A review of energy regeneration capabilities in controllable suspension for passengers’ car

Noor H. Amer¹, Rahizar Ramli ¹*, Hazril M. Isa², Wan Nor Liza Mahadi ², Mohd. Azman Zainul Abidin³

¹ University Malaya, Advanced Computational and Applied Mechanics (ACAM) Research Group, Department of Mechanical Engineering, Malaysia
² University Malaya, Electromagnetic Radiation and Devices (EMRD) Research Group, Department of Electrical Engineering, Kuala Lumpur, Malaysia
³ Proton Professor Office, PROTON Research Department, PROTON Headquarters, Shah Alam, Malaysia

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Abstract

In the past few decades, passive suspension system has been widely used in passenger vehicle suspension system. The needs of improving ride and handling performance has fueled up significant researches into controllable suspension which provide variable damping and controllable force to stabilize the vehicle motions. This study reviews various research outcomes carried out in the advancement of controllable suspension system and the prospect of energy regeneration within the suspension system. There have been numerous studies being conducted on controllable suspension and most of them were proven to improve ride and handling performance of a vehicle. Nonetheless, it requires the use of external energy to power-up the suspension system. To overcome this, energy regeneration concept has been introduced to supply additional power within the suspension system by harvesting energy from road surface excitations. In realizing this concept, a suitable control scheme should be developed. The review will cover the design aspect of energy regenerating controllable suspension and the development of its control strategy. It is intended for future prospect of developing a new electromagnetic suspension with energy regeneration capability.

Keywords: Active suspension; Semi-active suspension; Control strategy; Energy harvester; Energy regeneration; Electromagnetic suspension

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*Corresponding author: Tel.: +603-7967-7623; fax: +603-7967-5317.
E-mail address: rahizar@um.edu.my (R. Ramli).
1. Introduction

Suspension system improves passengers comfort in vehicle and minimizes the damage of vehicle components caused by road irregularities. In the past few decades, suspension system for passenger vehicles has been dominated by the conventional passive suspension. As shown in Fig. 1, they can be modeled by a spring and damper in parallel; both with stiffness and damping coefficients $k_1$ and $c_1$, connecting the wheels (unsprung mass with coefficients $k_2$ and $c_2$) and the vehicle body (sprung mass). While its simplicity and cost effective features has been proven beneficial, it can only provide limited damping and stiffness to the vehicle during maneuvers on irregular road surfaces. Thanks to the increasing availability of supercomputers and fast processors, controllable suspensions have been widely studied in the past few decades to provide variable damping and forces to cater to these needs [1-6]. These systems can be categorized into two main types; semi active and active suspension systems.

![Conventional passive “Quarter-car” suspension model.](image)

Fig. 1. Conventional passive “Quarter-car” suspension model.

Active suspension system has been studied since 1930s [7]. It consists of an actuator (usually hydraulic, pneumatic or electromechanics) to produce force in the suspension system to control the motion of the sprung mass and relative velocity between sprung and unsprung mass. Studies related to this system can be found in [5, 8-13] and it has been successfully implemented into actual production cars by several car manufacturers [14, 15]. However, few drawbacks have been observed mainly due to its high cost and large power consumption. This leads to the concept of semi-active suspension proposed by Karnopp et al [16] which provides more economical, lower power requirement and simpler control algorithm. The main difference between the semi-active and the active suspension is that semi-active suspension does not exert additional force. In other words, while active suspension can dissipate and generate energy within the system, semi-active can only dissipate energy. Instead of having an actuator as in active system, semi active system consists of a controllable damper that will offer variable damping which provide better solution than passive systems. Variable damping is achieved by varying resistant to fluid flow in the damper by controlling valves opening or smart fluids (electrorheological and magnetorheological fluids).

In a typical passengers’ vehicle, most of the energy generated by the powertrain will be dissipated during braking, through internal friction within vehicle components and aerodynamic drag during normal cruising. Approximately, only 10% of the generated energy was used efficiently to power up the vehicle. In a typical suspension system, energy from external
excitations mainly caused by the road surfaced usually absorbed by the damper. This energy is converted into heat energy within the damper fluid and dissipated to the surrounding. A lot of efforts have been made to harvest this energy from the suspension and supply it to the main powertrain for additional power supply and improved efficiency. Moreover, active suspension system has been claimed to require high power supply to operate [16]. The regenerated energy can be supplied to power up the suspension system itself. The contribution might be small but with proper energy management and suitable control strategy, the accumulated energy can be significant and useful.

This study reviews the efforts done by various researches in improving the performance of vehicle suspension. In Section II, we will discuss various mechanisms used in previous studies on controllable suspension systems. This is followed by the review of emerging technologies of employing electromagnetic suspension (EMS) and its benefits in realizing the energy harvester concept. The next section will focus on examining various control strategies implemented in controllable suspension systems. In section 5, several control strategies used in energy regeneration also critically reviewed.

2. Suspension mechanism

The choice of suspension mechanism is crucial before determining the control strategies to be implemented. Mechanism of suspension will govern the delivery process of suspension forces to the vehicle. This section will review various mechanisms usually employed in suspension unit to provide damping and vibration isolation required by the vehicle system. The most common suspension mechanisms are continuously variable damper, magnetorheological (MR) damper, electrorheological (ER) damper, and electromagnetic actuator.

Generally, suspension systems for vehicle consist of spring and damper. They are used to isolate the vehicle body from road disturbance and roll and pitch effect. Common type of damper used is hydraulic damper because it is cheap and reliable [17]. Hydraulic dampers are also easy to design, have high force density, and its parts are easy to find [18, 19]. However, due to constant damping coefficient possessed by hydraulic damper, it has very low bandwidth that is, it is only efficient in compensating low-frequency disturbances i.e roll and pitch of the vehicle. This is proven by Gysen et al.[18] when anti-roll bar comprising of hydraulic actuator was successfully prevented the roll and pitch movement of the car. Hydraulic damper do not successfully eliminate the high-frequency disturbance i.e. disturbance due to road irregularities when the vehicle transverse on a straight path [18]. So, the need of controllable damping force (semi-active and active system) in suspension system is crucial since it can operate in wider bandwidth compared to hydraulic damper. Generally, the main disadvantages of the hydraulic system are:

- Considered inefficient due to the required continuously pressurized system.
- Relatively high system time constant (pressure loss and flexible loss).
- Environmental pollution due to hose leaks and ruptures, where hydraulic fluids are toxic.
- Mass and intractable space requirements of the total system including supply system albeit that it mainly contributes to the sprung mass.

To overcome the shortcoming of hydraulic damper, semi-active or active suspension system can be employed. Semi-active suspension have received significant attention in recent years because they offer the adaptability of active suspension without requiring large power sources, as reported by Martins et al.[17] and Spencer Jr. et al.[20]. Semi-active suspension system for vehicle was proposed in the early 1970s, which exhibit satisfactory performance compared to the
fully active system in improving ride quality [21]. One of the early controllable suspension system has been introduced by Avner in his patent in 1967 [22]. In his patent, variable damping force was achieved by adjusting the orifice area in the oil-filled damper, thus changing the resistance to fluid flow; however, since the design was utilizing a mechanical motion of valve adjusting, the change of speed was expectedly slower. In 1988, Redfield and Karnopp [23] analyzed active suspension performance sensitivity as a function of the system feedback gains on a two degree-of-freedom vehicle model. Studies focusing on effects of active suspension system on vehicle dynamics has been conducted by Rajamani and Hendrick [24], Fialho and Balas [25], and Young Man and Rajamani [26]. However, these researches were focusing on the theoretical aspects with ideal condition assumptions without considering practical part.

In 1947, Winslow [27] discovered the potential of controllable fluids when he published the first electrorheological (ER) fluid patent and paper describing the ER effect. With this technology, the usage of ER and magnetorheological fluids (MR) in suspension system was introduced. The applicability of the controllable fluids in vehicle suspension system has been explored throughout decades in various publications In 1992, Hare [28] produced a patent on using ER damper for motor vehicle suspension system. Choi et al. [29] uses 7 degrees-of-freedom full-car model to investigate the performance of suspension system with ER damper. Wu et al. [30] investigated various control strategies for suspension system with an ER damper using computer simulation techniques as well as experimental set-up. As for MR damper, the development of MR material was initiated by Rabinow in 1940s at the US National Bureau of Standards [31]. Its application in vehicle suspension system was investigated by Yao [21] and Du [32]. In 1995 and 1996, further studies on behavior of MR material has been done by Jolly et al. [33] and Carlson et al. [34]. Both fluids have the same mode of operation. Polarizable particles were added inside the fluids so that they could transform into chain-like fibrous structures in the presence of a high electric/magnetic field. When the electric field/magnetic field strength reaches a certain value, the suspension will solidify with a high yield stress. This will increase its resistive force and thus increasing its damping capability. Conversely, the suspension can be liquefied and return to its original liquid state by removing the electric field/magnetic field [21]. Between these two fluids, MR fluid exhibits a much superior yield strength value i.e. around 100 kPa compared to their electrical counterparts i.e. only around 5 kPa thus making MR damper the first choice for semi-active vibration control [21, 33, 34].

In 2001, Mirzaei et al. [35] proposed the idea of using tubular linear induction motor (TLIM) in suspension system. The damping force is generated by linear actuator by interaction of magnetic field by permanent magnet (or electromagnet) with current-carrying conductors. Unlike previous mechanisms, linear actuator does not rely on any fluid to provide damping or auxiliary forces thus eliminating any leaking problem that can be hazardous in day-to-day operations. Based from Mirzaei’s study, The TLIM damping force is controlled by external direct-current (DC) source and it’s in parallel with hydraulic oil and spring, just in case of power failure of linear motor. In 2006, Paulides et al. [36] and Cech [37] proposed a series connection between linear actuator and spring to eliminate low-bandwidth disturbance and parallel connection to eliminate high-frequency disturbance. In reference to Gysen et al. [38], linear actuator can operate in wider bandwidth compared to hydraulic actuator, thus eliminating both low frequency disturbance (roll and pitch) and high frequency disturbance (potholes and bumpy road).

In 2010, Gysen et al. [18, 38] investigated in detail the applications of linear electromagnetic motor in vehicle suspension system. The experiment was done by installing the linear
electromagnetic actuator (LEA) in parallel with a spring on a BMW car and the performance is compared to hydraulic system. As a result, the linear actuator have isolated the road disturbance and maintaining the road-tire connection more efficiently compared to hydraulic system. However, the active force generated is not large enough to actively control the vehicle body acceleration. Therefore, an alternative design of linear actuator is needed. The disadvantages of using linear actuator in electromagnetic suspension system, as reported by Gysen et al. [18] are:

- Increased volume of the suspension.
- Relatively high current for 12-14V system.
- Conventional designs need excitation to provide continuous force.

Bose Corp. [39] came out with an idea to implement linear electromagnetic actuator that acts independently in vehicle suspension system, replacing hydraulic fluid and spring. The technology is based on the basic principles of speaker technology. However, the design details is kept secret by this company thus no further information can be obtained. Wang [40], Kou [41] and Bianchi [42] have predicted the performance of linear actuator that suitable for vehicle suspension system. However, the studies were conducted with various ideal assumptions that may not be possibly realized in the real world.

In this section, the various types of electromagnetic suspension systems have been reviewed. The hydraulic damper, adjustable valve inside the damper cylinder, MR and ER fluid and linear actuator has been studied in detail. Based on the researches, the usage of linear actuator in vehicle suspension system offers most advantages due to its controllable thrust force, possession of high force density, and the ability to act as an energy harvester by converting kinetic (vibration) energy to electrical energy either to be stored for future use, or fed back into the actuator. The energy harvesting properties of linear actuator will be described in the next section. The reaction time of linear actuator to produce damping force (or thrust force) is shorter than hydraulic actuator due to fluid properties thus making suspension system using linear actuator yields better time response. However, due to high cost, high volume, and complexity, linear actuator is not widely used in conventional cars. Therefore, further research on minimizing the cost, volume and complexity will be addressed.

3. EMS as energy harvester

Possibilities on employing linear actuator in electromagnetic suspension system as energy harvester in automotive sector were rarely studied. This may be caused by the advanced technology in hybrid vehicle that is sufficient enough to curb the fuel consumption problem. However, linear motor has been used widely in other sectors that involve energy regeneration such as harvesting wave energy from sea [43], [44]. In automotive sector, besides providing better driving quality, linear motor (or linear generator) also used to generate electrical energy from vehicle body vibration. The vibration energy is converted into electrical energy by means of magnetic induction. One of the studies was conducted by Okada and Harada[45]. In their research, they have replaced the hydraulic damper with linear generator in quarter-car model. They have synthesized some formula representing the frequency response of the system before doing the simulation to obtain the regenerated energy. They concluded that energy harvesting only possible when linear generator is moving with high frequency. For low frequency, the energy produced by linear generator is zero i.e. the linear generator is unable to regenerate energy.
Montazeri and Soleymani [46] have conducted another research on energy harvesting using EMS. They investigated the idea of the energy regeneration in active suspension unit in hybrid electric vehicles. An ultra capacitor (UC) has been introduced as energy storage device due to its specific power and the ability to tolerate the frequent charging and discharging without the risk of increasing internal heat and resistance, thus suitable for storing the harvested energy. The study also investigated the relationship between active suspension and fuel consumption in which, through simulation and experiment, hybrid electric vehicles with regenerative active suspension consumes less fuel compared to hybrid electric vehicles with non-regenerative active suspension but higher compared to hybrid electric vehicle without active suspension system. Hsu [47] investigated the relationship between linear actuator performance and power recovery in vehicle electromagnetic suspension system.

Martins et al. [17] proposed a combination of active and passive electromagnetic suspension system for vehicle. The simulation was performed by applying disturbance signal (emulating the road irregularities) to the quarter-car model to observe the force and power response. As a result, they have obtained a sinusoidal instantaneous power generated by each suspension on the vehicle. A pure passive electromagnetic suspension system has been designed by Paz [48]. In the research, linear generator was designed to be implemented on the vehicle suspension system to generate energy due to road disturbance. However, the calculated parameters were validated through simulation only with no experimental set-up being carried out. Without experimental data, the design can be considered incomplete. Furthermore, in the simulation, many parameters were assumed to be ideal whereas in experimental aspect, this is not the case and most of the parameters are depending to the environment conditions.

4. Control strategies in controllable suspension

One of the main challenges in controllable suspension is to choose the most suitable control strategy for the system. This section will review the implementation of several control strategies in the design of active and semi-active suspension over the years based on the linearity of suspension/vehicle model of the system to be controlled.

Any system is linear when the input and output are proportional to each other. For example, spring and dampers in passive suspension has a linear characteristic and proportional to displacement and velocity respectively. Also, active suspension studies may use electric linear motor [10] as actuator to maintain linearity in the vehicle model. However, if the output cannot be written as linear combination of its input, the system is said to be non-linear. For example, studies by Hyun-Chul et al. [49] and Basari [50] used non-linear models of quarter car with MacPherson strut suspension to ensure the study will be as close as possible to the real case. Also, most variable dampers and actuators used in controllable suspensions inherit the nonlinearity properties. For example, the behavior of continuous variable damper is governed by valve openings and variable viscosity smart fluids and their operating processes inherit nonlinearity aspects into dampers properties. Linear interpolation of these processes will only valid under certain conditions and under extreme velocity, unpredictable results will be observed [51]. Based on chaos theory, a little change in the input of a nonlinear system may cause unpredictable and complex effects to its output, increasing the complexity of the controller needed to govern the system itself [52]. Due to this point, control strategies governing linear and nonlinear systems should be considered separately.
In this section, symbols and abbreviations will be based on the same notation as in Fig. 1. Conventional passive “Quarter-car” suspension model unless stated otherwise. Additional nomenclatures will be explained within the paragraphs.

4. Control strategies for linear system

4.1. Skyhook control and other switching algorithm approach

Due to its simple algorithm, this is undoubtedly one of the most popular semi-active control strategy used. The concept of skyhook control has been originated in 1974 by Karnopp et. al. [16], based on a fictitious controllable damper placed between the vehicle body and a stationary sky. In practical, the concept can be modeled by two main control algorithms; two-state (on/off) control strategy, studied in [53-55] and linear variable damping skyhook control, studied in [49, 56]. In two-state skyhook control, the damper will only have a maximum and minimum (usually zero or very small) damping state, $c_{two-state}$, which is $c_{max}$ and $c_{min}$ respectively. In linear skyhook control, a continuous variable damper is employed which will provide any damping values, $c_{lin}(t)$, between $c_{max}$ and $c_{min}$. The control algorithm employed to determine the suitable values will be based on the relative motion between its unsprung mass and sprung mass. If the relative velocity and body velocity is in the same direction, which will give a positive value for its product, maximum damping should be produced. On the other hand, if the vehicle body and the relative motion are not in the same direction, minimum damping force should be produced.

Fig. 2 illustrates the skyhook control algorithm can be summarized in Eq. [Error! Reference source not found.] and Eq. [Error! Reference source not found.]. [56]. Here, $sat_{[c_{min},c_{max}]}$ is saturation operator for the continuous variable damper used in linear skyhook control.
Skyhook control has been proven to improve the ride characteristics by reducing body acceleration [55, 57, 58]. Canale et al. [59], used skyhook control results for comparison to validate their proposed control strategies. However, due to its focus on improving ride quality, the road holding performance is very limited. In 1996, ground-hook control theory has been proposed to improve road holding capabilities for controllable suspensions [4]. In this theory, the fictitious damper is placed on a stationary ground instead of sky which will give consideration to road handling capabilities to suspension system. Control algorithm can be summarized as in Eq. (1).

\[
\begin{array}{l}
\text{if } \dot{x}_1 (\ddot{x}_1 - \ddot{x}_2) \geq 0 \quad c_{\text{two-state}} = c_{\text{max}} \\
\text{if } \dot{x}_1 (\ddot{x}_1 - \ddot{x}_2) < 0 \quad c_{\text{two-state}} = c_{\text{min}} \\
\end{array}
\] (1)

\[
\begin{array}{l}
\text{if } \dot{x}_1 (\ddot{x}_1 - \ddot{x}_2) \geq 0 \quad c_{\text{lin}} (t) = \text{sat}_{[c_{\text{max}}, c_{\text{sat}}]} \left[ \alpha c_{\text{max}} (\ddot{x}_1 - \ddot{x}_2) + (1 + \alpha) c_{\text{max}} \dot{x}_1 \right] \\
\text{if } \dot{x}_1 (\ddot{x}_1 - \ddot{x}_2) < 0 \quad c_{\text{lin}} (t) = c_{\text{min}} \\
\end{array}
\] (2)

Savarese et al. [56] investigated the use of body acceleration instead of body velocity for its switching algorithm that resembles skyhook control which proven to give remarkable performance when compared to passive suspension. Another interesting switching algorithm, MiniMax control were studied in [57]. The algorithm will switch damping state between hard or soft based on current shock absorber state (compressed or stretched) and also wheel loading condition (whether there are increase or decrease in wheel loading). This controller was compared with skyhook controller and it was shown that MiniMax control improved road handling characteristics which skyhook control lacks.

4. 1. 2. Optimal control

Studies and applications of optimal control have been recorded since early 1970s. Hrovat et. al. [4] has reviewed optimal control applications on various setups of controllable suspension. Extensive studies on optimal control applied in semi active, active and also slow active suspension can be seen in [62, 63]. The most common optimal control methods are the Linear Quadratic Regulator (LQR), Linear Quadratic Gaussian (LQG), and Model Predictive Optimal
Control (MPC). Different performance index were introduced with different kind of optimization algorithm to solve the optimal problem. The concept of this type of control strategy is to optimize a set of different performance parameters (which usually are body acceleration, suspension travel and wheel-road interactions) modeled as linear quadratic performance index detailed in [63, 64]. Different approaches have been utilized for the purpose of optimizing these performance indexes.

In [65], an LQR approach with an optimal gain matrix was used in active suspension system of a 7-DOF full vehicle model. The gain matrix was obtained by optimizing an extensive cost function which integrates all ride and handling performances including bounce and pitch motions (12 parameters). To solve the optimal problem, the study utilizes a distributed computing network to calculate optimized parameters for all four part of the vehicle (front, rear, left and right). Zhang et al. [66] uses genetic algorithm to optimize the gain matrix in the LQR controller used in the study. The GA method was proven beneficial as to improve the LQR controller performance.

Zhu et al. [8] studied LQG method to be used as an active suspension controller in a software-in-the-loop (SIL) simulation set-up. The design of LQG controller was detailed and its application in the SIL was explored. Furthermore, in 2006, Peng et. al. [67] employ a complex, real time LQG controller to a hardware-in-loop (HIL) semi active suspension system setup using Magneto-Rheological (MR) damper.

In MPC strategy, a model that represents the optimal suspension system is designed which will be evaluated and optimized for each sampling time, $t$. This strategy has been studied and reviewed in [68, 69]. In 2006, Canale et al. [59] argued on the effectiveness of this strategy that the exhausting algorithm makes this type of controller impractical. Due to this problem, they utilized a “fast” MPC algorithm that was proven to save 44% on mean computational time required compared to a normal MPC strategy and shown significant improvement in ride performance compared to a skyhook approach. Study in [70] (and the references within) however used preview information of incoming road instead of using a vehicle suspension model. The semi-active suspension were applied at rear wheel of the vehicle and based on road measurement recorded from front wheels, the road excitation is modeled as a delayed signal so that the rear suspension can provide suitable reaction to isolate vehicle body from this excitation. Improvement in body acceleration was observed but always with an increase in tire load. Also, from the testing on rounded pulse road input, the performance cannot be improved with this approach. Consideration for using this approach in an active controller also been detailed in this study.

4.2. Control strategies for nonlinear system

Vehicle system suspension behavior always assumed to be linear to ease the process of coming out with a mathematical model to predict the state and control its processes [4, 5]. The studies of suspension control behavior should use the nonlinear representation to ensure its effectiveness and robustness under various conditions (vibration frequencies, velocities, etc.). Basari [50] include nonlinear MacPherson suspension quarter car model and controlled it with a robust controller using back-stepping technique. In [71], they used feedback linearization to linearize force/velocity response of MR damper which enables them to use a linear approach, skyhook control. This was done by employing feedback gain and feed-forward gain in the feedback controller.
One of the controller model used is adaptive controller. Adaptive control uses the vehicle state to adapt with varying condition the vehicle undergoes. Common approach used is feed-forward and feedback where the vehicle state is fed into the controller to calculate the suitable response. In 2008, Jiangtiao et. al. [5] reviewed on intelligent methods for adaptive control. They examined fuzzy logic, neural network and genetic algorithm to be employed in adaptive control. These approaches were applied into the adaptive controller to contribute ‘brain and experience’ to calculate better responses.

Applications of LPV/H\(_\infty\) controller were demonstrated by [51, 72, 73] with the additional of anti-roll distribution control by feedback-feedforward approach in [73]. To apply this approach, nonlinear vehicle model was transformed and reformulated into a Linear Parameter-Varying (LPV) system that involve gain scheduling parameters which will be suitable with H\(_\infty\) framework controller. The transformation makes this type of controller to be a robust controller suitable for ever-varying suspension system. In [10], an interesting study involving H\(_\infty\) controller with full vehicle model were carried out. Different controller setup (quarter, half and full H\(_\infty\) controller) were applied on the full vehicle model to observe the effectiveness of each setup. They concluded that a simple quarter car H\(_\infty\) controller setup provides the best result in ride and comfort performance compared to half and full car H\(_\infty\) controller setups.

For the past few years, the implementation of fuzzy logic controller (FLC) can be observed in several studies [74-77]. FLC controller determines suitable response based on a lookup table/data and rules which designed based on human experienced dealing with different conditions. The functionality of FLC was explained with great detail by Chen et. al. [74] using a 2-input-1-output rule base. The input considered is error of body acceleration, \(E\) and the change in error, \(EC\) to dictate the output control force. In [77], a lookup table was designed using the suspension deflections and sprung mass velocity to provide the control forces needed under current situation. Danesin et. al [76] demonstrate the use of FLC with Real Time Damper subsystem in MATLAB/SIMULINK simulations.

5. Control strategies in controllable suspension with energy harvester capabilities

In developing control strategy for controllable suspension, the processes can be divided into two stages. The first stage governs the amount of force should be delivered by suspension to the vehicle for stabilized responses. This usually denoted by “ideal control force” or “required control force”. The second stage governs the process to deliver the required force to vehicle. This stage would ensure that the output force from suspension follows the “ideal control force” from first stage as accurately as possible. These stages can be explained figuratively as in Fig. 3.
Fig. 3. Simplified explanations on different stages in control development.

Similar to previous section, this section will use symbols and abbreviations based on the same notation as in

Fig. 1. Conventional passive “Quarter-car” suspension model

Fig. 1 unless stated otherwise. Additional nomenclatures will be explained within the paragraphs.

The main idea of energy harvester within suspension system is to absorb as much energy as possible from road surface excitations and store it for future use or to be fed back into the suspension unit as a power source. From previous simulation observations, a normal passenger car cruising on a poor road surface at speed 13m/s can dissipate up to 200 W of power from all 4 dampers of its suspension [78, 79]. A typical active suspension system would require about 5 HP


of power (3.7kW) [45]. Gysen et al. [12] claimed that their proposed active EMS requires damping power of maximum 2kW but only 16W RMS was needed in normal cruising city driving. To supply power to these systems, total energy that can be harvested by the suspension varies depending on the driving conditions and road surface. Recently, Lei et al. [80] concluded that their proposed EMS can harvest 16-64 W with suspension velocity range of 0.25 – 0.5 ms⁻¹. In this case, Lei’s EMS energy harvester can actually power up Gysen’s active EMS suspension. However, without a suitable control scheme, the realization of this idea is nearly impossible.

In 1996, Okada et al. [45] presented a general concept of regenerative energy that can be applied to any suspension system for buildings or vehicles. They proposed a suspension system consists of an electro-dynamic actuator with a new control scheme to harvest energy and isolate vibrations. This suspension will be operating in two distinct modes characterized by the vibration frequency imposed by the road input to the actuator. These modes are regeneration and pure suspension (active or passive). To distinguish between the two modes, speed of the actuator motions was used as switching trigger between regeneration mode and active/passive suspension mode. In the case of high frequency vibrations (high speed motion), the suspension will be regenerating energy from the excitations. The energy was used for additional power source for the suspension unit besides the primary battery. In this study, low frequency vibrations range was described as dead zone due to the inability of the suspension to regenerate energy within this region. The actuator will be switched to passive damper mode or active suspension and power was supplied fully by the primary battery. In passive damper mode, the actuator will exert a fixed
breaking (damping) force with equivalent damping coefficient of $\psi R$ where $\psi$ is the actuator coefficient and $R$ is the electrical resistance connected to the actuator. In active mode, the actuator will exert variable force governed by displacement and velocity of the sprung mass, $f(t) = K_p x + K_v \dot{x}$, where $K_p$ and $K_v$ are displacement and velocity feedback gains respectively. The results indicate a good agreement between simulation and experimental data which points out a high possibility of energy harvesting within suspension system that will have good damping properties and energy harvesting capabilities. However, this study requires a highly efficient actuator to ensure the desired force transmitted to the vehicle system since the control system was done only in first stage.

In 2003, Nakano et al. [81] propose an active suspension using a DC linear motor with energy harvesting capability. Previously in Okada et al. study, the energy regenerated was used on the spot as power supply for the suspension unit. Differently, Nakano et al. include a condenser which acts as a buffer that stores the regenerated energy. They stated that for a good energy harvesting system, it should regenerate more power than it consumes. They carried out an energy balance analysis for consumed and regenerated energy using the system’s dynamical property of the system, the feedback gain of the active controller, the specification of the actuator, and the power spectral density of disturbance. A contour plot of power consumption was developed from this analysis and they came out with a feasible design of the self-powered active suspension. The control strategy employed skyhook theory to determine the desired force (first stage control) and its parameters was quantified by the ratio, $n$ between skyhook feedback gain, $c_{sky}$ and equivalent damping coefficient of the actuator, $c_{eq}$. Vibrations isolation performance was claimed to be better with larger $n$. Energy harvesting procedures were carried out in the second stage of the control strategy. A switching circuit with variable resistance was developed for this stage. They introduced a mode variable $\gamma$ as the switching trigger. $\gamma$ is a function of actuator speed, $c_{eq}$, and actuator force. Three modes were introduced based on the values of $\gamma$. For $0 < \gamma < 1$, the suspension will be switched to “regeneration” mode where the actuator regenerates energy from vibration and delivers it to the condenser. The variable resistance was tuned to produce control force equal to the desired value. When $\gamma \leq 0$ the suspension should be in “drive” mode where it produces damping force using power stored in the condenser. Alternatively, when $\gamma \geq 1$ the suspension will enter “brake” mode where it increases its damping force using both power from condenser and also primary power supply. Experimental and simulation results showed that a self-powered active suspension system is achievable when designed with an energy balance analysis. Also, with $n = 0.5$, the actuator was able to produce the desired force output more accurately.

In 2005, Okada et al.[82] published an improvised version of the 1996 study where they introduced a pulse width modulator (PWM) step up chopper that enables the suspension to regenerate energy even in the dead zone region. The PWM duty ratio governs the damping characteristic of the suspension system and changeable via dSPACE software in onboard computer. Also, they employed a more systematic control strategy which uses linear quadratic (LQ) control theory to calculate the desired force, $f^*$ (first stage control). In the second stage, a new control strategy was introduced for the energy flow from battery/regenerated energy to suspension with different switching circuit than in Nakano et al. with a novel switching algorithm. Here, only two modes exist, depending on whether the system able to regenerate
energy or not. The suspension system was available for energy harvesting when \( \frac{v^2}{R} \dot{x}^2 \leq f^* \times \dot{x} \leq 0 \)

where the symbols carry the same meaning as above. In this mode, damping force is powered by regenerated energy. Otherwise, the damping force from actuator would be generated by batteries. In this study, the regenerated energy was still not enough to power-up the system and vibration reduction performance observed were still not satisfactory enough. These were due to the fact that the process of changing the PWM duty ratio is slow using dSPACE interface. Lack of energy storage buffer as employed in Nakano et. al study previously may also be the cause that can be investigated further as a new research prospect.

In 2007, Kawamoto et al. [83] proposed an interesting solution that employed an electromagnetic damper EMD consists of a DC motor and the ball screw mechanism. The damper then was coupled with a spring and forms an electromagnetic system (EMS). In the study, they outlined the derivation of mathematical model for the EMD and carry out a two-stage control strategy on the suspension system. In the first stage, they use velocity feedbacks to calculate the ideal control force, \( f(t) = -C_s \dot{x}_s - C_u \dot{x}_u \) where \( C_s \) and \( C_u \) are velocity feedback gains of sprung and unsprung mass respectively and \( \dot{x}_s \) and \( \dot{x}_u \) are sprung mass and unsprung mass velocity respectively. This is a combination between skyhook and groundhook control theory as discussed in previous section where a positive \( C_s \) denotes a good vibration isolation property (skyhook attributes) and negative \( C_u \) denotes a good road holding property (groundhook attributes). To ensure the EMS exerts force accurately, they employed PI controller to the EMD. An energy saving algorithm was proposed as future development in this study which was followed up in 2008 [84]. In the study, they produced a contour map performance evaluation of the EMS in terms of vibration isolation and maneuverability. With this, they proved the existence of energy regeneration region for the system and suitable gains setting to achieve this.

Recently in 2010, Montazeri and Soleymani [46] proposed a novel energy harvester system for active suspension intended for Hybrid Electric Vehicle (HEV). The study involved a simultaneous simulation that links the vehicle suspension and powertrain. This will provide a clearer view to study the impact of active suspension power demand on the HEV fuel consumptions. Fuzzy based rules were used in the active suspension control strategy to determine the ideal control force (first stage control). The same control approach also used in the power management within the power train to ensure the internal combustion engine (ICE) operates at its optimal operating points. Moreover, they propose a novel hybrid energy storage system (ESS) that incorporate electro-chemical ultra capacitor which has superior energy storage properties compared to electrochemical battery. This system was proven to improve the efficiency and the lifespan of the HEV batteries. The results also showed an increase in HEV fuel consumption and emission when active suspension was employed but with energy regeneration, the power demand was decreased and the increase in fuel consumption and emission was compensated.

Eventhough there were significant researches been conducted throughout decades, the field is still new in developing a specific control strategies for tubular permanent magnet linear motors. Most of the control strategies presented here was developed in the first stage which will determine the ideal force to be transferred into suspension system. Second stage of control which will govern the process of delivering this force into the system will be specific to an individual suspension mechanism.

6. Conclusion and future work
Throughout this paper, detailed review has been conducted discussing developments of controllable suspension for passengers’ vehicle system. While focusing mainly on energy regenerating capabilities of the suspension, this review covers the design aspect and control strategy commonly employed in the controllable suspension field. Also, nonlinearity problem in modeling and control application has been briefly addressed. The prospect of employing electromagnetic concept in the suspension system can be beneficial in the future. High requirement of power consumed by the system can be compensated by the ability to regenerate energy from external excitations by road surface. In the near future, it can be an interesting research direction to develop a new control strategy focusing on a novel design of EMS. Second stage control strategy with energy regeneration capability should be investigated specifically for the EMS as discussed in Section V. A successful control strategy development will ensure the practicality and improved efficiency of a self powered active suspension system.

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References


[34] Carlson JD, Catanzarite DM, St. Clair KA. Commercial magneto-rheological fluid devices, Int. Conf. on ER, MR Suspensions And Assoc Tech, 1995.
[52] Kellert SH. In the wake of chaos: Unpredictable order in dynamical systems: University of Chicago Press, 1993


