A Valid Model of a Regenerative Hybrid Shock Absorber System

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ABSTRACT

At present, regenerative active suspension is more attractive than conventional suspension of road vehicles for the improvement of ride comfort, performance, stability, passenger safety and the reduction of energy dissipation with regenerative energy. In a real application, the energy dissipation results in a reduction of the performance of the vehicle as well as high-energy consumption. This paper presents a hybrid shock absorber model with a modified shock absorber, which combines a hydraulic motor with a generator to recover the energy that would be otherwise wasted from vibrational motion of the suspension and transform it into useful electricity. The instantaneous oil pressures have been evaluated in the inlet and outlet pipelines using different sinusoidal wave excitation. The feasibility of the energy recovery features of this system are investigated by measuring the hydraulic motor shaft speed and the pressures at the inlet and outlet pipelines. The existing structure will be further optimized as future work to improve its performance.

***Keywords*- shock absorber; energy recovery; pressure; speed.**

INTRODUCTION

Relative vibration between chassis and wheels are locked to the excitation by road irregularities, bumping, steering and speed. However, the excitation not only influences the passengers' comfort and safety, but also can lead to vehicle instabilities. Mechanical friction and the dissipation of heat are used to reduce suspension vibration. The key issues of a regenerative suspension system are to convert more useful energy and decrease power consumption while assuring high performance.

The most important issue of a regenerative shock absorber is to estimate the amount of recoverable energy and develop the methods for recovering the energy from vibrational motion. Since the later 1970s, relevant researches have been carried out and the feasibilities also have been analyzed theoretically. Karnopp [1]–[3] proposed that the mechanism and process of energy consumption in conventional shock absorbers theoretically. Reduction of vehicles' power consumption can be achieved by recovering energy from a passive suspension system, especially for electric vehicles. To achieve energy saving, the energy dissipation in a shock absorber has been investigated by many researchers. The evaluation of energy consumption in a 4 degrees of freedom model has been analyzed by relative velocity between shock absorber and tire and energy loss for 4-wheels and has been calculated on an irregular road [4], [5]. In the study of Hsu [6], a General Motors 'Impact' model was used to estimate the capability of recovering energy in motorway driving with 16m/s velocity, and the average recoverable energy for each wheel was 100W which equal to 5% of total vehicle power. In addition, Browne [7] employed a similar measurement on a normal road.

Generally, regenerative shock absorbers can be classified into 3 categories: mechanical, electromagnetic and hybrid.

The mechanical type is a hydraulic or pneumatic accumulator used as energy storage and to restrain vibration of the wheel. Jolly [8] employed a hydraulic device which used a passenger seat to recycle energy and control the vertical motion of the vehicle. The conclusion of Jolly's study was that the recoverable energy is not only a decrease oscillation but also depends on the type of control algorithm. The storage of exhaust gas is also able to self-power the control action itself to reduce the energy consumption in vehicles. [9].

Electromagnetic shock absorbers transform the relative motion between chassis and wheels to linear or rotary motion in an electrical machine in order to generate power. Hence, vibration energy is converted into electricity to recharge battery or power other devices. For linear motor type, Nakano *et al* [10] employed two DC motors for a self-powered active control to improve ride comfort. In their study, one motor rotated inversely as generator to act as power supplying to the other motor which was used as an actuator to control the vibration performance, and a single linear DC motor can achieve the purpose of self-power. The energy recovery in the high speed range is able to drive the motor during low speed [11], [12]. Bose's active suspension [13] employs regenerative power amplifiers to provide power into linear electromagnetic motors as the actuator unit and to recycle electrical energy back from the motor in response to signals from the controller. For rotary motor type shock absorbers, based on mechanical transmission, they can be classified into 3 types (ball-screw, gear &rack and planet gear). Suda [14] has proposed a new electromagnetic damper which consists of a DC motor, planetary gear and a ball screw mechanism. The DC motor rotates to supply power to the shock absorber and it can rotate inversely in regeneration mode as well. The Michelin Corporation [15] designed an active-wheel which integrates an electrical drive motor with an electrical suspension motor (active control). Its fast response time (3ms) leads to better energy absorption. The University of Texas designed a kind of active suspension system (ECASS) which employed an actuator to switch between electric motor and generator. Electromagnetic gear & rack and planet gear were also used. ECASS helps military vehicles (HUMVEE and Ulan) to improve their stability handling and to recover some energy as well [16], [17].

The hybrid type of shock absorber utilizes fluid reciprocating motion to drive a hydraulic motor producing unidirectional rotary motion, driving a generator to realize energy recovery. Levant Power Corporation (Genshock) [18] and Fang Z [19] employ a similar hybrid regenerative method (HESA).

In this paper, a similar prototype of hybrid regenerative shock absorber with Genshock and HESA is proposed to evaluate the performance of a hydraulic motor and a hydraulic (Check valves circulatory-bridge) and the feasibility of energy recovery from a hydraulic motor combined generator. The energy recovery device (DC Generator) is able to drive the hydraulic motor directly and drive the hydraulic flow to generate useful electricity indirectly.

THE CHARACTERISTICS OF HYBRID SHOCK ABSORBER SYSTEM

A hybrid shock absorber cannot only isolate vibration from excitation of road roughness, but it also can recover the dissipated energy by transferring fluid dynamic to electricity. The schematic of the testing system is shown in Fig.1, in which main components are detailed in Table 1.
A hybrid shock absorber is composed of a hydraulic cylinder, a check valve circulatory-bridge, hydraulic motor, a DC generator, an oil tank and pipelines. There are four check valves constituted a hydraulic circulatory-bridge, which is similar with the Wheatstone bridge. Check valves circulatory-bridge helps the fluid in the pipelines to form a continuously unidirectional flow. Check valves are able to rectify the past fluid to make the flow more stable and regular, and they can reduce the discontinuity of flow, which also influenced on the performance of damping characteristic. Two pressure transducers connected with inlet and outlet ports of cylinder to measure the effects of pressure for hydraulic motor. The oil with low viscosity is not compressible. The oil tank acts as oil transfer station to return or supplement oil for hybrid shock absorber system in order to reduce the temperature and eliminate the air cavity of the system. However, the energy wasted as heat in hybrid shock absorber is cooled by exchanging shock oil between oil tank and the system. An encoder is applied to measure the efficiency and the rotary speed of gerotor hydraulic motor for further analysis.

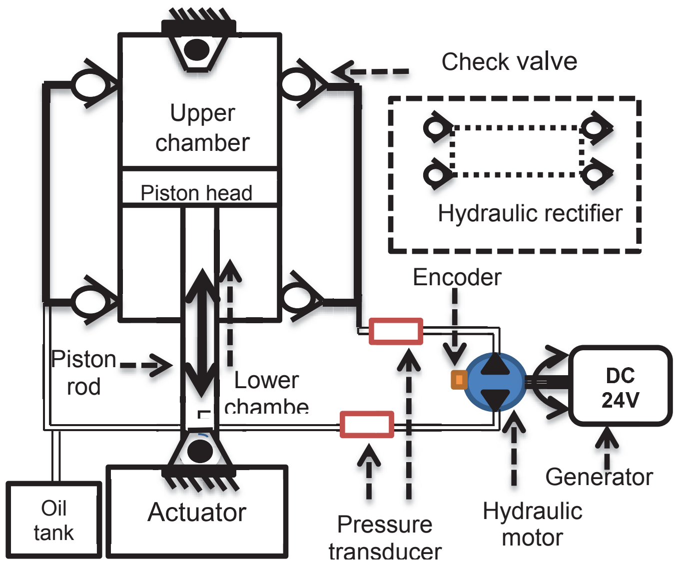

Figure 1 the schematic of hybrid shock absorber testing system

One of the actuators in a 4-post-test rig, which is integrated in the servo control system, generates the input excitation for hybrid shock absorber. Sinusoidal signals are employed as the profile of the input excitations at three frequencies: 0.5 Hz, 1.5Hz and 2.5Hz, each with the variety of the amplitudes (A) of 10mm, 20mm and 30mm respectively, which simulate the road with different degrees of roughness.

Table 1 KEY SPECIFICATION of HYBRID SHOCK ABSORBER

Cylinder Bore	Piston Rod	Stainless Steel Tubing	Hydraulic Hose	Hydraulic Motor			Shock oil	Volumetric efficiency
Diameter D_{bore} (mm)	Diameter D_{rod} (mm)	Diameter (mm)	Diameter (inch)	Displacement Q_{motor} (cm^3)	Maximum Speed (rpm) Cont./Int.	Maximum Oil Flow (l/min)	Viscosity (cSt)	η_v (%)
50	30	10	3/8	8.2	1950/2450	20	22	80

According to the parameters of the hybrid shock absorber, the theoretical calculation of flow can be expressed in below:
The theoretical volume V of hydraulic cylinder in each cycle:

$$V = \frac{\pi \cdot D_{bore}^2}{4} \times 2A + \frac{\pi}{4}(D_{bore}^2 - D_{rod}^2) \times 2A \tag{1}$$

The volumetric flow Q is proportional to the excitation rate or frequency f , and it can be expressed by:

$$Q = V \cdot f \tag{2}$$

Substituting Equation (1) into (2) gives

$$Q = \{\frac{\pi \cdot D_{bore}^2}{4} \times 2A + \frac{\pi}{4}(D_{bore}^2 - D_{rod}^2) \times 2A\} \cdot f \tag{3}$$

The theoretical rotary speed of a hydraulic motor can be calculated by equation (4):

$$v_{average} = \frac{Q}{q_{motor}} \cdot \eta_v \tag{4}$$

The efficiency of the motor is defined as the ratio of experimental and theoretical speed.

$$\eta_{motor} = \frac{V_{average}}{v_{average}} \times 100\% \tag{5}$$

Friction and turbulent flow in the pipeline cause energy loss, which is a direct influence on the efficiency of a hydraulic motor. The efficiency of the hydraulic motor indirectly reflects the efficiency of check valves in different excitation. Check valves are connected to the four ports on cylinder bore, two of them are mounted in the upper chamber and act as inlet and outlet and another two are mounted in the lower chamber similarly. The check valves force the fluid to form a unidirectional flow in the hybrid shock absorber system to rotate the motor. The cranking pressure directs opening and closing of the check valve during the operation. The power in the hydraulic motor inlet is written as:

$$Energy_{in} = \frac{P_{inlet} \cdot Q_{t-aver}}{60} \tag{6}$$

where, P_{inlet} is the pressure at the inlet port of the motor. Considering on fluid will flow into the inlet of hydraulic motor during both the compression and extension strokes, the performance of the system can be predicted based on the test conditions and shown in table, which will be compared late on with experimental results.

Table 2 THE THEORETICAL PERFORMANCE

V(Litre)	*Amplitude(A) (mm)*	*Q(L/min)/Q_{t-aver}(L/min) /$v_{average}$(rpm)*	*Q(L/min)/Q_{t-aver}(L/min) /$v_{average}$(rpm)*	*Q(L/min)/Q_{t-aver}(L/min) /$v_{average}$(rpm)*
0.0644L	10mm	1.9/1.4/188.5	5.8/2.5/565.5	9.66/3.9/942.439
0.1288L	20mm	3.864/2.6/377.0	11.6/4.0/1131.0	19.32/5.5/1884.878
0.1932L	30mm	5.8/2.7/565.5	17.4/4.0/1696.4	28.98/5.5/2827.317
	Excitation (Hz)	0.5Hz	1.5Hz	2.5Hz

THE RESULTS AND DISCUSSION OF HYBRID SHOCK ABSORBER SYSTEM

The hydraulic motor's inlet pressure, outlet pressure and speed are measured to evaluate the dynamic performance of flow and hydraulic motor that will be effect on energy regeneration.

In Fig 2, the hydraulic motor speed is proportional to the amplitude, and independent of the different frequencies. In comparison, it can be found that the waveforms in 1.5Hz and 2.5Hz with same amplitudes are similar with each other. Their maximum speed in compression and extension strokes are close to each other. The value of 2.5Hz is slightly higher than that in 1.5Hz. According to Fig 2, it can be seen that the speed of the hydraulic motor grows with the amplitudes. The speed falls to zero in a discontinuous manner between the compression stroke and extension stroke. In the 10mm amplitude case, the extension strokes have not driven the hydraulic motor with any of 0.5Hz, 1.5Hz and 2.5Hz excitations. The discontinuous periods become progressively less obvious with increasing frequency. With the growth of frequency, the discontinuity is reduced between compression stroke and extension stroke. According to the gerotor hydraulic motor's theory, it needs continuous flow to drive the rotors. In lower frequency and smaller amplitude, the extension strokes cannot provide enough flow and pressure to drive shaft rotation. Therefore, the pressure loss and turbulent flow will be measured to improve the continuity of hydraulic motor rotation.

The experimental average speed of the hydraulic motor is shown in Fig 3 with corresponding frequencies and amplitudes. It is obvious that the variation of average speed is similar with Fig 2 of the complete hydraulic motor speed. The average speed of the hydraulic motor is increasing with the growth of amplitude in each frequency. From a theoretical view, the average speed is proportional to the frequency. Fig 3 shows that the average speeds increase based on equations (2)-(4) by frequency. That would mean that the 2.5Hz excitation lost more energy because of leakage, pipe friction and pressure loss compared with that in 1.5Hz. In other words, the system at 1.5 Hz is more efficient than that at 2.5Hz.

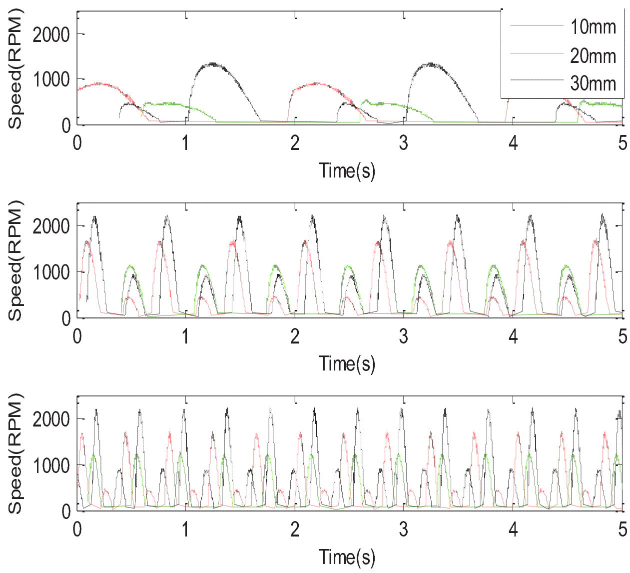

Figure 2 the speed of hydraulic motor

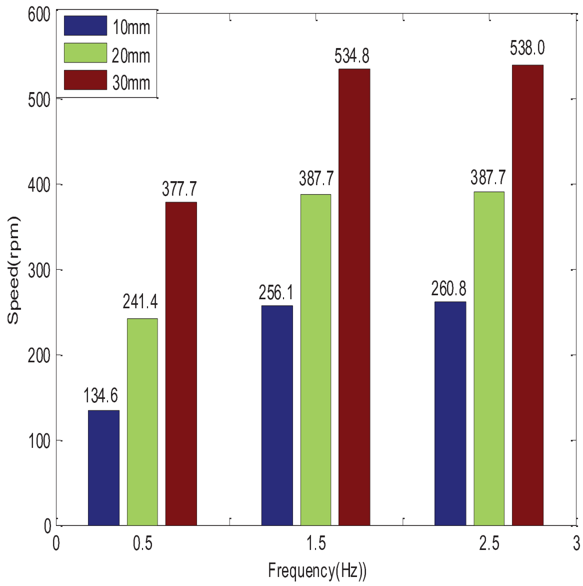

Figure 3 the experimental average speed of hydraulic motor

According to Equation (5), the efficiency of the hydraulic motor in the hybrid shock absorber system is analysed and shown in Fig 4. The volumetric efficiency is decreasing with the increase of both frequency and amplitude. The best efficiency is at low frequency (0.5Hz) and low amplitudes (10mm and 20mm) which are the only two over 50%. According to the gerotor hydraulic motor's characteristics, its maximum continuous speed is 1950 rpm and maximum intermittent operation rating applies to 6 seconds of every minute. As mentioned above, the flow of hybrid shock absorber system is not continuous flow in every full stroke. It shows that the period of intermittent operation in 1.5 Hz and 2.5Hz are 0.067s and 0.04s per cycle. Even if the speed exceeds the limitation of maximum intermittent operation, it will rotate around 2450 rpm. In addition, the limitation of the speed leads to a sharp increase in the hydraulic motor's temperature. It is liable to affect the performance of

the flow circuit and check valves. A high-speed gear motor is necessary to improve the efficiency of hydraulic motor.
In Fig 5, the variation of the waveforms for inlet port pressure of the hydraulic motor is similar with its speed. The flow is hindered by the speed limitation of the hydraulic motor. Large flow check valves are necessary for the hybrid shock absorber system to improve the efficiency of hydraulic motor.

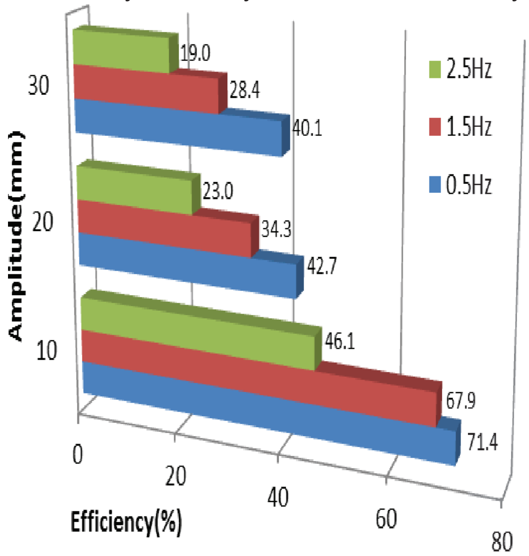

Figure 4 the efficiency of hydraulic motor

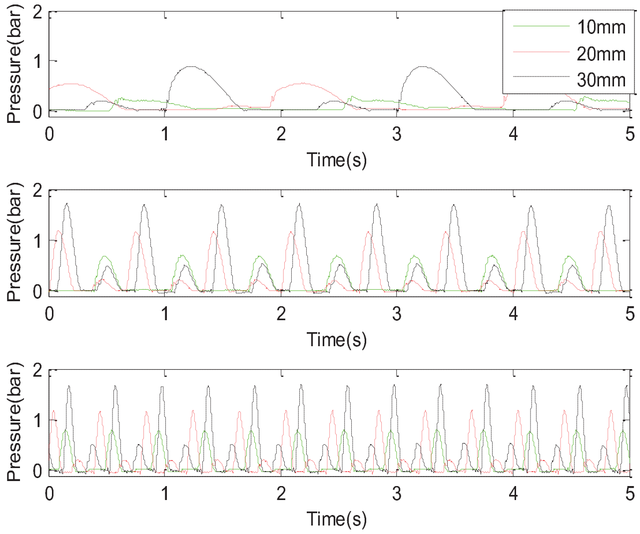

Figure 5 the pressure of hydraulic motor inlet

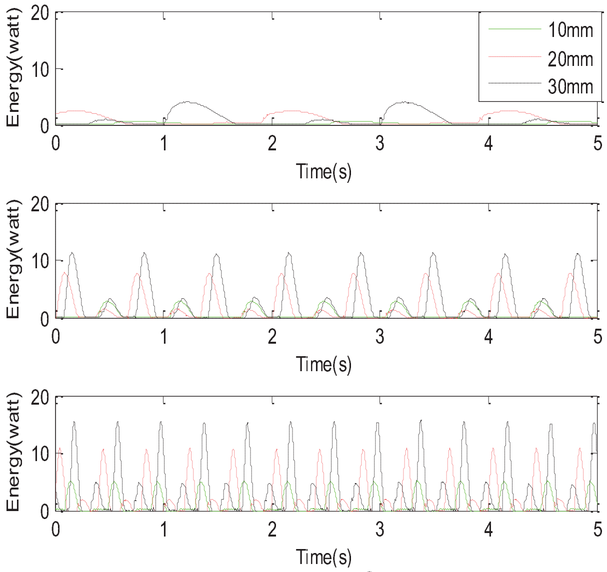

Figure 6 the energy input of hydraulic motor

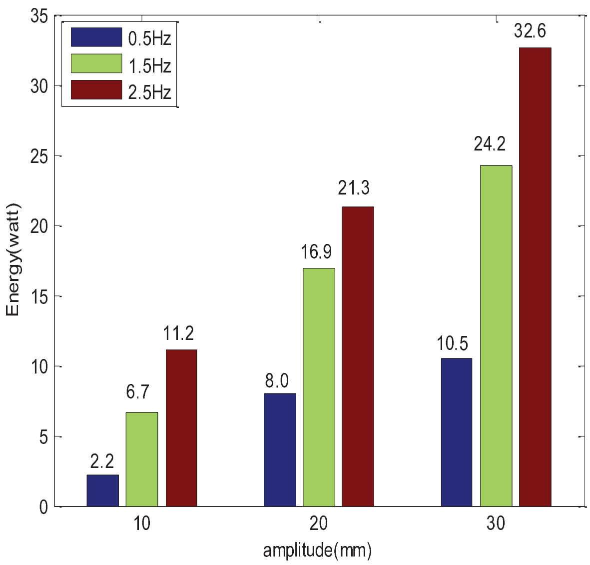

Figure 7 the total energy of hydraulic motor in 10s

According to Equation (6), the energy input to the hydraulic motor is shown in Fig 6. The pressure output at the outlet port is proportional to the speed of the hydraulic motor. In Fig 7, the total energy in 10 seconds are calculated and increased with the growth of frequencies and amplitudes. The hydraulic motor input energy and total energy in 10s indicates the capability of energy recovery in the hybrid shock absorber system by generator.

CONCLUSIONS

In this paper, the prototype of a hybrid shock absorber system is set up and tested. The pressure features and hydraulic motor characteristics have been investigated and analysed to improve the design of the hybrid shock absorber system. The results show that the system can achieve energy recovery by this system. The pressure and speed in the hydraulic motor increased with the growth of frequencies and amplitudes. However, the limitations of the hybrid hydraulic shock absorber have been found. It is intended that in future work the hydraulic gear motor and large flow check valves will be replaced in the test bench to improve the efficiency of hydraulic motor speed and the continuity of hydraulic flow to promote the capability of energy regeneration. The performance of the hydraulic motor are analysed to match the generator in the next study.

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