Performance Evaluation and Damping Characteristics of Hydro-Pneumatic Regenerative Suspension System

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Abstract
This paper presents an evaluation of Hydro-Pneumatic Regenerative Suspension System (HPRSS) based on Advanced Modeling Environment Simulations (AMESim). The general setup of the HPRSS and the working principle is explained. The performance of HPRSS is compared to the conventional suspension system, by using single and double acting cylinder suspension systems. In addition, the study investigates the effect of the system parameters on the system performance and the damping characteristics. The simulation results indicate that the HPRSS is more comfortable in riding compared to the other systems due to the reduction of peak oscillation by 20%. Also, the results show that the optimal accumulator size and the external load resistance have a significant impact on the suspension performance and harvested power. Large size of the accumulator up to 0.75 L increases the stability during the piston motion.

Keywords: Energy harvesting, regenerative suspension, hydraulic rectifier, damping characteristics, vehicle dynamics.

INTRODUCTION
Today the energy harvesting is widely used in many transportation applications such as road tunnels [1], railroad track [2] and energy recovery systems for automotive applications [3]. Furthermore vehicle applications such as braking, crankshaft and vehicle suspension. The oscillation in automotive wheels is a rich source of green energy and unfortunately this energy is dissipated in conventional suspension. Several studies have presented the wasted energy of shock absorber and proposed many ideas in this field to convert the dissipated energy to electric power. In addition, some studies have addressed maximizing the energy harvested from the suspension system [4-6]. Karnopp [4] studied the linear permanent magnet motors application with variable resistors as variable mechanical vehicle damper. This study proved that the electromagnetic damper is practical even though the response time has deteriorated with a long stroke. [5] Presented a regenerative shock absorber with special attention to enhancing ride comfort and road handling. An analytical optimization methodology is presented to determine the optimal stiffness and damping coefficients to achieve the best ride comfort and energy regeneration [6]. There are many different designs and schemes for transmission the forces subjected from road profile to the regenerative suspension system. The rack and pinion mechanism is used in the mechanical regenerative suspension to rectify the direction of DC motor rotation [7-9]. The linear and rotary electromagnetic regenerative suspension mechanism was investigated [10-13]. The hydraulic shock absorber is improved based on the hydraulic rectifier that maintains the unidirectional oil flow through the system to maximize the energy harvested [14-18]. In this paper, an accurate design for the regenerative suspension system is proposed, namely Hydro-Pneumatic Regenerative Suspension System (HPRSS). It is organized as follows: Section 2 describes the general setup and working principle for the hydro-pneumatic suspension system and the effect of the hydraulic rectifier. Section 3 the evaluation of the HPRSS system performance and damping characteristics is presented. Section 4 Simulation Model of HPRSS is presented. Section 5 discussed the simulation results and effect of system parameters. Finally the conclusion from the results are provided in section 6.

GENERAL SETUP AND WORKING PRINCIPLE
The system description
The configuration of the HPRSS is shown in Fig.1. The basic hydro-pneumatic suspension system depends on three main components: a hydraulic cylinder, hydro-pneumatic accumulator, and the hydraulic fluid. When the shock absorber subjected to external force from road profile, this force leads to increase the hydraulic pressure inside the shock absorber and compressed the gas inside the accumulators. The accumulator fluid volume and pressure are changed until the pressure level reached to the balance inside suspension system. The main influence of the hydraulic accumulator to absorb the sudden shocks and minimize pressure fluctuation. The components that used to harvest energy includes the hydraulic motor, electromagnetic generator, the hydraulic rectifier and the external load resistor. The energy harvesting process of the HPRSS is described in Fig. 2.
The Significance of the Hydraulic Rectifier

The main function of the hydraulic rectifier is to keep the hydraulic motor rotation in the one direction during compression (positive half cycle) and extension (negative half cycle) that maximizes the power of the electromagnetic generator. The hydraulic flow path through the system which subjected to external sinusoidal road input signal is shown in Fig 3. It can be seen that the flow rate during the extension cycle is lower than the compression cycle due to the different size of the cylinder chambers.

EVALUATION OF THE HPRSS SYSTEM PERFORMANCE

The HPRSS performance was evaluated by comparing it with the corresponding conventional mechanical suspension and hydro-pneumatic suspension with single and double acting cylinder. A step input signal is used to simulate the road profile with an amplitude 0.05m and simulation time 0.1 to 10 seconds generated by the signal and control library to study suspension performance and system efficiency to isolate road shocks. The schematic diagram of the quarter car model with the conventional mechanical suspension and hydro-pneumatic suspension based on single and double acting cylinder is shown in Fig 4. The quarter vehicle parameters used in this study are listed in table1.
Damping Characteristics for HPRSS

In order to analyze the system performance and evaluate damping characteristics of HPRSS, force-displacement and force-velocity response for the HPRSS system were compared with the corresponding conventional mechanical damper. The HPRSS model was built with and without accumulators to investigate the significance of the accumulators on the performance of the suspension system. Furthermore, a number of tests were performed using different standard accumulator sizes, road profiles and external load resistance to explain their effect on the system performance and the harvested power. The AMESim models of the conventional mechanical damper and the HPRSS model with and without accumulators are shown in Fig 5.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_1$</td>
<td>Accumulator 1 size</td>
<td>5 e-4 m$^3$</td>
</tr>
<tr>
<td>$P_1$</td>
<td>accumulator 1 pre-charge pressure</td>
<td>20 Bar</td>
</tr>
<tr>
<td>$V_2$</td>
<td>Accumulator 2 size</td>
<td>7.5 e-4 m$^3$</td>
</tr>
<tr>
<td>$P_2$</td>
<td>accumulator 2 pre-charge pressure</td>
<td>5 Bar</td>
</tr>
<tr>
<td>$D_{in}$</td>
<td>Accumulator inlet port diameter</td>
<td>0.012 m</td>
</tr>
<tr>
<td>$P_{cv}$</td>
<td>check valve nominal diameter</td>
<td>0.01 m</td>
</tr>
<tr>
<td>$P_{ov}$</td>
<td>check valve opening pressure</td>
<td>0.7 Bar</td>
</tr>
<tr>
<td>$R_L$</td>
<td>External load resistor</td>
<td>8 Ohm</td>
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<tr>
<td>$X_o$</td>
<td>Hydraulic cylinder balance position</td>
<td>0.1 m</td>
</tr>
<tr>
<td>$X_{fs}$</td>
<td>Hydraulic cylinder Full stroke</td>
<td>0.2 m</td>
</tr>
<tr>
<td>$D_m$</td>
<td>Hydraulic motor displacement</td>
<td>8.2 e-6 m$^3$/rev</td>
</tr>
<tr>
<td>$D_f$</td>
<td>Piston diameter</td>
<td>0.05 m</td>
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<tr>
<td>$D_r$</td>
<td>rod side piston diameter</td>
<td>0.02 m</td>
</tr>
<tr>
<td>$K_S$</td>
<td>Spring rate</td>
<td>15000 N/m</td>
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<tr>
<td>$M_s$</td>
<td>Sprung mass</td>
<td>300 kg</td>
</tr>
<tr>
<td>$M_u$</td>
<td>Unsprung mass</td>
<td>30 kg</td>
</tr>
<tr>
<td>$D_w$</td>
<td>Wheel damping</td>
<td>1000 N/(m/s)</td>
</tr>
<tr>
<td>$K_w$</td>
<td>Wheel stiffness</td>
<td>180000 N/m</td>
</tr>
</tbody>
</table>

**Table I**

THE QUARTER VEHICLE PARAMETERS

RESULTS

The displacement of sprung and unsprung masses of the conventional mechanical suspension system is shown in Fig. 7, where the amplitude of sprung mass is greater than the unsprung mass also the damping time of the unsprung mass about 1 second while the sprung mass is about 3 seconds. Fig. 8 illustrates the displacement of sprung and unsprung masses of the hydro-pneumatic suspension based on the single acting cylinder. The sprung and unsprung masses took about 9 seconds and 2 seconds respectively to reach the steady state zone and the maximum overshoot of the sprung mass is larger than unsprung mass. It can be noted that the behavior and the frequency characteristics of the hydro-pneumatic system and mechanical system are totally different. Similarly, Fig. 9 shows the displacement of sprung and unsprung masses of the hydro-pneumatic suspension based on the double acting cylinder. The

**Figure 4.** (a) The conventional mechanical vehicle suspension system. (b) The hydro-pneumatic suspension based on single acting hydraulic cylinder, (c) The hydro-pneumatic suspension based on double acting hydraulic cylinder

**Figure 5.** (a) The conventional mechanical damper (b) The HPRSS model with accumulator, (c) The HPRSS model without accumulator

**Figure 6.** The Hydro-Pneumatic Regenerative Suspension System (HPRSS) model.

**Figure 7.** The AMESim model of the conventional mechanical damper and the HPRSS model with and without accumulators with different sizes (0.75 L, 0.5 L, 0.35 L and 0.16 L) are shown in Fig 5.

**Figure 8.** The SIMULATION MODEL OF HPRSS

AMESim is one of the most powerful simulation programs that can accurately simulate the combined system, it contains various libraries such as hydraulic, mechanical and electrical libraries. The control library used to simulate the road profile test signals. The mechanical library is used to construct the main components of quarter car such as wheel tire model, spring, sprung and unsprung masses. The hydraulic library is used to build the hydraulic component such as double acting cylinder, check valves, accumulators, hoses and hydraulic motor. Lastly the electric circuit and electromagnetic generator were selected from the electric library. The block diagram of the regenerative suspension model was illustrated in Fig 6.
maximum overshoot of both sprung mass and unsprung mass response are less than the previous systems, but the conventional mechanical suspension has less damping time to reach the steady state zone. As shown in Fig. 10, it can be observed that the HPRSS achieves the best overshoot and damping time of sprung and unsprung masses compared to other suspension systems considered in this study.

Fig. 11 and Fig.12 shows the comparison of the damping force and force-displacement response for the conventional mechanical and HPRSS with and without accumulator respectively. For conventional mechanical and HPRSS without the accumulator, the damping force gradually changes with the shock absorber motion to reach the maximum value at the maximum displacement and then gradually decrease. The maximum damping force only appears for a short period in conjunction with the maximum speed of absorption. On the other hand, the accumulators play an important role to conserve the energy in HPRSS, the effect of the accumulators appears in maintaining the maximum damping force most of the oscillation time and minimizing the pressure fluctuation to ensure the stability of the hydraulic motor rotation.

The effect of the accumulator size on the damping characteristics was tested using different accumulator sizes (0.75 L, 0.5 L, 0.35 L and 0.16 L). Fig.13 and Fig.14 shows the force-displacement response and force-velocity response for the HPRSS system. It is clear that the large size of the accumulator increases the stability of the damping force during the piston motion.
In order to explore the impact of external load resistance on system performance and energy harvesting, different resistance values have been tested. The force-displacement and force-velocity response are shown in Fig. 17 and Fig. 18 respectively. It can be observed that the values of load resistance have a significant impact on the damping forces. The optimum resistance value is necessary to maximize absorption shock for each type of vehicle. Fig. 19 and Fig. 20 shows the variation of the electric generator output power and voltage respectively. The increasing the value of external load resistance leads to reduce the regenerative power.
CONCLUSION

In this paper, the study of Hydro-Pneumatic Regenerative Suspension System (HPRSS) is discussed. The HPRSS and its damping characteristics are assessed by comparing its performance with the conventional mechanical suspension and hydro-pneumatic suspension with single and double acting cylinder. The results show that HPRSS has better performance than other suspension systems in both reducing vibration and increased harvested energy by approximately 19%. The effect of the presence of accumulators is studied by building the HPRSS simulation model with and without accumulators. In addition, the effect of using different standard accumulator sizes, road profiles, and external load resistance is investigated. The accumulators could maintain the maximum damping force with the oscillation time and ensure the stability of the hydraulic motor rotation. The large size of the accumulator increases the stability of the damping force during vehicle vibration. Moreover, the appropriate selection for both external load resistance and accumulator size have a significant effect on the damping force of the suspension system and harvesting energy from road vibrations.

REFERENCES


