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A Self-sensing Magnetorheological Shock Absorber for Motorcycles

D. H. Wang[1,2,*], T. Wang[1,2], X. X. Bai[1,2], G. Yuan[1,2], and W. H. Liao[3]
[1] Key Laboratory of Optoelectronic Technology and Systems of the Ministry of Education of China, Chongqing University, Chongqing 400044 China
[2] Precision and Intelligence Laboratory, Department of Optoelectronic Engineering, Chongqing University, Chongqing 400044 China
[3] Smart Materials and Structures Laboratory, Department of Mechanical and Automation Engineering, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong China
* Corresponding author: Precision and Intelligent Laboratory, Chongqing University, Chongqing 400044 China.
Tel/Fax: 86 23 65112105, E-mail: dhwang@cqu.edu.cn.

ABSTRACT

In this paper, a self-sensing magnetorheological (MR) shock absorber for motorcycles was designed, fabricated, and tested in order to realize the motorcycle rear suspension, with the following requirements: controllable damping, low cost, minimum installation space, and low weight. In the developed prototype of the self-sensing MR shock absorber, the coil wound on the piston simultaneously acts as the exciting coil of the MR fluid and the integrated relative displacement sensor (IRDS) while the coil wound on the cylinder acts as the induction coil of the IRDS. The MR fluid in the annular fluid channel and the induction coil of the IRDS are simultaneously excited via the exciting coil by the DC driving current and the AC carrier, respectively. The damping and sensing characteristics of the prototype based on the rapid control prototype technique were tested. The experimental results indicate that the developed prototype of the self-sensing MR shock absorber for the motorcycle rear suspension possesses the controllable damping forces and good relative displacement sensing ability. Moreover, the sensing performance of the developed prototype of the self-sensing MR shock absorber is not influencecd by the driving currents to the exciting coil to obtain the different yield stress of the MR fluid to change the damping forces.

Keywords: Motorcycle shock absorber, Magnetorheological damper, Integrated relative displacement sensor, Self-sensing.

1. INTRODUCTION

It is well known that not only the damping forces of magnetorheological (MR) dampers can be controlled through driving currents, but also the required power for controlling the MR dampers is relatively low [1-3]. Thus the MR dampers have been developed for semi-active suspension systems for various kinds of vehicles, such as automobiles [4-7], trains [8, 9], motorcycles [10,11], mountain bicycles [12], and truck seats [13-15] in order to provide the best riding and handling performances. However, extra dynamic sensors, including accelerometers, velocimeters, or displacement sensors, are needed to realize the feedback control in order to make full use of the controllable damping characteristics of MR dampers [16]. The extra dynamic sensors added into the suspension systems will result in the following problems: (1) complicating the system, (2) occupying installation space, (3) increasing cost, (4) increasing weight, and (5) decreasing the realiability to some extent.

It would be desired that the dynamic responses of the plant integrated MR dampers can be accessed without the extra dynamic sensors through integrating the dynamic sensors into the MR dampers to compose the self-sensing MR dampers. Through integrating the dynamic sensors into the MR dampers, the separate dynamic sensors for monitoring the dynamic responses and their correspoding connectors are not needed again when utilizing the MR dampers to realize the semi-active systems. The semi-active suspension systems utilizing the self-sensing MR dampers will not only decrease the cost but also improve the reliability by eliminating the separate sensors and their connectors from the conventional semi-active systems. It should be noted that the damping performances of the MR dampers can not be influenced when integrating the dynamic sensors.

Nehl *et al* [17] studied an integrated relative velocity sensor for controllable dampers, in which a staticmagnetic field was used as the working magnetic field of its integrated sensor. Although the integrated relative velocity sensor is self-energizing, it is difficult to integrate the integrated relative velocity sensor into MR dampers because it use the magnetostatic field, which would be interfered with the magnetostatic field used to shear the MR fluid. On the other hand, the induction coil of the integrated relative velocity sensor should be wound on the cylinder cover of the controllable dampers, which will not only reduce the performance of the velocity sensor but also limit the usage in the MR dampers without the cylinder cover. Russell [18] developed an integrated magnetostrictive position sensor for the MR dampers. Although a magnetostrictive position sensor can be mounted internally into the MR dampers with the high performance, the complicated structure, strict manufacturing processes, and expensive magnetostrictive materials make their commercial application difficult. In order to make MR dampers be self-sensing, the authors proposed and studied the working principle of an integrated relative displacement sensor (IRDS) integrated into commercially available MR dampers based on the electromagnetic induction [19]. However, only the sensing capabilities of the IRDS without the current to magnetize the MR fluid were evaluated [19].

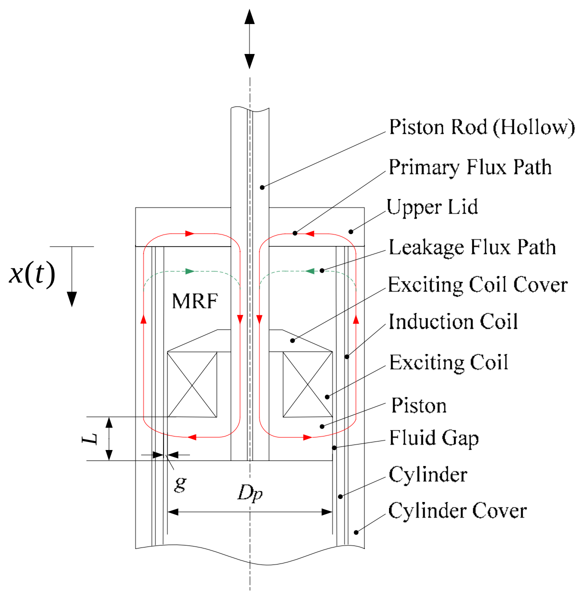
In this paper, a self-sensing MR shock absorber for motorcycles was designed, prototyped, and tested in order to realize the motorcycle rear suspension, with the following requirements: controllable damping, low cost, minimum installation space, and low weight. In the developed prototype of the self-sensing MR shock absorber based on the rapid control prototype (RCP) technique, the coil wound on the piston simultaneously acts as the exciting coil of the MR fluid and the IRDS while the coil wound on the cylinder acts as the induction coil of the IRDS. The MR fluid in the annular fluid channel and the induction coil of the IRDS are simultaneously excited via the exciting coil by the DC driving current and AC carrier, respectively. Aiming at the developed prototype of the self-sensing MR shock absorber for motorcycles, the experimental test setup based on the 849 shock absorber test system from the MTS was established and the damping and sensing characteristics of the prototype are presented.

2. DESIGN AND PROTOTYPE OF THE SELF-SENSING MR SHOCK ABSORBER

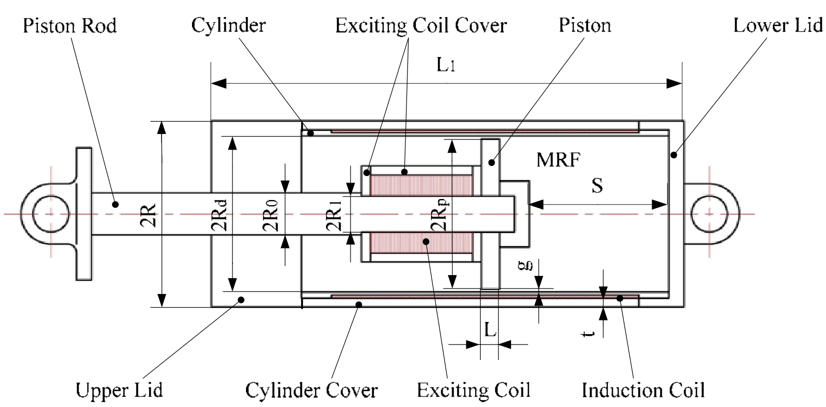
Up to now, the semi-active dampers based on MR fluids are one of the widely developed and used controllable devices in the academic fields. In order to move MR dampers into the market, especially in the automobile and motorcycle industries, it is the key point how to decrease the application cost of the MR dampers. According to [19], the IRDS technique aiming at the MR dampers may be the best choice to decrease the application costs of the MR dampers when realizing the semi-active systems. In this section, the structural design and prototype of the self-sensing MR shock absorber for motorcycles based on the operating principle of the IRDS for MR dampers are presented.

2-1. Operating principle and structural design

The operating principle and configuration of the self-sensing MR shock absorber for motorcycles based on electromagnetic induction are shown in figures 1(a) and 1(b), respectively. Observing figure 1(a), the self-sensing MR shock absorber mainly comprises an exciting coil wound on the piston and an induction coil wound on the nonmagnetic cylinder. In the self-sensing MR shock absorber, the coil wound on the piston of the self-sensing MR shock absorber acts as the exciting coil for both the MR damper to adapt the yield stress of the MR fluid and the IRDS simultaneously and the coil evenly wound on the cylinder acts as the induction coil of the IRDS. The induction coil of the IRDS positions in a cylindrical cover made from the soft steel material with high magnetic permeability. The structural design and material selection of the self-sensing MR shock absorber should ensure that the primary flux path is formulated along the piston, fluid gap, cylinder cover, up lid of the cylinder, and piston rod.



(a)



(b)

Figure 1. A self-sensing MR shock absorber for motorcycles based on electromagnetic induction: (a) the operating principle and (b) the structure.

In order to realize the self-sensing ability of the MR dampers, the exciting coil in figure 1 is energized by a mixed signal of the harmonic voltage signal (carrier signal) for the IRDS and an DC current for the MR fluid. According to figure 1, the yield stress of the MR fluid in the fluid gap can be directly adapted to provide the controllable damping force through changing the DC current from the current driver. The harmonic magnetic field along the primary flux path, as shown in figure 1(a), is induced by a harmonic voltage signal applied to the exciting coil and makes the induction coil wound on the cylinder induce the same frequency harmonic voltage signal. When the piston moves in and out the cylinder, the number of the active turns of the induction coil in the primary flux path corresponds to increase or decrease, which varies the flux linkage of the induction coil accordingly. In this way, the amplitude of the induced voltage in the induction coil is modulated by the displacement of the piston relative to the cylinder of the self-sensing MR shock absorber. Through demodulating the induced voltage from the induction coil, the relative displacement between the piston and the cylinder of the self-sensing MR shock absorber can be accessed and used to achieve the integrated relative displacement self-sensing based on electromagnetic induction.

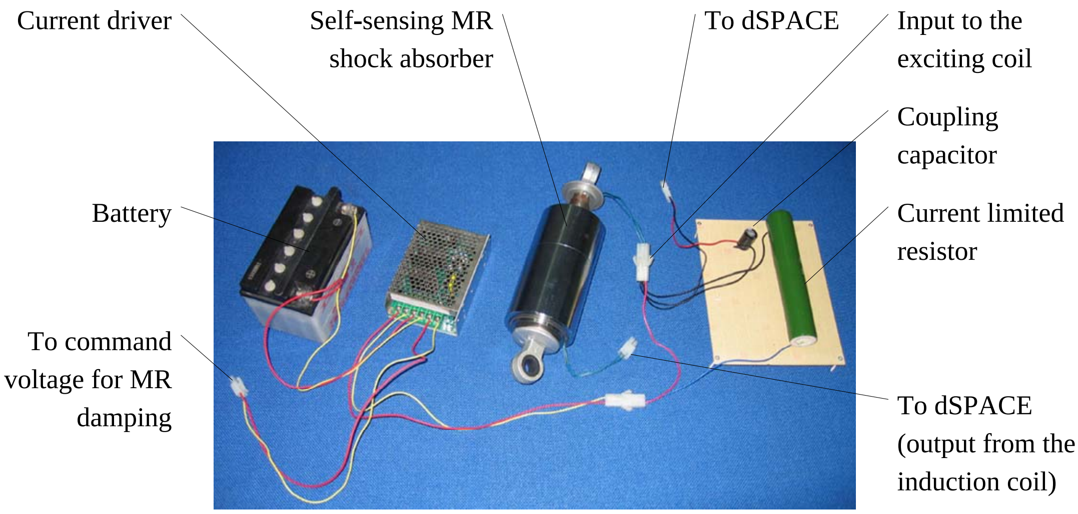


Figure 2. Photograph of the prototype of the self-sensing MR shock absorber for motorcycles companied with the current driver powered by the motorcycle battery.

Table 1. Parameter values of the prototype of the self-sensing MR shock absorber.

Parameter	Symbol	Value
Length	L_1	160 mm
Radius	R	40 mm
Gap thickness	G	1 mm
Gap length	L	6 mm
Piston radius	R_p	31 mm
Piston maximum displacement	S	50 mm
Piston rod radius	R_0	13 mm
Piston rod radius	R_1	12 mm
Cylinder inner radius	R_d	32 mm
Cylinder cover thickness	T	6 mm
Exciting coil number	N	600
Induction coil number		340

According to the operating principle of the self-sensing MR shock absorber shown in figure 1(a), the structure of the developed prototype of the self-sensing MR shock absorber is shown in figure 1(b). Observing figure 1(b), the exciting coil is wound on the piston rod and pressed to the piston through a nonmagnetic cover. The induction coil is wound evenly on the cylinder and covered by the cylinder cover. The piston, piston rod, upper cover, and cylinder cover must be made from the soft steel with high magnetic permeability whereas the cylinder, exciting coil cover, and lower cover are made from the nonmagnetic stainless steel. The meaning of the symbols and the values of the structural parameters of the prototype of the self-sensing MR shock absorber in figure 1(b) are listed in table 1. The photograph of the prototype of the self-sensing MR shock absorber for motorcycles, which is developed according to the operating principle and structure shown in figure 1, is shown in figure 2, in which the current driver powered by a motorcycle battery is also presented.

2-2. Prototype of the self-sensing MR shock absorber

The prototype of the self-sensing MR shock absorber based on the RCP technique is centered on the DS1103PPC controller board from the dSPACE GmbH and the schematic of the prototype is shown in figure 3. According to figure 3, the current from the current driver, which is powered by a motorcycle battery, is mixed with the carrier for the IRDS and then applied to the exciting coil. The carrier for the IRDS is the sinusoidal signal generated by a standard signal generator. In order to realize the demodulation of the induced voltage, the sinusoidal signal generated by a standard signal generator is first sampled by the DS1103PPC controller board and then applied to the mixing unit through the dSPACE I/O connector. The induced voltage from the induction coil is a modulated signal by the movement of the rod relative to the cyclinder of the self-sensing MR shock absorber and is sampled and demodulated by the DS1103PPC controller board. The function of the electronic unit to realize the demodulation of the induced voltage from the induction coil is realized with MATLAB/SIMULINK, then compiled and downloaded into the DS1103PPC controller board. The SIMULINK block diagram of the function of the electronic unit is shown in figure 4. Observing figure 4, the band pass filter and the low pass filter, which are digital filters realized in the DS1103PPC controller board, are used to filter the noise and the demodulated carrier in the induced voltage. The demodulated signal from the induced voltage of the induction coil can be used to represent the movement of the rod relative to the cylinder.

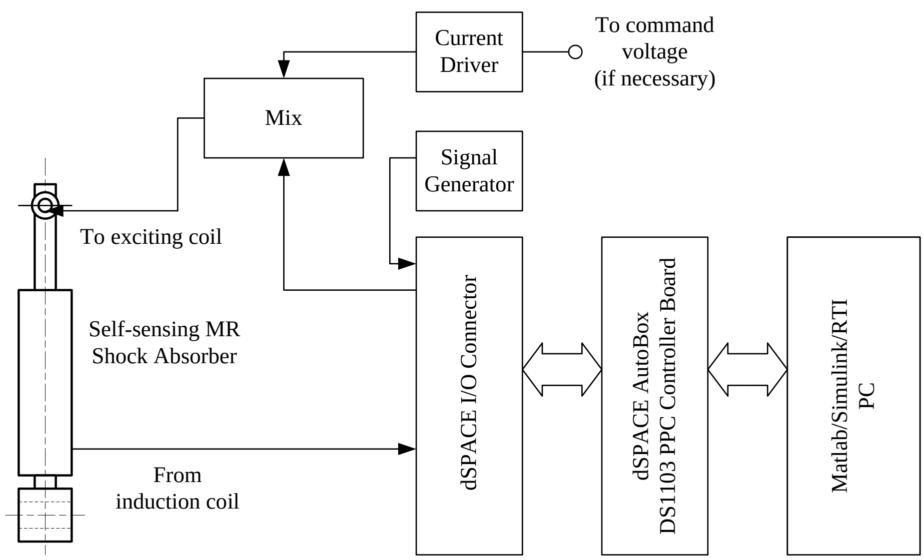


Figure 3. Schematic of the prototype of the self-sensing MR shock absorber based on the RCP technique.

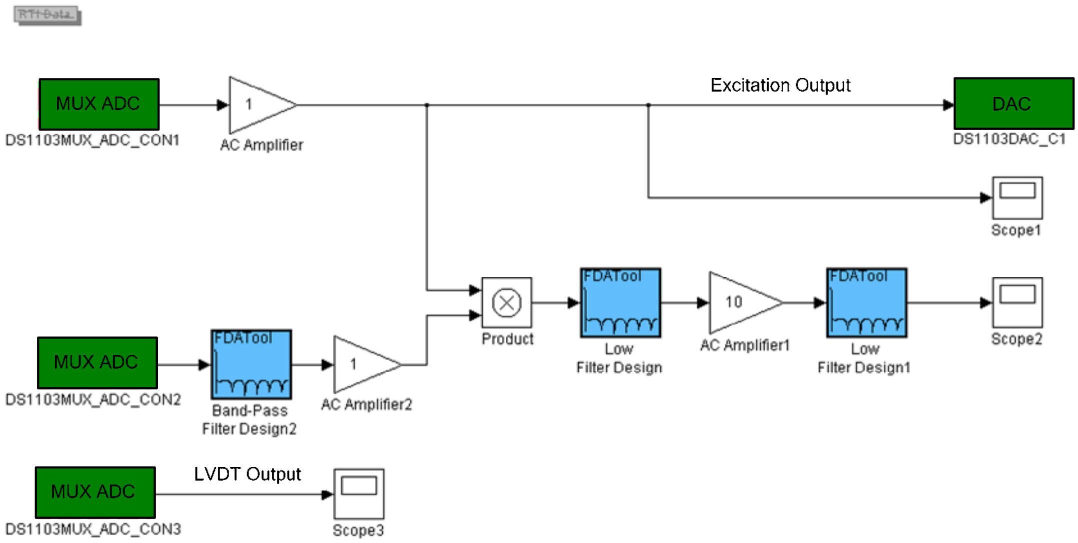


Figure 4. SIMULINK model of the electronic unit of the IRDS of the prototype of the self-sensing MR shock absorber.

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

In order to validate the sensory and damping performances of the prototype of the self-sensing MR shock absorber for the motorcycles, the experimental test setup was established based on the 849 shock absorber test system from the MTS and the DS1103PPC controller board from the dSPACE GmbH.

3-1. Experimental test setup

The photograph of the prototype of the self-sensing MR shock absorber installed on the 849 shock absorber test system companied with the linear variable displacement transducer (LVDT) is shown in figure 5. The test setup consists of three parts: (1) the prototype of the self-sensing MR shock absorber based on the RCP technique, (2) the measuring system for the sensing and damping performanes of the prototype of the self-sensing MR shock absorber, and (3) the 849 shock absorber test system.

According to figure 5, the LVDT, which is parallely installed with the prototype of the self-sensing MR shock absorber, is used to measure the movement of the rod of the prototype relative to the cylinder and acts as the reference for the IRDS of the prototype. The measuring system for the force versus displacement and the force versus velocity of the prototype of the self-sensing MR shock absorber relies on the 849 shock absorber test system, which also provides the displacement excitation to the tested prototype of the self-sensing MR shock absorber.

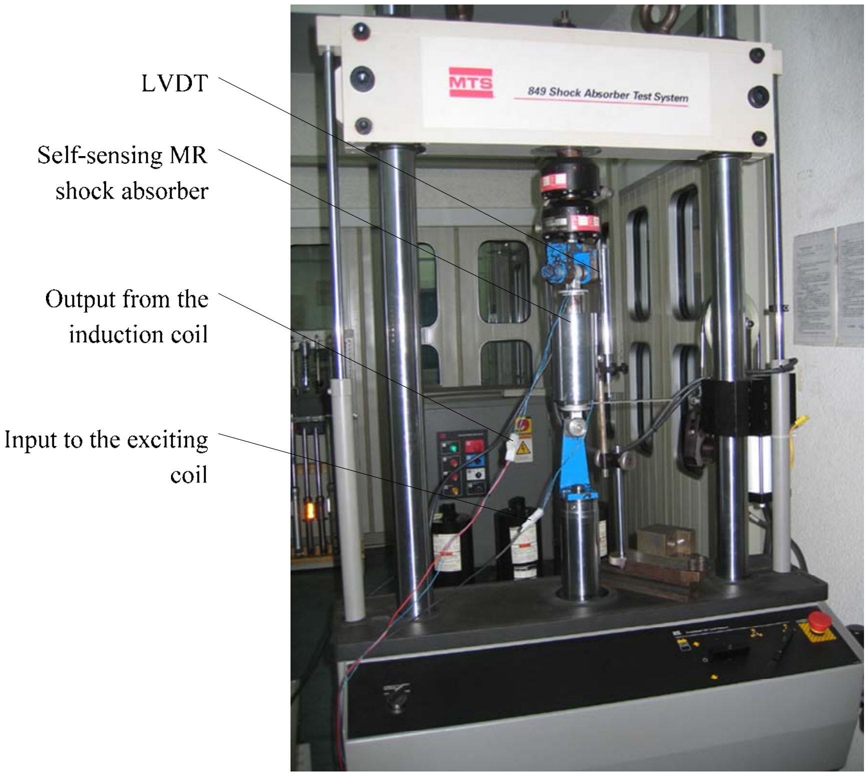


Figure 5. Photograph of the experimental test setup.

3-2. Sensing performances of the prototype of the self-sensing MR shock absorber

The experimentally measured time histories of the voltage from the IRDS of the prototype of the self-sensing MR shock absorber due to 1.00 Hz displacement excitation across it and six constant current levels to the exciting coil to obtain the different yield stress of the MR fluid are shown in figure 6. In order to compare, the time histories of the outputs from the LVDT are also presented. It should noted that the outputs from the IRDS and the LVDT represented the relative displacement across the self-sensing MR shock absorber. According to figures 6(a)-6(f), the outputs from the IRDS of the prototype of the self-sensing MR shock absorber don't vary with the variation of the currents to the exciting coil of the prototype of the self-sensing MR shock absorber. In addition, the outputs from the IRDS of the prototype of the self-sensing MR shock absorber can follow those from the LVDT although the outputs from the IRDS apparently lag behind those from the LVDT. The lag in time of the outputs of the IRDS is induced by the high-order digital low pass filter and the band pass filter of the MATLAB/SIMULINK model of the electronic unit of the IRDS of the prototype of the self-sensing MR shock absorber as shown in figure 4 when the prototype is established utizling the DS1103PPC controller board from the dSPACE GmbH. The influence of the order of the digital low pass filter and the band pass filter of the prototype of the self-sensing MR shock absorber on the sensing performance is shown in figures 7-9, in which the outputs from the IRDS of the prototype of the self-sensing MR shock absorber with different digitial low pass filter and band pass filter are shown. According to figures 7-9, the outputs from the IRDS of the prototype of the self-sensing MR shock absorber with the low-order digital low pass filter and band pass filter are apparently blurred by the noise while the lag in time is inapparent. However, the outputs from the IRDS with the high-order digital low pass filter lag behind those from the LVDT although the outputs are not blurred by the noise. When the electronic unit of the IRDS of the self-sensing MR shock absorber as shown in figure 4 is developed with the analog circuits, the lag phenomenon can be avoided.

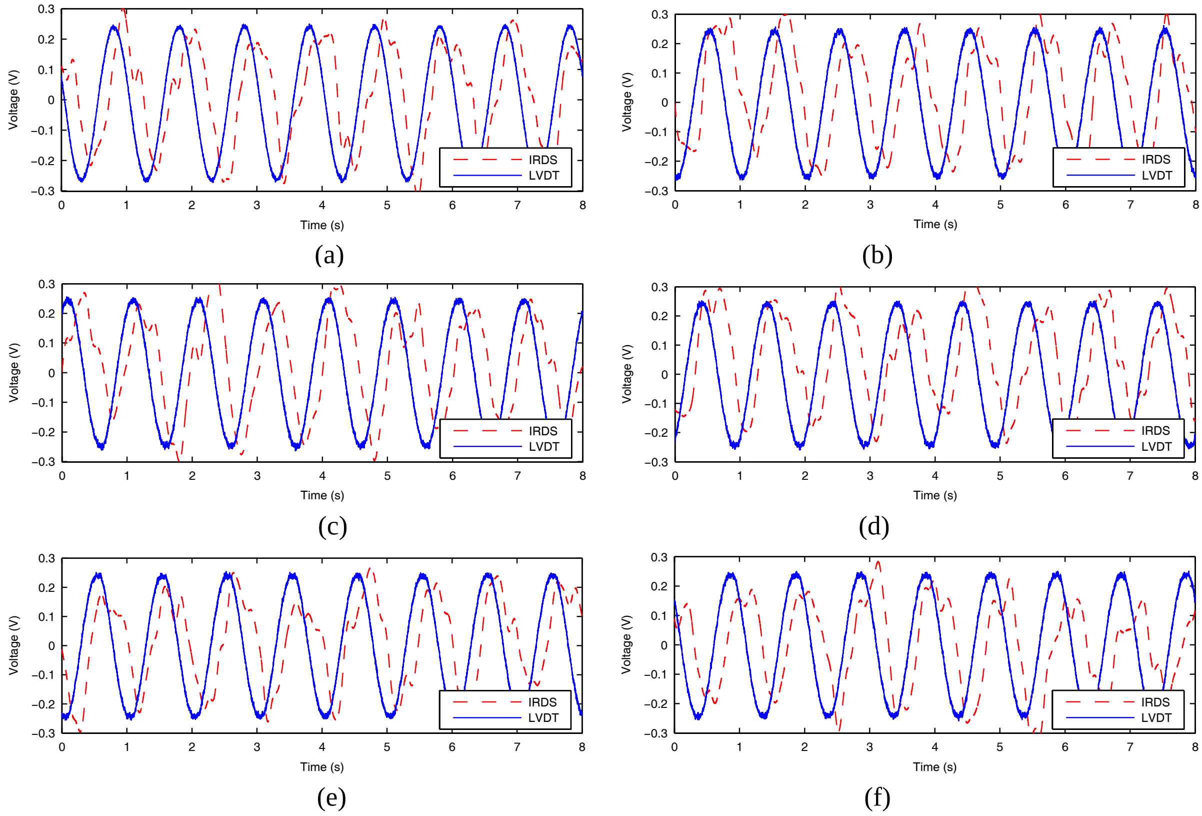


Figure 6. Measured time histories of the outputs from the IRDS of the prototype of the self-sensing MR shock absorber and the LVDT due to 1.00 Hz displacement excitation and different constant current levels to the exciting coil: (a) current = 0.00 A, (b) current = 0.20 A, (c) current = 0.40 A, (d) current = 0.60 A, (e) current = 0.80 A, and (f) current = 1.00 A.

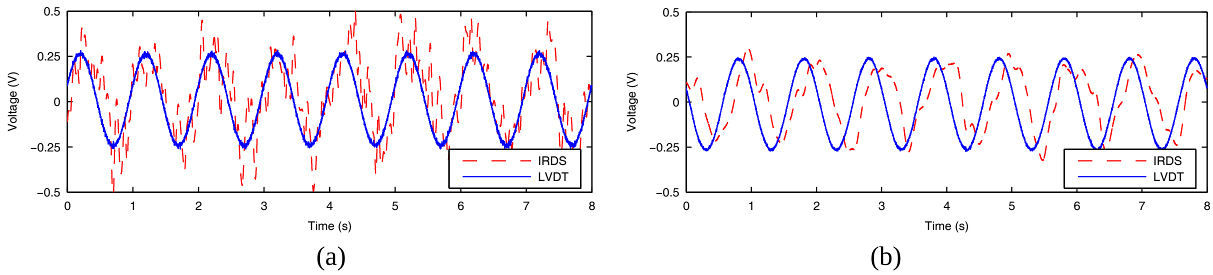


Figure 7. Measured time histories of the outputs from the IRDS of the prototype of the self-sensing MR shock absorber and the LVDT with 1.00 Hz displacement excitation, 0.00 A current, and different digital low pass filter: (a) order = 579 and (b) order = 1446.

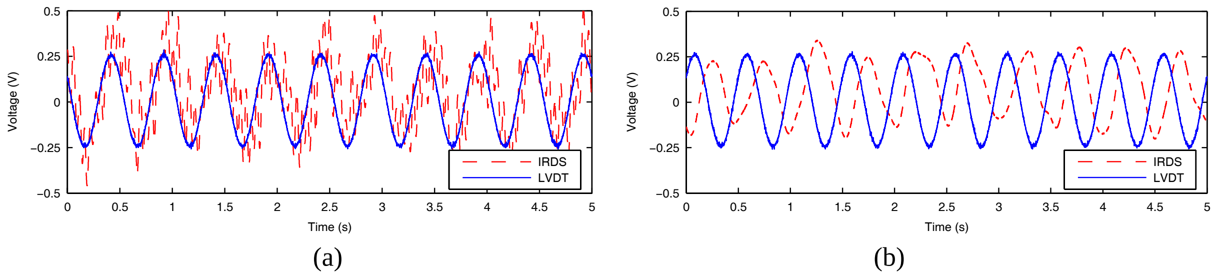


Figure 8. Measured time histories of the outputs from the IRDS of the prototype of the self-sensing MR shock absorber and the LVDT with 2.00 Hz displacement excitation, 0.00 A current, and different digital low pass filter: (a) order = 579 and (b) order = 1446.

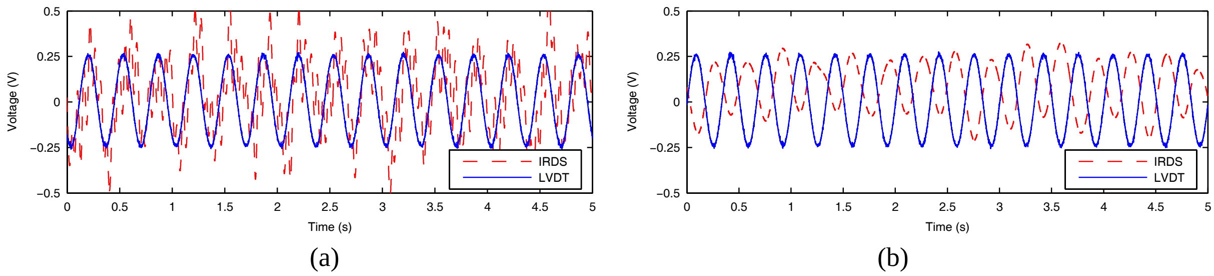


Figure 9. Measured time histories of the outputs from the IRDS of the prototype of the self-sensing MR shock absorber and the LVDT with 3.00 Hz displacement excitation, 0.00 A current, and different digital low pass filter: (a) order = 579 and (b) order = 1446.

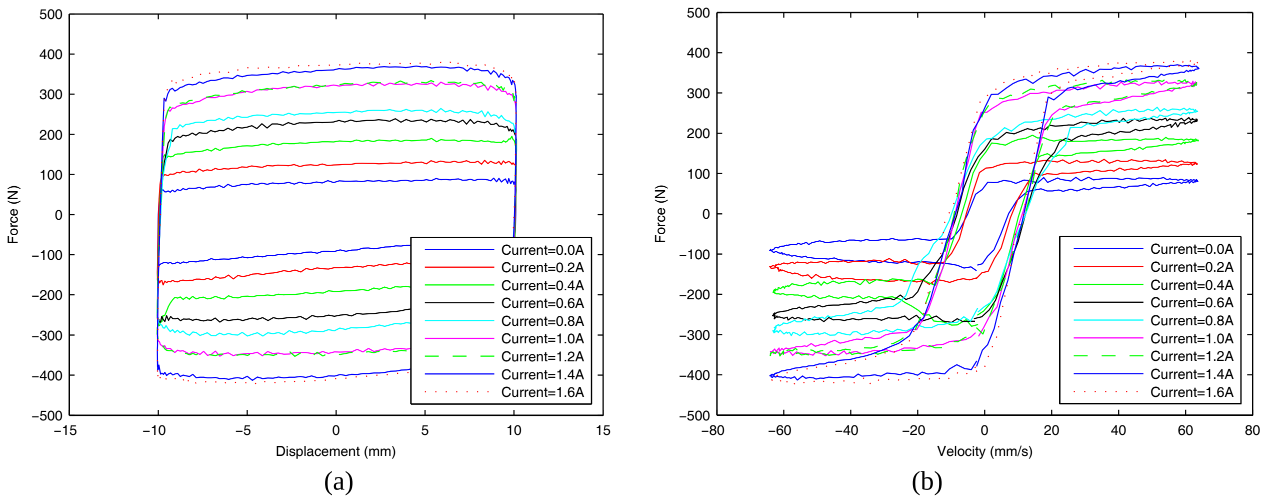


Figure 10. Measured damping forces of the prototype of the self-sensing MR shock absorber for motorcycles due to a 1.00 Hz sinusoidal displacement excitation with an amplitude of 10.00 mm under different currents: (a) force versus time and (b) force versus velocity.

3-3. Damping performance of the prototype of the self-sensing MR shock absorber

The measured damping forces of the prototype of the self-sensing MR shock absorber due to 1.00 Hz sinusoidal displacement excitation with an amplitude of 10.00 mm are shown in figure 10 for the nine constant current levels, 0.00 A, 0.20 A, 0.40 A, 0.60 A, 0.80 A, 1.00 A, 1.20 A, 1.40 A, and 1.60 A, provided by the current driver as shown in figures 2 and 3. The force-displacement loops and the force-velocity loops are shown in figures 10(a) and 10(b), respectively. Observing figure 10, the maximum damping force of the prototype of the self-sensing MR shock absorber is less than 100.00 N when the current from the current driver is 0.00 A and becomes larger than 300.00 N when the current is 1.60 A. The damping force of the prototype of the self-sensing MR shock absorber is apparently increased when the current to the exciting coil increases. Besides, the force-velocity diagram also exhibits highly nonlinear hysteresis.

4. CONCLUSIONS

In this paper, the prototype of a self-sensing MR shock absorber for motorcycles was designed and developed in order to realize the motorcycle rear suspension, with the following requirements: controllable damping, low cost, minimum installation space, and low weight. Based on the 849 shock absorber test system from the MTS and the DS1103PPC controller board from the dSPACE GmbH, the experimental test setup for the developed prototype of the self-sensing MR shock absorber was established and the damping and sensing capabilities of the prototype were tested. The results indicate that the developed prototype of the self-sensing MR shock absorber for the motorcycle rear suspension possesses the controllable damping forces under the current to the exciting coil and good relative displacement sensing capabilities. Moreover, the sensing performances of the developed prototype of the self-sensing MR shock absorber are not influencecd by the driving currents to the exciting coil to obtain the different yield stress of the MR fluid to change the damping forces. Utilizing the developed prototype of the self-sensing MR shock absorber, the semi-active controlled suspension systems can be developed without the use of extra sensors.

ACKNOWLEDGEMENTS

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