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Vehicle Suspension Systems Control: A Review

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***Abstract*—increased competition on the automotive market has forced companies to research alternative strategies to classical passive suspension systems. In order to improve handling and comfort performance, instead of a conventional static spring and damper system, semi-active and active systems are being developed. 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 this paper is to illustrate the application of intelligent 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 intelligent control and classical control is shown.

Index Terms—Active Suspensions; Vehicle System; Artificial Intelligence Technique; Intelligent Control.

I. INTRODUCTION

An active suspension system possesses the ability to reduce acceleration of sprung mass continuously as well as to minimize suspension deflection, which results in improvement of tire grip with the road surface, thus, brake, traction control and vehicle maneuverability can be considerably improved. Today, a rebellious race is taking place among the automotive industry so as to produce highly developed models. One of the performance requirements is advanced suspension systems which prevent the road disturbances to affect the passenger comfort while increasing riding capabilities and performing a smooth drive. While the purpose of the suspension system is to provide a smooth ride in the car and to help maintain control of the vehicle over rough terrain or in case of sudden stops, increasing ride comfort results in larger suspension stroke and smaller damping in the wheel hop mode [1]. Many control methods have been proposed to overcome these suspension problems. Many active suspension control approaches such as Linear Quadratic Gaussian (LQG) control, adaptive control, and non-linear control are developed and proposed so as to manage the occurring problems [2-4].

During the last decades fuzzy logic has implemented very fast hence the first paper in fuzzy set theory, which is now considered to be the influential paper of the subject, was written by Zadeh [5], who is considered the founding father of the field. Then in 1975, Mamdani, developed Zadeh`s work and demonstrated the viability of Fuzzy Logic Control (FLC) for a small model steam engine. Replacement of the spring-damper suspensions of automobiles by active systems has the potential of improving safety and comfort under nominal conditions. But perhaps more important, it allows continuous adaptation to different road surface quality and driving situations. For the design of active suspension we know how to build a model and how to define the objective of the control in order to reach a compromise between contradictory requirements like ride comfort and road holding by changing the force between the wheel and chassis masses. In the recent past, it has been reported on this problem successively, about the base of optimization techniques, adaptive control and even, H-infinity robust methods. The use of active suspension on road vehicles has been considered for many years [6- 10]. A large number of different arrangements from semi-active to fully active schemes have been investigated [11- 14]. There has also been interest in characterizing the degrees of freedom and constraints involved in active suspension design. Constraints on the achievable response have been investigated from “invariant points”, transfer-function and energy/passivity point of view in [15- 19]. In [18], a complete set of constraints was derived on the road and load disturbance response transfer functions and results on the choice of sensors needed to achieve these degrees of freedom independently were obtained for the quarter-car model. The generalization of these results to half- and full-car models was then presented in [20]. In [21] it was shown

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that the road and load disturbance responses cannot be adjusted independently for any passive suspension applied to a quarter-car model.

In this study, an automatic suspension system for a quarter car is considered and an intelligent controller is designed when the vehicle is experiencing any road disturbance (i.e. pot holes, cracks, and uneven pavement), the vehicle body should not have large oscillations, and the oscillations should dissipate quickly (see Fig.1). The road disturbance is simulated by a step input as a soft road test and rough road as a simulated to real way and the distance between the body mass and simulation mass is output of the system.

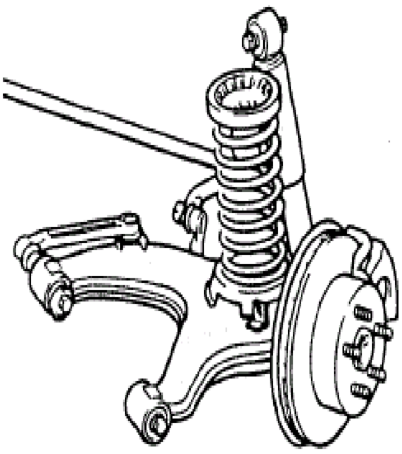

Fig.1. a. Schematic quarter car model.

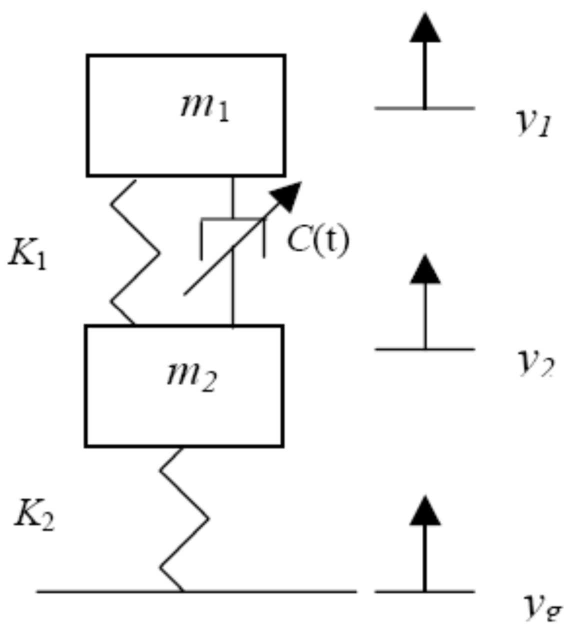

Fig.1.b. quarter car model

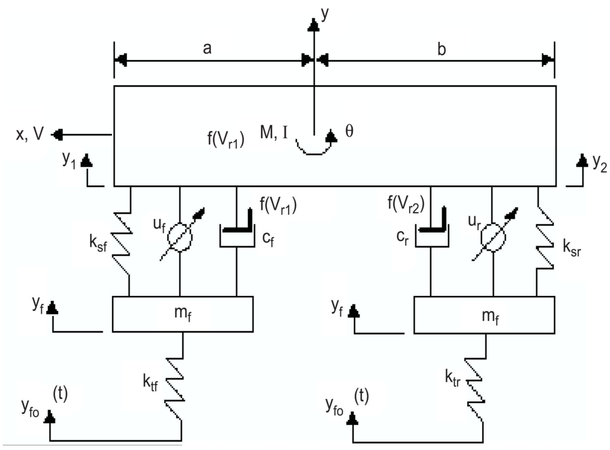

Fig.1.c half car model, [17].

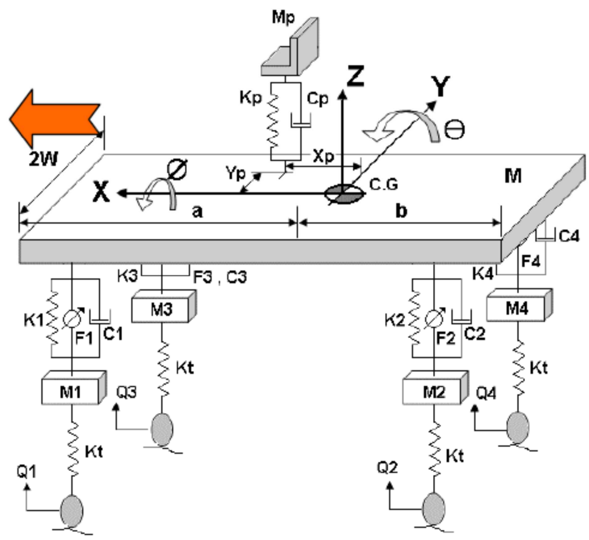

Fig.1.d. full car model, [18]

The objective of the present report is to highlight the different technological processes used for suspension Systems Control as a first step in the recent paper.

II. SUSPENSION SYSTEM MODEL

Passive suspensions as shown in Fig.1. can only achieve good ride comfort or good road holding since these two criteria conflict each other and necessitate different spring and damper characteristics. While semi-active suspense with their variable damping characteristics and low power consumption, on systems offer a considerable improvement, [22, 23].

A significant improvement can be achieved by using of an active suspension system, which supplied a higher power from an external source to generate suspension forces to achieve the desired performance. The force may be a function of several variables which can be measured or

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remotely sensed by various sensors, so the flexibility can be greatly increased.

With rapid advances in electronic technologies [24],The development of design techniques for the synthesis of active vehicle suspension systems has been an active area of research over the last two decades to achieve a better compromise during various driving conditions.[25-30].

Automotive companies are competing to make more developed cars, while comfort of passengers is an important demand and everyone expects from industries to improve it day by day. Therefore, in order to provide a smooth ride and satisfy passengers comfort, designing a modern suspension system is mandatory. A good and efficient suspension system must rapidly absorb road shocks and then return to its normal position, slowly. However, in a passive suspension system with a soft spring, movements will be high, while using hard springs causes hard moves due to road roughness [31-37]. Therefore, it's difficult to achieve good performance with a passive suspension system.

In order to fulfill the objective of designing an active suspension system i.e. to increase the ride comfort and road handling, there are three parameters to be observed in the simulations. The three parameters are the wheel deflection, dynamic tire load and car body acceleration. For definition of the allowable limits of car body acceleration, there is a frequency domain where human beings are most sensitive to vibration (human sensitivity band). Fig. 3 give a measured result from a report of ISO/DIS 5349 & ISO 2631 - 1978, which shows the human endurance limit to frequency band to vertical acceleration is 4 ~ 8Hz, which means that for the purpose of improving the ride comfort the car body acceleration gain should be in this range [38].
In order to improve the ride quality, it is important to isolate the body, also called sprung mass, from the road disturbances and to decrease the resonance peak of the sprung mass near 1 Hz, which is known to be a sensitive frequency to the human body. In order to improve the ride stability, it is important to keep the tire in contact with the road surface and therefore to decrease the resonance peak near 10 Hz, which is the resonance frequency of the wheel also called unsprung mass.

As can be seen from Fig. 4, the fixed setting of a passive suspension system is always a compromise between comfort and safety for any given input set of road conditions on one hand and payload suspension parameters on the other. Semi-active/active suspension systems try to solve or at least reduce this conflict. In this regard, the mechanism of semi-active suspension systems is the adaptation of the damping and/or the stiffness of the spring to the actual demands. Active suspension systems in contrast provide an extra force input in addition to possible existing passive systems and therefore need much more energy. The illustration of Fig. 4 also clarifies the dependency of a vehicle suspension setup on parameter changes as a result of temperature, deflection, and wear and tear. These changes must be taken into account when designing a controller for an active or semi-active suspension to avoid unnecessary performance loss.

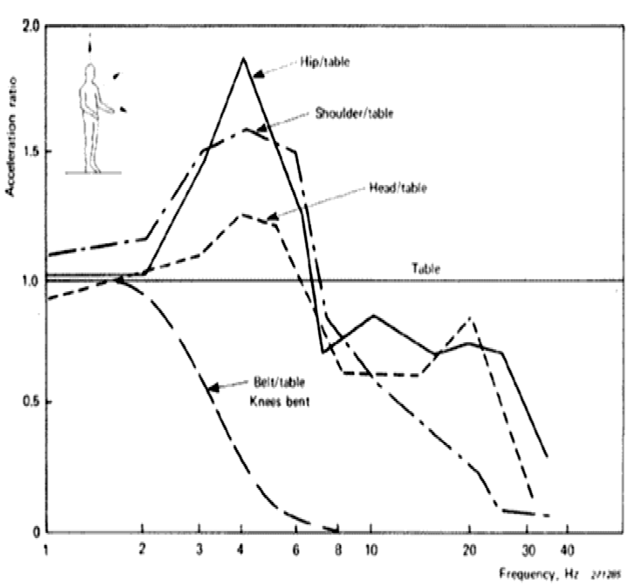

Fig.3. Transmissibility of vertical vibration from table to human body[38]

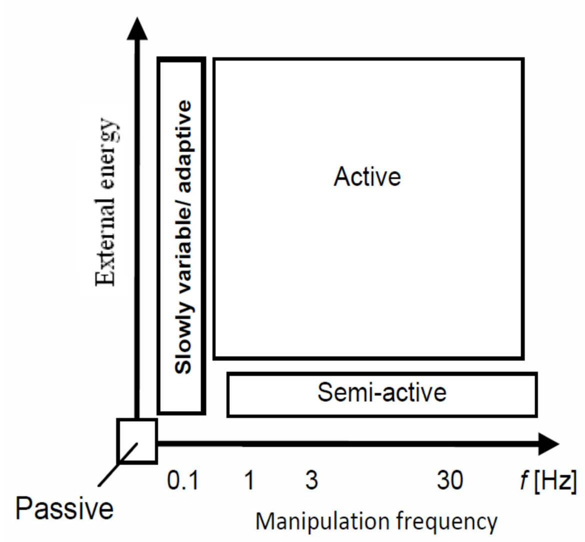

Fig. 4 Comparison between passive, adaptive, semi-active system, [40]

Ideally, a vehicle suspension would respond just as well to aggressive driving as it does to highway cruising. The intent of this work is to try to approach this ideal. Fig. 5 illustrates the classic suspension compromise.

A typical vehicle suspension is made up of two components: a spring and a damper. The spring is chosen based solely on the weight of the vehicle, while the damper is the component that defines the suspension's placement

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on the compromise curve. Depending on the type of vehicle, a damper is chosen to make the vehicle perform best in its application. Ideally, the damper should isolate passengers from low-frequency road disturbances and absorb high-frequency road disturbances. Passengers are best isolated from low-frequency disturbances when the damping is high. However, high damping provides poor high frequency absorption. Conversely, when the damping is low, the damper offers sufficient high-frequency absorption, at the expense of low-frequency isolation.

The need to reduce the effects of this compromise has given rise to several new advancements in automotive suspensions. Three types of suspensions that will be reviewed here are passive, fully active, and semi-active suspensions. A conventional passive suspension is composed of a spring and a damper. The suspension stores energy in the spring and dissipates energy through the damper. Both components are fixed at the design stage. For this reason, this type of suspension falls victim to the classic suspension compromise.

Figure 7. In general, only a compromise between these two conflicting criteria can be obtained if the suspension is developed by using passive springs and dampers. This also applies to modern wheel suspensions and therefore a break-through to build a safer and more comfortable car out of passive components is below expectation. The answer to this problem seems to be found only in the development of an active suspension system.

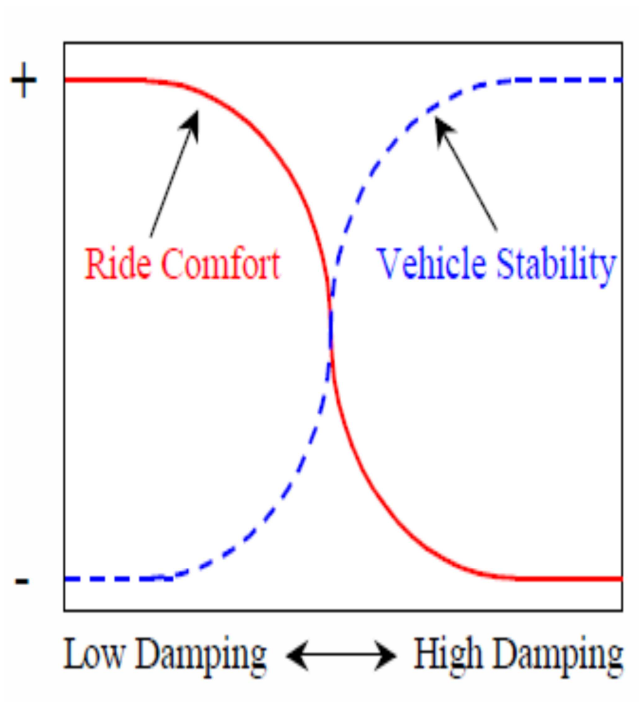

Fig. 5 Suspension Compromise, [41]

III. QUARTER VEHICLE ACTIVE SUSPENSION SYSTEM

In this search, we are considering a quarter car model with two degrees of freedom. This model uses a unit to create the control force between body mass and wheel mass, [36].

The motion equations of the car body and the wheel are as follows:

$$m_b \ddot{z}_b = f_a - k_1(z_b - z_w) - c_s(\dot{z}_b - \dot{z}_w)$$

$$m_w \ddot{z}_w = -f_a + k_1(z_b - z_w) - k_2(z_w - z_r)$$

with the following constants and variables which respect the static equilibrium position:

- m_b body mass (one quarter of the total body mass) 250 kg
- m_w wheel mass, 35 kg
- k_1 spring constant (stiffness) of the body 16 000 N/m
- k_2 spring constant (stiffness) of the wheel 160 000 N/m
- f_a desired force by the cylinder
- c_s damping ratio of the damper 980 Ns/m
- z_r road displacements
- z_b body displacement
- z_w wheel displacements

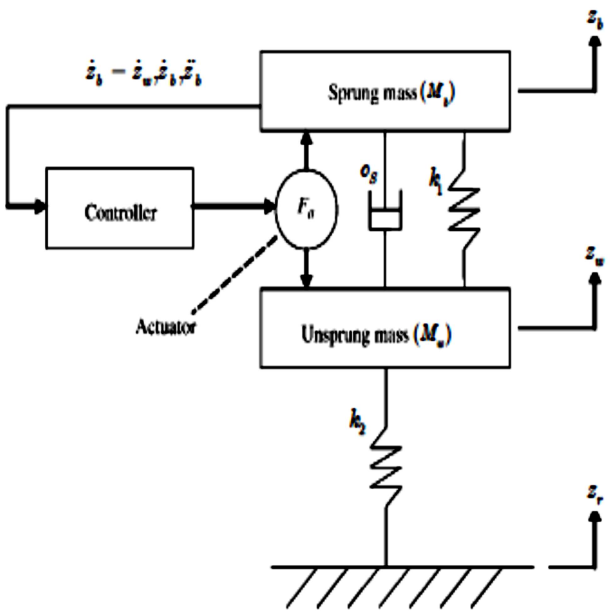

Fig.8 Suspension system block diagram

To model the road input let us assume that the vehicle is moving with a constant forward speed. Then the vertical velocity can be taken as a white noise process which is approximately true for most of real roadways.

To transform the motion equations of the quarter car model into a space state model, the following state variables are considered:

$$x=[x_1, x_2, x_3, x_4]^T$$

where:

$x_1= z_b-z_w$ body displacement
$x_2= z_w-z_r$ wheel displacement
$x_3= \dot{z}_b$ absolute velocity of the body
$x_4= \dot{z}_w$ absolute velocity of the wheel

Then the motion equations of the quarter car model for the active suspension can be written in state space form as follows:

$$\dot{x} = A.x + B.f_a + F.\dot{z}_r$$

with

$$A=\begin{bmatrix} 0 & 0 & 1 & -1 \\ 0 & 0 & 0 & 1 \\ -\frac{k_1}{m_b} & 0 & -\frac{c_s}{m_b} & \frac{c_s}{m_b} \\ \frac{k_1}{m_w} & -\frac{k_2}{m_w} & \frac{c_s}{m_w} & -\frac{c_s}{m_w} \end{bmatrix}$$

$$B=\begin{bmatrix} 0 \\ 0 \\ \frac{1}{m_b} \\ -\frac{1}{m_w} \end{bmatrix} \qquad F=\begin{bmatrix} 0 \\ -1 \\ 0 \\ 0 \end{bmatrix}$$

IV. SYSTEMS AND TECHNOLOGIES FOR SUSPENSIONS SYSTEMS CONTROL

Two criteria of good vehicle suspension performance are typically their ability to provide good road handling and increased passenger comfort. The main disturbance affecting these two criteria is terrain irregularities. Active suspension control systems reduce these undesirable effects by isolating car body motion from vibrations at the wheels.

Vehicle suspension system performance is typically rated by its ability to provide improved road handling and improved passenger comfort. Current automobile suspension systems using passive components can only offer a compromise between these two conflicting criteria by providing spring and damping coefficients with fixed rates.

Sport cars usually have stiff, harsh suspensions with poor passenger comfort while luxury sedans offer softer suspensions but poor road handling capabilities. The traditional engineering practice of designing spring and damping functions as two separate functions has been a compromise from its inception in the late 1800s. Poor road handling capability and decreased passenger comfort are due to excess car body vibrations resulting in artificial vehicle speed limitations, reduced vehicle-frame life, biological effects on passengers, and detrimental consequences to cargo. Active suspension control systems aim to ameliorate these undesirable effects by isolating the car body from wheel vibrations induced by uneven terrain.

The main objective of suspension systems is to reduce motions of the sprung mass. It is well known that motions of the sprung mass at the wheel frequency modes cannot be reduced if the only control input is a force applied between the sprung and unsprung masses (as is the case for vehicle suspension systems). Many control approaches have been investigated for the quarter-vehicle case such as nonlinear control [42-46], optimal control [47-49] and backstepping control [50]. Additionally, optimal control approaches have been applied to the full-vehicle case as well [45, 46]. An active suspension system should be able to provide different behavioral characteristics dependent upon various road conditions and be able to do so without going beyond its travel limits.

It is shown in [51] that using a force control loop to compensate for the hydraulic dynamics can destabilize the system. This full nonlinear control problem of active suspensions has been investigated using several approaches including optimal control

Moreover, several assumptions of linearity in the parameters are needed, which may not be satisfied by actual systems. The use of fuzzy logic (FL) systems has accelerated in recent years in many areas, including feedback control. A fuzzy logic approach for the active control of a hydropneumatic actuator is presented in [52]. Particularly important in FL control are the universal function approximation capabilities of FL systems [53, 54]. Given these recent results, some rigorous design techniques for FL feedback control based on adaptive control approaches have now been given [55, 56]. FL systems offer significant advantages over adaptive control, including no requirement for linearity in the parameters assumptions and no need to compute a regression matrix for each specific system.

Since Zadeh [57] initiated the fuzzy set theory, Fuzzy Logic Control (FLC) schemes have been widely developed and successfully applied to many real world applications [58]. Besides, FLC schemes have been used to control suspension systems. For example, Salem and Aly [36], designed a quarter-car system on the basis of the concept of a four-wheel independent suspension system. They proposed a fuzzy control for active suspension system to improve the ride comfort.

Gaspar et al. in Reference [59] have used a robust controller for a full vehicle linear active suspension system using the mixed parameter synthesis. A sliding mode technique is designed for a linear full vehicle active suspension system [60]. A method is developed for the purpose of sensor fault diagnosis and accommodation. In Reference [61], the authors presented the development of an integrated control system of active front steering and normal force control using fuzzy reasoning to enhance the full vehicle model handling performance.

Due to the fact that strong nonlinearity inherently exists in the damper and spring components [62-65], inevitably the nonlinear effect must be taken into account in designing the controller for practical active suspension systems. Account the three motions of the vehicle: vertical movement at centre of gravity, pitching movement and rolling movement. An intelligent controller can be used to design a control system for a full vehicle nonlinear active suspension system such as Neural Controller (NC). Neural Networks (NNs) are capable of handling complex and nonlinear problems, process information rapidly and can reduce the engineering effort required in controller model development. Artificial neural networks are made up of a simplified individual models of the biological neuron that are connected together to form a network. It consists of a pool of simple processing units which communicate by sending signals to each other over a large number of weighted connections. Capability of learning information by example; ability to generalize to new input and robustness to noisy data are the important properties of neural networks. From these properties, neural networks are able to solve complex problems that are currently intractable. The artificial neural network is an intelligent device wildly used to design robust controllers for nonlinear processes in engineering problems. In many publications, neural networks are used to design controllers, such as the model reference adaptive control, model predictive control, nonlinear internal model control, adaptive inverse control system and neural adaptive feedback linearization [66-67]. The control architectures in these papers depend on designing a neural network identifier and then this identifier is used as a path to propagate the error between the output of the process and output of the reference model to train and select the optimal values of the neural network control. Therefore, in those methods two neural networks were trained to track several control objectives. One of the main advantages of using a neural network as a controller is that neural networks are universal function approximations which learn on the basis of examples and may be immediately applied in an adaptive control system because of their capacity to adapt in real time. There are many learning algorithms available to obtain the optimal values of the trainable parameters of neural network. The back-propagation algorithm (BPA) has been known as an algorithm with a very poor convergence rate. The Levenberg-Marquardt Algorithm (LMA) is an iterative technique that locates the minimum of a multivariate function that is expressed as the sum of squares of nonlinear real-valued functions [68, 69]. To improve the riding comfort and road handling, a neural network controller for full vehicle nonlinear active suspension systems with hydraulic actuators has been proposed by the authors.

ANNs are mainly concerned with learning and curve fitting. These intelligent computing methodologies have resulted in the development of the “intelligent control” field, which consists of novel control approaches based on FL, ANNs, EC, and other techniques induced from artificial intelligence and their combination. These methods provide an extensive freedom for control engineers to deal with practical problems of vagueness, uncertainty, or imprecision. These intelligent methods are good candidates for alleviating the problems associated with active suspension control systems [70,71].

In comparison with hard computing, soft computing provides the tolerance for imprecision and uncertainty which is exploited to achieve a practically acceptable solution at a reasonable cost, tractability, and high machine intelligence quotient (MIQ). Zadeh argues that soft computing, rather than hard computing, should be viewed as the foundation of machine intelligence. A full comparison of their capabilities in different application fields was constructed by Fukuda and Shimojima in Table 1, together with those of control theory and artificial intelligence (Fukuda & Kubota, 1999), [72].

A sampling of the research done for different control approaches is shown in Fig. 9. One of the technologies that has been applied in the various aspects of suspension control system is soft computing.

V. CONCLUSIONS

Suspensions control is highly a difficult control problem due to the complicated relationship between its components and parameters. The researches were carried out in suspensions control systems cover a broad range of design issues and challenges. In the present survey we explored the techniques of solution procedures of different control policies such as classical and intelligent control strategies.

Table 2: Comparison of capabilities of different adaptive mthodologies, [72]

	Mathematical Model	Learning Data	Operator Knowledge	Real Time	Knowledge Representation	Non-linearity	Optimisation
Control Theory	Good or Suitable	Unsuitable	Needs other methods	Good or Suitable	Unsuitable	Unsuitable	Unsuitable
Neural Network	Unsuitable	Good or Suitable	Unsuitable	Good or Suitable	Unsuitable	Good or Suitable	Fair
Fuzzy Logic	Fair	Unsuitable	Good or Suitable	Good or Suitable	Needs other methods	Good or Suitable	Unsuitable
other Artificial Intelligence	Needs other methods	Unsuitable	Good or Suitable	Unsuitable	Good or Suitable	Needs other methods	Unsuitable
Genetic Algorithms	Unsuitable	Good or Suitable	Unsuitable	Needs other methods	Unsuitable	Good or Suitable	Good or Suitable

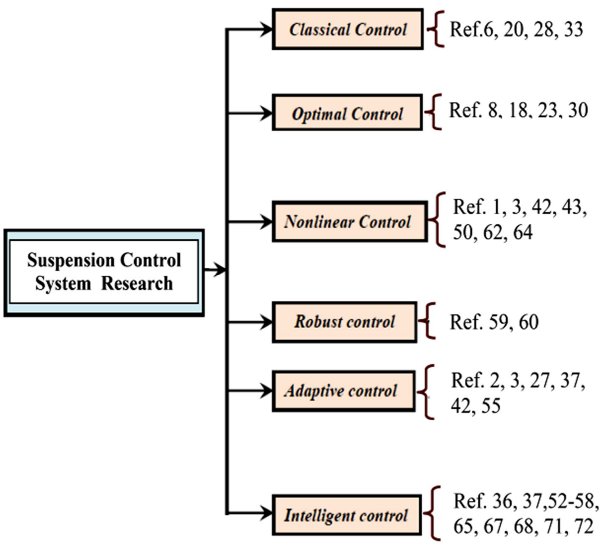

Fig. 9.Sampling of suspension systems control.

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