Optimization of PID Control for Engine Electronic Throttle System Using Iterative Feedback Tuning

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ABSTRACT

The Electronic Throttle Control (ETC) system is more and more used and increasingly becoming a standard part of the engine. It controls the amount of air intake into the cylinders by precisely positioning the throttle plate at the desired opening. An ETC system provides the possibility of improving the overall engine and vehicle performance because with such a mechanism, the engine controller can decide and set the throttle position not only based on driver intention, but also taking into consideration the specific engine operation mode information, such as safety factors, emission constraints, etc.

After the throttle position target is determined, the requirement for the ETC system is that the throttle plate should achieve the commanded position as accurately and as quickly as possible. In many cases the controller is designed by first establishing a model of the electronic throttle system using experimental identification. However, due to such nonlinear effects as static friction, dynamic friction, and nonlinear return springs etc., identification of a model for the electronic throttle system sometimes does not give good results. This makes a controller design based on the model far from optimal. Iterative Feedback Tuning (IFT) is a method for directly tuning the controller parameters based on the data of closed loop experiments without the need for an explicit model of the system. This property makes IFT an attractive method for ETC design. In this paper a Two-Degree-of-Freedom (2-DOF) Proportional-Integral-Derivative (PID) controller for an engine electronic throttle system is designed and the PID control gains are optimized using IFT. The application shows that the IFT method gives very good performance for controller tuning.

INTRODUCTION

The ETC system has gained success in high volume applications and is becoming a standard part of the engine [1-3]. By precisely positioning the throttle plate at the commanded opening, an ETC system controls the amount of air intake into the cylinders, and consequently the engine operation. Compared with the traditional throttle system that has direct mechanical connection with the acceleration pedal, an ETC system provides the possibility of improving the overall engine and vehicle performance because this mechanism allows the engine controller to decide and set the throttle position not only based on driver intention (the acceleration pedal behavior), but also taking into consideration the specific engine operation mode information, including safety factors and emission constraints etc. This helps to improve the air fuel ratio regulation in transients, and catalyst thermal management etc. An ETC system also makes it possible to integrate such functions as idle speed control, traction control, and cruise control etc. with a single controller/actuator, which provides significant benefits for the OEMs.

After the engine controller determines the throttle position target, an ETC system should achieve the commanded throttle position as accurately and as quickly as possible. Usually a comprehensive ETC strategy consists of a PID feedback controller and nonlinear compensators that handle such nonlinear
effects as static and dynamic friction, and limp-home effects [4-8]. While a lot of emphasis has been placed on the nonlinear strategy design, a PID feedback control that mainly handles the linear operating mode of the system plays an important role in the overall strategy. Good design and implementation of the PID feedback control is the basis for good performance of an electronic throttle system. This paper focuses on the optimization of the PID feedback control for ETC system.

To produce good control performance, usually sets of different PID control gains are obtained for different regions of the whole operating range of the throttle [1-8, 10-12]. Several approaches might be used for obtaining the PID control gains. With the most commonly used method, first a linear process model for the throttle system is obtained through identification experiment, then the control gains are designed based on the process model [4-6, 9-10]. In [11] the gains are initially obtained by direct hardware testing, and subsequently improved by the guidance using frequency response analysis. These methods require the establishment of a process model. In [12] the method involves tuning the PID gains on-line using sequential quadratic programming.

For the methods that require a process model, however, experimental identification might not provide a good result due to nonlinearity of the throttle system. This makes a controller design based on the model far from optimal. Iterative Feedback Tuning is a method for directly tuning the controller parameters based on the data of closed loop experiments without the need for an explicit model of the system [13-15]. Since its appearance in 1994 [13], IFT has been applied in the tuning of various controllers with good results. Many advances have been made, for example, the method has developed from the control of single input single output linear time invariant systems, to the control of linear multiple input multiple output systems [16-17] and the control of systems containing nonlinearities [18-21]. Many aspects of the method, such as stability, robustness, gradient estimation, optimal prefiltering, and various numerical simulations and experiments etc. have been reported [22-30].

IFT tunes the controller parameters iteratively along the gradient direction of a given criterion function. A model of the system, as well as knowledge of disturbances is not required. Since this design method is not based on the plant model, it inherently avoids the problems caused by deviation between the model and the plant. This makes it an attractive approach for ETC design. In this paper a 2-DOF PID controller is implemented to mainly handle the linear operating mode of an engine throttle system and the IFT method is used to optimize the PID control gains. The application shows that the IFT method is very effective for controller tuning.

The paper is organized as follows. Section 1 provides a brief description of the engine electronic throttle control system and the rapid prototyping controller used for the study. Section 2 describes the PID controller structure adopted. Formulae for implementing the PID controller are obtained. In Section 3, application of IFT of the controller is given and analyzed. Section 4 summarizes the paper.

**ENGINE ELECTRONIC THROTTLE CONTROL SYSTEM**

Figure 1 shows the hardware of an ETC system. The electronic throttle body consists of a brushed DC motor, gearbox, throttle plate, dual opposing return springs, and throttle position sensor (usually two outputs) which uses potentiometers. The controller samples the acceleration pedal sensor signals, and together with other related engine information, determines the required throttle opening. Based on the throttle position target and the measured real throttle position, the controller determines the Pulse Width Modulation (PWM) signal parameters, sends out the signals to an H-bridge driver to control the operation of the motor, and consequently the opening of the throttle plate. By using an H-bridge driver, the motor and the throttle plate can rotate in either direction. The motor torque is balanced by the return springs, which are opposing to each other so that the plate is put into its default position, which is called the limp-home position, in the case of power supply failure or other system malfunction.

![Figure 1. ETC Hardware](image)

A rapid prototyping controller is used for this study. Figure 2 shows the hardware framework of this controller. It has a dual CPU architecture, using a PentiumM processor for high-speed control, and a Renesas SH4 processor for running the human-machine interface, including color touch-screen LCD, function keys, and Ethernet communication with the host PC. A bus controller on the active back plane handles the data transfer between the function boards and the CPUs. Various function boards can be selected and integrated in the controller as required.

For ETC implementation, an analog input board is included in the controller for sampling acceleration pedal position and throttle position, and a PWM board is included for motor control. Model-based development methodology is used. Control logic is designed on the
host PC using MATLAB®/Simulink®/Stateflow®, taking
the form of block diagrams. The S-functions for system
hardware and function modules are developed and
integrated in the block diagram. Real-Time Workshop®
converts the block diagram into C code, which is then
compiled, linked, and downloaded automatically to the
rapid prototyping hardware platform for real-time
execution under the RT-Linux operating system. A
graphical user interface software is used which enables
the arrangement of various screen elements on the host
PC and on the color touch-screen LCD. These screen
elements are associated with the variables or
parameters of the Simulink® model, enabling real-time
parameter setting, signal monitoring and data logging.

Figure 2. Hardware Architecture of the Rapid
Prototyping Controller

2-DOF PID CONTROLLER AND IFT

In this section the structure of the PID controller adopted
for this study is shown, and the IFT formulae for this
structure are derived.

Thorough introductions to the IFT method can be found
in [13-15]. In this study, the feedback type 2-DOF
controller structure shown in Figure 3 is used. This is a
variation of the structure used in the above mentioned
literatures. This structure is more straightforward for
understanding the influence of the controller
components, which will be shown later in this section.

![Figure 3. 2-DOF Controller Structure](image)

The IFT formulae for this controller structure are
obtained as follows. In Figure 3, \( r \) is the desired
response, or called reference. \( y \) is the measurement of
the plant variable to be controlled. \( e \) is the error. \( G_1 \)
and \( G_2 \) comprise the controller. \( G_p \) represents the
plant. \( u \) is the control. It is obvious:

\[
\begin{align*}
  u &= G_1 r - (G_1 + G_2) y \\
  y &= G_p u
\end{align*}
\]

(1)  (2)

The criterion function is chosen to be the integrated
squared error between the desired response and the
achieved response:

\[
J(\rho) = \frac{1}{2T_f} \int_0^{T_f} e^2(t, \rho) dt
\]

(3)

where \( T_f \) is the time to reach equilibrium, and \( \rho \)
represents the controller parameters to be optimized.
The control design objective is to minimize this criterion
function. The gradient of this function with respect to the
controller parameters is:

\[
\frac{\partial J(\rho)}{\partial \rho} = \frac{1}{T_f} \int_0^{T_f} \frac{\partial e(t, \rho)}{\partial \rho} dt
\]

(4)

The iterative tuning of the controller parameters can be
carried out by:

\[
\rho(k+1) = \rho(k) - \gamma_k H_k^{-1} \frac{\partial J(\rho)}{\partial \rho}(k)
\]

(5)

where \( \gamma \) is the step size, and \( H \) is the Hessian of \( J \) for
which the following approximation is used:

\[
H = \frac{1}{T_f} \int_0^{T_f} \left( \frac{\partial e}{\partial \rho} \right)^2 dt
\]

(6)

It is evident that to implement this tuning process, the
key is to obtain the term \( \frac{\partial e}{\partial \rho} \). While in IFT, this is done
by performing some closed loop experiments.

For succinctness, \( \frac{\partial e}{\partial \rho} \) is denoted by \( \frac{\partial e}{\partial \rho} \) in the following
formulae. Taking derivative of (1) and (2) with respect to
the controller parameters leads to:

\[
\begin{align*}
  u' &= G_1 r - (G_1 + G_2) y' \\
  y' &= G_p u'
\end{align*}
\]

(7)  (8)

Rewrite (7) as follows:

\[
\begin{align*}
  u' &= G_1 \left( \frac{G_1'}{G_1} r - \frac{G_1' + G_2'}{G_1} y' \right) - (G_1 + G_2) y'
\end{align*}
\]

(9)

It can be seen that the pair of equations (9) and (8) has
exactly the same format as the pair of equations (1) and
(2). This means if \( \left( \frac{G_1'}{G_1} r - \frac{G_1' + G_2'}{G_1} y' \right) \) is used as
reference, the output from the plant will be \( y' \). This is
shown in Figure 4.
This reference is a combination of \( r \) and \( y \). To obtain the output \( y' \), experiments that use \( r \) (called normal experiment) and \( y \) (called gradient experiment) as references need be performed [15]. The normal experiment is shown in Figure 3. Figure 5 shows the scenario of the gradient experiment, in which \( y^* \), \( e^* \) and \( u^* \) are used to denote the output of the plant, the error and the control of this case.

Since \( \left( \frac{G_1'}{G_1} r - \frac{G_1' + G_2'}{G_1} y \right) \) is a combination of \( r \) and \( y \), considering the linearity from the reference to the output, \( y' \) can be obtained by the same combination of the plant outputs that use \( r \) and \( y \) as references, i.e., the outputs of the normal experiment and gradient experiment:

\[
y' = \frac{G_1'}{G_1} y - \frac{G_1' + G_2'}{G_1} y^*
\]  

(10)

Because \( e' = r' - y' = -y' \), it leads to:

\[
e' = \frac{G_1' + G_2'}{G_1} y^* - \frac{G_1'}{G_1} y
\]  

(11)

This is illustrated in Figure 6.

Thus it can be seen that \( e' \) can be calculated using the outputs of the normal and gradient experiments, which is the essence of the IFT method. Something that deserves note is that (11) shows \( e' \) and \( e \) are not uncorrelated, which makes the estimation of the gradient of the criterion function shown in (4) biased. To take care of this, the \( y \) in (11) should be replaced by the output from a third experiment which is conducted exactly the same as the normal experiment shown in Figure 3. Another thing deserving notice is that \( \frac{G_1' + G_2'}{G_1} \) and \( \frac{G_1'}{G_1} \) in (11) might be non-causal.

However, since the normal experiment and gradient experiment are carried out alternately and their data is collected and processed batch-wise, the calculation of \( e' \) can be performed. One can also add proper filters to place extra pole(s) to these transfer functions for the causality purpose. With \( e' \) obtained from the experiment data, iterative tuning of the controller parameters can now be implemented using (4) (5) (6).

For this study the specific format of the 2-DOF PID control is chosen as:

\[
G_1(\rho) = K_p + \frac{K_I}{s}
\]

(12)

\[
G_2(\rho) = \frac{K_D s}{100(0.001s + 1)}
\]

(13)

with \( \rho_1 = K_p \), \( \rho_2 = K_I \), \( \rho_3 = K_D \).

This means the proportional and integral controls are on the error and the derivative control is on the process variable, with low pass filtering added. This design takes care of the derivative kick encountered in conventional one-degree-of-freedom controller, and provides good performance for reference response and disturbance rejection. Based on experience, a constant number 100 is included in the format of \( G_2 \) to make the gain \( K_D \) in about the same magnitude as gain \( K_p \) and \( K_I \), which is helpful for the numerical computation.

From (12) and (13) it is obtained:

\[
1 \frac{\partial (G_1 + G_2)}{G_1} \frac{\partial e}{\partial \rho} = \begin{bmatrix}
\frac{s}{K_p s + K_I} \\
\frac{1}{K_p s + K_I} \\
\frac{s^2}{100(K_p s + K_I)(0.001s + 1)}
\end{bmatrix}
\]

(14)

\[
1 \frac{\partial G_1}{G_1} \frac{\partial \rho}{\partial \rho} = \begin{bmatrix}
\frac{s}{K_p s + K_I} \\
\frac{1}{K_p s + K_I} \\
0
\end{bmatrix}
\]

(15)

Now all necessary formulae to perform the IFT study for the ETC are obtained and the optimization of the control
parameters can be implemented using the rapid control prototyping system.

APPLICATION RESULTS AND ANALYSIS

The control scenario is set to be a 30 degree step command. Control loop time is set to be 1 millisecond. Considering the commonly adopted specification for ETC, e.g., throttle plate positioning within the measurement resolution and step response settling time of less than 100 millisecond, the 30 degree step command is prefiltered with a first order low pass filter which has a time constant of 30 millisecond, and its output is used as the desired response. The initial gains of the controller are obtained by doing Ziegler-Nichols testing and their values are as follows:

\[ K_p = 0.39, \quad K_I = 8.55, \quad K_D = 0.44 \]

Results of the normal experiment with the above control gains, including system response and motor voltage etc., are shown in Figure 7. It is obvious the overshoot of the response is large and the overall performance of the system is far from acceptable. The output of the normal experiment is used as a reference and the gradient experiment is carried out, the results of which are shown in Figure 8. By using the results of the normal experiment, the gradient experiment, and a third experiment the same as the normal experiment, the derivatives of the system error with respect to controller parameters are calculated. Figure 9 (a through c) shows these results. The Hessian, and the gradient of the criterion function with respect to the controller parameters can be subsequently calculated and the new gains are obtained.
and the criterion function is 1.7344. Figure 11 shows the system response of all the iterations for comparison purpose. It shows clearly the improvement of the system performance during the IFT process.

Thus the IFT method is successfully implemented in the optimization of 2-DOF PID control for the ETC and the system realizes very excellent control performance.

For the first iteration, the criterion function decreases from 4.0847 to 2.8161, and the system response improves. More iterations are carried out and the results of the whole IFT process are summarized in Table 1. Results of the last iteration are shown in Figure 10. It can be seen that after this iteration, the performance of the control is pretty good and the requirement is well fulfilled. The final control parameters are obtained as follows:

\[ K_p = 0.7292, \quad K_I = 7.4019, \quad K_D = 0.7824 \]

### Table 1. Results of the IFT Process for ETC Optimization

<table>
<thead>
<tr>
<th>Iteration</th>
<th>Starting Gains ([K_p, K_I, K_D])</th>
<th>(J)</th>
<th>(\partial J(\rho) / \partial \rho)</th>
<th>(H)</th>
<th>(\gamma)</th>
<th>New Gains ([K_p, K_I, K_D])</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>([0.3900, 8.5500, 0.4400])</td>
<td>4.0847</td>
<td>([-11.5777, 0.2542, -2.0895])</td>
<td>([140.2929, -0.0699, -17.4669], [0.6990, 0.1059, -1.3342], [-17.4669, -1.3342, 24.2001])</td>
<td>1.00</td>
<td>([0.4813, 7.1662, 0.5159])</td>
</tr>
<tr>
<td>2</td>
<td>([0.4813, 7.1662, 0.5159])</td>
<td>2.8161</td>
<td>([-5.7344, 0.0740, -0.1777])</td>
<td>([42.1881, -0.0198, -7.5738], [-0.0198, 0.0432, -0.3975], [-7.5738, -0.3975, 8.6862])</td>
<td>1.00</td>
<td>([0.6442, 6.9179, 0.6671])</td>
</tr>
<tr>
<td>3</td>
<td>([0.6442, 6.9179, 0.6671])</td>
<td>1.9813</td>
<td>([-2.2871, 0.0232, -0.5034])</td>
<td>([19.1583, -0.0094, -4.1641], [-0.0094, 0.0191, -0.1739], [-4.1641, -0.1739, 5.9831])</td>
<td>0.50</td>
<td>([0.7292, 7.4019, 0.7824])</td>
</tr>
<tr>
<td>Final</td>
<td>([0.7292, 7.4019, 0.7824])</td>
<td>1.7344</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
CONCLUSION

Because of nonlinearity of the engine electronic throttle system, experimental identification of a plant model might not give a good result and consequently a controller design based on the plant model might not provide good control performance. Iterative Feedback Tuning directly tunes the controller parameters based on the data of closed loop experiments without the need for an explicit model of the system, which makes it a desirable method for ETC design. In this paper a 2-DOF PID controller is implemented for engine electronic throttle system. IFT formulae for the controller structure are obtained. Optimization of the PID control parameters is successfully performed. The application shows that this method provides excellent performance for the controller tuning.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

2-DOF: Two-Degree-of-Freedom
ETC: Electronic Throttle Control
IFT: Iterative Feedback Tuning
PID: Proportional-Integral-Derivative
PWM: Pulse Width Modulation