Study and Comparison on Linear Electromagnetic Shock Absorbers among other Available Intelligent Vibration Dampers

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Abstract: *The main objective of a car suspension system is to improve the ride comfort without compromising the ride handling characteristic. The suspension system reduces the effect of vibration caused by the road and driving conditions. Over recent years the massive developments in actuators, sensors and microelectronics technology have made the intelligent suspension systems more feasible to implement in automobile industry. These systems are designed and fabricated in such a way that they are able to reduce the drivers' and passengers' exposure to harmful vertical acceleration. Leading automotive companies have started to use intelligent dampers in their high-end automobiles' suspension system. But much more research and developments are required in design, fabrication and testing the shock absorbers of the suspension system and many challenges need to be overcome in this area. This paper high lights five types of damping technology which are being widely used. It has been realized that linear electromagnetic damper is a better choice for the design of active and semi-active suspension system due to its fast response time and reliability.*

Keywords: Vehicle; Car; Semi-active; Suspension; Damper; Adaptive; Intelligent; review; comparison

1. Introduction

A damper, commonly referred to as shock absorber, is an important element in vehicle suspension system (Figure 1). It is a mechanical device that dissipates energy in the direction of the motion. In vehicle suspension systems, it is used to isolate the vehicle chassis from unwanted vibrations generated from the road disturbances, and to provide good ride comfort and road-handling.

The concept of linear damper that creates force proportional to its end relative velocity is commonly used and widely studied in vibration analysis. This relationship gives equations for which the solutions are well understood [1]. It is not mandatory that a damper must exhibit such characteristics; nevertheless, the typical modern hydraulic damper acts so because the manufacturer of the damper considers this desirable to be used in a suspension system [1-3].

Dampers have been studied over the history of automotive technology from simple friction dampers to modern electromagnetic dampers. Hadley had published a paper about mechanical friction dampers in 1928 [4]. Weaver [5] investigated damper's force-displacement relationship and plotted the curves. In 1932, James and Ullery [6] described the superior performance of the hydraulic damper over others and discussed a suitable force-velocity relationship.

Figure 1: **Damper and spring of a vehicle**

Hagela et al. [4] tested the first variable damper with Electro-Rheological (ER) fluids and solenoid valves in 1990. Eslaminasab [7] demonstrated that the damper with asymmetric damping behaviour has a positive effect on vehicle stability as the height of the vehicle body becomes lower because of this behaviour. Damper design is highly influenced by the required functionality and there is no general standard for damper performance in the automotive suspension context. Different commercial damper technologies such as passive, semi-active, active as well eddy current, hybrid and electro-magnetic dampers are introduced and the corresponding literature is reviewed.

2. Hydraulic Dampers

Still, most of the vehicles in the road utilize passive dampers to provide damping in their suspension systems. Most hydraulic shock absorbers handle the vehicle frame vibration by a piston moving through oil or fluid. To produce the damping effect, holes in the piston are attached to the valves, which resist the flow of the fluid through the holes in a controlled manner. Passive dampers are categories as twin-tube and mono-tube as shown in the figure 2 [8].
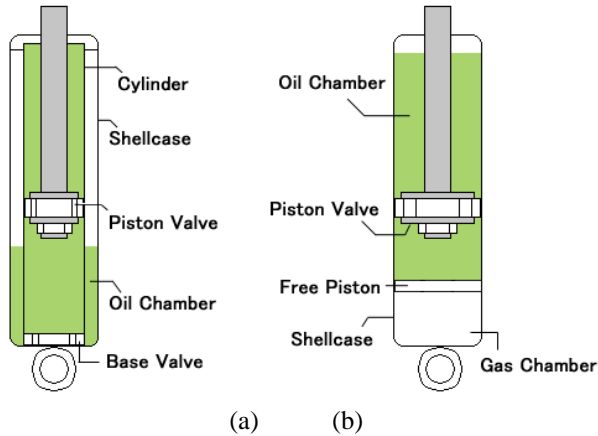

(a)   (b)
Figure 1: (a) Twin-tube and (b) Mono-tube dampers

The twin-tube damper has two tube chambers: outer and inner chambers. The outer chamber includes the gas chamber and acts as a reservoir for the fluid. The inner chamber has a piston which is allowed to move up and down in it. The outer chamber balances the fluid volume changes caused by the piston rod movement. A piston valve and a foot valve are also used in the twin-tube design. The foot valve and partially the piston valve determine the damping action of the suspension system during the suspension compression. The valves apply resistance to the flowing fluid according to the control command. However, when the suspension extends, the piston valve alone control the damping action.

On the other hand, a mono-tube damper composed of a single cylinder. It is partly occupied with fluid through which a piston with an orifice moves up and down. There is a gas chamber at the bottom which permits the volume of the piston rod to enter inside the damper. This gas chamber also exhibits a spring characteristic to the force created by the damper. It allows the damper to maintain its extended length when there is no force applied on it [9]. Passing the fluid of the tube through the orifice results a damping force due to the pressure drop between the extension and compression chambers. Twin-tube dampers are more complex than mono-tube and have issues with dissipating the generated heat but they can operate with low gas pressure. In contrast, mono-tube dampers are lighter due to the fewer parts, simpler in terms of manufacturing, but they requires higher gas pressure and are more susceptible to damage of the cylinder compared to the twin-tube dampers.

In contrast, variable dampers change the damping rate by controlling the size of the valve opening by using piezoelectric actuators, servo-valve, shim-valving, solenoid-valve, or using MR-fluid technology which varies the viscosity of the fluid instead of changing the size of the

valve opening. The following section describes Semi-active dampers which include the solenoid-valve and MR dampers.

3. Solenoid-valve dampers

To mechanically control the size of the piston valve's orifice, a solenoid-valve can be employed in a damper. A solenoid valve is added to this type of damper to alter the gush of the hydraulic medium inside the shock absorber (Figure 3 [10]). Thus it shifts the damping distinctiveness of the suspension arrangement.

A control system sends the instructions to the solenoid-valves according to the control algorithm designed by the manufacturer (usually the so called "Sky-Hook" technique). It is capable of impart a high speed and precise flow control at a high operating pressure. Furthermore, the solenoid-valves can be used as a two- or three-state damper since the damping coefficient can be varied between hard and soft by opening and closing a bypass valve.
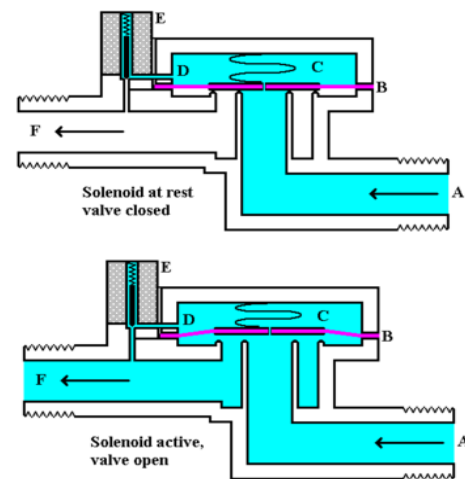

Figure 3: Solenoid-valve semi-active damper
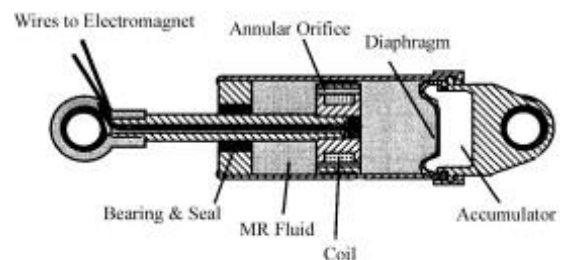
4. Magnetorheological fluid damper

Figure 4: Schematic of an MR **damper**

In the semi-active suspension systems, the magneto-rheological (MR) dampers have revealed to survive among the most promising mechanism due to their rapid response times which consequence from the deficiency of electromechanical actuators [11]. To exhibit force and torque proportional to the applied current, Magneto-rheological dampers are produced in both linear and rotational forms. To attain the variable damping properties, MR dampers are filled with magnetic particles suspended in liquid. When a current is applied crossway to the MR

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damper, the magnetic particles of the fluid align with one another. This behavior increases the viscosity of the fluid, which in turn change the damping rate of the MR damper. By applying magnetic field in a controlled manner, rheological fluids flow characteristics can be varied according to the designer's goal. The response of the fluids to the magnetic field change is almost abrupt and reversible.

As shown in Figure 4 [12], the fluid passages are bounded by an electromagnet in an MR damper. While the electromagnet is turned on, the iron particles in the fluid passages align to form fibers in the fluid. As a result, the rheological fluid becomes thicker and consequently exerts more resistant to run. By adjusting the current flowing through the coil, the thickness or glueyness of the fluid can be infinitely attuned from that of a base fluid to almost a plastic in less than two milliseconds. The fluid reverts to its base viscosity when the supply of the current is turned off almost instantly. Hu et al. [13] designed and manufactured a MRD50 type of large-scale Magnetorheological shock absorber in Smart Materials and Structures Laboratory of Nanjing University of Science and Technology. To evaluate the controllability of the dynamic behavior of MR shock absorber high impact loads test has been done. The result shows that the developed large-scale MR shock absorber was able to control the recoil dynamics effectively.

5. Eddy Current Dampers

While a conductor is exposed to a varying magnetic field, it creates eddy current. This is also acknowledged as Foucault current. If there is a movement of the conductor in the static field or variation in the power of the magnetic field, eddy current is induced which initiates electromotive forces. These forces allow the eddy current damper to exhibit suspension damper characteristics. Due to the repulsive forces generated by the eddy currents, the poignant magnet and conductor of the eddy current damper act like a viscous damper. The repulsive forces are proportional to the relative rapidity of the field and conductor. Once the eddy current is generated, it circulates in such a way that a magnetic field with opposite polarity of the applied field is induced. This in turn generates the repulsive force. However, the induced currents will dissipate into heat energy due to the electrical resistance of the conducting material, and the force will disappear. Since 1987, the function of eddy currents has been investigated for suspension damping purposes. Wiederick et al., [14], Heald [15], and Cadwell [16] have applied eddy current damper at magnetic braking systems.
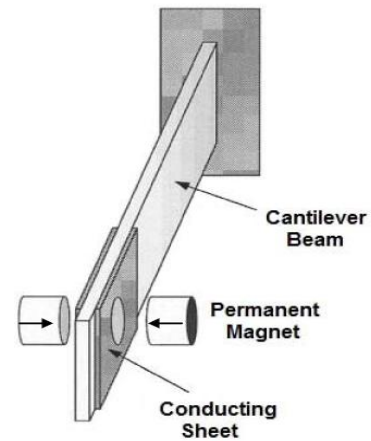

Figure 5: **Eddy current damper**

This damper has been used at structural vibration suppression by Sodano et al., [17], Bae et al., [18] and Sodano et al., [19]. Teshima et al., [20] and Elbuken et al., [21] has investigated eddy current damper for vibration isolation enhancement in levitation systems. Graves et al. [22] have developed a mathematical model for Eddy Current Dampers. The authors have also proposed a logical approach to measure up to the efficiency of the dampers based on the motional and transformer electromagnetic force. Genta et al., [23] applied it at the vibration control of rotary machinery.Sodano et al., [17] have examined the containment of cantilever beam vibrations, where a conducting sheet is attached to the beam tip. This also includes a permanent magnet that is fixed perpendicular to the beam motion. In their next publication, Sodano et al., [19] have customized the theoretical model of their proposed eddy current damper. They developed a damper that uses an image method to gratify the boundary form of the zero eddy current density at the conducting plate's boundaries. The proposed arrangement of their eddy current damping system is depicted in Figure 5 [17]. This figure shows their design of the damper which has a cantilever beam with a copper conducting plate positioned between the two fixed permanent magnets. Tonoli [24] has developed a physical dynamic model for eddy current dampers under common operating conditions. For high exactitude magnetic levitation, Elbuken et al. [21] have investigated the eddy current damping properties. They have shown in their research that the eddy current damper is able to stifle the vibration of the levitated object. Schmid and Varaga [25] have analyzed a vibration reduction system using eddy current damper for the construction of a high-resolution nanotechnology structures, for instance the Scanning Tunnelling Microscope (STM).

6. Electromagnetic Dampers

The electromagnetic damper is an electric contraption which can be used as an actuator or generator. The electromagnetic dampers or actuators have a great potential to be used in semi-active or active suspension systems. Shock absorbers change the mechanical energy of the vibration into heat energy in conventional hydraulic suspension systems, so this mechanical energy is dissolute [26]. Segal et al. [27] have found in their research that around 200 watts of power are

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degenerate in a regular sedan traversing a meager road at 13.4 m/s. Therefore, suspension systems have the potential for energy restoration. The mechanical energy of vehicle body vibration can be converted into useful electrical energy by using electromagnetic dampers. Many authors have developed self-powered semi-active or active control systems through regenerative electromagnetic damper [28]. Karnopp [29] has designed and developed a new electromechanical damper for vehicle applications. It consists of copper wires and permanent magnet. He has demonstrated that electro-dynamic variable shock absorbers are viable for oscillation frequencies, which is naturally predictable in road vehicle suspensions. Electromagnetic dampers can be divided into two parts, such as rotational electromagnetic damper and linear electromagnetic damper. Both of them are discussed below.

6.1 Rotational Electromagnetic Damper

Murty et al., [30] have developed an electric variable damper for vehicle suspension system. This damper mechanism converts vertical suspension motion into rotary motion using a ball screw mechanism. A rectifier bridge is applied to convert the three-phase alternator output to a single DC current. This reported device is not a regenerative one and it converts the vibration energy of the vehicle suspension system into heat energy through a variable load resistance and dissipates it to the environment.
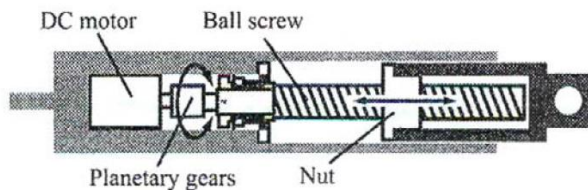

Figure 6: Proposed Electromagnetic Damper

Suda [31] has designed and developed an electromagnetic damper consists of a DC motor, planetary gears, and a ball screw mechanism (Figure 6 [31]) . It converts the linear vibrational motion between the car body and wheels into the rotating motion of the DC motor which in turns generate electric power and also capable to control the vibration. Before this invention, Suda *et al.* [26] have explored some trade-offs involved throughout the design process of the electromagnetic damper; for instance, there is a trade-off between the damping coefficient and the energy regeneration efficiency, that depends on DC machine inner and outer resistance. They also used two linear DC motors, one inside the primary suspension named as regenerative damper. It regenerates the vibration energy and stores it in a condenser. The second one is a linear DC motor which belongs to the secondary suspension system. It uses the stored energy of the condenser to control the active suspension of the vehicle [32]. An electric shock absorber for automobile suspension systems has proposed by Arsem [33] which is able to regenerate electricity by converting the mechanical energy. The produced electricity then used to charge the onboard battery. When the spiral screw of the mechanism moves up and down, the attached rotor starts to rotate. This spiral screw allows the mechanism to convert the transverse vibrational motion to the rotary motion, as well as it allows generating an electric current in the stator.

In this study the quarter car suspension system provided by Quanser Inc. has been used. The Quanser suspension plant incorporates a FAULHABER Coreless DC Motor (3863V006), as shown in Figure 7 [34]. This replica is a low inductance high efficiency motor which gives much earlier response than a conventional DC motor [34].

The Quanser suspension plant is a bench-scale model to imitate a quarter-car model. The plant has three floors (plates) on top of each other. The top floor emulates the vehicle corpse and is suspended over the middle plate with two springs. The high quality FAULHABER Coreless DC Motor (3863V006) stands between the top and middle plates to resemble a semi-active or active suspension mechanism. The motor is directly attached to the top plate. The middle plate is connected with the DC motor with two capstan cable as represented in the Figure 7 [34]. The major disparity between FAULHABER DC-Micromotors and conventional DC motors is in the rotor. The snaky does not have an iron core except consists of a self-sufficient skew-wound copper coil. This featherweight rotor has an enormously low moment of inertia; moreover it rotates with-out cogging. The outcome is the outstanding dynamics of FAULHABER motors. This motor has no cogging. It has highly dynamic performance due to having a low inductance coil, low inertia and precise speed control. Furthermore it is simple to control due to the linear performance characteristics. The schematic of FAULHABER motor has been given in Figure 8 [34].
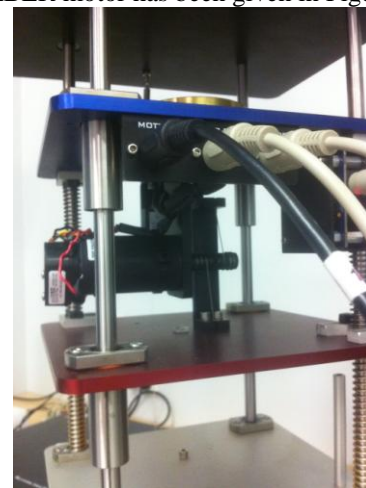

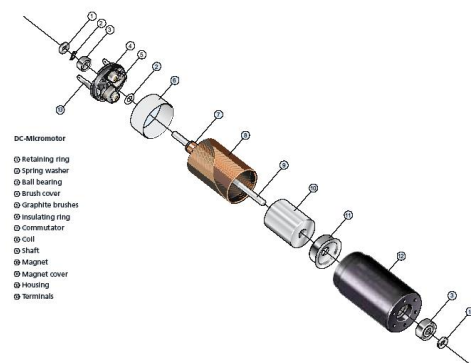Figure 7: Quanser electromagnetic damper assembly with FAULHABER Coreless DC Motor

Figure 8: The schematic of FAULHABER Coreless DC Motor (3863V006).

6.2 Linear Electromagnetic Damper

The magnificence of linear motors is that they directly translate electrical energy into usable linear mechanical force with motion, and vice versa. The motors can be formed in synchronous and asynchronous versions. Compared to conventional rotating electric motors, the stator and the shaft (translator) of the direct-drive linear motors are linear in shape. The most regular mode of function of Linear motor is like a Lorentz-type actuator, in where the functional force is linearly proportional to the current with the magnetic field ($F = qv \times B$). Linear motor is basically a multi-phase irregular current (AC) electric motor that has had its stator unrolled. Thus instead of generating a rotational torque, it creates a linear force beside its span. Kruczek et al. [35] have applied a Thrust Tube TBX3810 linear electric motor like an actuator controllers in their research. It can generate necessary forces to weigh against several H-infinity controls Figure 9 [35] represents the indispensable principle and configuration of the linear motor.
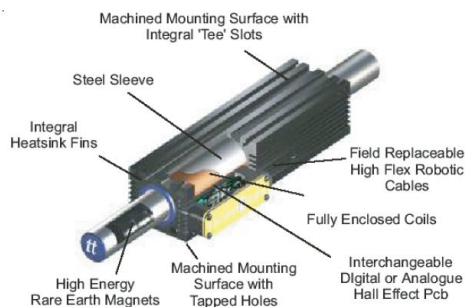

Figure 9: Linear electric motor TBX3810

Linear motor translator movement is able to work with high velocity motions up to 200m/min approximately. It can handle large accelerations up to g multiples and forces up to kilo Newton. As mentioned above, the electromagnetic force can be applied directly to the payload devoid of the intrusion of a mechanical transmission in a linear motor. This results in a high stiffness of the whole system. This motor has higher reliability and longer life span. In automotive industry, the most frequently used type of the leaner motor is the synchronous three-phase linear motor.

In 1980, Dr. Amar Bose, the founder and CEO of BOSE corporation, conducted a mathematical study to find out the optimum possible performance of an automotive suspension system, ignoring the margins of any existing suspension hardware [36]. The outcome of his 5-years of study indicated that it was feasible to achieve the performance that was a big step above anything available. Later conventional and changeable spring/damper systems and hydraulic approaches are evaluated and it was found that none had the arrangement of speed, force, and efficiency altogether which is required to provide the expected results. This research led to the linear electromagnetic suspension system as the main approach to comprehend the preferred suspension uniqueness.

Figure 10: The BOSE® Suspension Front Module

The Figure 10 [36] shows the face module of a BOSE suspension. The target of the BOSE suspension system was a momentous advancement in four key disciplines: power amplifiers, linear electromagnetic motors, control algorithms, and computation speed. The BOSE Corporation took the challenge of the first three disciplines and achieved a great success. Instead of a conventional shock-and-spring suspension system, the BOSE suspension system uses a linear electromagnetic motor at every wheel. The linear electromagnetic motor consists of magnets and coils of wire. The motor retracts and extends when electrical power is applied to the coils. This creates the activity between the wheel as well as car body. In each wheel, a current amplifier provides electricity to the motors to control the vibration. It also store the electric power regenerated by the every compression of the structure. The main advantage of the motors is that they are not restricted by the motion inertia which is inherent in conventional fluid-based dampers. Therefore, a linear electromagnetic damper is able to expand and compress at a much superior speed which can virtually eliminate all sensations in the passenger cabin of the vehicle. The body of the car remains level in spite of what is happening at the wheel because the wheel's vertical displacement is delicately proscribed. The linear electromagnetic damper is also reported to capable of neutralizing the body movement of the car while cornering, braking, and accelerating which gives the driver a greater sense of comfort and control.

The linear electromagnetic motor of the BOSE suspension system reacts quickly enough to counter the effects of bumps and potholes, maintaining a contented ride. Moreover, the motor has been designed for highest strength in a little package, allowing it to put out enough force to stop the car from rolling and pitching during violent driving manoeuvres of the vehicle. The BOSE suspension system offers easy two-point mounting. The only electrical links to the motor are for power and control. To counter the effects of bumps and potholes, retaining a contented ride the linear electromagnetic motor reacts quickly in BOSE suspension system. Moreover, this electromagnetic motor is designed for highest strength in a little package. This motor is able to exert enough strength to stop the car from undulating and somersaulting in violent driving manoeuvres. The performance of the vehicle equipped with the BOSE suspension system has been evaluated on different road condition and under many different circumstances that drivers will encounter during day to-day driving. Additionally, the vehicles handling and durability test has been evaluated at independent proving grounds. The elimination of body roll is admired when test drivers carry out aggressive cornering manoeuvres like a lane change.

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Similarly, the test drivers have reported that the vehicle body pitch throughout hard braking and acceleration decreased significantly. Professional test drivers rapidly observed an augmented sense of control and confidence resulting from these behaviours. When test drivers take the vehicle fitted with the Boss suspension over a bumpy road, they realized that the overall body motion and jerking vibrations of the vehicle reduced in a great extent which consequences in increased comfort and control. However, to date no commercial tests or design details are available to the world from the Bose Corporation which would allow the researchers to perform an accurate and unbiased comparison with other competitive suspension systems.

All the systems have some drawback and the BOSE suspension system is not an exception. The main drawback of the system is the manufacturing cost as it uses nyodinium magnet which is very expensive to manufacture. Therefore this makes this suspension system costlier than any other suspension available to this date. Thus this system can be used in only high end luxurious cars. The second drawback is, when this system breakdowns in a middle of travel, the vehicle need to stop. It is also very tricky and costly affair to fix this suspension system. The system is very composite and requires high precision machinery and trained workers to manufacture. Konotchick [37] has designed and developed several linear electric power generators which consist of rare earth magnets (NdFeB) and a cylindrical assembly of coils. The magnets and coils are allowed to move relative to each other. These electric power generators are more suitable for motions which have relatively large amplitude, such as wave energy generation. Merritt *et al.* [38] have designed a linear electrical generator using a reciprocating armature with rectangular permanent magnets. These magnets are coupled to a source of relative motion in this machine. These devises do not emerge to fully exploit the magnetic field which is generated by the permanent magnets. The generator utilizes only a single magnetic pole-coil interaction that reduces the device's competence. Goldner and Zerigian [39] have designed a new assembly of magnet and coil winding arrays to use the radial magnetic flux thickness in a linear generator. This devices act as shock absorbers. The damper is not designed to be controlled actively; as a result road-handling and ride comfort are sacrificed.

In late 2008, The Michelin Company unveiled its electric drive system. The Michelin novel active wheel incorporates an active suspension system as shown in Figure 11 [40]. The most important part of this system is a compact electric motor rated at 30 kW continuous outputs. Another motor which is fitted vertically across the diameter of the wheel, gives power for the active suspension system [40]. To gratis up space in the front of the car, propulsion and suspension components had been fixed in the wheel that could consequence in vehicle weight diminution, better impact energy absorption and better interior packaging. Moreover the suspension system of Michelin feedback time is 3 milliseconds.

Figure 11: Michelin designed active wheel with an active suspension system.

Goldner and Zerigian [39] proposed a linear shock absorber which composed of two concentric coil rings moving relative to the two concentric magnet rings. For a small all-terrain vehicle (ATV), Gupta *et al.* [41] described the manufacturing and execution of two electromagnetic shock absorbers (one based on a rotary dc motor and the second one based on a linear motor).

Allen [42] uses the electromagnetic damper concept to design his active suspension system. By a tubular linear motor with various control algorithms, the author offered the design of an active suspension on a quarter-car system. He has also done the fabrication, and testing of the model. His master thesis is to reduce the transmitted acceleration to the sprung-mass, by developing control algorithms for the linear motor in the suspension system.

Liu et al. [43] proposed a passive electromagnetic damper to increase the damping effect. The configuration of the damper is quite similar to the electromagnetic bearing devise. But no sensors and no closed loop control were added to the system. The electromagnetic damping is formed when the rotor is rotating, due to the eddy currents induced inside the surface layer of rotor to mitigate vibration. The experiment results show the improved damper can reduce vibration and eliminate oil whip of rotor-bearing system significantly.

Yan et al. [44] and they proposed a negative resistance electromagnetic shunt damping vibration isolator. The effectiveness of the isolator has also been investigated. To cancel the inherent resistance of the electromagnet, a kind of negative resistance shunt impedance were proposed in this research. The results show that the suppression of vibration transmitted to the structure could be effectively possible with the negative resistance electromagnetic shunt damping vibration isolator.
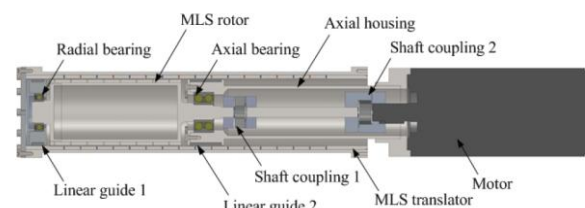

Figure 12: Magnetic Lead Screw V1.5 design

Finally, the most modern research is done by Berg et al. [45]. The author presented a novel Magnetic Lead Screw

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(MLS) design for active suspension system (Figure 12 [45]). This would facilitate active control of vehicle body movement and possible regeneration of the energy dispatched in the suspension system. This is actually remodeling of the MLS v1.0 which includes a new axial housing for the axial bearing. It will help to absorb any bending moment and counteracting axial force. Through the helically shaped magnets, the system transforms a low speed high force linear motion of a translator into a high speed low torque rotational motion of a rotor. Through a mechanical FEM model developed and solved in Ansys, it has been proven that von misses stress in the shaft connecting the rotor of the servo motor with the systems' rotor reduced significantly. The new MLS v1.5 design includes two new flexible couplings which permit some misalignment between the servo motor housing and the MLS rotor and this grants the system more flexibility.

7. Conclusion

Dampers have been studied over the history of automotive technology from simple friction dampers to modern electromagnetic dampers. An extensive literature review has been done in this paper on both academic research and industrial advancement of vehicle. Different commercial damper technologies such as passive, semi-active, active as well eddy current, hybrid and electro-magnetic dampers are introduced and the corresponding literature is reviewed in this article. 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.

References

[1] J. Dixon, "The Shock Absorber Handbook, Society of Automotive Engineers," *Inc., Warrendale, PA,* 1999.

[2] S. B. A. Kashem, M. Ektesabi, and R. Nagarajah, "Comparison between different sets of suspension parameters and introduction of new modified skyhook control strategy incorporating varying road condition," *Vehicle System Dynamics,* vol. 50, pp. 1173-1190, 2012.

[3] S. B. A. Kashem, S. Roy, and R. Mukharjee, "A modified skyhook control system (SKDT) to improve suspension control strategy of vehicles," in *Proceedings of IEEE 2014, International Conference on Informatics, Electronics & Vision (ICIEV), 2014,* 2014, pp. 1-8.

[4] E. K. Hagela K. H., Mettner M., Panther M., Tran Q. N., Rubel E., "Continuously adjustable shock absorbers for rapid acting ride control systems," *Proceedings of SAE 18th FISITA Congress,* pp. 37-46., 1990.

[5] E. Weaver, "Measure of shock absorber performance," *Automotive Industry,* pp. 870-972, 1929.

[6] W. James and F. Ullery, "An automatic shock-absorber," Society of Automotive Engineers, 400 Commonwealth Dr, Warrendale, PA, 15096, USA1932.

[7] N. Eslaminasab, M. Biglarbegian, W. W. Melek, and M. F. Golnaraghi, "A neural network based fuzzy control approach to improve ride comfort and road handling of heavy vehicles using semi-active dampers,"

International Journal of Heavy Vehicle Systems, vol. 14, pp. 135-157, 2007.

[8] web1, "http://www.tein.co.jp/e/special/ni_toryu/tigai.html," April, 2012.

[9] T. Gillespie, "Development of semi-active damper for heavy off-road military vehicles," 2006.

[10] web2, "http://en.wikipedia.org/wiki/File:Solenoid_Valve.png," March, 2012.

[11] L. Haibo and Y. Jianwei, "Study on semi-active suspension system simulation based on magnetorheological damper," 2009, pp. 936-939.

[12] A. B. Flatau and K. P. Chong, "Dynamic smart material and structural systems," *Engineering Structures,* vol. 24, pp. 261-270, 2002.

[13] H. Hu, X. Jiang, J. Wang, and Y. Li, "Design, modeling, and controlling of a large-scale magnetorheological shock absorber under high impact load," *Journal of Intelligent Material Systems and Structures,* 2012.

[14] H. Wiederick, N. Gauthier, D. Campbell, and P. Rochon, "Magnetic braking: Simple theory and experiment," *American journal of physics,* vol. 55, pp. 500-503, 1987.

[15] M. A. Heald, "Magnetic braking: Improved theory," *American journal of physics,* vol. 56, pp. 521-522, 1988.

[16] L. H. Cadwell, "Magnetic damping: Analysis of an eddy current brake using an airtrack," *American journal of physics,* vol. 64, pp. 917-922, 1996.

[17] H. A. Sodano, J. S. Bae, D. J. Inman, and W. Keith Belvin, "Concept and model of eddy current damper for vibration suppression of a beam," *Journal of Sound and Vibration,* vol. 288, pp. 1177-1196, 2005.

[18] J. S. Bae, M. K. Kwak, and D. J. Inman, "Vibration suppression of a cantilever beam using eddy current damper," *Journal of Sound and Vibration,* vol. 284, pp. 805-824, 2005.

[19] H. A. Sodano, J. S. Bae, D. J. Inman, and W. K. Belvin, "Improved concept and model of eddy current damper," *Journal of vibration and acoustics,* vol. 128, p. 294, 2006.

[20] H. Teshima, M. Tanaka, K. Miyamoto, K. Nohguchi, and K. Hinata, "Effect of eddy current dampers on the vibrational properties in superconducting levitation using melt-processed YBaCuO bulk superconductors," *Physica C: Superconductivity,* vol. 274, pp. 17-23, 1997.

[21] C. Elbuken, M. Khamesee, and M. Yavuz, "Eddy current damping for magnetic levitation: downscaling from macro-to micro-levitation," *Journal of Physics D: Applied Physics,* vol. 39, p. 3932, 2006.

[22] K. E. Graves, D. Toncich, and P. Iovenitti, "Theoretical comparison of motional and transformer EMF device damping efficiency," *Journal of Sound and Vibration,* vol. 233, pp. 441-453, 2000.

[23] G. Genta, C. Delprete, A. Tonoli, E. Rava, and L. Mazzocchetti, "Analytical and experimental investigation of a magnetic radial passive damper," in *Proceedings of the Third International Symposium of Magnetic Bearings* Washington D.C., July 1992, pp. 255-264.

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[24] A. Tonoli, "Dynamic characteristics of eddy current dampers and couplers," *Journal of Sound and Vibration,* vol. 301, pp. 576-591, 2007.

[25] M. Schmid and P. Varga, "Analysis of vibration-isolating systems for scanning tunneling microscopes," *Ultramicroscopy,* vol. 42, pp. 1610-1615, 1992.

[26] Y. Suda and T. Shiiba, "A new hybrid suspension system with active control and energy regeneration," *Vehicle System Dynamics,* vol. 25, pp. 641-654, 1996.

[27] L. Segel and L. Xiao-Pei, "Vehicular resistance to motion as influenced by road roughness and highway alignment," *Australian road research,* vol. 12, 1982.

[28] G. R. Wendel and G. L. Stecklein, "A regenerative active suspension system," Society of Automotive Engineers, 400 Commonwealth Dr, Warrendale, PA, 15096, USA1991.

[29] D. Karnopp, "Permanent Magnet Linear Motors Used as Variable Mechanical Dampers for Vehicle Suspensions," *Vehicle System Dynamics: International Journal of Vehicle Mechanics and Mobility,* vol. 18, pp. 187 - 200, 1989.

[30] B. V. Murty, "Electric, variable damping vehicle suspension," Google Patents, 1989.

[31] Y. Suda, T. Shiiba, K. Hio, Y. Kawamoto, T. Kondo, and H. Yamagata, "Study on electromagnetic damper for automobiles with nonlinear damping force characteristics:(Road test and theoretical analysis)," *Vehicle System Dynamics,* vol. 41, pp. 637-646, 2004.

[32] Y. Suda, S. Nakadai, and K. Nakano, "Study on the self-powered active vibration control," *ratio,* vol. 10, p. 9, 1998.

[33] H. B. Arsem, "Electric shock absorber," Google Patents, 1971.

[34] "Faulhaber DC MOTOR Technical information, Faulhaber DC motor specs, Germany," 2011.

[35] A. Kruczek, A. StÅ™ÃbrskÃ½, J. HoncÅ¯, and M. HlinovskÃ½, "Active suspension - Case study on robust control," *World Academy of Science, Engineering and Technology,* vol. 78, pp. 411-416, 2011.

[36] web5, "http://www.gizmag.com/go/3259," April, 2012.

[37] J. A. Konotchick, "Linear motion electric power generator," Google Patents, 1994.

[38] T. D. Merritt and M. J. Pasichinskyj, "Linear reciprocating electrical generator," Google Patents, 1985.

[39] R. B. Goldner and P. Zerigian, "Electromagnetic linear generator and shock absorber," Google Patents, 2005.

[40] J. Kendall, "Michelin re-invents the wheel," *Automotive Engineering International, SAE,* p. 35, 2008.

[41] A. Gupta, J. Jendrzejczyk, T. Mulcahy, and J. Hull, "Design of electromagnetic shock absorbers," *International Journal of Mechanics and Materials in Design,* vol. 3, pp. 285-291, 2006.

[42] J. A. Allen, "Design of active suspension control based upon use of tubular linear motor and quarter-car model," Texas A&M University, 2008.

[43] S. L. Liu and S. Y. Zheng, "Improved passive electromagnetic damper and its application," *Journal of Vibration and Shock,* vol. 30, pp. 94-97, 2011.

[44] B. Yan, X. Zhang, and H. Niu, "Design and test of a novel isolator with negative resistance electromagnetic shunt damping," *Smart Materials and Structures,* vol. 21, p. 035003, 2012.

[45] N. I. Berg, R. K. Holm, and P. O. Rasmussen, "A novel magnetic lead screw active suspension system for vehicles," in *Energy Conversion Congress and Exposition (ECCE), 2014 IEEE*, 2014, pp. 3139-3146.