Feasibility Study and Design of Electromagnetic Suspension Systems: A Review

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Abstract - *In this paper, we look at the feasibility and design of electromagnetic suspension systems, and propose a hybrid design for the same. Firstly, we note and compare general design features of alternative systems. Then we review multiple design systems proposed and fabricated in earlier research, covering control strategies, programming, and mechanical linkage synthesis. Finally, we combine this information to generate a design that uses both new and traditional subsystems, aimed at balancing cost and quality of the product.*

Key Words: Electromagnetic, Suspension, Design, Active, Semi-Active, QoV Model, MR Fluids, Feasibility, Automobile.

1.INTRODUCTION

Vehicular suspensions are systems that act as intermediaries between a vehicle chassis and its wheels – they ensure that ride comfort (i.e. independence of chassis and wheel movement) and smooth handling (efficient communication of motion from steering to wheels) is possible, and are thus important in the design of vehicle systems.

The two main types are as follows:

i) Passive (react to the road surface, is a simple response element)
ii) Active (sense the road surface, take an active role in stabilizing the chassis)

Passive systems are the traditional spring-based systems that reduce the amplitude and frequency of chassis oscillation by absorbing the kinetic energy of a jolted vehicle and storing it in a spring.

Such systems are simple, easy to make and install, reliable and cheap, but wear out over time, require maintenance, provide relatively low ride comfort, and bad road-handling.

In contrast, active suspensions use a combination of mechanical and electrical elements to actively sense the road surface, and actuate the wheel shaft accordingly. They are quiet, require low maintenance, can be used in heavy-duty applications, and provide far greater ride comfort and handling capability.

Two common Active suspension systems are Hydraulic and Electromagnetic based systems. The latter form the most recent systems analysed for use.

In this paper, we qualitatively review the work done by various researchers on the feasibility and usability of electromagnetic suspension systems. Based on the conclusions, we propose a concept that attempts to avoid the pitfalls of current systems, and which can be expanded upon in further research.

1.1 Brief Introduction to Terminology Used:

i) QoV – Quarter-of-Vehicle Model: A model of a 4-wheeled vehicle in which the loads and forces acting on a quarter-unit, i.e. a single wheel, are focused upon.
ii) Axiomatic Design – A methodology of system design that traces the independence between Functional Requirements of the system and the Design Parameters that form it.
iii) FEB (Frequency Estimation Based) Controller – A type of electronic processor that attempts to estimate the frequency of an input signal in order to produce responses in advance of the input
iv) LPV (Linear Parameter Varying) Controller – A controller that mathematically models systems as linear, with parameters that behave nonlinearly, in order to define the behavior of nonlinear systems
v) Skyhook Controller: A controller that attempts to implement "Skyhook" design, which refers to maintenance of vehicle posture such that it appears to be suspended from a "hook in the sky", unaffected by ground conditions.
vi) Groundhook Controller: A controller that attempts to dampen the motion of the unsprung mass by connecting it between the mass and the ground, rather than to the sky.
vii) MR (Magnetorheological) Fluid – A fluid that can vary its viscosity and its yield stress depending on the intensity of a magnetic field that is applied externally on it.

2. LITERATURE REVIEW

2.1 Analysis of Existing Systems

In the analysis of physical systems a valuable criterion for analysing the functionality of a product is the independence of the various design parameters (DPs) and the functional requirements (FPs) of the resulting design. This approach is called axiomatic design analysis, developed at MIT in the 1990s by Dr. Suh Nam Pyo.

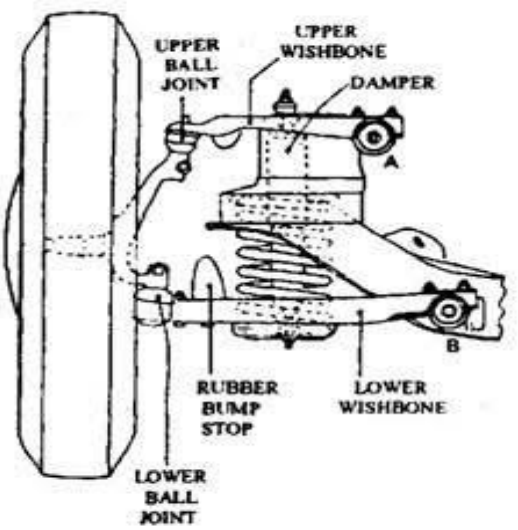

Fig -1: Double Wishbone
(Source: http://what-when-how.com/)

Using an axiomatic design analysis, Bael et al.(1), compared the McPherson Strut, Double Wishbone and Multilink suspension systems. From this analysis, they found that the most effective at isolating and allocating functional requirements is the Multilink Suspension, which we shall consider as the basis for any upcoming work.

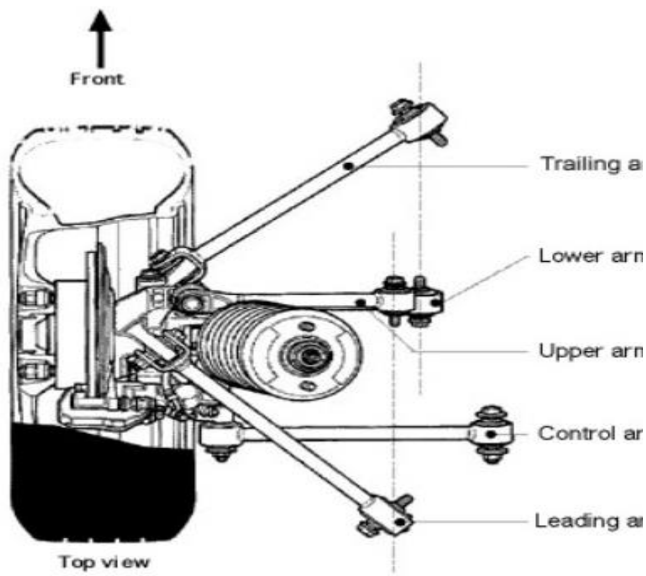

Fig -2: Multilink Suspension
(Source: http://world.honda.com/)

When quantitatively analysing a suspension system, various mathematical models can be used to approximate the behaviour of a 4-wheeled vehicle, such as (DOF = Degrees of Freedom)

i) the 1-DOF model,
ii) 2-DOF Quarter Car Model,
iii) 2-DOF Half-Car Model, and
iv) 4-DOF Half-Car Model).

Of these, the one we most commonly observed in use was the Quarter-Car Model of 2-DOF.The basic assumption in the QoV method is that each quarter of the vehicle (quarter defined as containing two spring elements, a sprung mass, an unsprung mass and a damping element) is dynamically equivalent. The basic equations that are produced on application of Newton's Laws to this system are (2):

$$m_s\ddot{z}_s = -\eta^2 F_{ks}(z) - \eta^2 F_c(z,\dot{z},\ddot{z}),$$
$$m_{us}\ddot{z}_{us} = \eta^2 F_{ks}(z) + \eta^2 F_c(z,\dot{z},\ddot{z}) - k_t(z_{us} - z_r)$$

Although this method is a vast simplification, it approximates a complete vehicle well enough to allow development of actionable design parameters. Paulides et al.(3), using this model, developed two ride comfort parameters, which are listed as follows:

i) Motion Sickness Avoidance: Frequencies of vertical oscillation around 0.2 Hz cause the most discomfort and likelihood of motion sickness; therefore, oscillations below 1 Hz (with a Factor of Safety of 5.0) must be avoided;
ii) Head Toss Avoidance: When the vehicle undergoes a rolling motion (e.g. front wheels dip suddenly as with a pot-hole), an angular acceleration is imparted to the passenger's head; at frequencies of acceleration below 2 Hz, the head moves with the body, but higher than this, and the passenger's head is thrown forward more than his body, causing discomfort and possible injury. Therefore, frequencies between 1 and 10 Hz should be minimized or damped completely.

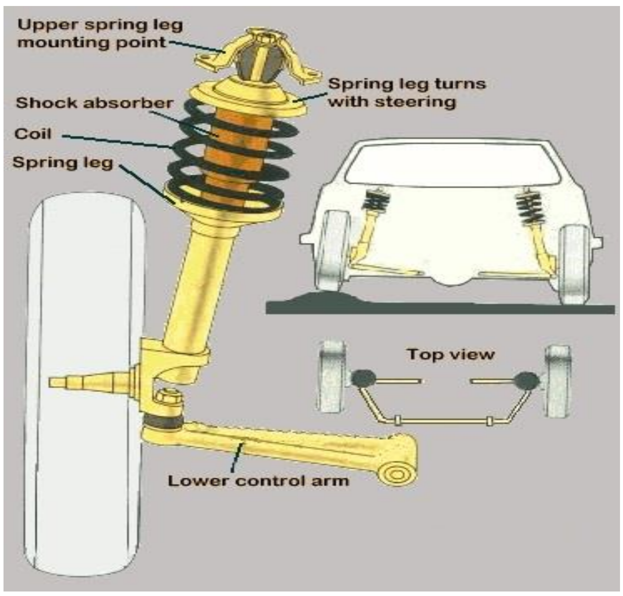

Fig -3: McPherson Strut
(Source: http://myautomobileguide.blogspot.in)

An analysis of the potential of various Electromagnetic Suspension Systems to reduce the vibrations occurring during vehicle use was done by Isa & Liza et al.(4), in which the possibility of complete elimination of vibrations using a Fully Active Suspension system was considered – however, the main disadvantage with such a system is the running cost (since continuous monitoring, feedback and actuation of suspension elements is required), the weight, and the size of the system.

2.1 Analysis of Electromagnetic Systems

In the design of electromagnetic suspension systems two main designs prevailed:

i) Utilizing an electromagnetic motor:

A suspension module is attached to each wheel with each module consisting of an electromagnetic motor-the input to this motor is provide by a centralized controller and the output of the motor is coupled to a gear box that converts the rotary motion of the motor shaft to linear motion of the wheels.

The controller detects variations in the road surface and actuates the motor such that the wheels follow the road surface while isolating this responsive motion from the motion of the chassis.

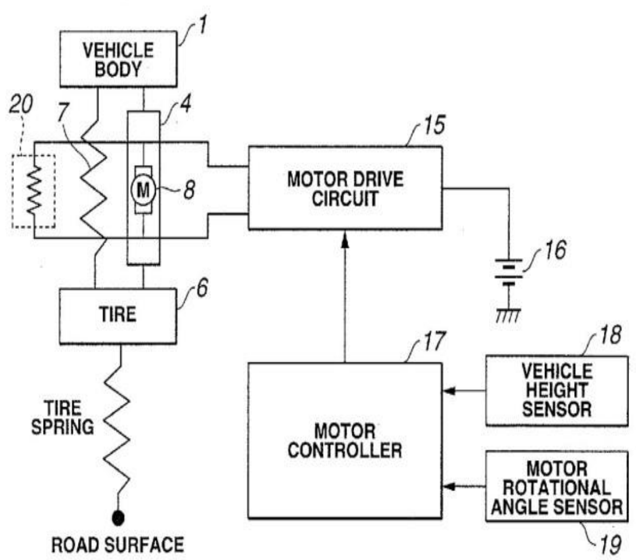

Fig - 4: Block Diagram of Motor-Based Controller (Google Patents, © Nissan Motor Company, Limited)

Bose developed a Fully Active Electromagnetic Suspension which is displayed superiority over all other forms of suspensions, and it was of this type – however, the size and weight of the gearbox, motor and chassis support elements for the same, as well as the cost of attaching such elements to each wheel rendered this suspension unfeasible for mass-market adoption.

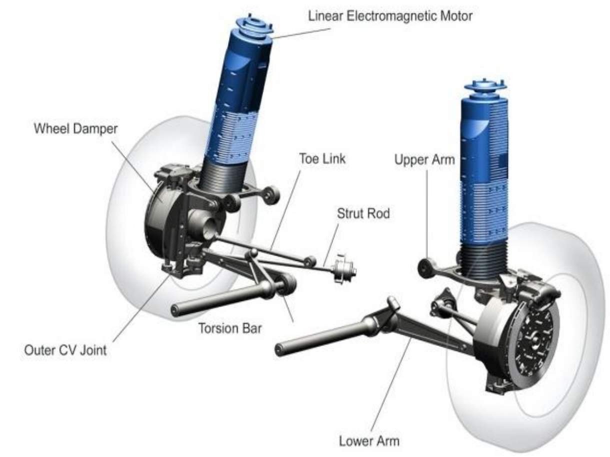

Fig - 5: Bose EM Motor-based suspension (Source: http://www.siliconeer.com/ ©Bose Corporation)

ii) Using a magnetorheological damper:

In this semi-active system, a damper containing a Magnetorheological fluid is energized by a coil which receives input from the controller in a manner similar to that described in the previous design.

Here however, the input from the controller serves to exert a magnetic field on the MR fluid, which in response becomes more or less viscous in order to provide appropriate damping to the vehicle chassis.

Recent research has begun to focus more on this area, since it provides an inexpensive and simple alternative to the costly, complex fully-active, EM Motor-based suspension system design.

From the first class of designs, a Hybrid Magnet, Easu and Siddharthan (5), and a Brushless PM Tubular Actuator, Paulides et al.(6), were analyzed for the purpose of usage in an electromagnetic system.

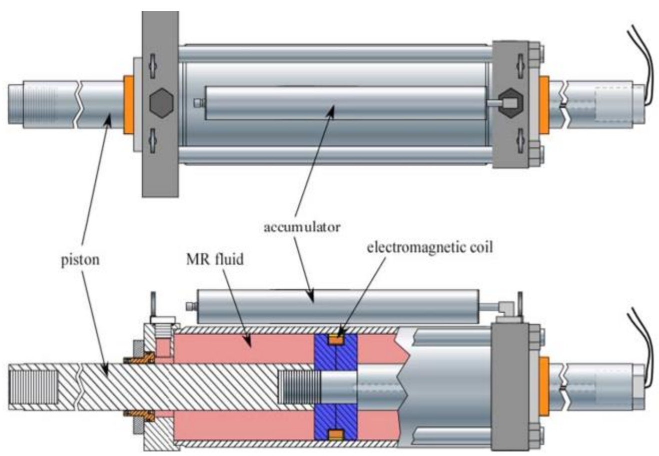

Fig - 6: Schematic of MR Fluid Dampers (Source: http://iopscience.iop.org/)

Aside from the motors utilized in this design another topic of investigation is the controller being used; Lozoya-Santos et al (2). determined that the FEB (Frequency Estimation Based) controller was more effective than the Skyhook, Groundhook and LPV (Linear Parameter Varying Control) controllers; Jansen & Lomonova et al.(7) developed a robust controller that improved ride comfort by around 41%, and Amer at al.(8) simulated Software-In-Loop and Hardware-In-Loop control, to highly positive results.

From the second class of designs, Sherje & Deshmukh (9) investigated the various factors affecting the viscosity of MR Fluids (e.g. additives, particle size, etc) and recorded the results. The complex, non-linear behavior of these fluids was also investigated using the Kwok, Li and Dahl model (among others) by Ambhore et al.(10) – the result is a comprehensive knowledge of the various parameters that can control the properties and effectiveness of MR Fluid Dampers.

Having considered all the design possibilities that have been investigated by various researchers, we began searching for practical implementations of suspension/stabilization systems using Electromagnetic devices. Such a practical model was developed by Palazollo et al.(11), for a flywheel suspension to be mounted on the ISS using stacks of laminar magnets, which held the shaft in a cavity in their centre, effectively forming non-contact bushings; similarly, Paulides et al.(12) simulated a direct-drive regenerative suspension system on a BMV 530i, Martins & Esteves et al.(13) built a linear actuator using NdFeB (Neodymium) cylindrical magnets, and tested the same. Lastly, Paulides et al.(14) observed on-road measurements with a BMV 545i in the Nürburgring racing complex and used the results they obtained from the test as the functional requirement for a Quarter of Vehicle test rig with a Brushless Tubular Permanent Magnet Actuator (as the suspension element), and compared the output of the suspension they had developed with the requirement as obtained from the ground test.

Overall, it was found that electromagnetic actuators and MR fluid damper suspensions were far more effective than traditional systems – however, considering the cost and mass constraints, we propose an alternative system that combines traditional suspension systems, with the load-bearing (deflecting) unit replaced by an electromagnetic system.

3. CONCLUSIONS

In this paper, we have reviewed the basics of suspension system design and the application of electromagnetic systems to the same. We have placed emphasis on the feasibility of electromagnetic suspension systems and proposed a new hybrid design for the same. We compared various designs and prototypes of suspension systems, various analysis methods and the uses of various controller settings in order to function accordingly.
A few immediate conclusions came through:

i) For dynamic analysis, the QoV model with 2 DOF was preferred, suggesting its viability for further design attempts;
ii) As evidenced by the Bose Suspension system, electronically controlled motor-operated suspension systems are far too expensive (due to the need for gearboxes, motors, controllers, etc) to be mass-producible without a significant advancement in the technology of the same;
iii) The use of MR fluids in dampers for such suspension systems seems to be the latest trend, with research pointing in this direction.

We propose, as a tentative solution, an MR Fluid-Damper based hybrid suspension system, based off the design of a Multilink Suspension, in which the coil is actuated by the deflection of the mechanical linkages – actuation of this coil will energize the MR Fluid and modify the damping properties as per the deflection/rate of deflection of the mechanical linkage, in order to provide additional ride comfort, and a controllable frequency response of oscillation.

To conclude, electromagnetic suspensions as envisioned by Bose were not viable for market expansion – however, with sufficient research into alternatives, the use of electromagnetic suspension systems with MR fluids as a hybrid system can become the best replacement for the traditional mechanical systems.

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