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Study and Review on Vehicle Suspension Control Theories and Introduction of Novel Adaptive Skyhook Control System

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ABSTRACT

A suspension system is an essential element of a vehicle structure to isolate the frame from occurring road disturbances. Among the passive, semi-active and active suspension system, the latter two are incorporated with intelligent control system. Since the early 1970s, across different literatures, various types of active and semi-active suspension systems have been proposed to achieve better vehicle ride comfort. In this paper, some of the systems, such as the linear time invariant H-infinity control (LTIH), the linear parameter varying control (LPV) and model-predictive controls (MPC) will be reviewed. Five widely known control approaches, namely the Linear quadratic regulator & Linear Quadratic Gaussian, sliding mode control, Fuzzy and neuro-fuzzy control, sky-hook and ground-hook approaches are further studied and reviewed. The work studies the modified skyhook control closed loop feedback system and analyses its effectiveness in active suspension system. The paper also evaluates three widely used existing skyhook control algorithms, namely continuous skyhook control, modified skyhook control, optimal skyhook control.

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INTRODUCTION

The comfort and safety of the passenger travelling in a vehicle can be improved by minimizing the body vibration, roll and heave of the vehicle body through an optimal road contact for the tyres. The system in the vehicle that provides these actions is the vehicle suspension, i.e., a complex system consisting of various arms, springs and dampers that separate the vehicle body from the tyres and axles (Figure 1). In general, vehicles are equipped with fully passive suspension systems. These systems are easier to manufacture with low associated costs. The passive suspension consists of springs, dampers and anti-roll bars with fixed characteristics. The major drawback of the passive suspension design is that one cannot simultaneously maximize vehicle ride and handling performance.

To achieve better and comfortable ride performance, a "soft" suspension needs to be introduced to maintain contact between vehicle body and the tyre. The "soft" suspension easily absorbs road disturbances. The road handling is the other measure of vehicle performance. The road handling refers to a vehicle's ability to maintain contact between the vehicle's tyre and the road during turns and other dynamic manoeuvres. This can be achieved by "stiff" suspensions as seen in sports cars.

The challenge of the passive suspension system is in achieving the right compromise between the two characteristics of vehicle performance which will best suit the targeted consumer. However by introducing the active or semi-active suspension system in the vehicle (Figure 2), a more desirable compromise can be achieved between the benefits of the soft and stiff suspension system.

The active or semi-active suspension systems are incorporated with the active components, such as actuators and semi-active dampers, coupled with various dynamic control strategies. With active components, these systems can provide adjustable spring stiffness and damping coefficients adapted to various road conditions. Since the early 1970s, many types of active and semi-active suspension systems have been proposed to achieve better control of damping characteristics. Although the active suspension system shows better performance in a wide frequency range, its implementation complexity

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and cost prevents wider commercial applications. That is why the semi-active suspension system has been widely studied to achieve high levels of performance in terms of vehicle suspension system.

Fig.1: Rear suspension system without wheel of a vehicle.

To control the damper of the semi-active suspension system, many control strategies including Skyhook Surface Sliding Mode Control (Chen, Y., 2009), neural network control (Gao, W., 2008), H-infinity control (Choi, S.B., 2002), skyhook control, ground hook control, Hybrid control (Ahmadian, M. and D.E. Simon, 2003; Ahmadian, M. and N. Vahdati, 2006), fuzzy logic control (Yagiz, N. and L.E. Sakman, 2005; Yu, M., *et al*., 2006), neural network-based fuzzy control (Eslaminasab, N., *et al*., 2007), neuro-fuzzy control (Choi, S., 2001), discrete time fuzzy sliding mode control (Sung, K.G., *et al*., 2007), optimal fuzzy control (Fang, X. and W. Chen, 1999), adaptive fuzzy logic control (Dong, X., *et al*., 2006) have been explored. Between all of the above control systems, the skyhook control proposed by Karnopp *et al*. in 1974 is widely used since it yields the best compromise between vehicle performance and practical implementation of semi-active suspension systems.

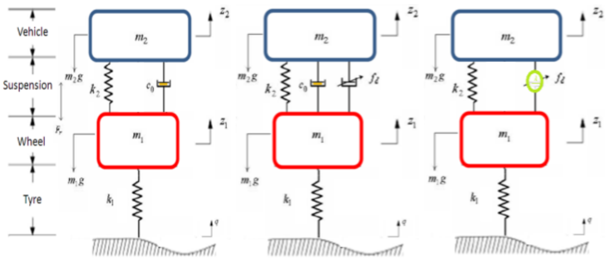

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Fig. 2: (a) Passive, (b) Semi-active and (c) Active suspension system.

In the past few decades researchers have modified the basic skyhook control strategy by adding some variations and have named them optimal, modified or adaptive type skyhook control strategies (Besinger, F., 1995; Nguyen, L.H., *et al*., 2009). But in most of these studies, Skyhook Gain (SG) of the control strategy remains as a constant value and it is usually chosen from a set of values as suited for the vehicle in the simulation environment. One of the major goals of this research is to present a new modified skyhook control strategy with adaptive SG.

Control Strategies:

In general, a controlled system consists of a plant with sensors, actuators and a control method is called a semi-active control strategy. A semi-active system is a compromise between the active and passive systems. It offers some essential advantages over the active suspension systems.

The active control system depends entirely on an external power source to control the actuators and supply the control forces. In many active suspension applications this control approach needs a large power source.

On the other hand, semi-active devices need a lot less energy than the active ones. Another critical issue of the active control system is the stability robustness problem with respect to sensors or the whole system failure; this issue becomes a big concern when centralized controllers are employed in vehicle suspension design. The semi-active control device is similar to the passive devices in which properties of the damper can be adjusted such that spring stiffness and damping coefficient of the damper can be changed (Kashem, S.B.A., *et al*., 2015); thus, they are robustly stable. That is why the semi-active suspension system is widely used in the automotive industry.

Since Karnopp *et al*. (1973) developed the Skyhook control strategy, extensive research has been done in semi-active control strategies (Kashem, S.B.A., 2014; Kashem, S.B.A., 2012). Most of this research has been done to find practical and easy implementation methods or to achieve a higher level of vibration isolation, or both. Adaptive-passive and semi-active vibration isolation is able to change the suspension system properties, such as spring stiffness and damping rate of the damper or actuator as a function of time. But the properties are changed relatively slowly in an adaptive-passive suspension system. However in the semi-active system, the suspension properties are able to change within a cycle of vibration. The linear quadratic control is able to achieve both comfort and road holding improvements through the semi-active or active suspension system. But it requires the full state measurement or estimation which is difficult to achieve (Hrovat, D., 1997; Poussot-Vassal, C., *et al*., 2008). Linear time invariant H-infinity control (LTIH) is able to provide better results, improving both ride comfort and road handling ensuring pre-defined frequency behaviour. Due to the fixed weights, this control system is limited to provide fixed performances (Rossi, C. and G. Lucente, 2004; Zin, A., 2005). In 2006, Giorgetti *et al*. (2006) compared different semi-active control strategies based on optimal control. They proposed a hybrid model with predictive optimal controller. This control law is implemented via a hybrid controller, which is able to switch between a large numbers of controllers that depends on the function of the prediction horizon. It also requires a full state measurement which is difficult to achieve. Recently, the uses of linear parameter varying (LPV) approaches have become quite popular (Poussot-Vassal, C., *et al*., 2007; Gaspar, P., 2004). A LPV controller can either improve the robustness considering the nonlinearities of the system or adapt the performances according to measured signals of road displacement and suspension deflection (Zin, A., *et al*., 2008). Another model-predictive control (MPC) system has been proposed by Canale *et al*., in 2006. The MPC controller is able to provide good performances but it requires an on-line fast optimization procedure. As it involves optimal control approach, a good knowledge of the model parameters and the full state measurements are necessary to design the control system (Giua, A., *et al*., 2004). Choudhury *et al*. (2012) compared active and passive control strategies based on PID controller. There are many semi-active control systems designed, implemented and tested by many researchers. A few of them are described briefly in the following sub sections.

Linear Quadratic Regulator & Linear Quadratic Gaussian:

In the field of vehicle suspension control systems, the Linear Quadratic Regulator (LQR) approach is a widely used and studied control system. It has been studied and derived for a simple quarter-car model (ElMadany, M.M. and Z.S. Abduljabbar, 1999), half-vehicle models (Krtolica, R. and D. Hrovat, 1992) and also for a full vehicle (Hrovat, D., 1991). An optimal result is possible to achieve when tthe factors of the performance index such that acceleration of the body and dynamic tyre load variation are taken into account. In the LQR approach, a state estimator must be utilized if all the states are not available in the system, such as, tyre deflections are difficult to measure in a moving vehicle. An estimator can narrow the phase margin of the LQR suspension system to a great extent, but it heightens the stability problems of the vehicle, especially if the suspension system is a fully active system. To solve this problem, Doyle & Stein proposed that the desired gain and phase properties can be obtained with a proper choice of estimator gains (Doyle, J. and G. Stein, 1981). When implementing the LQR system on a full vehicle, another problem arises. The Riccati equation of the LQR system must be solved numerically for a full vehicle model. The equation becomes very complex even though the vehicle is assumed to be symmetrical and all the non-linear effects created by the inertial effects and kinematical properties of the suspension system are not included. Different types of numerical algorithms are proposed to solve this issue but none of them could guarantee convergence and the stability of the solution. The possibility of achieving a convergent solution decreases significantly when the number of actuator decreases or the order of the control system increases, or both, in a same system (Fuller, C.R., 1997).

The LQR approach has also the inability to take the changes in steady-state into consideration. These changes are caused by the change of payload at steady-state cornering of the vehicle. Elmadany & Abduljabbar (1999), discussed a method to overcome this problem. That method is integral control. The task of integral control is to ensure the zero steady-state offset which would be applied to a quarter-car model. For a full vehicle model, the integrator itself can deteriorate the performance of the controller. The proper selection of the integrator term and the gain of the integration time are a difficult problem in this approach due to the external forces caused by the non-zero offset which vary widely.

The optimal control method has been commonly used to accomplish a better comfort or handling performance of a vehicle. Hrovat (1991) has done extensive research with half-car models, full-car models, one degree of freedom models and two degree of freedom models. He minimized the cost functions of the system combining excessive suspension stroke, sprung-mass jerk and sprung-mass acceleration together using Linear Quadratic (LQ) optimal control.

Shisheie *et al*., (2012) presented a novel algorithm based on the LQR approach. It is able to optimally tune the PI controller's gains of a first order plus time delay system. In this approach, the cost function's weighting matrices are adjusted by damping ratio and the natural frequency of the closed loop system. In 1995 Prokop (1995) used LQR and Linear Quadratic Gaussian (LQG) optimal control theories utilizing road preview data or information to get better ride quality. But the fact is, with respect to the system modelling errors, the LQG controller is less robust and still today, determining the weighting coefficients for the LQG is a very hard job. According to Shen (2005), most of the weighting coefficients for LQG/LQR control have been concluded by trial and error. Shen also revealed that the renowned skyhook feedback strategy provides the best outputs for the optimal feedback gain which reduces the mean square control effort and the cost function of the sprung-mass's mean square velocity.

Sliding mode control:

In the last 20 years, sliding mode control (SMC) has become one of the most active parts of control theory exploration. This exploration has established successful applications in a variety of engineering control systems, for example, aircrafts, automotive engines, suspension, electrical motors and robot manipulators (Foo, G. and M. Rahman, 2010; Gupta, R., 2010; Shi, P., *et al*., 2006). Shiri (2012) has designed a sliding mode controller that is robust to electric resistance changes and bounded mass and also able to reject external disturbances. The simplicity system makes it adaptable to the Electromagnetic Suspension System. The results of the simulation confirm the robustness and the satisfactory performance of the designed controller against uncertainties and disturbances. There has also been a considerable amount of research done on the development of the theory of SMC problems for different types of systems, such as, the fuzzy systems (Orowska-Kowalska, T., 2010), the stochastic systems (Huang, L. and X. Mao, 2010; Wu, L. and D.W.C. Ho, 2010) and the uncertain systems (Choi, H.H., 2007).

In a real dynamical system, it is impossible to avoid uncertainties due to the external disturbances and the modelling of the system. What is crucial is a solution to the robust control problem for uncertain systems. SMC can be used to deal with this problem. It is able to work with both uncertain linear and nonlinear systems successfully in a unified frame work (Tsai, Y.W., 2006). SMC design gives a systematic approach to the problem of maintaining consistent performance and stability in the face of the system's modelling imprecision. Since the variable structure with sliding mode (VSM) possesses the intrinsic nature of robustness, the VSM is found to be an effective technique to control the systems with uncertainties (Chan, M.L., 2000). But the drawback of this system is; when the system reaches the sliding mode state, the system with variable structure control becomes insensitive to the variations of the plant parameters. Many different techniques to design sliding mode controllers exist but the baselines of all the techniques are very similar and can be divided into two main steps.

Firstly, design the control law of SMC in such a way that the trajectories of the closed-loop motion of the system are directed towards the SMC sliding surface and make an effort to keep the motion on the surface thereafter. Secondly, develop the sliding surface in the state space in such a way that the reduced-order sliding motion is able to satisfy the specifications specified by the designers.

Utkin introduced a novel PID type sliding mode control in which the sliding mode starts at the initial instant. As a result, during the entire process, the robustness of the system can be guaranteed. This system is also called an integral sliding mode control (ISMC). Yagiz *et al*., (2000) has proposed and developed a sliding mode controller for a nonlinear vehicle model to overcome the problem of fault diagnosis and tolerance. A modified SMC was designed by Chamseddine *et al*., (2006) for a linear full vehicle active suspension system with partial knowledge of states of the system. For the conventional SMC strategy, the desired dynamic state can only be achieved when the sliding mode occurs.

Fuzzy and neuro-fuzzy control:

A vehicle suspension system is highly non-linear and very complicated. Suspension actuation force changes when a vehicle rides on different road conditions. Conventional control strategies are not able to adapt to different environmental conditions. Fuzzy and neuro-fuzzy strategies can be used in controlled suspension systems in many ways. Fuzzy Logic Control (FLC) is appropriate for nonlinear systems. It can work with a complex system with no precise math model. This is why; FLC is used in semi-active and active suspension systems to control the disturbance rejection. FLC is able to be insensitive to model and parameter inaccuracies with proper membership functions and rule bases.

To calculate the desired damping coefficients for semi-active systems, FLC can be utilized directly according to Al-Holou & Shaout (1994). Al-Holou & Shaout compared FLC to both a passive and sky-hook controllers. The authors employed FLC to the semi-active actuator to calculate the desired damping coefficient. In this study, a wide range of semi-active actuators were used. An important finding of this research was that most of the FLC systems show similar results to the sky-hook control system. It has been found that compared to the sky-hook control system, a fuzzy controlled semi-active suspension system showed slightly smaller RMS-values of the body acceleration. Al-Holou & Shaout also showed that the semi-active suspension system with FLC increased the variation of dynamic tyre contact force compared to the skyhook controlled semi-active suspension system.

FLC can also be used to calculate the required force for the active suspension system (Barr, A.J. and J. Ray, 1996). Barr & Ray compared the fuzzy-controlled active system with both the passive suspension system and the LQR active suspension systems. The authors have shown that the ride handling characteristic (the variation of dynamic tyre load) of FLC is better than the LQR and the passive suspension system. This result is slightly surprising, at least in the LQR active suspension system case. Moreover, the LQR-regulator cost function was not presented in this research.

On the other hand, Neural Networks consists of a variety of alternative features such as computation, distributed representation, massive parallelism, adaptability, generalization ability, and inherent contextual information processing. They can be utilized to model different types of ambiguities and uncertainties, which are often experienced in real life. Zhang *et al*., (2012) presented a multi-body vehicle dynamics model using ADAMS and a multilayer feed forward neural network of a series parallel structure. The weights and threshold of neural networks have been optimized in this research. The result of the combine simulation of MatLab and ADAMS shows that the network convergence took place rapidly and the maximum error of identification is less than 0.05%. The authors claimed that the designed genetic neural network can avoid the difficulty of establishing accurately mathematical model for the vehicle semi-active suspension system.

The main objective of the hybridization of the control systems (using neural networks and fuzzy logic) is to overcome the weaknesses in one technology by using the strengths of the other during its application with appropriate integration. In the majority of the studies concerning neural networks and fuzzy logic, the force of the actuator of the active suspension system or the damping coefficient of the semi-active suspension system is not controlled directly. Choi *et al*. (2001) proposed a combination of neuro-fuzzy control approach to dictate a military tracked vehicle semi-active suspension system. The fuzzification phase of the presented controller was continuously modified through a neural network. In this study, the models of real existing electro-rheological semi-active actuator units and a 16-degree of freedom vehicle model were utilized. For Direct Current Motor speed control on line, Youssef *et al*. (2009) have proposed an adaptive particle swarm optimization method for adapting the weights of fuzzy neural networks. An adaptive neuro-fuzzy control has been introduced by Khalid *et al*., (2010) on the basis of particle swarm optimization tuned subtractive clustering to provide critical information about the presence or absence of a fault in a two tank process. Kashani & Strelow derived (1999) a control system which consists of multiple Linear Quadratic Gaussian controllers around different operating points of the suspension system, and blended the desired control actions of each controller with a fuzzy-logic mixed algorithm. FLC was utilized to prevent the suspension from bottoming in this study. Kashani & Strelow claimed that this type of blending of controller action is a fruitful idea and able to improve the vehicle suspension system. But the limitations of practical implementation; such as maximum free rattle space can be taken into account with decision logic of fuzzy logic control.

Groundhook control method:

The Groundhook control approach is almost similar to the Karnopp's ON-OFF Skyhook control method, except that the control system is based on the unsprung mass damping control, as shown in Figure 3.

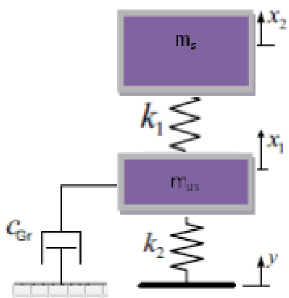

Fig. 3: A schematic of the Groundhook control system.

The Groundhook semi-active suspension system is a tyre displacement control system of a passive damper where one end is hooked on the ground or road surface and the other end is hooked to the tyre. The main idea of the Groundhook control strategy is that it can be utilized to minimize the tyre contact force variation. These vibrational forces have a large impact on a vehicle's manoeuvrability and road handling performance (Valasek, M., *et al*., 1998; Yi, K., *et al*., 1992). Valášek *et al*., (1997) have dealt with the novel Groundhook control concept for both active and semi-active suspension system of vehicles. Their ultimate objective is to reduce the tyre road forces of the suspension system. They have extended the basic Groundhook control concept to several variants that enable the controller to increase driver comfort and decrease criteria of road damage for a broad range of road disturbances. The parameter optimization procedure has been used to determine the parameters of the control scheme for the generally nonlinear model. The influence and interaction of the time constants and damping rate limits of the variable shock absorbers are also addressed in this Groundhook control approach.

Skyhook control method:

The Skyhook control is an effective vibration control algorithm which is able to dissipate the energy of the system at a high rate. For more than three decades, the skyhook control strategy has been widely researched. In 1974, Karnopp *et al*. (1974) introduced the skyhook control strategy which is still used frequently in vehicle suspension applications. The name ''skyhook'' originates from the idea where a passive damper is imagined to be hooked from an imaginary inertial reference point or the sky. Skyhook damping is a damping force that is in the opposite direction to the sprung-mass absolute velocity and is proportional to the absolute velocity of the sprung-mass.

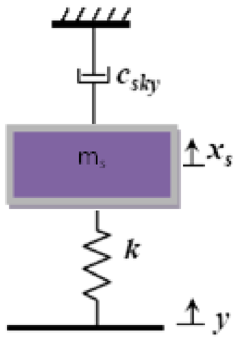

Fig. 4: An ideal skyhook configuration.

Figure 4 presents an ideal configuration of the skyhook semi-active control with a sprung mass m_s hooked by a damper with skyhook damping constant c_{sky} from an imaginary sky (fixed ceiling); hence the name "skyhook" was used. With the damping force of the skyhook damper being F_{damp}, the ideal skyhook control law is presented in Equation 1.

$$F_{damp} = -c_{sky}\dot{x}_s \qquad (1)$$

Here, x_s is the displacement. The skyhook controlled semi-active suspension system (damper) utilizes a small amount of energy to run a valve, which adjusts the damping force. The damper valve can be a fluid valve or a mechanical element if it is a mechanically adjustable damper. In a magnetorheological (MR) damper, the behaviour of rheological fluid changes according to the designed control system.

The active continuous skyhook control policy can also be ideally realized using an actuator or active force generator. Karnopp *et al*. (1994) proposed the skyhook having a two-state control scheme named an ON-OFF control system. This control strategy switches between high and low damping states in order to achieve body comfort specifications. But this control policy offers the damping force as equal to zero when the direction of sprung mass velocity and the relative velocity of the sprung mass with respect to un-sprung mass or ground is opposite. But in practice applying zero damping force is not practicable for any semi-active damper. In 1974 Karnopp *et al*. (1974) realized the complexity of the skyhook ON-OFF control method when it claims the force is need to be equal to zero. However because of the simplicity and practical implementation of the skyhook ON-OFF control strategy, it is widely used for vehicle suspension control (Shen, Y., 2006). In 1983, Karnopp (1983) also proposed a new approach for a semi-active control system which consists of a variable stiffness method. In this control scheme the damper is in a series connection with a spring of high stiffness and the author suggested changing the stiffness of the spring according to the change in the damping coefficient of the damper.

Ahmadian and Vahdati (2006) revealed that much research has been done on other variations of the skyhook control strategy in the past two decades, such as, ON–OFF sky-hook control, optimal sky-hook control, continuous sky-hook control and its modified versions. Li and Goodall (1999) have introduced different control strategies which apply the skyhook damping control strategy for railway vehicle's active suspension system.

In 1983 Margolis *et al*. (Professor, D.L.M., 1983) proposed another ON-OFF control method which simply switches off the damper when the un-sprung mass and the sprung mass move in the same direction, and the un-sprung mass has larger velocity than the sprung mass. Savaresi *et al*., proposed Mixed Skyhook and the ADD control approach (Savaresi, S.M., 2005; Savaresi, S.M. and C. Spelta, 2007) which is a comfort oriented control strategy having the switching strategy. Many researchers have investigated the clipped approaches which lead to unpredictable behaviours. Bessinger *et al*. (1995) presented a modified skyhook control strategy. They modified the original skyhook control strategy proposed by Karnopp *et al*. in 1974. Bakar *et al*., (2008) have also investigated the same strategy in their research. According to this modified skyhook control algorithm, both the passive damper and the skyhook damper effects are included to overcome the problem caused by the application of the original skyhook controller known as the water hammer (Miller, L.R. and C.M. Nobles, 1990; Tong, R.T., 2001). The water hammer problem is one in which the passengers of the vehicle experience unwanted audible noise and harsh jerks produced by the discontinuous forces (caused by low damping switches to high damping or vice versa). Nguyen *et al*. (2009) have proposed a new semi-active control strategy called the optimal skyhook control approach. Soliman *et al*., (2012) proposed an active suspension system controller employing the fuzzy-skyhook control strategy. This control system offered a new opportunity for vehicle ride performance improvement. The simulation result presented in the study shows the improvement of the vehicle ride quality by the proposed active suspension system with fuzzy-skyhook control strategy. Compared to the passive suspension system, the body acceleration of the proposed system decreased. The suspension working space and the dynamic tyre load of the model show better performances too. Islam *et al*., (2005) used skyhook control to compare the performance of Magneto-Rheological, linear passive and asymmetric non-linear dampers. Saad Kashem *et al*., (2012) have proposed a new modified continuous skyhook control strategy with adaptive gain which dictates the vehicle's semi-active suspension system. The proposed closed loop feedback system first captures the road profile input over a certain period. Then it calculates the best possible value of the skyhook gain for the subsequent process. Meanwhile the system is controlled according to the new modified skyhook control law using an initial or previous value of the skyhook gain. In this paper, the proposed suspension system is compared with passive and other recently reported skyhook controlled semi-active suspension systems. Its performances have been evaluated in terms of ride comfort and road handling performance. The model has been validated in accordance to the international standards of admissible acceleration levels ISO2631 and human vibration perception.

The continuous skyhook control of Karnopp *et al*. (1974), modified skyhook control of Bessinger *et al*. (1995), optimal skyhook control of Nguyen *et al*. (2009), and the proposed modified skyhook control strategies used in designing the semi-active suspension system. The control strategies are described below.

Continuous skyhook control of Karnopp et al. (1974):

The semi-active continuous skyhook control strategy of Karnopp *et al*. (1974) is represented by Equation 2.

$$f_d = \begin{cases} \left[\max\left[C_{\min} . \min\left[\dfrac{C_{sky}\, \dot{z}_2}{|\dot{z}_2\, \dot{z}_1|} C_{\max} \right]\right]\right] |\dot{z}_2 - \dot{z}_1| & \text{for } \dot{z}_2 |\dot{z}_2\, \dot{z}_1| \geq 0 \\ C_{\min}\left(\dot{z}_2\, \dot{z}_1\right) & \text{for } \dot{z}_2\left(\dot{z}_2 - \dot{z}_1\right) < 0 \end{cases} \quad (2)$$

Where f_d is the semi-active damping force of the actuator. This strategy is used in many recent studies (Collette, C. and A. Preumont, 2010; Shamsi, A. and N. Choupani, 2008). According to this control strategy, the effective damping of the skyhook damper is bounded by a high and a low level. Determining, whether the damper is to be adjusted to either its low state or its high state depends on the product of the velocity of the spring mass attached to that damper $\dot{z}_2$ and the relative velocity across the suspension damper $\dot{z}_2 - \dot{z}_1$. If this product is greater than or equal to zero, then the high state of the damper is applied. If this product is negative, the damper is adjusted to its low state. In this situation, it is better to supply no force at all but in practice the semi-active damper coefficient is limited by the physical parameters of the conventional damper, which means that there is both an upper bound, C_{max}; and a lower bound, $C_{\min}$ and they have certain values depending on the chosen damper. Here C_{sky} is the nominal damping coefficient selected by the designer and $C_{\max} < C_{\text{sky}} < C_{\min}$.

Modified skyhook control of Bessinger et al. (1995):

The modified skyhook control strategy presented by Bessinger *et al*. (1995) is a modification of the original skyhook control strategy proposed by Karnopp *et al*. in 1974. Bakar *et al*., (2008) have also used the same strategy in their research. Both the passive damper and skyhook damper effects are included in the modified skyhook control algorithm to overcome the problem caused by the application of the original skyhook controller known as the water hammer. The water hammer problem is one where the passenger experiences unwanted harsh jerks and audible noise created by the force discontinuity (caused by low damping switches to high damping or vice versa). Equation 3 presents the equation governing the modified skyhook control algorithm.

$$f_d = C_{sky}\left[\alpha\left(\dot{z}_2 - \dot{z}_1\right) + (1-\alpha)\dot{z}_2\right] \quad (3)$$

Where α is the passive to skyhook ratio and C_{sky} is the damping constant of a modified skyhook control. The value of α is chosen to be 0.5 and an optimal value of C_{sky} is chosen such that the desired force estimated from this control algorithm is to be within the range of damping forces of the designed damper.

Optimal skyhook control of Nguyen et al. (2009):

Nguyen *et al*. (2009) have described the semi-active optimal skyhook control strategy, Equation 4.

$$f_{actual} = \begin{cases} f_{max} & \text{if } f_{max} \le u \\ u & \text{if } f_{min} < u < f_{max} \\ f_{min} & \text{if } f_{min} \ge u \end{cases} \quad (4)$$

Where $f_{actual} = f_d$ is the semi-active damping force of the actuator, $f_{max} = C_{max} \times (\dot{z}_2 - \dot{z}_1)$ and $f_{min} = C_{min} \times (\dot{z}_2 - \dot{z}_1)$ are the maximum and minimum damping forces that can be exerted by the actual damper at a given relative velocity, respectively. $u = C_{sky} \times \dot{z}_2$ is the damping force exerted by the damper where C_{sky} is the optimal damping coefficient obtained from Equations 5 and 6 in the simulation environment.

$$\left(C_{sky}\right)_{Optimal} = \min\left\{ \text{RMS}\left[J\right] \right\} \quad (5)$$

Where

$$RMS\left[J\right] = RMS\left[w_1 \ddot{z}_2 + w_2\left(z_2 - z_1\right) + w_3\left(z_1 - q\right)\right] \quad (6)$$

Here w_i, i =1, 2, 3 are the set values of weighting factors according to the defined objective which is minimizing the criterion of $C_{sky\,(optimal)}$.

Proposed skyhook control with adaptive skyhook gain:

The proposed modified skyhook control algorithm is chosen to provide the desired force in attenuating road harshness in the real world. From the discussion in the literature review, it has been understood that the designers have chosen or derived (trial and error methodology) a constant value of C_{sky} for their skyhook control strategy and used the same value for all road conditions. In the real world, a vehicle is not always travelling on the same type of road and it is very difficult to imitate all types of road surfaces in a simulation environment. The road disturbance interacting with the vehicle tyre in the real world is quite different compared to the road disturbance modelled in the simulation environment. A good semi-active suspension system should provide high damping on good roads for better body isolation, low damping on average roads to achieve good comfort and finally, adequate damping on the poor roads for structural modes. Skyhook gain should be varied according to the road surface on which the vehicle is travelling. The proposed modified skyhook control strategy with adaptive gain (illustrated in Figure 5) is developed to address this problem. A modification of conventional continuous skyhook control has been proposed and it is described by Equation 7.

$$f_d = \begin{cases} C_{max}\left(\dot{z}_1 - \dot{z}_2\right) & \text{if } \dfrac{\dot{z}_2}{\left(\dot{z}_1 - \dot{z}_2\right)} \ge \dfrac{C_{sky}}{C_{max}} \\ C_{sky}\,\dot{z}_2 & \text{if } \dfrac{C_{sky}}{C_{max}} > \dfrac{\dot{z}_2}{\left(\dot{z}_1 - \dot{z}_2\right)} > \dfrac{C_{sky}}{C_{min}} \\ C_{min}\left(\dot{z}_1 - \dot{z}_2\right) & \text{Otherwise} \end{cases} \quad (7)$$

C_{max} and C_{min} represent the maximum and minimum damping coefficient of the actuator respectively. The value of C_{sky} is varied in accordance with the road profile input. The velocity of the sprung mass relative to the un-sprung mass $(\dot{z}_2 - \dot{z}_1)$ is denoted as positive when the base and mass of the suspension system are splitting (i.e., when $z_2 > z_1$). If in Figure 2**Error! Reference source not found.**(b), the sprung and un-sprung masses are splitting, the semi-active damper becomes in tension. As a result, the force f_d works in the negative z_2 direction which is applied to the sprung mass by the actuator. In Equation 8, f_d is pointing in the opposite direction of z_2.

$$f_d = -C_0 \times \dot{z}_2 \quad (8)$$

C_0 is the required damping coefficient of the actuator. Since the actuator is capable of producing a force in the appropriate direction, the only requirement to match the skyhook suspension is presented by Equation 9.

$$C_0 = C_{sky}\frac{\left(\dot{z}_1 - \dot{z}_2\right)}{\dot{z}_2} \quad (9)$$

This control strategy dictates the actuator movement and also determines the specific value of C_{sky} for the road surface on which the vehicle is travelling. At first the road profile input is captured by the tyre deflection measurement over a certain period of time while the vehicle is travelling on the road. Then the quarter-car model identical to 1/4th of the vehicle suspension system is simulated in the simulation environment (on-board system placed in the vehicle) as both uncontrolled (Passive) and controlled (Semi-active) suspension system. The controlled suspension system is dictated by the modified skyhook control strategy described in Equation 7 with a range of C_{sky} (The range is depicted by the rated maximum and minimum damping coefficient of the actuator). The RMS values of sprung mass acceleration of both controlled and uncontrolled suspension systems are calculated and a performance index (PI) is derived by Equation 10 (Sung, K., *et al*., 2008).

$$PI = \frac{\sqrt{\sum_{i=1}^{N} \ddot{z}_{2,C}(i)^2}}{\sqrt{\sum_{i=1}^{N} \ddot{z}_{2,UC}(i)^2}} \qquad (10)$$

The optimal value of C_{sky} is chosen (Equation 11) for which the PI becomes minimum.

$$(C_{sky})_{Optimal} = \min \left\{ [PI] \right\} \qquad (11)$$

This optimal value of C_{sky} replaces the initial value of the skyhook gain of the modified skyhook controller which is dictating 1/4th of the vehicle suspension system for the next certain period of time. This time interval would be determined by the processor speed of the onboard computer of a vehicle. While C_{sky} is calculated the suspension system behaves according to the modified skyhook control law with an initial or previous value of C_{sky}. After each certain period of time interval C_{sky} is adapted according to the road surface to achieve better performance. The whole process is represented in the Figure 5.

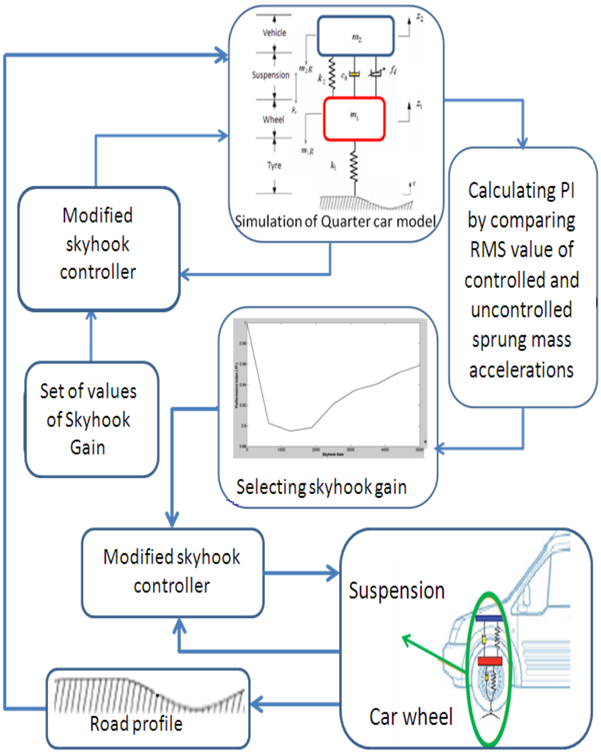

Fig. 5: Schematic of the suspension systems based on proposed modified skyhook control system with adaptive skyhook gain.

Conclusion:

For a long time, active and semi-active suspension systems have been used as a practical application for modern control theory. In this study, many robust and optimal control approaches or algorithms have been reviewed including linear time invariant H-infinity control (LTIH), linear parameter varying control (LPV) and model-predictive controls (MPC). Five widely known control approaches are reviewed more deeply, namely the Linear quadratic regulator & Linear Quadratic Gaussian, sliding mode control, Fuzzy and neuro-fuzzy control and the sky-hook and ground-hook approaches.

It has been found that the skyhook control strategy is the most widely used due to its simplicity for practical implementation. But still, there is a great scope of work yet to be done to modify the skyhook control strategy to achieve better performance. In this paper, a brief discussion on the proposed modified skyhook control approach, optimal skyhook control of Nguyen *et al*. (2009), modified skyhook control of Bessinger *et al*. (1995) and continuous skyhook control of Karnopp *et al*. (1974) has been presented.

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