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A Review On Electromagnetic Suspension Systems For Passenger Vehicle

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***Abstract*—This paper discussing all the design literature review for electromagnetic suspension systems for passenger vehicle. Electromagnetic suspension is the alternative for existing conventional suspension system that uses passive suspension system. Generally, linear motor is used in the design of the suspension. This is due to the behavior of the motor that can exert linear force directly to the attached load. In addition, the linear force from linear motor is controllable. This paperreview with the effects of all types of electromagnetic suspension systems to the passenger`s comfort. The reliability of fully active suspension system for vehicle also highlighted in this paper.A quarter-car model is used to assess the vehicle body vibration. This paper also deals with regenerative properties of linear motor that can improve the performance of lightweight vehicle.**

Keywords—Electromagnetic suspension system, tubular linear motor, quarter-car-model.

I. INTRODUCTION

At present, most of the cars are using a passive hydraulic suspension. One of the main features of hydraulic suspension is it uses hydraulic oil as a damper. Whenever a vehicle traverses road irregularities, the excitation force from road surface is absorbed by the damper. The absorbed energy is converted into heat inside the damper. The vehicle body weight is supported by the mechanical spring attached with the damper. However, there are some disadvantages of hydraulic system. According to Gysen[1], hydraulic damper contributes to environmental pollution due to hose leaks and ruptures, where hydraulic fluids are toxic. Then, the hydraulic systems are considered inefficient due to the required continuously pressurized system. On the contrary, electromagnetic suspension systems (EMS) not require hydraulic fluid. It consists of sets of permanent magnet and series of current coil. Each of them can either act as translator or static armature. The interaction between permanent magnet flux and voltage-supplied armature winding will cause movement or thrust on the translator. Tubular linear motor is suitable in designing electromagnetic suspension system due to it have a relatively high force density that can control the vehicle body vibration same as hydraulic damper [2]. Several researches have been conducted to study the performance of tubular linear motor. Wang et al.[3] has provided a detailed analysis on tubular linear permanent magnet machines. In their paper, theanalytical method is used to establish the magnetic field distribution inside the machine, and the results are verified by using finite element analysis. They also state that predicting the magnetic field distribution by using analytical method is more efficient compared to by using equivalent circuit method. This is due to the problems associated with model inaccuracy, particularly when flux leakage is significant and the flux paths are complex. Analytical solution is done by using cylindrical coordinate system. The analytical method is done on various topologies of linear machine i.eHalbach, axial and radial magnetization pattern, air-cored and iron-cored armature. Parameters like thrust force and magnetic field density are calculated by using analytical solution and then compared with finite element analysis, whereas coil inductance and armature reaction field are calculated by using analytical solution only. The difference between analytical solution and finite element solution are small as expected. Bianchi et al.[4]have studied the comparison between all the configurations of tubular linear motor. Various configurations of linear motor such as buried and surface permanent magnet inside the rotor, air-cored and iron-cored armature, and moving armature or rotor.Analytical solutions is used by them to compare the performance of all the configurations. Linear motor parameters such as magnetic flux density, electrical and thermal conditions, thrust force, and force density were generated for all the linear motor configurations. The result is then compared with finite element method and both of them were in agreement. However, the reliability of linear motor as suspension systems is limited by existence of cogging force inside the motor. Paulides et al.[5] stated that cogging force in linear motor will effect the performance of it by reducing its speed control accuracy and smoothness of linear movement. They also characterized the cogging force inside the motor by using finite element analysis and the managed to generate the relationships between cogging force and pole pitch. The controllable force in linear motor allows researchers [6-10] to apply it into vehicle suspension system in which it is called an EMS.

Linear motor can work on generator mode by converting the motion energy from translator into electrical energy[1]. In electromagnetic suspension system, the regenerative property of linear generator can dampen the translator`s oscillation by absorbing the kinetic energy that results from road excitation , same as the hydraulic suspension except thatthis energy is then supplied into storage system to be used by other loads in the vehicle [11].

Due to adjustable parameters in linear motor, the electromagnetic suspension system can be categorizedinto three, namely :

- Passive EMS
- Semi-Active EMS
- Active EMS.

In addition, the regenerative behavior of EMS is also studied due to the importance of that behavior in fuel economy and battery efficiency especially in hybrid car or in full electric car.

II. PASSIVE EMS

Generally, passive suspension systems consists of all purely passive elements i.e passive mechanical spring and passive damper that totally not rely on external environment to tune up their characteristics. In case of electromagnetic suspension system, passive mechanical spring and linear synchronous generator is used as proposed by Paz [12]. In his paper, the linear generator acts as a damper by absorbing the kinetic energy that results from road excitation and convert it into electrical energy in which it is called electromotive force (emf). The magnetic flux from Neodymium(Nd)-Iron(Fe)-Boron(B) magnets will interact with passive armature winding to generate electrical energy to be stored in energy accumulator. The lumped equivalent circuit is used by Paz to determine the suitable parameters in EMS including coil inductance, coil resistance, and electromotive force. Paz also generate the relationship between linear speed of moving translator to the generatedemf and both of the parameters are linearly dependent.

Another research on purelypassive EMSthat applicable in lightweight vehicle is conducted by Gupta et al [13]. In their paper, they have developed a novel configuration of linear generator that absorbs kinetic energy from road vibrationand convert it into electromotive force (emf), thus dampen the oscillation of the permanent magnet translator. they also stated that the amount of voltage generated from linear generator, V is:

$$V = nhvB_i \text{..........................(1)}$$

Where n is the number of turns of the conductor coil, h is the effective height of pole ring, v is the linear velocity of the permanent magnet translator and B_i is magnetic flux from the permanent magnet assembly.

The damping force generated inside the linear generator, F as stated by them is:

$$F = ILB_i \text{............................(2)}$$

Where $I$is the generated current inside the coil, L is the length of the coils and B_i is the magnetic flux from permanent magnet assembly.

The amount of damping force generated depending on the amount of current generated. Thus, when the electromagnetic suspension is connected with external resistor R_L, and with coil resistance of R_c, the damping force can be modified into:

$$F = \frac{K^2 v}{R_L + R_c} \text{.............................(3)}$$

The designed electromagnetic suspension is then tested with all-terrain vehicle (ATV) and the output response of electromagnetic suspension is recorded.

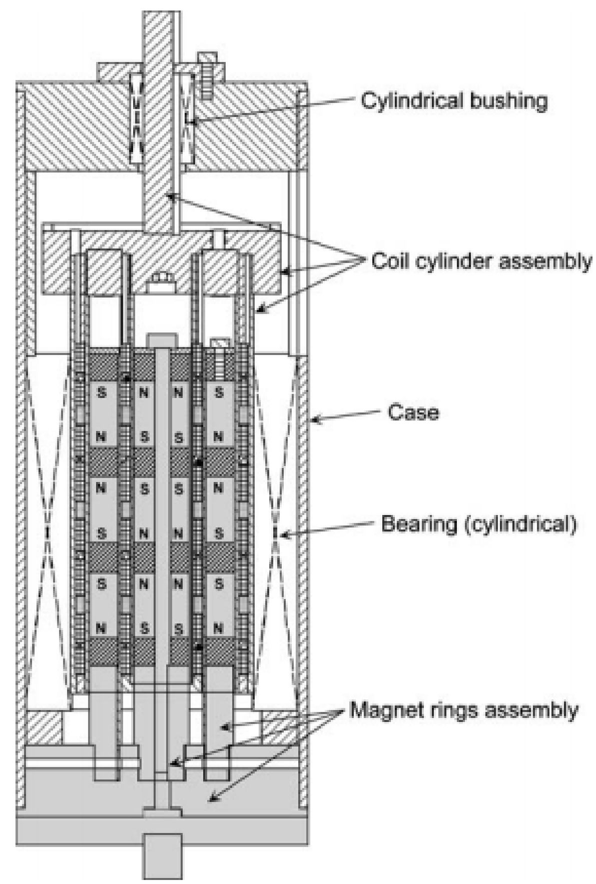

Fig. 1.Passive EMS proposed by Gupta[13]

Ebrahimi et al. [14] proposed a novel passive EMS that use eddy current concept. In the paper, the passive EMS consists of permanent magnets with iron pole that act as a translator and a hollow cylinder conductor as the stator. The relative movement between the permanent magnets and the conductor generates eddy current inside the conductor. This eddy current have the direction that opposes the movement direction of permanent magnets thus act as an oscillation damper. Analytical method is used to calculate damping force, and magnetic flux density inside the suspension. The performance of eddy current damper is then compared with other commercialized dampers and as a result, the eddy current suspension performance is slightly better in terms of vibration control than other commercialized dampers that using magnetorheological (MR) fluids and passive hydraulic dampers.

However, passive EMS cannot totally isolate the vehicle body from vibration. This is due to their passive properties in which the damping force produced is low, can operate on limited bandwidth [1] and have fixed parameters [15]. Thus, an active system is required to overcome all the disadvantages possessed by the passive EMS as will discussed on the next section.

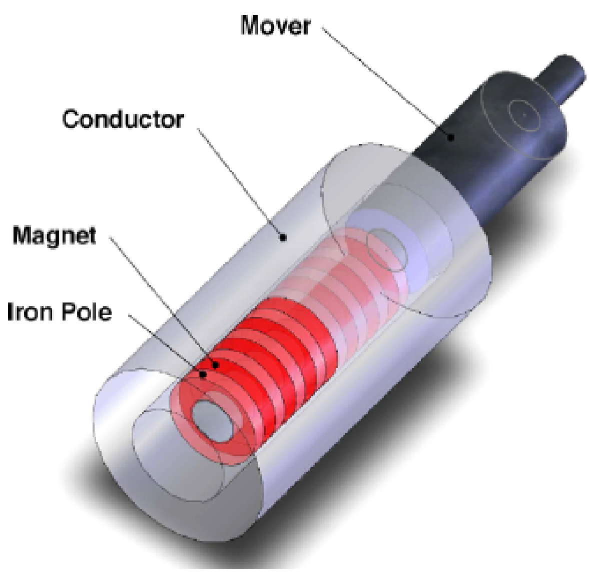

Fig. 2. Passive EMS proposed by Ebrahimi[15]

III. SEMI-ACTIVEEMS

Semi-active EMS combines the advantages of passive and fully active suspension system. It consists of both passive and active element. Paulides [20] provided the comparison of various design of linear actuator to be applied as semi-active suspension system. As a result, the brushless permanent magnet (PM) actuator is a viable choice for a semi-active suspension system.

Mirzaei [15] proposed a novel tubular induction machine as semi-active EMS. In his design, no permanent magnets are used, only windings on both translator and stator. The translator coil is connected with external direct-current (DC) source in which the generated magnetic flux density can be controlled by tuning the amount of DC current supplied. The passive winding at the stator act as a damper by damping the oscillation of translator. The damping force generated is related with the linear velocity of translator and the magnetic flux density generated by translator coil. The translator is then immersed in the hydraulic fluid that act as secondary damper. An experiment is conducted by him and it shows that the performance of the semi-active EMS is similar to tubular linear machine that uses permanent magnet as flux source.

Magnetorheological (MR) and electrorheological (ER) damper is currently used in semi-active suspension system [21-23]. Unfortunately, only MR damper is widely used because MR damper shows a greater increase in viscosity compared to ER damper when external current is applied [24]. Yao et al. [24] conducted an experiment by using MR damper in semi-active suspension system. The result of the experiment shows that the viscosity of MR damper is directly proportional to current applied to it, thus making the damping force controllable. However, when the amount of current reaches certain value (in this case, exceed 0.75A), the increase of the damping force is no longer significant and the MR damper has reach the saturation level.

IV. FULLY ACTIVE EMS

Unlike passive system, fully active EMS is a system that totally relies on external environment i.e control system to control all the critical parameters such as thrust force, and damping force. Fully active EMS can completely eliminate the vibration on vehicle body but consume a lot of power to supply the control system and the EMS itself [16]. Several researches has been done to investigate the availability of fully active suspension system for lightweight vehicle.

Yahaya et al. [17] proposed the active suspension system by using the concept of linear-quadratic (LQ) control. The analytical solution is used to design the suspension controller and the result is then simulated inside Matlab. As a result, they discovered that active EMS gives a better performance in terms of comfort ride compared to the passive suspension.

Yoshimura et al. [18] have constructed an active EMS by using the concept of sliding mode control. According to him, the sliding mode control is much more better than LQ control concept and passive suspension system. Analytical solution is used in his paper to design the suspension system. As a result, the active suspension system by using sliding mode control is much more better than active suspension that using LQ control concept and passive suspension system in terms of vibration isolation.

Gysen et al. [1] studied the availability of linear motor in active EMS. In their paper, they state that the thrust force can be generated actively by supplying the external voltage inside the armature winding. The active armature is then interacts with permanent magnet translator thus causing linear movement. They also stated that the linear motor also can works as a generator by absorbing the vibration energy to be converted into electrical energy thus increasing the vibration isolation. The performance of proposed active suspension system is compared with passive suspension system and the results shows that the active suspension system is slightly better than the passive system in terms of vibration isolation. The topologies of linear motor can affect the performance of electromagnetic suspension system [2]. Gysen et al. evaluate finite element and analytical method is used to evaluate the performance of various topologies of linear motor (Halbach, radial and axial magnetization pattern, air-cored and iron-cored winding, and translating armature or permanent magnets). As a result, the linear motor with moving permanent magnet with Halbach magnetization pattern provide the highest damping force based on the amount of voltage generated referring to formula from [13].

Lee and Kim [19] studied the applicability of direct-drive tubular linear brushless permanent-magnet motor in active suspension system. A quarter-car test is used to evaluate the performance of suspension system. The control system for active suspension system is also designed by using a mathematical model and its performance in terms of frequency response is evaluated.

V. REGENERATIVE PROPERTIES OF EMS

Besides providing the damping force to improve the passenger comfort, electromagnetic suspension also possess regenerative behavior. Electromagnetic suspension system can act as a generator by producing an alternating voltage resulted from relative movement between permanent magnet stacks and armature winding. Storage system to store the generated electrical energy can also be designed in order to support the energy requirement by other loads in the car thus reducing the power consumption especially in hybrid and fully electric car. Montazeri and Soleymani [11] investigated the energy regeneration of active suspension system in hybrid electric vehicles. The generated energy contributes to the improvement of the battery efficiency and fuel economy. The resistance-capacitance battery model and ultra-cap model are designed as a power storage system to store the energy generated by suspension system.

Okada et al. [16] proposed an energy regenerative active suspension system which applied a linear DC electromagnetic motor as the actuator. A double-voltage charging circuit was used to regenerate electrical energy during high speed motion of the actuator.

Martins et al. [25] produced a prototype of permanent magnet linear actuator and studied the dynamic performances of the actuator in low and high frequency excitation. The experimental results showed the agreement of the simulation results. However, the weight and dimensions values were too large and needed to be reduced further.

VI. CONCLUSION

The development of all types of electromagnetic suspension and its regeneration properties are reviewed in this paper. For passive electromagnetic suspension, it not require external control system to adjust the damping coefficient to maintain passenger comfort and stability. Generally the damping force is directly linear with relative velocity between sprung mass (car body) and sprung mass (car tyre). Therefore, the power consumption for passive electromagnetic suspension system is far very low compared to semi-active and fully active electromagnetic suspension system. Unfortunately, in terms of force density, passive electromagnetic suspension is the lowest of all, thus passive EMS alone is not enough to provide desired comfort for passenger. Semi active suspension system contains both the fully active and passive elements thus making it more reliable from passive EMS but slightly bad than active EMS due to its passive properties.MR damper is used recently in semi-active EMS. But several researches have proposed a fluidless version of semi-active EMS to be applied in lightweight vehicle. Active suspension system uses external control system to control the damping force, thus improving the passenger comfort and stability. Unfortunately, active suspension system consumes a lot of power and the structure is complex to design. However, this paper highlights the reliability of active suspension system to be applied in the lightweight vehicle. The enhanced mode for passive EMS and semi-active EMS may be can be done in future in order to make their performance on par with fully active EMS thus can be applied on lightweight vehicle. The regenerative properties of electromagnetic suspension are summarized. With improvement of technology, a fully active suspension may become one of promising trends of active suspension.

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