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Original Research

Design and Simulation of the Speed Response of an Automobile Cruise Control System

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Abstract

Automobile accidents are becoming more common as a result of individuals driving at excessive speeds. It lost countless lives and expensive possessions because of simple mistakes made when navigating around the school zones, slopes, and highways. One of the biggest obstacles the modern car industry faces is the need for a safe and controlled cruise control system. The design and modeling of automobile cruise control systems using Proportional Integral Derivative (PID) controllers, closed-loop, and open-loop designs were the principal topics of this study. The most useful controller for automatically maintaining a car's speed among the three is PID. The system's primary focus is inter-distance control on highways, where vehicle velocity mostly stays constant. It also handles traffic in towns where there are a lot of pauses and accelerations. The objectives of comfort and safety are to be met in both cases. Using a PID control system, the system's improvement aims to regulate vehicle speed and prevent collisions. The speed at which cars travel can be monitored and controlled. MATLAB/SIMULINK software was used to carry out the simulation.

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INTRODUCTION

It is well known that the number of car-related traffic accidents is rising. Even in areas with abrupt bends and intersections, driving at high speeds is the primary cause of many accidents (Rage et al., 2023). Numerous systems have been created to stop these auto accidents. A cruise control system that allows the driver to set the speed and a sensor that keeps the car a safer distance from the car in front of it are two examples of these (Zhu et al., 2023). A common feedback (closed-loop) control mechanism in many contemporary cars is the automatic cruise control system. It's sometimes referred to as "speed control," and it regulates an automobile's speed automatically (Zhu et al., 2023).

Cruise control, which only functions as a speed limiter by utilizing the concept of an automated cruise control system, is intended to address issues that affect both drivers and passengers, such as fatigue and traffic accidents (Desmira et al., 2024). The task of the cruise control system is to maintain the driver's intended speed by activating the accelerator-throttle pedal linkage without the driver having to change the throttle position.

Statement of the Problem

Automobile cruise control systems have become an essential feature in modern vehicles, offering convenience and reduced driver fatigue. However, achieving optimal speed responses remains a critical challenge due to various factors, such as road conditions, vehicle dynamics, and external disturbances.

This study aims to design and simulate an advanced cruise control system that enhances speed response accuracy while ensuring smooth transitions under varying conditions. By using proportional-integral-derivative (PID) controllers, the study seeks to develop a more adaptive and efficient system that minimizes overshoot, steady-state error, and response delays to improve automobile cruise control systems.

Research Questions

How does a PID controller perform in regulating vehicle speed in a cruise control system?

What simulation-based insights can be derived to improve the design of automobile cruise control systems?

What is the impact of external disturbances on cruise control performance?

MATERIALS AND METHODS

Cruise Control System

Constant velocity control: The technology maintains the driver's car at a steady velocity even when there are no vehicles in front of them or when there is a significant gap between them (Zhu et al., 2023).

Deceleration control: The technology applies the brakes on the driver's car to slow it down when it detects another vehicle approaching at a lower speed (Zainuddin et al., 2023).

Following control: The mechanism regulates the brake and throttle when the driver's car is trailing the car in front of it (Zainuddin et al., 2023).

Acceleration control: When the driver's vehicle encounters a deviation in its path, the system swiftly increases the vehicle's speed to match the driver's preset velocity before stabilizing it (Zainuddin et al., 2023).

Mathematical Modeling and Analysis

Physical model: A common example of a feedback control system in current cars is the cruise control, which keeps the car moving at a steady speed even when there are outside factors like wind or elevation changes in the road (Chaturvedi & Kumar, 2023). To do this, the vehicle's speed is measured and compared to the target speed. Figure 1 displays a car's free-body schematic (He et al., 2019).

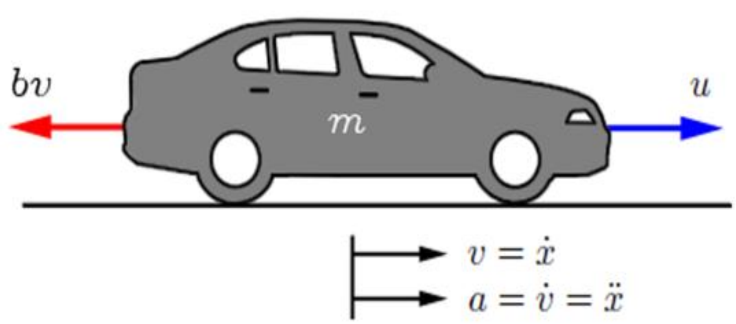

Figure 1. *Free body schematic*

System equation: Equation 1 provides the sum of forces in the x direction of the automobile's cruise control model using Newton's second law of motion (Zainuddin et al., 2023).

$$m\frac{dv}{dt} + bv(t) = u(t) \tag{1}$$

Where V is the velocity of the car, b is the friction (damping) coefficient of the car, and u is the force from the engine. Equation 1 is then transformed into Equation 2 by applying the Laplace transform. Since regulating the vehicle's speed is the goal, equation 3 is the output equation (Zainuddin et al., 2023).

$$U(s) = msV(s) + bV(s) \quad (2)$$

$$U(s) = (ms + b)V(s) \quad (3)$$

Equations 4 and 5 can be used to get the velocity of the vehicle and the transfer function of the open-loop cruise control system after rearranging equation 3 (Zainuddin et al., 2023).

$$\frac{V(s)}{U(s)} = \frac{1}{ms + b} \quad (4)$$

$$V(s) = \frac{U(s)}{ms + b} \quad (5)$$

Transfer function model: Equation 4 above provides the cruise control system's transfer function under the assumption of zero initial conditions and the Laplace transform of the governing differential equation.

Controller Design

Open-Loop System

As illustrated in Figure 2, the real speed cannot be automatically made to approach the intended speed in the open-loop system (Zhu et al., 2023).

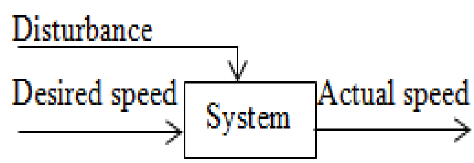

Figure 2. *Open-loop control system*

Closed-Loop System

Figure 3 depicts a basic closed-loop system. It features a system that automatically makes sure the speed is roughly where it should be (Zhu et al., 2023).

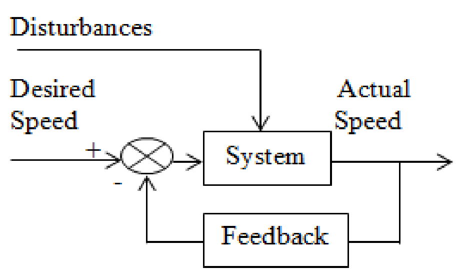

Figure 3. *Closed-loop control system*

PID Controller

PID control, which stands for Proportional-Integral-Derivative control, is used to control a wide range of systems. To get the necessary speed response, the system is enhanced with a PID. Car cruise control systems use it, which is a combination of the proportional, integral, and derivative of the error signal (Nie & Farzaneh, 2020). Mathematically, equation 6 represents the entire control function of PID. Figure 4 presents the proposed schematic for the automobile's cruise control system. The PID controller adjusts an output variable based on the error between a desired set point and a measured process variable to achieve faster responses, minimizing overshoot and steady-state error.

$$U(t) = Kpe(t) + Ki\int e(t)dt + Kd\frac{de(t)}{dt} \quad (6)$$

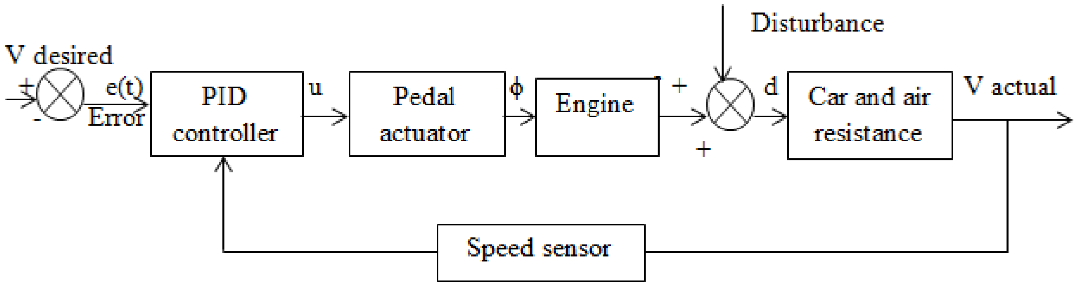

Figure 4. *Proposed block diagram*

RESULTS AND DISCUSSIONS

Results

Figure 5 exemplifies how MATLAB/SIMULINK simulates a cruise control system without a controller. The speed at which the automobile is driving is not taken into account by the speed control system. Although the steady-state inaccuracy is large, the overshoot response is acceptable. In order to remove the steady-state error, a control approach is required. This system uses a step input of 1 and then just continues to grow until it reaches its maximum possible speed of 30 m/s. The system needs much improvement. A quick improvement that can be made is to add a feedback loop (Figure 3).

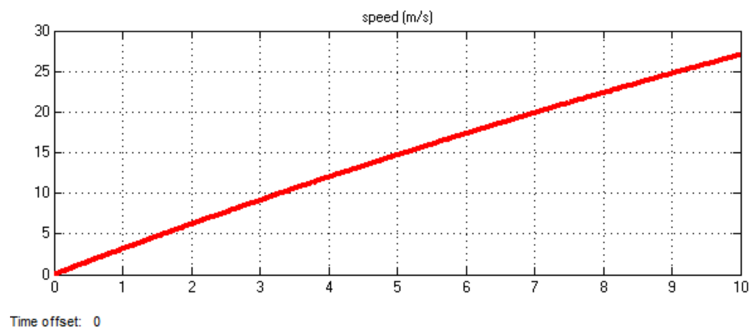

Figure 5. *Speed response with an open-loop system*

The feedback loop causes the output to try to equal the input of the initial step function. Since the step function was still set at 1 for this simulation, the output tries to go to 1 m/s instead of the desired 25 m/s. With a feedback loop, the input to the system must be equal to the desired output. Figure 6 illustrates the cruise control systems of the closed-loop control system's response.

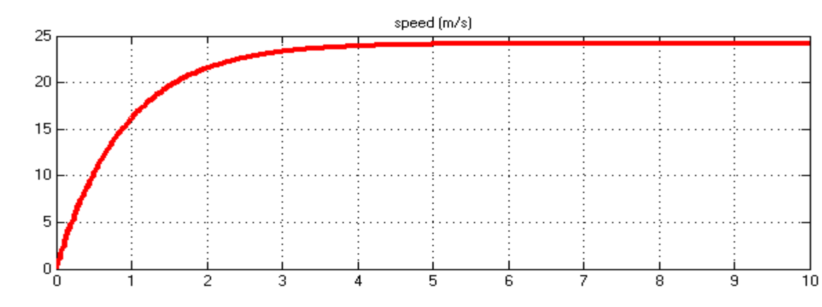

Figure 6. *Speed response with a closed-loop system*

As illustrated in Figure 7, a PID controller is added to the cruise control system model. As a result, the PID controller model fits the automobile's cruise control system's design requirements to reach the desired speed. The controller parameters and specifications used in this study are P=6, I=0.02, D=0.00, rising time=0.1ms, overshoot=8.15%, steady state error=0.00.

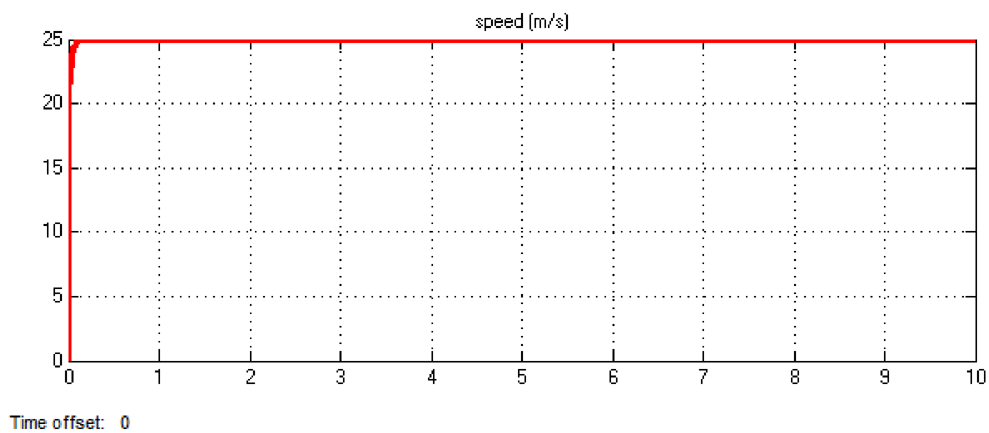

Figure 7. Speed response with a PID controller

Bode and Step Plot Analysis

Bode and step plot analysis is used to analyze the frequency response (magnitude and phase plot) and amplitude and time of the cruise control system based on the PID controller parameters to determine the control stability of the system, as shown in the Figures. 8 & 9, respectively.

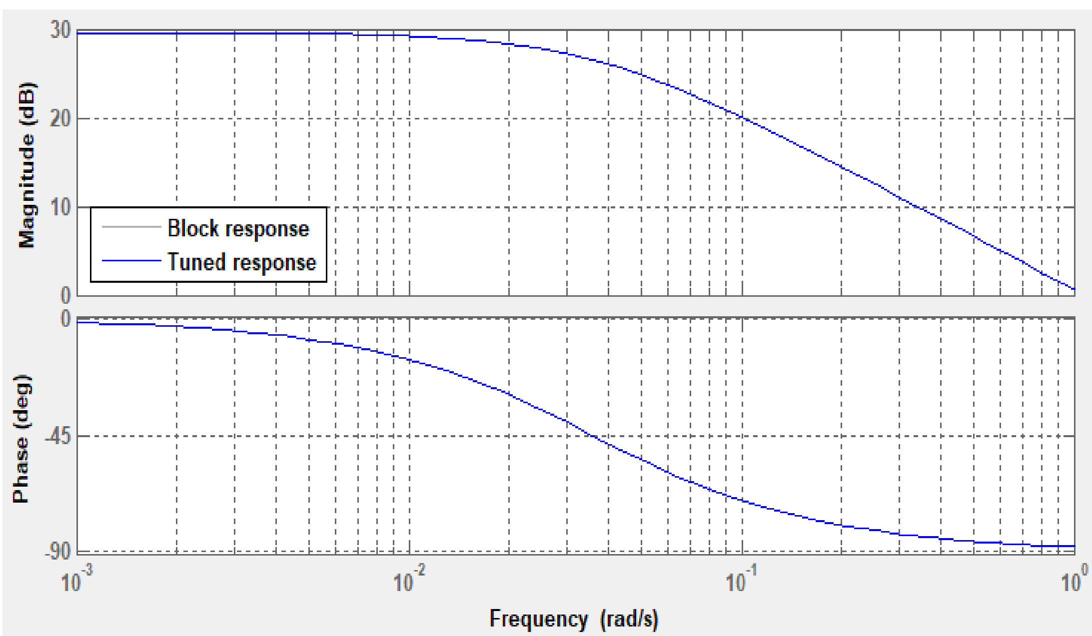

Figure 8. *Magnitude and phase plot analysis*

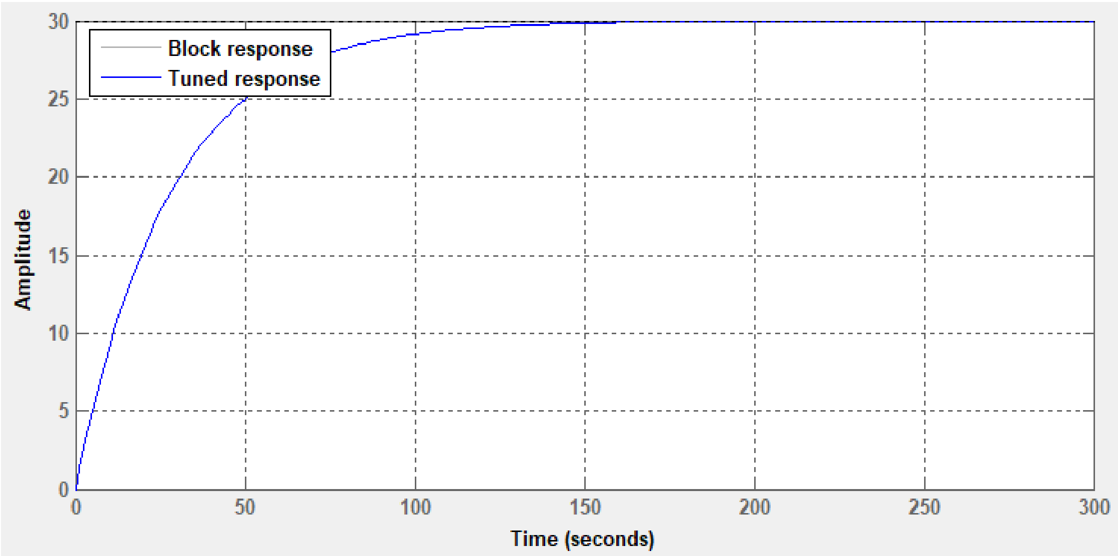

Figure 9. *Amplitude and time plot analysis*

Discussions

In the MATLAB/SIMULINK simulation of a cruise control system without a controller, the open-loop nature of the system means that the actual vehicle speed is not fed back for comparison with the desired speed. As a result, the system fails to adjust for deviations, leading to a significant steady-state error where the vehicle does not maintain the intended speed accurately. While the transient response exhibits acceptable overshoot, the lack of feedback causes the speed to continuously increase until it reaches the maximum limit of 30 m/s when subjected to a step input of 1. This performance highlights a critical flaw in the open-loop design, as a useful cruise control system must regulate speed precisely without unbounded acceleration. To address this issue, introducing a feedback loop/closed loop would allow the system to compare the actual speed with the reference input and adjust the speed accordingly, thereby minimizing steady-state error and improving overall performance. Employing a control strategy, such as a proportional-integral-derivative (PID) controller, would further enhance the system by dynamically correcting errors and ensuring stable speed regulation. Thus, while the initial simulation shows the limitations of an open-loop approach, it also - - underscores the necessity of feedback control for effective cruise control functionality.

Bode plot analysis allows the evaluation of the frequency response of the system by visualizing how the magnitude and phase shift across different frequencies, helping to determine stability margins. The step response plot, on the other hand, provides insight into the time-domain characteristics, such as rise time, settling time, overshoot, and steady-state error for assessing the PID controller's effectiveness in regulating speed. When tuning the PID parameters, the Bode plot helps ensure that the system has adequate phase margin and gain margin, preventing instability. Meanwhile, the step response plot confirms whether the controller achieves smooth and rapid speed tracking without excessive oscillations.

CONCLUSIONS

In this study, design and simulation using open-loop, closed-loop, and PID controllers have been proposed to undertake the cruise control systems of automobiles. The result of the PID controller-based system shows that there is a great enhancement in the response speed over other controllers. A step and Bode plot analysis has been simulated using MATLAB/SIMULINK to check the control stability of the system.

Recommendations

To well design and simulate the speed response of a cruise control system for automobiles, it is recommended to first improve a comprehensive mathematical model that represents the vehicle dynamics, including engine power, transmission efficiency, road resistance, and aerodynamic drag. A PID controller offers simplicity and efficiency, while more advanced techniques like Fuzzy Logic Controller (FLC) or Model Predictive Control (MPC) enhance adaptability to varying road conditions. In the future, the cruise control system will require the use of sophisticated sensors with quicker switching speeds composed of semiconductor materials, as well as knowledge of Artificial Intelligence (AI) and machine learning techniques.

CRediT Authorship Contribution Statement

The author affirms sole responsibility for the conception of the study, the presented results, and manuscript preparation.

Declaration of Competing Interest

The author declares that there is no conflict of interest.

Data Availability

The data used in this study is available upon request.

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