A Study on Integration of Energy Harvesting System and Semi-Active Control for a Hydraulic Suspension System

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Abstract

Suspension systems are used to diminish the vibration of vehicles. The hydraulic dampers in conventional suspension systems are mainly designed with the orifices of the piston; however, the vibration energy will be transferred into waste heat. In recent years, conventional vehicles with internal combustion engines and hybrid vehicles are used commonly. However, with the gradual depletion of fossil fuels, electric vehicles are developing. For this reason, the research focuses on recycling energy from the suspension of vehicles to improve the vehicle's endurance. The purpose of this study is to develop a semi-active suspension control system with an energy harvesting system. Instead of the fixed orifices in conventional vehicles, an adjusting damping force method with variable resistance circuits system is studied for the semi-active suspension control system. Thus, we are able to develop semi-active control to improve the riding comfort. The energy harvesting system contains a hydraulic gear motor and a DC generator. When vehicles vibrate, the hydraulic damper serves as a hydraulic pump to compress the oil and drive the hydraulic motor. At the same time, the hydraulic motor drives the generator to generate electricity which will be stored in a battery. In this study, the test rig is the quarter-car system. We first design the novel hydraulic suspension system combining with the energy harvesting system. The simulation of dynamic mathematical model will be performed and analyzed by MATLAB/Simulink. Besides that, the semi-active control by the fuzzy sliding mode controller will be realized in the hydraulic suspension system with energy harvesting system. Finally, a test rig is set up for practical experimental implementation and verification.

1. Introduction

In recent years, environmental pollution and the depletion of oil have become key global issues as a result of global warming caused by rapid technological advancements and economic growth. In order to address these issues, most countries have committed themselves to the research on renewable energy, such as solar energy, wind energy, wave power, geothermal energy, and tidal power, and also on other technologies designed to improve energy efficiency.

Especially, the main culprits behind global warming are vehicles which emit greenhouse gases but undeniably, play an indispensable role in our daily life. With the growing emphasis on the green concept and steep petroleum prices, the Hybrid Electric Vehicle (HEV) was invented to tackle these issues. However, these HEVs still consume oil therefore, the Battery Electrical Vehicle (BEV) which is fully battery-powered, is developing. While the BEV seems to offer the solution to our problems, it is not feasible yet, given the existing problems such as battery technology, low energy density, and low penetration.

For this reason, this research will focused on the recycling energy for electric vehicles. A key aspect of research in vehicles has always been to increase the vehicle's endurance, and the regenerative braking system is commonly used in the recent years. In order to improve the vehicle's endurance, the kinetic energy produced upon breaking is recycled to enhance the battery's endurance.

The vibrations felt by passengers when the vehicle is driven over an uneven road surface are also a kind of energy. These vibrations caused by road irregularities occur mainly in the vertical direction and the shock absorber, an energy dissipating device, is used in parallel with the suspension spring to reduce these vibrations. However, if we can transmit this vibration energy to the generator, it can be converted to electrical energy which can then be stored in the battery. Hence, an innovative energy recovery system have developed to further improve the vehicle's shock absorber with the hydraulic system. The vibration energy of moving vehicles can be recycled to increase the endurance of the electric vehicles. In addition, the passenger's comfort has also been taken into consideration, thus the semi-active control is also investigated.

The development of suspensions for vehicles has received increasing attention in recent years both theoretically and experimentally. Suspensions may be classified into three distinct configurations, such as passive, semi-active and active.

A passive suspension system is has un-adjustable characteristics of the components. The damping coefficient is decided by the number of orifice on the piston. It has simple structures, but the damping coefficient is not adjustable for considering riding comfort and handling stability at the same time. In 1981, Segel and Lang /1/ used the relationship between force and piston speed to test the performance of vehicles; in 1983, Vliet and

Sankar /2/ applied the force-displacement (F-D) diagrams to analyze the damping force of the motorcycle shock absorber.

Active suspensions are capable of both supplying and dissipating power through an active actuator, unlike a passive damper, which can only dissipate energy. With an active suspension, the damper works as an active actuator that can generate force and displacement in the suspension. Through suitable control strategy, better compromise between riding comfort and vehicle stability can be achieved. In 1990, Satoh *et al.* /3/ analyzed the hydraulic system functions required in an active suspension built with an electro-hydraulic pressure control system. However, active suspensions are costly as they need external power and have complicated structures.

Semi-active suspensions can only dissipate power by means of a controllable damper, and is operated by a set of sensors. Semi-active control is an increasingly important method of control, which is used in a wide range of structural control applications. For example, in 2000, Kitching /4/ used a simple proportional valve to generate the variable damping coefficient and the detrimental effects of the oil flow forces acting on the valve spool in conventional suspensions. In 2002, Yao *et al*. /5/ proposed a semi-active control of vehicle suspension system with a magneto-rheological (MR) damper and tested the performance of the damper. In 2010, Collette and Preumont /6/ analyzed the effect of unintended high frequency excitations generated by the semi-active skyhook control algorithm on the isolation properties of a car suspension.

Energy harvesting has become an important subject for the past decades. One of the solutions is to recover energy. The research on energy recovery from vehicle suspensions began more than ten years ago. In 1992, Fodor and Redfield /7/ showed that the energy regenerative damper could be realized by the use of their proposed variable linear transmission (V.L.T.). They examined the characteristics of V.L.T. in detail by numerical simulations, but experimental approach was not achieved. In 2003, Nakano *et al.* /8/ also investigated the self-power vibration control using a single motor, in which a variable resistor, a charging capacitor and relay switches were used to control the motor force to achieve the desired skyhook damping force. To further magnify the motion and increase efficiency, in 2007, Zhang Y *et al*. /9/ used absorbers composed of ball screw and rotational electric motors to recycle energy. In 2009, Avadhany /10/ inputted oil to a hydraulic motor on one direction by means of oil circuit arrangement. This concept has been applied by the Levant Power Corporation to design a new absorber which was used in the HMMWV of American military.

2. Test rig layout

The quarter-car system is used to simulate the actual characteristics of a driving vehicle. The car body will vibrate according to the different heights of the road. In conventional suspension systems, the damper coefficient is decided by the orifices of the piston.

In the variable resistance system, the variable electric resistance circuits are installed to regulate the generator. Thus, the counter-electromotive force (counter-EMF) will increase to slow down the DC generator with coupled with hydraulic motor. At the same time, the speed of flow through hydraulic motor will drop. Hence, the damping effect of the damper will be enhanced at once. The electric energy generated from the generator can be stored in a battery.

Based on the proposed concept, an integrated test rig is established in **Fig.1**, which can be divided into three parts, such as the hydraulic vibration exciting system, the hydraulic damper system, and the energy harvesting system. The hydraulic vibration exciting system is used to provide the shock absorber with external disturbance according to the conditions of road. It consists of a hydraulic cylinder, a servo valve, a hydraulic power source, DAQ cards, and a PC-based controller.

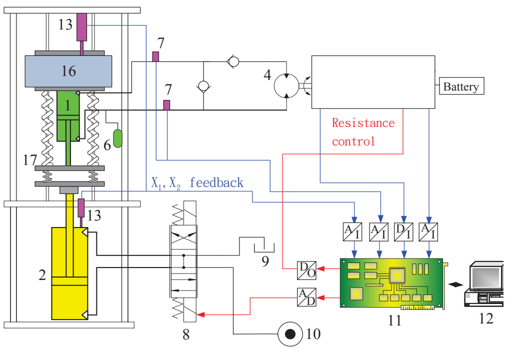

Figure 1: Layout of quarter-car system with variable resistance control

The third part is the energy harvesting system. A hydraulic motor is installed in the hydraulic circuit to drive the DC generator; the electricity will be recycled and stored in the low-voltage battery. The feedback signals of the motor speed and generator current will be respectively detected by proximity switch and current sensor. The variable resistance circuit is consisted of 8 cement resistors and a 16-ch relay board. By binary logic, the resistance value could be continuous. The range of the resistances is between 0 ~ 255 ohm. As long as the hydraulic motor rotates in one direction, the generating current is the direct current. As the piston moves upward, the oil will drive the motor. However, when the piston moves downward, the oil will flow into the damper directly.

The main goal of the research is to simulate the real condition of the vehicle, instead of the skyhook damper system (one degree of freedom); therefore, the quarter-car system (two degrees of freedom) is used. The wheel mass is considered in the concept. A typical schematic of semi-active suspension system represents two-DOF model of vibration system that is the quarter part of a vehicle. The hydraulic damper and suspension spring k_2 are mounted between the sprung mass and the wheel mass. The suspension spring is considered a linear spring. The tire is lumped to be a linear spring element k_1.

3. Controller design

3.1 Intelligent controller

In the conventional fuzzy control system, the rules are composed by using the error *e* and the rate of error $\dot{e}$, but we have compressed these two types of information into one, noted by a variable σ . That is to say, we are only using one variable as opposed to using two variables, the error and the rate of error, used in the antecedents of the fuzzy rules in the past researches. The rationale for doing so is to reduce the dimension of the input space and the number of fuzzy rules. The fuzzy rules of the proposed fuzzy controller are generated by using the proposed fuzzy sliding surface.

The fuzzy sliding surface comprises of two parts: sliding surface estimator and fuzzy controller. (i) Sliding surface estimator: Transforming the feedback signals to error *e* and the rate of error $\dot{e}$, we take *e* and $\dot{e}$ to sliding surface function σ ,

$$\sigma = \alpha \cdot e + \dot{e} \tag{1}$$

that we had earlier designed. (ii) Fuzzy controller: This is a basic fuzzy logic controller that uses the sliding surface σ to replace the conventional fuzzy control parameter, the error *e* and the rate of error $\dot{e}$. Moreover, the control target is not $e \to 0$ and $\dot{e} \to 0$ anymore but rather $\sigma = \alpha \cdot e + \dot{e} \to 0$. Thus, output states will slide on the sliding surface and finally approach the default target.

In general, the judgment inputs are replaced from $e = 0$ and $\dot{e} = 0$ to $\sigma = \alpha \cdot e + \dot{e} = 0$ in the fuzzy sliding rules base. Therefore, the difficulties of designing traditional fuzzy control rules have decreased significantly. If we let the system states maintain on sliding surface $\sigma = \alpha \cdot e + \dot{e} = 0$, the system final output will converge to target value.

After choosing a suitable fuzzy controller, we have to design the sliding surface to be applied in different control systems. There are 49 rules in 7×7 rule base of conventional fuzzy controller. Φ is the boundary of convergence area on fuzzy sliding surface $\sigma = \alpha e + \dot{e} = 0$. Fine-tuning of Φ value is dependent on FSMC control input and the operation of actual systems.

Fuzzy sliding surface controller design does not require a mathematical model of the system; thus, it can be used for experimental estimation to tune the most appropriate value. These parameters will affect the dynamic response and performance of the system, so we must make adjustments depending on the actual situation.

4. Skyhook control strategy for quarter-car system

The skyhook control strategy is necessary to use in quarter-car system since it is a two-DOF model. The damping effect and ride comfort are both concerned. However, it is not the most efficient when the damping value reaches the maximum value. The skyhook control, introduced by Karnopp in 1995, provides an effective solution in terms of the simplicity of the control algorithm. In this way a fictitious damper is inserted between the sprung mass and the stationary sky as a way of suppressing the vibratory motion of the sprung mass and as a tool to compute the desired damping force.

This control strategy can be described as follows:

If $\dot{x}_2(\dot{x}_2 - \dot{x}_1) \geq 0$, then the bigger damping is required.

If $\dot{x}_2(\dot{x}_2 - \dot{x}_1) < 0$, then the minimum damping is required.

This strategy indicates that if the relative velocity of the sprung mass with respect to the wheel mass is in the same direction as that of the sprung mass velocity; then a bigger damping force should be applied to reduce the sprung mass acceleration. The damping force is depending on the error e and the rate of error $\dot{e}$. On the other hand, if the two velocities are in the opposite direction, the damping force should be at a minimum to minimize the acceleration of the sprung mass. At the same time, the hydraulic damper is compressed to recycle energy. This control strategy requires the measurement of the absolute velocity of the sprung mass. Although the accurate measurement of the absolute vibration velocity of the sprung mass on a moving vehicle is very difficult to achieve, it is easy to do for the laboratory experiment in order to evaluate the performance of damper.

The error e and the rate of error $\dot{e}$ can be obtained for the fuzzy sliding mode controller to output control signal u ; therefore, according to the control signal, the actual resistance *R* can be regulated to adjust the damping force for achieving the desired velocity. In this thesis, the adjusting range of resistance is set from 0 to 100Ω. The resistance required can be calculated by Eq. (2). If control signal u is zero, the resistance will be 100Ω.

The definition of actual resistance value R is shown as

$$R = 100 - u \tag{2}$$

5. Experimental results

In this section, the experimental results of resistance control for the quarter-car system are described. The different vibration conditions are applied to simulate actual driving situations. The load of test rig is 80kgf and the mass of wheel is 10kgf. **Figure 4 to Figure** 4 show the experimental results in 0.02 m pulse vibration. **Figure 1** shows the displacement input for quarter-car system of $X(t) = 0.02m$ pulse. **Figure 2** indicates the experimental results of semi-active control for quarter-car system in vibration of pulse $X(t) = 0.02m$, including (a) input power, (b) output power, and (c) output current. Through the semi-active control, the output power can be reduced obviously. Besides, the output power generated by the DC generator can be obtained. **Figure 3** shows the experimental results of semi-active control for quarter-car system in vibration of pulse $X(t) = 0.02m$, including (a) output displacement, (b) output speed, (c) output acceleration, and (d) resistance signal. The comparisons of experimental results of semi-active control for quarter-car system with the vibrations are described in Table 1.

Through the semi-active control, the car body speed can be reduced by 13.3%; the acceleration can be diminished by -9.2%; the $PSD_{acc,peak}$ can be reduced by 33.7%. The electric power regeneration can also achieved 12.1% with the semi-active control. The results of the semi-active control system have demonstrated that the speed and the acceleration power spectral density (PSD) are significantly reduced. The time of comfortable riding has been extended in Meister chart. Although the efficiency of energy harvesting attain to 10%~30%, the harvesting energy is little due to light weight of the load and limit of the test rig.

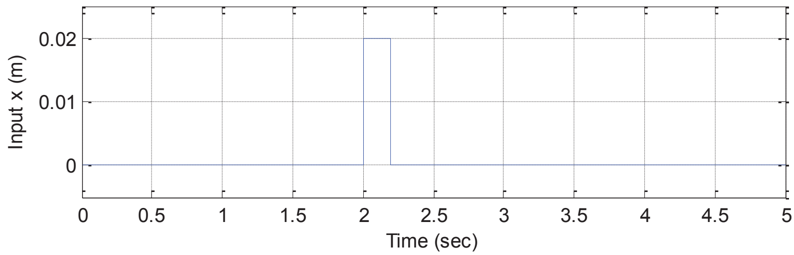

Figure 4: Displacement input for quarter-car system $X(t) = 0.02m$ pulse

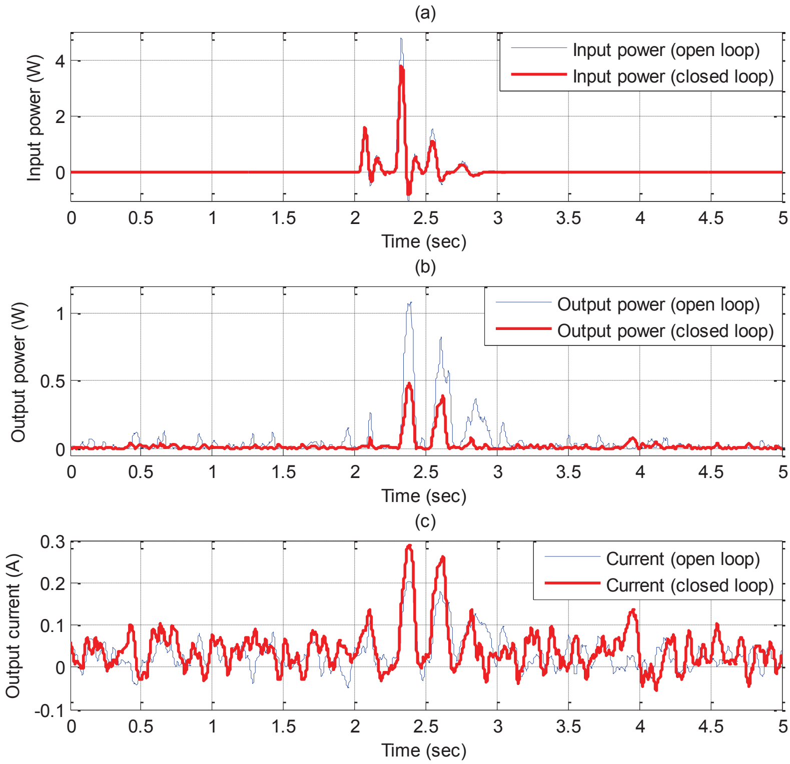

Figure 5: Experimental results of semi-active control for quarter-car system in vibration of pulse $X(t) = 0.02m$: (a) input power (b) output power (c) output current

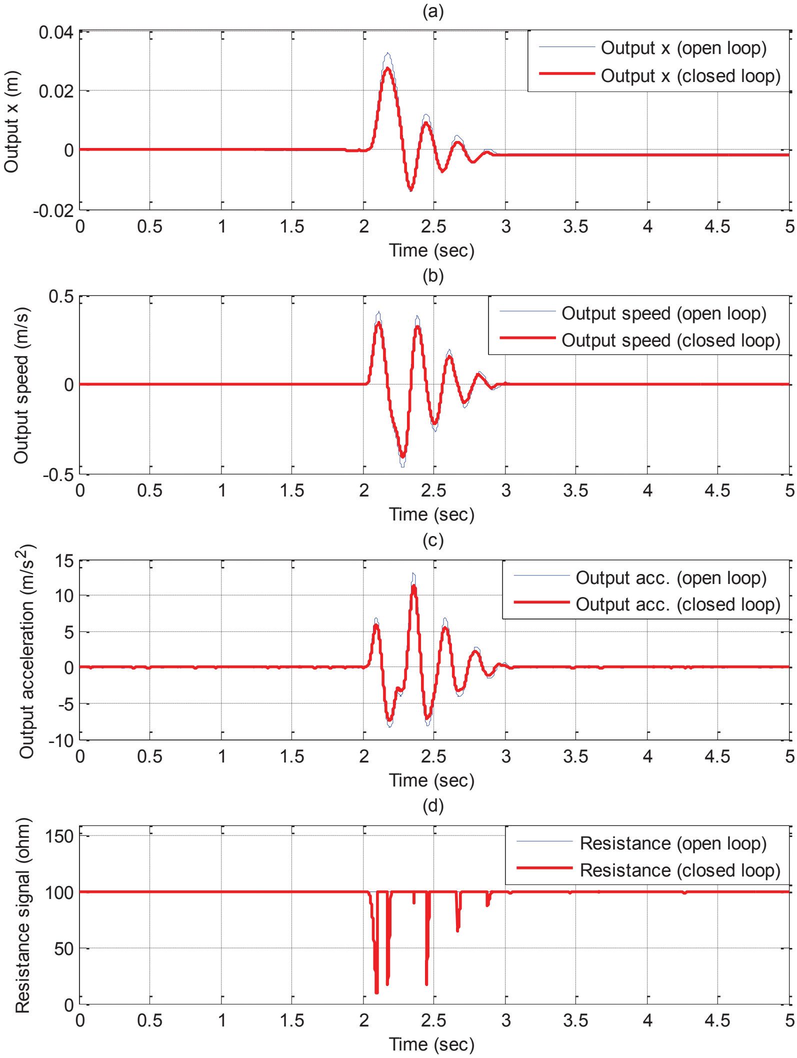

Figure 6 : Experimental results of semi-active control for quarter-car system in vibration of pulse $X(t) = 0.02m$: (a) output displacement (b) output speed (c) output acceleration (d) resistance signal

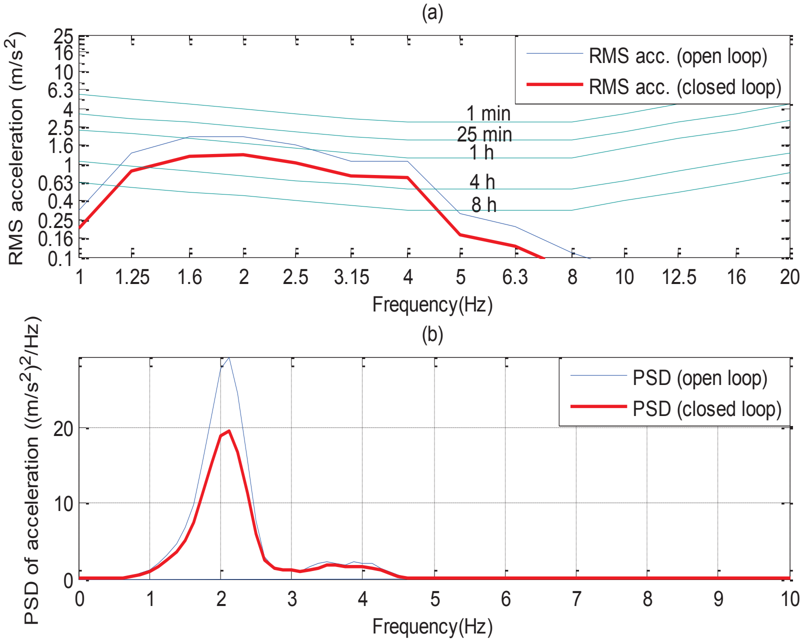

Figure 7 : Experimental results of semi-active control for quarter-car system in vibration of pulse $X(t) = 0.02m$: (a) Meister chart (b) PSD of acceleration

pulse $X(t) = 0.02m$	Passive	Semi-active
Efficiency (%)	24.8%	12.1%
Car body speed $\dot{x}_{max}$ (m/s)	0.45 m/s	0.395 m/s (-13.3%)
Acceleration $\ddot{x}_{max}$ (m/s²)	13.1 m/s²	11.9 m/s² (-9.2%)
Current (A)	0.2 A	0.293 A
$PSD_{acc,peak}$ ((m/s²)²/Hz)	29.1	19.3 (-33.7%)
Time of comfortable riding	25min ~ 1h	1h ~ 4h

Table 1: Comparison of experimental results of semi-active control for quarter-car system with the vibrations of $X(t) = 0.02m$ pulse

6. Conclusions

The purpose of this study is to develop a semi-active suspension control system and an energy harvesting system. Instead of the fixed orifices in conventional cars, the adjusting damping force methods with variable resistance circuits are studied for the semi-active suspension control system to improve riding comfort. The energy harvesting system contains a hydraulic gear motor and a DC generator. When vehicles vibrate, the hydraulic damper serves as a hydraulic pump to compress the oil and drive the hydraulic motor. At the same time, the hydraulic motor drives the generator to generate electricity which will be stored in a battery.

The novel hydraulic suspension system combining with the energy harvesting system is proposed. The test rig for practical experiments is set up for experimental implementation and verification. In the quarter-car system, the control strategy is combined with the skyhook concept and the fuzzy sliding mode control. The results of the semi-active control system have demonstrated that the speed and the acceleration power spectral density (PSD) are significantly reduced. The time of comfortable riding has been extended in Meister chart. Although the efficiency of energy harvesting attain to 10%~30%, the harvesting energy is little due to light weight of the load and limit of the test rig. If the scale of the system can be increase, the performance of energy harvesting will be more significant.

7. Acknowledgement

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