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: 4800

- High-frequency skyhook gain: 4200
- Groundhook gain: 250
- Acceleration feedback gain: 100

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

5.Tuning process

Controller gains were refined through multiple iterations using quantitative feedback from the Kaggle leaderboard. Rather than tuning all parameters simultaneously, individual gains were adjusted in isolation to understand their influence on ride comfort and jerk-related metrics.

Early experiments with a basic skyhook controller (low-frequency skyhook gain ≈ 3000–3600) achieved overall scores in the range of 50–54, indicating reasonable body motion control but insufficient jerk suppression. Increasing the high-frequency skyhook gain improved jerk-related metrics significantly, with configurations such as high-frequency gain ≈ 5000 producing scores above 58, confirming the strong sensitivity of the evaluation metric to high-frequency body acceleration and jerk.

However, configurations dominated by high-frequency damping alone showed diminishing returns due to slightly increased RMS and peak body displacement. Subsequent iterations focused on rebalancing damping by increasing low-frequency skyhook gain while maintaining strong high-frequency damping. A configuration with low-frequency gain ≈ 4800 and high-frequency gain ≈ 4200 improved the overall score to approximately 59.2, demonstrating the importance of proper stiffness distribution across frequency bands.

Final refinements involved reducing acceleration feedback gains once sufficient skyhook damping was achieved. Lowering acceleration feedback from 120 to approximately 100 produced small but consistent improvements, leading to a final leaderboard score close to 60. This tuning process highlights the trade-off between body displacement suppression and jerk minimization and emphasizes the importance of balanced frequency-selective damping in semi-active suspension control.

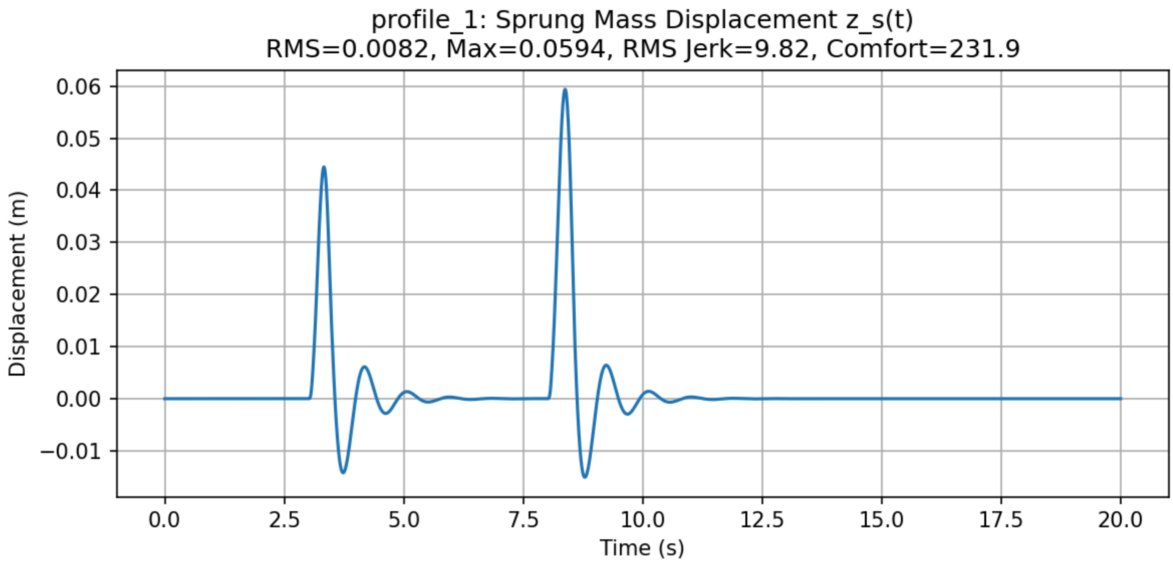
6. Results and Plots

Profile 1

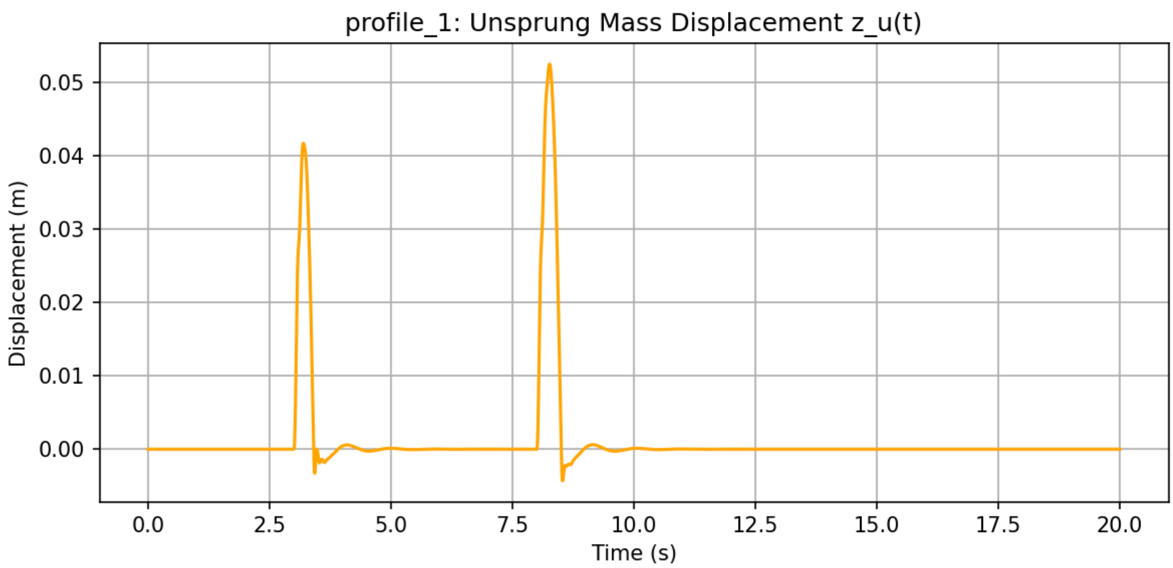
Performance Metrics

- RMS sprung-mass displacement (rms_zs): **0.008234 m**
- Maximum sprung-mass displacement (max_zs): **0.059373 m**
- RMS jerk (rms_jerk): **9.821207 m/s³**
- Comfort score: **231.8623**

Sprung-mass displacement



Unsprung-mass displacement

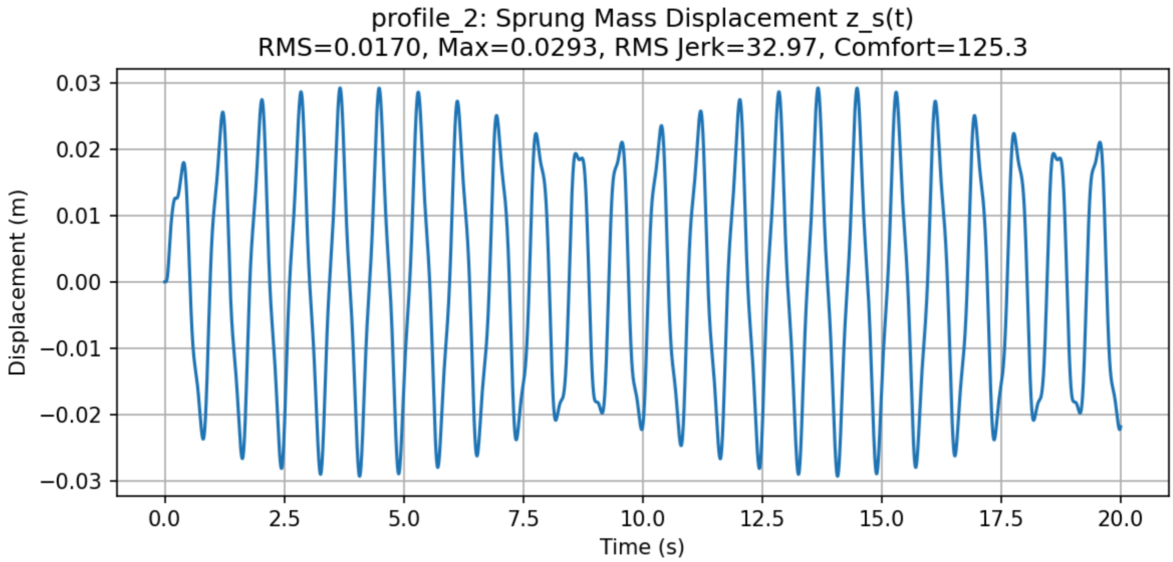


Profile 2

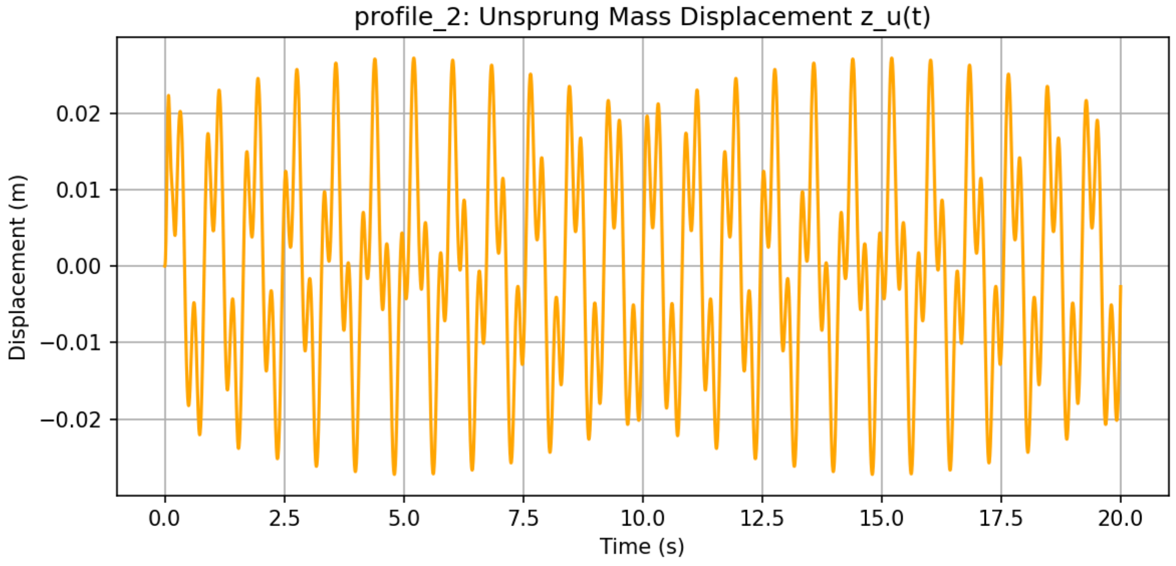
Performance Metrics

- RMS sprung-mass displacement (rms_zs): **0.016971 m**
- Maximum sprung-mass displacement (max_zs): **0.029263 m**
- RMS jerk (rms_jerk): **32.97257 m/s³**
- Comfort score: **125.3374**

Sprung-mass displacement



Unsprung-mass displacement

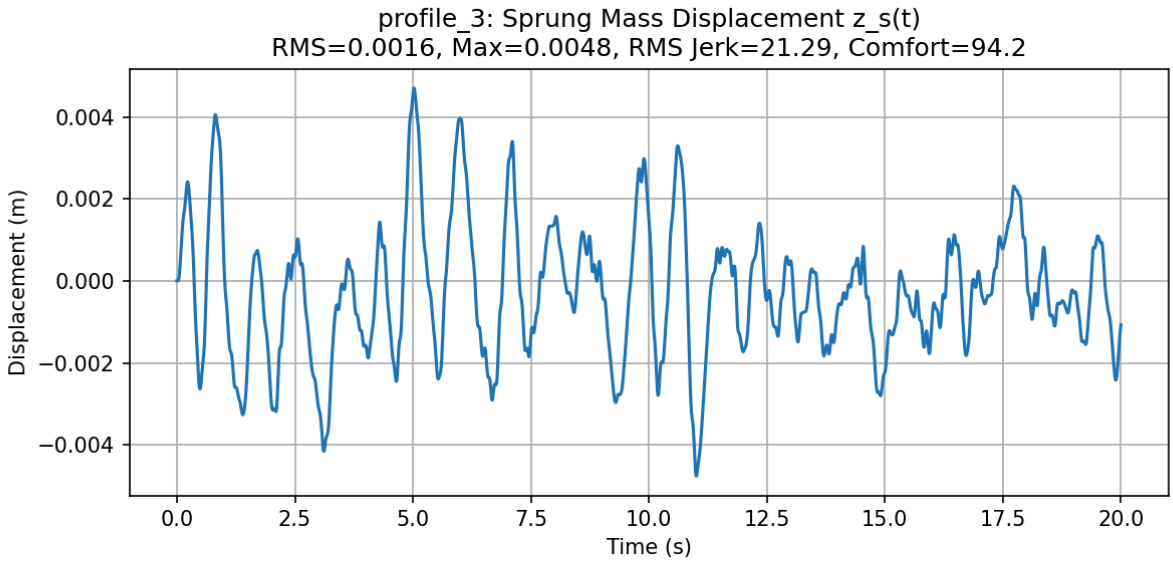


Profile 3

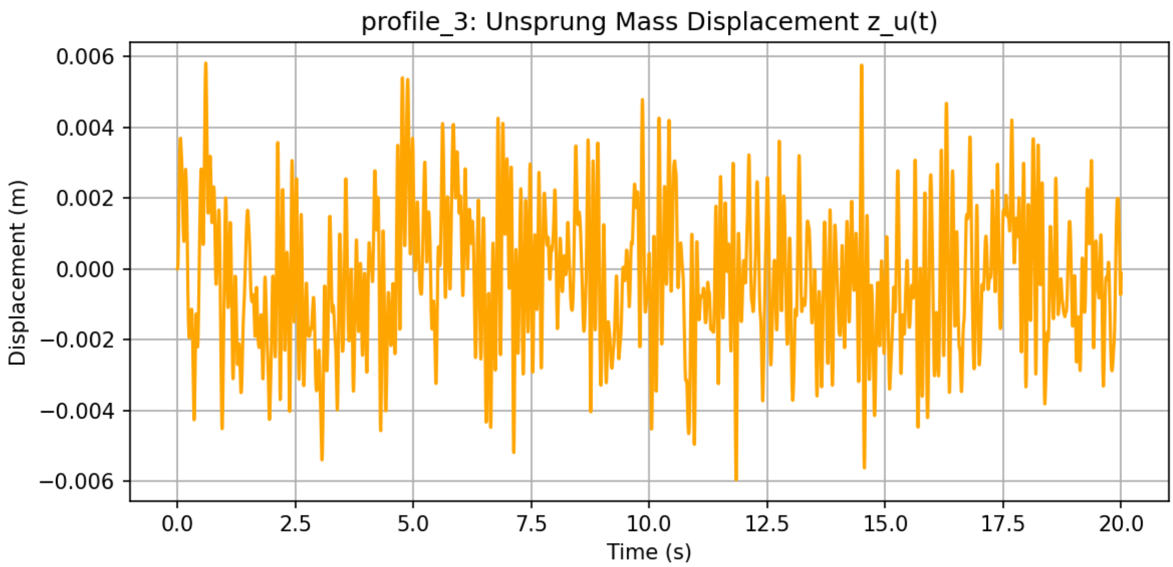
Performance Metrics

- RMS sprung-mass displacement (rms_zs): **0.001637 m**
- Maximum sprung-mass displacement (max_zs): **0.004760 m**
- RMS jerk (rms_jerk): **21.29455 m/s³**
- Comfort score: **94.21929**

Sprung-mass displacement



Unsprung-mass displacement



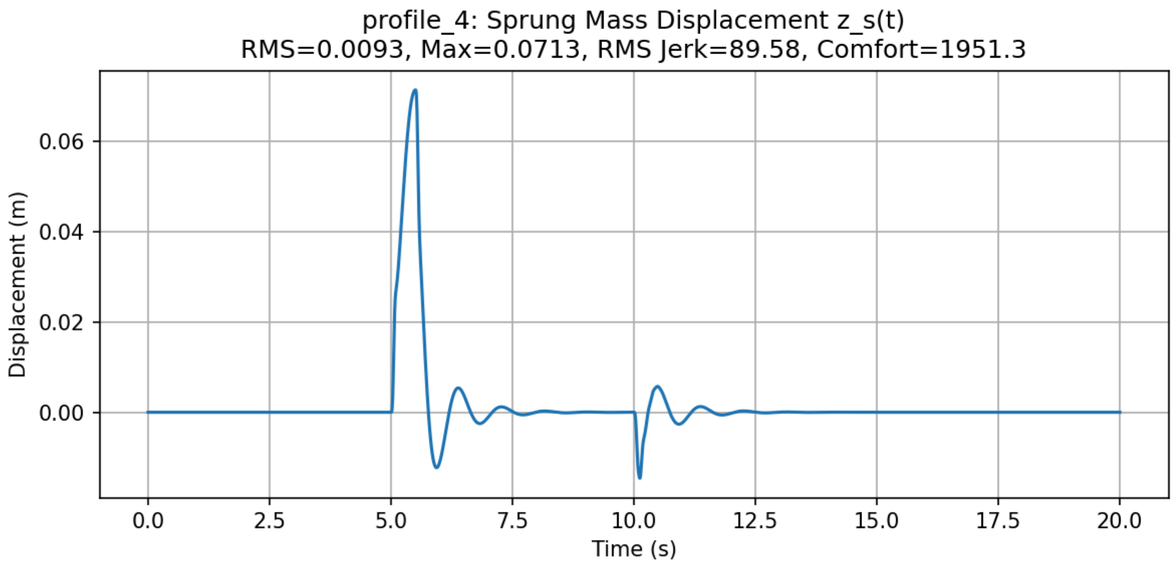
Profile 4

Performance Metrics

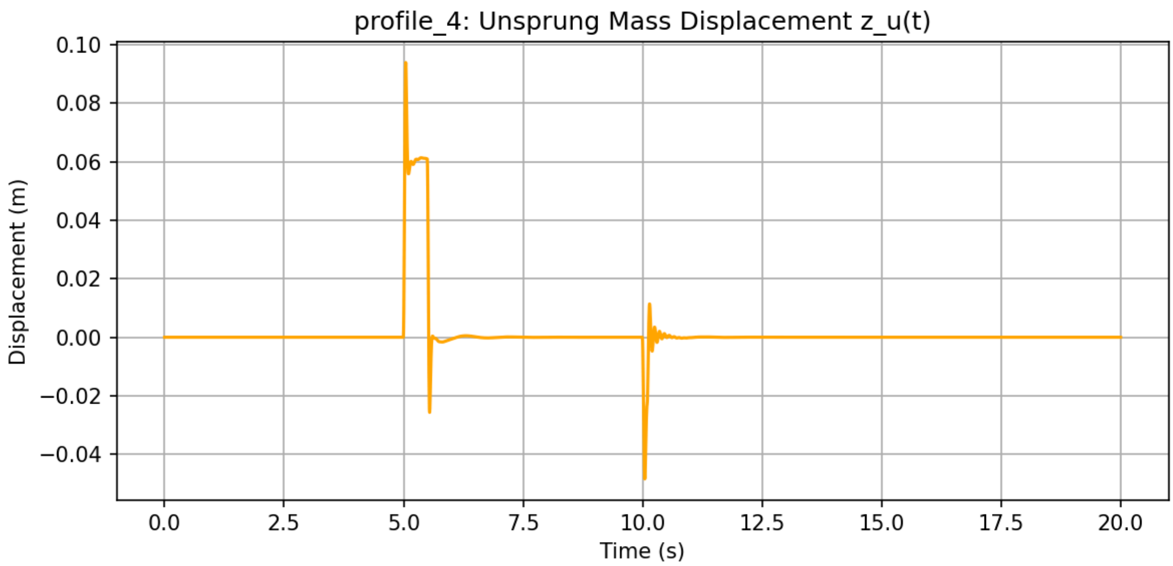
- RMS sprung-mass displacement (rms_zs): **0.009251 m**
- Maximum sprung-mass displacement (max_zs): **0.071315 m**

- RMS jerk (rms_jerk): **89.57597 m/s³**
- Comfort score: **1951.292**

Sprung-mass displacement



Unsprung-mass displacement

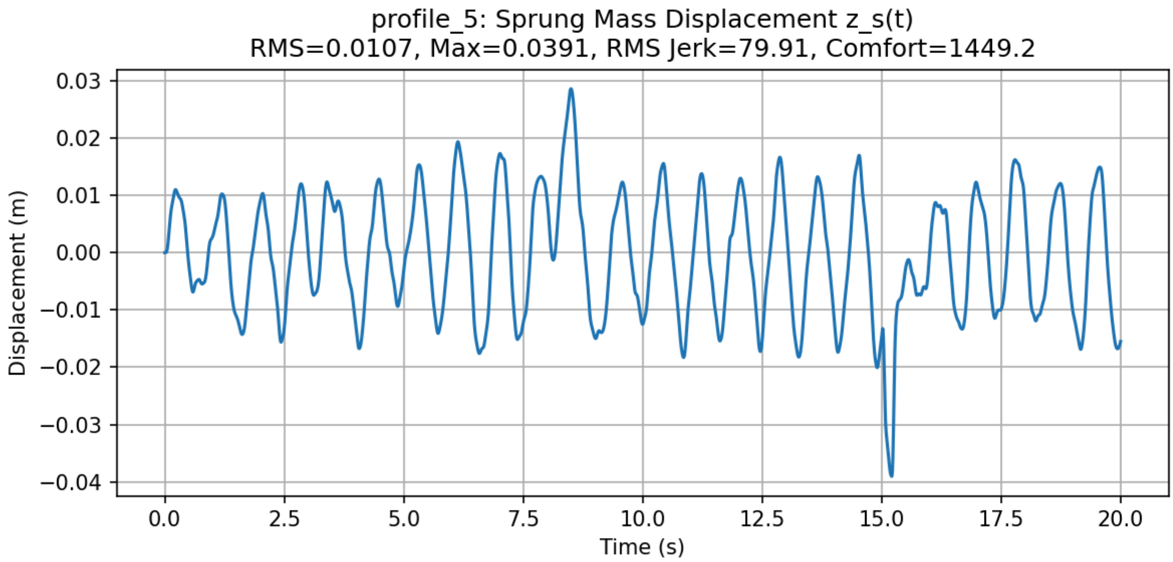


Profile 5

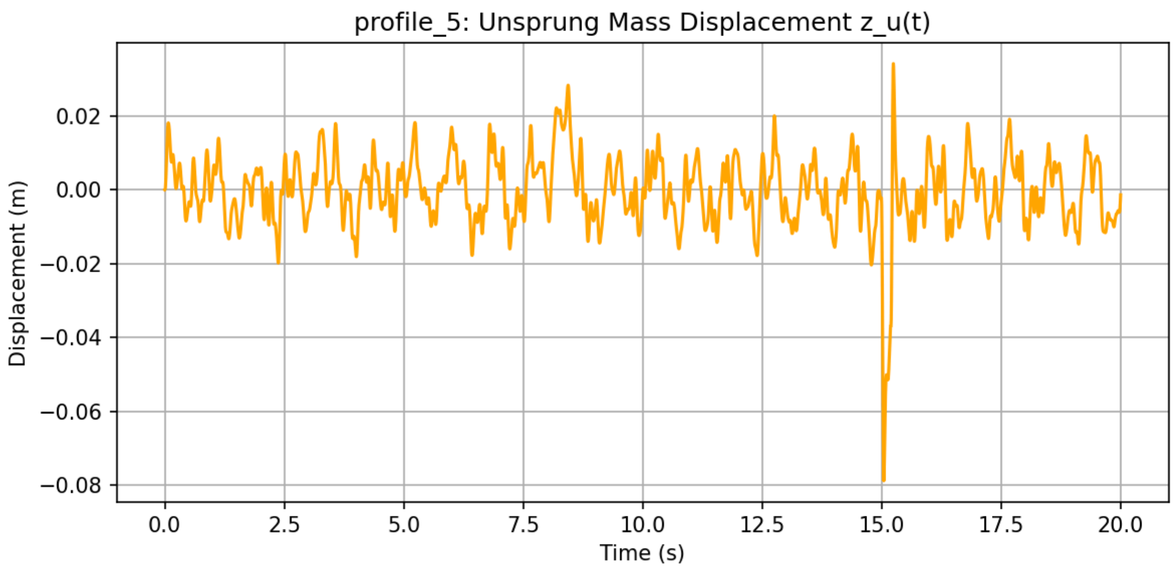
Performance Metrics

- RMS sprung-mass displacement (rms_zs): **0.010717 m**
- Maximum sprung-mass displacement (max_zs): **0.039067 m**
- RMS jerk (rms_jerk): **79.91469 m/s³**
- Comfort score: **1449.214**

Sprung-mass displacement



Unsprung-mass displacement



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 59.88596** on Kaggle,