Active Suspension System for Passenger Vehicle using Active Force Control with Iterative Learning Algorithm

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Abstract: - The paper describes the practical implementation of a new hybrid control method to a vehicle suspension system using Active Force Control (AFC) with Iterative Learning (IL) and proportional-integral-derivative (PID) control strategy. The overall control system essentially comprises three feedback control loops to cater for a number of specific tasks; the innermost loop for the force tracking of the pneumatic actuator using a PI controller, the intermediate loops implementing AFC with IL algorithm strategy for the compensation of the disturbances, and the outermost loop using a PID controller for the computation of the desired force. A number of experiments were carried out on a physical quarter car test rig with hardware-in-the-loop simulation (HILS) feature that fully incorporates the theoretical elements. The performance of the proposed control method was evaluated and benchmarked to examine the effectiveness of the system in suppressing the vibration effect. It was found that the experimental results demonstrate the superiority of the active suspension system with AFCIL scheme compared to the PID and passive counterparts. The vertical body acceleration and displacements are clearly reduced, thereby implying that the ride comfort aspect of the system is improved via the proposed control scheme.

Key-Words: - Active Suspension, Active Force Control, Iterative Learning Algorithm, Ride Comfort, Hardware-in-the-loop Simulation.

1 Introduction

Ride comfort has become one of the important criteria in a passenger vehicle. Isolating the passenger compartment from the vibration sources is the main idea in achieving a good ride comfort. This role is mainly covered by the suspension system of a car. Conventional suspension system has fix criteria of spring and damping coefficient usually cannot give the best ride comfort as the road profile is different depending on area. Besides, it is also subjected to the needs of maintaining the handling as the suspension system also plays a main role on vehicle stability. Thus, this conventional passive suspension system is usually designed based on certain criteria of the vehicle which the suspension will be installed. The basic part of a passive suspension system is a damper and a coil spring. These two mechanical components have some limitation in isolating vibration especially in various types of road profiles.

It is quite evident that the automotive manufacturers tend to compete with each other to produce reliable and having good ride comfort characteristics while at the same time, very stable during cornering and braking (good ride handling). Passive suspension, however could only offer one of those characteristics or a compromise between ride comfort and handling. Some manufacturers then offer adjustable suspension system which can be adjusted to be very comfort or stable according to the driver needs. Researchers then proposed and implemented various semi-active and active vehicle suspension systems both theoretically as well experimentally [1]. Ride comfort which is the main concern of this study is determined by looking at how much the suspension could keep the vehicle passenger (i.e., the vehicle body or sprung mass) from the vibration source whereas stability or handling refers more to controlling the dynamic behaviour of the vehicle during steering and braking [2]. Both characteristics are actually the main factor that contributes to safety and driver action in various traffic situations [3]. As an indicator, a ride is considered to be comfort when the natural frequency is around 1-1.5 Hz. When the natural frequency has reached 2 Hz, it is considered as an uncomfortable ride [4]. It is also essential to keep the body acceleration as low as possible for a comfortable ride.

Researchers recently give more attention in applying active suspension approach into real-time application. Huang and Cheng used hydraulic actuator on a quarter car suspension system and develop a sliding controller with self-tuning fuzzy compensation that is able to accommodate the nonlinearity of the hydraulic actuator [5]. The research is based on an improved conventional sliding mode controller method capable to reduce the sprung mass oscillation amplitude in the wake of uncertainties. Lin *et al.* proposed a similar control scheme as Huang and Cheng [6]. They utilised a sliding mode controller with fuzzy compensation but did not manage to improve the ride comfort. Instead, the proposed method manages to enhance the driving quality and provide better handling of the vehicle.

Yildirim and Eski used an artificial intelligence (AI) method, i.e., neural network applied to the active suspension system [7]. They considered a full vehicle suspension model involving seven degree-of-freedom (DOF) vehicle system. The study managed to demonstrate that the proposed control scheme able to track the road profiles numerically without any practical validation to show the robustness and ability of the proposed technique in improving the ride comfort in real-time condition. Yazig and Hacioglu also used a full suspension system model considering a seven DOF in their study [8]. The study makes use of the *Lyapunov* functions and feedback control law to design a backstepping control scheme for active suspension. A number of road profiles had been generated as the disturbances and using time domain and frequency domain analyses, they manage to show the controller ability to improve the ride comfort.

In investigating the ride comfort of a vehicle, a number of parameters are crucial to be studied, namely, the *body acceleration* and *body displacement* which are deemd to have the most contribution and influential effect to the ride comfort in a vehicle. It is highly desirable to control the two parameters in order to achieve a good ride comfort as discussed in [9] together with the aspects related to the ride handling and stability. However, this research focuses only on the ride comfort and thus, other non-relating parameters shall not be presented or discussed in this paper.

This paper is organized as follows; the problem formulation is described in section 2. The mathematical modelling of a quarter car suspension model is presented section 3 while the design of the proposed hybrid controller scheme (involving the incorporation of PID, AFC, IL and schemes), implementation of the control loops and its simulated conditions with some results are presented in section 4. Section 5 discusses the practical implementation of the proposed scheme via a number of experimentations done on the physical test rig in the laboratory. Finally, the paper is concluded in section 6.

2 Problem Formulation

In order to improve the ride comfort, researchers have come out with a number of active vehicle suspension strategies through experimental works and many more through simulation study as presented in [10-13]. Most of them proposed complicated models considering non-linearity, uncertainty and some involving artificial intelligence (AI) methods like fuzzy logic [14-16] and neural network [17, 18]. Most of these researches show some improvement in the ride comfort aspect that the proposed active suspension systems (via various compensation algorithms) could provide but at the expense of increasing the complexity and computational burden to the system. Besides, the non-linearity inherent in the system aggravates the situation. Hence, they were best demonstrated numerically via simulation studies. Only a handful of the researches are realized via practical experimentation (using the proposed techniques) for validating the concept. This is mainly due to difficulty in real-time implementation (caused by a large delay/lag leading to problems in numerical computation and processing).

The objective of this paper is to design and develop a new simpler method to control an active vehicle suspension system via the proposed AFC-based controller with the embedded IL algorithm. It is in fact an extension to the proposed research work conducted by Priyandoko *et al.* [18]. The research will be carried out through simulation and experimental works to validate the theoretical counterpart. A practical HILS technique was later applied to a quarter car suspension test rig developed in a laboratory setting. It was utilised to execute various experiments to investigate the ride comfort aspect of the system.

3 Active Suspension Model

The quarter car suspension model used in the study is schematically depicted in Fig. 1.

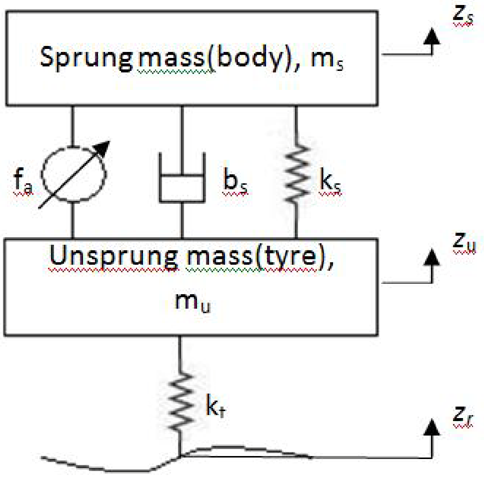


Fig. 1 A quarter car active suspension model

The dynamic equations governing the suspension model are given by:

$$m_s\ddot{z}_s = -k_s(z_s - z_u) - b_s(\dot{z}_s - \dot{z}_u) + f_a \quad (1)$$

$$m_u\ddot{z}_u = k_s(z_s - z_u) + b_s(\dot{z}_s - \dot{z}_u) - k_t(z_u - z_r) - f_a \quad (2)$$

Where

m_s and m_u : sprung and unsprung masses, respectively

b_s : damping coefficient

k_s and k_t : stiffness of the spring and tyre, respectively

z_s and z_u : displacement of the sprung and unsprung masses, respectively

z_r : displacement of the road profile

$\dot{z}_s$ and $\dot{z}_u$: velocity of the sprung and unsprung masses, respectively

$\ddot{z}_s$ and $\ddot{z}_u$: acceleration of the sprung and unsprung masses, respectively

f_a : actuator force

Note that it is assumed that the tyre is firmly held in contact with the road surface, i.e., no slipping occurs and that only vertical motion is considered.

4 The Proposed Controller Scheme

To compensate the disturbance in this research, an AFC-based controller is introduced. AFC has successfully used as disturbance rejection control system in various applications such as in flexible structure [19], muscle models [20], spacecraft attitude control system [21] and biped robot [22]. With the integration of ILC algorithm, the proposed controller named, AFCIL is implemented into a conventional PID controller. The overall proposed AFCIL control strategy is illustrated in Fig. 2. In this scheme, there are three main control loops. The outermost loop is the conventional PID control loop functioned as a position controller, the intermediate loop consists of the AFC with IL control loop which compensate for the disturbances and an innermost loop which is intended to control the actuating force of the actuator (i.e., the force tracking control loop). Note that G_a(s) in Fig. 2 takes into account a closed loop feedback controller for force tracking task of the actuator.

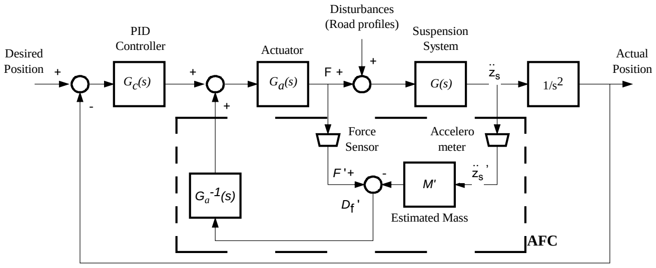


Fig. 2 AFC strategy applied to active suspension

4.1 Force Tracking Control Loop

In literature, a number of researchers assume that the commanded force can be achieved accurately without considering the actuator dynamics [23]. In practice, however, the actuator dynamics and its non-linearity can be very complicated and hence it cannot be easily neglected. The actuator used in this research is a pneumatic type which is highly non-linear. To obtain the desired force, it is necessary to perform an inner loop control tuning to track the force so that the actuating force is as close as possible to the desired force [24]. There are a number of approaches to perform the force tracking task as discussed in [24]. In the proposed study, a conventional PI controller was used to perform the force tracking task of the pneumatic actuator. The scheme is shown in Fig. 3.

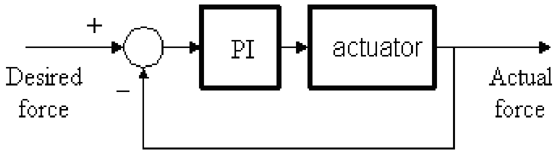


Fig. 3 Force tracking control loop

To produce the best results, the actuator must be able to track the desired force with acceptable accuracy. A number of signals were tested to observe the adaptability of the controller against various types of signals. When the best PI tuning via sensitivity method is found, the force tracking control loop serving as a 'black box' is then integrated into the other section of the AFCIL scheme. A common method used to get the appropriate values of P and I constant gains is through a heuristic trial and error method. The typical transfer function of a PID controller is given as follows [25]:

$$G_{\mathrm{c}}(s) = K_{\mathrm{p}}\left(e + \frac{1}{T_{\mathrm{i}}s} + T_{\mathrm{d}}s\right) \tag{3}$$

where $T_i = K_p/K_i$, $T_d = K_d/K_p$, and e is the error between the reference and the output of the system, T_i is the integral time, T_d is derivative time and K_p, K_i, and K_d are the proportional, integral, and derivative gains, respectively. In digital control and for a small time sampling, T_s, the equation can be approximated as follows [25]:

$$G_{\mathrm{c}} = K_{\mathrm{p}}\left(e_{\mathrm{n}} + \frac{1}{T_{\mathrm{i}}}\sum_{j=1}^{n} e_{\mathrm{j}}T_{\mathrm{s}} + T_{\mathrm{d}}\frac{e_{\mathrm{n}} - e_{\mathrm{n-1}}}{T_{\mathrm{s}}}\right) \tag{4}$$

Where the index, n refers to the current time instant. The experimental results of the force tracking control are shown in Fig. 4 which clearly shows that the PI controller produces the actual trajectories approaching the desired ones with acceptable error margins.

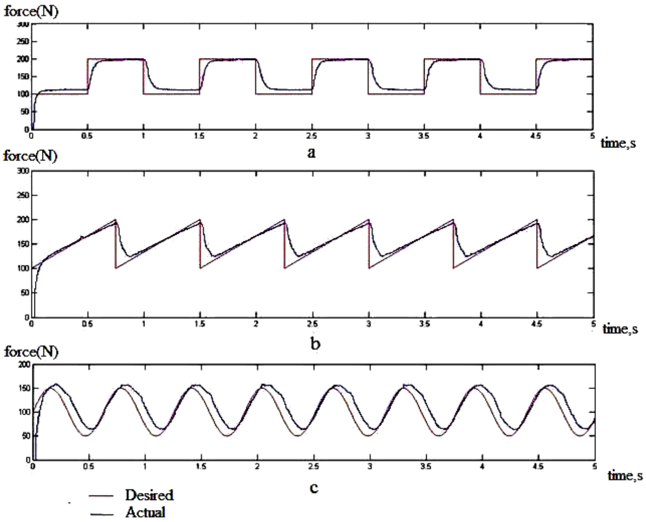


Fig. 4 Force tracking of the pneumatic actuator

This signifies that the appropriate controller setting enables the actuator to follow closely the trajectories of the desired actuating force.

4.2 AFC with IL Loop

Active Force Control (AFC) is known as a robust disturbance compensator. Though it is simple, AFC is considered to be superior compared to other conventional methods especially against various types of disturbances [26]. AFC directly applies the *Newton* second law of motion which makes it an attractive option for the compensation of known/unknown disturbances and parametric uncertainties of the dynamical systems. It works by indirectly estimating the disturbance force via appropriate measurements of the actuator force through the use of a force sensor and acceleration via accelerometer as shown in Fig. 5. At the same time, an estimated mass should be computed using a suitable method. Ultimately, the estimated mass parameter has to be multiplied with the measured acceleration signal via signal processing.

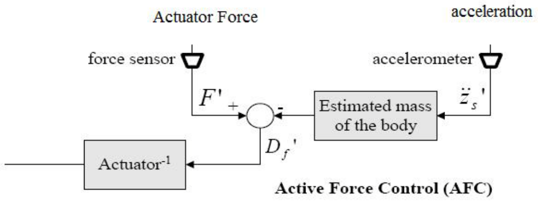


Fig. 5 Schematic showing the interaction of the main AFC parameters

The important equation governing the AFC algorithm is thus expressed as:

$$D_f' = F' - M'\ddot{z}_s \tag{5}$$

Where D_f' is the estimated disturbance force, M' is the estimated mass and $\ddot{z}_s'$ is the measured linear acceleration of the sprung mass (body). If the measured or estimated parameters are appropriately acquired, a very robust performance is assured. The estimated disturbance signal is subsequently relayed to the actuator for compensation purpose. Note that the inverse dynamic of the actuator is obtained based on the method described in [18] using an adaptive neural network treated here as a black box. The other important parameter, i.e., the estimated mass is computed using the IL algorithm which complements the AFC controller. The basic concept of IL is that for time approaching infinity (i.e., $t\rightarrow\infty$), the error shall be driven to approach the zero datum ($e\rightarrow 0$) after a number of iteration. The detailed concept and mathematical treatment of the IL algorithm is discussed in [26]. The algorithm has the ability to learn from previous error on repetitive tasks. ILC algorithm will aid AFC in estimating the mass needed by the AFC loop. *Arimoto* IL algorithm is usually employed due to its simplicity and ease of use due to the fact that its mathematical structure is very similar to the classical PID scheme that uses the fixed-gain parameters related to P, I and D terms [27]. These constant learning parameters are utilised in order to accelerate the convergence of the algorithm to reach the zero error goal with the smallest number of possible iteration. A good tuning in the learning parameters will provide a good convergence of the desired output. The convergence, stability and robustness of the *Arimoto* PID-type IL algorithms can be found in [28]. Other types of IL algorithms for specific applications can be found in [29, 30]. The three PID-type IL algorithms can be expressed as follows:

$$\text{PD}-\text{type}: M'_{k+1} = M'_k + (\phi + \Gamma d/dt)e_k \tag{6a}$$

$$\text{PI}-\text{type}: M'_{k+1} = M'_k + (\phi + \psi\int dt)e_k \tag{6b}$$

$$\text{PID}-\text{type}: M'_{k+1} = M'_k + (\phi + \psi\int dt + \Gamma d/dt)e_k \tag{6c}$$

Where M'_k is the current value of the estimated mass; M'_{k+1} is next step value of the estimated mass, e_k is the current error; ϕ, ψ, and Γ are the suitable proportional (P), integral (I) and derivative (D) learning parameters, respectively. In the study, the PID-type IL algorithm as expressed in (6c) was utilised and directly embedded into the AFC loop to compute the estimated mass. Fig. 6 shows the tuning results of the learning parameters for the proposed system. Among the set of learning parameters tuned heuristically by means of a number of trial runs, the best configuration is found to be ϕ (P) = 5, ψ (I) = 5 and Γ (D) = 5.

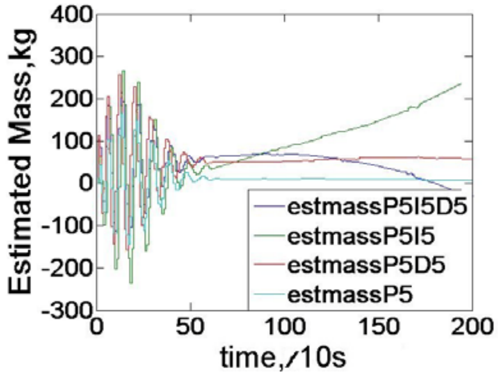


Fig. 6 Tuning the IL learning parameters

4.3 PID Control Loop

The outermost loop which used to control the position of the active suspension system is PID control loop. As described in section 4.1, this control loop was also tuned using a number of trial runs. The fine tuning results are shown in Fig. 7 in which the resulting controller gains were computed as K_p (P) = 80, K_i (I) = 100 and K_d (D) = 50.

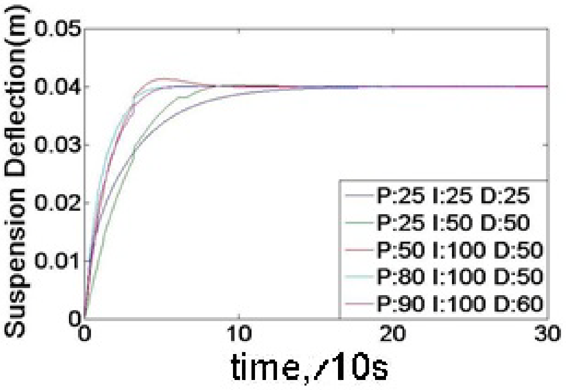


Fig. 7 PID tuning of the controller gains

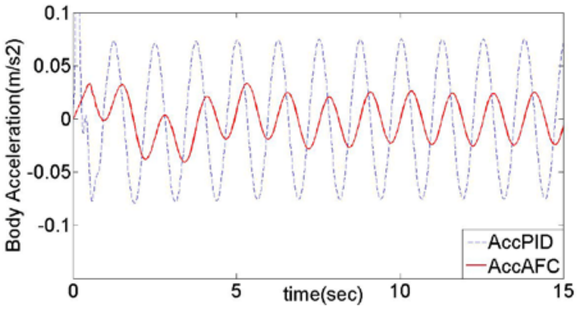
After all the three loops were successfully tuned, and yield good results with acceptable degree of accuracy, they were integrated to form a hybrid control scheme known as AFCIL. The input of the outermost loop controller is the desired or commanded body displacement (position) signal, whereas the output is the actual body displacement response produced by the proposed controller. A sinusoidal signal representing the road profile as a disturbance is created and later applied to the suspension system. The simulation study was done using MATLAB/Simulink software considering a number of parameters related to the controller gains (PID and AFC), IL learning parameters and suspension parameters, the last of which is shown in Table 1.

Table 1 Suspension parameters

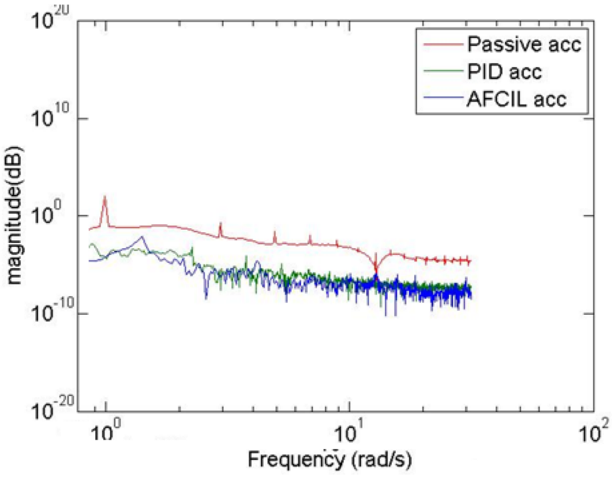
Parameter	Value
Sprung mass (kg)	180
Unsprung mass (kg)	25
Suspension stiffness (N/m)	16000
Damping coefficient (Ns/m)	1000
Tyre stiffness (N/m)	190 000

4.4 Simulation Results

The simulation results for the application of the proposed AFCIL scheme and experimented for ride comfort performance shown in Figs. 8 and 9. The parameters of interest are related to the body (or sprung mass) acceleration and displacement. They are presented both in time and frequency domains. Note that the result for the body acceleration for the passive suspension system is too large compared to the PID and AFCIL scheme; thus it is not shown in the figure. In both figures, the amplitude of the body acceleration and displacement for the active suspension implementing AFCIL is smaller than the PID counterpart. The magnitudes in the frequency domain for AFCIL are again smaller than both the passive and pure PID schemes throughout the simulation period. This evidently implies that AFCIL demonstrates better ride comfort compared the other two suspension systems.

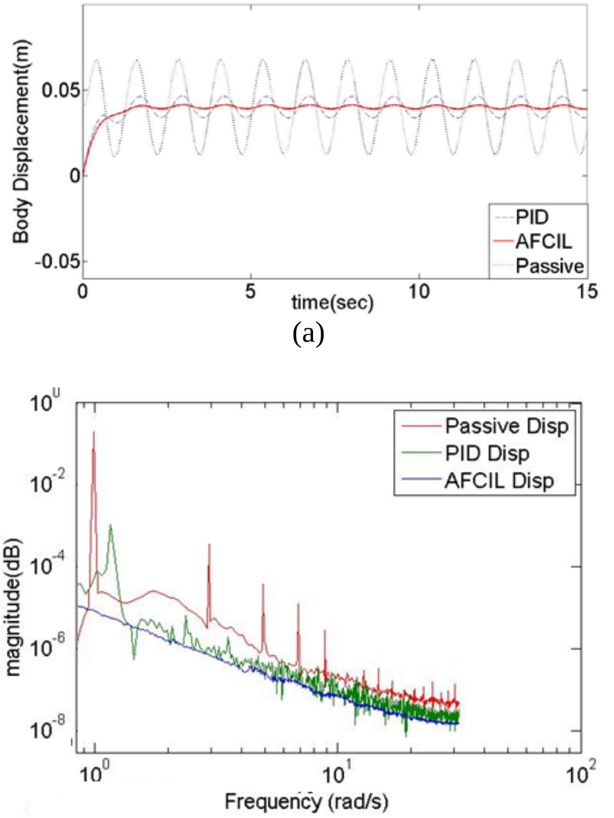


(a)



(b)

Fig. 8 Body acceleration response in (a) time domain and (b) frequency domain



(a)

(b)

Fig. 9 Body displacement response in (a) time-domain and (b) frequency domain

Within the frequency range of interest, it can be seen that proposed controller scheme exhibits lower magnitude of the amplitudes related to body acceleration and displacement for the duration of the experimental period. This suggests that the proposed controller manages to produce better disturbance (vibration) suppression of the suspension system based on the road profile input excitation.

5 Experimental Implementation

In this section, the practical implementation of AFCIL scheme is presented. A quarter-car suspension system is used with a pneumatic actuator as the main active element. HILS approach is used in conjunction with the *Real Time Workshop* (RTW) feature in MATLAB/Simulink environment. It is used to provide an effective procedure for developing and testing the performance of the physical suspension test rig in real-time. The interlinking between the real hardware including sensors and actuators with the controller scheme through the data acquisition system (DAS) are schematically shown in Fig. 10. In HILS, the electrical signals generated by the sensors (five of them, namely, LVDT, accelerometer (2x), pressure (force) sensor and current sensor) were acquired by the DAS via the analogue-to-digital (A/D) converters and processed in the computer-based controller (through the simulated controller algorithms derived from the relevant mathematical models) which then gives an appropriate output signal to the pneumatic actuator via the digital-to-analogue (D/A) converter. The actuator then provides the force needed to compensate the disturbances (road profiles) acting on the suspension test rig. By applying HILS approach, a number of factors related to the actuator dynamics, non-linearity of the pneumatic system and time delay are assumed to be small and can be conveniently neglected in the modelling.

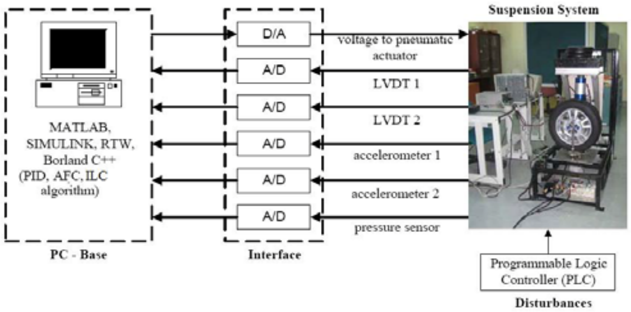


Fig. 10 Schematic diagram of the experimental setup

Fig. 11 shows a view of the test rig via HILS technique developed in the laboratory. The main components of the rig are clearly indicated.

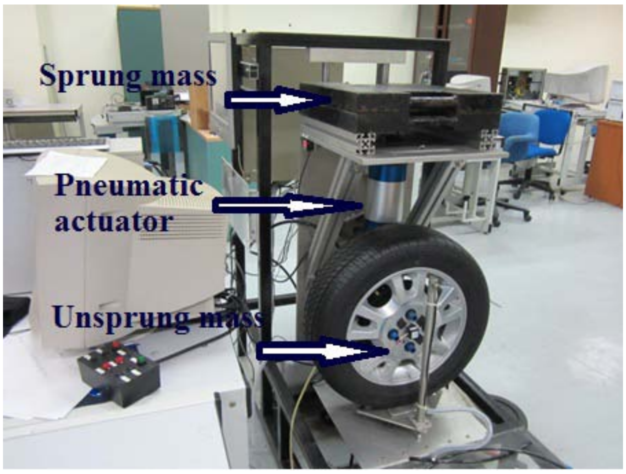
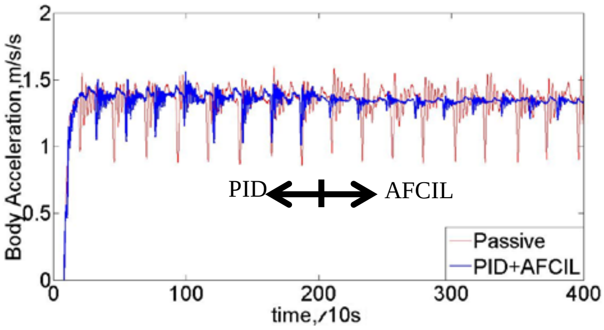
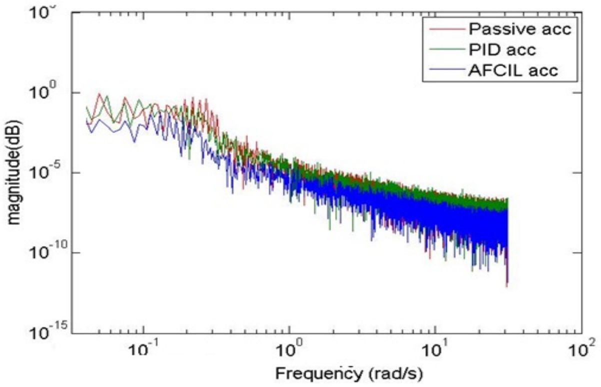


Fig.11 Quarter car active suspension test rig

A programmable logic controller (PLC) powered by another pneumatic actuator is used to generate a sinusoidal signal as the road profile to study the disturbance effect on the ride comfort of the suspension system. A 5 cm amplitude sinusoidal signal with 1.5 Hz frequency is generated by the PLC. The disturbance is applied sequentially, first to the passive suspension system, then the PID controller and finally the AFCIL scheme according to suitable time duration using an automatic switch created in the program. For the PID and AFCIL schemes, the first 20 s is when only the PID controller is operated while for the next 20 s, the AFCIL mode is triggered by means of an automatic switch created in MATLAB/Simulink environment via the HILS configuration. Since the research focuses on the ride comfort, only the results related to the body acceleration and displacement responses are considered. The body acceleration is measured using an accelerometer attached to the sprung mass as depicted in Fig. 11. Using a double integration technique, the body displacement can be easily obtained. The complete results are presented in Figs. 12 and 13, both in time and frequency domains.

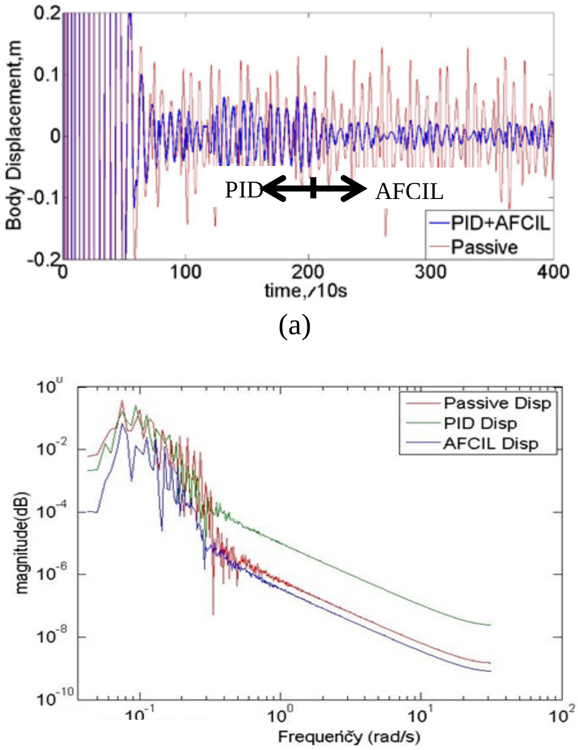


(a)



(b)

Fig.12 Body acceleration responses obtained from the experiment in (a) time-domain and (b) frequency domain



(a)

(b)

Fig.13 Body displacement responses obtained from the experiment in (a) time-domain and (b) frequency domain

From Figs. 12(a) and 13(a), it is clearly observed that after the 20 s interval, the amplitudes of the body acceleration and displacement for the AFCIL scheme are consistently lower than the ‘pure’ PID controller and passive suspension throughout the duration after it was triggered to AFCIL mode via an automatic switch. Similarly, the trend of the magnitudes of the related parameters in the frequency domain also register lower readings in the AFCIL scheme as depicted in Figs. 12(b) and 13(b) in comparison to the passive and PID schemes. This further illustrates that the active suspension with AFCIL scheme again produces a better ride comfort performance compared to the PID controller and passive suspension.

6 Conclusion

A novel hybrid AFC-based controller, the proposed AFCIL scheme has been designed, simulated and practically implemented for the control of a vehicle quarter car active suspension system. From both simulation and experimental results, the active suspension with AFCIL controller outperforms the PID controller and passive suspension in terms of its ability to suppress the vertical body movement (acceleration and displacement) which contribute to direct enhancement and improvement of the vehicle ride comfort performance. The results also indicate that the proposed algorithms (PID + AFC + IL) are indeed practically viable and readily implemented in real-time. Future works may include more effort in improving the system performance, considering other operating and loading conditions. A full car suspension system could also be developed and tested, to take into account the road handling and stability.

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