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Characteristics of Dynamic Response of Suspension Hydraulic Motor - Regenerative Shock Absorber (HMRSA)

Kaspul Anuar [a,*] and Harus Laksana Guntur [b]

[a)] *Department of Mechanical Engineering, Universitas Riau, Indonesia*
[b)] *Department of Mechanical Engineering, Institut Teknologi Sepuluh November, Indonesia*

*Corresponding author: kaspul.anuar@lecturer.unri.ac.id

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ABSTRACT

Translational motion that happens in the vehicle's suspension due to unevenness of the road surface can be used as a source of electrical energy. A suspension that can convert translational motion into electrical energy is known as regenerative type suspension. To know the characteristics of the dynamic response, such as electrical energy potential and driving coziness which resulted by a suspension system, we need to examine the suspension. In this study, a test will be conducted to a suspension system that has been designed by researchers and was named Hydraulic Motor - Regenerative Shock Absorber (HMRSA). The test will be conducted statically and dynamically. The goal of the static testing is to obtain the spring's constant value and the damping's constant value of HMRSA. In the dynamic testing, excitation was given in the form of periodic and impulse. Periodic excitations are varied between these several frequencies such as 1.4Hz, 1.75 Hz and 2 Hz. Instead of variant of frequencies, electrical resistivity loads are varies in periodic excitations with each resistive loads such as 6 ohm, 12 ohm and 18 ohm. From dynamic testing, the electricity power values and sprung's mass acceleration which resulted by HMRSA suspension system on each frequency and electrical resistivity will be obtained. The sprung's mass acceleration value will be fundamental on how to analyze driving coziness that produced by HMRSA suspension system.

KEY WORDS: *Hydraulic Motor - Regenerative Shock Absorber (HMRSA), sprung's mass, acceleration.*

NOMENCLATURE

K	spring's constant (N/m)
C	damping's constants (Ns/m)
m	vehicle mass (kg)
x	displacement (m)
$\dot{x}$	velocity (m/s)
$\ddot{x}$	acceleration (m/s^2)
Te	electrical torque (N.m)
F	force (N)
N	amount of coil turns
B	Flux density vector
I	Electric current (A)
R	Resistance (ohm)
t	Time (s)

1.0 INTRODUCTION

Realizing the amount of energy wasted on vehicles [1], a device to harvest those wasted energies is needed. By this, the consumption of fuels on vehicles will be saved in such a way. One of a mechanism that be able to relieve energy loss in vehicles is suspension that known as regenerative shock absorber (RSA). Regenerative shock absorber can change the vibrations on vehicles that happened by unevenness of the road surfaces into electrical energy [2].

There are several researches about RSA that have been conducted by some researchers. In 2009, a team from Massachusetts Institute of Technology [3], have developed a regenerative shock absorber system that can produce electricity based on hydraulic principles. Inside this regenerative shock absorber there is a piston that used to push fluid that flows to turbine, after that the spin of the turbine will also spin the generator. This regenerative shock absorber suspension could produce a power of 1 KW on normal roads.

In 2010, Zuo [1] from Stony Brook University design and develop a device to collect energy on a vehicle's suspension. The wasted vibrations on the suspension are used to produce

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electricity. This device was developed with 2 different principles of electricity generator, linear electromagnetic absorber and rotational absorber. The power that produced by linear electromagnetic is about 2 - 8 watt, while rotational absorber could produce a power of 80 watt [1].

Arziti [2] develop a regenerative shock absorber that based on piezoelectric. This suspension uses a piezoelectric at the top of the piston as its energy generator. In this regenerative shock absorber, the electrical voltage generated is 0.0176 volts. Next, fang [3] from Wuhan University of Technology China, create an absorber from actuator hydraulic component which is connected with the hydraulic generator motor. Based on the test, the energy generated from this regenerative shock absorber reaches 193 watts.

In Indonesia, The development of regenerative type suspension is done by Guntur, L. Harus [4]. This regenerative type suspension converts translational motion into rotational motion to rotate generator. The development of this RSA type rotational absorber is capable of generating power of 15 -18.6 watts.

2.0 FUNDAMENTAL THEORY

2.1 Motion of Base

The vibrations in the vehicle suspensions can be modeled as shown in Figure 1. below.

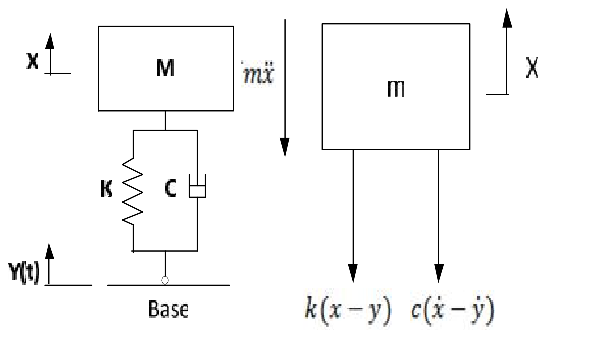

Figure 1: Base excitation (a) Physical system base excitation (b) Free body diagram for base excitation system [5]

As shown in figure 1(a), The mass-spring-damping system undergoes harmonic motion. Excitation input y(t) state displacement from base, and x(t) state mass displacement from the static equilibrium position at time t. Then the elongation of the spring is $(x-y)$ and The relative speed between the two ends of the damper is $(\dot{x}-\dot{y})$. From free body diagram shown in figure 1 (b), we obtain the equation of motion :

$$m\ddot{x} + c\dot{x} + kx = c\dot{y} + ky \quad (1)$$

The force received by the spring mass due to the base exciter can be formulated as follows:

$$F = m\omega^2 X \sin(\omega t - \emptyset) = F_t \sin(\omega t - \emptyset) \quad (2)$$

2.2 Spring

Spring is a mechanical connector which widely used in many applicants. Spring is assumed to have no mass and no damping. The type of spring commonly used in a vehicle is a helical coil spring. Any object that has elasticity can be assumed to be a spring [5], figure 2 shows springs that was charged to compression loads and tensile loads.

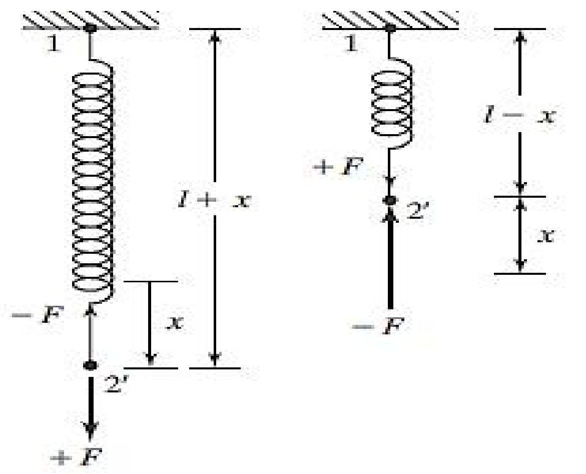

Figure 2: Springs that was charged to compression loads and tensile loads [5]

In accordance with the 3rd Newton's law, if a spring is given a tensile force or compression force then the direction of the spring's reaction force will be opposite. The spring is called linear if the relation between force and spring deflection satisfies the following equation [3]:

$$F = k.\,x \quad (3)$$

If the relations between the force given and the spring deflection do not satisfy the equation (3), then the spring is called non-linear. Figure 3 shows graph of force vs deflection on non linear springs

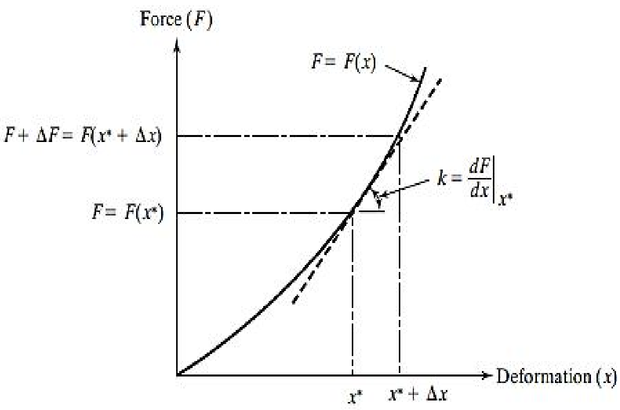

Figure 3: Graph of force vs deflection on non linear springs [5]

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On non linear springs, the relations between force gain and deflection gain, satisfies the following equation:

$$\Delta F = k \,.\, \Delta x \quad (4)$$

On non linear springs [5], the spring's Constants can be linierized by using the following equation:

$$k = \frac{dF}{dx} \quad (5)$$

2.3 Damping
Damping is part of the vibration system that converts vibration energy into heat and sound [5]. Damping is assumed to have no masses and elasticity. In non-linear damping [5], the damping Constanta can be dilinierized by using the following equation:

$$C = \frac{dF}{dv} \quad (6)$$

2.4 Electric generator
A generator is a device that converts mechanical energy into electrical energy. The electric generator induces electrical motion by rotating the coils in a magnetic field. Figure 4 shows Schematic of electric generator

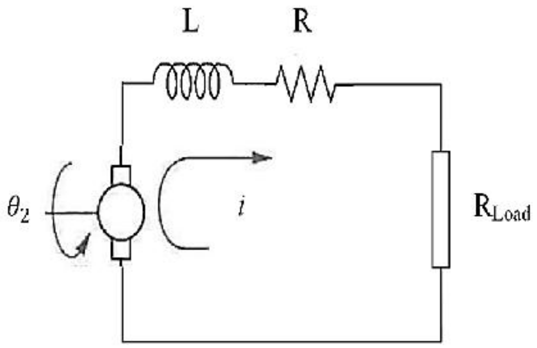

Figure 4: Schematic of electric generator [6]

On the generator, the electric torque generated can be determined using the following equation [6]:

$$T_e = 2.N.B.l.a.I \quad (7)$$

2.5 The effect of Vehicle Acceleration towards coziness.
Information about human body resistance to acceleration is very important as a reference in the design of vehicle body resistance to impact. The comfort criteria based on acceleration according to ISO 2631 standard, is shown in table 1 below:

Table 1: Comfort reaction to acceleration – ISO 2631

No.	Acceleration (RMS)	Details
1.	< 0,315 m/s^2	No complaints
2.	0,315 m/s^2 to 0,63 m/s^2	A bit uncomfortable
3.	0,5 m/s^2 to 1 m/s^2	Somewhat uncomfortable
4.	0,8 m/s^2 to1,6 m/s^2	Uncomfortable
5.	1,25 m/s^2 to 2,5 m/s^2	Very uncomfortable
6.	a > 2 m/s^2	Very very uncomfortable

3.0 METHODOLOGY

3.1 Static Testing
This study begins by measuring the value of the damping's constants and the spring's constants of the HMRSA suspension system. The measurement of spring's constant value is done by giving seven variations of mass load between 217.9 kg up to 277.9 kg above test rig test equipment. From the load we will obtain spring deflection (Δx) HMRSA suspension. Here is shown figure 5 testing the spring deflection value with the rig test equipment.

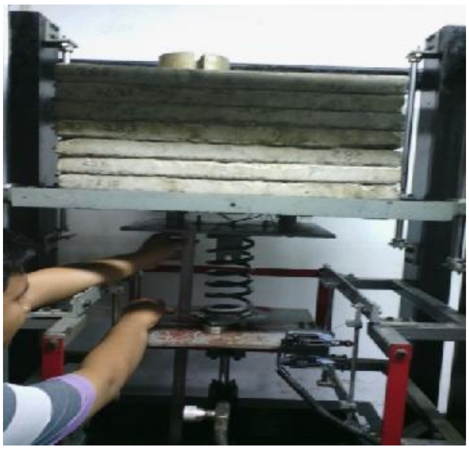

Figure 5: Testing the spring deflection value

The value of spring's Constants is obtained by doing calculations according to the equation (4) and (5).

The test to obtain the value of damping's constants is done by giving 3 variations of mass load on HMRSA suspension. The result will be the speed of vertical motion of the absorber when subjected to mass load. Here is shown figure 6 Scheme about testing the speed of vertical absorber motion when subjected to mass load.

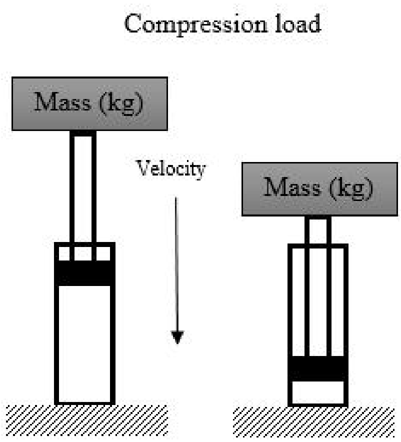

Figure 6: Static testing mechanism of compression damping value

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The value of damping constants is obtained by calculating according to the equation (6)

3.2 Dynamic Testing

This test is done to obtain dynamic response of HMRSA suspension in the form of sprung's mass acceleration and electric power generated. The testing mechanism being used quarter car's model. In this test the mass of concrete is assumed as a sprung's mass (mass on the vehicle), while on the bottom plate (excitation sources) used as base exciter.

The input on the dynamic testing are excitation impulse and harmonic with an amplitude of 1.5 cm and varies of excitation frequency of 1.4 Hz, 1.75 Hz and 2 Hz. The testing load being used is 250 kg (quarter of urban vehicles weight). Here is shown figure 7, Dynamic testing of HMRSA suspension.

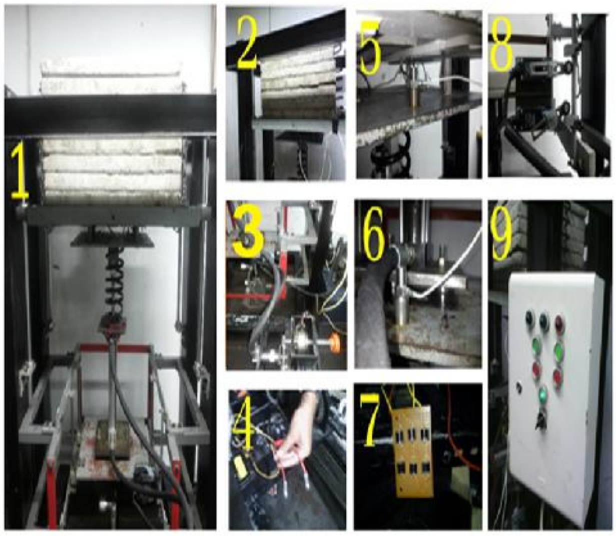

Figure 7: Dynamic testing of HMRSA suspension

Details of figure 7:
1. Installation of HMRSA on Suspension test rig;
2. Test load (250 kg)
3. Hydraulic motor, gear transmission and HMRSA generator
4. Lamp installation as a load
5. Accelero sensor on spring mass
6. Accelero sensor on base exciter
7. Rectifier (AC to DC rectifier circuit)
8. Limit switch (excitation amplitude regulator)
9. Control Panel

4.0 RESULTS AND DISCUSSION

4.1 Static test results

The spring deflection data retrieval process is done using seven variations. Here is shown Table 2 Data of spring deflection test results.

Table 2: Data of spring deflection test

Condition	Mass(kg)	W(N)	ΔW(N)	X(m)	ΔX(m)
Compression	0	0	0	0.310	0
	217.9	-2137.6	-2137.6	0.260	-0.050
	227.9	-2235.7	-98.1	0.258	-0.052
	237.9	-2333.8	-98.1	0.257	-0.053
	247.9	-2431.9	-98.1	0.255	-0.055
	257.9	-2530.0	-98.1	0.253	-0.057
	267.9	-2628.1	-98.1	0.251	-0.059
	277.9	-2726.2	-98.1	0.250	-0.060
Rebound	277.9	2726.2	0.0	0.250	0.060
	267.9	2628.1	98.1	0.251	0.059
	257.9	2530.0	98.1	0.252	0.058
	247.9	2431.9	98.1	0.255	0.055
	237.9	2333.8	98.1	0.258	0.052
	227.9	2235.7	98.1	0.260	0.050
	217.9	2137.6	98.1	0.262	0.048

Results of spring deflection test on table 2 then ploth on graphical of force vs deflection when there is compression and rebound from spring. Figure 8 shows graph of force vs spring deflection as test results.

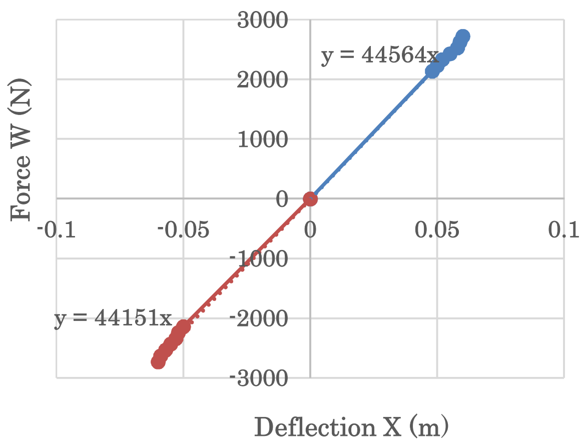

Figure 8: Graph of force vs spring deflection

From the graph above, Graph's gradient of force vs deflection experienced a slight increase on 2628.1 N to 2726.2 N loads. This indicates the beginning of nonlinearity from spring's constants on that load. So, according to the equation (5), the value of spring's constants when compression and rebound are 44564 N/m and 44151 N/m respectively.

The tests to find the damping value of HMRSA were done by giving forces for compression. Three kinds of loads were given

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on the test and repeated as much as three times. Below shown Table 3. data of HMRSA damping test results

Table 3: Data of HMRSA damping test result

Test	Force (N)	Velocity (V)	C (N.s/m)
1	877.505	0.08000	10968.806
2	877.505	0.08205	10694.586
3	877.505	0.08421	10420.366
Average	877.505	0.08209	10694.590
4	1005.035	0.09412	10678.490
5	1005.035	0.09412	10678.490
6	1005.035	0.09412	10678.490
Average	1005.035	0.09412	10678.490
7	1073.705	0.10667	10065.980
8	1073.705	0.10323	10401.512
9	1073.705	0.10526	10200.193
Average	1073.705	0.10505	10222.560

From the test result data, then plot a graph force vs velocity so that the total damping compression value will be obtained from HMRSA suspension. Here is shown figure 9. Graph force vs velocity test results.

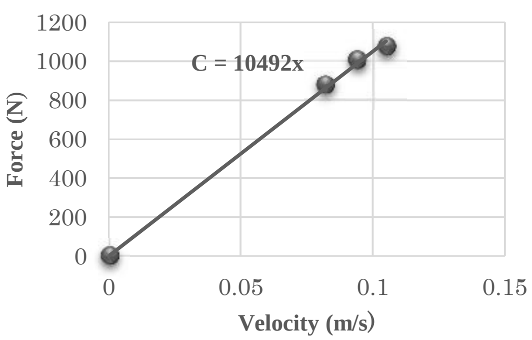

Figure 9: Graphical plot force vs velocity

On figure 9 above gradient of the graph damping force (Fd) vs velocity (v) is directly proportional, the bigger the force given, the higher the velocity. This is in accordance with the equation (6) where c is the gradient or the damping constant of HMRSA suspension. From the graph above given the gradient or HMRSA suspension damping value equal to 10492 N.s/m.

4.2 Dynamic test results

Excitation impulses are given only on amplitude 1.5 cm with varies of electrical resistance load on the generator of 6 ohm, 12 ohm and 18 ohm. The results of tests with impulse excitations are shown in Figure 10 below.

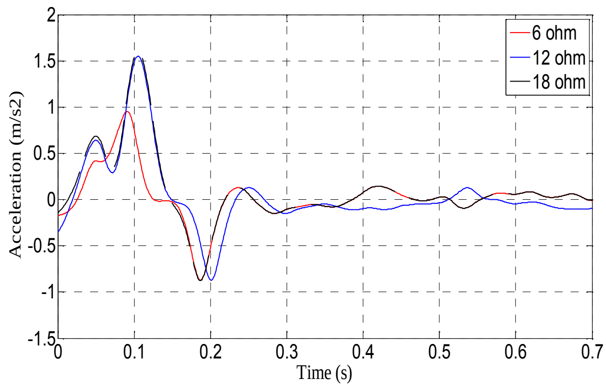

Figure 10: Graph of results of the mass spring acceleration responses test due to impulse excitation with varies of electrical loads of 6 ohms, 12 ohms and 18 ohms

From figure 10 above, we can see the difference of response on sprung's mass on each loading. The smallest peak amplitude of sprung's mass occurs in the 6 ohm electrical resistance with value 0.95 m/s^2. On the 12 Ohm load, the peak amplitude is bigger than the 18 ohm loading of 1.55 m/s^2. And the highest peak amplitude value occurs at 18 ohm power loading which equal to 1.605 m/s^2. This shows that the smallest damping value occurs on HMRSA that used 18 ohm load which create big peak amplitude. From the figure above also seen, the time it takes to reach stable condition on every load is almost the same which about 0.3 seconds.

Varies of electrical resistance values will affect the strong current generator generated. On the test with bigger electrical resistance will cause the current generated become smaller. If the generated current generator is smaller it will cause electric torque values (electrical damps) also small. This corresponds to the equation (7). With the shrinking value of electrical damps (electrical torque) will decrease HMRSA damping coefficient so that the peak amplitude value of the spring mass acceleration will get bigger.

Here is shown figure 11 graph of spring mass acceleration response due to periodic excitation on 1.4 Hz frequency and amplitude of 1.5 cm.

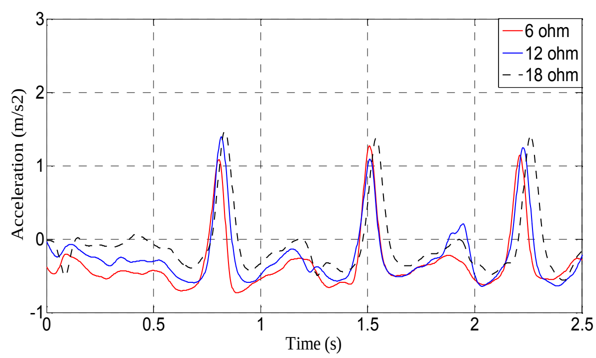

Figure 11: Test results graph of sprung's mass of periodic excitation response with load of 6 ohm, 12 ohm and 18 ohm on frequency of 1.4 Hz

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In the test using excitation frequency as much as 1.4 Hz, the highest Root-Mean Square (RMS) of sprung's acceleration occurred at 18 ohm loading with value 0.402m/s^2. On 12 ohm load, the RMS value of sprung's mass acceleration as much as 0.387 m/s^2. The smallest RMS of sprung's mass acceleration occurs at 6 ohm load which is 0.248 m/s^2. This shows that the smallest damping value occurs in HMRSA using 18 ohms resistance so that the RMS of sprung's mass acceleration is the greatest.

According to ISO 2361, the three sprung's mass acceleration responses have an RMS value below 0.8m/s^2, This indicates that HMRSA is able to maintain driving comfort in periodic excitation with frequency 1.4 Hz and amplitude 1.5 cm.

At periodic excitation frequency of 1.75 Hz, the load of electrical resistance is also varied by 6 ohm, 12 ohm and 18 ohm. Here is shown figure 12 graph of sprung's mass acceleration response due to periodic excitation at 1.75 Hz and amplitude 1.5 cm.

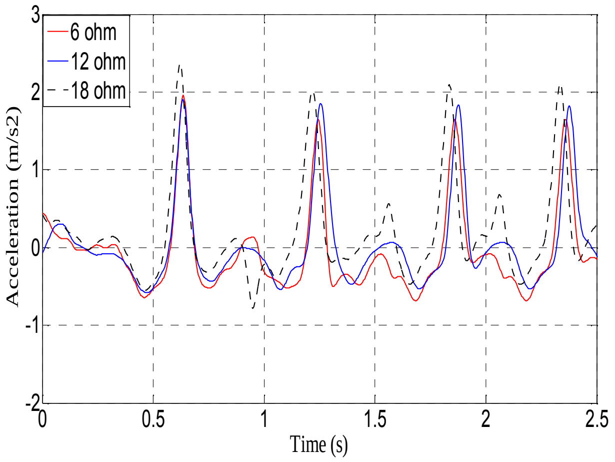

Figure 12: Test results graph of Sprung's mass response of periodic excitation at 6 ohm, 12 ohm and 18 ohm loading at 1.75 Hz frequency

From figure 12 it can be seen that the difference of sprung's mass acceleration response at each loading is not so much because the variation of load of electrical resistance being used also not so much difference. In the test using the excitation frequency of 1.75 Hz, the greatest RMS of sprung's acceleration occurred at 18 ohm loading with value 0.729 m/s^2, followed by 12 ohm loading of 0.5979 m/s^2 and the smallest RMS occurs at 6 ohm loads with value 0.5534 m/s^2. This also shows that the smallest damping value occurs in HMRSA using 18 ohm resistance so that the RMS mass spring acceleration will be the greatest.

According to ISO 2361, the three spring mass acceleration responses have an RMS value below 0.8m/s^2. This indicates that HMRSA is able to maintain driving comfort in periodic excitation with frequency 1.75 Hz.

Periodic excitation at a frequency of 2 Hz varies the load of electrical resistance by 6 ohms, 12 ohms and 18 ohms. Here is shown figure 13 graph of sprung's mass acceleration response due to periodic excitation at 2 Hz frequency and amplitude 1.5 cm.

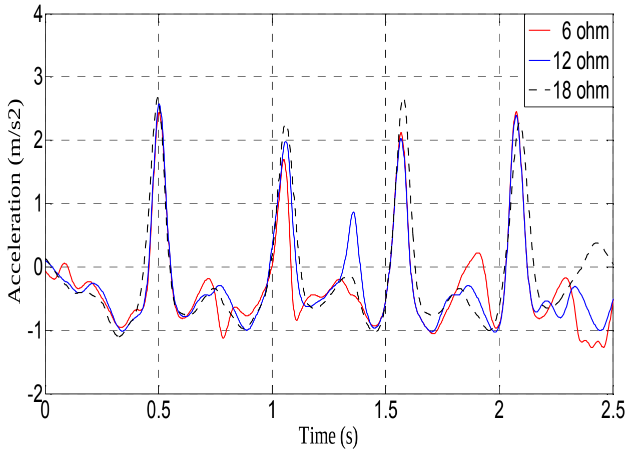

Figure 13: Test results graph of sprung's mass of periodic excitation response with load of 6 ohm, 12 ohm and 18 ohm on frequency of 2 Hz

In the test using the excitation frequency of 2 Hz, The largest RMS of sprung's mass acceleration occurs at 18 ohm loading with value of 1.02 m/s^2. On 12 ohm load, the RMS value of sprung's mass acceleration is 1.009 m/s^2. RMS acceleration of the smallest sprung's mass occurs at 6 ohm electrical load which equal to 0.6383 m/s^2.

According to ISO 2361 the sprung's mass acceleration response at 12 ohm and 18 ohm electrical resistance has an RMS value of more than 0.8 m/s^2. This indicates that HMRSA is not able to maintain the comfort of driving when working at a frequency of 2 Hz.

4.3 The Power Generated by HMRSA

From the above periodic excitation testing, we obtained the amount of energy generated at each excitation frequency. Here is shown table 4 Electric power generated HMRSA suspension.

Table 4: HMRSA Generated Electric Power

Load	**Power generated (watt)**		
	1.4 Hz	1.7 Hz	2Hz
6 ohm	0.198	0.063	0.024
12 ohm	0.6771	0.623	0.3465
18 ohm	1.1078	0.5157	0.4932

From table 4, then displayed in the form of a bar chart as shown in Figure 14. below.

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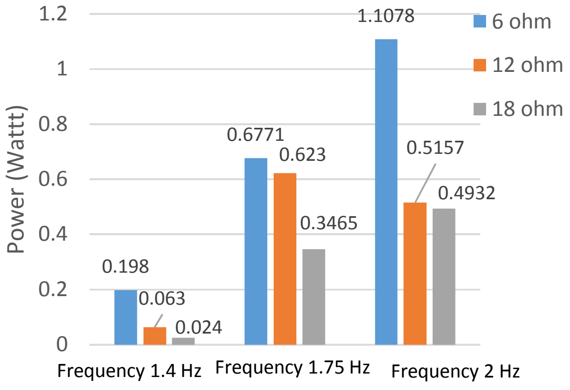

Figure 14: Electric power generated by HMRSA

From figure 14 above, it is known that the electric power generated HMRSA suspension is very small that is ranging from 0.024 watts to 1.1078 watts. The small electric power generated by HMRSA suspension is due to the small excitation amplitude being used is 1.5 cm. Furthermore, the electric generator rotation of the HMRSA suspension is relatively slow. This is inversely proportional to the specification of HMRSA's generator which is high-speed type power generator.

Viewed from the increasing frequency side, generally the electric power generated by HMRSA suspension keeps increasing as frequency increases. The highest power produced by HMRSA occurs at 2 Hz excitation frequency and 6 ohm electrical resistance which is 1.1078 watts.

5.0 CONCLUSION

In this research, HMRSA suspension testing is done statically and dynamically. Static test aims to determine the value of spring and damping constants. While the dynamic testing aims to determine electric power and acceleration of spring mass produced HMRSA suspension. The following describes the conclusions of this study.

1. HMRSA suspension is able to maintain the driving comfort in periodic excitation of frequency 1.4 and Hz 1.7 Hz on all variations of electrical resistance. While at the frequency of 2 Hz, HMRSA suspension only able to maintain driving comfort at 6 ohm electrical resistance.
2. There is an increasing trend of RMS value of sprung's mass acceleration along with increasing of electrical resistance value.
3. The power generated by HMRSA suspension is very small which ranges from 0.024 watt to 1.078 watts. This is because the excitation amplitude being used is only 1.5 cm.

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