CHAPTER 2
LITERATURE REVIEW

2.1 INTRODUCTION

It is seen that, over many years, automotive designers are working on the development of a state-of-the-art car with a view to provide better ride comfort and handling characteristics and reliable operation. The focus of their work seems to be on changing the passive suspension principle to innovative active suspension. As such, in this chapter, a brief review of the literature on dynamics of vehicle systems has been carried out. A number of theoretical and experimental investigations on the dynamic response of passive, active and semi-active suspension systems for ground vehicles have been reported. In these investigations various aspects of suspension system design such as, ride comfort, road holding, vehicle handling, road safety and reliability have been studied. Therefore, a literature survey has been carried out on the above mentioned and other related topics connected with design of passive, active and semi-active suspension systems by referring various International Journals: Vehicle System Dynamics, Transactions of the ASME: Journal of Mechanical Design, Journal of Dynamic Systems, Measurement and Control, Journal of Vibration and Acoustics, JSME International Journal Series C, IEEE / ASME Transactions on Mechatronics, Journal of Sound and Vibration, Computing and Control Journal, Proceedings of Institution of Mechanical Engineering (London), SAE Technical Papers etc. and Proceedings of International Conferences such as, American Control Conference, IFToMM World Congress, Biennial ASME Conferences on Engineering Systems Design and Analysis, IEEE Conferences on
Control Applications etc. From this literature survey, some selected research papers have been reviewed, taking into consideration, the following aspects. ...

I) Basic fundamental Studies, human comfort studies, techniques and classifications for Suspension Systems.

II) Theoretical investigations and modeling schemes. Exposure to the main potential benefits and limitations of different suspension systems: passive, semi-active and active systems.

III) Investigation and development of actuation techniques for Active Suspension.

IV) Experimental analysis and modeling with simulation of the suspension strategy.

V) Optimization analysis and control law adaptability, Feasibility and real time applications.

2.2 REVIEW OF BASIC FUNDAMENTAL STUDIES, HUMAN COMFORT STUDIES, TECHNIQUES AND CLASSIFICATIONS FOR SUSPENSION SYSTEMS

D. Hrovat [1] of Ford Research Laboratory, surveys applications of optimal control techniques to the design of active suspensions, starting from simple quarter-car, 1D models, which are followed by their half-car, 2D, and full-car, 3D, counterparts. While the main emphasis is on Linear–Quadratic (LQ) optimal control and active suspensions, the paper also addresses a number of related subjects including semi-active suspensions; robust, adaptive and nonlinear control aspects and some of the important practical considerations. He used the simplest possible, one-degree-of-freedom (DOF), quarter-car models. The resulting optimal suspension design problem fits naturally into the Linear–Quadratic-Gaussian (LQG) technique. It will be argued below that, despite their simplicity, these early contributions had a profound impact on the practical implementation some 15–20 years later,
when the utilization of these theoretical results was made possible by the ever increasing capacity of microcomputers in the automotive industry. Hrovat has studied the effects of the unsprung mass on the active suspension system. The carpet plots were introduced to give a clear global view of the effect of various parameters on the system performances. The carpet plots are the plots of the root mean square (r.m.s) values of the sprung mass acceleration and unsprung mass acceleration versus the suspension travel. The R.M.S. values of all parameters are obtained from a series of simulations on different weights of the performance index.

Prokop and Sharp [2] presents a refined approach for the implementation of preview control in discrete time based on methods from earlier work. This allows the use of multiple preview inputs and reduces the system order of a discrete-time preview system significantly with respect to former methods, while describing the dynamic system in an exact form and yielding an equivalent control law. This method is applied to a limited-bandwidth quarter car system, which incorporates an actuator in series with a passive spring, the combination being in parallel with a passive damper. Control design is carried out using discrete-time linear quadratic regulator (LQR) theory with tyre deflection, suspension working space, vertical body acceleration and control demand. How the optimal preview control law works in a physical sense is worked out regarding the feed forward gain matrix. It is shown that, as a par of the optimal control strategy, the preview controller ‘concentrates’ in some sense on what it can do best for any amount of preview time. The conclusions from that are backed up considering performance indices and their components for variation of preview time, actuator bandwidth and the constraints in the cost function. Emphasis is put on the investigation of how the actuator bandwidth influences the performance capabilities of
the system. General relationships between cost reduction, cost component reduction, preview time and system bandwidth are exposed. By increasing preview time, the cost function can be reduced until it reaches a saturation value, which depends on the actuator bandwidth chosen. Increasing the actuator bandwidth beyond a certain value has only a small influence on the preview time needed for the diminishing returns to set in. Improving the road holding requires fast actuators, but comparatively short preview distances. Ride comfort can be influenced by a rather slow controller, but requires a long preview time.

Watton et al. [3] presented a car suspension incorporating a Lotus actuator and a TVR suspension/wheel unit is studied both experimentally and analytically. An emphasis is placed on hydraulic modeling using a series of transfer functions linking the hydraulic and suspension components. This is significantly aided by the use of a Moog 2000 programmable servo controller (PSC) to equalize the extending and retracting low gains of the servo-valve in the Lotus actuator control loop, justifying the use of combined extending and retracting transient data for parameter identification. This then allows the system equations to be developed using linear state-space theory, and a suitable form is proposed for further design studies. It is shown that the hydraulic components significantly contribute to the system dynamics and hence cannot be neglected when control schemes are formulated. In particular, the significance of hydraulic bulk modulus on dynamic performance is evaluated, and the importance of accurately determining all components of velocity-type damping is highlighted.

Eric Little et al. [4] have presented the most universally accepted ride comfort model, the NASA model. They investigated that, when coupled with a repeatable testing methodology, this model can provide a solid foundation for comparative analysis and effective
optimization of a vehicles ride behavior. They investigated that in combination with a four channel road simulator, engineering design decisions can be efficiently augmented.

Sharp and Crolla [5] has described road surfaces, modeling vehicles and setting up performance criteria to passive, active and semi-active suspension systems. They also elaborated methods of deriving control laws for active systems. They have written an excellent and exhaustive review paper on the research results reported in the literature in the area of development of automotive suspension systems designed for better ride comfort and road holding qualities. Initially taking a brief review of active, semi-active and slow active suspension systems, the paper describes modeling of the road surfaces and performance criteria of suspension systems which include working space, wheel load variations, static and dynamic attitude control etc. Interesting information has been given that the lotus electro-hydraulic active system employed on racing cars and passenger cars and currently being used in Formula -1 Racing. The paper stresses the need of change in the principle of the conventional passive system to convert it in a good suspension system which has better attitude controlling, maneuvering, handling qualities and ride comfort.

D. A. Crolla [6], in his review paper reviews the contributions of vehicle dynamics theory to practical vehicle design. He has nicely highlighted the effect of the suspension on improving the vehicle performance and safety.

The practical constraints which are restricting the commercial development of limited bandwidth active suspension systems have been mentioned. He has observed that electro-hydraulic technology holds the most commercial promise, but major breakthrough in electrohydraulic valve technology will be required leading to reduce
costs if significant further developments are to occur over the next few years.

Dean Karnopp [7] describes the theoretical limitations in active suspensions. He shows, using simple linear two degree-of-freedom suspension system, model that even using complete state feedback, there still are limitations to suspension performance, in the fully active case. The mathematical model of vehicle and suspension is presented in detail. He concluded that many new possibilities exist when a passive suspension is replaced by a feedback controlled force generator.

Masao Nagai [8], has described the limitations of the passive suspension systems and has discussed the solution to overcome the basic problem. The problem of invariant properties of the passive suspension has been described and it has been shown that if the tyre has some damping force, these invariant points do not exist. The merits and limitations of active suspension using hydraulic actuators have been discussed. The optimal control of the active suspension using linear quadratic regulator optimal control theory has been described. It has been pointed out that the active or semi-active suspensions replacing conventional passive elements with controlled actuators can theoretically and practically improve the vibration isolation properties and better handling and stability.

R. A. Williams [9] [10] has categorized suspension systems as adaptive suspensions, semi-active suspensions, low-bandwidth / soft suspensions, high bandwidth / stiff suspensions. It has been pointed out that good vibration isolation requires low resonance frequencies and modest damping, whereas load changes are reacted more effectively by stiff springs and high damping. Two-state and continuously variable dampers for semi-active suspensions have been compared. It has been shown that, combining a semi-active damper with either a low bandwidth or a
high bandwidth active suspension system has the benefit in terms of power requirements.

Semiha et al. [11], constraints on the transfer functions from the road disturbance to the vertical acceleration, the suspension travel, and the tire deflection are derived for a quarter-car active suspension system using the vertical acceleration and the suspension travel measurements for feedback. The derived constraints complement the similar constraints in the literature. By using the factorization approach to feedback stability, it is shown that tire damping couples the motions of the sprung and unsprung masses; and eliminates a constraint at the wheel-hop frequency. 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 is also illustrated.

Alleyne et al. [12], developed Lyapunov-based control algorithm for force tracking control of an electro-hydraulic actuator. Lyapunov-based parameter adaptation is applied, to compensate for the parametric uncertainties. The developed controller relies on an accurate model of the system. To compensate for the parametric uncertainties, a Lyapunov-based parameter adaptation is applied. The adaptation uses a variable structure approach to account for asymmetries present in the system. The coupled control law and the adaptation scheme are applied to an experimental valve-controlled cylinder. Friction modeling and compensation are also discussed. The experimental results show that the nonlinear control algorithm, together with the adaptation scheme, gives a good performance for the specified tracking task. The original adaptive control law is then simplified in several stages with an examination of the output tracking at each stage of simplification. It is shown that the original algorithm can be significantly simplified without too significant a loss of performance. The simplest algorithm corresponds to an adaptive velocity feedback term coupled with a simple force error feedback.
Alleyne et al.[13], presented analysis of a particular force tracking control problem for rectilinear hydraulic actuators governed by servo-valve. He made an attempt to explain why a seemingly innocuous problem is more subtle than initially believed. A motivation for this problem is given along with prior attempts at a simple solution. The solution method evaluated is a common Proportional-Integral-Derivative type of controller. It is shown that the simple PID is quite adequate for other types of control objectives such as force regulation or position tracking. However, this simple solution method is shown to be inadequate for force tracking due to fundamental limitations of the problem formulation on Therefore, more advanced control algorithms (Alleyne, 1994) are shown to be a necessity rather than a luxury.

Bassam [14], investigated Preview control for active suspension systems. Two preview concepts are used: (a) look-ahead preview, where the information relating to roadway disturbances about to be encountered by the moving vehicle is assumed to be sensed, and (b) wheelbase preview, where knowledge of the front wheel states is used to improve performance at the rear of the vehicle. An optimal preview control method is developed for application to half car suspension systems having full active and slow active vibration control elements. The slow active system used consists of an actuator of limited bandwidth in series with a passive spring, the combination being in parallel with a passive damper. Integral constraints are included in the performance index to achieve better body attitude control. The effect of preview control on vehicle performance characteristics in terms of ride comfort, suspension deflections, and road-holding ability is investigated.

Jung-Shan Lin [15], proposed a new nonlinear backstepping design for active suspension systems which aims to improve the tradeoff between ride quality and suspension travel. They showed that intentional introduction of nonlinearity through the controller into an otherwise linear system can be beneficial in cases where the
desired closed-loop response is different in different operating regions. The control design aims to improve the ride quality without letting the suspension travel reach its limits. This requires the closed-loop response to be different for different road disturbance inputs. Using a nonlinear backstepping design, we can easily accommodate this dual objective through the appropriate choice of the variable, that is, of the output to be regulated. In particular, they want to define this output so that it minimizes the displacement of the car body (for ride quality) as long as the suspension travel is small, but shifts its attention to the suspension travel whenever the suspension approaches its travel limits.

Dahlberg [16], optimized the suspension of two-degree-of freedom vehicle travelling on a random corrugated road with respect to both road holding and ride comfort. Optimal comfort is defined as a minimum mean value of the largest maxima of a stationary Gaussian random process. This process is the vertical vehicle seat acceleration weighted with respect to human sensitivity (ISO 2631). Optimal road holding is defined as a minimum probability that the road-wheel contact force will be smaller than a given level. This contact force is conceived as another stationary Gaussian random process. The two criteria are synthesized and the suspension system is optimized with respect to the joint criterion obtained. One restriction accounted for is the limited working space of the vehicle suspension.

Majjad [17] has described a quarter car suspension system model and analyzed it with the help of parameter variations. Simulation results of parameter variation studies show that the variation of the damping characteristics has a big influence on resonance frequencies, which means that, the damper parameters have a notable influence on the ride comfort. It has been shown that a way to improve this comfort is to develop a damper controller. The identification of the damper characteristics and the chassis mass
will be the base for a good design of suspension controller to improve ride comfort.

Karuppaiah et al. [18] have reported the study of vibration analysis of a light passenger vehicle model using a half car model and the finite element method. The rigid body model considered for this analysis of the vehicle is a 4DOF, half car model. The four degrees of freedom are the sprung mass bounce, sprung mass pitching, front axle bounce and rear axle bounce. Also link element modeling has been carried out by discretizing the vehicle in the models like chassis, longitudinal / cross members, the suspensions, the axles and tyres. The chassis and axle members have been modeled as three dimensional beam elements with 6DOF at each mode. The damping characteristics of suspension and tyres have been taken into consideration during dynamic response analysis. Lanczo’s method has been used in computing large number of closely spaced Eigen frequencies of the vehicle. The mode shapes for sprung mass in bounce, pitch and roll modes at various natural frequencies have been obtained. Modeling of random road input has been carried out measuring road profile with height sensors and attendant software.

Wagner et al.[19] has described nonlinear modeling and control of vibration isolation of suspension systems, to minimize the transmission of road surface disturbances to the vehicle occupants. Three such systems have been investigated i. e. passive, semi-active and active. For this semi-active and active actuator configurations such as semi-active hydraulic damper and active electro-mechanical hydraulic actuator have been discussed in detail. Controller design schemes such as, sky hook type, proportional plus integral and variable structure control have also been presented. The experimental investigation has shown that the active actuator achieves better overall vibration isolation performance in comparison to the semi-active actuator.
William Thayer [20] has proposed standards for the specification of electrohydraulic flow control servo-valves. These recommendations were initially compiled and submitted to the AIEE Subcommittee on Component Specifications. In general the recommended specifications tell what parameters are significant for evaluating a servo-valve, rather than stating specific numerical requirements. By this approach valve manufacturers are left reasonable design flexibility to permit and encourage optimum designs for specific applications. Certainly the physical and performance characteristics dictated by different systems and different environments require a diversity of design emphasis. It is well-recognized that certain valve characteristics can often be improved, but usually at the expense of others (including cost).

2.3 REVIEW OF THEORETICAL INVESTIGATIONS AND MODELING SCHEMES. EXPOSURE TO THE MAIN POTENTIAL BENEFITS AND LIMITATIONS OF DIFFERENT SUSPENSION SYSTEMS: PASSIVE, SEMI-ACTIVE AND ACTIVE SYSTEMS

Kloiber Guido Koch and Boris Lohmann [21], presented new control approach for active vehicle suspensions based on modified optimal control problem, which considers the nonlinear damper characteristic of a vehicle suspension setup. In this context a new method for the systematic construction of a control Lyapunov function is presented, that is applicable to a class of nonlinear systems. The states that are required by the controller are estimated from the available measurement signals using a nonlinear Kalman filter concept recently presented by the authors. In order to achieve the best possible performance with respect to the conflicting objectives passenger comfort, ride safety and suspension deflection, the controller parameters are determined by means of a multi objective genetic optimization algorithm. The potential of the controller is demonstrated by comparing it to a conventional linear quadratic regulator. The concept is validated on
a quarter-vehicle test rig using measurements of real road profiles as disturbance input.

Libin Li and Qiang Li [22] presented suspension based on the characteristic of a type of commercial vehicle; a multi-body model of its full suspension system with twenty Degree of Freedom (DOF) was established in MSC.ADAMS. After evaluating relative condition parameters such as stiffness and damping index on the simulation model, the effects of outside exciting on the suspension system have been worked out numerically. The harmonic response of the mass center of the seat at model coordinate space provides reference for the general performance of the suspension system which enables the future design improving.

Shao et al. [23] built the mathematical model of electro-hydraulic position servo control system. They carried out the identification and verification of electro-hydraulic position servo system based on MATLAB Simulation environment. The simulation results show that the steady state error of system is eliminated and the rapidity is enhanced by the hybrid control strategy.

B Gao et al. [24] proposed the Control of a hydro-pneumatic active suspension based on a non-linear quarter-car model, he states that it is extremely difficult to maintain simultaneously a high standard of ride, handling, and body control in a vehicle with a conventional passive suspension. However, it is well known that active suspensions provide a possible solution to this problem, albeit with additional cost and weight. This paper describes the design and analysis of a hydro-pneumatic slow active suspension. The design is based on hydro-pneumatic suspension components taken from a commercial system. A non-linear quarter-car model is developed, which includes a gas strut model developed in a previous study and a non-linear dynamic flow control valve model. A hybrid control strategy is proposed for the disturbance rejection and self-leveling requirements. The disturbance rejection control is based on limited state feedbacks and the linear quadratic method plus a
Kalman filter that is used to optimize the performance index. The self-levelling control employs a proportional, integral, and derivative (PID) control strategy. Practical issues, such as power consumption, controller robustness, and valve dynamics, are also investigated. Simulations show that the proposed system has good performance and robustness.

Kruczek et al. [25] designed the electric linear motor as an actuator for active suspension. They have used the H-Infinity control strategy for quarter, half as well as full car models. Focus is on comparison of different controllers designed for quarter, half and full car models.

Du et al. [26], applied parameter design controller approach to a two-degree-of-freedom quarter-car suspension model for vehicle active suspensions. This approach deals with changes in vehicle inertial properties and existence of actuator time delays. They also presented a fuzzy static output feedback controller design approach for vehicle electrohydraulic active suspensions based on Takagi–Sugeno (T–S) fuzzy modeling technique. The T–S fuzzy model is first applied to represent the nonlinear dynamics of an electrohydraulic suspension. Then, the fuzzy static output feedback controller is designed for the obtained T–S fuzzy model to optimize the H performance of ride comfort through the parallel distributed compensation scheme. The sufficient conditions for the existence of such a controller are derived in terms of linear matrix inequalities (LMIs) with an equality constraint. A computational algorithm is presented to convert the equality constraint into a LMI so that the controller gains can be obtained by solving a minimization problem with LMI constraints. To validate the effectiveness of the proposed approach, two kinds of static output feedback controllers, which use suspension deflection and sprung mass velocity, and suspension deflection only, respectively, as feedback signals, are designed. It is confirmed by the simulations that the designed controllers can achieve good suspension
performance similar to that of the active suspension with optimal skyhook damper.

Kou and Fang [27], have established mathematical model of EHA suspension which shows that sprung mass acceleration for fuzzy active suspension descends by around 35.5 % as compared to passive suspension system. A vehicle active suspension was put forward based on the electro-static actuator which is kind of Power-by-Wire actuation system. A quarter car dynamic model was presented with mechanical cam vibration exciter to generate sinusoidal road signals.

Youn et al. [28], proposed optimal PID controller which includes the PID terms of suspension deflections and the D term of roll and pitch angles. A 7 DOF full car model with optimal active control suspension is utilized to evaluate the vehicle dynamic performances which are achieved through the proposed controller. The optimal controller, which includes the integral action for the suspension deflection, considerably improves the attitude control of a vehicle because the rolling and pitching motion in cornering and braking maneuvers are reduced, respectively.

Shuttlewood, Crolla and Sharp [29], provided the theoretical Results of an Electrically Actuated Hydro-pneumatic Slow-active Suspension. They described the basis of the mechanical arrangement and control structure of a ¼ car representation of an electrically actuated hydro-pneumatic suspension. Control law gains for providing closed loop position control of the pump piston are derived using linear stochastic optimal control theory. Performance results are presented highlighting the possible improvements in ride quality. Mean power consumptions are compared for the electrical system with those for a similar performing flow controlled slow-active suspension. Peak power electrical requirements are also assessed and conclusions drawn as
to the suitability of the system considered for automotive applications.

Cao et al.[30], provides an overview of the latest advances in road vehicle suspension design, dynamics, and control, together with the authors’ perspectives, in the context of vehicle ride, handling, and stability. The general aspects of road vehicle suspension dynamics and design are discussed, followed by descriptions of road-roughness excitations with a particular emphasis on road potholes. Passive suspension system designs and their effects on road vehicle dynamics and stability are presented in terms of in-plane and full-vehicle arrangements. Controlled suspensions are also reviewed and discussed. The paper concludes with some potential research topics, in particular those associated with the development of hybrid and electric vehicles.

Fialho and Balas [31], presents a novel approach to the design of road adaptive active suspensions via a combination of linear parameter-varying control and nonlinear backstepping techniques. Two levels of adaptation are considered: the lower level control design shapes the nonlinear characteristics of the vehicle suspension as a function road conditions, while the higher level design involves adaptive switching between these different nonlinear characteristics, based on the road conditions. A quarter car suspension model with a nonlinear dynamic model of the hydraulic actuator is employed. Suspension deflection, car body acceleration, hydraulic pressure drop, and spool valve displacement are used as feedback signals. Nonlinear simulations show that these adaptive suspension controllers provide superior passenger comfort over the whole range of road conditions.

Rajmani and Hedrick [32], developed the adaptive observer for a class of nonlinear systems, using realistic model of the suspension system incorporating the dynamics of the hydraulic actuator. Adaptive observer yield good experimental performance when
implemented on a half-car suspension test-rig. Conditions for convergence of state and parameter estimates are presented. The developed theory is used for observer-based parameter identification in the active suspension system of an automobile. A realistic model of the suspension system incorporating the dynamics of the hydraulic actuator is used. The observer is used to adapt on dry friction which is usually present in significant magnitudes in hydraulic actuators. The observer can also be used to adapt on spring stiffnesses, viscous damping and hydraulic bulk modulus. A special adaptive observer is proposed for identification of the sprung mass of the automobile. Since the sprung mass depends on the number of passengers and the load on the automobile, it needs to be regularly updated. The adaptive observers use measurements from two accelerometers and an LVDT.

2.4 INVESTIGATION AND DEVELOPMENT OF ACTUATION TECHNIQUES FOR ACTIVE SUSPENSIONS

Mache and Joshi [33] have carried out theoretical and experimental dynamic response analysis of a road vehicle suspension system using an electro-magnetic damper. A 2DOF quarter car model has been analyzed for frequency response analysis. The electro-magnetic damper has been developed using a combination of permanent magnet (PM) and an electromagnet (EM) keeping an air gap between them. Linearizing the magnetic damping force between PM and EM, the values of current and position stiffnesses have been obtained. It has been shown that the electromagnetic damper is effective in reducing the amplitude of vibration over a given range of excitation frequencies, in particular at resonant frequencies. Position and current stiffnesses have been experimentally determined by using the combination of operating curves of force vs current and force vs gap between PM and EM. It is shown that the electrical design of PM and EM combination with an air gap between them is crucial for the damper performance.
Richard Poley [34] described the working and applications of DSP control of electro-hydraulic servo actuators for active suspension system. He states that, Hydraulic actuators are characterized by their ability to impart large forces at high speeds and are used in many industrial motion systems. In applications where good dynamic performance is important it is common to contain the actuator in a servo loop comprising a feedback transducer and electronic controller. The majority of electronic servo-controllers used in these systems are analogue based implementations of the well-known PID type. However, the requirement to implement advanced control strategies has led to an increased interest in the use of digital signal processors (DSPs) in this field. One design approach which merits special consideration is the use of computer simulation software to model the hydraulic plant and electronic servo-controller, and to generate and test embedded code for the target DSP. This application report discusses some of the issues involved in controlling linear hydraulic actuators, and the suitability of the TMS320C28x DSP for such systems.

Zhang and Alleyne [35], have introduced a novel reformulation of the active suspension problem, based on prescribing a given displacement between the sprung and unsprung masses presents a hybrid control approach to circumvent the basic trade-off between performance and robustness from an individual controller. This hybrid control strategy utilizes a robust controller for guaranteed robustness when the plant model is not well known, and employs an adaptive controller for high performance after sufficient plant information has been collected. To avoid a degraded transient after controller switching, a bumpless transfer scheme is designed and incorporated into this hybrid control approach. This bumpless transfer design is an extension from a conventional latent tracking bumpless transfer design for a single input single-output (SISO) plant with 1 degree of freedom (DOF) controllers to either a SISO
plant with multiple DOF controllers or a multi-input multi-output (MIMO) plant. Experimental results implemented on an active vibration isolation test bed demonstrate the effectiveness of the proposed hybrid control strategy.

Shen and Peng [36] compared the AS servo-loop control problem with that of durability test rigs. For both AS and durability test rigs, linearized equations are used so that transfer functions and frequency response can be used for the analysis. Since the lightly-damped zeros (LDZ) of the closed-loop system are the main source of performance limit, the closed-loop transfer functions of the two tracking problems (both force and displacement) analytically. The poles and zeros of the closed-loop transfer functions will then be analyzed. By doing so, the fundamental limits imposed by the LDZ will be clearly understood. It is shown that the displacement control problem also has its own pair of LDZ. Furthermore, while the natural frequency of the displacement control LDZ is a little higher, their damping ratio is lower. Therefore, switching to a displacement control problem is not a complete answer. Subsequently, remedies to reduce the adverse effect of the LDZ are studied. Four candidate approaches are analyzed—new actuator; suspension parameter optimization; add-on mode such as vibration absorbers; and advanced control algorithms. Analysis and simulation results are presented to show the effect of the proposed remedies.

Sam et al. [37], compared the performance of the active suspension system using proportional Integral Sliding mode control scheme and linear quadratic regulator method present a robust strategy in controlling a hydraulically actuated active suspension system. The controller consists of the two controller loops namely inner loop controller for force tracking control of the hydraulic actuator and outer loop controller to reject the effects of road induced disturbances. The outer loop controller utilized a proportional integral sliding mode control (PISMC) scheme. Whereas,
proportional integral (PI) control is used in the inner loop controller to track the hydraulic actuator in such a way that it able to provide the actual force as close as possible with the optimum target force produced by the PISMC controller. A quarter-car model is used in this study and the performance of the controller is compared with the state feedback controller and the existing passive suspension system. A simulation study is performed to prove the effectiveness and robustness of the control approach. Force tracking performance of the hydraulic actuator is also investigated. Kim et al. [38], in their research, provided the design and implementation of a magnetic damper system to reduce the vibration of a suspension system actively. This paper is concerned with the design and implementation of a magnetic damper system to reduce the vibration of a suspension system actively. A cylindrical-type electromagnetic actuator with a permanent magnet is analysed and an effective controller design is made. An accurate force analysis is carried out for the given system. An accurate transfer function for the total system is determined by experimental data using an error minimization method. For experiments, a simple suspension structure system is utilized, in which a magnetic damper composed of a permanent magnet and digital controller is attached. In order to drive the system, a bipolar power amplifier of the voltage control type is utilized. A stable and high speed control board is used to implement digital control logic for the given system. This paper shows that the magnetic damper system using a phase lead controller is excellent in reducing the vibration of a one-degree-of-freedom suspension system.

2.5 EXPERIMENTAL ANALYSIS AND MODELING WITH SIMULATION OF THE SUSPENSION STRATEGY

Senthikumar and Vijayarangan [39], show with their experimentation that active suspension system works better than passive suspension. Also, they have found that, at higher frequencies (1 Hz and more) the performance of active suspension
system deteriorates as force tracking at higher frequencies is difficult. The controller is designed to take necessary actions to improve the performance abilities already set. The controller amplifies the signals which are fed to the actuator to generate the required forces to form closed loop system (active suspension system). The performance of this system is then compared with that of the open loop system (passive suspension system). The developed design allows the suspension system to behave differently in different operating conditions, without compromising on road-holding ability. The effectiveness of this control method has been explained by data from time domains. Proportional-Integral-Derivative (PID) controller has been developed. The Ziegler–Nichols tuning rules are used to determine proportional gain, reset rate and derivative time of PID controller. The experimental investigations on the performance of the developed active suspension control are demonstrated through comparative simulations.

Megahed and Razik [40] presented the dynamic modeling and simulation of a proposed modified design of the vibration control of two d. o. f. primary systems. Lagrange formulation is used to obtain its dynamic model in an analytical form. This model, which is highly nonlinear, is used to develop a computational algorithm to study the absorber performance characteristics. This algorithm is programmed and simulated in Matlab. The obtained results are numerically verified using software. The effect of mass and stiffness of the proposed design on its performance and tuning is discussed. An optimization algorithm is developed to select the best absorber parameters for vibration suppression of a specific primary system. The obtained results show a good agreement with those obtained using similar techniques. In addition, a linearized model of dynamics is developed, tested and simulated for the same data used in its nonlinear model. The relative deviation between results
of the linear and nonlinear models is less than 1%, which confirms the realistic use of this linearized model.

Chatzakos and Papadopoulos [41] presented a fully detailed model of an electrohydraulic servo system, which includes fluid, servo valve, servo actuator and load dynamics, is presented and used for evaluating the proposed model-based controller for force tracking control, both in free and constrained motion. It also compares its position tracking performance to that of a classical linear controller, using intensive simulations. Load dynamic and static parameters are varied widely so as to test the proposed controller in various load conditions. Simulation results show the technique to be promising in providing robust position and force control and in extending the approach to hydraulically driven manipulators and motion platforms.

Lauwerys et al. [42] provided the design and experimental validation of a robust linear controller for an active suspension mounted in a quarter car test rig. The presented approach does not require a (nonlinear) physical model of either the car or the shock-absorber, which are very time consuming to derive. The presented method is based on linear techniques well supported by CACSD-software tools, yielding a fast control design approach, applicable to almost any active suspension system. Linear black box models are identified using frequency domain identification techniques, while robust linear control design techniques (HN and m-synthesis) account for the model uncertainties introduced by the linear model approximation of the nonlinear dynamics. Although this linear approach introduces some conservatism, it is shown that the desired performance is achieved in simulation as well as on the experimental test rig.

C Crivellaro and D C Donha, [43], presents both the theoretical and the experimental approaches of the development of a mathematical model to be used in multi-variable control system designs of an active suspension for a sport utility vehicle (SUV), in this case a
light pickup truck. A complete seven-degree-of-freedom model is successfully quickly identified, with very satisfactory results in simulations and in real experiments conducted with the pickup truck. The novelty of the proposed methodology is the use of commercial software in the early stages of the identification to speed up the process and to minimize the need for a large number of costly experiments. The paper also presents major contributions to the identification of uncertainties in vehicle suspension models and in the development of identification methods using the sequential quadratic programming, where an innovation regarding the calculation of the objective function is proposed and implemented.

Niksefat and Sepehri [44], presents the design and experimental evaluation of an explicit force controller for a hydraulic actuator in the presence of significant system uncertainties and nonlinearities. The nonlinear version of quantitative feedback theory (QFT) is employed to design a robust time-invariant controller. Two approaches are developed to identify linear time-invariant equivalent model that can precisely represent the nonlinear plant, operating over a wide range. The first approach is based on experimental input output measurements, obtained directly from the actual system. The second approach is model-based, and utilizes the general nonlinear mathematical model of a hydraulic actuator interacting with an uncertain environment. Given the equivalent models, a controller is then designed to satisfy a priori specified tracking and stability specifications. The controller enjoys the simplicity of fixed-gain controllers while exhibiting robustness. Experimental tests are performed on a hydraulic actuator equipped with a low-cost proportional valve. The results show that the compensated system is not sensitive to the variation of parameters such as environmental stiffness or supply pressure and can equally work well for various set-point forces.
Benedetto Allotta [45] has designed the layout of the control system (actuation system, sensors, drive and control algorithm, etc.). The proposed control strategy has been successfully calibrated with experimental tests. Testing procedures and experimental results are shown in order to demonstrate the feasibility of the proposed solution and performances achieved by the first Trenitalia prototype, the T2006 pantograph. The semi active suspension system proposed for the T2006 Trenitalia prototype has successfully passed preliminary laboratory tests.

2.6 OPTIMIZATION ANALYSIS AND CONTROL LAW ADAPTABILITY, FEASIBILITY AND REAL TIME APPLICATIONS

Nakkarat and Kuntanapreeda [46], provided a backstepping approach to design a nonlinear controller for force control of a single-rod electro-hydraulic actuator. The control design guarantees the convergence of the tracking error. The implementation of the control design requires system states for feedback, but in this case only the force output is available. To overcome this problem, a PI observer is used to estimate the states of the system. Experimental results have illustrated the success of the observer-based backstepping controller. The results are also compared to those obtained with conventional P and PI controllers. It can be shown that the observer-based backstepping controller has a relatively better tracking performance.

In Salem, and Aly [47], an active suspension system has been proposed to improve the ride comfort. A quarter-car 2 degree-of-freedom (DOF) system is designed and constructed on the basis of the concept of a four-wheel independent suspension to simulate the actions of an active vehicle suspension system. The purpose of a suspension system is to support the vehicle body and increase ride comfort. The aim of the work described in the paper was to illustrate the application of fuzzy logic technique to the control of a
continuously damping automotive suspension system. The ride comfort is improved by means of the reduction of the body acceleration caused by the car body when road disturbances from smooth road and real road roughness. The paper describes also the model and controller used in the study and discusses the vehicle response results obtained from a range of road input simulations. In the conclusion, a comparison of active suspension fuzzy control and Proportional Integration derivative (PID) control is shown using MATLAB simulations.

Choi and Sung [48], in their paper, presented vibration control of a semi-active magneto rheological (MR) suspension system subjected to parameter variations. They examined the effect of an electromagnetically optimized magnetorheological (MR) damper for vehicle suspension on vibration control performance. In order to achieve this goal, a cylindrical MR damper that satisfies design specifications for a middle-sized commercial passenger vehicle is designed using an optimization methodology. The optimization problem is to find the optimal geometric dimensions of the electromagnetic circuit for the MR damper in order to maximize the damping force. A first-order optimization method using commercial finite element method (FEM) software is adopted for the constrained optimization algorithm. After manufacturing the MR damper with optimally obtained design parameters, its field-dependent characteristics are experimentally evaluated. The effect of the optimal MR damper on suspension control is then investigated using a quarter-vehicle test facility. Control performances such as vertical acceleration, suspension travel, and power consumption are evaluated and compared between the initial and optimal dampers. In addition, vibration control performances of the optimal MR damper are experimentally evaluated under bump and random road conditions and presented in both time and frequency domains.
Liu and Luo [49], presents gain scheduling control strategy. Combination of LQR control and nonlinear backstepping techniques are adapted to the changes of road input in order to provide optimal suspension performance in different conditions. This paper presents an adaptive gain scheduling control strategy for vehicle suspension design. A quarter car suspension model with a nonlinear dynamic model of the hydraulic actuator is employed. The feedback control gains of the controller designed using a combination of LQR control and nonlinear backstepping techniques are adapted to the changes of road input in order to provide optimal suspension performance in different conditions. Simulations show that the control strategy is feasible and effective.

Kaddissi et al. [50], studies the control of an electro-hydraulic active suspension, based on the backstepping control strategy. Electrohydraulic systems are known to be highly nonlinear and non-differentiable. Backstepping is used for being a powerful, nonlinear control strategy and for its ability to ensure an asymptotic stability of the controlled system without canceling useful nonlinearities. On the other hand, hydraulic parameters are prone to variations; it is, therefore, useful to employ an adaptive control strategy in order to update the controller with the parameters variation. In such a case, indirect adaptive control is highly recommended, among other adaptive controller types, as it has the benefit of identifying the real system parameters value. Since not much literature is available for the indirect method as applied to the hydraulic systems, because of its implementation complexity, this paper shows how efficiently this method can handle the parameter estimates.

Chantranuwathana and Peng [51], have applied the modular adaptive robust control (MARC) technique to design the force loop controller of an electro-hydraulic active suspension system. This paper presents a nonlinear active suspension controller, which achieves high performance by compensating for the hydraulic
actuator dynamics. The control design problem is decomposed into two loops. At the top is the main loop, which calculates the desired force signal by using a standard LQ design process. An Adaptive Robust Control technique is used to design a force controller such that it is robust against actuator uncertainties. Both State feedback and output feedback algorithms are presented. Simulation results show that the proposed controller works well compared with conventional controllers.

Vaughan et.al [52], discusses the effects of payload changes in heavy machinery and a suspension control system to compensate for these changes. A half vehicle model is used in which the vertical and pitch motions of the mass supported by the suspension and the vertical motion of the suspension masses are considered. Upon receiving a load, the dynamics of a vehicle can change significantly. To simulate the change in vehicle load, the center of mass is moved and the total mass is increased. Various load changes are simulated by changing the amount by which the center of mass moves and varying the increase in the total mass. Suspension performance is measured for unloaded and loaded vehicles, and for loaded vehicles with passive and active suspension systems. Actively controlled suspensions system are shown to improve vehicle dynamics for both front and rear loaded vehicles.

Song et.al [53], provides an overview of the latest advances in road vehicle suspension design, dynamics, and control, together with the authors’ perspectives, in the context of vehicle ride, handling, and stability. The general aspects of road vehicle suspension dynamics and design are discussed, followed by descriptions of road-roughness excitations with a particular emphasis on road potholes. Passive suspension system designs and their effects on road vehicle dynamics and stability are presented in terms of in-plane and full-vehicle arrangements. Controlled suspensions are also reviewed and discussed. The paper concludes with some
potential research topics, in particular those associated with the development of hybrid and electric vehicles.

They presented a new adaptive semi-active control algorithm developed for nonlinear systems exposed to broadband non-stationary random vibration sources.

Anakwa et al [54], describes prototype pneumatic active suspension systems and its mathematical model using MATLAB and Simulink. They described a prototype pneumatic active suspension system, which was designed and built over a number of years as a sequence of student projects. The physical plant, which models a quarter-car suspension, consists of a wheel, coil springs, a pneumatic actuator for active damping, position, and velocity sensors, and an alternating current (ac) motor for simulating road disturbance input signal. An electronic subsystem is used to process the sensor signals which are sent to a Motorola 68HC16 microcontroller-based evaluation board. The microcontroller controls a four-bit automatic binary regulator that controls airflow to the pneumatic actuator for damping. A mathematical model of the suspension system was derived analytically and validated experimentally. MATLAB and Simulink were used to analyze and design a digital state feedback plus integral controller for the system. The digital controller was implemented.

J Cao and Liu [55] reviewed the computational intelligence involved approaches in active vehicle suspension control systems with a focus on the problems raised in practical implementations by their non-linear and uncertain properties. After a brief introduction on active suspension models, the paper explores state of the art in fuzzy inference systems, neural networks, genetic algorithms and their combination for suspension control issues. Discussion and comments are provided based on the reviewed simulation and experimental results. The paper is concluded with remarks and future directions.
Yucheng Liu [56] has described briefly review of some of the recent patents (since 2000) in designing advanced suspension systems. He has described different types of suspension systems, properties and important auxiliary components. Also, some future trends of research in the suspension system design have been discussed. He has stated that compared to the mechanical linkages, in addition to providing better reliability, the hydraulic and electronic control systems can react to road conditions or short term vehicle acceleration instantly and perform appropriate adjustments automatically. **In sum, the incorporation of hydraulic and electronic systems in the suspension systems can be a future trend of research in this area.**

Also, various websites related to the topic of the research have been visited. Industrial and Research visits have been carried out to A.R.A.I., Pune, I.I.T., Gwalior, I.I.T., Guwahati, I.I.T., Bombay, Indian Smelting Corporation Ltd., Mumbai, and V.R.D.E., Ahamednagar.

In the next chapter, the theoretical analysis of the 2DOF Quarter Car Active Suspension System has been presented.