The Future Development and Analysis of Vehicle Active Suspension System

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Abstract: Ride comfort and the handling capabilities of vehicle are mainly determined by its suspension system, which transmits the forces between the vehicle and the road. In recent years, using active control mechanisms for design of active suspension system has attracted considerable attention. The main concept is use an active suspension to reduce the vibration energy of the vehicle body induced by the road excitation, while keeping the vehicle stability within an acceptable limit. The present paper aims at providing a picture - as complete as possible of the present state of the art in the active suspension control field in terms of ride comfort and road-holding performance evaluation. This paper discussed all the design literature review for active suspension systems for vehicle. This paper also deals with a number of control aspects and some of the important practical considerations.

Keywords: Active vehicle suspension; Fuzzy logic control; Preview control

I. Introduction

Suspension system is one of the critical components in the present of vehicle system. Ride safety and the handling capabilities of vehicle are mainly determined by its suspension system, which transmits the forces between the vehicle and the road. Suspension consists of the system of springs, shock absorbers and linkages that connects a vehicle to its wheels. In other meaning, suspension system is a mechanism that physically separates the car body from the car wheel. The main function of vehicle suspension system is to minimize the vertical acceleration transmitted to the passenger which directly provides road comfort. In the past few decades, many researchers have paid considerable attention to the issues on how to guarantee the stability of the suspension systems and how to improve the required suspension performances, namely, ride comfort, road handling and suspension deflection. So far, many vehicle suspension- system models have been proposed [1:4].

Generally, there are three types of system namely; passive, semi-active and active suspension system that have been widely investigated by many researchers with different techniques and algorithms. The passive suspension system showed lack of performance of vehicle stability as compared with semi-active and active suspension system. The dynamic behavior of passive automotive suspension systems is determined by the selection of the spring stiffness and the damper coefficient. The fixed damper and spring component of passive system has not well enough for energy absorption to sustain the load or road disturbance acted into the vehicle system [5:6]. The semi-active suspension system uses a variable damper or other variable dissipation component in the automotive suspension. An example of a variable dissipater is a twin tube viscous damper in which the damping coefficient can be varied by changing the diameter of the orifice in a piston [7:10]. Another example of semi-active dissipater is a magneto rheological (MR) damper which used MR fluid [11:14]. The MR fluids are materials that respond to an applied magnetic field with a change in rheological behavior. Typically, this change is manifested by the development of a yield stress that increases with applied magnetic field the dissipative force provided by the damper can be controlled by controlling the electromagnetic field. Semi-active suspension systems have been investigated in various literatures in order to achieve lower energy consumption and as good performance as full-active suspension systems [15:18]. The semi-active system can adjust the damping and thus improve either ride comfort or ride safety compared to the passive system. Active suspensions are equipped with electronic control systems that control the operation of the suspension elements. They have not a limited performance like passive suspensions and create a new advancement in removing the drawbacks of the design compromise present in passive suspensions. Active suspension systems reduce car body accelerations by allowing the suspension to ‘absorb’ wheel accelerations using an actuator [19:22].

Recently works and researches on active suspension have been carried out by many researchers in order to improve the stability and ride handling performance of the vehicle. So far, many control approaches such as Linear Quadratic Regulator (LQR) [23], Linear Quadratic Gaussian (LQG) control [24], Adaptive sliding control [25], H∞ control [26], sliding mode control [27], fuzzy logic [28], preview control [29], optimal control [30] and neural network methods [31] have been used in the area of active suspensions. The performance of the active suspension system can be improved by control methods. However, these approaches
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need a complicated learning mechanism or a specific performance decision table and a certain difficulties in applications.

The present paper aims at providing a picture as complete as possible of the present state of the art in the active suspension control field in terms of ride comfort and handling. The paper will discuss all the design literature review for active suspension systems for vehicle. This review paper also deals with some of control strategies used for investigating active suspension.

II. Development of Active Suspension Systems

The basic idea in active control of suspensions is to use an active element (the actuator, e.g., a hydraulic cylinder) to apply a desired force between the vehicle and the wheel. Car’s control unit computes the desired force to reach certain performance objectives under external disturbances (e.g., passenger comfort under road imperfections). The active suspension systems require several components such as ACs, servo valves, high-pressure tanks for the control fluid, sensors for detecting the system, etc. [32]. Figure 1 describes basic component of active suspension. The associated power, which must be provided by the vehicle engine, may be very high depending on the required performance. Furthermore, these suspension systems are very expensive [33]. But, the full-active suspensions have better performance than passive suspensions.

Suspensions control is highly a difficult control problem due to the complicated relationship between its components and parameters. The researches were carried out in suspensions control systems cover a broad range of design issues and challenges. The control strategies of full-active suspension have been studied in many suspension systems to describe and improve the ride comfort and handling. For example, Hrovat [34] explored the connections between LQG-optimal one DOF (degrees of freedom) and two DOF models. The optimal two DOF systems indicated that both ride and handling can be improved by reducing the vehicle unsprung mass. Turkay and Akcay [35] used a quarter-car active suspension system by using the vertical acceleration and/or the suspension travel measurements for feedback. The influence of tire damping on the design of an active suspension system for a quarter-car model by a mixture of the LQG methodology and the interpolation approach was also illustrated. It was shown that tire damping by coupling the motions of the sprung and unsprung masses eliminates a constraint on the wheel-hop mode.

Recently, Aref Soliman 2011 [36] presented LQR control design for the control of a vehicle active suspension system. Seven DOF, full vehicle model was used. LQR control system was prepared as well as adaptive LQR control system (gain scheduling strategy) to study the effect of each control system using the active suspension on ride performance. The acceleration and dynamic tyre load were evaluated. For the time domain analysis, different road conditions were considered in order to reveal the performance of the two controllers. The simulation results showed that adaptive LQR control system gives a better ride performance compared with LQR control system.

In 2003, Abdelhady [37] presented a fuzzy scheme which offers new opportunities in the improvement of vehicle ride performance. The scheme handles uncertainties of the problem, and tunes the controller to treat the conflict requirements of ride comfort and road holding parameters within a specified amount of the suspension deflection. The two DOF quarter car model was used to evaluate the performance parameters when the vehicle was subjected to a random road input. Results of an active suspension system based on linear quadratic regulator (LQR) optimal control theory were also generated and used as a guide in scaling the performance of active systems with fuzzy control. It was indicated that the fuzzy logic control system improves both the ride comfort and road holding parameters in comparison with the LQR active suspension system.

Fateh and Alavi [38] developed an impedance control system to control dynamic behavior of a vehicle subject to road disturbances and applied the impedance control on an active vehicle suspension system operated by a hydraulic actuator. A quarter-car model of suspension system and a nonlinear model of hydraulic actuator were used to simulate the control system. The impedance control of active suspension system was performed well as it was preferred to passive suspension system. In comparison with model based control laws such as optimal control law, the IR showed important advantages.

Eski and Yildirim [39] designed neural network based robust control system to control vibration of vehicle’s suspensions for full vehicle model. The proposed control system was consisted of a robust controller, a neural controller, a model neural network of vehicle’s suspension system. Also they used the PID controller. Consequently, random road roughness was used as disturbance of control system. The performance of the neural network based robust control system is better than standard PID controller.

Demic et al. [40] introduced a design of active suspension systems using spatial vehicle model, without filtered feedback of the control system. A method of “stochastic parameters optimisation” has been utilized for the optimisation of the parameters of active suspension system. The optimisation objective was simultaneous minimization of sprung mass vibration and standard deviation of forces in tire-to-ground contact area and vehicle handling. The active suspension system has shown favorable characteristics in car operating conditions, even without the filters in the feedback loops. A more sophisticated mathematical linear model for a
roll-plane active hydraulically interconnected suspension (HIS) system was developed by Zhu et al. in 2014 [41]. For the verification of the new model, two simulations and corresponding experiments were conducted. Data comparisons between the simulations and experiments showed high consistent responses of the model and the real system, which validated the robustness and accuracy of the new mathematical model. In this process, the characteristics of the pressure response and the rise time inside the actuators have been revealed due to the presence of the flow.

Nguyen et al. [42] presented an active suspension system using H∞ control method for quarter car model with two DOF. Absolute velocity of car body was measured. The system parameter variations are treated with multiplicative uncertainty model. The simulation and experimental results showed that the H∞ controller can reduce considerably the gains from road disturbance to car body acceleration, to suspension deflection and to tire deflection at the frequencies around 1 Hz.

In recent decades, fuzzy logic control has been suggested as an alternative approach to conventional control techniques for complex nonlinear systems. It was developed as a model-free control design approach, and it has been applied to active suspensions system to deal with the nonlinearities associated with the actuator dynamics, shock absorbers, suspension springs, etc. However, the model-free fuzzy logic control suffers from a number of criticisms, such as the lack of systematic stability analysis and controller design. It also faces a challenge in the development of fuzzy rules. Significant progress has been made in the past decades in the development of fuzzy logic control and it has been devoted to model based fuzzy control systems that guarantee not only stability, but also performance of closed-loop fuzzy control systems.

Yoshimura and Takagi [47] presented the construction of a pneumatic active suspension system for a one-wheel car model using fuzzy reasoning and a disturbance observer. The active control was composed of fuzzy and disturbance observers. The active control force is constructed by actuating a pneumatic actuator. A phase lead compensator was inserted to counter the performance degradation due to the delay of the pneumatic actuator. It was found that the proposed active suspension improves much the vibration suppression of the car model.

In order to achieve optimal vehicle performances and adaptability to the changes of plant parameters based on the defined objectives, a genetic algorithm is introduced to tune the parameters of PID controller, the scaling factors, gain values and the membership function of fuzzy logic controller on-line by Jinzhi et al. [48]. He proposed a new control strategy for active vehicle suspension systems using a combined control scheme, i.e., respectively using a genetic algorithm (GA) based self-tuning PID controller and a fuzzy logic controller in two loops. The PID controller was used to minimize vehicle body vertical acceleration and the fuzzy logic controller...
was to minimize pitch acceleration and meanwhile to attenuate vehicle body vertical acceleration further by tuning weighting factors. By a four DOF nonlinear vehicle model, the proposed control scheme was implemented and simulations were carried out in different road disturbance input conditions. The simulation results showed that the existing control scheme was very effective in reducing peak values of vehicle body accelerations, especially within the most sensitive frequency range of human response, and attenuating the excessive tire deflection to enhance road holding performance. It also showed a good stability and adaptability even if the system is subject to adverse road conditions, such as a pothole, an obstacle or a step input.

In 2007, Hany et al [49] considered Genetic Algorithm (GA) optimization technique to design an active suspension based on force cancellation concept when the vehicles crossing road humps. A longitudinal half vehicle model was used to represent passenger’s car and truck models. These models were used to evaluate the performance of active suspension over the road speed humps. The force cancellation concept was employed to isolate the force between the sprung and unsprung mass. Virtual damper and skyhook damper concepts were also used for reducing the sprung mass acceleration and tire dynamic loads. GA was adopted to obtain the better coefficients of a virtual damper and a skyhook damper for its effective searching ability. The results were generated in time domain and represented as a root mean square values (RMS) and bar charts. It is shown both ride comfort and handling quality is greatly improved without exceeding the suspension stroke constraints.

Chiou et al. [50] designed a fuzzy logic controller (FLC) for an active automobile suspension system in which the membership functions and control rules were optimized using a genetic algorithm (GA). The objective of the FLC was to strike an optimal balance between the ride comfort and the vehicle stability. The values of the crossover and mutation parameters in the GA were adapted dynamically during the convergence procedure using a fuzzy control scheme. The GA-assisted FLC controller not only reduces the suspension deflection, sprung mass acceleration, and beating distance between the tire and the ground relative to that observed in a passive suspension system, but also provides a noticeably improved ride comfort and vehicle stability compared to that obtained when using a conventional optimal linear feedback control method.

T–S (Takagi–Sugeno) fuzzy system is considered as one of the most popular systems in model-based fuzzy control. Since the T–S fuzzy model is very effective in presenting complex nonlinear systems, it is feasible to apply for handling the uncertainties of active suspension. There are many results on controller synthesis, stability analysis, and filter design for T–S fuzzy systems have been obtained [51-52]. For example, H. Du and N. Zhang, [53] introduced a T–S model-based fuzzy control-design for electrohydraulic active suspension systems with input constraint. It was described by fuzzy IF-THEN rules that presented local linear input–output relations of a nonlinear system. The overall fuzzy model of the nonlinear system was found by fuzzy “blending” of the linear models. The T–S model is capable of approximating many real nonlinear systems, e.g., mechanical systems and chaotic systems. Since it utilizes linear models in the consequent part, linear control theory can be applied for system analysis and synthesis accordingly, based on the parallel-distributed compensation (PDC) scheme. Therefore, T–S fuzzy becomes powerful engineering tools for the modeling and control of complex dynamic systems.

One of the methods of active control of vehicle vibrations termed "preview control," involves measurement of road irregularities in front of the vehicle and utilizes this information to prepare the vehicle system for the oncoming input. While feedback control of vibrations has been extensively studied in the past, consideration of preview vibration control is relatively new. Preview active control of suspension involves the acquisition and use of information concerning the road profile ahead of the vehicle. Use of road preview information for improving vehicle suspension system was first proposed by Bender [54], as cited by Marzbanrad et al. [55]. Tomizuka [56] depicted the implementation aspect of the preview control of suspension in practice. The major tasks in the synthesis of preview control system for the actively controlled suspensions are (a) formulation of vehicle mathematical model; (ii) on-line synthesis of feed forward control policy to track the road elevation and partially counteract the forces imparted to the vehicle at the tire-road interface; and (iii) synthesis of an off-on or on-line feedback control policy to augment the damping and suppress the vibrations caused by road irregularities.

In preview active control of suspension, there are two sets of variables that need to be sensed and used in the control scheme. Preview of road irregularity information is used as the feed forward component of the control strategy, while the state variables of the suspension system provide the basis for the feedback part of the control scheme. These variables need to be measured and be used in the implementation of the optimal control law. Arunachalam et al. [57] in their review paper described the road disturbances caused by the road followed by the need and history of preview system. Also, Oraby et al. 2007, [58] used a practical hydro-pneumatic limited bandwidth active suspension system with and without wheelbase preview control to study its influence on the vehicle stability in lateral direction. The model was a longitudinal half car with four degrees of freedom. Vehicle lateral dynamics was modeled as a two degrees bicycle model and a driver model. The controllable suspension system was designed based on linear optimal control theory using LQR control technique with front to rear axle preview is taken into account. The interaction between the performance of active suspension and...
vehicle lateral dynamics is studied through a non-linear Magic Formula tire model. The results were generated in the time domain to simulate the vehicle response in handling maneuvers while road wheels were subjected to vertical road input.

Further development has been made in 2014 by Mina Kaldas and Aref Soliman [59]. They investigate the influence of the preview control of the active suspension on the vehicle ride and braking performance. The vehicle performance was examined theoretically using a longitudinal half vehicle model with four degrees of freedom considering the rotational motion of the tires. The active suspension system model, tire-road interface model and braking system model are included in the vehicle model. Also, Akihito Yamamoto et al. in 2014 [60], examined the effect of a preview control using the eActive3 electric active suspension system, which is capable of controlling the roll, pitch, and warp modes of vehicle motion. They reported the results of a study into a preview control that uses the displacement of the road surface in front of the vehicle to improve for front and rear actuator responsiveness delays, as well as delays due to calculation, communication, and the like.

III. Conclusions

The following observations can be made from the previous survey:

1. For three different types of suspension systems, it has been extensively accepted that active suspension controller is more effective in improving suspension performance than the conventional passive and semi active suspension systems.

2. The performance of the neural network based robust control system is better than standard PID controller.

3. The fuzzy logic control system improves both the ride comfort and road holding parameters in comparison with the LQR active suspension system.

4. The T–S fuzzy models are becoming powerful engineering tools for the modeling and control of complex dynamic systems.

5. The GA-assisted FLC controller not only reduces the suspension deflection, sprung mass acceleration, and beating distance between the tire and the ground relative to that observed in a passive suspension system, but also provides a noticeably improved ride comfort and vehicle stability compared to that obtained when using a conventional optimal linear feedback control method.

6. The simulation results showed that adaptive LQR control system gives a better ride performance compared with LQR control system.

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