

Using magnetorheological fluids in an innovative hybrid bicycle damper

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Abstract. Magnetorheological fluids are capable of changing their viscosity quickly. This can provide good controllability and fast dynamic response. A conventional passive suspension system with air spring or hydraulic damper has simple design and financial benefit for bicycles, but its operation is uncontrollable and non-adaptive. This paper presented a semi-active hybrid bicycle suspension system which combines conventional air spring and a new magnetorheological damping brake together to reduce vibration of a bicycle. A multi-layer magnetorheological brake and linkage mechanism are connected to bike fork to form the adaptive damping part of the innovative hybrid suspension system. The simulation results proved that the semi-active suspension system can reduce bike vibration effectively.

1. Introduction

Vehicular suspension system is used to absorb shock impact from roads, and can be classified into categories of passive, semi-active and active devices according to their performances. This paper presented a hybrid bicycle suspension system which combines conventional air spring and a magnetorheological damping brake together to reduce vibration of a bicycle.

Conventional front suspension system in a bike uses air spring as the main source of damping force. The damping force depends on moving speed of piston, and the force is not controllable to effectively reduce bike vibration. Thus the control force cannot be adaptive to different road conditions. A suspension system with controllable force and extended force range is required to provide more comfortable riding to bike rider.

Magnetorheological devices (MR devices) and their applications get attentions these years because of their control flexibility and fast response [1]. MR devices were commonly designed as linear translation dampers to be applied in vehicular suspension system. But such kind of damper needs large space to be installed. Instead of the linear damper, a rotary MR brake is used in this research to provide similar damping force for bike suspension.

2. Hybrid bike suspension system

The proposed hybrid suspension system combines an air spring and a MR brake, as shown in figure 1, to provide damping force together. An MR brake can provide large angular resistance torque with smaller volume compared to linear translation damper. Since MR brake provides resistance force to

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against angular motion, not translation motion, a slider-crank mechanism is needed to convert the translation motion of bike fork into angular motion of MR brake. This hybrid suspension system has advantages of simple design, acceptable cost, good controllability, fast response and high accuracy.

The in-line slider crank (as shown in figure 2) consists of three rotating joints and one sliding joint. The linear motion of slider drives the rotation of crank. Since the slider travels along a straight line which passes through the base joint of the crank, a symmetric back-and-forward slider motion is created. Thus, the in-line slider crank mechanism has advantages of harmonic motion and easy assembly over other four-bar linkage mechanisms.



Figure 1. Hybrid bike suspension system.

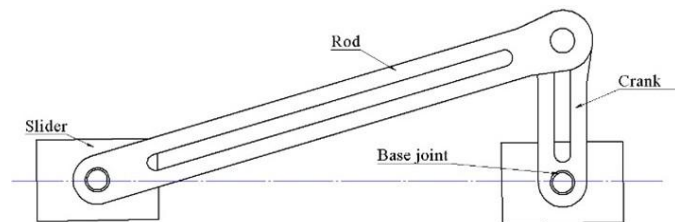


Figure 2. Slider-crank mechanism.

In the designed system in figure 1, the slider is the front fork of a bicycle and the pillar joint of rod connects to the top of front fork. The crank is the rotating part of MR brake which is fixed to the head tube of a bike. Parameters of this slider-crank mechanism are listed in table 1. For the sake of smooth movement of slider and crank, an appropriate proportion of crank length to rod length is from 1:3 to 1:5.

Table 1. Parameter of designed slider-crank.

parameters	crank length (mm)	rod Length (mm)	maximum stroke (mm)
Value	40	130	120

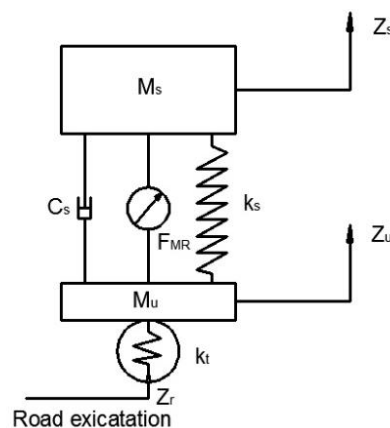


Figure 3. Model of slider-crank mechanism for hybrid suspension system.

To understand the dynamics of this hybrid suspension system, a dynamic model was built as shown in figure 3. The variables z_s , z_u and z_r are the displacements of sprung mass, unsprung mass and road excitation respectively. The sprung mass m_s and unsprung mass m_u correspond to the upper and lower

weights of bike fork, while k_s and k_t are the stiffness of air spring and bike tire. Parameter c_s represents the viscous damping of suspension system, and F_{mr} is the controllable force from MR brake.

3. MR brake design

The term “magnetorheological fluid” (MR fluid) was firstly proposed by Rabinow in 1948. MR fluid, which is one of intelligent materials, can rapidly change its state from liquid state into quasi-solid state after applying an external magnetic field. Devices with MR fluid commonly work in three working modes: valve mode, direct-shear mode and squeeze mode (figure 4). For applications of braking, an MR brake works under the direct shear mode for its operation. Because of the characteristics of fast response, good controllability and quiet operation, MR brake is gradually adopted in many fields for braking, deceleration or precise motion control.

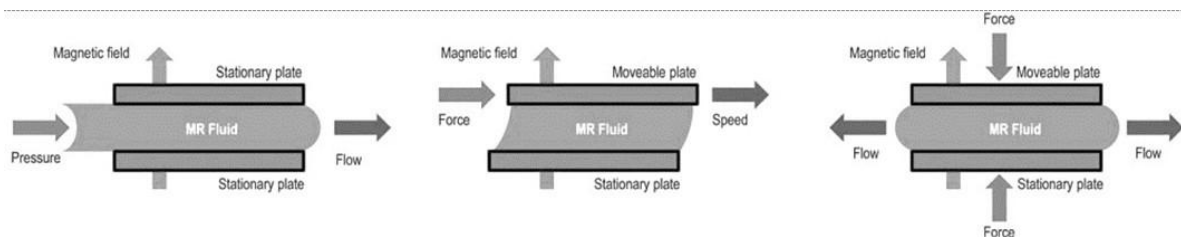


Figure 4. Three operational modes of MR fluid [2].

The magnitude of brake torque of an MR brake is directly related to the effective acting area between inner brake surface and MR fluid. In order to enhance brake force of an MR brake, its acting area of MR fluid needs to be increased. However, increment of the active area usually accompanies increase of unwanted brake size and weight. It is a target of this research to find a way to increase the effective active area of MR fluid and to keep the small size of MR brake at the same time. Therefore, a multi-layer disk structure instead of conventional single-layer disk structure is considered in this research.

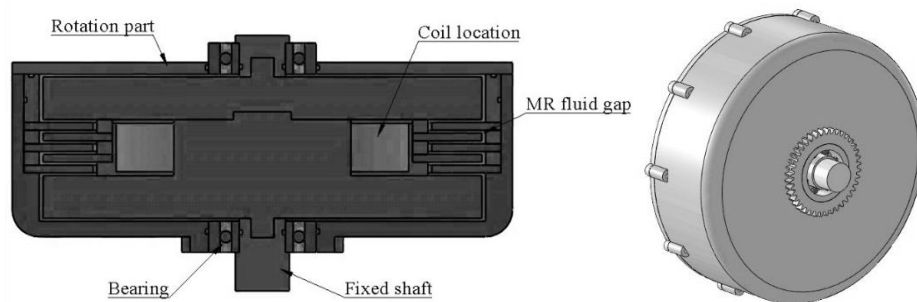


Figure 5. New multi-layer MR brake.

Figure 5 shows the configuration of a multi-layer MR brake [3]. This MR brake has a stationary part which is enclosed by a rotary casing. Coils are wound around the axle of stationary part to produce magnetic field after applying current to the coils. Two and three discs are infixed into the stationary part and rotary casing respectively, and gaps between the corresponding discs are filled with MR fluid. Then braking force is produced due to the viscous force between MR fluid and brake inner surface. Magnetic simulation of the MR brake, shown in figure 6, shows that strong magnetic flux penetrates the discs and MR fluid in gaps to produce strong viscous force and corresponding brake torque. The magnitude of brake force or brake torque varies as input current changed. Figure 7 shows the simulated relation of brake force and input current. Approximately linear relation of force and current can be observed in the figure.

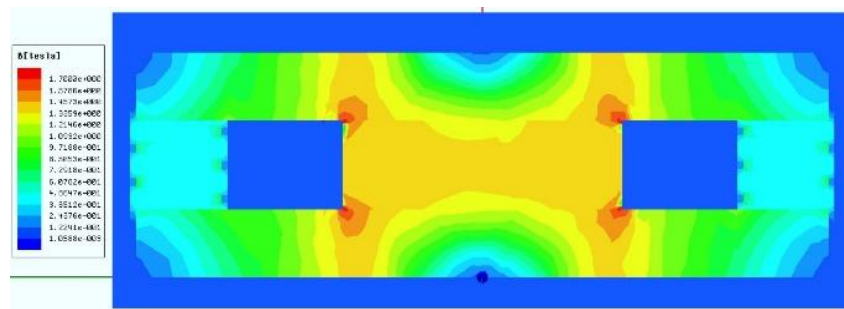


Figure 6. Magnetic simulation of the MR brake.

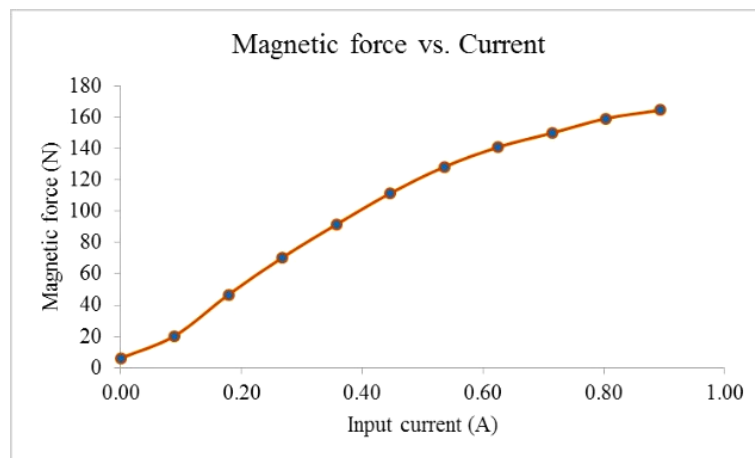


Figure 7. Relation of magnetic force and input current.

4. Vibration control

Because of structure similarity, a model of quarter car's suspension model, shown in figure 8, can be adopted in this research. The sprung mass m_s denotes the total weight applied to the upper head tube, including the weight of MR brake. The unsprung mass m_u is the weight of fork, shock absorber and wheel. Stiffness of spring and tire are k_s and k_t respectively.

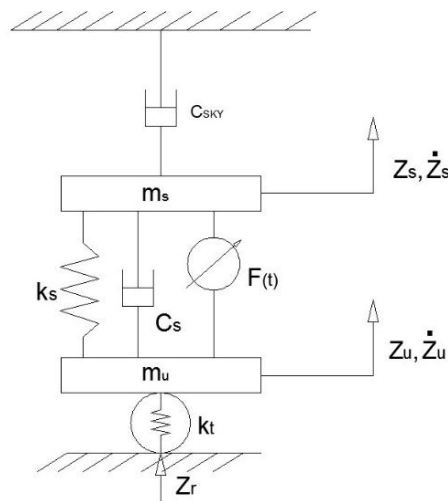


Figure 8. Skyhook control algorithm.

There were various studies proposed to control a semi-active suspension system. In most of studies

and reports, skyhook method is highlighted as an optimal control for semi-active suspension system [4]. Figure 8 illustrates model of sky hook control for this two-order suspension system. The sprung mass is linked to the sky to reduce the vertical oscillation of the chassis.

Equations for the Skyhook model are presented as follows:

$$m_u \ddot{z}_u(t) + c_s [\dot{z}_u(t) - \dot{z}_s(t)] + k_s [z_u(t) - z_s(t)] + k_t [z_u(t) - z_r(t)] = -F(t) \quad (1)$$

$$m_s \ddot{z}_s(t) + c_s [\dot{z}_s(t) - \dot{z}_u(t)] + k_s [z_s(t) - z_u(t)] = F(t) \quad (2)$$

where $\dot{z}_s$ and $\dot{z}_u$ are velocities; $\ddot{z}_s$ and $\ddot{z}_u$ are the accelerations of the sprung and unsprung masses respectively. $F(t)$ is the controllable force from MR brake.

Among all controllers, PID controller is the most common form of feedback control. It was an essential element of early governors, and then became the standard tool when process control emerged in 1940s. With advantages of easy implementation, high accuracy and fast response, PID is used widely in process and dynamic control today. The control law of a PID controller is shown in equation (3):

$$u(t) = K(e(t)) + \frac{1}{Ti} \int_0^t e(t) dt + T_d \frac{de(t)}{dt} \quad (3)$$

Block diagram of the closed-loop control utilizing PID controller is illustrated as shown in figure 9. The system error e , which is the difference of reference signal r and output signal y , is used as input of PID controller. Then the control signal u will be computed and input to the plant. The steady state error always possesses in proportional control. Increasing of gain P will result in decreasing of system steady state error and increasing of oscillation in output. Adopting an integral gain I can effectively reduce steady state error. The increase of derivative gain D will enhance the response speed and reduce output overshoot.

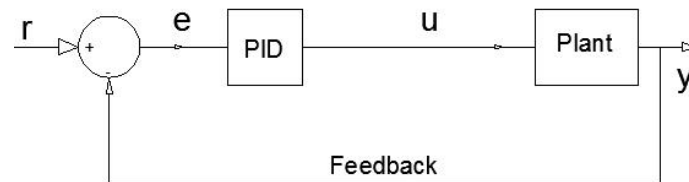


Figure 9. Closed-loop with PID controller.

To simplify the dynamic model, some assumptions are set as following: The tire is as similar as a linear spring with the spring rate k_t , and it always contacts with road surface; Behaviors of spring and damper are linear; The friction in the joints are neglected. As the results, the model of this hybrid suspension is nearly a two-order suspension system. Considering the weight distribution of a bicycle, there is about 30% to 35% weight applied to the front wheel and 65% to 70 % to rear wheel. Consequently, if the total weight of bike and cyclist is 100 kg, then the weight applied to the front wheel is about 30 kg to 35 kg. The weight, which mentioned above, is the sprung weight of this model. Table 2 lists the parameters for simulation.

Table 2. Simulation parameters [5].

Parameters	Value	Unit
Sprung mass (m_s)	32.5c	Kg
Unsprung mass (m_u)	5.5	Kg
Spring rate (k_s)	2950	N/m
Tire stiffness (k_t)	35055	N/m
Damping coefficient (c_s)	105	Ns/m

Damping performance of the suspension system needs to be controlled according to the motion of suspension travel. Intuitively, the MR brake's force F_{brake} increases while it has the same direction with the relative velocity between sprung and unsprung masses. Otherwise, the force F_{brake} is set to zero. This semi-active condition [4] is expressed in equation (4):

$$F_{\text{brake}} = \begin{cases} F_{\text{brake}}, F_{\text{brake}}(\dot{z}_s - \dot{z}_u) > 0 \\ 0, F_{\text{brake}}(\dot{z}_s - \dot{z}_u) \leq 0 \end{cases} \quad (4)$$

Vibration control performances of bike fork with hybrid MR suspension system are evaluated under bumping road condition. The road condition setting in this simulation is shown in figure 10 and equation (5) [6]:

$$z_r = a \frac{1 - \cos(8\pi t)}{2} \quad (5)$$

where $a = 6$ cm for $0.5 \leq t \leq 0.75$, $a = 3$ cm for $3.0 \leq t \leq 3.25$ and 0 otherwise.

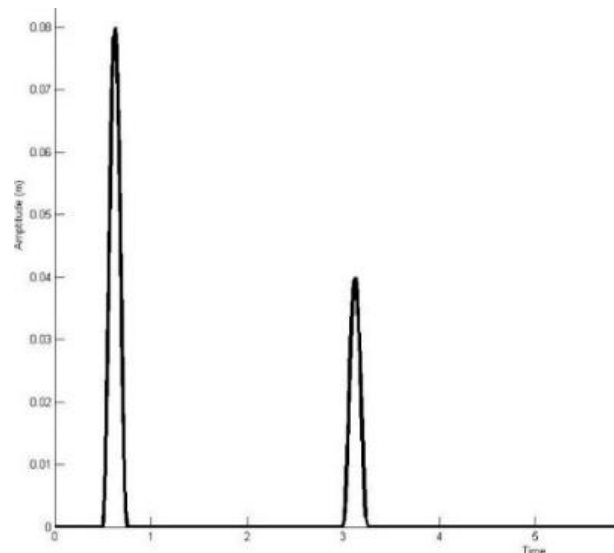


Figure 10. Road's profile for simulation.

For designing the PID controller, Ziegler-Nichols tuning method was employed to find the gain parameters K_p , K_i , and K_d with value of 25.5, 11.7, and 0.15, respectively.

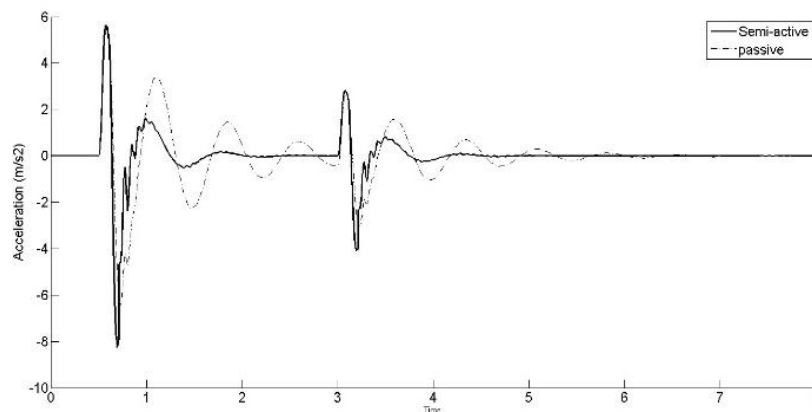


Figure 11. Accelerations responses of hybrid suspension system.

5. Results and discussion

The comparisons of semi-active and passive suspension behavior are depicted as shown in figures 11 to 13. The amplitudes and vibration frequency of the displacement, acceleration are both smaller significantly when we adopted MR brake as a variable actuator. The combination of skyhook model and PID controller is not only an effective solution for the control of semi-active suspension system in vehicles, but also in bicycles.

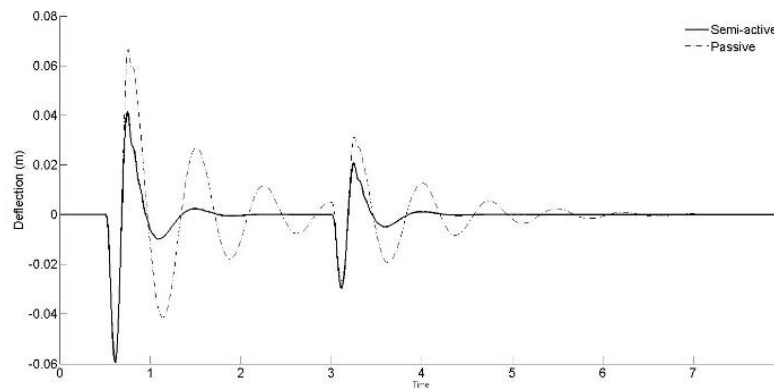


Figure 12. Displacements of hybrid suspension system.

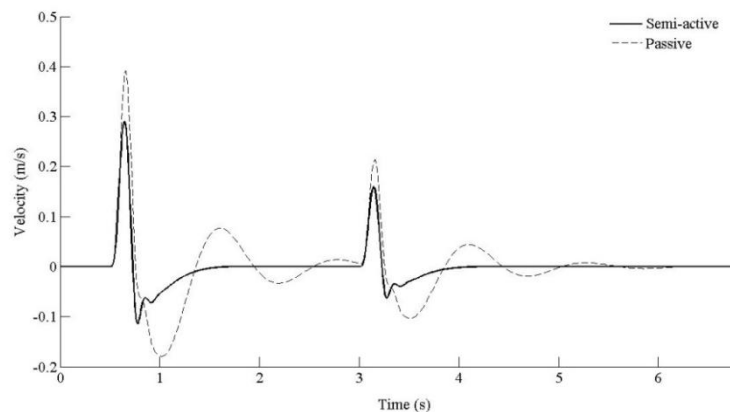


Figure 13. Velocities of hybrid suspension system.

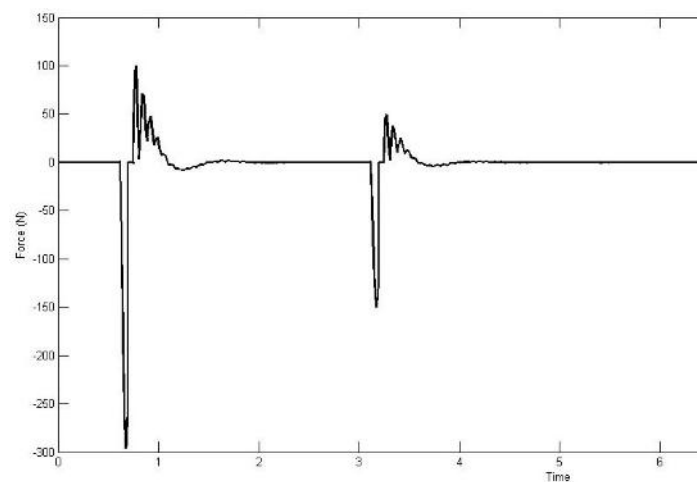


Figure 14. Controllable force.

The results shown in figure 14 indicate that the control force had to vary in a wide range in a short time. According to the magnetic force in figure 7, this MR brake can provide a rapid variable force that is bigger than the required force. It means that MR brake is obviously adaptable for application on front bike suspension.

6. Conclusions

In this paper, we introduced a new hybrid suspension system which consists of a multi-layer MRB with compact size and large brake torque. The simulation results proved that the semi-active suspension system can reduce bike vibration effectively. With these advantages revealed in this paper, the new suspension has the potentials to replace the passive bike's suspensions in the market and provides cyclists with comfortable riding.

References

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