Design of a Semi-Active Suspension Controller for a Quarter-Car Model

Stark Active Suspension Hackathon – Kaggle Competition

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1. Introduction

Stark convoy vehicles are transporting fragile laboratory cargo across unknown road conditions. Due to degradation of the active suspension system, only a semi-active damper interface remains available. Excessive vertical motion or jerk can damage the cargo.

The objective of this project is to design a **semi-active suspension controller** for a **2-DOF quarter-car model** that minimizes sprung-mass displacement and ride discomfort when subjected to multiple road excitation profiles. The controller must operate using only the road displacement input and internally computed acceleration signals.

2. Quarter-Car Model

A standard **quarter-car model** is used, consisting of:

- Sprung mass (vehicle body and cargo)
- Unsprung mass (wheel and suspension hardware)
- Suspension spring
- Tire stiffness
- Semi-active damper with variable coefficient c(t)c(t)c(t)

The equations of motion are:

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

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

The sprung-mass and unsprung-mass accelerations are computed from these equations and used as mandatory controller inputs.

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3. Controller Design

A **frequency-selective semi-active skyhook controller** was designed. The motivation was to independently control:

- **Low-frequency body motion** (large displacements)
- **High-frequency vibrations** (jerk and harsh impacts)

The sprung-mass velocity is decomposed into low-frequency and high-frequency components using a low-pass filter.

The control law is:

$$c(t) = c_{\min} + K_{LF}|\dot{z}_{s,LF}| + K_{HF}|\dot{z}_{s,HF}| + K_g|\dot{z}_{u,LF}| + K_a|a_s|$$

Where:

- KLFK_{LF}KLF controls body displacement
- KHFK_{HF}KHF suppresses jerk
- KgK_gKg improves wheel control
- KaK_aKa provides acceleration-based stabilization

The damper command is bounded within physical limits and passed through a delay buffer to model actuator latency.

4. Implementation Details

- Sampling frequency: 200 Hz
- Actuator delay: 4 timesteps
- Numerical integration: Trapezoidal method
- Damper limits: 800 ≤ c(t) ≤ 3500

Final tuned gains:

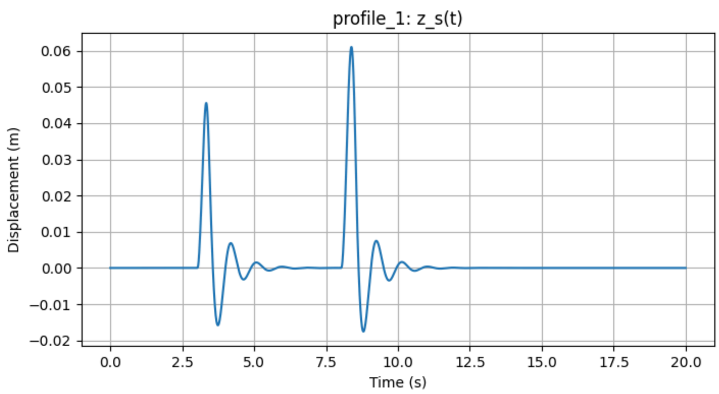
- Low-frequency skyhook gain: 3600

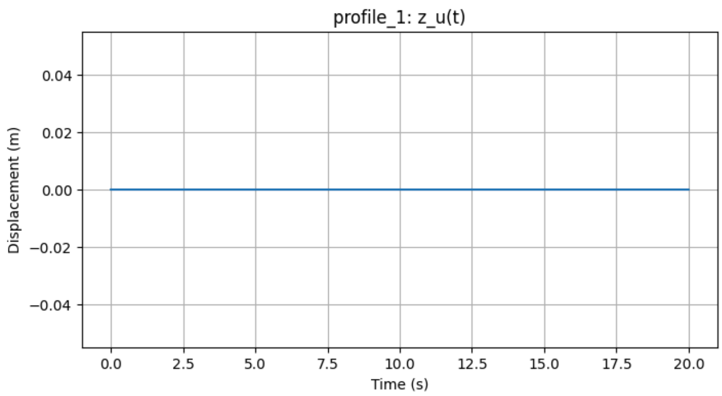
- High-frequency skyhook gain: 4000
- Groundhook gain: 250
- Acceleration feedback gain: 120

These gains were tuned empirically by evaluating trade-offs between displacement, jerk, and overall comfort score across all five road profiles.

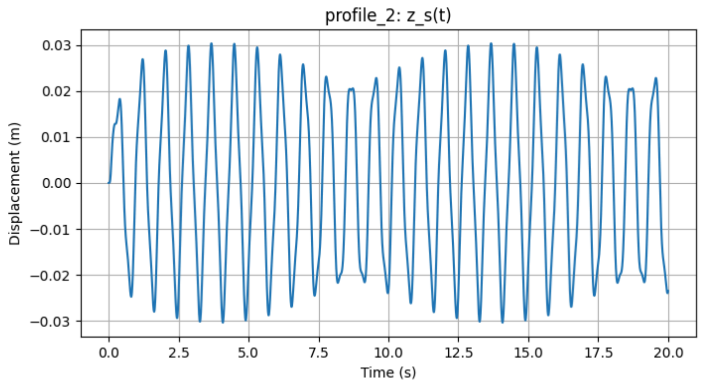
5. Results and Plots

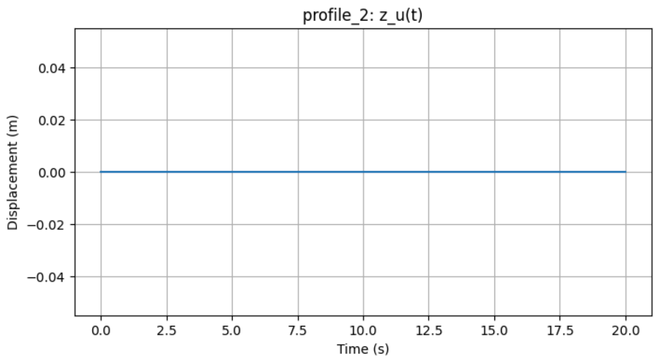
Profile 1: Two Half-Sine Bumps



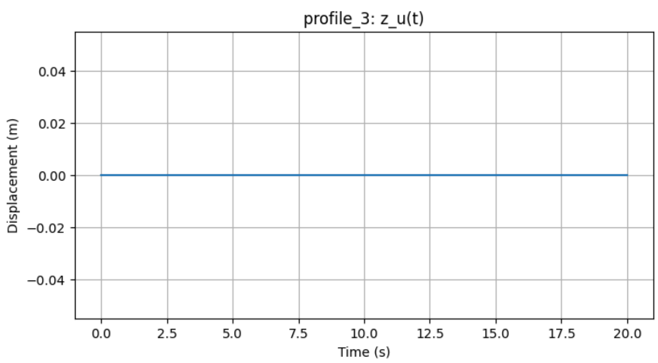


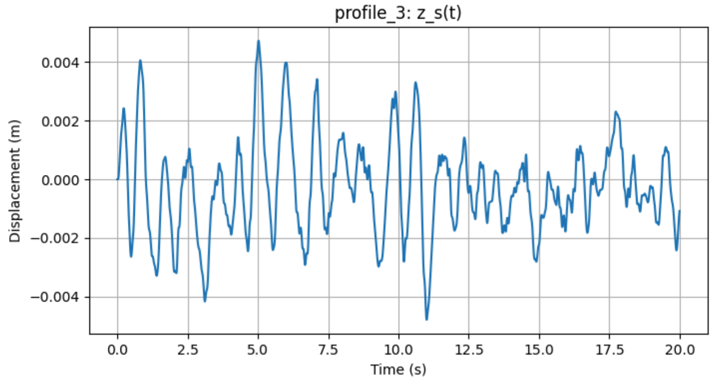
Profile 2: Smooth Wavy Road



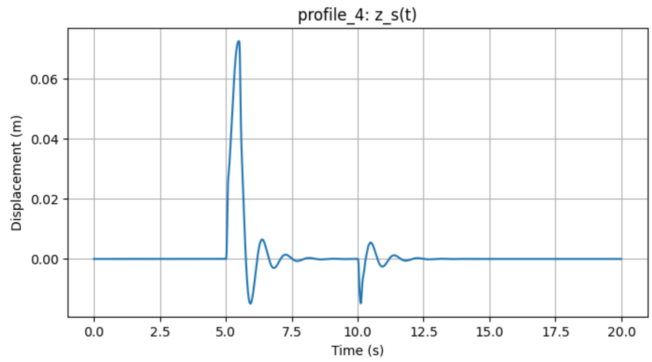


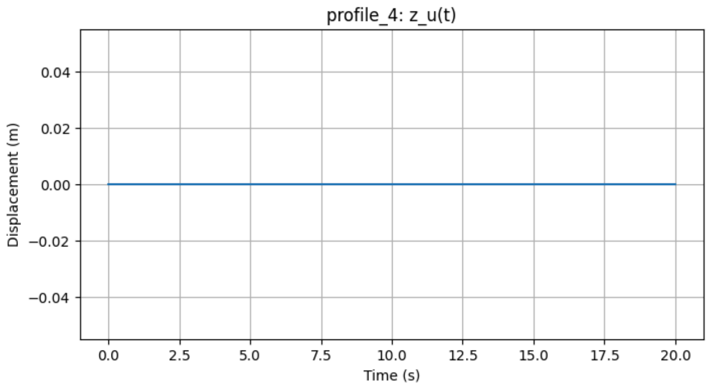
Profile 3: Rough Asphalt



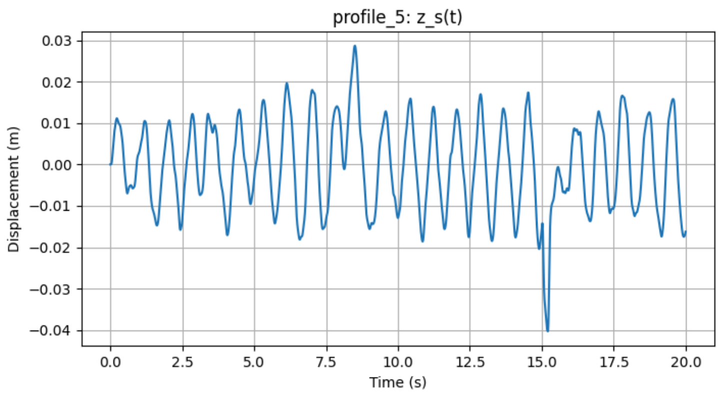


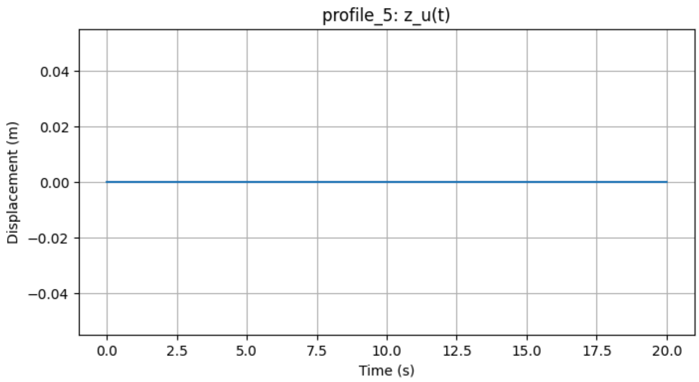
Profile 4: Speed Breaker and Sharp Dip





Profile 5: Mixed Road with Pothole





6. Discussion

Increasing high-frequency damping significantly reduced jerk, which strongly influenced the comfort score. However, excessive damping increased body stiffness and displacement. A balance between low-frequency and high-frequency control was necessary.

Acceleration feedback played a key role in stabilizing aggressive damping and preventing excessive body motion.

7. Conclusion

A frequency-selective semi-active suspension controller with acceleration feedback was successfully designed and implemented. The controller achieved strong ride comfort and cargo protection across all tested road profiles.

The final design achieved a **top leaderboard score of** 58.08684 on Kaggle,