Fuel Pressure Regulation via PID Control for High-Performance Automotive Systems

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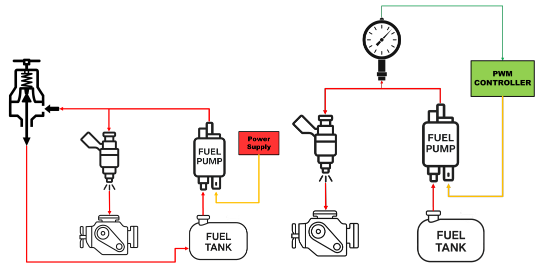
***Abstract*— This paper presents a closed-loop fuel pressure control system for internal combustion engines using pulse-width modulation to regulate the fuel pump based on real-time pressure feedback. A proportional-integral-derivative controller was tuned using experimental data to improve the response. Validation was performed using the fuel system of an FSAE race car. Compared to a mechanical regulator, the electronic system reduced the pump's power consumption by 76.8%, with a root-mean-square pressure error of 107 mBar (3.6%). Although efficiency has improved, the introduction of electronics adds potential failure points, requiring robust design and fault-tolerant strategies to ensure safe and reliable operation.**

***Keywords*— Fuel Pressure Control, PID Controller, Automotive Electronics, Fuel Injection, System Modeling**



(a) Mechanical System (b) Electronic System

Fig. 1: Fuel Line Diagrams

I. Introduction

The evolution of fuel-injection systems in internal combustion engines has shifted from purely mechanical designs to electronically controlled systems. This transformation is driven by the growing demand for improved fuel efficiency, reduced emissions, and more responsive engine control strategies[1][2]. As the transportation sector faces increasing pressure to enhance sustainability, the development of fuel systems that offer both high precision and adaptability is essential to meet future energy and performance standards.

Although mechanical regulators are simple and robust, those regulators operate without feedback from real-time system conditions, often leading to inefficiencies, unnecessary energy consumption, and limited adaptability to dynamic engine demand [3].

This work proposes an electronic control strategy to regulate fuel pressure by directly modulating the fuel pump through a Pulse Width Modulation (PWM) signal, based on continuous pressure measurements. A proportional-integral-derivative (PID) controller processes the pressure feedback to dynamically adjust the pump power, offering improved precision, faster response to load changes, and reduced overall energy consumption compared with traditional mechanical systems[4].

The control strategy was implemented in a Formula SAE vehicle (FSAE), a student designed and build formula car[5], with the acquisition of real-world data from the fuel system. The system modeling was based on the pressure behavior observed during injector operation using historical injection pulse data to simulate realistic engine demands. The PID controller was tuned to optimize the system response, and was subsequently implemented and validated in an operational FSAE race car.

By introducing a closed-loop digital control system into a previous mechanical domain, this approach demonstrates how intelligent, data-driven control can enhance system efficiency, reduce energy waste, and modernize critical vehicle subsystems, supporting the broader trend toward more sustainable and connected vehicle technologies.

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II. System Overview

A. Mechanical Fuel Regulation

Conventional fuel delivery systems in internal combustion engines often utilize mechanical pressure regulators comprising of spring and diaphragm mechanisms[3]. This setup maintains a consistent fuel pressure by diverting the excess fuel back to the tank through a return line. The fuel pump operates continuously at full capacity, providing a steady flow regardless of the instantaneous fuel demand of the engine. The mechanical regulator ensures pressure stability by allowing excess fuel to recirculate into the tank, as illustrated in the diagram in Figure 1a and the real system in Figure 2.

Although this method provides reliable pressure control, it has several drawbacks.

1) Energy Consumption: Running the fuel pump continuously at full capacity leads to power waste, especially during low engine demand, as it ignores the engine's varying fuel needs.

2) Thermal Stress: Excessive recirculation raises fuel temperature, increasing the risk of vapor lock and reducing fuel density, which can impact engine performance[6].

3) Fuel Tank Design Challenges: In motorsports, compact fuel tanks are essential. High flow rates can disrupt anti-slosh features, causing uneven fuel delivery and potential stalling during high lateral acceleration.

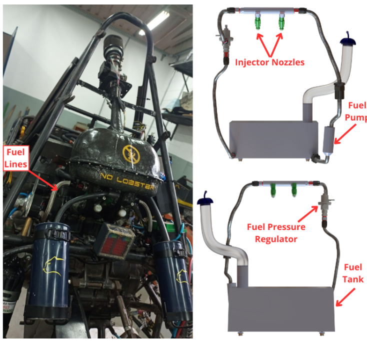

Fig. 2: Real Fuel System

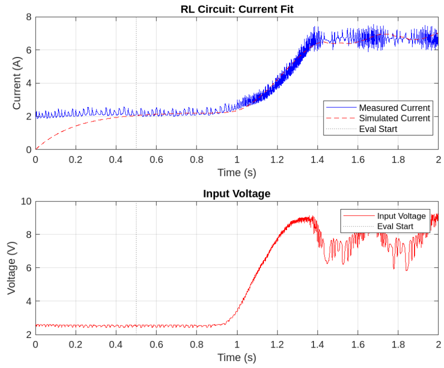

Fig. 3: Current and Voltage Curves Pump

B. Proposed Closed-Loop Electronic Control System

To address the limitations of mechanical fuel regulation, this study proposes a closed-loop electronic control system that dynamically adjusts the operation of a fuel pump based on real-time pressure feedback. The system comprises:

1) Pressure Sensor: An electronic sensor installed in the fuel line continuously monitors pressure and transmits analog or digital signals to the controller.

2) PID Controller: Implemented on a microcontroller, it processes pressure data and computes a control signal to regulate pump speed.

3) PWM-Controlled Fuel Pump: An electric pump driven by a transistor-based actuator (e.g., MOSFET), modulated via a PWM signal generated by the microcontroller.

This configuration eliminates the need for a return line by modulating the pump output to match engine fuel demand. As a result:

Energy Efficiency: The pump operates only at the required capacity, thus reducing energy consumption and thermal load.

Reduced Pump Wear: Operating the fuel pump at lower power levels decreases mechanical stress and heat generation, leading to an extended pump lifespan and improved reliability.

Lower Weight: Eliminating the return line and mechanical regulator reduces the system mass by removing unnecessary components.

Simplified Fuel Tank Design: Lower and more consistent fuel flow rates facilitate integration of anti-slosh mechanisms.

Figure 1b shows the proposed architecture for the closed-loop system.

III. Fuel Pump Controller

A. Controller Hardware Overview

To implement the closed-loop control of the fuel pump, a electronic controller was utilized, it continuously monitors the fuel pressure via an analog input sampled at 17.5 kHz and applies a 64-sample moving average filter to reduce noise and smooth the signal. The controller then adjusts the pump output using a high-side P-channel MOSFET, actuated through a PWM signal.

B. PWM Frequency Selection and Load Characterization

To ensure stable operation and an adequate dynamic response, the PWM switching frequency was selected based on the electrical characteristics of the fuel pump, which was modeled as an equivalent RL circuit.

The resistance and inductance of the pump were identified by applying a DC voltage using a variable power supply and measuring the resulting current profile on a 100 mΩ shunt resistor with an oscilloscope. The captured voltage and current waveforms were then used in a curve fitting script to minimize the error between the measured response and the theoretical RL circuit model. The resulting curve with the optimized response is shown in Figure 3, which results in a resistance of 1.22 Ω and an inductance of 0.23 H.

Using these parameters, the minimum PWM frequency was calculated to limit the ripple current to less than 1% for a 10% duty cycle. The analysis resulted in a minimum frequency of 500 Hz. However, given the controller's hardware capability of up to 1.6 kHz, a higher frequency was selected to further reduce the ripple and enhance pressure stability.

IV. System Characterization and Controller Optimization

A. Open-Loop Data Acquisition

Experimental data were gathered by operating the system in an open-loop configuration to define the initial parameters for the development of the closed-loop fuel-pump control system. To achieve this, the fuel line was removed from the engine and the injector pulses were simulated by referencing historical injector nozzle frequencies and duty cycles from previous car runs, as shown in Figure 4. With a realistic fuel flow, the fuel pump was powered with a PWM signal that stepped at a given period to evaluate the system response to a given input. The recorded pressure versus time and duty cycle versus time profiles are shown in the first two plots of Figure 5.

B. System Modeling and Transfer Function Estimation

After data acquisition, a regression analysis was applied to the experimental data to identify the transfer function that best represents the observed behavior [7]. This function characterizes the relationship between the PWM duty cycle and the resulting fuel pressure.

A hybrid identification approach was adopted due to the presence of periodic disturbances from injector pulses superimposed on the plant response. The plant was modeled using

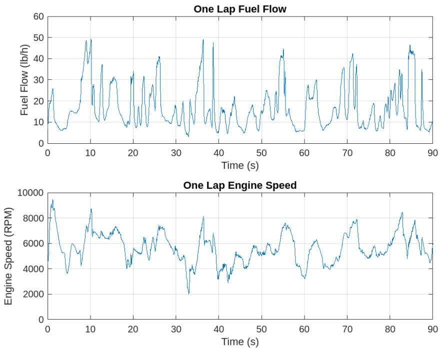

Fig. 4: Fuel Flow and Engine Speed from Car Run

the standard structure for electric pump motors [8], incorporating mechanical (T_L) and electrical (T_S) time constants, and the system gain (K_L), as shown in Equation 1.

$$G(s) = \frac{k_L}{(T_L s + 1)(T_S s + 1)} \tag{1}$$

Model parameters were estimated using the Nonlinear Least Squares (NLLS) method. Although the transfer function of the fuel pump system is linear in its parameters, the identification problem becomes nonlinear in practice due to factors such as signal scaling, actuator saturation, and the presence of structured disturbances (e.g., injector pulses). These characteristics compromise the effectiveness of classical linear identification methods like ARX or output error.

The choice of NLLS was therefore motivated not by an intrinsically nonlinear model structure, but by the need for a more robust and flexible estimation approach capable of handling real-world conditions typical of fuel pump systems, such as low signal-to-noise ratio, coupling between plant and disturbance dynamics, and time-varying response behavior. It is important to emphasize that no Hammerstein model structure was applied in this work.

The injector-induced disturbance was modeled using an Auto-Regressive Moving Average (ARMA) structure, suitable for capturing the system's oscillatory behavior. Its parameters were also estimated using NLLS to ensure consistency. The identification was performed using MATLAB's System Identification Toolbox, allowing joint modeling of the plant and disturbance. The resulting models are presented in Equations 2, 3, and 4, with the system fit shown in Figure 5.

$$G(s) = \frac{3381}{0.001159s^2 + 0.0691s + 1} \tag{2}$$

$$K(s) = \frac{s^2 + 41.65s}{s^2 + 0.2586s} \tag{3}$$

$$y(s) = G(s)u + K(s)e \tag{4}$$

C. Controller Tuning

The PID controller gains (K_p, K_i and K_d) were optimized to achieve a low steady-state error (SSe), controlled overshoot (Mp), and fast settling time (St) while maintaining actuator

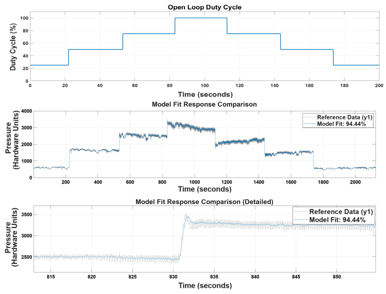

Fig. 5: Model Fit for the System

Metric	PID 1	PID 2	PID 3	PID 4
K_p	8.5520×10^{-4}	4.0881×10^{-4}	8.1762×10^{-5}	1.1680×10^{-4}
K_i	0.0162	0.0059	0.0012	0.0017
K_d	1.0951×10^{-5}	6.8357×10^{-6}	0	1.5069×10^{-6}
St (s)	0.135	0.198	1.01	0.696
Mp (%)	5	0	0	0

TABLE I: Summary of PID Controller Performance Metrics

saturation. The plant was discretized using Tustin's method with a fixed sampling time, from which the discrete version $G(z)$ can be seen in Equation 5.

$$G(z) = \frac{288.2z^2 + 576.5z + 288.2}{z^2 - 0.8234z + 0.1644} \tag{5}$$

For this analysis, the MATLAB PID Tuner toolbox was used, with the robustness criterion set to maximum and the response time criterion set as a variable, for the purpose of response comparison. For each set of gains, the closed-loop response was simulated. The gains and performance parameters are listed in Table I, and the step responses are presented in Figure 6.

V. Implementation

A. Mechanical Regulator Baseline Evaluation

To establish a baseline for evaluating the performance of the electronic controller, the mechanical fuel pressure regulator was tested under identical conditions as previously described. The resulting pressure behavior is shown in Figure 7.

Due to electrical noise from the brushed DC fuel pump, the raw pressure signal contained a 35 Hz component, which was attenuated using a low-pass filter. The red curve in the figure represents the filtered pressure data. Analysis of the filtered signal revealed a root-mean-square (RMS) error of 46.5 mBar, corresponding to 1.7% deviation from the mean pressure. At low engine fuel demand (10 lb/h), the system maintained an average pressure of 2.78 bar. The maximum

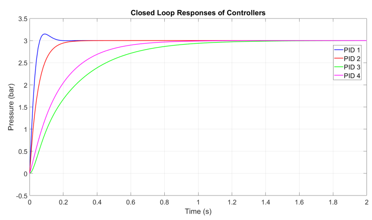

Fig. 6: Simulated PID responses

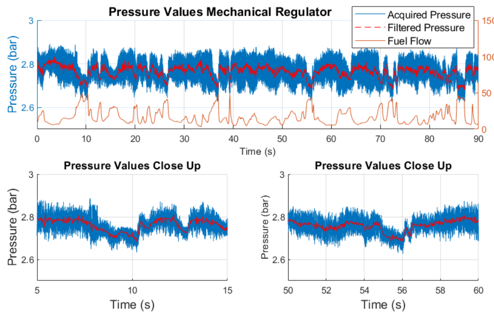

Fig. 7: Mechanical Regulator Pressure

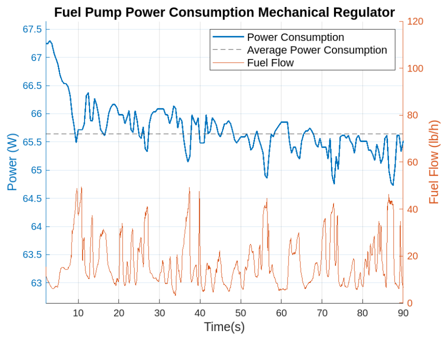

Fig. 8: Mechanical Regulator Power Consumption

deviation observed during increased fuel flow reached 116.1 mBar (4.17%).

The power consumption measurements are shown in Figure 8. The average power consumption recorded for the mechanical system was 65.6 W.

B. Performance with the Electronic PWM Controller

Based on the tuned parameters, four PID controllers were implemented in the system, and the results are shown in Figure 9. The performance of each controller was assessed in terms of pressure accuracy, transient response, and power consumption.

The maximum deviations from the filtered average pressure were 173, 140, 345, and 285 mbar for controllers 1 through 4, respectively. The root mean square (RMS) errors of the unfiltered pressure signals were 111, 107, 106, and 106 mbar, respectively, as shown in Figure 9. The corresponding PWM duty cycle signals for each controller are displayed in Figure 10.

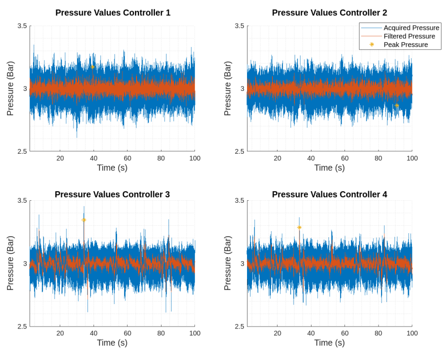

Fig. 9: Pressure Response for each Controller

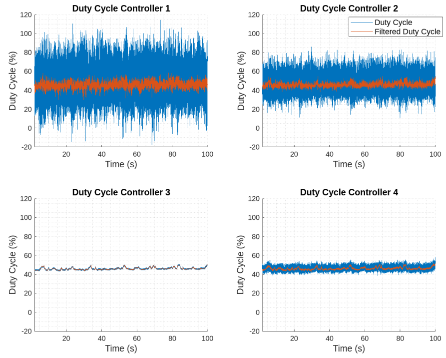

Fig. 10: PID Controllers Duty Cycle

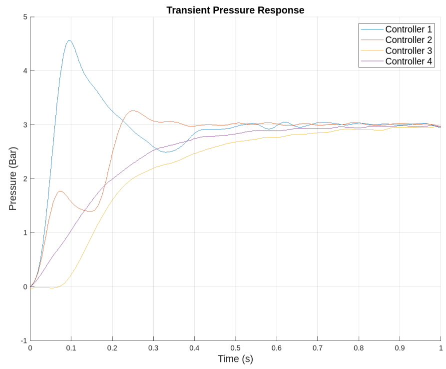

Fig. 11: Transient Pressure Response from Controller

The transient response characteristics are shown in Figure 11, highlighting accommodation times of 470, 362, 760, and 633 ms, respectively. Overshoot was observed only in Controllers 1 and 2, with values of 54% and 10%, respectively, while Controllers 3 and 4 exhibited no overshoot.

The duty-cycle behavior during the transient phase is shown in Figure 12.

Figure 13 shows the power consumption data. The average power consumptions for controllers 1 through 4 were 16.9 W, 15.2 W, 14.4 W, and 14.6 W, respectively.

A summary of the key performance metrics for each controller is provided in Table II.

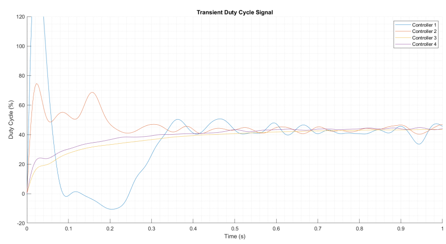

Fig. 12: Transient Duty Cycle Signal

Metric	Controller 1	Controller 2	Controller 3	Controller 4
Max Error From Filtered Avg (mBar)	173	140	345	285
RMS Error (mBar)	111	107	106	106
Accommodation Time (ms)	470	362	760	633
Overshoot (%)	54	10	-	-
Avg Power Consumption (W)	16.9	15.2	14.4	14.6

TABLE II: Summary of PID Controller Performance Metrics

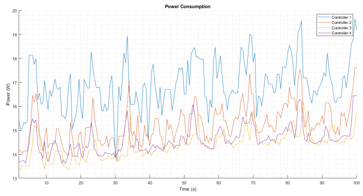

Fig. 13: PID Controller Power Consumption

VI. Results and Conclusions

Distinct behavioral characteristics were observed among the four controllers tested. Because the PID tuning method did not account for output saturation, the more aggressive controllers, specifically controllers 1 and 2, experienced output saturation, which altered the expected system dynamics and introduced non-ideal behavior. This saturation resulted in a noisier duty cycle response, which was particularly noticeable in Controller 1.

In contrast, the less aggressive controllers (controllers 3 and 4) exhibited more stable and smoother control signals, as seen in their duty cycle profiles. However, they were less effective in maintaining the target pressure during sudden increases in fuel demand. This leads to pressure spikes and undershoots, which are undesirable in fuel-delivery systems.

Among all the configurations, controller 2 presented the best trade-off between responsiveness and stability within the set parameters. It successfully maintained the pressure stability under dynamic conditions without inducing excessive saturation. Compared to the baseline mechanical regulator, Controller 2 reduced average power consumption from 65.6 W to 15.2 W, a 76.8% reduction.

Under transient conditions, controller 2 exhibits a 10% overshoot. However, this did not significantly affect the performance because the primary evaluation metric was the maximum error during steady operation. This error was 30 mbar higher than that of the mechanical system, and the RMS pressure error was measured at 60.5 mbar. Despite these deviations, the resulting pressure variation remained within acceptable limits for fuel injection systems, as the fuel flow deviation due to pressure changes in this range is negligible.

The electronic controller outperformed the mechanical regulator in maintaining pressure during a sustained high fuel flow. Although the mechanical regulator showed a drop in pressure that did not recover until the flow demand decreased, the electronic controller maintained the target pressure.

This large difference in power consumption shows an oversizing in this fuel pump for this application; however, for a mechanically regulated system, this pump is suitable, as it is necessary to maintain a minimum flow through the return line to maintain proper pressure regulation.

Analyzing the performance of the PID controller, it becomes clear that its control capabilities are limited for this system. This limitation arises from the high dynamic variability introduced by the injector nozzles, which cause fast and nonlinear disturbances in the pressure line. PID controllers are designed for linear time-invariant (LTI) systems and are therefore constrained by their rigid gain structure.

To achieve improved performance, one may consider using an adaptive controller or a model predictive control (MPC) strategy. These approaches can dynamically adjust the control gains according to the system dynamics or anticipate variations based on a system model, offering better performance, although at the cost of increased computational energy consumption of the actuator [9].

Despite improvements in efficiency, the introduction of electronics into fuel delivery systems has potential drawbacks related to system reliability. As a critical automotive subsystem, the fuel pump controller must be carefully evaluated for possible failure points.

Sensor Dependency: The system relies on a pressure sensor to provide feedback to the PID controller. Failure of the sensor itself or in its associated wiring can prevent proper regulation.

Controller Hardware: The microcontroller running the PID algorithm can malfunctions due to software bugs that may compromise the control.

High-Side Switch Failure: The power stage driving the pump is subject to failure owing to switching effects by the PWM.

Each of these failure points can be mitigated through appropriate design practices. Strategies such as redundant sensing, limp-home modes, watchdog timers, and hardware diagnostics can significantly improve the fault tolerance. These methodologies must be carefully planned and implemented to ensure system safety and to maintain operability under degraded conditions.

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