Optimal proportional-integral speed control for closed-loop engine timing system

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ABSTRACT

In internal combustion engines, adjusting the air-fuel ratio is essential to control the speed and minimize the burnt fuel. The throttle opening is the actuator to control the air-fuel. A better design for the used/conventional controller can give a better response without additional cost. In this work, the proposed controller gains of the proportional-integral (PI) controller are tuned to enhance the speed in constant and variable drive cycle modes. The tuning process is conducted based on two of the most efficient performance indices used in this field. The performance indices are integral absolute error (IAE) and integral time absolute error (ITAE). The optimization problem is solved using three reliable stochastic optimization algorithms to ensure mature convergence of the solutions, to avoid local optima solutions, and to ensure effective shrinking of the search space. The optimization algorithms are teaching-learning-based optimization (TLBO), particle swarm optimization (PSO), and genetic algorithm (GA). Different simulations are conducted to validate the results. The results are compared with conventional tuning methods regarding the system's time response.

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1. INTRODUCTION

Improving the heavy-duty vehicle (HDV) engine's performance is essential as this reduces energy consumption and air pollution significantly. The exhaust gases from diesel engines that run most of the HDV, especially nitrogen oxides, are a major environmental problem. The sequences of this economic-environmental issue can be mitigated using different fuel injection techniques. As the ignition process is a nonlinear system, it is challenging to model the engine and tune the used controllers. Typical internal combustion (IC) engines convert chemical energy and fuel to mechanical energy and continuously repeat four strokes. Suction, compression, power, and exhaust strokes are the strokes that form the cycle of continuous power production. Therefore, the mechanical design, the IC engine, and the tuning of the used controllers are crucial in optimizing the fuel consumption and performance in HDV.

Three different stochastic optimization algorithms are adopted in this study. Genetic algorithm (GA) [1]–[4] and particle swarm optimization (PSO) [5]–[8] as the most efficient metaheuristic techniques besides the newly adopted teaching-learning-based optimization (TLBO) [9], [10] are the employed algorithms in the minimization problem. Those three algorithms show excellent results in many nonlinear control systems in different engineering fields where GA was effectively used in multilevel inverters for the photovoltaic system as a replacement for the conventional tuning method [11] and doubly-fed induction generator for maximizing the power extracted from the wind [12]. PSO and its modified versions were used to select the optimal location of charging stations for electric vehicles (EV) [13] and permanent magnet direct current motors [14]. TLBO was recently used to solve optimal power flow problems and showed competitive results compared with different optimization techniques [15], inductor-capacitor-inductor (LCL) filter design [16], and voltage source inverter design [17]. TLBO outperformed many other rigorous optimization techniques due to the absence of any tunable gains and weighting factors. Recently, many different evolutionary algorithms have been used, which include the gravitational-search algorithm [18]–[21], grey wolf optimizer [22]–[24], and artificial bee colony algorithm [25]–[27].

This paper optimizes the HDV speed controller's proportional-integral (PI) gains (K_P and K_I) to achieve better accurate reference tracking performance under variable drive cycles. Besides stochastic algorithms, some other tuning methods can be used, but they are mainly subjected to linear systems [28]. Two objective functions are used in this study, the integral time-weighted absolute error (ITAE) and the integral absolute error (IAE), to quantify the performance of the control system under the proposed optimization precisely [29].

2. MODELLING OF THE ENGINE TIMING SYSTEM

The system under study is summarized in Figure 1. The engine is loaded, and the speed of the engine is controlled. The speed controller will send the control command to the throttle and manifold. The throttle and manifold can be modeled using (1) through (5).

$$\dot{m}_\iota = y(\theta)q(P) \quad (1)$$

$$y(\theta) = 2.821 - 0.05231(\theta) + 0.10299(\theta^2) - 0.00063(\theta^3) \quad (2)$$

$$q(P) = \begin{cases} 1 & P \leq 0.5P_a \\ \frac{2\sqrt{PP_a - P^2}}{P_a} & 0.5P_a \leq P \leq P_a \\ \frac{-2\sqrt{PP_a - P^2}}{P} & P_a \leq P \leq 2P_a \\ -1 & P \geq 2P_a \end{cases} \quad (3)$$

Where $\dot{m}_\iota$ is the manifold input mass flow rate, θ is the throttle angle, y is the throttle empirical formula, and P and P_a are manifold and the ambient pressure, respectively.

$$\dot{P_m} = \frac{RT(\dot{m}_\iota - \dot{m}_o)}{V_m} \quad (4)$$

$$\dot{m}_o = -366x10^{-3} + 8979x10^5(\omega)(P) - 337x10^4(\omega)(P^2) + 1x10^4(\omega^2)(P) \quad (5)$$

Where $\dot{P_m}$ is the manifold pressure rate of change, $\dot{m}_o$ is the manifold output mass flow rate, R is the specific gas constant, T is the temperature, ω is the angular crank speed, and V_m is the manifold volume.

After finishing the compression, the fuel mass will start the combustion stage. In the combustion stage, the developed torque is related to the air (A) to fuel (F) ratio (δ), speed, spark advance σ, and air mass (m_a) according to (6).

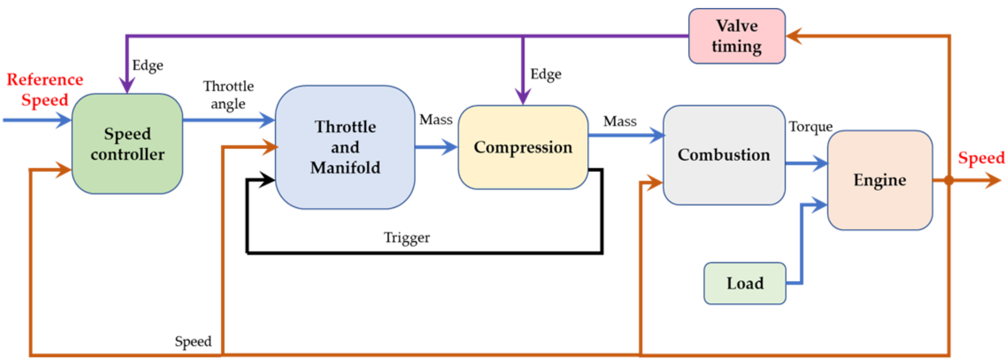

Figure 1. Speed-controlled engine timing system

$$\tau = -181.3 + 379.36(m_a) + 21.91(\delta) - 0.85(\delta^2) + 0.26(\sigma) - 0.0028(\sigma^2) + 0.027(\omega) - 1.07x10^{-4}(\omega^2) + 4.8x10^{-4}(\omega)(\sigma) + 2.55(\sigma)(m_a) - 0.05(m_a)(\sigma^2) \quad (6)$$

The engine's acceleration is related to the dynamic of the rotating parts. The accelerating torque, the difference between the developed and load torque, is the main factor determining if the engine is in accelerating or decelerating mode. According to Newton's second law, the acceleration of the engine ($\dot{\omega}$) can be expressed as in (7).

$$\dot{\omega} = \frac{\tau - \tau_L}{J} \quad (7)$$

Where J is the inertia and τ_L is the load torque.

3. FORMULATION OF THE OPTIMIZATION PROBLEM

In this work, as the controller is a PI-controller and the objective function is ITAE or IAE, the optimization problem can be formulated as (8).

$$\begin{aligned} &\min \quad \{ITAE \ or \ IAE \\ &Subject\ to \\ &\begin{cases} K_I^{min} & \leq K_I \leq & K_I^{max} \\ K_P^{min} & \leq K_P \leq & K_P^{max} \\ & |e_{ss}| \leq & \varepsilon \end{cases} \end{aligned} \quad (8)$$

The equations describe the objective functions or error indices as (9) and (10).

$$ITAE = \int t \cdot e(t)\, dt \quad (9)$$

$$IAE = \int |e(t)|\, dt \quad (10)$$

The values; K_I^{min}, K_I^{max}, K_P^{min}, K_P^{max} are the minimum and the maximum limits of the PI gains (K_P and K_I), respectively, e_{ss} is the steady-state error, $e(t)$ is the error signal, and t is the time. Both the integral and the proportional controllers are needed to achieve the required performance of the speed controller. Adding an integral controller is essential as the operating speed changes with time. On the other hand, the phase lag associated with the integral controller needs to be reduced by the proportional controller. The maximum limits for the two gains are selected first by solving the optimization problem at many different loading and speed conditions while considering the realistic drive cycle of the HDV. Then, the maximum obtained gain is multiplied by at least 10. The minimum limit for both gains is set to be exceedingly small ($K_{I,P}^{min}$=10^{-12}) to avoid any simulation errors. It is essential to highlight that the optimization problem failed to have a feasible solution when the objective function is ISE as defined in (8).

4. SIMULATION RESULTS

Initially, to verify the power of the three used algorithms and the proposed work, the results will be compared with the well-tuned speed controller in [30] where (K_P=0.05 and K_I=0.1). Then, three performance indices are selected to assess the transient response performance. The rise time (t_r) and the settling time (t_s) are strong indicators of the speed of the controlled system. At the same time, the percentage overshoot (*O.S*) indicates the maximum deviation before reaching the new steady state value.

The results from the three algorithms (GA, PSO, and TLBO) are close, and the best result for each objective function is selected as in Table 1. The number of fractions in Table 1 has no meaning and is listed to show the difference between the results from the two objectives. In practice, this accuracy is complex to be implemented in some microcontrollers.

From Table 1, the optimal gains considering the two objectives are close, and the number of digits is high to clarify this point. For the system described in Figure 1, the speed reference is suddenly changed from 2,000 rpm to 3,000 rpm at *t=5* s, and the step responses are shown in Figure 2 for the three cases. The transient response analysis and the three performance indices are summarized in Table 2.

From Table 2, the system exhibits faster dynamic performance when the objective function is not time-dependent, and the O.S is minimal when ITAE is the objective function. For all performance indices, the results from the proposed work are better than those from the reference case. Compared with the reference [30] gains, the proposed work has better results; tr is less than by 31.49%, t_s is less by 9.76%, and the O.S is less by 9.76%. In HDV applications, the objective function includes minimizing the overshoot.

– **Case-2:** this case represents the controller with K_P=0.033 and K_I=0.064. The objective of 'Case 2' is to minimize the vehicle speed overshoot.
– **Case 3:** this case represents the controller with K_P=0.061 and K_I=0.072. These values are required to eliminate speed overshoot.

Figure 3 shows the relation between the controller's speed and the overshoot. The proposed work has the highest O.S and the fastest response. The same logic applies to 'Case 2' and 'Case 3'. The O.S is eliminated in 'Case 3', but the response is the slowest. As listed in Table 3 and assuming the IAE case as a reference, t_r of 'Case 2' is slower by 102.2%, and t_s is slower by 7.17%. The controller of 'Case 3' is slower. The t_r is slower by 55.34%, and t_s is slower by 8.93%. Considering the overshoot, 'Case 2' has a better response of 76.87% and 100% for 'Case 3' as it is eliminated.

Table 1. Optimal results for K_P and K_I based on two objective functions (ITAE and IAE)

Objective function	K_P	K_I
ITAE	0.253537678	0.118603873
IAE	0.27397976	0.119128857
|ITAE-IAE|	0. 020442082	0.000524984

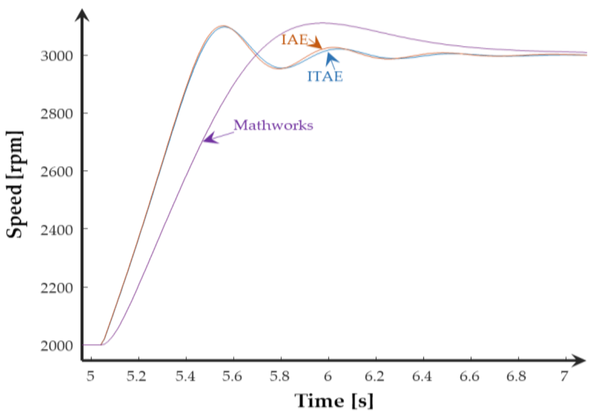

Figure 2. Step responses of three different controllers

Table 2. Comparative results for the transient response

	IAE	MathWorks	Improvement (%)
t_r	0.315889	0.461088	31
t_s	6.07092	6.72723	9.6
O.S	10.04829	11.124158	9.6

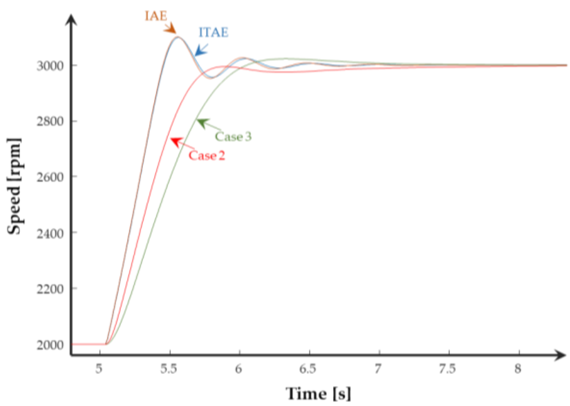

Figure 3. Step responses for the two proposed controllers and the new objectives

Table 3. Comparative results for the transient response of the proposed work and the minimum O.S controllers

	ITAE	IAE	Case 2	Case 3
t_r (s)	0.31836	0.315889	0.63876	0.49069
t_s (s)	6.08049	6.07092	6.506006	6.61319
O.S	9.793149	10.04829	2.32440	0

5. CONCLUSION

In this work, three different optimization algorithms are adopted to tune the gains of the PI controller of the speed-controlled engine timing system. GA, PSO, and TLBO are used to make sure that the results are optimal. Two objective functions are selected to enhance the transient response of the speed controller. The ITAE and IAE are measured when a sudden change in the speed reference is applied. The effectiveness of the proposed work is tested by comparing the results with highly tuned speed controllers. Three transient response indicators validate the work's superiority: the rise time, the settling time, and the overshoot. The objective function is also compared with another objective in which the maximum transient deviation has to be minimized or eliminated.

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