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Simulation Studies of Vibration Isolation Using Electromagnetic Damper

(Kajian Simulasi Pengasingan Getaran Menggunakan Peredam Elektromagnetik)

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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 elucidated by referring to several paper that demonstrate the usage of electromagnetic damper. Finite element magnetic method (FEMM) software has been used in order to identify the best configuration of geometry in the system. A simulation in Matlab was done by considering a quarter car model with a theoretical value from the Faraday's Law equation involved in electromagnetic damper. The slotted and cylindrical geometry configurations have been simulated using FEMM and the result clearly shows that the slotted configuration has a better effect on the electromagnetic damper system.

Keywords: Electromagnetic damper; eddy current; vibration; suspension system

ABSTRAK

Makalah ini memaparkan tinjauan peredam elektromagnetik sebagai bahan getaran / pengasingan. Sekumpulan artikel mengenai getaran dan sistem penggantungan telah dikaji dan faktor utama yang menyumbang kepada peredam elektromagnetik dikenal pasti. Peredam elektromagnetik telah diberi perhatian khusus dari banyak penyelidik dan dengan itu menjadi antara bidang penyelidikan penting dalam sistem getaran. Konsep getaran peredam elektromagnetik telah dijelaskan dengan merujuk kepada beberapa kertas yang menunjukkan penggunaan peredam elektromagnetik. Perisian kaedah magnet elemen terhingga (FEMM) telah digunakan untuk mengenal pasti konfigurasi geometri terbaik dalam sistem. Simulasi di Matlab dilakukan dengan mempertimbangkan model kereta seperempat dengan nilai teori dari persamaan Hukum Faraday yang terlibat dalam peredam elektromagnetik. Konfigurasi geometri slot dan silinder telah disimulasikan menggunakan FEMM dan hasilnya jelas menunjukkan bahawa konfigurasi berslot mempunyai kesan yang lebih baik terhadap sistem peredam elektromagnetik.

Kata kunci: Peredam elektromagnetik; arus eddy; getaran; sistem penggantungan

INTRODUCTION

Vibration has been in our daily life for a long time. In definition, vibration refers to mechanical oscillations about an equilibrium point. The oscillations may be periodic such as the motion of a pendulum or random such as the movement of a tire on a gravel road. Vibration has its positive and negative effects. Vibration is occasionally "desirable". For example, the motion of a tuning fork, the reed in a woodwind instrument or harmonica, or the cone of a loudspeaker is desirable vibration, necessary for the correct functioning of the various devices. Other occasions where vibration is useful is in guitar vibration which tends to produce soothing music for our ears, vibrating sieve separate particles of fine and coarse sand and vibration mode in our mobile phone which alert us without disturbing others.

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. The mechanical vibration in the equipment causes excessive wear of bearings, cracking, shorts due to the abrades insulation around electrical conductors and noise. 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 (Silva 2007). The three general ways are:

1. Isolation (buffers system from excitation)
2. Design modification (modifying the system)
3. Control (Absorb or dissipate vibrations)

In layman terms, the three approaches can be seen as three different way of reducing or eliminating the vibration effects. The first approach is tackling the source of excitation while the second approach is dealing with the modification of the system or machine. The last method is to absorb or dissipate the vibrations using external devices attached to the system.

An electromagnetic damping occurs when there is a relative motion between the conductor and the magnetic field. Eddy current developed in the conductor and created magnetic field with opposite polarity of the original magnetic field. Thus, resulting in a force that hinders the relative motion of the system (Haiyan 2017). An eddy current is caused when a moving conductor intersects a stationary magnetic field, or vice-versa. The relative motion between the conductor and the magnetic field generates the circulation of the eddy current within the conductor. These circulating eddy currents induce their own magnetic field with the opposite polarity of the applied field that causes a resistive force. These currents dissipate due to the electrical resistance and this force will eventually disappear. Hence, the energy of the dynamic system will be removed. The resistive force induced by eddy currents is proportional to the relative velocity, the conductor and the magnet can be allowed to function as a form of viscous damping (J.S. Bae et al. 2010; Ebrahimi, Khamesee, & Golnaraghi 2009b).

An eddy current concept has been applied by Haiyan et al. in order to reduce a disc vibration that is rotating (Haiyan et al. 2017). The electromagnetic field was created by applying current to the coil which was wrapped around an inner surface of the silicon steel sheet to form a magnetic pole. The created magnetic pole would then interact with the surface disk which will induce an eddy current on the surface. The disc vibration then can be reduced by the damping force occurs between the interaction.

The eddy current damping force can be expressed as

$$F = \int_V J \times B \, dV$$

where the current conductor density, J can be written as

$$J = \sigma (v \times B)$$

In these equations, F is the eddy current damping, σ is electrical conductivity of planar plates, v is relative velocity between plane and magnetic field and B is magnetic flux density. The flux density along x, y, z, is similar, the electromagnetic damping can be written in the x direction as

$$F_x = \sigma v_x c l_y \int_{-N_x\tau/4}^{N_x\tau/4} B^2 dx$$

where v is the velocity of the x direction, c is the thickness of the surface conductor x plate, l_y is the effective length in the y direction of the planar conductor plate, and N is the number x of permanent magnets contained in the permanent magnet array in the x direction. Thus, damping coefficient can be considered as the ratio of damping force and velocity D = F /V.

The schematic diagram of surface eddy current damper and experimental block diagram are shown in Figure 1 and 2.

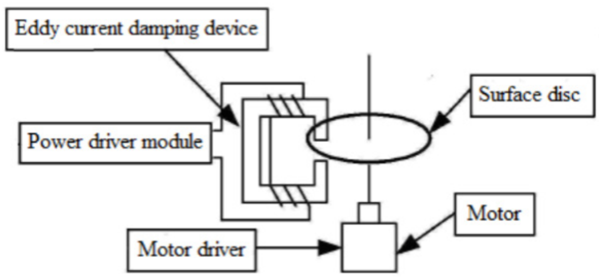


FIGURE 1. Schematic diagram of surface eddy current damper
Source: Haiyan (2017)

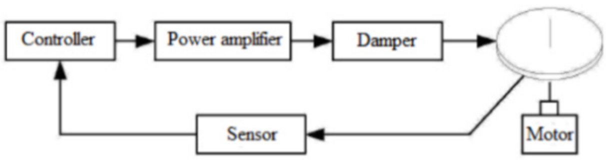


FIGURE 2. Experimental block diagram process
Source: Haiyan (2017)

According to Siavash (Siavash Haji Akbari Fini 2016) in his thesis, there are two types of electromagnetic dampers, Coil-Based Electromagnetic Damper (CBED) and Eddy Current Dampers (ECD). Relative motion between the permanent magnets and the conductive material induced electrical current and created the damping force. In the ECD, the electrical current will appear in a swirling pattern in the conductive material while in CBED, the electrical current is diverted into the electrical coil and can be stored in a battery.

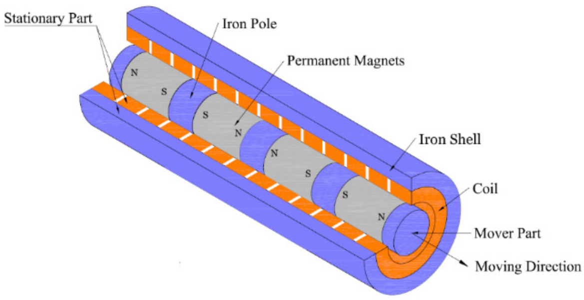


FIGURE 3. Coil based electromagnetic damper (CBED) configuration
Source: Siavash Haji Akbari Fini (2016)

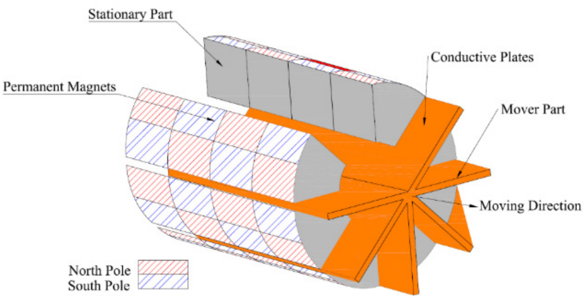


FIGURE 4. Eddy Current Damper (ECD) configuration
Source: Siavash Haji Akbari Fini (2016)

This paper aims to investigate the effect of electromagnetic damper to a vibration test rig by considering the system as mass spring damper system. The damping effect from the electromagnetic damper has been investigated by simulating the phenomenon that occurs in the system. The system has been simulated using MATLAB and FEMM. It has been shown that the halbach array of magnet and slotted cylinder give higher effect of electromagnetic damper.

METHODOLOGY

EQUATION GOVERN THE ELECTROMAGNETIC DAMPER

According to Saslow's (Wayne 2002) mathematical expression for the force experienced by the magnet as in the Figure below is:

Sodano et al. studied the application of an eddy current damper (ECD) in controlling the vibrations of small cantilever beam (Sodano et al. 2005). While, (Ebrahimi et al. 2009b; Ebrahimi, Khamesee & Golnaraghi 2009a; Gysen et al. 2010; Mirzaei 2007; Montazeri-Gh & Kavianipour 2012; Paz 2004; Siavash Haji Akbari Fini 2016) studied the application of eddy current damper as a vibration control system in vehicles and structures.

Currently there exist many damping devices which work under the principal of electromagnetism. Various research and development were related to electromagnetic damping (Asadi et al. 2015; J. Bae et al. 2009; Ebrahimi et al. 2009b; Gerber et al. 2007; Gupta et al. 2007; Gysen et al. 2010; Milanesi 2009; Mirzaei, 2007; Montazeri-Gh & Kavianipour 2012; Paz 2004). All of these researches show that there is high level of interest from various researchers towards electromagnetic damper effects. Even though the area of application is very vast, but most of the researchers are keen towards the automotive industries. The main objective of the researches is 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.

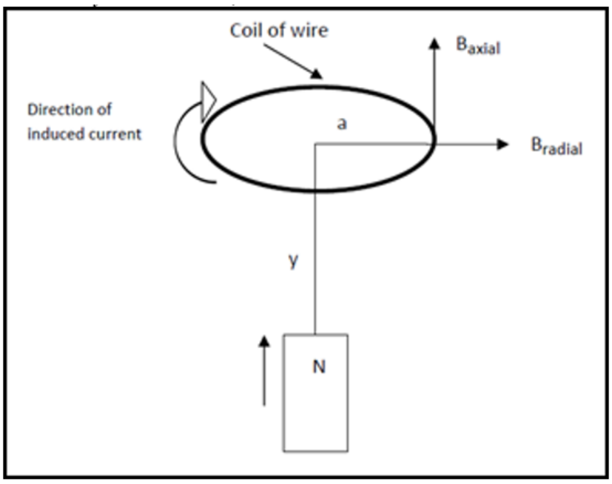


FIGURE 5. Schematic diagram for magnetic force

$$F=2\pi aNIB\_rad \quad (1)$$

where I is induced current, Brad 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 up toward the coil, voltage is induced according to Faraday's Law as

$$V_{induced} = -N\frac{d\emptyset}{dt} \quad (2)$$

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

$$I_{induced} = \frac{v_{induced}}{R} \qquad (3)$$

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

$$F = cv \qquad (4)$$

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

SIMULATION OF ELECTROMAGNETIC DAMPER IN FINITE ELEMENT MAGNETIC METHOD (FEMM)

The electromagnetic damper has been simulated in Finite element magnetic method (FEMM) in order to investigate the effect of magnet and geometry of the outside cylinder. FEMM is a software or program used for solving the problems on two-dimensional planar and axisymmetric domains of low-frequency electromagnetic problems. The magnet has been designed using Halbach-array concept and the outer cylinder was created to be either slotted or normal cylinder. The parameter of the Halbach-array design is shown in Figure 6 below. Each of the selected distance has been labelled and described in Table 1.

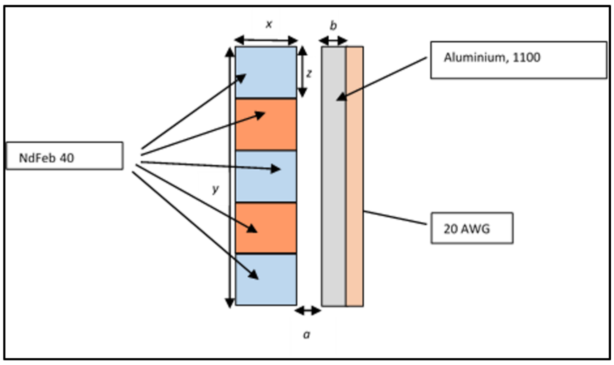


FIGURE 6. The 2D axisymmetric design of Halbach-array.

TABLE 1. The measurement of the design

Symbol	Name	Distance (mm)
x	Length of the magnet	17
y	Length of the magnet (combined)	70
z	Length of the magnet (each)	14
a	Gaps between magnet and aluminium	8
b	The thickness of the aluminium	7

After the parameter has been identified, the schematic diagram has been designed in the FEMM Simulation. Figure 7 shows the design for the cylindrical geometry while Figure 8 shows the design for the slotted geometry.

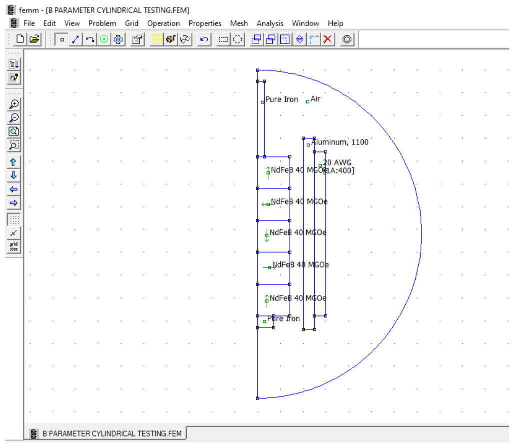


FIGURE 7. The design for cylindrical geometry

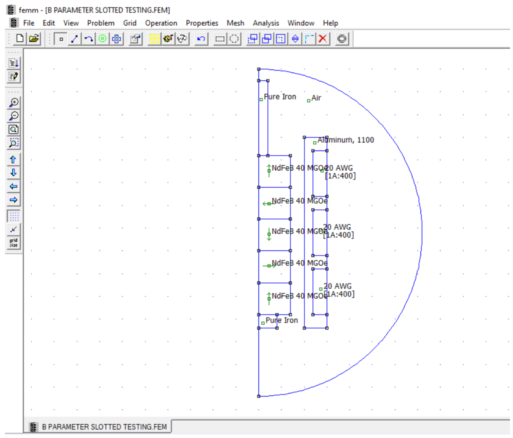


FIGURE 8. The design for slotted geometry

SIMULATION RESULT

Figure 9 and Figure 10 show the simulation result of the magnetic flux density for both configurations.

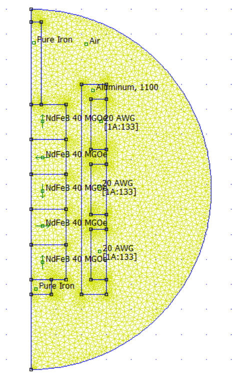


FIGURE 9(a). Parameter of the slotted configuration of the electromagnetic damper

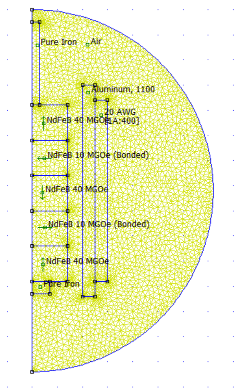


FIGURE 9(b). Parameter of the cylindrical configuration of the electromagnetic damper

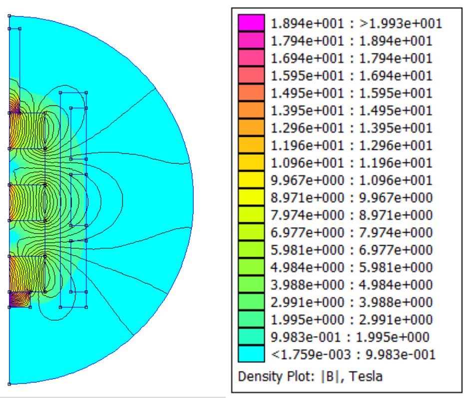


FIGURE 10(a). Simulation result of the slotted configuration

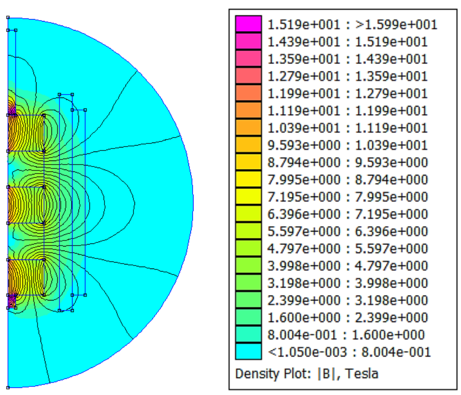


FIGURE 10(b). Simulation result of the cylindrical configuration

The simulation results in FEMM indicated that the geometrical shape of aluminium can produce more magnetic flux density to the system. The maximum value of 18.94 Tesla has been recorded in the middle of permanent magnet. About 3 to 7 Tesla of magnetic flux value has been recorded in the gap of permanent magnet and the coil. Thus, this value is the corresponding force that will directly affect the c (damping value) of the mass spring damper system.

MATLAB SIMULATION

The Matlab simulation was done by considering the test rig as a quarter car model equation which involve the spring constant, k and damping coefficient, c value. 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 11.

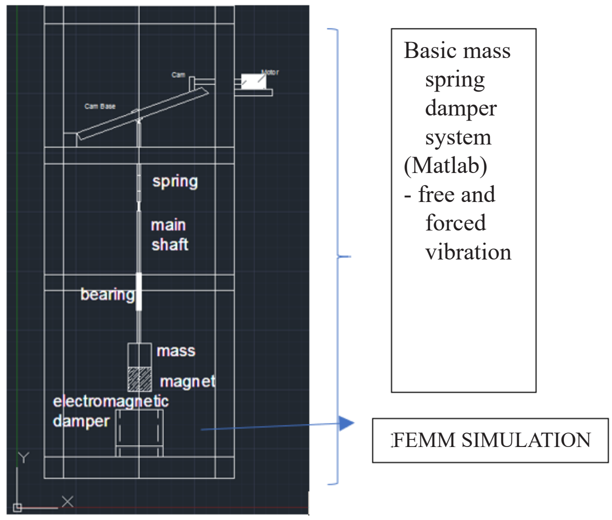


FIGURE 11. Apparatus test rig

Figure 12 shows the semi-active quarter car model that will be used to simulate in MATLAB. The parameter involved in the system were m1= sprung mass, m2= unsprung mass, c= damping coefficient, k1= spring mass stiffness (sprung mass) and k2= spring mass stiffness (unsprung stiffness). Parameter x,y, and z are the displacement with respect to sprung mass, unsprung mass, and road.

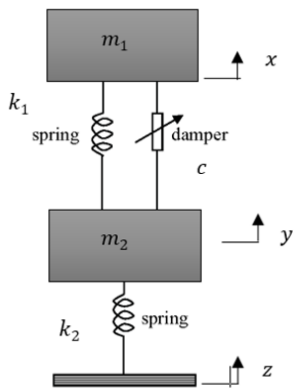
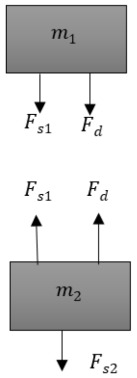


FIGURE 12. Semi-active quarter car model

Based on the quarter car model, the equation below is obtained. The Simulink in the MATLAB has been built by using this equation to get the response of the theoretical results.



$$m_1\ddot{x} = -k_1(x - y) - c(\dot{x} - \dot{y})$$

$$m_2\ddot{x} = k_1(x - y) + c(\dot{x} - \dot{y}) - k_2(y - z)$$

Equation 5 from the methodology section has been deployed to calculate the damping coefficient value, c by considering the parameter value that has been taken from various related literature and has been listed in Table 2.

TABLE 2. Parameter for theoretical value

	Slotted configuration	Cylindrical configuration
Coil thickness, a (m)	$5\text{x}10^{-4}$	$5\text{x}10^{-4}$
Number of turns, N	400	400
Radial magnetic field intensity, B_{rad} (T)	0.18	0.18
Velocity, v (ms^{-1})	1	1
Coil resistance, R (Ω)	5	5
Magnetic flux, $\emptyset(T)$	17.44	13.98
Rate of magnetic flux, $\frac{d\emptyset}{dt}$ (Ts^{-1})	1.16	0.93
Spring stiffness, k (N/m)	735.75	735.75
Mass , m (kg)	2	2

The value for damping ratio, ξ also has been calculated based on the equation

$$= \frac{c}{2\sqrt{mk}}$$

The value of the damping coefficient and damping ratio has been recorded in the Table 3.

TABLE 3. Value of the damping coefficient and damping ratio for both configuration

	Slotted Configuration	Cylindrical Configuration
Damping coefficient, c (Nsm-1)	19.02	16.83
Damping ratio, ξ	0.25	0.22

RESULTS AND DISCUSSION

SIMULATION RESULT

The value of the damping coefficient has been simulated in the MATLAB/Simulink and the responses of the vibration were compared between both of the configurations.

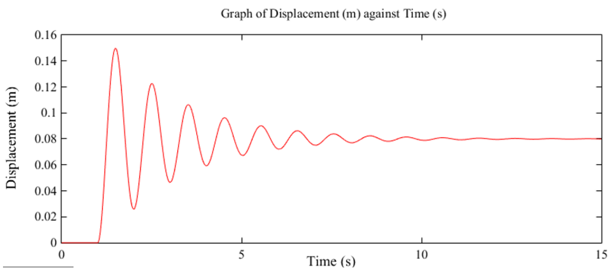


FIGURE 13. Response of the slotted configuration

Figure 13 shows the response of the slotted configuration when using the damping coefficient that has been calculated theoretically. The damping coefficient and damping ratio of the configuration are 6.85 Nsm-1 and 0.09, respectively. The time taken for the response to achieve the steady-state was around 12 s.

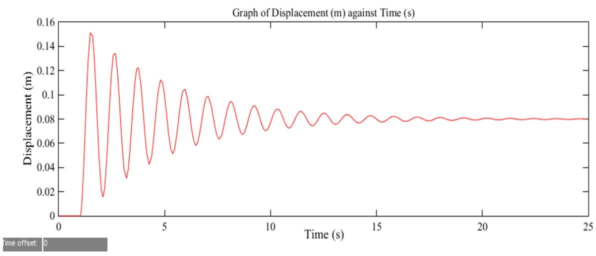


FIGURE 14. Response of the cylindrical configuration

Figure 14 shows the response of the cylindrical configuration when using the damping coefficient that has been calculated theoretically. The damping coefficient and damping ratio of the configuration are 5.47 Nsm-1 and 0.07, respectively. The time taken for the response to achieve the steady-state was around 23s.

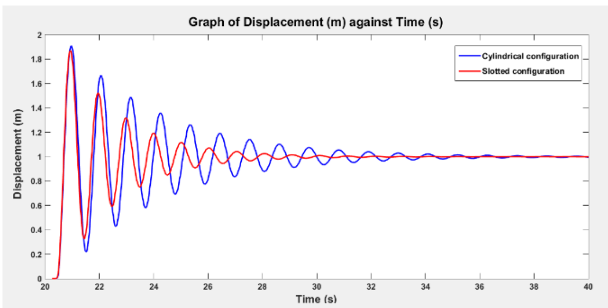


FIGURE 15. Comparison of the responses for both of the configuration

The comparison of the responses for both of the configuration is clearly shown in Figure 15. The time taken for the response to achieve steady-state for the slotted configuration is shorter than the cylindrical configuration. This happened because the slotted configuration of the system has a high amount of magnetic flux density which affected by the geometry of the electromagnetic damper. When the configuration has a high amount of the magnetic flux, the value of the damping will increase too. The movement of the permanent magnet through the configuration will experience the damping effect caused by the formation of the magnetic flux.

CONCLUSION

Based on the simulation done using FEMM and MATLAB, it is justified that the geometry design of the aluminum will affect the magnetic flux density value of the electromagnetic damper. The slotted configuration will damp out the system much faster compared to the cylindrical configuration. This can be investigated by looking at the damping coefficient value and settling time of the response. For further analysis, the slotted configuration should be developed and tested in a vibration test rig such that the result can be compared with the simulation result.

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. However, more detailed study needs to be done in order 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 of the parameters are varied in order to obtain higher magnetic field in the system such that the damping force of the system can be increased.

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DECLARATION OF COMPETING INTEREST

None

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