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ANALYSIS OF THE INFLUENCE OF HYDRAULIC CYLINDER DIAMETER TO THE TOTAL DAMPING FORCE AND THE GENERATED ELECTRICITY OF REGENERATIVE SHOCK ABSORBER

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ABSTRACT

This paper deals with analysis on the influence of hydarulic cylinder diameter and oil viscousity to the total damping force and the regenerated electric power of hydro-magneto-electric-regenerative shock absorber (HMERSA). HMERSA is aimed to convert the vibration energy losses from the vehicle suspension into electricity. As HMERSA consists of mechanical and electrical system, the total damping force characteristics and the regenerated electric power will be influenced by its mechanical and electrical damper characteristics. In HMERSA, the mechanical damper depends on the design of the hydraulic cylinder diameter, oil viscousity and the existing head loss, while the electrical damper is affected by the electric generator characteristics and battery state of charge.In this study, a previously developed prototype of HMERSA was mathematically modelled, simulated and analyzed. The influence of hydraulic cylinder-tube diameter ratio (3.2, 4, 5) to the total damping force and the regenerated electric power of HMERSA were simulated. The results are presented, analyzed and discussed in this paper.

Keywords: regenerative shock absorber, cylinder diameter, oil viscousity, damping force, regenerated electric power.

INTRODUCTION

In the last two decades, regenerative shock absorber (RSA) for vehicle suspension has been vigorously researched and developed. Several types of RSA and methods of regenerating the vibration energy losses into electricity are reported. Zuo [1-2], Laksana Guntur [3-5], Gupa [6], Fang [7], Xu [8], Zhang [9], Umeda [10] and many others reported the development of RSA using mechanic-magneto-electric, hydraulic-magneto-electric and mechanic-piezoelectric methods of regenerating the vibration energy losses from vehicle suspension into electricity. The researches were focused on the ouput electric power that can be produced by RSA. Analyzing the characteristics of RSA is also very important to be done to acquire high performance of suspension and vehicle ride comfort.

Laksana Guntur *et al* reported the development of a regenerative shock absorber using gear transmission system and electric generator [3]. The prototype can produce electricity up to 20 Watt per suspension and its characteristics were experimentaly investigated. The result shows that its characteristics are affected by the gear system-which closed to dry friction damper and electrical damper of the generator. In his further research, Laksana Guntur *et al* carried out a comparative study of the damping force and energy absorbtion capacity of a typical conventional-viscous and a regenerative shock absorber for vehicle suspension [4].

Lin Xu *et al* evaluated the strength and weakness of several kinds of energy-regenerative shock absorbers [8]. Xu proposed a Hydraulic Energy-regenerative Shock Absorber (HESA) and analyzed the damping characteristic and the energy recovery of HESA. As RSA consists of mechanical and electrical system, the total damping force characteristics and the regenerated electric power will be influenced by its mechanical and electrical damper characteristics.

In this study, a prototype of HMERSA is mathematically modelled, simulated and analyzed. The study is focused on the influence of hydraulic-tube diameter ratio to the total damping force and the regenerated electric power of HMERSA. The results are reported in this paper.

DYNAMIC MODEL AND EQUATIONS

Figure-1 shows the developed prototype of HMERSA and Figure-2 shows the schematic image. HMERSA consists of hydarulic cylinder, flexible pipe (tube), hydarulic motor and electric generator. The total damping force and the generated electricity will be influenced by its mechanical and electrical damper characteristics.

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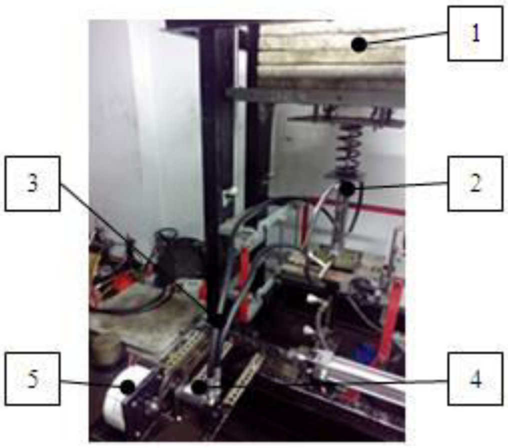

Figure-1. Prototype of HMERSA: 1.Sprung mass; 2.Hydarulic cylinder; 3.Flexible tube; 4.Hydarulic motor; 5.Generator.

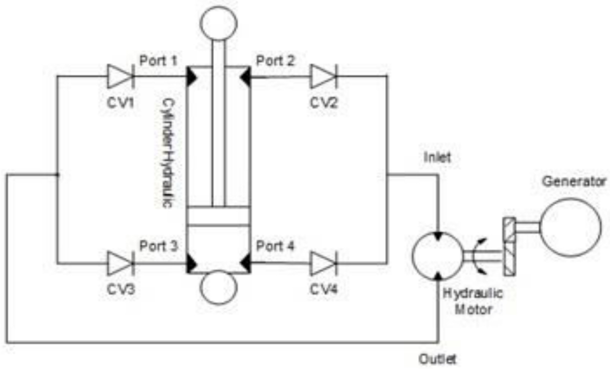

Figure-2. Schematic image of HMERSA.

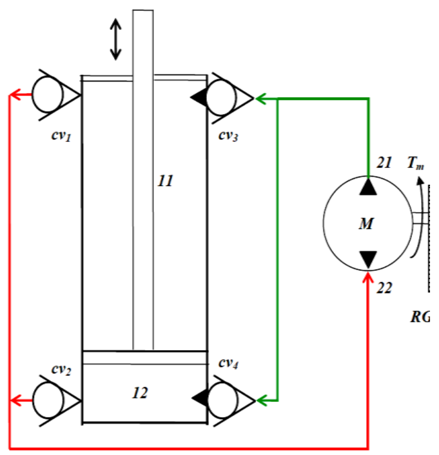

Figure-3. Schematic image of hydarulic system.

In HMERSA, the mechanical damper depends on the design of the hydraulic cylinder diameter, oil viscousity and the existing head loss, while the electrical damper is affected by the electric generator characteristics and battery state of charge. In this study, the previously developed prototype of HMERSA was mathematically modelled. As shown in figure-3, the influence of hydraulic cylinder-tube diameter ratio can be expressed by its pressure drop (ΔP_{ct}) as shown by the following equations:

(a) expansion:

$$\Delta P_{ct} = \frac{\rho}{2}\left(\left(\frac{A_{11}}{A_{cv}}\right)^2 - 1\right)v^2 \tag{1}$$

(b) compression:

$$\Delta P_{ct} = \frac{\rho}{2}\left(\left(\frac{A_{12}}{A_{cv}}\right)^2 - 1\right)v^2 \tag{2}$$

with ρ: oil density, A : cylinder/tube area, v: fluid velocity. Based on the continuity equation, the relation between tube velocity (v_t) and hydraulic cylinder velocity (v_c) can be found, as follows:

$$v_t = \frac{A_c}{A_t} v_c \tag{3}$$

Pressure drop due to pipe head loss (ΔP_p) is expressed by:

$$\Delta P_t = \rho\left(32\mu\frac{Lv_t}{\rho {D_t}^2} + k\frac{v_t^2}{2}\right) \tag{4}$$

Substituting equation (3) into (4), pressure drop due to pipe head loss can be written as:

(a) expansion:

$$\Delta P_t = \frac{8.A_{11}}{\pi^2.{D_t}^4}(16.\mu.\pi.L.v + k.\rho.A_{11}.v^2) \tag{5}$$

(b) compression

$$\Delta P_t = \frac{8.A_{12}}{\pi^2.{D_t}^4}(16.\mu.\pi.L.v + k.\rho.A_{12}.v^2) \tag{6}$$

with L: pipe/tube length, μ:oil viscousity. Angular velocity and torque of the hydarulic motor in HMERSA are obtained by the following equaitons:

$$\omega = \frac{Q_{hm}}{-}\eta_v \tag{7}$$

$$T_{hm} = \Delta P_{hm}.q.\eta_m \tag{8}$$

with T_{hm}:pipe/tube length, μ:oil viscousity, Q_{mh}:flow rate, η_v:volumetric efficiency, q:motor displacement. As mechanical torque is defined by multiplication of inertia (J) and angular acceleration ($\dot{\omega}$):

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$$T = J.\dot{\omega} \tag{9}$$

Substituting equation (7), (8) into (9), pressure drop in the hydraulic motor (ΔP_{hm}) can be written as follows:

$$\Delta P_{hm} = \frac{J.\eta_v}{\eta_m.q^2}\dot{Q}_{hm} \tag{10}$$

One gear pair within the hydarulic motor which connect the hydraulic system with the electric generator will influence the damping force of the HMERSA and their mehcanical torque can be derived by the following equations:

$$J_1\ddot{\theta}_1 + \frac{r_1}{r_2}\left[J_2\ddot{\theta}_2 + T_e\right] = T_m \tag{11}$$

$$(J_1 + J_2N^2)\ddot{\theta}_1 + T_e.N = T_m \tag{12}$$

with T_e:electric torque induced by generator, J_1:gear 1 moment of inertia, J_2:gear 2 moment of inertia, N:number of teeth.Substituting equation (11), (12) into equation (10), the hydraulic motor's pressure drop is shown in the following equations:

(a) expansion*:*

$$\Delta P_{hm,exp} = \frac{(J_1+J_2N^2).\eta_v.A_{11}}{\eta_m.q^2}\dot{v} + \frac{k_t.k_m.\eta_v.N^2.A_{11}}{(R_{in}+R_{ex})\eta_m.q^2}v \tag{13}$$

(b) compression*:*

$$\Delta P_{hm,comp} = \frac{(J_1+J_2N^2).\eta_v.A_{12}}{\eta_m.q^2}\dot{v} + \frac{k_t.k_m.\eta_v.N^2.A_{12}}{(R_{in}+R_{ex})\eta_m.q^2}v \tag{14}$$

And the expansive and compressive damping force of the HMERSA are defined by the following equations:

(a) expansion*:*

$$F_{D,e} = \frac{\rho}{2}\left(\left(\frac{A_{11}}{A_{cv}}\right)^2 - 1\right)v^2 + \frac{8.A_{11}}{\pi^2.D_p{}^4}(16.\mu.\pi.L.v + k.\rho.A_{11}.v^2)$$

$$+\frac{(J_1+J_2N^2).\eta_v.A_{11}}{\eta_m.q^2}\dot{v} + \frac{k_t.k_m.\eta_v.N^2.A_{11}}{(R_{in}+R_{ex})\eta_m.q^2}v \tag{15}$$

(b) compression*:*

$$F_{D,c} = \frac{\rho}{2}\left(\left(\frac{A_{12}}{A_{cv}}\right)^2 - 1\right)v^2 + \frac{8.A_{12}}{\pi^2.D_p{}^4}(16.\mu.\pi.L.v + k.\rho.A_{12}.v^2)$$

$$+\frac{(J_1+J_2N^2).\eta_v.A_{12}}{\eta_m.q^2}\dot{v} + \frac{k_t.k_m.\eta_v.N^2.A_{12}}{(R_{in}+R_{ex})\eta_m.q^2}v \tag{16}$$

Three phase AC of DC generator shown in figure 3 can be modeled as RL Circuit. Owing to Kirchoff law, the following equation is obtained:

$$L\frac{di}{dt} + R.i + R_{Load}.i = E_m.\dot{\theta}_2 \tag{17}$$

And the electric torque is:

$$T_e = \frac{V.i}{\dot{\theta}_2} \tag{18}$$

SIMULATION RESULTS AND ANALYSIS

Based on the dynamic model of HMERSA elaborated in the previous section, simulations were carried out using computation software and the results are discussed.

Damping Force Characteristics

Figure 5 and 6 shows the hydarulic system damping force of HMERSA at various cylinder-tube diameter ratios (3.2, 4 and 5) subjected to sinusoidal excitation, as a function of excitation displacement and velocity, respectively. The results show that increasing cylinder-tube diameter ratio increase the damping force of the hydraulic system.

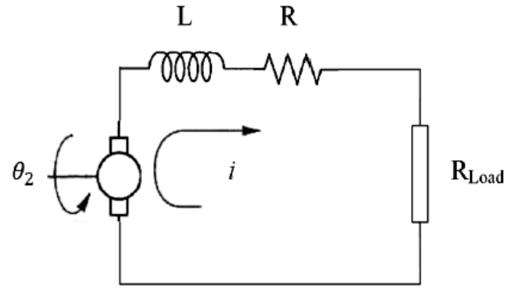

Figure-4. Schematic image of hydarulic system.

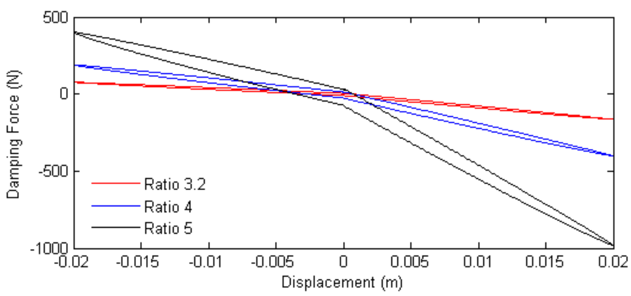

Figure-5. Hydraulic system damping force vs displacement.

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Figure 7 and 8 show the total damping force of the HMERSA at various cylinder-tube diameter ratios subjected to sinusoidal excitation, as a function of excitation displacement and velocity, respectively. The results show that increasing cylinder-tube diameter ratio influence the total damping force of HMERSA significantly.

Electricity Characteristics

Figure-9 and 10 shows the output current of HMERSA at various cylinder-tube diameter ratios subjected to sinusoidal excitation, as a function of excitation displacement and velocity, respectively. Meanwhile, Figure-11 and 12 shows the output voltage of HMERSA at various cylinder-tube diameter ratios subjected to sinusoidal excitation, as a function of excitation displacement and velocity, respectively. The results show that increasing cylinder-tube diameter ratio increase the ouput current and voltage, and reach its maximum value of 4.5 Amp and 18 Volt due to generator maximum output constraint.The characteritics of the ouput voltage can be seen in the figure have three gradient ranging from particular velocity.

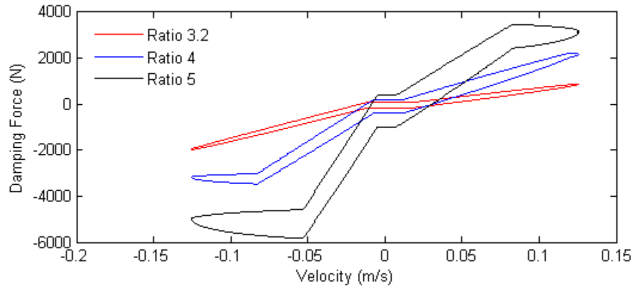

Figure-8. Total damping force vs velocity.

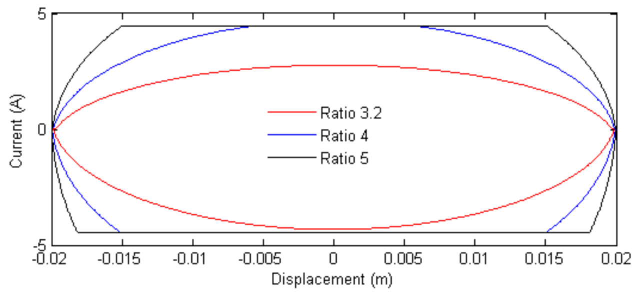

Figure-9. Current vs displacement.

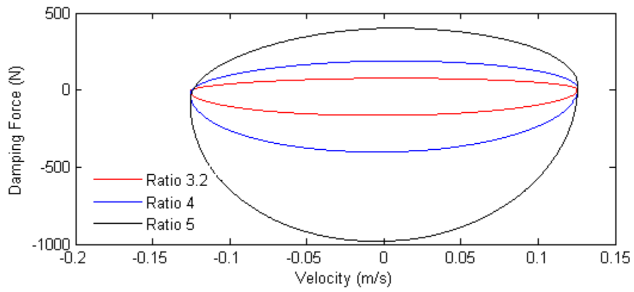

Figure-6. Hydraulic system damping force vs velocity.

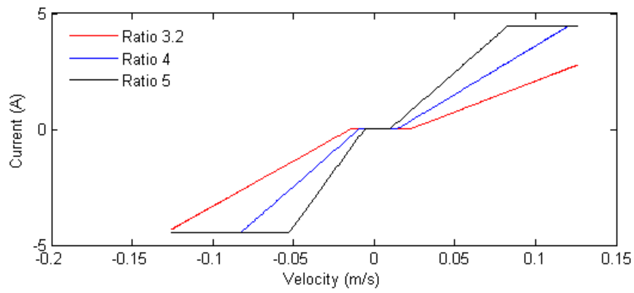

Figure-10. Current vs velocity.

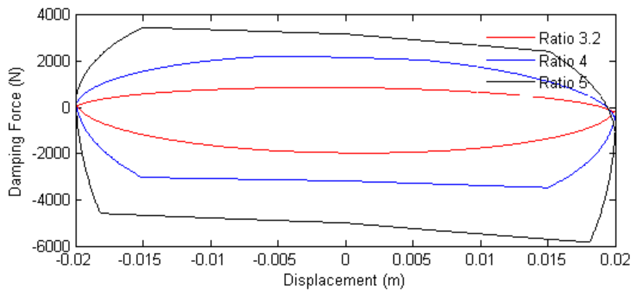

Figure-7. Total damping force vs displacement.

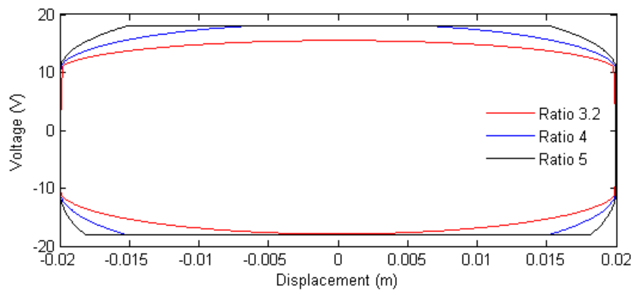

Figure-11. Voltage vs displacement.

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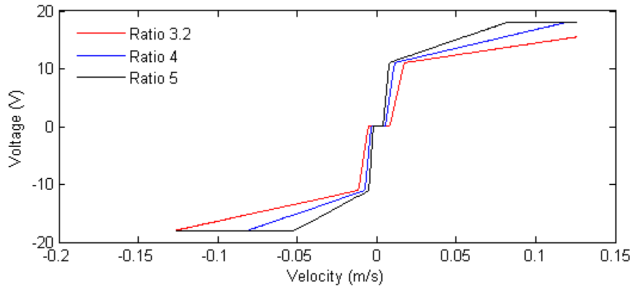

Figure-12. Voltage vs velocity.

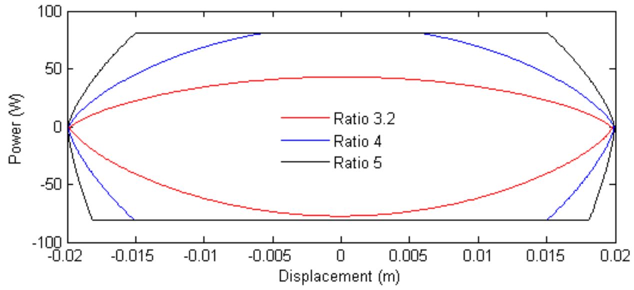

Figure-13. Power vs displacement.

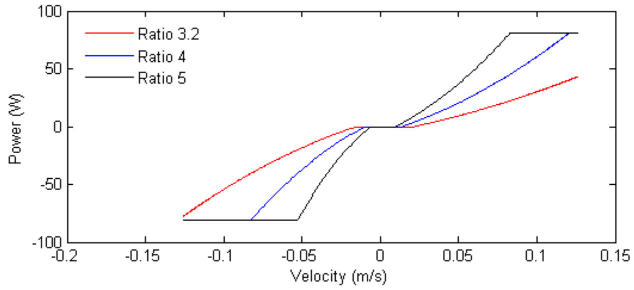

Figure-14. Power vs velocity.

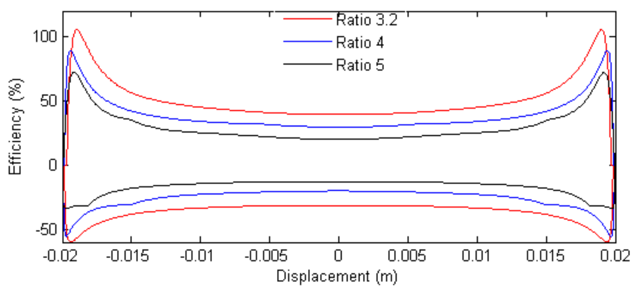

Figure-15. Efficiency vs displacement.

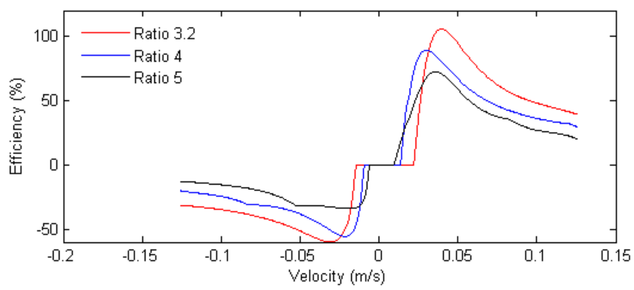

Figure-16. Efficiency vs velocity.

Figure 13 and 14 shows the output power of HMERSA at various cylinder-tube diameter ratios subjected to sinusoidal excitation, as a function of excitation displacement and velocity, respectively. The output power of HMERSA shows similar phenomena with voltage and current.

Efficiency of HMERSA

The efficiency of HMERSA at various cylinder-tube diameter ratios subjected to sinusoidal excitation, as a function of excitation displacement and velocity are shown in Figure 15 and 16, respectively. The efficiency of HMERSA obtained by deviding the output power with the mathematical approach (curve-fitting) of the mechanical power, as shown in figure-17. The efficiency increase drastically at low velocity less than 0.005 m/s and reach its maximum value at velocity of about 0.005 m/s. However, the efficiency decrease slightly after reaching its maximum value. At cylinder displacement (stroke) less than 0.015m, the efficiency almost constant but at stroke higher than that, HMERSA efficiency change drastically.

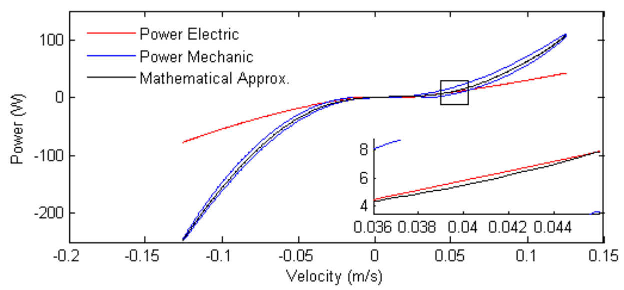

Figure-17. Mechanical power and electrical power vs velocity.

CONCLUSIONS

The previously developed prototype of HMERSA was mathematically modelled, simulated and analyzed. The influence of hydraulic cylinder-tube diameter ratio (3.2, 4, 5) to the total damping force and the generated electric power were the focus of this study. The results can be summarized as follows:

- Increasing cylinder-tube diameter ratio will increase the damping force of the hydraulic system, as a results the total damping force of HMERSA will also increase.
- Increasing cylinder-tube diameter ratio increase the ouput current and voltage, and reach its maximum value of 4.5 Amp and 18Volt due to generator maximum output constraint. The ouput voltage has three s ranging from particular velocity, and the output power shows similar phenomena with the output current.
- Efficiency of HMERSA increases drastically at low velocity less than 0.005 m/s and reach its maximum value at velocity of about 0.005 m/s. However, efficiency decreases slightly after reaching its maximum value. At cylinder displacement (stroke) less than 0.015m, the efficiency almost constant but at stroke higher than that, HMERSA efficiency change drastically.

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