University of Wollongong

Research Online

Faculty of Engineering and Information Sciences - Papers: Part A

Faculty of Engineering and Information Sciences

1-1-2014

A variable stiffness and damping suspension system for trains

Shuaishuai Sun
University of Wollongong, ss886@uowmail.edu.au

Huaxia deng
Hefei University of Technology

Weihua Li
University of Wollongong, weihuali@uow.edu.au

Follow this and additional works at: https://ro.uow.edu.au/eispapers

Part of the Engineering Commons, and the Science and Technology Studies Commons

Research Online is the open access institutional repository for the University of Wollongong. For further information contact the UOW Library: research-pubs@uow.edu.au

A variable stiffness and damping suspension system for trains

Abstract

As the vibration of high speed train becomes fierce when the train runs at high speed, it is crucial to develop a novel suspension system to negotiate train's vibration. This paper presents a novel suspension based on Magnetorheological fluid (MRF) damper and MRF based smart air spring. The MRF damper is used to generate variable damping while the smart air spring is used to generate field-dependent stiffness. In this paper, the two kind smart devices, MRF dampers and smart air spring, are developed firstly. Then the dynamic performances of these two devices are tested by MTS. Based on the testing results, the two devices are equipped to a high speed train which is built in ADAMS. The skyhook control algorithm is employed to control the novel suspension. In order to compare the vibration suppression capability of the novel suspension with other kind suspensions, three other different suspension systems are also considered and simulated in this paper. The other three kind suspensions are variable damping with fixed stiffness suspension, variable stiffness with fixed damping suspension and passive suspension. The simulation results indicate that the variable damping and stiffness suspension suppresses the vibration of high speed train better than the other three suspension systems.

Keywords

system, suspension, trains, damping, variable, stiffness

Disciplines

Engineering | Science and Technology Studies

Publication Details

Sun, S., deng, H. & Li, W. (2014). A variable stiffness and damping suspension system for trains. Proceedings of SPIE: Active and Passive Smart Structures and Integrated Systems 2014 (pp. 1-12). United States: SPIE - International Society for Optical Engineering.

This conference paper is available at Research Online: https://ro.uow.edu.au/eispapers/2179

Variable Stiffness and Damping Suspension System for Trains

Shuaishuai Sun[a], Huaxia Deng*[b], Weihua Li**[a]

[a]School of Mechanical, Material and Mechatronic Engineering, University of Wollongong, NSW 2522, Australia

[b]School of Instrument Science and Opto-electronics Engineering, Hefei University of Technology, Hefei, Anhui, 230009, P.R.China

ABSTRACT

As the vibration of high speed train becomes fierce when the train runs at high speed, it is crucial to develop a novel suspension system to negotiate train's vibration. This paper presents a novel suspension based on Magnetorheological fluid (MRF) damper and MRF based smart air spring. The MRF damper is used to generate variable damping while the smart air spring is used to generate field-dependent stiffness. In this paper, the two kind smart devices, MRF dampers and smart air spring, are developed firstly. Then the dynamic performances of these two devices are tested by MTS. Based on the testing results, the two devices are equipped to a high speed train which is built in ADAMS. The skyhook control algorithm is employed to control the novel suspension. In order to compare the vibration suppression capability of the novel suspension with other kind suspensions, three other different suspension systems are also considered and simulated in this paper. The other three kind suspensions are variable damping with fixed stiffness suspension, variable stiffness with fixed damping suspension and passive suspension. The simulation results indicate that the variable damping and stiffness suspension suppresses the vibration of high speed train better than the other three suspension systems.

Keywords: Variable stiffness and damping suspension, MRF based air spring, MRF damper, Vibration mitigation, High speed train.

1. INTRODUCTION

High-speed trains are an efficient solution of the demand for high speed transportation in a globalized economy. Compared with other forms of transportation, high-speed trains stand out for they are friendlier to the environment, they have cheaper unit delivery costs and they are safer[1, 2]. However, as the speed of the train increases, a big challenge occurs that the train-induced vibration and noise increases significantly, which may lead to a series of problems such as ride comfort, environmental noise in the neighborhood, possible accumulated damage to buildings and stability[3].

For solving these issues, a well-designed passive suspension which has some advantage of design simplicity and cost effectiveness is commonly used. However as the parameters of passive damper is fixed, its performance on the wide frequency range and different rail conditions are limited. It is therefore crucial to develop a controllable suspension to address the issues.

Recently, semi-active suspension has gained considerable interests because it requires less energy and can adjust system parameters in real time[4, 5]. Semi-active suspension mainly contains variable stiffness spring or variable damping damper or both of them. In this paragraph, the variable damping damper filled with controllable fluids is reviewed. Electrorheological (ER) fluids and magnetorheological (MR) fluids are two typical controllable fluids which can change from a free flowing viscous fluid into semi-solid. Their composition without extra moving parts makes them simple and reliable. ER fluids are excited by high voltage, which limits its use in many areas because of safety concerns. Comparatively speaking, MR fluids only need a low voltage source to excite a magnetic field, which means a semi-active suspension with MR fluids is more suitable for high-speed trains. A Magnetorheological fluid (MRF) damper makes use of the unique characteristics of MR fluids whose mechanical properties can be quickly and reversely controlled by an external magnetic field. The research of MRF damper on train has been reported by a few groups. Wang and Liao did simulation and theoretical analysis in studying railway vehicles using MRF dampers[6, 7].

Another important part of semi-active suspension, variable stiffness suspension, is reviewed in this paragraph. The air spring which is a typical element for train to support the weight of car body will be mainly reviewed in this part. As we mentioned above, the passive air spring cannot satisfy all our need. Therefore, some researchers have investigated some active stiffness variable air spring. Graf proposed an active variable spring for heavy truck[8]. The experiment denotes that the active smart air spring can attenuate truck's vibration significantly. Chen developed a Parameter-self-adjusted

fuzzy control method for semi-active air spring suspension of vehicle[9]. Zhang proposed and investigated The Dynamics Characteristic and Active Control of Air spring for Railway Vehicle[10]. However, the existing active or semi-active air spring is mainly based on an air pump which enhances the effectiveness cost. Also the time delay of this system is relatively large and will decrease vibration control performance. Thus, it is critical to find a high speed response with low cost semi-active air spring for train. Also, although the semi-active damping suspension and semi-active stiffness suspension has been investigated, they combination as a variable stiffness and damping suspension has rarely studied before, especially for train.

In this paper, the effect of variable stiffness and damping suspension on train's vibration performance is studied. The schematic structure of the train with variable stiffness and damping suspension is illustrated firstly. Then the MRF damper and MRF based smart air spring are designed, fabricated respectively. Then, the train's secondary vertical dampers and air springs are replaced by MRF dampers and MRF based smart air springs to cope with the vertical vibration of the train body. A high-speed train model imbedded with an MRF damper and smart air spring is established by ADMAS software and the control strategy was built in MATLAB/SIMULINK. The train mounted with variable stiffness and damping suspension is evaluated by simulating on a random irregular track. As a compare, three other different suspension systems are simulated. Lastly, the simulation results are given to evaluate the vibration attenuation effectiveness of the variable stiffness and damping suspension.

2. STRUCTURE OF VARIABLE STIFFNESS AND DAMPING SUSPENSION SYSTEM

The train built in this part mainly contains a car body, two truck frames, and four wheelsets. As shown in Fig.1, the primary suspension system consisted of passive springs and dampers connect the wheelsets and truck frames. Similarly, the car body and truck frames are connected by smart springs and MR dampers in vertical direction and viscous dampers in lateral direction, which are considered as the secondary suspension system. The schematic structure of the variable stiffness and damping suspension is shown in Figure 2. In this system, accelerometers are used to measure the vertical acceleration of car body and truck frames in both left and right side of train. The acceleration measured by accelerometer is transferred to spring controller and damper controller respectively. Based on the acceleration signals, the controllers calculate the desired coil current for smart spring and MR damper. Then, the desired coil current will function as control signal to control the MR damper and smart spring.

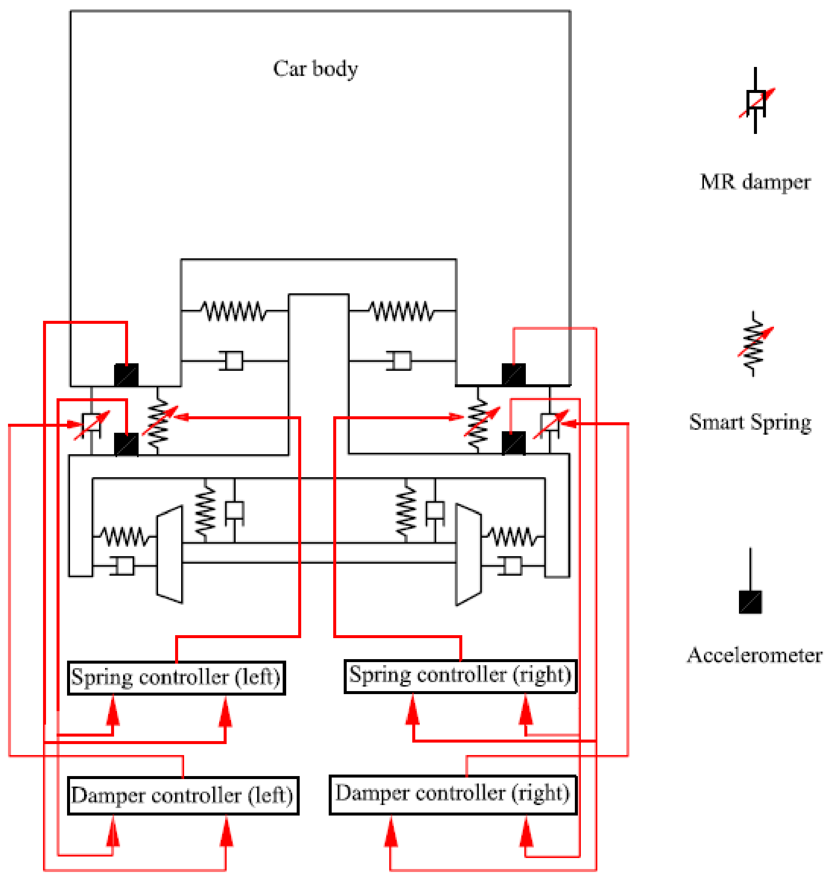


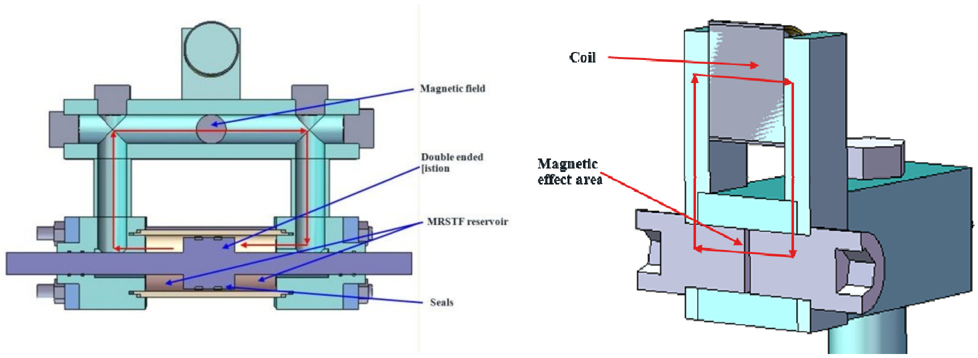
Fig.1 Structure of variable stiffness and damping suspension system

3. FABRICATION AND TESTING OF MRF DAMPER FOR TRAIN

Based on an oil cylinder, a bypass MRF damper is developed to replace the secondary vertical damper. Then the MRF damper is tested on a MTS machine under different current.

3.1 The structure of MRF damper.

The MRF filled damper was designed as shown in Fig.2 and Fig.3. This damper mainly consisted of piston head, piston rod, tube, MRF reservoir, bearing and seals and magnetic generation part, which is shown in Fig.2. The MRF will flow as the red line shown in Fig.2a when the piston head move from right to left and the MRF flow in the opposite way when the piston head move from left to right. On the bypass channel there is a coil which can generate electromagnetic field and affect the MRF's mechanical properties. The magnetic circuit is shown in Fig2b.



a b

Fig.2. The Cutaway view of bypass MRF damper

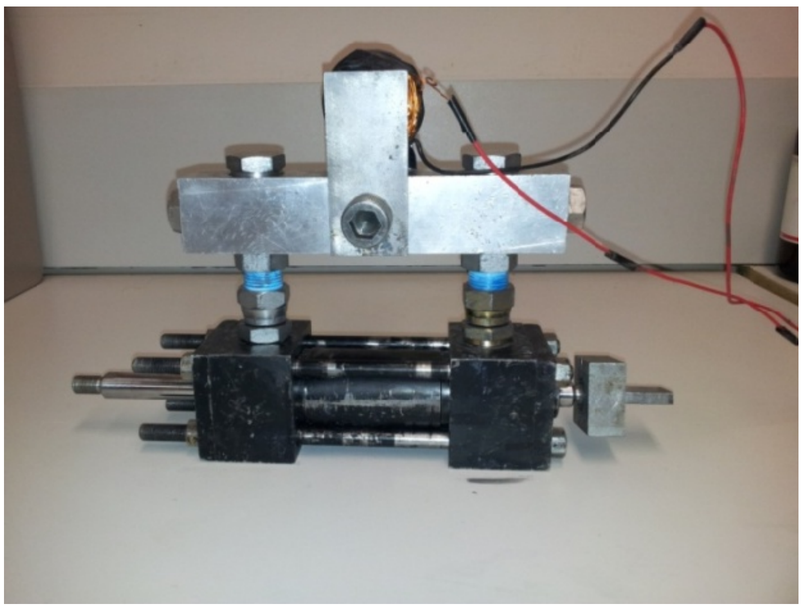


Fig.3. The structure of bypass MRF damper

3.2 Test of MRF damper

As shown in Fig.3. The prototype damper was clamped within an MTS machine. A load cell is mounted between the mounts and base. The MTS machine operates by servo hydraulic system capable of exerting large axial loads on the test specimen. The damper test system provides harmonic excitation to the damper and records force signals through the load cell. Then the signals were saved to a computer via a data acquisition (DAQ) board. The damper performance was tested under the simple harmonic motion (sine function). The MR effect is tested by altering applied coil current to vary its magnetic field. In this test, the excitation frequencies of MTS machine is 0.2Hz while the coil current varies from 0 to 2 A with 1A step.

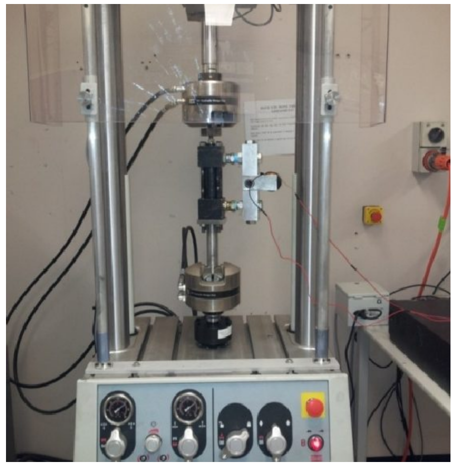


Fig.4 Test of MRF damper

Fig. 4 and Fig.5 show the measured force–displacement and force–velocity behaviors of the MR damper under sinusoidal excitations at various input current levels. Figure 9(a) shows the MR damper behaviors under a 20 mm, 0.5 Hz sinusoidal displacement excitation. From this figure, it can be seen that the MR damper can increase its peak force from 579 N at 0 A to 1893 N at 2A.

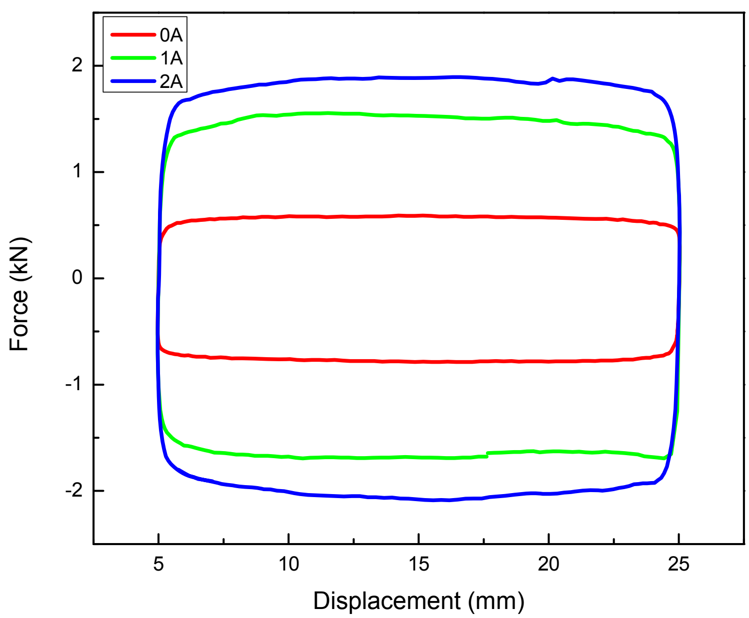


Fig.5. Damping force versus displacement under different current

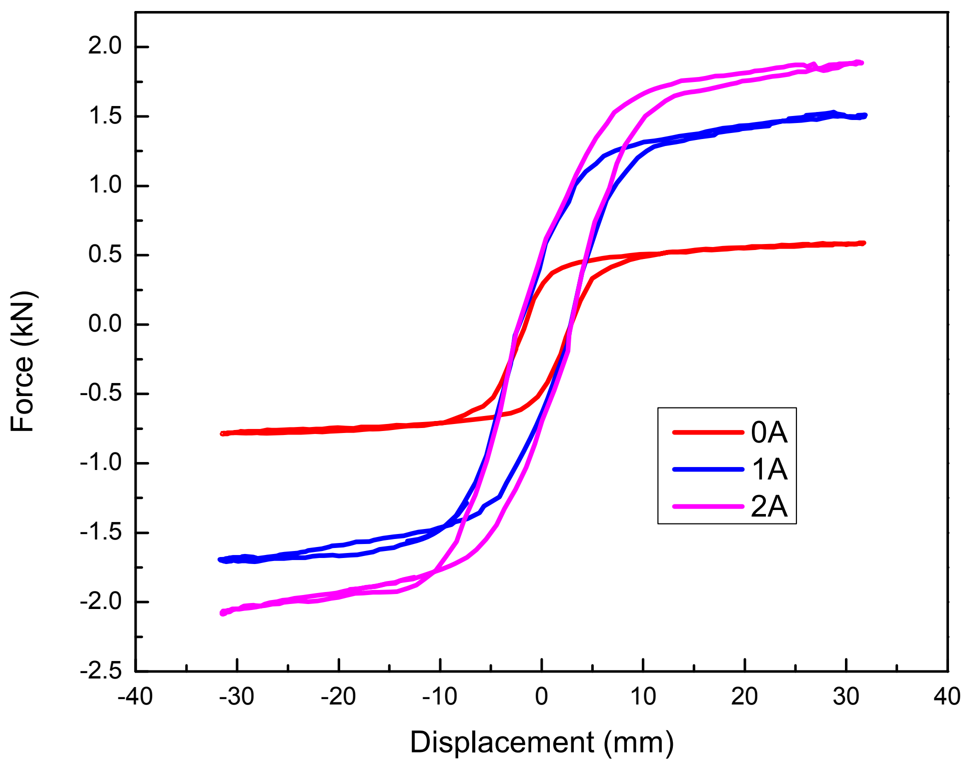


Fig.6. Damping force versus velocity under different current

4. FABRICATION AND TESTING OF A STIFFNESS VARIABLE AIR SPRING FOR TRAIN

4. 1 The structure and working principle of the stiffness variable air spring

The developed MRF based air spring is shown in Fig.7. The proposed smart spring is composed of two variable volume rubber bladders filled with MR fluid, a pipe and a MR valve connecting them. One of the bladders supports a disturbance force and MR fluid flows between two bladders because of the variation of bladder volume due to deformation. The shear stress of the MR fluid in MR valve is varied by the applied magnetic field, which thereby varies the characteristics of the smart spring.

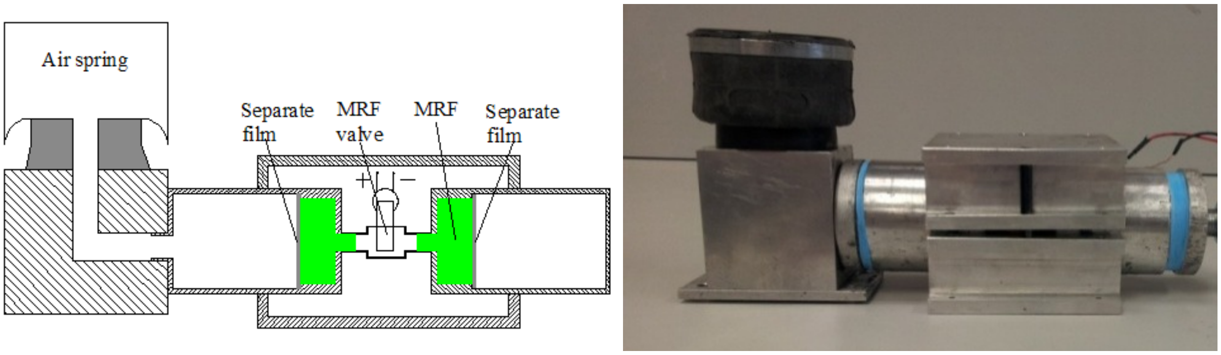


Fig.7. Schematic and structure of the MRF isolator system.

4. 2 Test and result of the stiffness variable air spring

The stiffness variable air spring is tested on MTS machine similar with MRF damper. The test result is shown in Fig.8. From the figure we can see that the air spring can vary its stiffness from 14000N/m to 22700N/m. This is a scaled air spring for train. When it is enlarged 10 times, it is a perfect choice to suppress train's vibration and the 10 times scale-up data is used in the simulation in the following part.

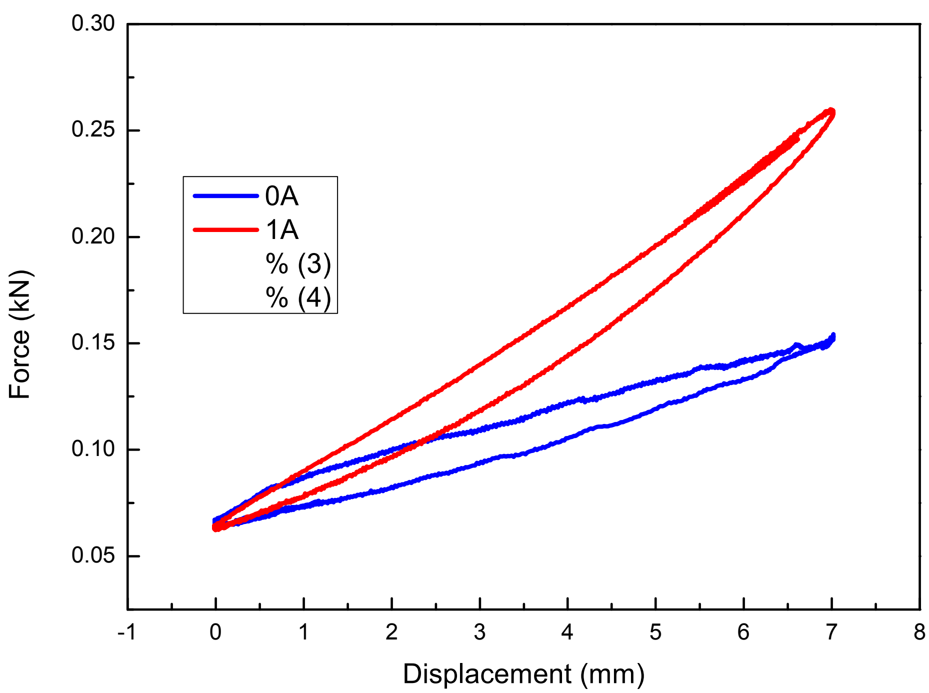


Fig.8 Test result of smart air spring

5. SIMULATION OF HIGH SPEED TRAIN WITH VARIABLE STIFFNESS AND DAMPING SUSPENSION

In this section, variable stiffness and damping suspension systems are discussed. As compare, three other different suspensions are also simulated which are variable damping with fixed stiffness suspension, variable stiffness with fixed damping suspension and passive suspension.

5.1. Modeling of a high-speed train

In order to establish the dynamic model of the high-speed train, software called ADAMS/RAIL is used in this research because it contains detailed models of suspension components such as the wheelset, bogie frame, train body, and so on. The model established in this paper is a two-axle railway vehicle containing a front truck and rear truck frame. The primary suspension consists of four primary vertical dampers and four primary vertical springs while the secondary suspension consists of two secondary vertical dampers, two secondary vertical springs, and secondary lateral dampers.

5.2 control strategy

The control strategy involved in this paper contains two parts. The first part is the MR damper control algorithm. The main purpose of the MR damper controller is to determine the desired damping. The control strategy adopted in this article is sky-hook. Details of the sky-hook control strategy are as follows

$$\mathrm{F} = \begin{cases} -c_{\max}(\dot{x} - \dot{x}_o) & \dot{x}(\dot{x} - \dot{x}_o) \geq 0 \\ -c_{\min}(\dot{x} - \dot{x}_o) & \dot{x}(\dot{x} - \dot{x}_o) < 0 \end{cases} \tag{1}$$

The second item is the controller of smart spring which is functioned as variable stiffness spring. The control method adopted to track the desired spring force is sky-hook. The spring force control scheme is proposed as

$$\mathrm{f}_s = \begin{cases} -k_{max}(x - x_o) & \dot{x}(x - x_o) \geq 0 \\ -k_{min}(x - x_o) & \dot{x}(x - x_o) < 0 \end{cases} \tag{2}$$

Where f_s is the spring force, the stiffness k_{max} is the on-state stiffness and k_{min} is in the off-state, and $x - x_0$ is the relative displacement of the spring. The on-off spring force is controlled by the sign of $\dot{x}(x - x_0)$. When $x - x_0$ is positive, the spring is extended and can generate a downward force for the mass. When $\dot{x}$ is positive, the mass moves upwards. Thus, the spring can exert a force to reduce $\dot{x}$. When $\dot{x}$ is negative, the mass moves downwards. In this case, the best spring can do is to supply no force as the passive spring cannot generate an upward force. When $x - x_0$ is negative, the

control logic is described similarly as the above process.

The dynamic model of the high-speed train is established in ADAMS, while the control strategy, MR damper model and smart spring model are built in MATLAB. Since ADAMS and MATLAB are compatible, the semi-active train is established by integrating the MR damper and smart spring model built by MATLAB with the railway vehicle suspension system built by ADAMS.

5.3 Simulation results and discussions

As mentioned above, four different type suspensions are simulated in this paper. In this simulation, the train runs on random irregular track at the speed of 250km/h. The simulation parameter of MR damper and smart spring is based on the test result presented in section 3 and section 4. The simulation results shows in Fig.9

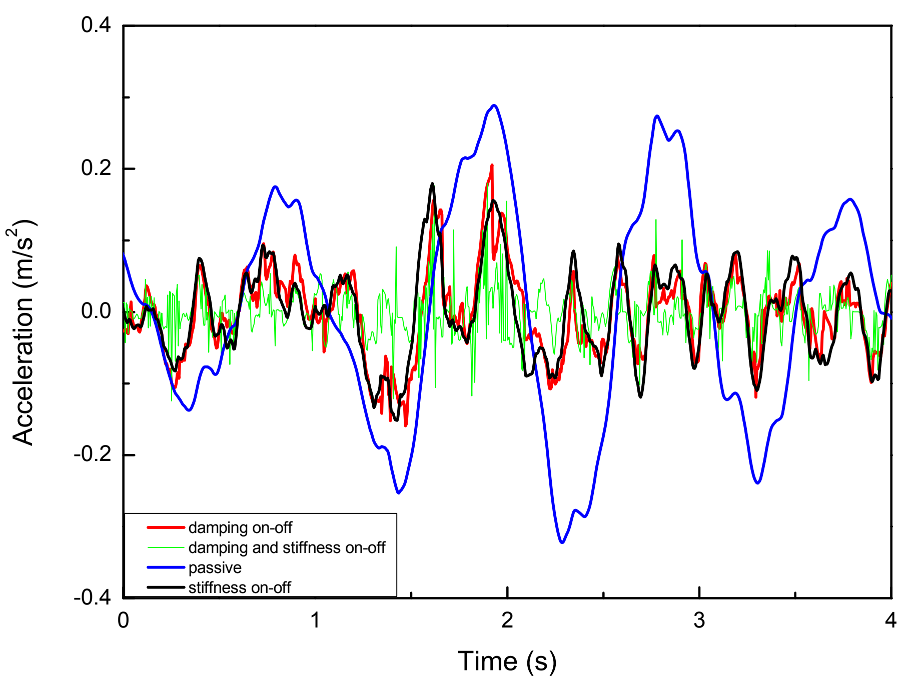


Fig. 9 Response of the four different suspensions

By compare the passive suspension with damping on-off suspension and stiffness suspension, it can be seen that the both variable damping and variable stiffness contribute to further suppress train's vertical vibration. It also can be concluded that the suspension with variable stiffness and damping can further attenuate train's vibration

compared with stiffness variable suspension or damping variable suspension.

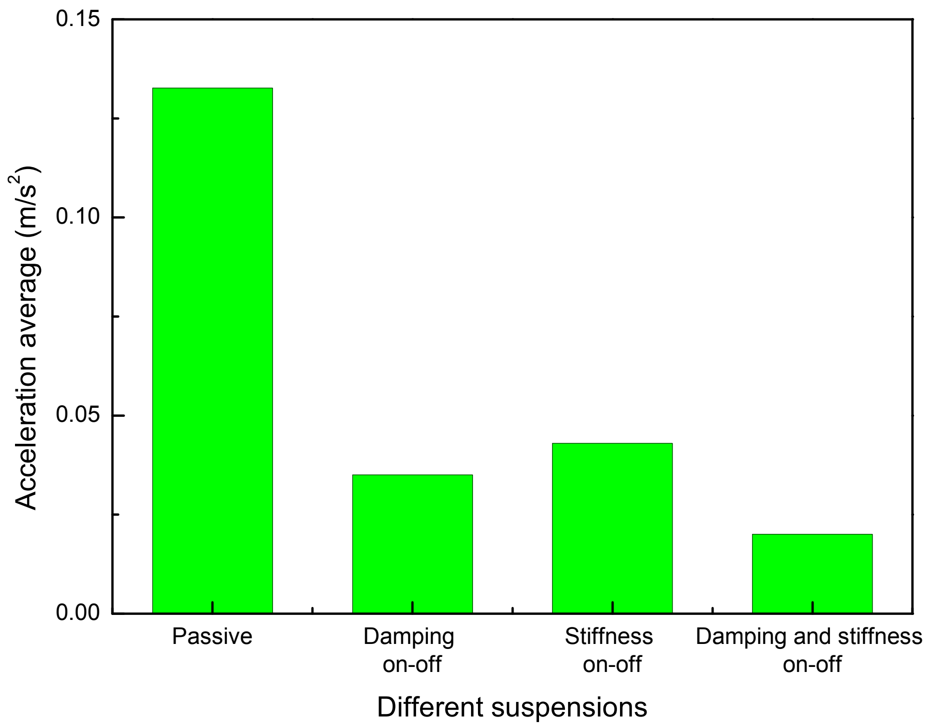


Fig.10 The compare of the four different suspensions

Fig.10 shows the average of the absolute value of vertical acceleration. From this figure, it can be seen that suspension with damping on-off decreases the vertical vibration by 73.6% while the variable stiffness suspension can further attenuate train's vibration by 67.5% compared with passive suspension. The variable damping and stiffness suspension are most efficient on train vibration suppression and its vibration attenuation effectiveness reaches 84.9%.

6. CONCLUSION

In this paper, the MRF damper and MRF based air spring is developed and tested firstly. The testing results denote they perform well in varying damping and stiffness. Based on the test results, the MRF damper is used to replace the secondary vertical damper while the MRF based air spring is applied to replace the secondary vertical spring to further suppress train's vibration. The train mounted with this damping and stiffness variable suspension is simulated by

ADAMS software. The test result illustrates the variable stiffness and damping suspension performs best on train's vibration attenuation compared with other suspensions.

ACKNOWLEDGEMENTS

Funding for this workis provided by the National Natural Science Foundation of China (No. 51205100, No. 51328502), 111 project (No. B12019) and the University of Wollongong-China Scholarship Council joint scholarship (grant no.201206430031). These financial supports are gratefully acknowledged.

REFERENCE

[1] M. Givoni, "Development and Impact of the Modern High‐speed Train: A Review," *Transport reviews,* vol. 26, pp. 593-611, 2006.

[2] C. E. Hanson*, et al.*, "High-speed ground transportation noise and vibration impact assessment," 2012.

[3] R. S. Raghunathan*, et al.*, "Aerodynamics of high-speed railway train," *Progress in Aerospace sciences,* vol. 38, pp. 469-514, 2002.

[4] E. Elbeheiry and D. Karnopp, "Optimal control of vehicle random vibration with constrained suspension deflection," *Journal of sound and vibration,* vol. 189, pp. 547-564, 1996.

[5] T. Gordon, "Non-linear optimal control of a semi-active vehicle suspension system," *Chaos, Solitons & Fractals,* vol. 5, pp. 1603-1617, 1995.

[6] D. Wang and W. Liao, "Semi-active suspension systems for railway vehicles using magnetorheological dampers. Part I: system integration and modelling," *Vehicle System Dynamics,* vol. 47, pp. 1305-1325, 2009.

[7] D. Wang and W. Liao, "Semi-active suspension systems for railway vehicles using magnetorheological dampers. Part II: simulation and analysis," *Vehicle System Dynamics,* vol. 47, pp. 1439-1471, 2009.

[8] C. Graf and J. Maas, "Commercial vehicle cabin with active air suspension for improved ride comfort," in *Advanced Intelligent Mechatronics (AIM), 2011 IEEE/ASME International Conference on*, 2011, pp. 259-264.

[9] C. Y*, et al.*, "Parameter-self-adjusted fuzzy control method applied to semi-active air spring suspension of vehicle," *Journal of Jilin University of Technology (Natural Science Edition),* vol. 3, 2003.

[10] L. Zenghua, "Study on the Dynamics Characteristic and Active Control of Airspring on Railway Vehicle " *Southwest jiaotong university,* vol. PhD thesis, 2007.