Chapter 6

Experimental Time Domain Analysis

The purpose of this chapter is to determine the source of the objectionable jerks, or nervous ride, of the seat suspension through a time domain analysis. First, the baseline time data for the Lord semiactive controller will be presented, along with the source of the acceleration jerks. Next, a revision to Lord's semiactive control policy which improves the subjective feel of the seat will be presented. Finally, the experimental results of the new control policy will be discussed.

6.1 Baseline Time Data

The next logical step in testing was to perform a time domain analysis of the seat for various excitations. The ISO2 excitation time data was synchronized so that all of the data occurs at the same section of the ISO2 displacement profile, as shown in Fig. 6.1. This allows a direct comparison of the time domain data for any of the different control policies.

![ISO2 Base Displacement for All Time Data](image)

Figure 6.1. ISO2 Synchronized Base Displacement for Time Domain Analysis.
Figures 6.2 and 6.3 show the seat acceleration and damper current for a 1.4-Hz pure tone excitation and ISO2 excitation using a semiactive skyhook controller and an output gain, G, of 32. The figures indicate that there is a large amount of rapid change in the acceleration trace, and at each off-state to on-state switch, the damper current undergoes a step jump. The force-velocity characteristics of the MR damper, shown in Fig. 2.11, indicates that if we make a step change in current, we will also create a step change in the damper force. This step change of the damper force creates a sudden change in force and acceleration of the suspended seat. Any sudden change of the seat acceleration is perceived by the person in the seat as a 'thump' or 'jerk.' Therefore, the source of the seat jerkiness is the sudden change in the damping force due to the skyhook control policy and the damping characteristics of the MR dampers.

Figure 6.2. Skyhook Controller, G=32, 1.4-Hz Pure Tone Input Excitation.
6.2 Reducing the Acceleration Jerks

Carefully inspecting Fig. 6.2 shows that as the damper changes from the off-state to the on-state, the damper current undergoes a step jump. During the on-state to off-state transition, however, the damper current follows the semiactive control in Eq. (3.1) in the sense that the current is proportional to the seat velocity, $V_1$.

The semiactive suspension jerk problem appears to have been studied by other researchers in the past. Miller and Nobles [37] noticed this problem for an automobile suspension, and suggested limiting the damper force in the low velocity region of damper operation by reducing the current when the relative velocity across the damper is low. Their analytical study shows a reduction in the RMS levels of jerk in the suspension.

Another solution to the current discontinuities is to modify the skyhook control policy, shown in Eq. (3.1), to

$$
\begin{align*}
&|V_1 V_{12}| > 0 & i = \gamma V_1 V_{12} \\
&|V_1 V_{12}| < 0 & i = 0
\end{align*}
$$

(6.1)

where $\gamma$ is a constant and $i$ is the damper current. This version of the skyhook control will be referred to as modified skyhook control throughout this study. The modified
skyhook control policy takes advantage of the fact that at the off-to-on and on-to-off transitions, at least one of the velocities will be zero. Thus, the product of the two velocities forces the off-on and on-off transitions to identically match the off-state damper current of zero Amperes. Figure 6.4 shows how the modified skyhook control current is forced to be a continuous function in time.

![Figure 6.4. Modified Skyhook Continuous Control Current](image)

Figures 6.5 and 6.6 show the 1.4-Hz pure tone and ISO2 time domain responses for the modified skyhook controller for a value of $\gamma$ equal to 128. Notice that the sharp peaks in Figs. 6.2 and 6.3 have been significantly reduced. In subjective testing of the seat, the modified skyhook controller resulted in a much better (less jerky) ride as compared to the skyhook controller, effectively validating the results in Figs. 6.5 and 6.6.

To confirm these results the jerk for each test was numerically computed using the acceleration data. Figures 6.7-6.10 show the computed levels of jerk for the skyhook and modified skyhook controllers with a 1.4 Hz pure tone and ISO2 base input. Notice that the levels of jerk are considerably lower for the modified skyhook controller.
Figure 6.5. Modified Skyhook Controller, $\gamma=128$, 1.4-Hz Pure Tone Excitation.

Figure 6.6. Modified Skyhook Controller, $\gamma=128$, ISO2 Excitation.
Figure 6.7. Computed Jerk for Skyhook Control and 1.4 Hz Input.

Figure 6.8. Computed Jerk for Skyhook Control and ISO2 Input.
6.3 Tuning the Controller Gains G and $\gamma$

The values of G and $\gamma$, the controller current output gains for the skyhook and modified skyhook control, can be adjusted to meet specific performance criteria. For instance, ISO and SAE often judge the performance of a seat suspension by how much
the input is amplified at the resonant frequency. Therefore, one method of evaluating the performance of a seat suspension is to evaluate the transmissibility. Figures 6.11 and 6.12 show the transmissibilities for the Isringhausen seat using the skyhook and modified skyhook control policies.

Figure 6.11. Skyhook Control Seat Suspension Transmissibility.

Figure 6.12. Modified Skyhook Control Seat Suspension Transmissibility.
The gain, $\gamma$, for the modified skyhook controller allows a very limited amount of shaping of the transmissibility, as shown in Fig. 6.12. For the low gain ($\gamma=128$), the modified skyhook controller exhibits a low level of jerk, as shown in Fig. 6.6. However, as $\gamma$ increases, the seat jerk also increases. Similarly, changing the gain for the skyhook controller allows us to shape the transmissibility to a greater extent. An increase in $G$ is analogous to an increase in the ideal skyhook damping ratio, $\zeta_{SKY}$. Similar to the modified skyhook controller, decreasing the gain decreases the seat jerk. This phenomenon occurs because reducing the gain reduces the magnitude of the step change in the applied damper force, which in turn reduces the level of discontinuity in the acceleration of the seat suspension. This phenomenon can be a rather subtle change and may be difficult to quantitatively analyze, since visually inspecting or objectively quantifying subtle changes in the time domain data often does not directly correlate with the subjective feel of the seat suspension performance. Therefore, the best method of determining the acceptability of a particular suspension system is to perform a great amount of subjective testing. This is especially important for a consumer product, since the ultimate goal is to please the consumer.