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An Experimental Study of Eddy Current Damping In Automobiles Using Electromagnetism

KanishkTyagi, Sharon

1. INTRODUCTION

Suspension systems, in the automotive application, have been designed to maintain contactbetween a vehicle's tires and the road, and to isolate the frame of the vehicle from road disturbances. These systems have been extensively explored in the past few decades, contributing to ride comfort, handling and safety improvements. Dampers, or so-called shock absorbers, reduce theeffect of a sudden bump by smoothing out the shock. In most shock absorbers, the energy isconverted into heat via viscous fluid. In hydraulic cylinders, the hydraulic fluid is heated up. In aircylinders, the hot air is emitted into the atmosphere. There are several common approaches for shockabsorption, including material hysteresis, dry friction, fluid friction, compression of gas, and eddycurrents. The new generation of powertrain and propulsion systems, as a new trend in modern vehicles, poses significant challenges to suspension system design. However, thedevelopment of new-generation suspension system necessitates advanced suspension components.

In the past few years, improvements in power electronics and magnetic materials have resulted in to significant improvements in electro-mechanical devices, reducing their volume, weight, and cost, and improving their overall efficiency and reliability. These developments justify an analysis and implementation of electromagnetic devices in suspension systems. The use of electromagnetic dampers in suspension systems has several benefits compared to hydraulic, pneumatic, or other mechanical dampers. Electromagnetic dampers can function simultaneously as sensors and actuators. The spring effect can be added to the system by means of electromagnets, powered by Permanent Magnets. Moreover, electromagnetic dampers can work under very low static friction. Here, the damping coefficient is controlled rapidly and reliably through electrical manipulations. Although active suspensions have excellent performance, they have high energy consumption, are notfail-safe in case of power failure, and are heavy and expensive compared to conventional variabledampers, using other technologies such as electromagnetic-valve and Magneto-Rheological (MR)fluid dampers. Electromagnetic dampers are potential solutions to the high weight, high cost, and fail-safety issues in an active suspension system. The hybrid electromagnetic damper combines the performance and controllability of an active electromagnetic damper with the reliability of passive dampers in a single package, saving weight and cost, and making the damper fail-safe in case of power failure. Since the active electromagnetic damper utilizes magnetic components, one potential design for supplying the passive damping effect is the eddy current damping phenomenon.

Eddy currents (also known as Foucault currents) are generated in a conductor in a time-varying magnetic field. They are induced either by themovement of the conductor in the static field or by changing the strength of the magnetic field, initiatingmotional and transformer electromotive forces (emfs), respectively. Since the generated eddy currents create a repulsive force that is proportional to the velocity of the conductor, the moving magnet and conductor behave like a viscous damper.

2. VEHICLE SUSPENSION SYSTEM

The primary function of the vehicle suspension system is to provide a comfortable ride, through isolation of the vehicle body from road irregularities, and enhance the ride handling by producing a continuous road-wheel contact. According to the level of controllability, suspension systems are classified as passive, active, or semi-active. It is verified that the passive and semi-active suspension systems cannot provide the above-mentioned requirements satisfactorily, because of the contrasting nature of these requirements. Active suspension in its various forms offers a means to relax those compromises (Wendel et al., 1991). There are several qualitative measures that must be considered by the suspension system designer in order to achieve the desired performance, including: ride comfort (corresponds to the acceleration felt by the passenger), road-handling, the relative motion between the vehicle body and wheels, and the body motions during critical maneuvers such as braking and cornering (Biglarbegian et al., 2008). The vehicle suspension performance indexes are discussed below in detail.

2.1 Passive Suspension Systems

Passive suspension systems are the most common systems that are used in commercial passenger cars. They are composed of conventional springs, and single or twin-tube oil dampers with constant damping properties. The designer pre-sets the fix damping properties to achieve optimum performance for the intended application. The disadvantage of passive suspension systems with constant damping characteristics is that setting the design parameters is a compromise between the ride quality and handling. Generally, softer dampers provide a more comfortable ride, while stiffer ones provide better stability and thus better road-handling. Passive suspension systems are tuned according to the expected operating conditions, but a compromise is always made between designing for the two opposing goals. Therefore, the performance in each area is limited according to this compromise (Gillespie, 2006). However, traditional passive suspension systems are low cost, and relatively simple to manufacture.

2.2 Semi-active Suspension Systems

Since first proposed by Crosby and Karnopp (1973), semi-active suspension systems continue to gain popularity in vehicle suspension system applications, due to their advantageous characteristics over passive suspension systems. Semi-active (also known as adaptive-passive) suspension systems are essentially passive systems in which the damping properties can be adjusted to some extent. Thus, semi-active suspension systems extend the possible range of damping characteristics obtainable from a passive damper (Carter, 1998), (Barak, 1992), and (Koo, et al., 2004). The damping characteristics of a semi-active damper can be adjusted through applying a low-power signal. Semi-active systems are a compromise between the active and passive systems (Alanoly et al., 1986). They are commercialized recently by means of either a solenoid valve as an adjustable orifice, or MR-fluid dampers, both of which are very expensive. Leading automotive manufacturers such as General Motors (GM) and Volvo have started the implementation of these semi-active suspension systems for their high-end automobiles. However, there exist many challenges that must be overcome for these technologies. The MR dampers have still some crucial issues, such as MR degradation with time, temperature sensitivity, sealing problems; etc.

2.3 Active Suspension Systems

Active suspension system refers to a system that uses an active power source to actuate the suspension links by extending or contracting them as required (Gillespie, 2006). The main challenge in the automobile suspension system design is the trade-off between the conflicting requirements of ride-comfort and handling. In the past few decades, due to advances in sensors/actuators technologies, active suspension systems have emerged as an active research field to address those compromises. In an active suspension, controlled forces are introduced to the suspension by means of hydraulic or electric actuators, between the sprung and unsprung-mass of the wheel assemblies (Brown, 2005). Karnopp (1983) studied the effect of adding an active damping force to the suspension system. Milliken (1988) developed the first fully active suspension to be used in a suspensions system application. A variable force is provided by the active suspension at each wheel to continuously modify the ride and handling characteristics. The key difference between semi-active and active suspension systems is that the latter applies an external force to the vehicle body either in an upward or downward direction, regardless of the absolute vehicle body velocity. Active suspension overcomes the compromise required in tuning passive dampers. Sensors, as essential elements of anactive suspension, are used to measure the suspension movements at different points. Although active suspensions have superb performance, the practical implementation of active suspension in vehicles has been limited due to their high weight, cost, power consumption, and reduced reliability that are not justified by the limited incremental benefit to the passenger (Deo, 2007).

3. EDDY CURRENT DAMPING

When a non-magnetic conductive metal is placed in a magnetic field, eddy currents aregenerated. These eddy currents circulate in such a way that they induce their own magnetic fieldwith opposite polarity of the applied field causing a resistive force. However, due to the electricalresistance of the metal, the induced currents will be dissipated into heat at the rate of I^2R and theforce will disappear. In the case of a dynamic system the conductive metal is continuously movingin the magnetic field and experiences a continuous change in flux that induces an electromotiveforce (emf) allowing the induced currents to regenerate and in turn produce a repulsive force thatis proportional to the velocity of the conductive metal. This process causes the eddy currents tofunction like a viscous damper and dissipate energy causing the vibrations to die out faster. Theuse of eddy currents for damping of dynamic systems has been known for decades and itsapplication to magnetic braking systems and lateral vibration control of rotating machinery has been thoroughly investigated.When using eddy currents the typical method of introducing an emf in the conductive metal isto place the metal directly between two oppositely poled magnets with the metal movingperpendicular to the magnets poling axis, a schematic diagram of this process is shown in Fig. 1. This configuration is ideal because the magnetic field isconcentrated between the two magnets causing the magnetic flux applied to the conductor to begreater and thus the damping force to be increased.

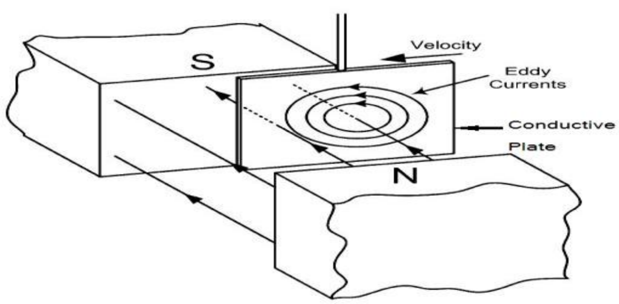

Fig. 1 Schematic diagram of conductive material passing through a magnetic field and generation of eddy current [28]

The relative movement of the magnets causes the conducting plate to undergo a time-varying magnetic field such that a transformer eddy current is generated. Since there is a relative movement between magnets and the conducting plate, a motional eddy current is generated as well. By Maxwell's law, a time-varying magnetic field produces an electric field. This causes ''eddy'' currents to flow in the conductor. These currents dissipate energy as they flow through the resistance of the conductor. The resulting drag force on the conductor is proportional to its velocity relative to the field. The device thus functions as a viscous damping element. Eddy currents have been used in our home electric appliances, non-contact measurement devices, and brake systems for high-speed trains.

3.1 Advantages of eddy current damper are :

- Better performance
- Oil free
- Low maintenance
- Reliable
- Adaptive in nature

3.2 Motivation for Research

There are many industries, in which thin shells like flexible structures are used e.g. in aerospace, which are subjected to dynamic loads and damping mechanisms are limited for these structures. Either we can use layers of visco-elastic material or we can modify the existing alloys so that their internal damping coefficient can be increased. Conventional damping mechanisms cannot be employed to these flexible structures as they can cause localized damage to the structure due to mechanical contact between the damper and flexible structure.Eddy current dampers can be designed to suppress these vibrations. This methods of vibration attenuation not only avoid localized imperfections by generating distributed forces, but also add significant damping to the structure while avoiding mass loading and added stiffness, thus allowing the dynamics to be unaffected by the addition of the damper into the system.

4. LITERATURE REVIEW

Eddy currents are caused when a conductor is exposed to a varying magnetic field. They are induced either by the movement of the conductor in the static field or by changing the strength of the magnetic field, initiating motional and transformer electromotive forces (emf), respectively. Since the generated eddy currents create a repulsive force that is proportional to the relative velocity of the field and conductor, the moving magnet and conductor behave like a viscous damper.

4.1. Research in field of eddy current magnetic braking system

- For more than two decades, the application of eddy currents for damping purposes has been investigated, while the theory and applications of rotary magnetic braking systems have been well documented, there are many more applications of eddy current dampers. **Karnopp (1989)** introduced the idea that a linear electrodynamics motor consisting of coils of copper wire and permanent magnets could be used as an electromechanical damper for vehicle suspension systems. It was shown that this actuator could be much smaller and lighter than conventional dampers while still providing effective damping in the frequency range typically encountered by road vehicle suspension systems.

4.2. Research of eddy current damping in structures

- **Schmid and Varaga (1992)** have designed and analyzed a vibration attenuation system for the construction of high-resolution nanotechnology structures such as the Scanning Tunneling Microscope (STM) by using Eddy current damper (ECDs). **Takagi et al. (1992)** studied the deflection of a thin copper plate subjected to magnetic fields both analytically and experimentally. They used an electromagnet with very high current (several hundred Amperes) to generate the magnetic field, and then analyzed the response of the plate to the applied field.
- **Kienholtz et al. (1994)** with Cullen-Sherry & Associates, Engineering Inc.(CSA) investigated the use of a magnetic tuned mass damper for vibration suppression of a spacecraft solar array and a magnetically

damped isolation mount for the payload inside of a space shuttle. The magnetic tuned mass damper system targeted two modes of the solar array (1st torsion at 0.153 Hz and 1st out of plane bending of 0.222 Hz) and increased the damping by 30 and 28 dB, respectively, while the higher frequency untargeted modes 0.4–0.8 Hz were damped in the range of 11–16 dB.

- **Matsuzaki et al. (1997)** proposed the concept of a new vibration control system in which the vibration of a beam, periodically magnetized along the span, is suppressed by using electromagnetic forces generated by a current passing between the magnetized sections. To confirm the vibration suppression capabilities of their proposed system, they performed a theoretical analysis of a thin beam with two magnetized segments subjected to an impulsive force and showed the concept to suppress the beams first three modes of vibration.
- Recently, **Kwak et al. (2003)** investigated the effects of an eddy current damper on the vibration ofa cantilever beam and their experimental results showed that the eddy current damper can be ineffective device for vibration suppression. The authors ECD uses a fixed copper conducting plate and flexible linkage attached to the tip of the beam in order to utilize the axial magnetic flux and generate eddy current damping forces
- **Sodano et al., (2005),** studied the Concept and model of eddy current damper for vibration suppression of a beam, a new electromagnetic damping mechanism is introduced. This mechanism is different from previously developed electromagnetic braking systems and eddy current dampers because the system investigated in the subsequent manuscript uses the radial magnetic flux to generate the electromagnetic damping force rather than the flux perpendicular to the magnet's face as done in other studies.
- **Singh et al. (2011)** studied the concept of eddy current damping in structures.

4.3. Research of eddy current dampers in theory and practical models

- **Teshima et al. (1997)** investigated the effects of an eddy current damper on the vibrational characteristics of superconducting levitation and showed that the damping of vertical vibrations was about 100 times improved by eddy current dampers.
- The concept of using a viscoelastic material to dissipate energy from a structure was modified to incorporate magnets by **Oh et al. (1999).** The study sandwiched a viscoelastic material between magnetic strips that were configured to attract each other in one case and to repel in the other. It was determined that the passive magnetic composite (PMC) treatments function best when the magnets were set to attract each other. However, this method of damping does not use eddy currents to apply damping to the structure.
- **Graves et al. (2000)**derived the mathematical model of electromagnetic dampers based on a motional emf and transformer emf devices and presented a theoretical comparison between these two devices. A motional emf device generates eddy currents due to the movement of a closed conduction circuit or a conductor through a stationary magnetic field, while a transformer emf device generates an emf within a stationary conducting circuit, due to a time-varying magnetic field. Both of these electromagnetic devices can be used for vibration damping purposes..**Bae et al. (2004)** modified and developed the theoretical model of the eddy current damper constructed by **Kwak et al. (2003).**
- Authors **Sodano et al,(2006)**also have modified the theoretical model of their ECD, and further developed it by applying an image method to satisfy the boundary condition of the zero eddy current density at the conducting plate's boundaries.
- For high precision magnetic levitation, **Elbuken et al. (2006)** have investigated the eddy current damping. Also it has been suggested that an ECD can suppress the vibration of the levitated object (Elbuken et al., 2006).Using this new model, the authors investigated the damping characteristics of the ECD and simulated the vibration suppression capabilities of a cantilever beam with an attached ECD numerically.

For ECDs and couplers under rather general operating conditions, **Tonoli (2007)** has presented a physical, dynamic model.

5. Working

The concept of Eddy Current Damping works on the principle of Electromagnetic Induction. According to the theory of electromagnetic induction, a current flows in a conductor whenever a change in magnetic flux is linked with it. Change in magnetic flux takes place when a conductor moves in a stationary or transient magnetic field. And according to Lenz's law, the resulting magnetic field opposes the cause of changing magnetic flux. The cause in present study is the motion of the conductor.Hence the resulting magnetic field opposes the motion of conductor.

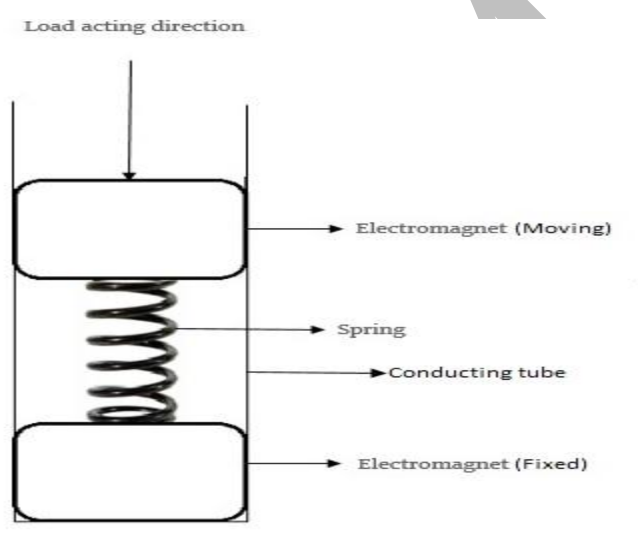

Fig 1. Block diagram depicting use of eddy currents in damping

The damper makes use of two electromagnets placed inside a conducting tube which are held together with the help of a spring between them. The lower electromagnet is fixed in the groove while the upper is free to travel within the conductor due to the application of load. During normal working, there is no relative motion between the two electromagnets, as a result no eddy currents flow but whenever a bump or a pit is encountered relative motion between the two electromagnets takes place due to the downward movement of the upper electromagnet on account of load. This results in the Eddy current formation which resists the motion of the conductor.

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