m} = \frac{\dot{U}}{ch} + T\dot{S} + m \vec{r}$ 

$$\dot{U} = -P\dot{V} + T\dot{S} + \mu_{ch}\dot{m} \tag{7}$$

The bond graph model of the basic C-field for collapsible volume of gas is shown in Fig 4. The mechanical port of the C-filed has flow and effort variable as  $\dot{V}$  and -P respectively. The thermal port has  $\dot{S}$  and T as the flow and effort variable. The material port has  $\dot{m}$  and  $\mu_{ch}$  as the flow and effort variable.

The thermodynamic relations for the C-field are derived from the ideal gas relations (see Mukherjee, et al. [1] 2012 and Merzouki, et al. [10] 2013).

Refer Mukherjee, et al. [1] for modeling of heat transfer between the gas in accumulator chamber and the environment.

#### B. Friction model

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The other mechanism for damping is friction between the various moving parts of the MR damper. The effect of friction between various mating parts is considered in the model. The friction between floating piston & housing and piston & housing is considered to be of dry friction type. In general the mechanical friction between two mating surface has a steep rise in the force for small relative velocity till the critical force is reached, then a constant or slowly varying positive definite function.

The friction force is modeled as

$$F = F_{cr} \operatorname{x} \tanh(Z_{cr} \operatorname{x} v) \tag{9}$$

where  $F_{cr} = \mu \times N$ , where  $\mu$  is the coefficient of friction,

*N* is normal force, *v* is the relative velocity and  $Z_{cr}$  is another constitutive constant, usually taken as large number depending on the rise time of the sticking part at low velocities [12].

In the bond graph model the friction between the floating piston & housing is designated as SE47 and friction between the piston and the housing as SE44.

$$SE47 = F_{cr1} \operatorname{x} \tanh(Z_{cr1} \operatorname{x} f46) \tag{10}$$

$$SE44 = F_{cr2} \operatorname{x} \tanh(Z_{cr2} \operatorname{x} f43)$$
(11)

Where f46 represents the relative velocities of the floating piston w.r.t. the housing and f43 represents the relative velocities of the piston w.r.t. the housing.

The bond graph model of MR damper is shown in Fig 5. The MR fluid is assumed to be incompressible; therefore the gas pressure in the accumulator is a function of piston displacement. Ideal gas laws are applied to get relation for pressure inside the accumulator. The thermal port, material port and mechanical port are represented by bond #1, #2 and #3 respectively. The thermal port is connected to thermal resistance capsule that accounts for heat transfer between gas and the environment. The mass

of the gas in the accumulator is constant and there is no mass transfer, therefore mass flow rate in the material port is set to zero by taking SF5=0.0. The entropy of the constant gas mass in the accumulator is initialized and as there is no mass transfer of gas during the operation there is no mixing of entropies in the model.

In bond graph model 'I'-element represent the inertia, the 'C'-element represent compliance of the components and 'R'-element represents the damper or the dissipative component. The '1' junction denotes the equality of the flow of the elements attached to it and the '0' junction implies the equality of the effort on the elements attached to the junction. The transformer elements 'TF' between bond #9 & #7 and bond #10 & #17 convert the floating piston velocity to corresponding volumetric changes of the accumulator; between bond #8 & #11 and bond #12 & #18 convert the housing velocity to corresponding volumetric changes of the accumulator; between bond #19 & #20 and bond #34 & #30 convert the housing velocity to corresponding volumetric changes of the compression chamber and rod end chamber. Similarly TF-element attached to bond #27 & #25 and #28 & #29 convert the piston velocity to corresponding volumetric changes of compression chamber & rod end chamber.

# V. RESULTS AND DISCUSSIONS

The modeling of the MR damper is generalized in terms of parameters affecting its performance. The



Fig. 5. Bond graph model of MR damper

generalized model has the possibilities of varying these parameters to study the response of the system. Some representative simulation results are presented in the following pages for selected parameter values. The graphs are taken from SYMBOLS Sonata Simulator module.

The MR damper has housing diameter of 0.04 m and the piston diameter is 0.039m. The magnetic field is applied radially across this radial gap of 0.5mm. The axial length of the fluid flow channel exposed to magnetic field is 0.01m. One end of the MR damper is fixed and sinusoidal excitation is applied at the other end. The housing end of the MR damper is fixed by setting SF57= 0.0 and sinusoidal excitation is applied at piston end through SF58 bond. The response of the MR damper due to sinusoidal excitation of 0.015m amplitude and 2 Hz frequency for different magnetic field dependent yield stress are shown below. The simulation results for yield stress of 10 kPa and 20 kPa are shown in Fig 6 and Fig 7 respectively. The MR damper force variation with time are shown in Fig 6a and Fig 7a, the Force-Displacement loops are shown in Fig 6b and Fig 7b, the Force-Velocity loops are shown in Fig 6c and 7c. The effect of change in the magnetic field is quiet visible in the results shown in Fig 5 and Fig 6. As a result of increase in magnetic field there is increase in magnetic field dependent yield stress. Therefore, the MR damper force increases with increase in magnetic field dependent yield stress as force required to yield the MR fluid increases.

The gas in the accumulator chamber acts like a spring element. The presence of pressurized gas in the accumulator chamber results in offset in the MR damper force as can be seen in the simulation results of Fig 6 and Fig 7. The pressurized gas in the accumulator chamber helps in preventing cavitation and accommodates the volume of the MR fluid displaced by piston movement.



amplitude of 0.015m and magnetic field dependent yield stress is taken as 10 kPa

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stress is taken as 20 kPa

### VI. CONCLUSIONS

MR damper is one of the most promising control devices. This semi-active device filled with controllable fluid has great potential for many control applications. The main advantages of these device are that they need very less control power, have simple construction, fast response to control signal, stable properties over wide temperature range etc.

The MR damper involves interaction between different energy domains. Bond graph is a unified approach to modeling, simulation and synthesis of physical systems in different energy domains. The modeling and simulation of MR damper has been carried out through bond graph using Symbols Sonata software. The parametric model has the ability to vary the significant model parameter and study their effect on the performance of the system. The bond graph model of the MR damper models the gas in the accumulator chamber, the heat transfer between the gas in the accumulator chamber and environment, friction between the moving parts and the MR fluid as bingham plastic.

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