Semi-Active Suspension Control Using Modified Skyhook-Based Logic

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GIT REPOSITORY LINK:

`https://github.com/shashank0r/suspension-controller-design`

1 Introduction

Vehicle suspension systems are required to isolate the vehicle body from road disturbances while maintaining tire contact with the road. Passive suspension systems rely on fixed damping characteristics and therefore cannot adapt to varying road conditions. Semi-active suspension systems improve this limitation by allowing the damping coefficient to change in real time.

In this work, a quarter-car suspension model equipped with a semi-active damper has been given a damper controller command. A controller inspired by the skyhook damping principle is implemented and extended using simple rule-based logic. The aim is to reduce sprung mass displacement and oscillations under different road excitations while maintaining acceptable ride comfort.

2 Quarter-Car Model

A two-degree-of-freedom quarter-car model is considered, consisting of a sprung mass m_s, an unsprung mass m_u, a suspension spring with stiffness k_s, a tire stiffness k_t, and a semi-active damper with time-varying coefficient $c(t)$. The road profile is applied as a vertical displacement input $z_r(t)$.

The equations of motion are:

$$m_s\ddot{z}_s = -k_s(z_s - z_u) - c(t)(\dot{z}_s - \dot{z}_u) \tag{1}$$

$$m_u\ddot{z}_u = k_s(z_s - z_u) + c(t)(\dot{z}_s - \dot{z}_u) - k_t(z_u - z_r) \tag{2}$$

3 Controller Design

3.1 Control Philosophy

A rule-based semi-active damping strategy is adopted instead of a complex model-based optimal controller. This approach is chosen to keep the controller simple, intuitive, and easy to interpret, especially for understanding the physical behavior of suspension systems.

The key reasons for choosing this approach are:

- Simplicity and ease of implementation
- Clear physical interpretation of control decisions
- Robust performance under nonlinear road inputs

The controller switches between discrete damping levels depending on suspension behavior. Under normal driving conditions, comfort is prioritized, while during severe disturbances the controller increases damping to protect the vehicle and reduce oscillations.

3.2 Damping Levels

Three damping levels are defined:

- $c_{\min}$: low damping (comfort mode)

- c_{mid}: moderate damping (balanced mode)
- c_{max}: high damping (impact protection mode)

At each time step, the controller selects one of these values based on suspension displacement, velocity, and acceleration.

3.3 Impact Detection and Memory Mechanism

Harsh road events such as bumps or potholes are detected using:

- Sprung mass acceleration exceeding a threshold
- Relative suspension displacement exceeding a threshold

If either condition is met, an impact is detected. The damper is immediately switched to a high damping level. A timer-based memory mechanism keeps the damper stiff for a short duration after the impact, preventing rapid switching and ensuring sufficient energy dissipation.

3.4 Motion Phase and Energy-Based Logic

The controller distinguishes between compression and rebound phases using the sign of relative displacement and velocity. Additionally, simple energy-based logic is applied by examining the product of acceleration and relative velocity. This helps determine whether increasing damping will effectively reduce body oscillations and stabilize wheel motion.

3.5 Control Law Summary

At each time step, the controller applies the following rules:

- **Impact handling:** If an impact is detected or recently occurred,
$$c = c_{\text{max}}$$
- **Rebound phase:** During suspension rebound,
$$c = 0.8\, c_{\text{max}}$$
- **Balanced condition:** If damping helps both body and wheel dynamics,
$$c = c_{\text{mid}}$$
- **Normal driving:** Otherwise,
$$c = c_{\text{min}}$$

4 Controller Tuning Strategy and Parameter Sensitivity

The controller parameters were tuned iteratively through simulation, with each parameter adjusted based on its physical influence on suspension response.

4.1 Damping Coefficients

Minimum damping ($c_{\min}$):

Increasing $c_{\min}$ reduces small body oscillations but increases transmission of high-frequency road inputs, reducing comfort. Decreasing $c_{\min}$ improves ride comfort on smooth roads but increases settling time after mild disturbances.

Medium damping (c_{mid}):

Increasing c_{mid} reduces steady-state oscillation amplitude and improves vibration attenuation, but increases perceived stiffness. Decreasing c_{mid} improves comfort while allowing larger body motion.

Observation: All sinusoidal and random road profiles show that c_{mid} directly governs oscillation amplitude of $z_s(t)$.

Maximum damping ($c_{\max}$):

Increasing $c_{\max}$ strongly limits suspension travel and rapidly dissipates impact energy, but may transmit higher forces. Decreasing $c_{\max}$ results in softer impacts but increases the risk of bottoming out and residual oscillations.

4.2 Impact Detection Thresholds

Higher acceleration thresholds reduce sensitivity to small disturbances, while lower values trigger high damping more frequently. Similarly, higher displacement thresholds allow greater suspension travel, whereas lower values activate protective damping earlier.

4.3 Impact Hold Time

A longer hold time maintains high damping for longer durations, improving oscillation suppression after impacts. Shorter hold times allow quicker return to comfort but may leave residual vibrations.

4.4 Tuning Summary

Table 1: Effect of Controller Parameters

Parameter	Increase Effect	Decrease Effect
$c_{\min}$	Stiffer baseline	More comfort
c_{mid}	Smaller oscillations	Larger body motion
$c_{\max}$	Strong impact control	Softer impacts
a_{th}	Less sensitivity	Frequent stiffening
z_{th}	Larger travel allowed	Early protection
T_{hold}	Persistent damping	Faster recovery

5 Simulation Results

Five road profiles were used to evaluate controller performance.

5.1 Profile 1: Two Half-Sine Bumps

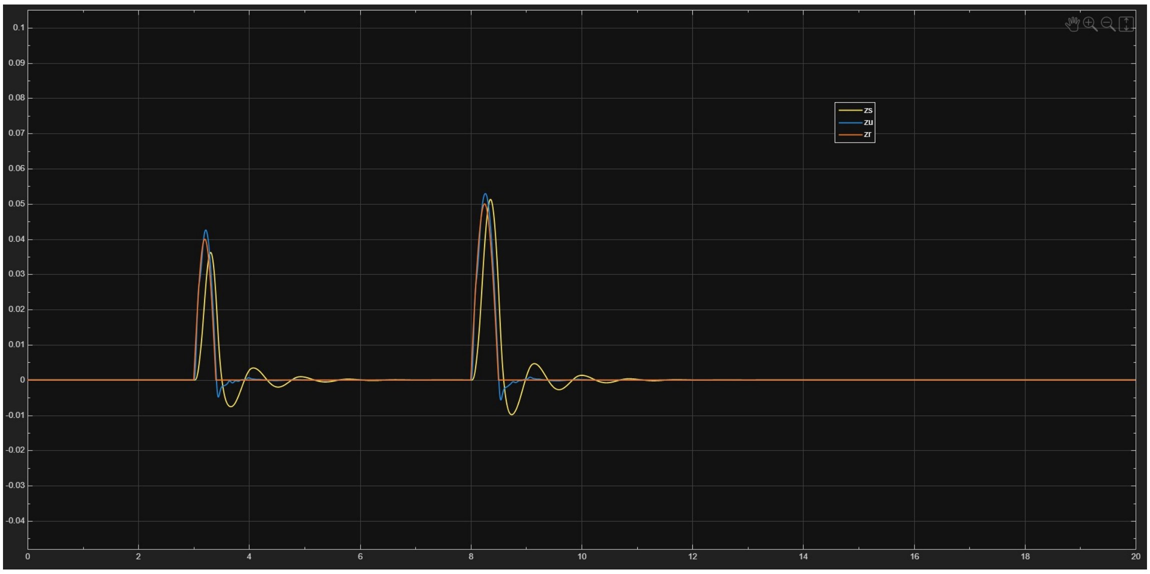

Figure 1: Two half-sine bumps representing isolated obstacles

5.2 Profile 2: Smooth Wavy Road

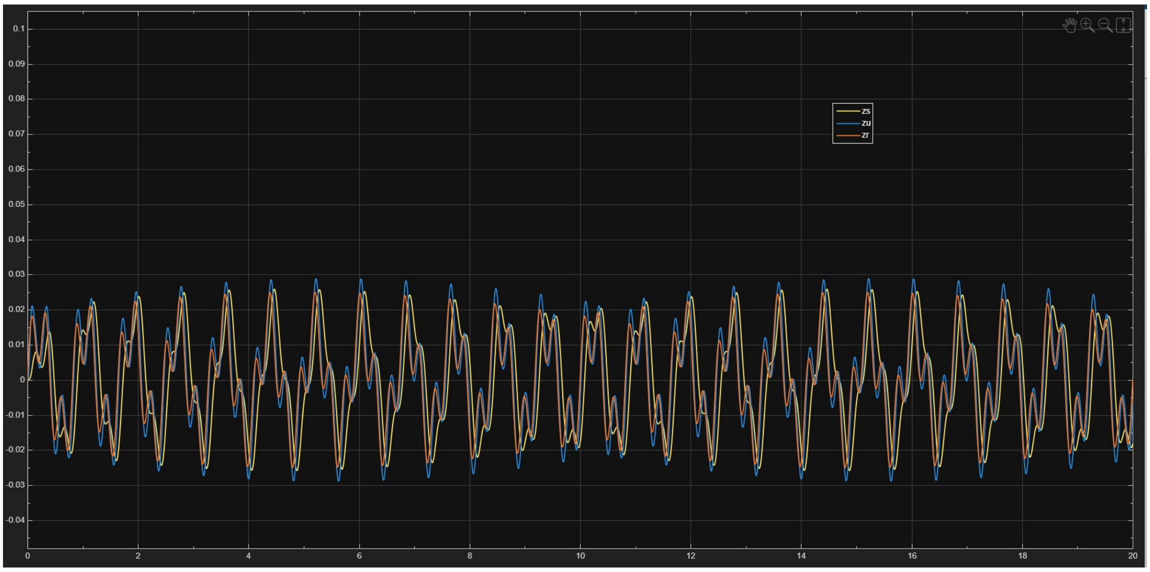

Figure 2: Smooth wavy road with low-frequency undulations

5.3 Profile 3: Rough Asphalt

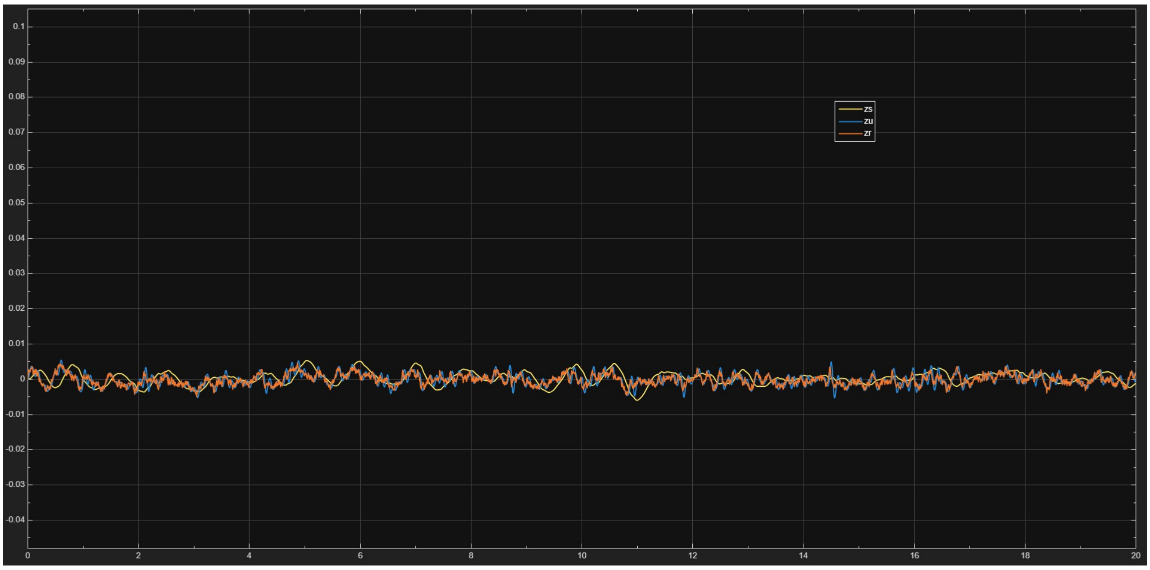

Figure 3: Rough asphalt with noise-like high-frequency content

5.4 Profile 4: Speed Breaker with Sharp Dip

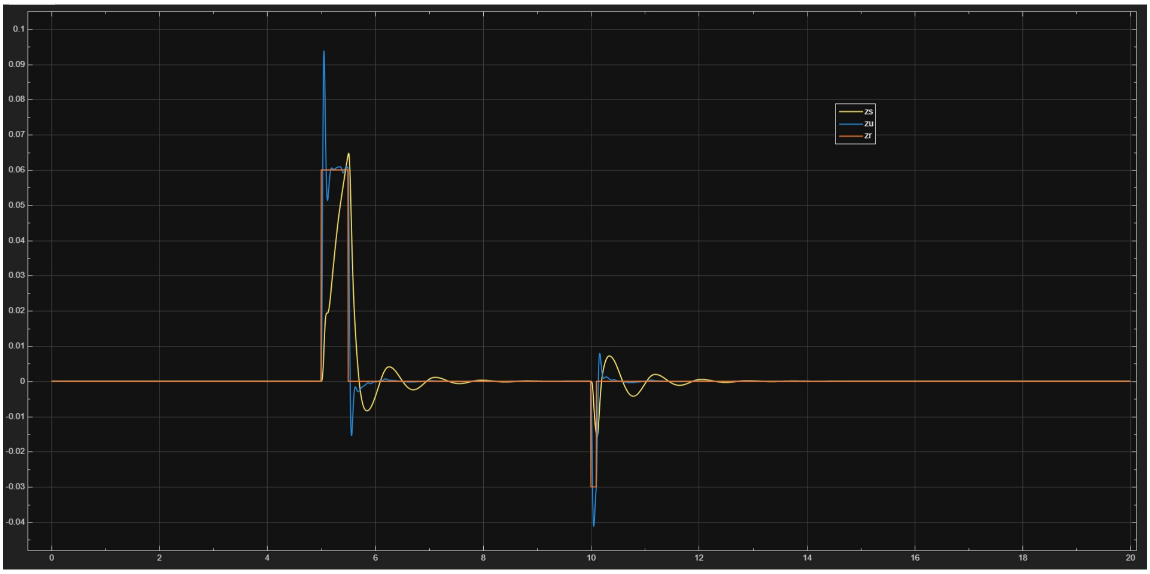

Figure 4: Speed breaker followed by a sharp dip

5.5 Profile 5: The Coffee Run

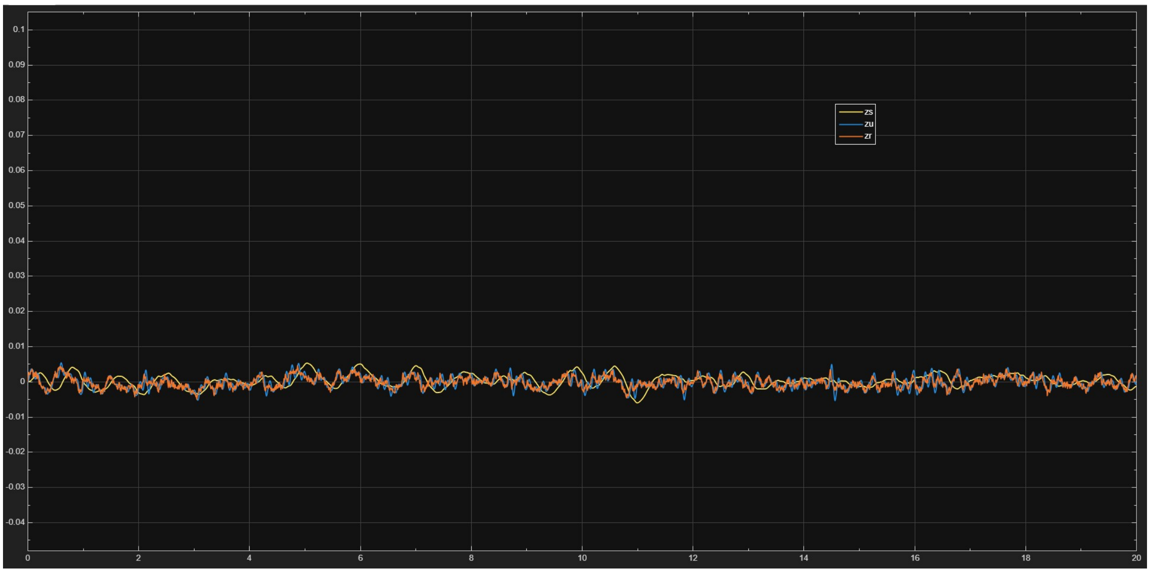

Figure 5: Mixed sine waves, noise, and a pothole event around $t \approx 15\,\mathrm{s}$

6 Conclusion

A semi-active suspension controller based on modified skyhook logic was implemented and evaluated using a quarter-car model. Results across five representative road profiles demonstrate effective reduction of sprung mass displacement while maintaining acceptable unsprung mass behavior.