Model-Based Design and Active PID Control of a Quarter-Car Suspension System

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1 Introduction

Modern automotive systems are increasingly developed using Model-Based Design (MBD) methodologies, which allow engineers to model, simulate, and validate system behavior before hardware implementation. One important validation approach is Hardware-in-the-Loop (HIL), where real-time simulation models interact with physical control hardware.

This project focuses on the modeling and simulation of a quarter-car suspension system and the design of an active control strategy to improve ride comfort and vehicle stability. A Proportional–Integral–Derivative (PID) controller is implemented to regulate the vertical motion of the vehicle body in response to road disturbances.

2 System Modeling (The Plant)

The quarter-car model represents the dynamics of a single corner of a vehicle and captures the essential behavior of the suspension system. This simplified model is widely used because it provides a good balance between accuracy and computational simplicity.

The plant model is derived using Newton's Second Law and describes the interaction between the vehicle body, the suspension components, and the wheel assembly under vertical motion.

2.1 Physical Components

The system consists of the following main components:

- **Sprung Mass (m_1):** Represents the vehicle chassis and passenger mass supported by the suspension.
- **Unsprung Mass (m_2):** Represents the wheel, tire, and axle assembly.

- **Suspension Spring (k_1):** Stores and releases energy due to vertical displacement.
- **Suspension Damper (b_1):** Dissipates energy and reduces oscillations.
- **Tire Stiffness (k_2):** Models the elastic behavior of the tire in contact with the road.

2.2 Governing Equations

The vertical dynamics of the quarter-car suspension system are governed by Newton's Second Law. The equations of motion for the sprung and unsprung masses are given as follows:

$$m_1\ddot{x}_1 = U - k_1(x_1 - x_2) - b_1(\dot{x}_1 - \dot{x}_2) \tag{1}$$

$$m_2\ddot{x}_2 = k_1(x_1 - x_2) + b_1(\dot{x}_1 - \dot{x}_2) - U + k_2(w - x_2) \tag{2}$$

where x_1 and x_2 represent the vertical displacements of the sprung and unsprung masses, respectively. The term U denotes the control force generated by the active suspension actuator, and w represents the road disturbance input.

3 Control System Design

To improve ride comfort and reduce vehicle body vibrations, an active suspension control strategy is implemented using a PID controller. The controller continuously adjusts the actuator force based on the measured vehicle body displacement.

The PID controller is chosen due to its simplicity, robustness, and effectiveness in regulating dynamic systems.

3.1 Closed-Loop Architecture

The control system operates in a closed-loop configuration. The desired body displacement is set to zero, representing an ideal level ride height. The actual body displacement is measured and compared with the reference value to generate an error signal.

$$e(t) = x_{\text{ref}} - x_1 \tag{3}$$

The PID controller processes this error and generates the control force U applied to the suspension actuator to minimize the displacement and suppress oscillations.

4 Simulation Results

The performance of the active suspension system is evaluated through simulation using a road disturbance input, such as a step or pulse profile. The response of the vehicle body displacement is observed to assess system stability and damping characteristics.

The results show that although an initial displacement occurs due to the road disturbance, the system quickly settles to the desired equilibrium position. The oscillations are effectively reduced, indicating stable closed-loop behavior.

5 Conclusion

In this project, a complete quarter-car suspension system was modeled using a model-based design approach. An active PID controller was successfully implemented to regulate the vertical motion of the vehicle body.

Simulation results demonstrate that the active suspension system significantly improves ride comfort by reducing body displacement and vibration. The developed model provides a strong foundation for further extensions, including real-time implementation, HIL testing, and advanced control strategies.