CHAPTER 4

DEVELOPMENT AND ANALYSIS OF 2 DOF QUARTER CAR PASSIVE SUSPENSION SYSTEM (QC-PSS) AND 2 DOF QUARTER CAR ELECTROHYDRAULIC ACTIVE SUSPENSION SYSTEM (QC-EH-ASS) USING MATLAB SIMULATION

4.1 INTRODUCTION

With the advent of the state-of-the-art technology for computational analysis, modeling and simulation of complicated dynamic product characteristics is widely used by the designers. These software environments not only facilitate the modeling comfort but also they will be of great support to analyse and investigate the complicated potential strategies in the light of certain specific optimizing objectives. One such simulation technique is the advanced ‘MATLAB SIMULINK 2010 A’ environment. It has high computational capabilities and sound analysis tools for complicated vibration analysis systems such as the road vehicle systems. As such, in this work, MATLAB SIMULINK (MathWorks, Inc., Natick, USA) Environment has been incorporated to investigate and simulate the proposed 2DOF Quarter Car Electro-Hydraulic Active Suspension System (QC-EH-ASS) Model developed in previous section. Two state-of-the-art Matlab Environments are identified for a specific application and it is implemented as follows:

SIMULINK

With state-of-the-art advanced Simulink environment, some of the key electrical and electronic components and instrumentation
elements are developed. Following are some of these Simulink components:

1. Signal Builder: - It is used to excite the system according to the signal that we are providing.
2. PID Controller: - It is used to damp the vibration according to the control signal.
3. Scope: - It is used to show the output analog signal on the computer screen.

**SIMSCAPE**

Alongwith Simulink, Simscape platform is incorporated for embedding the dynamic behaviour of the critical mechanical, Hydraulic and data acquisition elements alongwith their typical performance characteristics.

For a typical 2DOF Quarter Car Electro-Hydraulic Active Suspension System (QC-EH-ASS), following are the some of the major elements modeled and executed for facilitating the simulation interface.

1. Mechanical Translational Reference: Mechanical Translational Reference used to create reference to system. It is just like foundation structure and binding reference for embedding the further development.
2. Translational Spring :-It is used for setting tire spring stiffness as well as suspension spring stiffness
3. Translational damper:-It is used for setting suspension damping coefficient.
4. Translational Mass: -Translational block is used for constructing the typical car body mass (sprung mass) and wheel mass (unsprung mass).
5. Simulink –PS convertor: - This feature is employed to convert the virtual Simulink signal into the physical single.
6. Ideal Force Source: -Ideal force source is provided for generate the road irregularity signal into to the proportional force to be translated to the unsprung mass.

7. Ideal Translational Sensor: -It is used to sense the velocity and displacement of sprung and unsprung masses.

8. PS-Simulink convertor-It is used to convert physical signal into the Simulink signal for getting the output on screen.

9. Solver Configuration: - It is employed to provide the necessary mathematical configuration required to simulate the characteristic behaviour of the system.

10. Double Acting Hydraulic Actuator: - This Simulink block is created to generate the actuation force according to controller signal.

11. 4 Way Servo Valve: - the Servo Valve is modeled to facilitate the quick and precise conversion of electrical control signal input into a proportionate actuation force by the double acting Hydraulic Actuator through control of the flow of fluid to the double acting cylinder.

12. Ideal velocity source: - It is used to regulate the proportional servo-valve actuator according to displacement and velocity of sprung and unsprung masses.

13. Variable displacement pressure compensated pump:-It is modeled to depict the pumping of the fluid from tank to the hydraulic cylinder.

14. Hydraulic reference: - this is the provision made as per the requirement of the Simscape fluid system reference.

The next section is devoted to brief portrayal of the construction and investigation analysis carried out for the 2 DOF Quarter Car Passive Suspension System in developed Matlab Simulink Environment; which, further, can facilitate the fair comparative tool for the performance of the 2 DOF Quarter Car Electro-
Hydraulic Active Suspension System (QC-EH-ASS) which is the prime focus of the research project.

4.2 CONSTRUCTION AND ANALYSIS OF 2 DOF QUARTER CAR PASSIVE SUSPENSION SYSTEM (QC-PSS) IN MATLAB SIMULINK ENVIRONMENT

A 2DOF Quarter car passive suspension system using Matlab (Simulink & Simscape) is developed for a typical road vehicle (car). The typical Small Car Dynamics (e.g. Sprung to unsprung mass ratio ≈ 5) as well as Physical Characteristics are employed for this simulation construction as given in Table 4.1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sprung mass (M_s)</td>
<td>8 kg</td>
</tr>
<tr>
<td>Unsprung mass (M_us)</td>
<td>1.5 kg</td>
</tr>
<tr>
<td>Suspension spring stiffness (K_s)</td>
<td>11900 N/m</td>
</tr>
<tr>
<td>Suspension Damping coefficient (C_s)</td>
<td>518 Ns/m</td>
</tr>
<tr>
<td>Tire spring stiffness (K_t)</td>
<td>85000 N/m</td>
</tr>
</tbody>
</table>

1. Development of Mechanical Translational System with input signal:

Mechanical Translational Reference is constructed by selecting and connecting subsequent means as mentioned in brief and illustrated in fig. 4.1.

[The mechanical Library » Simscape » foundation library » mechanical » translational element »Mechanical translational reference » translational masses » translational spring » translational damper]
2. Adding the input signal to mechanical system:

3. Converting Simulink signal from signal builder to the physical signal & to solve the system configuration
   [Library » Simscape » utilities » Simulink to PS converter & solver configuration]

4. Producing ideal force source
   [Library » Simscape » foundation library » mechanical sources » ideal force source »]

5. Obtaining the output analog results of developed mechanical suspension system
   [Library » Simscape » foundation library » mechanical sensor » ideal translational sensor »]

6. To use the PS – Simulink convertor
   [Library » Simscape » utilities » PS-Simulink convertor »]

7. Display of the analog signal.
   [Library » commonly used » scope]

Further, by depicting the typical performance characteristics, equivalent to those of experimental test rig, at each of the above mentioned modeling stage, the complete suspension system virtual prototype is ready for the simulation. This Simulink Prototype is shown in fig. 4.4.
The sinusoidal road input as shown in fig. 4.3, is given to the developed mechanical passive suspension system using Simulink-Simscape. The analysis is carried out for the given road input, with the typical suspension parameter characteristics as provided in Table 4.1. The output results are obtained using translational mechanical sensor which captures the analog response of both the masses; sprung mass as well as unsprung mass; of the system in terms of displacement, velocity and acceleration of the mass in meter and meter per second respectively.
Fig. 4.4: Simulink Simscape Model of 2 DOF Passive Quarter Car Suspension System for Road Vehicles.
Fig. 4.5: $x_s(t)$ vs Time
(The peak amplitude of Sprung Mass is 0.215$\mu$m)

Fig. 4.6: $x_{us}(t)$ vs Time
(The peak amplitude of Unsprung Mass is 0.450$\mu$m)

Result fig.4.5 shows amplitude of maximum displacement of sprung mass as $2.150 \times 10^{-7}$ m. Fig.4.6 shows the maximum displacement of unsprung mass as $4.50 \times 10^{-7}$ m. So the motion transmissibility $\xi_m$ (the ratio of max. displacements of sprung mass to max. displacement of unsprung mass) is equal to 0.477.

Fig. 4.7: $x_s(t')$ vs Time
(Peak value of Velocity of Sprung Mass is $8.8 \times 10^{-4}$ mm/s)
As seen from the result fig. 4.8, maximum velocity of unsprung mass in case of passive system is approximately equal to 30.0\times10^{-4} \text{ mm/s} and is repetitive in nature. While in the fig. 4.7, the velocity of sprung mass in case of passive system is approximately 8.8\times10^{-4} \text{ mm/s}, which is less than that of unsprung mass velocity. So the transmissibility $\xi_v$ (the ratio of max. velocity of sprung mass to max. velocity of unsprung mass) is equal to 0.293.
Also the values of the sprung mass acceleration and unsprung mass acceleration are found to be $4.9 \times 10^{-6} \text{ m/s}^2$ for sprung mass and $11.3 \times 10^{-5} \text{ m/s}^2$ for unsprung mass respectively as seen in the graphs 4.9 and 4.10. So the transmissibility $\xi_a$ (the ratio of max. acceleration of sprung mass to max. acceleration of unsprung mass) is equal to 0.0435.

Thus, with these transmissibilities, there is a considerable scope to improve the passenger comfort by adopting the active means for the vehicle suspension system.

In the consecutive section, the development and investigation analysis for the 2 DOF Quarter Car Electro-Hydraulic Active Suspension System in discussed in Matlab Simulink Environment.

### 4.3 CONSTRUCTION AND ANALYSIS OF 2 DOF QUARTER CAR ACTIVE SUSPENSION SYSTEM (QC-ASS) IN MATLAB SIMULINK ENVIRONMENT

The development of 2DOF Active Suspension System using Matlab is now facilitated with following considerations.

1. To depict the excitations due to the uneven road surface, the external controlling force is modeled alongwith the double acting hydraulic actuator.

   ![Library » Simscape » simhydraulics » hydraulic cylinder » double acting hydraulic cylinder »](image)

2. To control the direction of fluid to be supplied to the actuator, the 4-way directional control servo valve is developed.

   ![Library » Simscape » simhydraulics » valves » directional valves » 4-way directional control servo valve »](image)

3. To control the flow of fluid, to regulate the force of actuation, the proportional and servo-valve actuator is incorporated. The ideal translational velocity source to operate the proportional servo-valve actuator is also constructed.
4. Further, the hydraulic power supply unit is modeled with all important subassemblies.

5. The variable pressure of fluid according to the displacement of masses is facilitated.

6. The proper SAE oil is selected with the use of following path.

7. The referencing is provided to all these power unit.

8. Microcontroller to provide the active control signal to the servo valve which further regulates the flow of fluid to double acting cylinder with the transfer functions mentioned in 3.3.1, 3.3.2 and 3.5.

With these constructions, the full-fledged typical model of 2 DOF Electro-Hydraulic Quarter Car Active Suspension System (QC-ASS) is ready to be analysed for a road input signal as shown in fig. 4.8.

The 2 DOF Active Suspension System is analysed for a typical input and the output results are recorded in terms of displacement and velocity of sprung and unsprung masses of active system.
Fig. 4.11: Modeling of Typical Active Suspension Components e.g. Hydraulic Actuator and Servo Valve etc.

Fig. 4.12: Modeling of 2DOF Active Suspension System with Hydraulic Power Supply Unit

Input Controller signal used for Microcontroller is as shown in fig 4.13.

Fig 4.13:- Input Signal Used With Integral=0.009
Fig. 4.14 MATLAB Model of 2 DOF Quarter Car EH-ASS System for Road Vehicles
Fig. 4.15: $x_s(t)$ vs Time
(The peak amplitude of Sprung Mass is 0.110 µm)

Fig. 4.16: $x_u(t)$ vs Time
(The peak amplitude of Unsprung Mass is 0.450 µm)

As seen in the result fig. 4.16, the maximum displacement of unsprung mass of 2 DOF QC-EH active suspension system is 0.450 µm ($4.5 \times 10^{-7}$ m) while the performance parameter seems to be came down drastically with the implementation of Electro-Hydraulic Actuation along with a potential control strategy, as depicted in result output fig. 4.15, to a value of 0.110 µm ($1.10 \times 10^{-7}$ m) giving a motion transmissibility $\xi_m = 0.244$.

Result Fig. 4.17: $x_s'(t)$ vs Time
(The Peak Value of Velocity of Sprung Mass is $4.3 \times 10^{-4}$ mm/s)

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As seen from the result figures 4.17 and 4.18, the maximum sprung mass velocity is recorded equal to $4.3 \times 10^{-4}$ mm/s and the velocity of unsprung mass which is recorded as $8.0 \times 10^{-4}$ mm/s. Here it is observed that, the sprung mass velocity stabilizes very quickly after initial jerks because of the active role of controller ($\xi_v = 0.537$).
Also the values of the sprung mass acceleration and unsprung mass acceleration are obtained as $3.2 \times 10^{-6}$ m/s$^2$ for sprung mass and $11.0 \times 10^{-5}$ m/s$^2$ for unsprung mass respectively as seen in result figures 4.19 and 4.20 respectively giving acceleration transmissibility equal to 0.029.

These results of response of 2 DOF QC-EH-ASS consolidate the importance of the potential candidature of the 2 DOF QC-EH-ASS Strategy to be considered for the real time implementation in Road Vehicles.

### 4.4 THE COMPARISON OF THE RESULTS

Table 4.2 gives the comparison of the results of QC-PSS and QC-EH-ASS obtained using the Simulation technique.

<table>
<thead>
<tr>
<th>RESPONSE PARAMETERS</th>
<th>QC-PSS</th>
<th>QC-EH-ASS</th>
</tr>
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<tbody>
<tr>
<td>Maximum Sprung mass Displacement (μm) ($X_s$)</td>
<td>0.215</td>
<td>0.110</td>
</tr>
<tr>
<td>Maximum Unsprung mass Displacement (μm) ($X_{us}$)</td>
<td>0.450</td>
<td>0.450</td>
</tr>
<tr>
<td>Motion Transmissibility $\xi_m$</td>
<td>0.477</td>
<td>0.244</td>
</tr>
<tr>
<td>Maximum Sprung mass Velocity (mm/s) ($\dot{X}_s$)</td>
<td>$8.8 \times 10^{-4}$</td>
<td>$4.3 \times 10^{-4}$</td>
</tr>
<tr>
<td>Maximum Unsprung mass Velocity (mm/s) ($\dot{X}_{us}$)</td>
<td>$30.0 \times 10^{-4}$</td>
<td>$8.0 \times 10^{-4}$</td>
</tr>
<tr>
<td>Velocity Transmissibility $\xi_v$</td>
<td>0.293</td>
<td>0.537</td>
</tr>
<tr>
<td>Maximum Sprung mass Acceleration (m/s$^2$) ($\ddot{X}_s$)</td>
<td>$4.9 \times 10^{-6}$</td>
<td>$3.2 \times 10^{-6}$</td>
</tr>
<tr>
<td>Maximum Unsprung mass Acceleration (m/s$^2$) ($\ddot{X}_{us}$)</td>
<td>$11.3 \times 10^{-5}$</td>
<td>$11.0 \times 10^{-5}$</td>
</tr>
<tr>
<td>Acceleration Transmissibility $\xi_a$</td>
<td>0.0435</td>
<td>0.029</td>
</tr>
</tbody>
</table>

From the results given in Table 4.2, it is concluded that the proposed 2 DOF QC-EH-ASS shows considerable improvement in the response characteristics over those of conventional QC-PSS.
Hence the Electro-Hydraulic Suspension System approach is taken up for the experimental analysis.

In the next chapter, the Development of experimental set ups for following systems is described.

i) 2 DOF Quarter Car Passive Suspension System (QC-PSS)

ii) 2 DOF Quarter Car Hydraulic Active Suspension System (QC-H-ASS)

iii) 2 DOF Quarter Car Electro-Hydraulic Active Suspension System (QC-EH-ASS).