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Comparative Study of Hydro-Magneto-Electric Regenerative Shock Absorber (HMERSA) with Two Outputs Hydraulic Generator Installed Series and Parallels

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Abstract

Through the Regenerative Shock Absorber (RSA) mechanism, wasted energy will be utilized into electrical energy. Hydro-Magneto-Electric Regenerative Shock Absorber (HMERSA) was designed and analyzed with 2 generator outputs installed in series and parallel. The twin-tube shock absorber was modified, so that fluid flow in the chamber is only unidirectional flow. It is passed to four check valves that keep the fluid flow in one direction and towards the 2 hydro-generators installed on the system in series and parallel positions. The hydro-generator converts the linear fluid flow into a rotational motion which causes the generator to rotate and generate energy. HMERSA was tested on minibus with speed bumps types of roads. In the bump test, the harvested energy were 8.2 Volts and 5.97 Volts for HMERSA with 2 generator outputs installed in series, and 5.169 Volts and 4.33 Volts for HMERSA with 2 parallel output generators. From the result, we can conclude that HMERSA with 2 generator outputs installed in series is better than HMERSA with 2 parallel output generators.

Keywords: Hydraulic, regenerative shock absorber, series, parallels, vehicle suspension

1. Introduction

A shock absorber is installed as a part of the vehicle's suspension. They work in the tire's ability to maintain traction and control of the driver. In conjunction with the springs to improve the comfort of riding [1]. Regenerative suspension is divided into two types based on its working principle, namely mechanical regenerative suspension and electromagnetic regenerative suspension. Electromagnetic regenerative suspension transforms shock energy into electrical energy that can be stored and reused [2].

However, the development of regenerative suspension must pay attention to two aspects, among others aspects is the ability0 to regenerate energy and still be comfortable for riding [3].

The type of hydraulic electromagnetic suspension, known as the hydraulic Magnetoelectric regenerative shock absorber (HMERSA), has the advantage of the hydraulic system's flexibility and energy regeneration. The structure is simple and does not require many components, making it easy to apply [4–7].

Rack and pinion regenerative shock absorber is a prototype of RSA that mainly consists of a gear transmission system, one-way bearing, and an electromagnetic generator [8]. Ball Screw Regenerative Shock absorber (BSRSA) is the prototype of RSA mainly consists of the bevel gear mechanism as a two-way turn-to-one converter and ball screw, which is a mechanism for converting rotational motion to linear motion or vice versa [9].

HMERSA, which uses a type of hydraulic suspension with 2 inputs and 1 output on a hydraulic motor with a generator, the generation energy of HMERSA is 2.47 Watt [10].

This research is focused on the concept of improving testing with several changes to objects and variables in HMERSA with 1 input and 2 output generators whose installation will be examined at several positions and compared to their ability to harvest energy.

2. Theoretical Method

The type of absorber that is used in this research is the twin-tube type absorber, shown in Figure 1. The object is different from the previous absorber type, namely the mono-tube type. The dynamic modeling for the hydraulic suspension system is shown in Figure 2.

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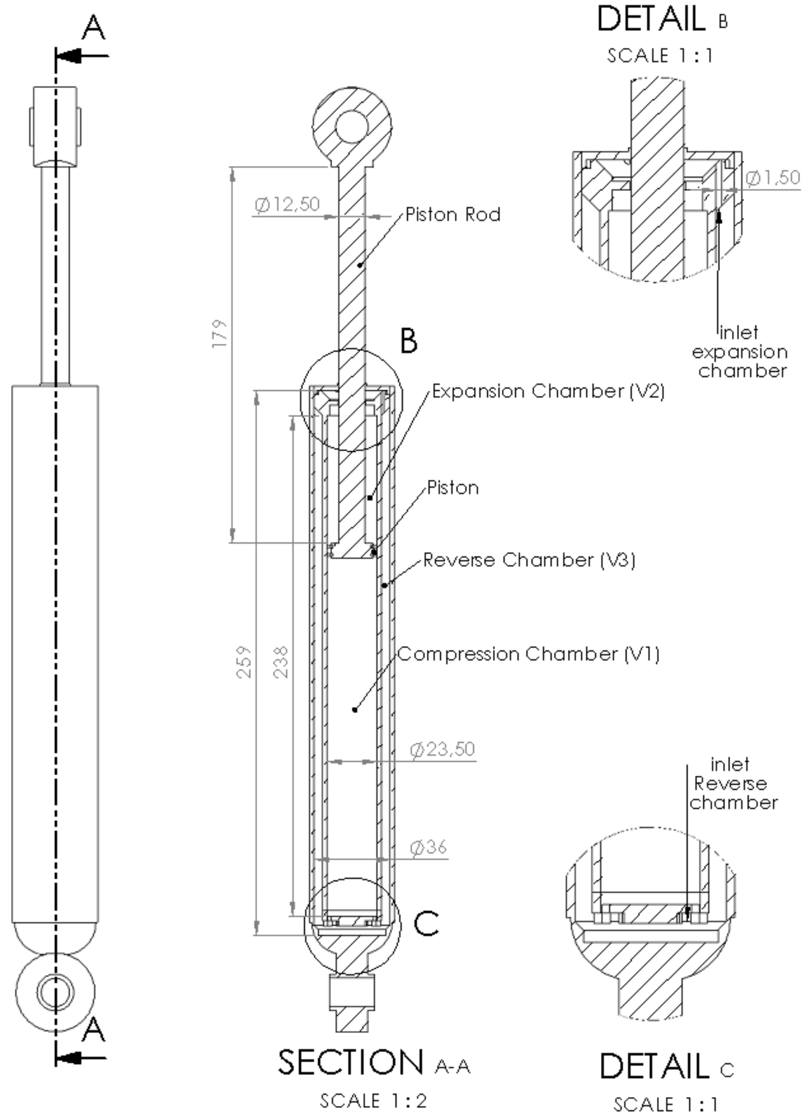

Figure 1. Conventional Shock Absorber Twin Tube Type

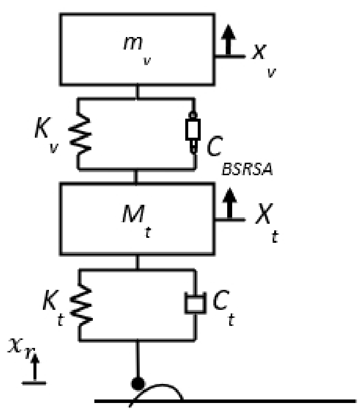

Figure 2. Dynamic modeling of HMERSA ¼ vehicles

The equation that is used in the conventional shock absorber system is as following. The hydraulic cylinder equation that is shown in Equation 1 is the Bernoulli equation.

$$\frac{p_1}{\rho} + \frac{v_1^2}{2} + gh_1 = \frac{p_3}{\rho} + \frac{v_3^2}{2} + gh_3$$

$$\frac{p_3}{\rho} + \frac{v_3^2}{2} + gh_3 = \frac{p_2}{\rho} + \frac{v_2^2}{2} + gh_2$$

Assume $h_1 = h_3$, so the equation becomes:

$$\frac{p_3}{\rho} + \frac{v_3^2}{2} = \frac{p_2}{\rho} + \frac{v_2^2}{2}$$

$$p_3 - p_2 = \frac{\rho}{2}(v_2^2 - v_3^2)$$

$$p_3 = (\frac{\rho}{2}(v_2^2 - v_3^2)) + p_2$$

$$(-\frac{\rho}{2}(v_3^2 - v_1^2)) + p_1 = (\frac{\rho}{2}(v_2^2 - v_3^2)) + p_2$$

$$(-\frac{\rho}{2}(v_3^2 - v_1^2)) - (\frac{\rho}{2}(v_2^2 - v_3^2)) = p_2 - p_1$$

$$p_2 - p_1 = \frac{\rho}{2}(v_1^2 - v_2^2)$$

$$\Delta p = \frac{\rho}{2}(v_1^2 - v_2^2) \tag{1}$$

Where is:

1: at the initial condition

2: when the condition is at the end

The hydraulic cylinder relationship with the tube uses the mass conservation equation during an expansion state,

$$Q_1 = Q_{tube}$$

$$v_1 A_1 = v_{tube} A_{tube}$$

$$v_{tube} = \frac{A_1}{A_{tube}} \times v_1 \tag{2}$$

Then substitute Equation 2 to Equation 1 with a note of condition 2 on the pipe and condition 1 on the hydraulic cylinder so that the equation becomes,

$$\Delta p = \frac{\rho}{2}(v_1^2 - v_{tube}^2)$$

$$\Delta p = \frac{\rho}{2}(v_1^2 - (\frac{A_1}{A_{tube}} \times v_1)^2)$$

$$\Delta p = \frac{\rho}{2}v_2^2(1 - (\frac{A_1}{A_{tube}})^2) \tag{3}$$

The damping force equation from equation 3 is shown in Equation 4.

$$F_d = \Delta p \times A_1$$

$$F_d = \frac{\rho}{2}A_1 v_1^2(1 - (\frac{A_1}{A_{tube}})^2) \tag{4}$$

During compression conditions,

$$Q_2 = Q_{tube}$$

$$v_2 A_2 = v_{tube} A_{tube}$$

$$v_{tube} = \frac{A_2}{A_{tube}} \times v_2 \tag{5}$$

Then substitute Equation 5 to Equation 1 with a note of condition 2 on the pipe and condition 1 on the hydraulic cylinder so that the equation becomes,

$$\Delta p = \frac{\rho}{2}(v_2^2 - v_{tube}^2)$$

$$\Delta p = \frac{\rho}{2}(v_2^2 - (\frac{A_2}{A_{tube}} \times v_2)^2)$$

$$\Delta p = \frac{\rho}{2}v_2^2(1 - (\frac{A_2}{A_{tube}})^2) \tag{6}$$

The damping force equation from equation 6 is shown in Equation 7.

$$F_d = \Delta p \times A_2$$

$$F_d = \frac{\rho}{2}A_2 v_2^2(1 - (\frac{A_2}{A_{tube}})^2) \tag{7}$$

Where is:

$$A_1 = \frac{\pi}{4}(D^2 - d^2)$$

$$A_2 = \frac{\pi D^2}{4}$$

$$A_{tube} = \frac{\pi d_{tube}^2}{4}$$

- The mathematical equation of m_v is as follows,

$$m_v \ddot{x}_v + F_t + F_v = 0$$

$$m_v \ddot{x}_v + k_v(x_v - x_t) + F_t = 0 \tag{8}$$

with:

x_v	is vehicle mass displacement
k_v	is the spring coefficient of the Vehicle
F_t	is the damping force generated from the HMERSA system
x_t	is displacement of tire mass

Input the forces that become a damper for the piston to move,

$$m_v \ddot{x}_v = -k_v(x_v - x_t) - \frac{\rho}{2}A_2 v_2^2(1 - (\frac{A_2}{A_{tube}})^2) - \frac{2T_e}{q\eta_m} - \rho A_2 hl$$

$$\ddot{x}_v = \frac{1}{m_v}[-k_v(x_v - x_t) - \frac{\rho}{2}A_2 v_2^2(1 - (\frac{A_2}{A_{tube}})^2) - \frac{2T_e}{q\eta_m} - \rho A_2 hl] \tag{9}$$

- The mathematical equation of m_t is as follows:

$$m_t\ddot{x}_t + Fd_t - F_t - Fk_v + Fk_t = 0$$

$$m_t\ddot{x}_t + c_t(\dot{x}_t - \dot{x}_r) - \frac{\rho}{2}A_2 v_2^2(1 - (\frac{A_2}{A_{tube}})^2) - \frac{2T_e A_2}{q\eta_m} - \rho A_2 hl - k_v(x_v - x_t) + k_t(x_t - x_r) = 0$$

$$m_t\ddot{x}_t = -c_t(\dot{x}_t - \dot{x}_r) + \frac{\rho}{2}A_2 v_2^2(1 - (\frac{A_2}{A_{tube}})^2) + \frac{2T_e A_2}{q\eta_m} + \rho A_2 hl + k_v(x_v - x_t) - k_t(x_t - x_r)$$

$$\ddot{x}_t = \frac{1}{m_t}[-c_t(\dot{x}_t - \dot{x}_r) + \frac{\rho}{2}A_2 v_2^2(1 - (\frac{A_2}{A_{tube}})^2) + \frac{2T_e A_2}{q\eta_m} + \rho A_2 hl + k_v(x_v - x_t) - k_t(x_t - x_r)] \tag{10}$$

with:

m_t is tire mass
k_t is the spring coefficient of the tire
c_t is tire damping coefficient
x_r is displacement of road contours

3. Result and Discussion

There are 2 types of HMERSA to be installed on vehicles, namely HMERSA with 2 generators installed in series and HMERSA with 2 generators installed in parallel. In Figure 3, the difference between HMERSA with 2 generators installed in series output and 2 generators installed in parallel output is shown. The difference is only in the series and parallel arrangement of the generator. The input pressure on these two HMERSA is 1.8 bar.

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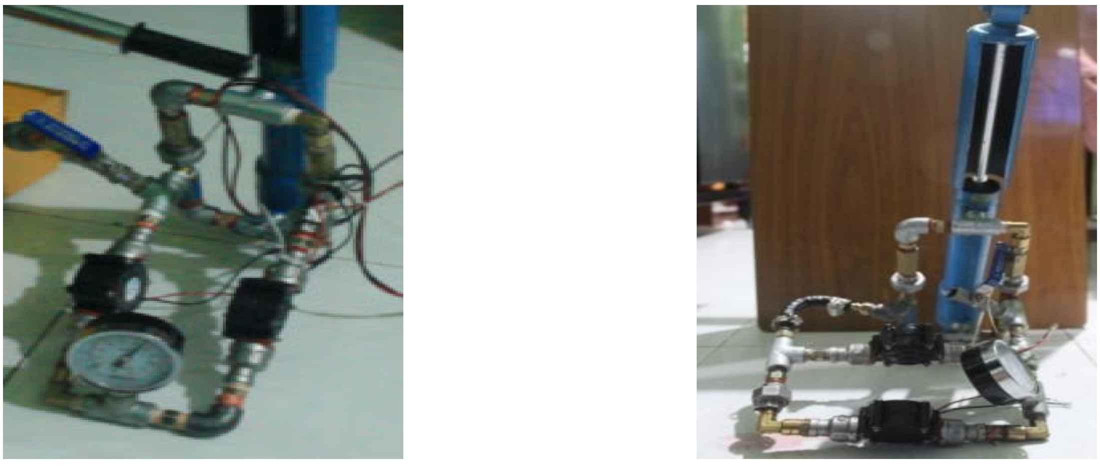
After the HMERSA was assembled, an experiment was conducted to determine whether the HMERSA was feasible to be tested on a vehicle. The suspension oil was put back into HMERSA using a hydrostatic pressure test. Figure 4. shows the working principle of a hydrostatic pressure test as an oil pump as well as a leakage test tool. Hydraulic oil was put in the hydrostatic pressure test chamber. Before pumping, make sure the hose is connected to HMERSA. To find out whether HMERSA is leaking or not, HMERSA is given the pressure of 5 bar and waited for 4 hours.



(a) (b)

Figure 3. HMERSA System with 2 Generator Outputs (a) Installed in Series (b) Installed in Parallel

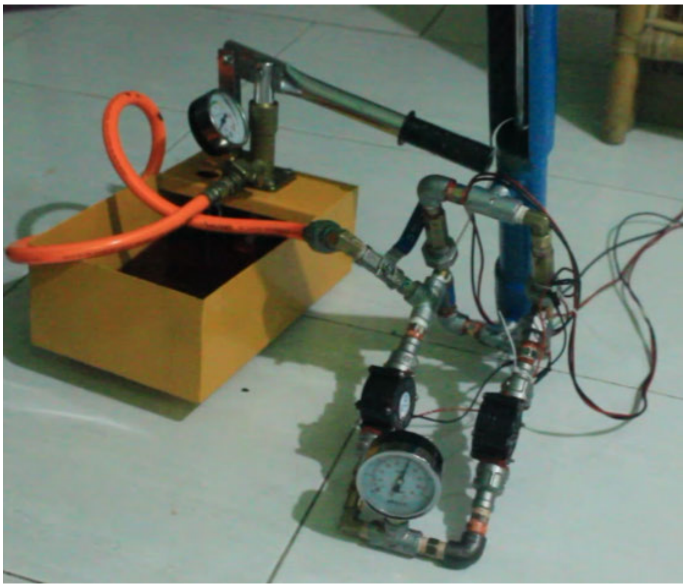


Figure 4. HMERSA Leakage Test

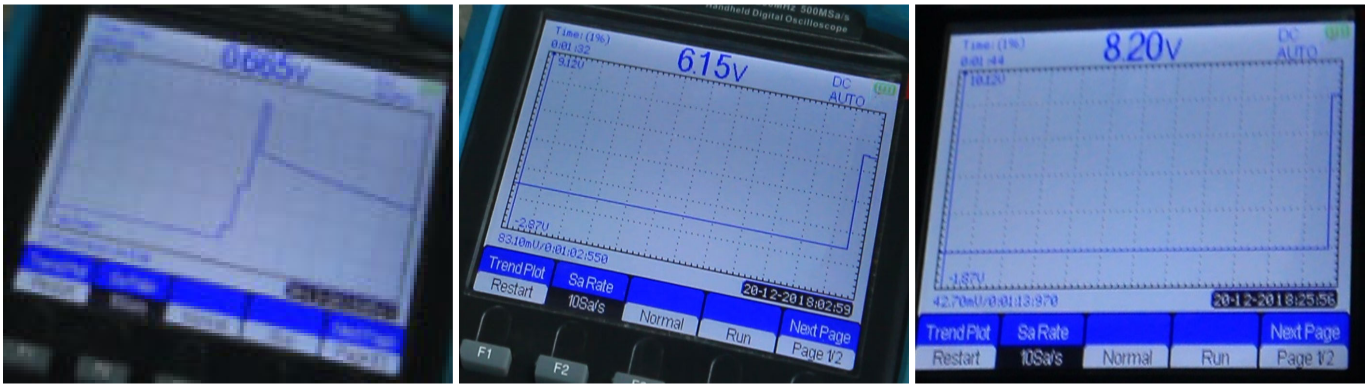
HMERSA system testing was carried out on the Toyota Avanza S-type vehicle. The Toyota Avanza was chosen because it is one of the most widely used vehicles by Indonesians as a means of transportation. HMERSA installation process can be seen in Figure 5. The HMERSA installation process began with removing the conventional shock absorber on the right rear of the vehicle.

Testing was done when vehicles passing speed bumps; there were 3 variations of speed, namely 10 km/h, 15 km/h, and 20 km/h. There is data in the form of voltage generation for each variation of speed and data retrieval and dynamic response in the form of chassis acceleration. The results of the vehicle chassis acceleration with the installation of HMERSA will be compared with conventional shock absorbers.

Figure 6(a) shows the voltage generated by HMERSA when it passes through a speed bump at 10 km/h. The maximum voltage generated is 1.29 Volts with a maximum generation power is 0.24 Watts for generator 1; and 0.6 Volts with maximum power is 0.21 Watts for generator 2. When viewed from the maximum value, the power generated is quite small. This is influenced by the maximum capacity of the generator, which is only 12 Volts, and the maximum ampere is 400 mA.

Figure 6(b) shows the voltage generated by HMERSA arranged in series when it passes through a speed bump at a speed of 15 km/h. The maximum voltage and power generated will increase with increasing speed, namely 6.15 Volts and 1.29 Watts for generator 1; and 3.98 Volts with maximum power is 0.83 Watts for Generator 2. Figure 6(c) shows HMERSA voltage and power pass the speed bump at a speed of 20 km/h. At the highest test speed, the voltage and power were also the highest compared to 10 km/h and 15 km/h, reaching 8.2 Volts and 1.72 Watts for generator 1; and 5.97 Volts with a maximum power of 1.25 Watts for generator 2.

Figure 5. Installation of HMERSA on Cars



(a) **(b)** **(c)**

Figure 6. Voltage generated by HMERSA in Series from Generator 1 passes speed bumps (a) speed 10 km/h, (b) speed 15 km/h, (c) speed 20 km/h

Table 1 shows a recapitulation of data in maximum power and voltage from each speed and experiment. As previously explained, while the vehicle speed increases, the energy generated is higher than before. The power generated is affected by the generator rotational speed. With increasing vehicle speed, the frequency of HMERSA excitation through speed bumps will also be greater, causing the generator's rotating speed to increase. In this case, the maximum power generated occurs at a speed of 20 km/h with a power of 1.72 Watts. Figure 7 shows the direct difference in the generation power at each vehicle's speed.

Table 1. Voltage recapitulation and power generation through the HMERSA series

Velocity (km/Hr)	Maximum Result			
	Voltage (Volt)		Power (Watt)	
	Generator 1	Generator 2	Generator 1	Generator 2
10	1.29	0.6	0.24	0.12
15	6.12	3.98	1.28	0.83
20	8.2	5.97	1.722	1.25

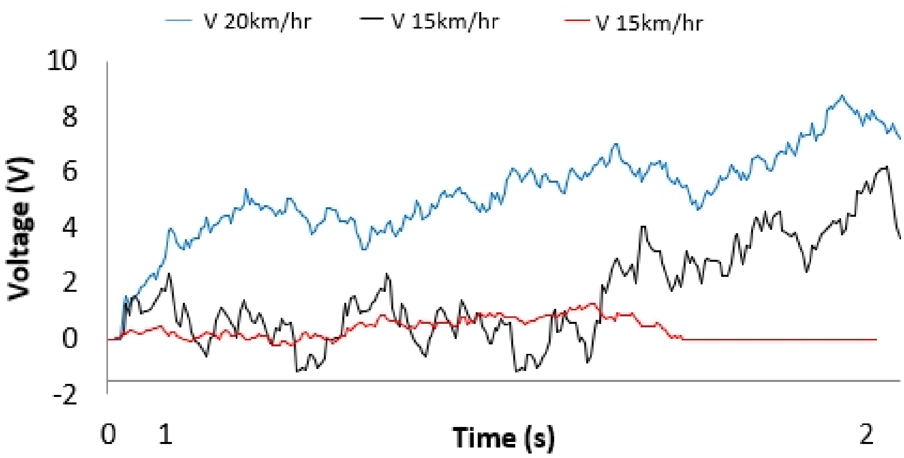
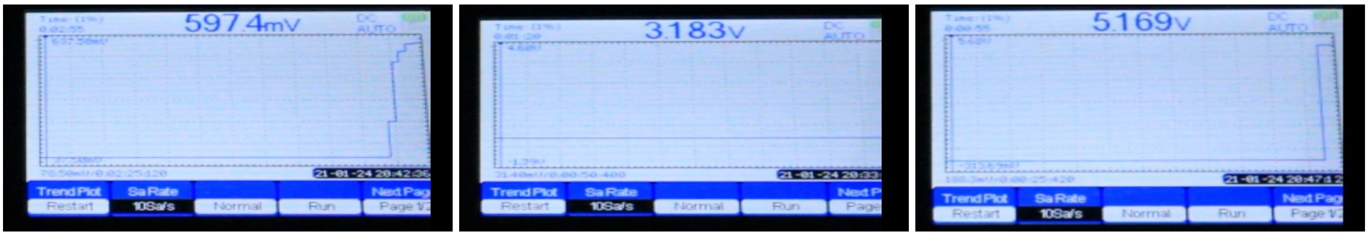


Figure 7. Comparison of The Voltage generated by HMERSA in Series Passing Speed Bump with speed of 10 km/h, 15 km/h, 20 km/h

Figure 8(a) shows the voltage and power generated by HMERSA arranged in parallel when it passes through a speed bump at a speed of 10 km/h. The maximum generated voltage was 0.59 Volts with a maximum power of 0.12 Watts for Generator 1; and 0.52 Volts with a maximum power of 0.10 Watts for Generator 2, as shown in Table 2.

Figure 8(b) shows the voltage and power generated by HMERSA when it passes the speed bump at 15 km/h. The maximum voltage and power generated will increase with increasing speed, which was 3.183 volts and 0.66 watts for generator 1; and 2.56 Volts with a maximum power of 0.537 Watts for Generator 2. Figure 8(c) shows the HMERSA voltage and power. Passing speed bumps at a speed of 20 km/h. At the highest speed of the test, passing speed bumps, the voltage and power were also the highest compared to 10 km/h and 15 km/h, reaching 5.169 Volts and 1.08 Watts for generators 1, and 4.33 Volts with a maximum power of 0.91 Watts for generator 2.

Figure 9 shows the difference in the power generated at each vehicle speed.



(a) (b) (c)

Figure 8. Voltage generated by HMERSA in Parallel from Generator 1 passes speed bumps (a) speed 10 km/h, (b) speed 15 km/h, (c) speed 20 km/h

Table 2. Voltage recapitulation and power generation through the HMERSA in Parallel

Velocity (km/h)	Maximum Result			
	Voltage (Volt)		Power (Watt)	
	Generator 1	Generator 2	Generator 1	Generator 2
10	0.59	0.52	0.12	0.10
15	3.183	2.56	0.66	0.537
20	5.169	4.33	1.08	0.91

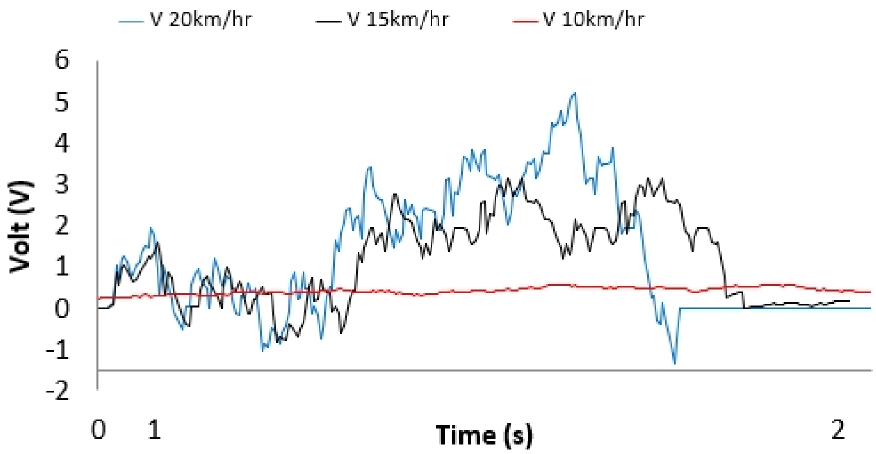


Figure 9. Comparison of Voltage generated by HMERSA in Parallel with passing speed of speed 10 km/h, 15 km/h, 20 km/h

On Avanza vehicles with engine capacity of 1500cc, 1 liter of gasoline can cover a distance of 13.4 km. While in the electric car, an average of 1 kWh of electricity can cover a distance of 4.6 km, or it can be assumed 1 liter of gasoline is about 2.6 kWh. In electric vehicles, the energy loss is not too much, which is about 35%. From the energy loss with the consumption of electric power comparable to 1 liter of gasoline, the total power is 3664 Watts. In this study, the maximum power generated is 1.72 Watts. From the comparison between the conversion of gasoline fuel to electric power, it can be concluded that the energy efficiency is 0.046%.

The dynamic response measured is body displacement, speed, and vertical acceleration of the vehicle chassis. The value of body displacement, speed, and acceleration between vehicles using a conventional shock absorber and HMERSA was compared. Figure 10 shows the dynamic response of the vehicle with a conventional absorber with a speed of (a) 10 km/h, (b) 15 km/h, and (c) 20 km/h.

Table 3 describes the results of the dynamic response of a conventional absorber for each speed. The discussion is focused on the value of acceleration because it is a reference value for the level of driving comfort. At a speed of 10 km/h, the resulting velocity was 2.43 m/s. Meanwhile, at speeds of 15 km/h and 20 km/h, the values were 4.21 m/s and 5.18 m/s.

Figure 11 shows the dynamic response of the vehicle for the HMERSA in Series with a speed of (a) 10 km/h, (b) 15 km/h, and (c) 20 km/h. Table 4 describes the results of the dynamic response of the HMERSA Series for each speed. At a speed of 10 km/h, the resulting velocity was 1.35 m/s. Meanwhile, at speeds of 15 km/h and 20 km/h, the values are 4.55 m/s and 13.71 m/s.

(a) (b) (c)

Figure 10. Comparison of Dynamic Response from Conventional Absorber Passing Speed Bump for Each Speed (a) 10 km/h, (b) 15 km/h, and (c) 20 km/h.

Table 3. Results of Dynamic Response of Conventional Absorber Passing the speed bump

Velocity (km/h)	Dynamic Response		
	Displacement (mm)	velocity (m/s)	Acceleration (m/s^2)
10	7.5	2.43	1.1
15	11	4.21	3.84
20	21.5	5.18	5.95

(a) (b) (c)

Figure 11. Comparison of Dynamic Response from HMERSA in Series Passing Speed Bump for Each Speed (a) 10 km/h, (b) 15 km/h, and (c) 20 km/h.

Table 4. Results of Dynamic Response of HMERSA in Series Passing the speed bump

Velocity (km/h)	Dynamic Response		
	Displacement (mm)	velocity (m/s)	Acceleration (m/s^2)
10	12	1.35	0.76
15	11	4.55	10.14
20	13.4	13.71	11.83

Figure 12 shows the dynamic response of the vehicle for the HMERSA Series with a speed of (a) 10 km/h, (b) 15 km/h, and (c) 20 km/h. In Table 5, the dynamic response results from HMERSA Parallel are described for each speed. At a speed of 10 km/h, the resulting Velocity was 0.58 m/s. Meanwhile, at speeds of 15 km/h and 20 km/h, the values were 4.07 m/s and 4.23 m/s.

Figure 13 shows the comparison of acceleration for conventional shock absorbers and HMERSA. In conventional shock absorbers, the acceleration value will increase with increasing speed. The maximum acceleration in conventional absorbers was 5.95 m/s^2 at a 20 km/h speed, as with HMERSA. Overall, the acceleration value of both the Series and Parallel HMERSA was 2 times higher than the conventional shock absorber. When referring to vehicle comfort parameters concerning the vertical acceleration of the vehicle chassis, the ability to dampen vibrations from HMERSA is still not optimal compared to conventional shock absorbers because of the difference in absorber type. The original absorber uses gas and oil hydraulic for the filling absorber, and the modified absorber only uses oil hydraulic to fill the absorber. However, if seen from the results of the damping acceleration between Series and Parallel HMERSA in general, HMERSA Series is better than HMERSA Parallel.

(a) (b) (c)

Figure 12. Comparison of Dynamic Response from HMERSA in Parallel Passing Speed Bump for Each Speed (a) 10 km/h, (b) 15 km/h, and (c) 20 km/h.

Table 5. Results of Dynamic Response HMERSA in Parallel Passing the speed bump

Velocity km/h	Dynamic Response		
	Displacement (mm)	velocity (m/s)	Acceleration (m/s^2)
10	6.4	0.58	3.7
15	33.8	4.07	5.25
20	54.1	4.23	25.65

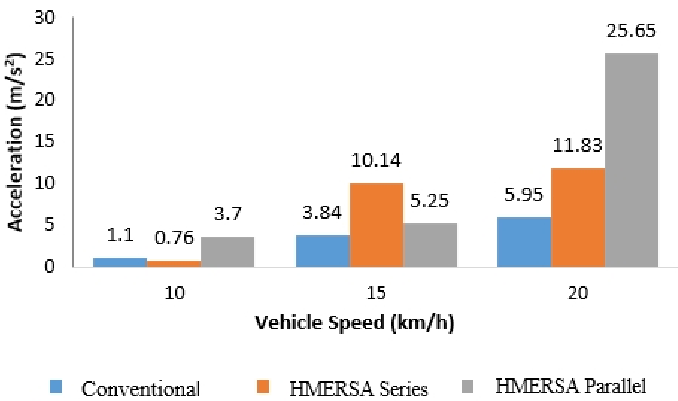


Figure 13. Comparison of Conventional Shock Absorber Acceleration with HMERSA on Speed Bump Profile

4. Conclusions

In the test of passing speed bumps, the HMERSA maximum voltage series that occurred at a speed of 20 km/h was 8.20 volts at generator 1. While in HMERSA in parallel, the maximum voltage occurred at a speed of 20 km/h, which was 5.169 volts at generator 1. In this HMERSA, the resulting efficiency was 0.046%. Results Comparison between HMERSA with two generator outputs installed in series and parallel is better for HMERSA installed in series, both in dynamic response and generated power. The amount of generated energy generated is strongly influenced by the contour of the road that is passed. The coarser and more varied the amplitude of the road that is passed, the greater the energy are generated.

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