CHAPTER 5

INTELLIGENT ACTIVE FORCE CONTROL

5.1 INTRODUCTION

Outer loop controllers are discussed in the previous chapters assuming that actuator produces the target force. Actuator dynamics are quite complicated and the interaction between the actuator and the vehicle suspension cannot be ignored. Hence it is necessary to produce the actuator force close to the target force by implementing a force tracking controller. This chapter presents an Active Force Control (AFC) strategy applied to vehicle suspension system of quarter car model with actuator dynamics (Mailah and Priyandoko (2007)). AFC uses fuzzy logic method of estimation of mass and hence it is intelligent AFC. The controller structure consists of three loops. Outer loop controller is used for the target force computation to reject the road disturbances. Inner force tracking loop is used to keep the actual force close to the target force. AFC feedback loop is used for the estimation of force due to disturbance and it results in robustness of the proposed control scheme. The performance of the suspension system with and without AFC scheme is analyzed. PSD analysis of body acceleration is also carried out to evaluate the vehicle ride comfort.

5.2 ACTUATOR DYNAMICS

The hydraulic actuator is modeled as a power cylinder with the piston controlled by a servo valve and it is shown in Figure 5.1.
Figure 5.1 Hydraulic actuator

$P_s$ and $P_r$ are the pressure of the hydraulic fluid entering and leaving the spool valve respectively. $x_{sp}$ is the spool valve position. $P_u$ and $P_l$ are the oil pressure in the upper and lower cylinder chambers. $x_w - x_c$ is the hydraulic piston displacement. Positioning of the spool $x_{sp}$ directs high pressure fluid flow to either one of the cylinder chambers and connects the other chamber to the pump reservoir. This flow creates a pressure difference $P_l (P_u - P_l)$ across the piston. The pressure difference multiplied by the piston area $A$ is the active force $F_a$ for the suspension system. The spool valve displacement ($x_{sp}$) is assumed to relate to the servo-valve current ($i_{sv}$) through the following linear transfer function

$$\frac{x_{sp}(s)}{i_{sv}(s)} = \frac{K_{sv}}{\tau s + 1}$$  \hspace{1cm} (5.1)

where $K_{sv}$ is the valve gain and $\tau$ is the time constant of the servo valve. This dynamics is sufficiently fast and will not be considered in the control
design process (Chantranuwathana and Peng (1999)). Following assumptions are made to derive the force dynamics of the hydraulic actuator.

(i) Valve opening area is linearly related to spool valve displacement,
(ii) upstream area is much larger than the orifice area,
(iii) the fluid is incompressible
(iv) the piston inertia is negligible and
(v) changes in magnitude of pressure in the two chambers are approximately equal

i.e. \( \Delta P_u = -\Delta P = \Delta P \) and the force dynamics are given as

\[
\dot{F}_a = \frac{\sqrt{\pi A_p \beta K_{xd}}}{V} \left( x_{sp} \cdot \text{sign} \sqrt{P_s - \text{sgn}(x_{sp})F_a/A_p} \right) + \frac{2A_p^2 \beta K_{as}}{V} (\dot{z}_u - \dot{z}_s) \quad (5.2)
\]

where \( A_p \) - actuator ram area,
\( V \) - average volume of each chamber at equilibrium
\( \beta \) - fluid bulk modulus
\( K_{xd} \) - orifice flow coefficient and
\( K_{as} \) - average ratio between suspension stroke and actual actuator cylinder displacement.

Equation (5.2) is linearized and given as (Shen and Peng (2003))

\[
2C_x x_{sp} + 2A_p (\dot{z}_u - \dot{z}_s) = \frac{V}{\beta A_p} \dot{F}_a \quad (5.3)
\]

where \( C_x \) is the flow gain for spool displacement.
5.3 ACTIVE FORCE CONTROL

Hewitt and Burdess (1981) introduced the AFC concept. It has been shown that by using AFC, the system remains stable, robust and effective in the presence of known/unknown disturbances, uncertainties and various operating conditions (Hewitt and Burdess (1986) and Mailah (1999)). AFC loop compensates the actual disturbance force obtained from the error between the ideal and actual force vector. AFC has a fast decoupling property and it can be applied to various loading conditions.

\[ \Sigma F = m \times a \quad (5.4) \]

**Figure 5.2 Block Diagram of AFC scheme**

Figure 5.2 shows the schematic of the AFC scheme applied to a dynamic system. From Newton’s 2nd law of motion, sum of forces (F) acting on the body is the product of the mass (m) and the acceleration (a) of the body in the direction of applied forces.
For the dynamic system shown in Figure 5.2 the equation of motion is,

\[ F_a + Q = m \cdot a \]  \hspace{1cm} (5.5)

where \( F_a \) is the actuator force and \( Q \) is the disturbance force. The estimated value of the disturbance force can be formulated as

\[ Q' = m' \cdot a' - F_a' \]  \hspace{1cm} (5.6)

where the subscript ‘ denotes a measured or computed value. The error provides an adjustment signal to the actuation system which equals \(-Q'\) and it can be used to decouple the actual disturbance force \( Q \). Hence the system will be stable even under variable external force. The actuator force and body acceleration can be accurately measured by means of suitable transducers. Estimation of mass is essential for a successful AFC strategy. Mass \( m' \) can be estimated by intelligent methods (Sam and Hudha (2006)).

### 5.4 CONTROLLER STRUCTURE

The controller structure adopted in this study is shown in Figure 5.3 and it utilizes three controller loops. FLC is used in the outer loop for the computation of the optimum target force. Force tracking of the hydraulic actuator is carried out by a conventional PI controller. AFC loop is integrated with outer FLC and inner Force tracking controller. AFC loop use intelligent method (Fuzzy Logic) for the estimation of mass and from the measured values of acceleration and force of the dynamic system to compute the estimated force. This error signal is used to compensate for the known/unknown disturbances.
5.4.1 Outer Loop Controller

Controllers discussed in the previous chapters can be used for target force computation in the outer loop. Since the outer loop controller is used along with AFC loop, it needs to have stable performance than robust performance. Optimal controller and FLC are suitable for the outer loop. Since FLC is model free and more suitable for complex nonlinear systems, it is preferred in the outer loop controller.

5.4.2 Force Tracking Controller

The inner loop of force tracking control of hydraulic actuator is shown in Figure 5.4. The hydraulic actuator model takes two inputs, the spool valve position and the real time piston speed. Force tracking of hydraulic actuator is carried out using a PI controller with proportional gain and integral gain set according to Zeigler-Nichols setting. PI control is implemented with
force tracking error as the input and control current as the output to drive the spool valve.

![Figure 5.4 Force tracking control of hydraulic actuator](image)

The target force is represented by sinusoidal, square and saw-tooth functions to validate the force tracking performance of the controller.

### 5.4.3 Active Force Control Loop

AFC loop is designed to compensate for the unknown disturbances. The efficiency of the AFC strategy relies on the mass estimator as the body acceleration and the actuator force are easily obtained. Sugeno type of Fuzzy Inference System (FIS) is used to estimate the mass. The main aim of using the fuzzy logic in the study is to estimate the mass intelligently so that it can be utilized by AFC mechanism to effect its control strategy. Input to the mass estimation FLC is sprung mass acceleration (Gaussian membership function) and the output is a singleton value of the estimated mass. Once FLC is designed, it is embedded in the overall control strategy for online estimation of the mass and thereafter estimates force. The estimated force is fed forward through a transfer function block (inverse dynamics of actuator) so that controller output cancels the disturbance force.
Inverse dynamics of the hydraulic actuator is approximated by an Adaptive Neuro Fuzzy Inference System (ANFIS), where the input is the actuator force $F_a$ and the output being the target force. ANFIS uses the training data set to build the fuzzy system in which, membership functions are adjusted using the back propagation algorithm, allowing that the system learns with the data that it is modeling (Jang (1993)).

5.5 SIMULATION RESULTS

The parameters of the quarter car model and hydraulic actuator are taken from (Chantranuwathana and Peng (1999)) and listed in Table 5.1.

Table 5.1 Quarter car parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sprung Mass ($m_s$)</td>
<td>290 kg</td>
</tr>
<tr>
<td>Unsprung Mass ($m_u$)</td>
<td>59 kg</td>
</tr>
<tr>
<td>Damper coefficient ($b_s$)</td>
<td>1000 Ns/m</td>
</tr>
<tr>
<td>Suspension Stiffness ($k_s$)</td>
<td>16,812 N/m</td>
</tr>
<tr>
<td>Tyre Stiffness ($k_t$)</td>
<td>190,000 N/m</td>
</tr>
<tr>
<td>$P_s$</td>
<td>10342500 Pa</td>
</tr>
<tr>
<td>$\tau$</td>
<td>0.03 sec</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>$4.515 \times 10^{13}$ N/m$^5$</td>
</tr>
<tr>
<td>$\beta$</td>
<td>1 sec$^{-1}$</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>$1.545 \times 10^9$ N/(m$^{5/2}$ Kg$^{1/2}$)</td>
</tr>
<tr>
<td>$A_p$</td>
<td>$3.35 \times 10^{-4}$ m$^2$</td>
</tr>
</tbody>
</table>
Two different road profiles (dual bump and sinusoidal) are considered in the study. Simulations are conducted for open loop passive, active suspension with FLC (outer loop alone) and active suspension with intelligent AFC.

The force tracking control of the hydraulic actuator model using PI controller for sinusoidal target force is shown in Figure 5.5. The proportional gain and integral gain are set according to Zeigler Nichols method as 1.25 and 0.75 respectively. Force tracking performance at various frequencies of sinusoidal input is tabulated in terms of RMS value of the tracking error and given Table 5.2. This is to check the controllability of the force tracking controller for a wide range of frequencies. From Figures 5.6 and 5.7, it is shown that the hydraulic actuator tracks the desired force for bump input and sinusoidal input.

**Figure 5.5** Force tracking with sinusoidal reference

**Table 5.2** Force tracking at various frequencies

<table>
<thead>
<tr>
<th>Frequency</th>
<th>RMS of tracking error</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Hz</td>
<td>0.788</td>
</tr>
<tr>
<td>3 Hz</td>
<td>0.8116</td>
</tr>
<tr>
<td>5 HZ</td>
<td>1.281</td>
</tr>
</tbody>
</table>
Mass estimation is computed using FLC in AFC loop. Figure 5.8 shows the estimated mass for bump road input. The mass parameter initially dips and then stabilizes to a constant value. For the sinusoidal input the mass parameter fluctuates around the middle value of 50 kg as shown in Figure 5.9.
Figures 5.10-5.13 present the simulation results for an active suspension system using intelligent AFC control scheme for a bump input. It is understood from the Figure 5.10 that the sprung mass displacement is much reduced by AFC scheme and the maximum displacement is less than 2cm. Figure 5.11 shows that the body acceleration by AFC scheme is reduced by 54.73% compared to passive and 18% compared to FLC. The RMS values of the acceleration oscillation amplitudes are 1.43, 0.7955 and 0.6468 m/s\(^2\) respectively for passive, FLC and AFC based suspension system. Figure 5.12
indicates that the suspension deflection controlled by AFC is well within the suspension travel limits of ± 8 cm and well reduced compared to that of passive suspension system. Tyre deflection for both active systems is 4% to 9% more than passive and it is illustrated in Figure 5.13. It shows that active suspension system absorbs the vehicle vibration better than passive system.

Figure 5.10 Sprung mass displacement- bump input

Figure 5.11 Sprung mass acceleration – bump input
Figure 5.12  Suspension deflection – bump input

Figure 5.13  Tyre deflection – bump input
Figures 5.14 - 5.17 present the simulation results for an active suspension system using intelligent AFC control scheme for sinusoidal road input. Figure 5.14 shows the sprung mass position oscillation of the vehicle body is less than 1cm for AFC scheme. Figure 5.15 shows that the body acceleration by AFC scheme is reduced by 83% compared to passive and 50% compared to FLC scheme. The RMS values of the acceleration oscillation amplitudes are 7.383, 2.48 and 1.244m/s$^2$ respectively for passive, FLC and AFC based suspension system. Thus the AFC scheme guarantees better ride comfort. Figure 5.16 indicates that the suspension deflection controlled by AFC and FLC is of same magnitude but smaller than that of passive. Figure 5.17 illustrates that tyre deflection is more for both FLC and AFC schemes compared to the passive suspension system. This shows that considerable improvement in sprung mass displacement and sprung mass acceleration is displayed at the cost of tyre deflection. The performance of the vehicle suspension system clearly indicates the superiority of the active suspension with AFC over its counterparts in improving the ride comfort.

The comparison of all three control schemes are presented in Table 5.3, which shows the RMS value of the body acceleration, suspension deflection, body displacement and tyre deflection. The results show that intelligent AFC scheme outperforms the conventional passive, FLC in providing desired ride comfort and road handling qualities.
Figure 5.14 Sprung mass displacement – sinusoidal input

Figure 5.15 Sprung mass acceleration – sinusoidal input
Figure 5.16 Suspension deflection – sinusoidal input

Figure 5.17 Tyre deflection - sinusoidal input
Table 5.3 RMS values of the time responses of the quarter car model

<table>
<thead>
<tr>
<th>Input</th>
<th>Controller</th>
<th>Sprung Mass Displacement $10^{-3}$(m)</th>
<th>Suspension Deflection $10^{-2}$(m)</th>
<th>Body Acceleration (m/s$^2$)</th>
<th>Tyre deflection $10^{-3}$(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bump input</td>
<td>Passive</td>
<td>19.98</td>
<td>1.88</td>
<td>1.431</td>
<td>2.825</td>
</tr>
<tr>
<td></td>
<td>FLC</td>
<td>7.45</td>
<td>1.40</td>
<td>0.7955</td>
<td>3.106</td>
</tr>
<tr>
<td></td>
<td>AFC</td>
<td>5.91</td>
<td>1.45</td>
<td>0.6468</td>
<td>3.507</td>
</tr>
<tr>
<td>Sinusoidal Road profile</td>
<td>Passive</td>
<td>22</td>
<td>8.5</td>
<td>7.383</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>FLC</td>
<td>4.7</td>
<td>7.8</td>
<td>2.48</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>AFC</td>
<td>5.3</td>
<td>7.9</td>
<td>1.244</td>
<td>12</td>
</tr>
</tbody>
</table>

In the evaluation of vehicle ride quality, the PSD of sprung mass acceleration as a function of frequency is plotted for both road profiles. PSD of body acceleration for bump and sinusoidal input are shown in Figures 5.18 and 5.19. For both road conditions, intelligent AFC scheme has significantly suppressed the acceleration of sprung mass effectively in the low frequency band. It can be observed from the PSD plot that the acceleration has been brought down within the frequency between 0.4 Hz to 10 Hz by an active suspension system. Outer loop controller and intelligent AFC based suspension systems exhibits more or less similar performance below 0.4 to 4Hz. From Figure 5.19 it is understood that AFC scheme shows better ride comfort above 4.5Hz compared to the outer loop controller alone. Hence, integrated loop (AFC and outer loop) performance is better for frequency above 4.5Hz to 10Hz. Thus the active suspension with intelligent AFC scheme could greatly contribute to the improvement of the vehicle ride comfort.
Figure 5.18  PSD of sprung mass acceleration (Bump input)

Figure 5.19  PSD of sprung mass acceleration (Sinusoidal input)
5.6 CONCLUSION

In this chapter intelligent Active force control scheme is designed for vehicle suspension system of a quarter car model with a nonlinear hydraulic actuator. The result of the study shows that the hydraulic actuator is able to provide the actual force close to the target force. AFC loop estimated the force due to the disturbance and this signal is fed forward in the control loop. Hence, it resulted in a robust and stable performance. From the simulation results it is obvious that the AFC based active suspension provides better ride comfort when compared to existing passive and outer loop controller without AFC loop.