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PRELIMINARIES STUDIES OF VIBRATION ISOLATION USING ELECTROMAGNETIC DAMPER

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ABSTRACT

This paper presents the review of electromagnetic damper as a vibration/isolation material. A bunch of articles about vibration and suspension system was reviewed and the key factors that contribute to electromagnetic damper was identified. Electromagnetic damper has been given special attention from many researchers and thus being among the important research area in vibration system. Vibration concept of electromagnetic damper has been elucidating by referring to several paper that demonstrate the usage of electromagnetic damper. A vibration test rig with a simple electromagnetic damper has been designed and tested to investigate the effect of electromagnetic force. Preliminaries simulation of electromagnetic damper was done using FEMM and initial experimental result from the vibration test rig also has been captured. The result indicated that the concept of electromagnetic damper does give effect to the vibration system such that the amplitude and settling time of the vibration system being reduced.

1.0 INTRODUCTION

Vibration phenomenon in vehicle dynamic system has been an issue for a comfortable ride since long ago. On top of that, it also affected the road holding ability of a car. In conjunction, the stability of the car will also be being affected such that it may cause an incident occurs. It is due the fact that an excessive oscillation in vertical as well as horizontal direction of a car may cause instability to the system. Apart from that, the driver will undergo serious fatigue when being exposed to such vibration oscillation for a longer period. This will induce tiredness to the driver which will affect his concentration and performance while driving. On the other hand, the vibration, which occurs in most machines, structures, and dynamic systems, is undesirable, not only because of the resulting unpleasant motions, the noise, and the dynamic stresses, which may lead to fatigue and failure of the structure or machine, but also because of the energy losses and the reduction of the performance which accompany the vibrations. Such vibrations can be caused by imbalances in the rotating parts, uneven friction, the meshing of gear teeth, etc. Generally, the vibration is uncomfortable for humans and a careful design usually is needed to minimize the unwanted vibrations.

A vibration can be controlled through three methods [1]. The three general ways are isolation (buffers system from excitation), design modification (modifying the system) and control (absorb or dissipate vibrations). The vibration isolation can be categorized as passive, semi -active and passive [2]. Isolation refers to the prevention of vibrations from entering a system that need to be isolated while damping means absorption of the vibration energy that is entering the system and dissipating it by changing the kinetic energy of a vibration into a different form of energy. Traditionally, a linear spring and a damper is

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the main element in the system such that it begins to isolate any system nearby $\sqrt{2}\,\omega_n$, where ω_n is the corresponding natural frequency of the isolated system.

From vibration system point of view, natural frequency of a system plays an important parameter towards the system performances. The natural frequency of the vibration isolation system should be lower than the forced frequency to avoid resonance during normal conditions [3]. Hence the isolator should be designed such that the operating frequencies ω are greater than $\sqrt{2}\,\omega_n$. It can be seen from Figure 1 the transmissibility value is decreasing onwards when the frequency ratio reached $\sqrt{2}$. This implies that dynamic stiffness and damping of the isolator should be frequency and amplitude dependent. Therefore, the development of any isolator system is mostly concentrated on improvement of frequency and amplitude dependent properties. This is where electromagnetic damper can play its role as vibration isolator in the suspension system. The application of electromagnetic damper as a vibration isolation mechanism will be an interesting research area due to its properties that can be controlled or changed under the magnetic field. Its magnetic flux density value is rapidly and reversible controllable under the magnetic field. Electromagnetic damper is expected to be able to perform as a vibration isolator either in low or high frequency range. It is because the frequency of the external excitation to any isolation system will be varied according to the external disturbances characteristics.

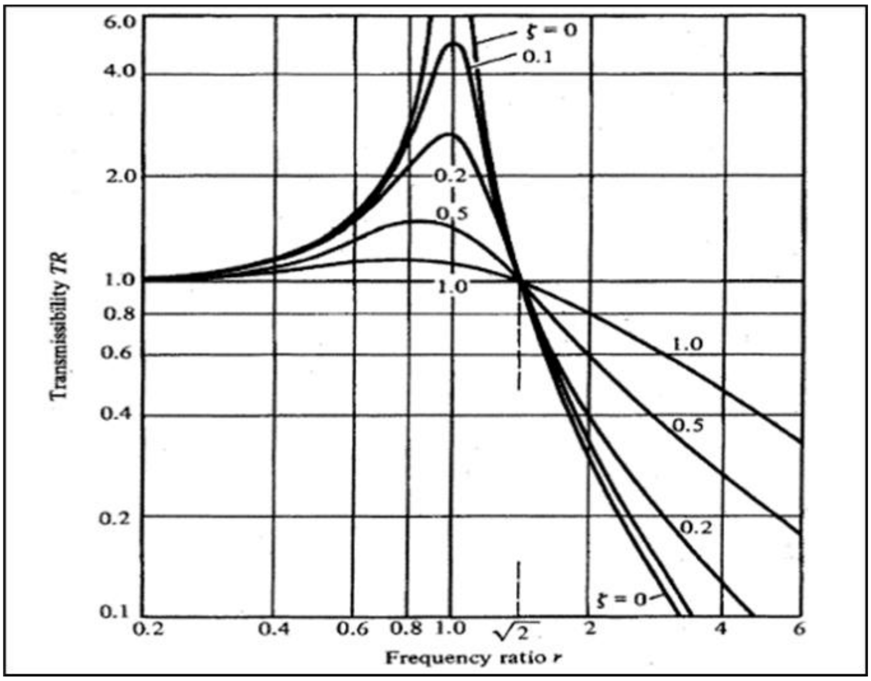

Figure 1. Effect of frequency and damping to transmissibility [3]

2.0 APPLICATION OF ELECTROMAGNETIC DAMPER AS ISOLATOR

Currently there exist many damping devices which work under the principal of electromagnetism. Researchers are still investigating and improving the electromagnetic application in various sectors [7-24]. In general, several aspects of research that being explored are design concept, theoretical modelling (analytical studies), optimization of design (finite element analysis) and characterization of the system (experimental or simulation techniques). A simple electromagnetic damper application has been applied to a one degree of freedom magnetic suspension system which contain a mass, spring and damper [4]. The equation of motion was obtained from the free body diagram analysis of the mass, spring damper system. The transfer function between the displacement $X(s)$ versus control current, $I(s)$, can be obtained by considering the external input $Y(s)$ as zero. The transfer function was

$$\frac{\mathrm{X(s)}}{\mathrm{I(s)}} = \frac{\mathrm{k_i}}{\mathrm{ms^2 + cs + (k + kx)}} \tag{1}$$

where X(s) is the displacement of the system, and I(s) is the current supplied to the coil of the system (electromagnetic).

An active digital signal processing (DSP) controller was applied to the electromagnetic damper in the range of 2 to 30 Hz of frequencies. The schematic diagram can be seen as in Figure 2.

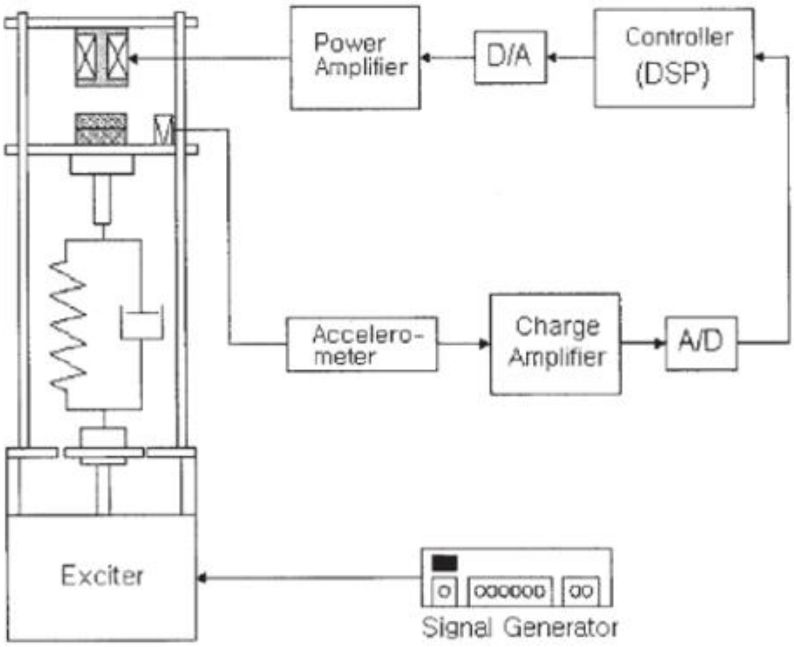

Figure 1. Schematic diagram of the active control system using magnetic damper [4]

About 50 -70 % reduction was possible with the proposed damper. However, in this research the electromagnetic damper has been combined with normal hydraulic damper in the passive suspension system such that the electromagnetic damper can be considered as an auxiliary component in the system as in Figure 3.

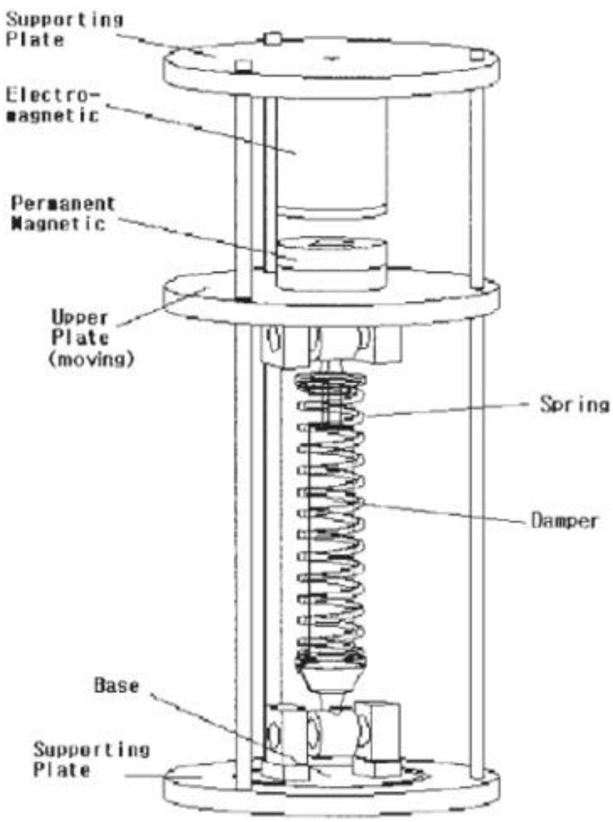

Figure 3. Structure of the magnetic suspension system [4]

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An electromagnetic damper conceptual has been designed and analysed by a group of researchers from India [5]. The idea was to use two electromagnets in a suspension system to control the vertical movement of the tire. One of the electromagnets has been keep fixed while the other is moving as it is being tied up with the tyre movement. To vary the electromagnetic field effect a rheostat was deployed to the moving electromagnet such that it can be varied according to the tyre motion. As a result, the repulsive force between those two electromagnets can be controlled. The overall concept and idea can be seen as in Figure 4.

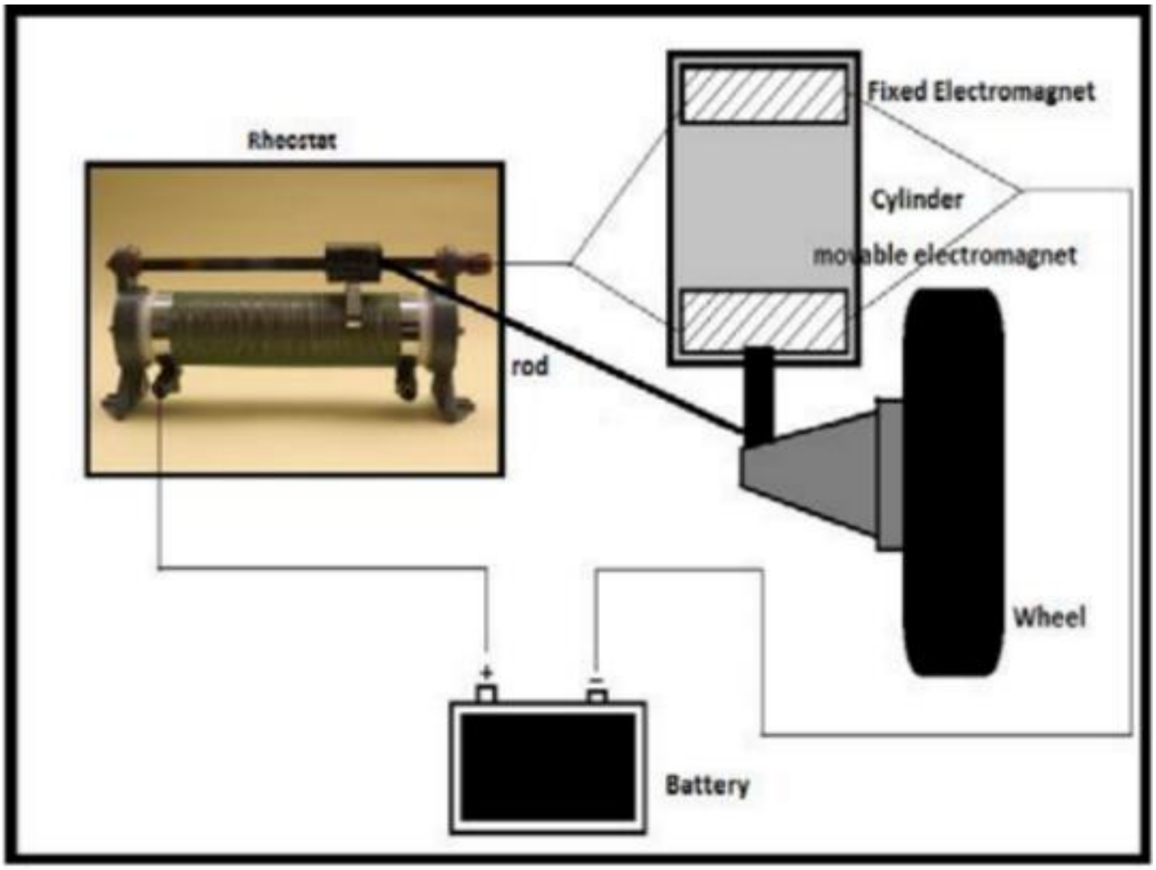

Figure 2. Electromagnetic damper concept [5]

Conceptual model of electromagnetic damper for a motorcycle suspension system has been proposed by Elankovan et al. in his paper. The magnetic field can be controlled electronically makes the overall suspension to be semi-active, and possibility of energy harvesting[6]. However, no quantitative analysis was made in the paper. In a vehicle system, the most frequent system applied this physical phenomenon is in suspension system [7-10]. Karnoop has been considered among the pioneers in this research area by investigating the possibilities of implementing the concept in a suspension system [11]. Karnopp introduced a small and light linear electrodynamic motor consisting of copper coils and permanent magnets which can be used as an electromechanical damper for vehicle suspension systems [11]. However, it the size was big, and the power densities was low [12].

The ideal automotive suspension would rapidly independently absorb road shocks and would slowly return to its normal position while maintaining optimal tire-to-road contact. The ideal suspension system should minimize the frequency response of the sprung mass accelerations to the road disturbances in the band between 0.2 and 10 Hz while maintaining a stiff ride during cornering [13]. Typical value of a prototype novel magnetic spring–damper damping ratio was as high as 40Ns/m[14]. An electromagnetic damper was design, fabricated and tested by Sultoni et. al. in an auto damping force machine. The electrical model was extracted from the design configuration of linear electromagnetic shock absorber [15]. The dynamic model was incorporated into the quarter car modelling system. The electromagnetic damper force was considered either as motor or generator with equation of force is proportional to the linear speed v ($F = K_{EV}$). The result of the experiment testing shown that the damping value recorded 416 Ns/m in rebound and 300 Ns/m in compression. It also able to harvest 11.43 W at 0.1 m/s of velocity.

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Paz has designed an electric shock absorber consists of a permanent magnet linear synchronous generator (PMLSG), a spring, and an electric energy accumulator. Its converts the kinetic energy of an oscillating object into electrical energy [12]. Simulation of the system was carried out using MATLAB-SIMULINK and compared with mechanical parameters of mechanical shock absorber. It was shown that, the electric shock absorber able to store part of the recovered energy in the battery while the others lost in the generator resistance.

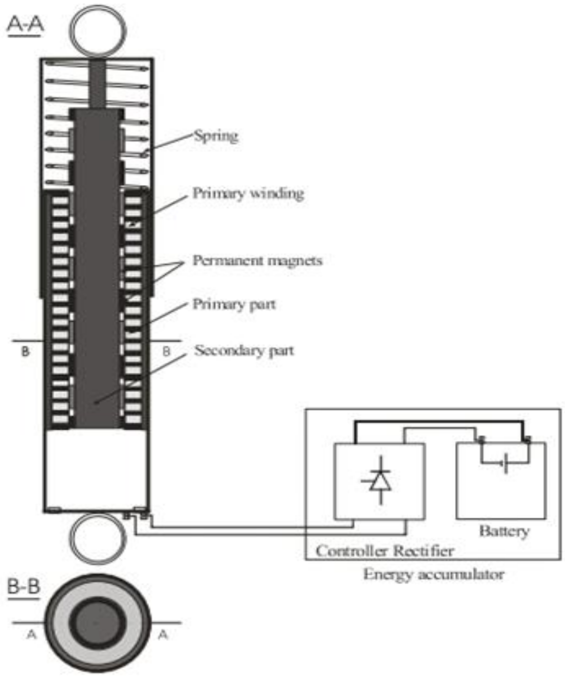

Figure 5. Diagram of electric shock absorber [16]

Several years after that, Gupta et al. has developed a novel electromagnetic shock absorber (prototype) and test it on all- terrain vehicles. Two configurations of regenerative electromagnetic shock absorber have been developed for this purpose: a linear device and a rotary device [17]. Voltage is induced in the shock windings when the coil assembly moves relative to the magnet assemblies. Different approach has been taken by Mirzaei et al. by developing an electromagnetic damper comprising of winding only on both translator and stator. The damping force generated is related with the linear velocity of translator and the magnetic flux density generated by translator coil. The translator is then immersed in the hydraulic fluid that act as secondary damper [18].

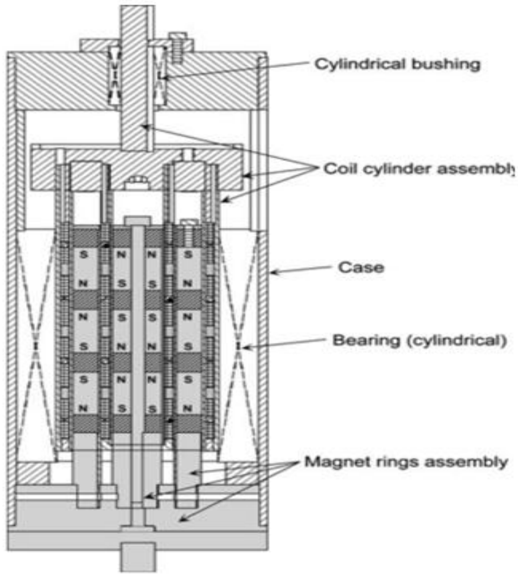

Figure 6. Schematic of permanent magnet assembly , coil assembly and case assembly [17]

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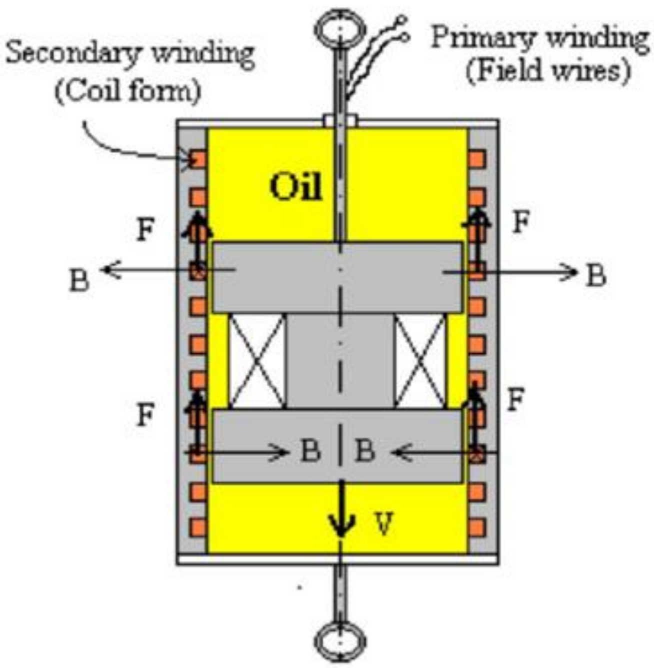

Figure 7. Scheme of electromagnetic damper [18]

In favour of active electromagnetic suspension system Bart et al. discusses an active electromagnetic suspension system incorporating a brushless tubular permanent-magnet actuator (TPMA) in parallel with a mechanical spring in his paper [13]. The suspension was incorporated in a quarter car modelling to analyse its responds in terms of roll and pitch behaviour and road disturbance. It has been shown that active electromagnetic suspension systems can maintain the required stability and comfort due to the ability of adaptation in correspondence with the state of the vehicle. Montazeri et al. investigates the feasibility of an electromagnetic damper (EMD) in providing adequate damping for isolation of vibration while generates energy from relative motion between sprung and unsprang masses [10]. The EMD, which is composed of a permanent-magnet DC motor, a ball screw and a nut, is analysed as a passive damper in a quarter car model. It has been shown through simulation that the designed passive EMD maintain the desired performance while external excitation from road excitation can be regenerated and transformed into electric energy.

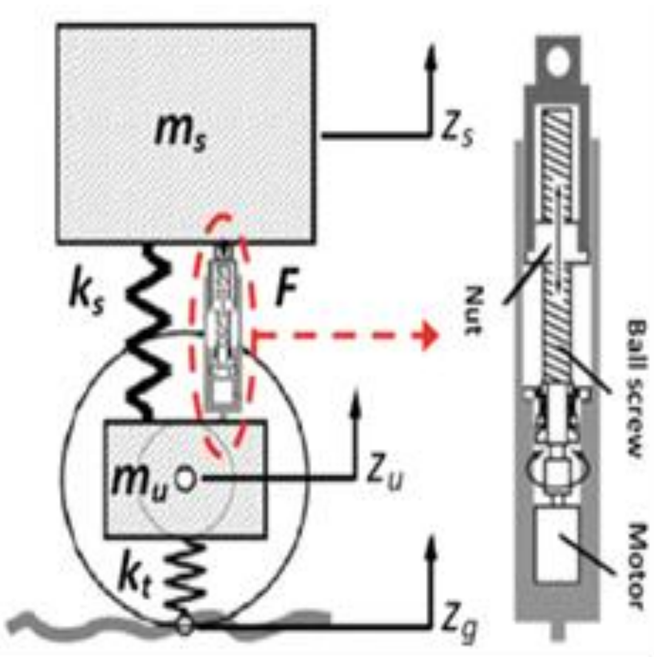

Figure 8. Passive electromagnetic suspension system [10]

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There are six types of electromagnetic regenerative suspension classified by structure configuration has been stated by Jin-Qiu et al. [19]. Based on the structure or mechanism of the suspension system, all six types have been called as Direct-Drive, Ball Screw, Rack-Pinion, Planetary Gear, Hydraulic Transmission Electromagnetic Suspension, and Self-Powered Magnetorheological Suspension. An example of direct drive electromagnetic suspension system that has been fabricated by Bose Company was in vehicle suspension as shown in Figure 9. The system ends up consuming one-third of the energy used by a car's air conditioner [20].

Figure 9. Electromagnetic suspension developed by Bose [20]

Asadi et al. [21] has developed a prototype of adaptive and regenerative damper which was categorized as a hybrid electromagnetic damper is proposed. The hybrid damper is configured to operate with viscous and electromagnetic subsystems. The electromagnetic component was modelled and analysed using analytical (lumped equivalent magnetic circuit) and Finite element method (FEM) software namely COMSOL and being investigated experimentally. The results from simulation and experiment shows that the damper can produce damping viscous coefficients of 1300 Nsm^{-1} and 0 to 238Nsm^{-1} for the electromagnetic damping.

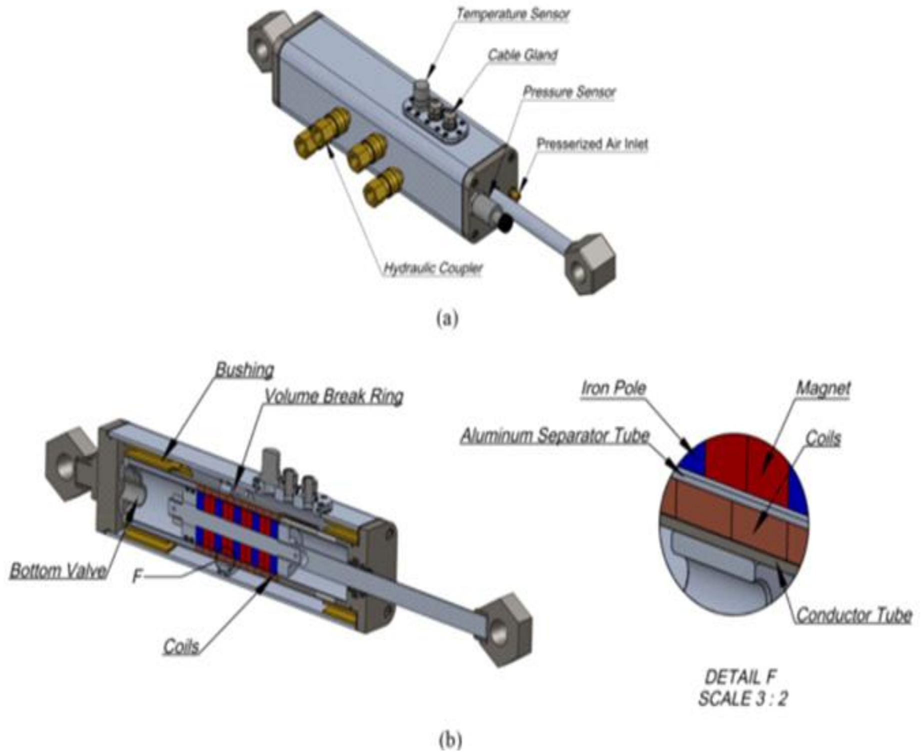

Figure 10. Hybrid damper design: (a) isometric view and (b) cross sectioned view [21]

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Figure 11. Hybrid damper prototype [21]

Another application of electromagnetic concept was portrayed by Bo Yan et al. The electromagnetic effect has been shown can be used as actuators, sensors, or both. The idea of the electromagnetic damper came from the piezoelectric transducer concept. The piezoelectric transducer is bonded to host structure. As the host structure vibrates, the transducer produces an electricity. An external shunt circuit dissipates the electrical energy thereby dissipating the mechanical vibration energy, and the vibration of the host structure is suppressed [22].

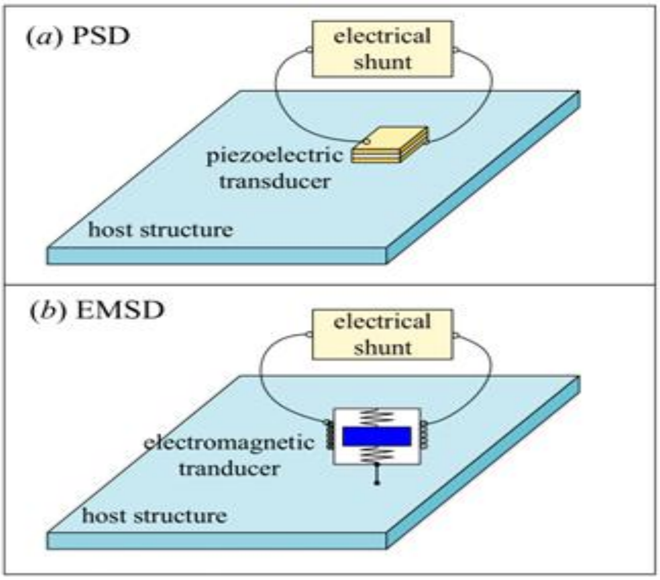

Figure 12. *a*) Piezoelectric shunt damping (PSD) b) electromagnetic shunt damping (EMSD) [22]

Figure 12 shows how the electromagnetic transducer can be used as actuators, sensors, or both. When current is applied as actuators, sensors, or both. When current was supplied to terminals of the electromagnetic transducer a force is generated. Conversely, when a transducer experiences a velocity, an electromotive force (emf) is induced[22].All of these research shows that, there are high level of interest from various researchers towards electromagnetic induction effects. Even though the area of application is very vast, but most of the researchers are keen towards the automotive industries. The main objectives of the research are to create higher magnitude of magnetic field inside the system such that an adaptive, regenerative and fail- safe damping device can be designed for various applications.

2.1 Equation Governs The Electromagnetic Damper

According to Saslow's [23] mathematical expression for the force experienced by the magnet as in the figure below is:

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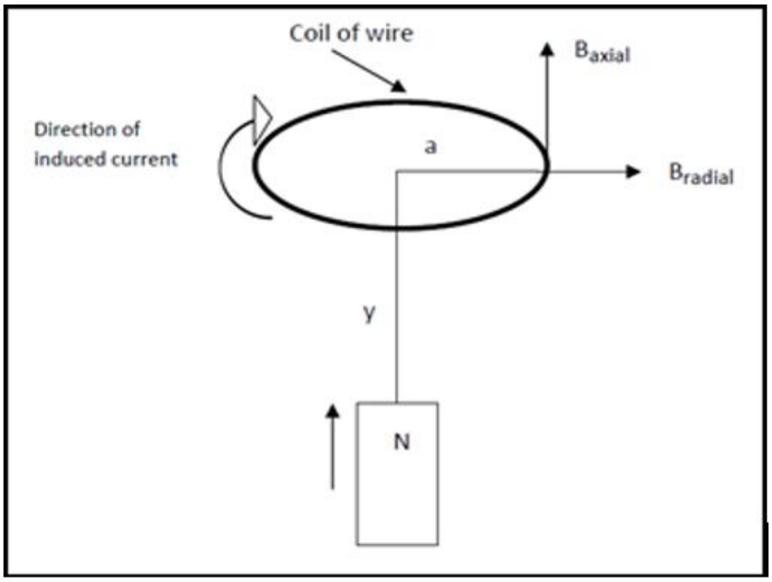

Figure 13. Schematic diagram for magnetic force

$$F = 2\pi a N I B_{rad} \tag{1}$$

where I, is induced current, B_{rad} is the radial magnetic field intensity, N is number of turns of the coil and a is the coil's radius. As the magnet rises toward the coil, voltage is induced according to Faraday's Law as

$$V_{induced} = -N\frac{d\emptyset}{dt} \tag{2}$$

where N is the number of turns in the coil and ϕ is the magnetic flux. At the same time the induced current in the coil is given by Ohm's law as

$$\mathbf{I_{induced}} = \frac{\mathbf{V_{induced}}}{\mathbf{R}} \tag{3}$$

Equation 2 and 3 can be combined with Equation 1 to get a general equation of

$$F = cV \tag{4}$$

where

$$c = 2\pi a \frac{N^2 B_{rad}}{R}\left(\frac{d\emptyset}{dt}\right)\left(\frac{1}{v}\right) \tag{5}$$

3.0 EXPERIMENT SETUP

A magnetic meter has been used in this experiment to measure the magnetic flux density of the permanent magnet. Figure 14 shows the magnetic meter and its application. Figure 15 shows all the important apparatus in the test rig.

Figure 14. Magnetic meter reading

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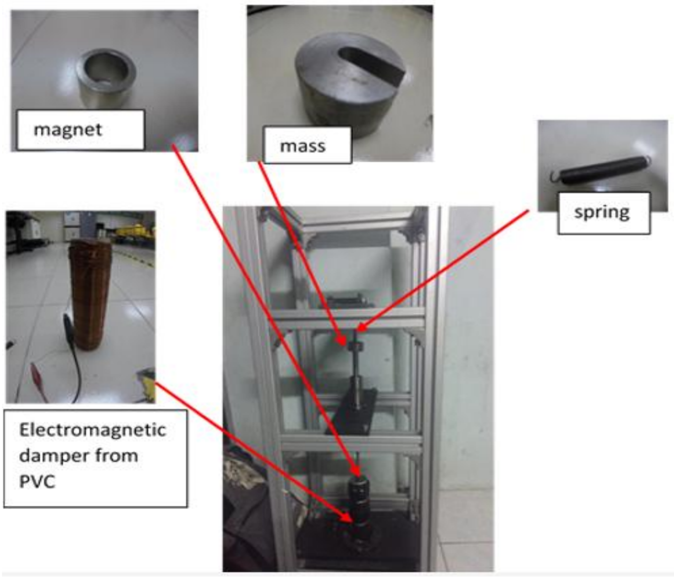

Figure 15. Overall vibration test rig system

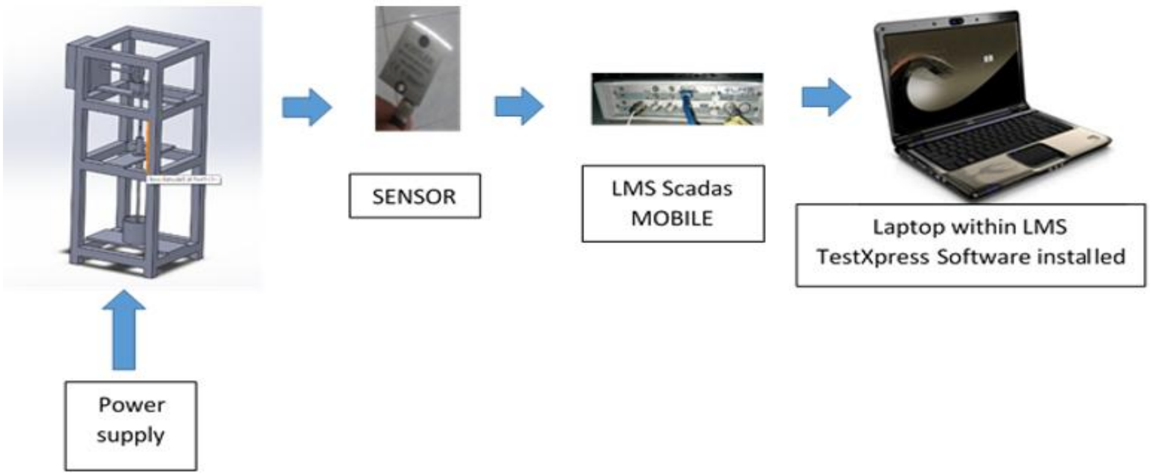

Figure 16. System layout in experimental setup

The experimental setup consists of sensors, LMS Scadas Mobile measurement hardware, and a computer with the installed software as shown in Figure 16. LMS TestXpress software have been used to connect the LMS Scadas Mobile with the accelerometer. The accelerometer will extract the response of the system which then will be converted to velocity as well as displacement response. The experimental test rig system has been drawn using Auto Cad such that the component of the system can be shown clearly as shown in Figure 17.

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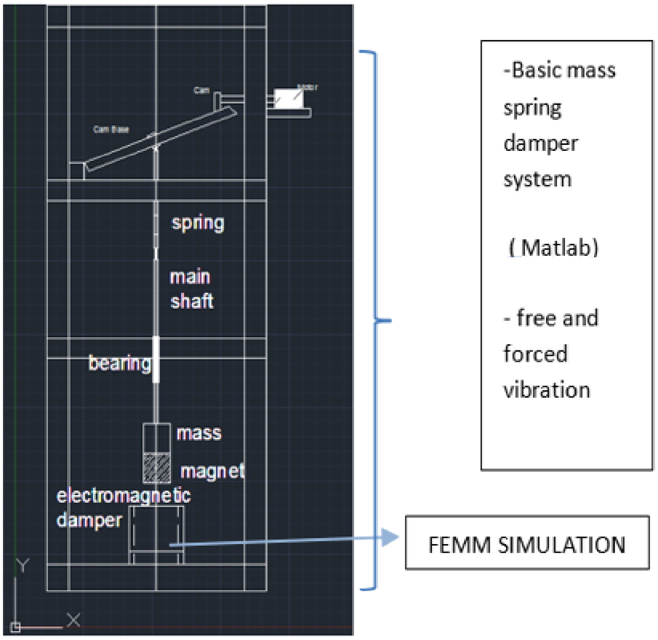

Figure 17. Apparatus test rig

3.1 Simulation Of Finite Element Magnetic Method (FEMM)

Several types of electromagnetic damper have been fabricated for an initial investigation. Initially the electromagnetic damper was taken to be a solid cylinder with a coil surrounding it (as shown in Figure 18). The effect of the coil and the solid iron with permanent magnet has been simulated into FEMM to show the effect of magnetic field occurred. The magnetic flux effect from the electromagnetic damper was obtained by setting the current to 1A and a total of 103 turns of copper wire surrounding the steel. There are two simulations been done. The first one obtained by considering the mass and magnet as different entity while on the second part, the mass and magnet has been taken as a magnet (Nd Fe B). To get a better effect of damping in the system, another configuration of electromagnetic damper was developed. Three solenoid was wounded around a hollow aluminium as shown in Figure 19.

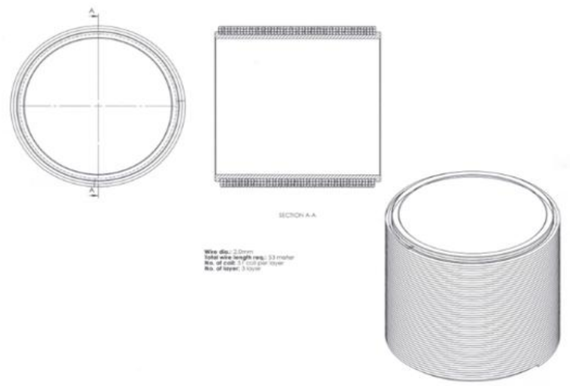

Figure 18. Basic electromagnetic damper with a coil surrounds it

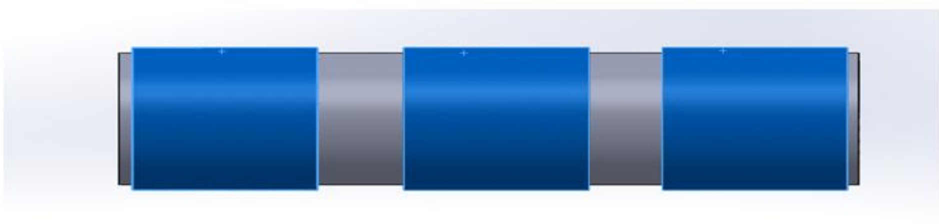

Figure 19. Second electromagnetic damper design

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A simulation of FEMM have been studied to investigate the relation of permanent magnet and solenoid. Figure 20 shows the simulation of the magnetic flux distribution. A permanent magnet (Neodymium magnet) and a 0.6 mm copper coil are used to simulate in FEMM. The magnetic field B, can be estimated based on formula below

$$B = \mu_0 n I \tag{6}$$

$$n = \frac{N}{L} \tag{7}$$

where $\mu_0 = 4\Pi x 10^{-7}$ Tesla, T is the constant magnetic of permeability of magnet in free space, I = current in Ampere, A, N= the number of turns of coil, L = length of solenoid.

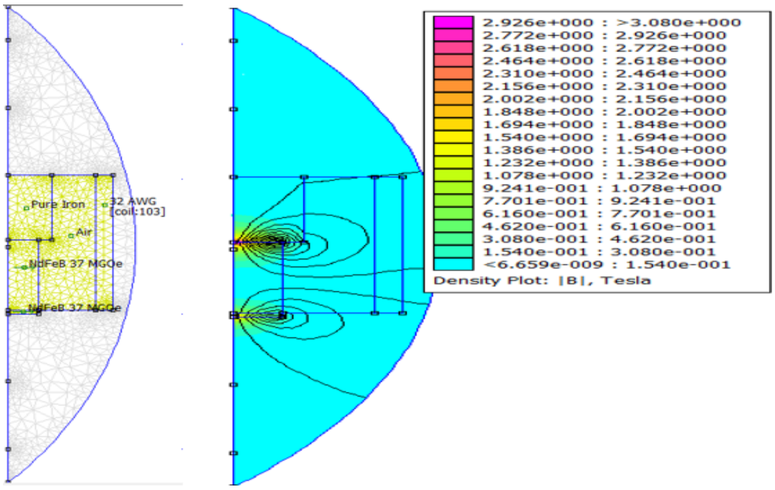


Figure 20. Magnetic flux simulation

The overall response of the magnetic flux has been tabulated in Table 1 and the magnetic flux density (B) versus current supplied to the coil has been drawn in Figure 21.

Table 1. Magnetic flux Density result against current and number of turns

Current, A	Magnetic flux density (Tesla)		
	100 n	300 n	700 n
1	0.000225	0.00035	0.00048
2	0.000475	0.00070	0.00100
3	0.000900	0.00110	0.00145

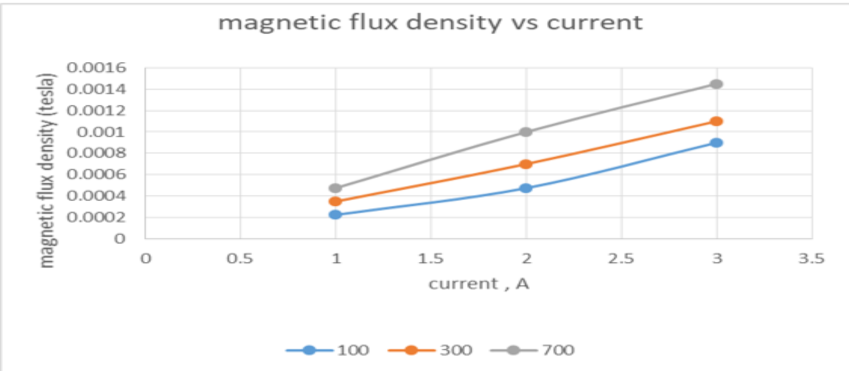


Figure 21. Graph of magnetic flux density against current supplied

4.0 EXPERIMENT RESULTS

For the experimental result, another electromagnetic damper using PVC has been fabricated as shown in Figure 22. This was done to see the effect of electromagnetic damper to the system. Previously fabricated electromagnetic damper gives very small effect to the system because the oscillation dies out very quickly and the magnet attached to the system being attracted to the metal of the electromagnetic damper. The acceleration, velocity and displacement result obtained can be found as in Figure 23.

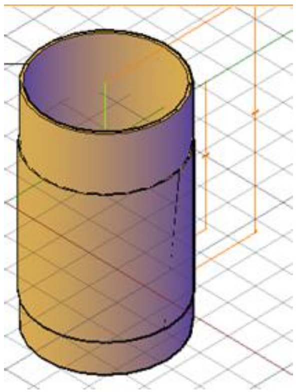
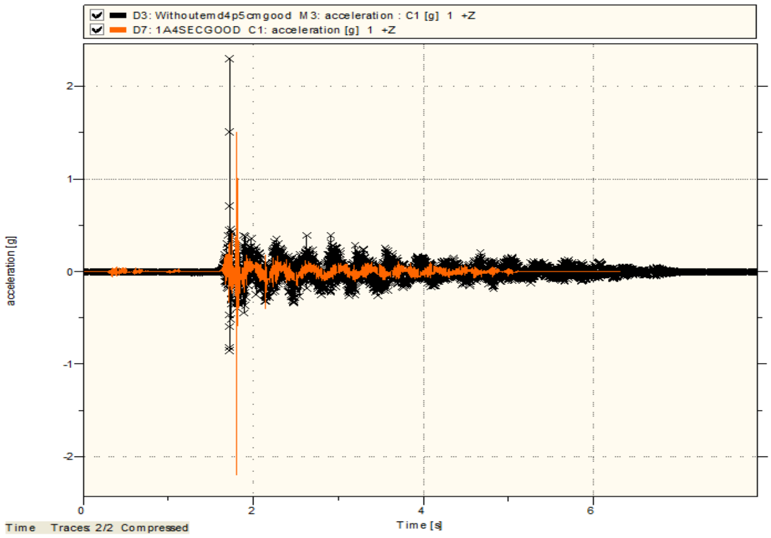
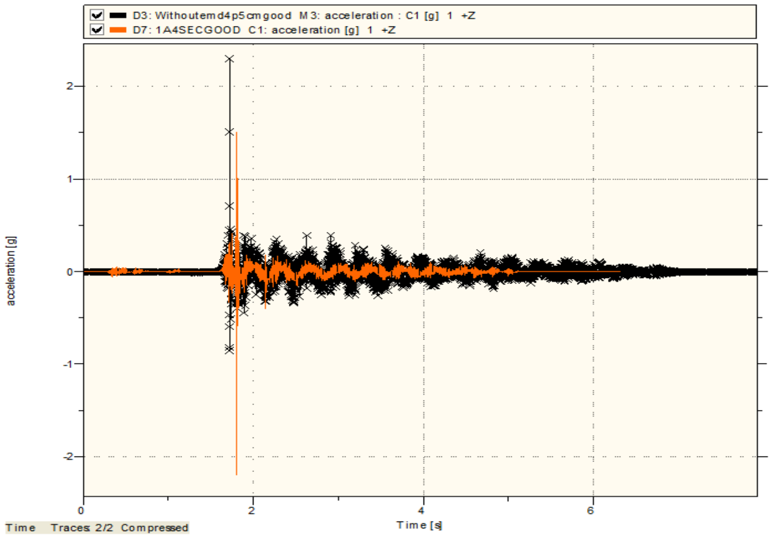


Figure 22. PVC electromagnetic damper with coil wounded around



(a)



(b)

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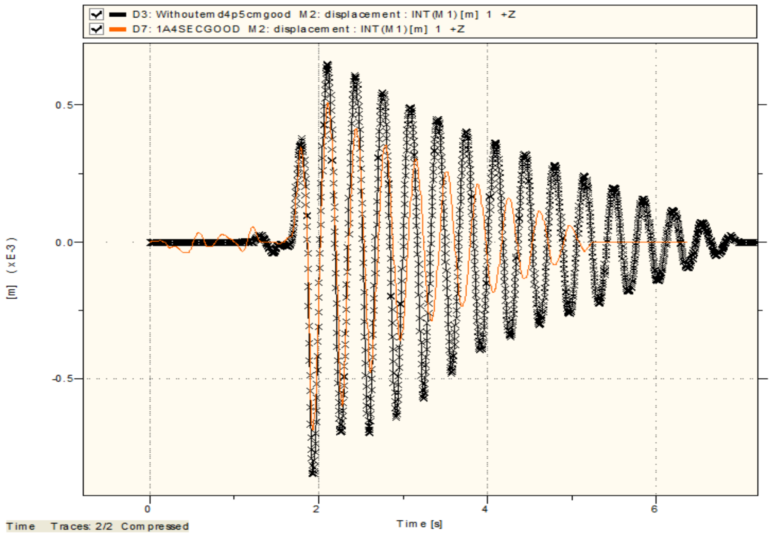

(c)

Figure 23. a) Acceleration comparison between with and without current supply (1A), b) Velocity comparison between with and without current supply (1A), and c) Displacement comparison with and without current supply (1 Amp)

It can be concluded that this magnetic damper can absorb the vibration by using an electromagnetic force and a strong permanent magnet. The response time for the system to damp out will be affected by the current supplied. As the current increased, the response time will be shortened. This effect can be verified through the calculation of damping value in the logarithm decrement equation.

4.0 CONCLUSIONS

Several conclusions can be obtained from the research. First, the electromagnetism concept can be created by using a permanent magnet and a wounded coil over a cylinder. Initial simulation using FEMM shows that the magnetic flux density being affected by several factors such as type of material, type of permanent magnet, type of coil and the magnitude of current being supplied. From the prior experiment it can be shown that, there is effect of electromagnetic from the system. This can be seen from the graph obtained. This result shows that there is a significant effect of electromagnetic damper in the vibration system. Reduction of amplitude and the settling time does give the indication of the damper effect to the system. In real life application, electromagnetic damper can be used as a vibration isolator and from the review articles researchers have already try and investigate the concept in several application particularly in automotive industries. However, more detail study needs to be done to achieve more significant value of damping coefficient from the electromagnetic damper. Key parameters for the electromagnetic effect need to be explored more. Some of the parameters are, current supplied to the system, number of coils turn, type of coil, geometries of the damper, velocity of the magnet, friction in the system and type of material used. In general, all these parameters are varied to obtain higher magnetic field in the system such that the damping force of the system can be increased. Thus, this parameter needs to be considered for the next experimental session to get the best effect of electromagnetic damper.

5.0 CONFLICT OF INTEREST

The authors declare no conflicts of interest.

6.0 AUTHORS CONTRIBUTION

Mohd Yusoff, M. F. (Conceptualisation; Methodology; Validation; Formal analysis; Data curation; Formal analysis; Investigation; Resources; Software; Visualisation; Writing - original draft; Writing - review & editing; Funding acquisition; Project administration; Supervision)
Ahmad Zaidi, A. M. (Conceptualisation; Methodology; Validation; Formal analysis; Data curation; Formal analysis; Investigation; Resources; Software; Visualisation; Writing - original draft; Writing - review & editing; Funding acquisition; Project administration; Supervision)

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Mohamed Ishak, S. A. F. (Conceptualisation; Methodology; Validation; Formal analysis; Data curation; Formal analysis; Investigation; Resources; Software; Visualisation; Writing - original draft; Writing - review & editing; Funding acquisition; Project administration; Supervision)
Mohd Sohaimi, R. (Conceptualisation; Methodology; Validation; Formal analysis; Data curation; Formal analysis; Investigation; Resources; Software; Visualisation; Writing - original draft; Writing - review & editing; Funding acquisition; Project administration; Supervision)
Md Din, M. F. (Conceptualisation; Methodology; Validation; Formal analysis; Data curation; Formal analysis; Investigation; Resources; Software; Visualisation; Writing - original draft; Writing - review & editing; Funding acquisition; Project administration; Supervision)

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