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PERFORMANCE OF HYBRID ELECTROMAGNETIC DAMPER FOR VEHICLE SUSPENSION

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INTRODUCTION

Suspension systems, in the automotive application context, have been designed to maintain contact between a vehicle's tires and the road, and to isolate the frame of the vehicle from road disturbances. Dampers, or so-called shock absorbers, as the undeniable heart of suspension systems, reduce the effect of a sudden bump by smoothing out the shock. In most shock absorbers, the energy is converted into heat via viscous fluid. In hydraulic cylinders, the hydraulic fluid is heated up. In air cylinders, the hot air is emitted into the atmosphere. There are several common approaches for shock absorption, including material hysteresis, dry friction, fluid friction, compression of gas, and eddy currents.

Eddy currents are induced in a conductor either by the movement of the conductor in a static field or a change in the strength of the magnetic field. The generated eddy currents create electromagnets with magnetic fields that oppose the change in an external magnetic field, causing a repulsive force proportional to the relative velocity of the field and conductor. Consequently, the eddy current damping device acts like a viscous damper, causing the vibration energy of the moving mass to dissipate through resistive/Joule heating, generated in the conducting component. The use of the eddy current damping phenomenon is appealing, because the damper structure is simple and requires neither external power supply nor electronic devices; in addition, no fluid is involved in the damper, and the moving parts of the damper have no mechanical contact.

Applications of the eddy current damping effect in vibration suppression studies have been reported, but, to the best of the author's knowledge, the application of the eddy current in vehicle suspension systems has not been addressed in prior publications. Chapter 3 covers the development and feasibility study of utilizing eddy current damping effect as a potential passive damping source in vehicle suspension applications.

In conventional hydraulic suspension systems, shock absorbers convert the mechanical energy of the vibration into heat energy, so this mechanical energy is dissipated (Suda *et al.*, 1996). Segal et al. (1982) have demonstrated that roughly 200 watts of power are dissipated in an ordinary sedan traversing a poor road at 13.4 m/s; hence, suspension systems have the potential for energy regeneration. Using electromagnetic dampers (composed of electromechanical elements), the kinetic energy of vehicle body vibration can be regenerated as useful electrical energy. The electromagnetic dampers (as actuators) have the potential to be used in active suspension systems.

In this paper it is proposed to prepare a model of Permanent magnetic eddy current damper. For the advantages of non-contact, mechanical friction free, lubrication free, controllable and measurable stiffness and damping properties, Permanent magnetic damper does not require extra power supply or excitation winding, so it is energy-saving, highly efficient and greater in braking density [3]. The design of a new permanent magnetic eddy current damper is proposed in this thesis, which can provide planar electromagnetic damping force on maglev positioning platform [4] and other accurate positioning systems and meet the needs of fast, accurate and stable positioning. Based on the structural design, the dissertation work suggests a model of permanent magnetic eddy current damper by using FFT analysis.

LITERATURE REVIEW

The review mainly focuses on replacement of Classical Damper with the Electromagnetic Damper in the application of automobile vehicles.

For example, Lin et al. _1_ introduced an eddy current damper to suppress the flexural suspension mechanism in a precision positioning stage.

Plissi et al. _2_ investigated eddy current damping for multistage pendulum suspensions for use in interferometric gravitational wave detection.

Kienholz et al. _3_ employed an eddy current damper for a vibration isolation system of space structures.

Kligerman et al. _4_ investigated rotor dynamics with electromagnetic eddy current damping in high speed operation.

Kim et al. _5_ and Ebrahimi et al. _6,7_ designed and implemented eddy current dampers for vehicle suspension systems.

Cheng and Oh _8_ developed a coiled-based electromagnetic damper for vibration suppression of cantilever beams.

Larose et al. _9_ designed tuned mass dampers for full-scale bridge vibration with adjustable damping provided by an eddy current mechanism. More applications and developments can be seen in the review by Sodano and Bae _10_. Compared with other types of dampers, such as viscous, viscoelastic, or piezoelectric dampers, the eddy current damper has advantages of no mechanical contact, high reliability, high thermal stability, and vacuum compatibility. However, it has disadvantages of large mass and packing size.

Finally, the most recent research in using the electromagnetic damper concept is done by Allen (2008). He presented the design, fabrication, and testing of an active suspension on a quarter-car system, using a tubular linear motor with various controls algorithms. His master thesis is on developing control algorithms for the linear motor in the suspension system to minimize the transmitted acceleration to the sprung-mass.

THEORY AND EXPERIMENT

Eddy currents (also known as Foucault currents) are caused when a conductor is exposed to a varying magnetic field. These circulating currents can be induced due to relative motion of the field source and conductor, called motional eddy currents. They create electromagnets with

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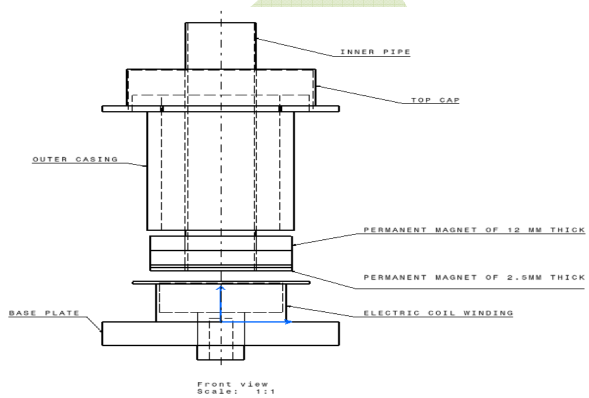
magnetic fields that oppose the change in an external magnetic field, causing a repulsive force proportional to the relative velocity of the field and conductor. The generated electromagnetic forces can provide a strong damping/braking effect

This dissertation employs the eddy current damping effect for the development of a damper for vibration isolation applications. An isolation system protects a delicate object either from excessive displacement or from acceleration transmitted to it from its supporting structure. A vibration isolation experimental test rig is set up, as represented in figure 1, to investigate the eddy current damper performance and verify the derived analytical eddy current damper model. Figure 2 depicts a schematic configuration of the proposed eddy current damper. Like the damper used in the study by Ebrahimi et al (2009), the proposed damper consists of a conductor as an outer tube and an array of axially magnetized, ring-shaped permanent magnets separated by iron poles as a mover. The relative movement of the magnets and the conductor causes the conductor to undergo motional eddy currents.



ASSEMBLY OF ELECTROMAGNETIC DAMPER

According to the Lorentz force law, the relative movement of the magnets and the conductor causes the eddy currents to induce in the conductor, producing the magnetic flux that opposes the external magnetic flux density, resulting in a damping force per each pole piece (Ebrahimi et al 2008b)

$$\boldsymbol{F} = \int_{\Gamma} \boldsymbol{J} \times \boldsymbol{B} \, \mathrm{d}\Gamma,$$

where Γ, $\boldsymbol{J}$ and $\boldsymbol{B}$ are the conductor's volume, induced current density and magnetic flux density, respectively. The induced current density $\boldsymbol{J}$ in the conductor is calculated as follows, assuming a constant magnetic flux density:

$$\boldsymbol{J} = \sigma(\boldsymbol{v} \times \boldsymbol{B}),$$

where σ and $\boldsymbol{v}$ are the conductor's conductivity and the relative velocity of the magnetic flux density and the conductor, respectively. Combining equations (1) and (2), the damping force per pole piece in the z-direction is simplified as

$$F_z = -\sigma(\tau - \tau_m)v_z \int_0^{2\pi} \int_{r_{\text{inside}}}^{r_{\text{outside}}} r B_r^2(r, z_0)\, \mathrm{d}r\, \mathrm{d}\theta,$$

where *Br* , *r*inside and *r*outside are the radial component of the magnetic flux density, conductor's inside radius and conductor's outside radius, respectively. It is concluded from equation (3) that the equivalent constant damping coefficient *C* for the proposed eddy current damper is

$$C = -\sigma(\tau - \tau_m) \int_0^{2\pi} \int_{r_{\text{inside}}}^{r_{\text{outside}}} r B_r^2(r, z_0)\, \mathrm{d}r\, \mathrm{d}\theta.$$

It should be mentioned that the air damping is neglected in the calculations due to its insignificant effect. For a permanent magnet with length *τm* and radius *R*, the magnetic flux density at a distance (*r, z*) from the magnet geometric centre is obtained (Craik 1995) by computing

$$\begin{aligned} B_r(r,z)|_{R,\tau_m} = \frac{\mu_0 I}{2\pi\tau_m} \int_{-\tau_m/2}^{\tau_m/2} & \frac{(z-z')}{r[(R+r)^2+(z-z')^2]^{1/2}} \\ & + \left[-\int_0^{\pi/2} \frac{\mathrm{d}\theta}{\sqrt{1-4Rr[(R+r)^2+(z-z')^2]^{-1}\sin^2\theta}} \right. \\ & + \cdots + \frac{R^2+r^2+(z-z')^2}{(R-r)^2+(z-z')^2} \\ & \left. \times \int_0^{\pi/2} \sqrt{1-4Rr[(R+r)^2+(z-z')^2]^{-1}\sin^2\theta}\, \mathrm{d}\theta \right] \mathrm{d}z' \end{aligned}$$

I = *M* · *τm* is the equivalent current of the permanent magnet (Furlani 2001), where *M* is the constant magnetization of the magnet.

For the proposed magnets' configuration in figure 2, the total radial component of the magnetic flux density expelling from each iron pole piece is the sum of the magnetic flux density produced by each adjacent magnets as

$$B_r(r,z) = 2(B_r(r,z)|_{l_m+s,\tau_m} - B_r(r,z)|_{s,\tau_m}).$$

Equation (4) is computed for the damping coefficient estimation of the proposed eddy current damper configuration; it is validated with the experimental results in the next section.

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EXPERIMENTAL SETUP AND RESULTS

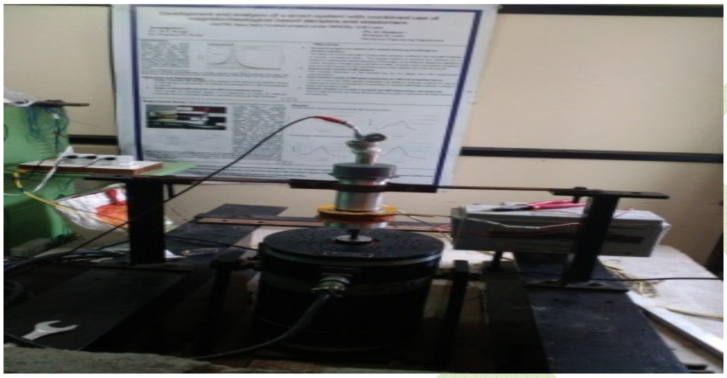
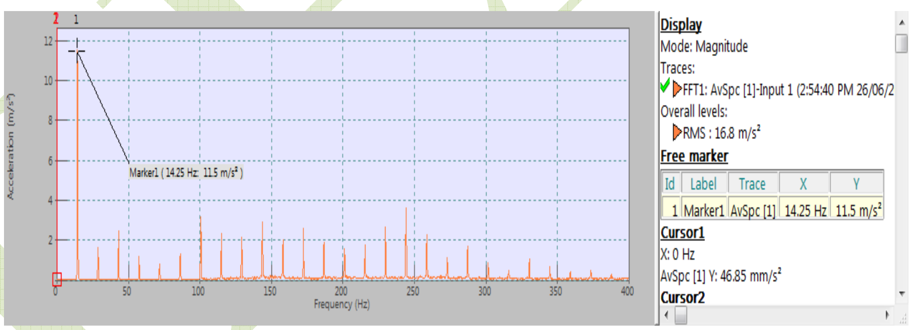
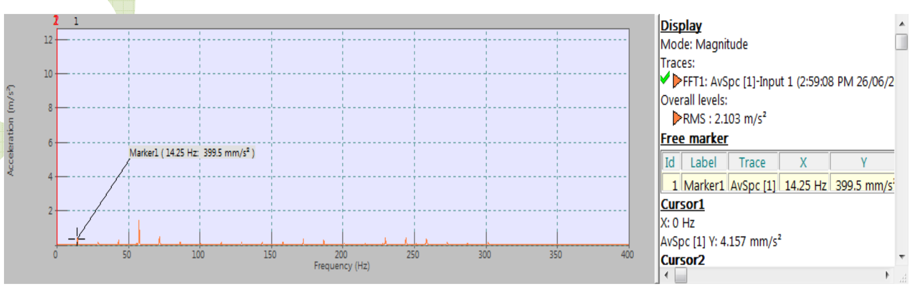


Fig. 1 Model with FFT Analyzer

1 Total weight = Model wt+ External Wt.
= 410 gm + 0 gm
= 410 gm.
Voltage = 12 v constant
Input Frequency = 15 Hz to 60 Hz
Output Obtained = Acceleration



1 Acceleration without damper at 15 Hz



2 Acceleration with damper at 15 Hz

Similarly at different External weight and voltage following results were obtained in FFT analyzer

Total weight = Model wt+ External Wt.

= 410 gm + 0 gm

= 410 gm.

Voltage = 12 v constant

Input Frequency = 15 Hz to 60 Hz

Output Obtained = Acceleration

Table No. 1 Result analysis of Damper with Total Weight is 410gm

Frequency	Acceleration without Damper In m/s2	Acceleration with Damper In mm/s2	Acceleration with Damper in m/s2	Reduction in acceleration by Eddy current Damper (%)
15	11.5 m/s2	399.5 mm/s2	0.3995	96.52%
20	9.02	19.71	0.01971	99.78
25	7.47	18.04	0.01804	99.75
30	5.97	17.42	0.01742	99.70
35	5.26	21.07	0.02107	99.59
40	4.82	26.51	0.02651	99.45
45	5.88	70	0.070	98.80
50	4.62	122.3	0.1223	97.35
55	5.14	28.11	0.02811	99.45
60	5.26	14.02	0.01402	99.73

4.1 Total weight = Model wt+ External Wt.

= Total wt = 410+ 50= 460gm

Table No. 2 Result analysis of Damper with Total Weight is 460 gm

Frequency	Acceleration without Damper In m/s2	Acceleration with Damper In mm/s2	Acceleration with Damper in m/s2	Reduction in acceleration by Eddy current Damper (%)
15	13.5	353.4	0.3534	97.38
20	8.91	22.57	0.02257	99.74
25	5.91	13.11	0.01311	99.77
30	5.68	14.28	0.01428	99.74
35	5.23	20.35	0.02035	99.61
40	5.2	24.01	0.02401	99.53
45	5.22	44.6	0.0446	99.14
50	5.39	87.1	0.0871	98.38
55	5.8	26.25	0.02625	99.54
60	5.99	6.49	0.00649	99.89

4.2 Total wt = 410+75 = 485 gm

Table No.3 Result analysis of Damper with Total Weight is 485 gm

Frequency	Acceleration without Damper In m/s2	Acceleration with Damper In mm/s2	Acceleration with Damper in m/s2	Reduction in acceleration by Eddy current Damper (%)
15	18.5	40.49	0.04049	99.78
20	9.07	29.42	0.02942	99.67
25	5.63	22.86	0.02286	99.59
30	4.92	12.57	0.01257	99.74
35	4.65	26.06	0.02606	99.43
40	4.82	38.69	0.03869	99.19
45	4.88	89.9	0.0899	98.15
50	3.75	159.4	0.1594	95.74
55	4.47	23.33	0.02333	99.47
60	5	5.66	0.00566	99.88

4.3 Total wt= 410 + 100 = 510gm

Table No. 4 Result analysis of Damper with Total Weight is 510gm

Frequency	Acceleration without Damper In m/s2	Acceleration with Damper In mm/s2	Acceleration with Damper in m/s2	Reduction in acceleration by Eddy current Damper (%)
15	23.25	304.8	0.3048	98.68
20	7.14	19.56	0.01956	99.72
25	4.92	19.45	0.01945	99.60
30	5.31	15.91	0.01591	99.70
35	5.2	32.51	0.03251	99.37
40	4.154	30.13	0.03013	99.27
45	4.214	87	0.087	97.93
50	3.878	57.5	0.0575	98.51
55	4.802	25.23	0.02523	99.47
60	3.696	1.88	0.00188	99.94

4.4 Total Wt = 410 + 125 = 535 gm

Table No. 5 Result analysis of Damper with Total Weight is 535 gm

Frequency	Acceleration without Damper In m/s2	Acceleration with Damper In mm/s2	Acceleration with Damper in m/s2	Reduction in acceleration by Eddy current Damper (%)
15	26.46	534	0.534	97.98
20	7.28	17.23	0.01723	99.76
25	5.16	22.21	0.02221	99.56
30	4.651	16.29	0.01629	99.64
35	3.418	19.95	0.01995	99.41
40	4.539	35.3	0.0353	99.22
45	3.314	94.1	0.0941	97.16
50	5.89	64.7	0.0647	98.90
55	4.388	24.89	0.02489	99.43
60	4.189	1.745	0.001745	99.95

CONCLUSIONS

1. Reduction in acceleration at without any external load on model, In the applied frequency range of 15 Hz to 60 Hz at 12 V is 96.52% to 99.78%.
2. Reduction in acceleration at 50g external load on model, In the applied frequency range of 15 Hz to 60 Hz at 12 V is 97.38% to 99.89%.
3. Reduction in acceleration at 75g external load on model, In the applied frequency range of 15 Hz to 60 Hz at 12 V is 95.74% to 99.88%.
4. Reduction in acceleration at 100g external load on model, In the applied frequency range of 15 Hz to 60 Hz at 12 V is 97.93% to 99.94%.
5. Reduction in acceleration at 125g external load on model, In the applied frequency range of 15 Hz to 60 Hz at 12 V is 97.16 % to 99.95%.

It has been realized that linear electromagnetic damper is the most appropriate for the design of active and semi-active suspension system due to its fast response time and reliability.

SCOPE OF FUTURE WORK

1. In this dissertation, manufacturing and testing of Electromagnetic damper is studied. Advanced studies can be done to
2. Reduce the total weight of model.
3. Provide compact and effective external assembly to classical damper
4. Improve magnetic properties and efficiency of damper.

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