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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

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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 IFT of the controller are obtained. In Section 3, application of the method on an electronic throttle system is performed. Results are 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.

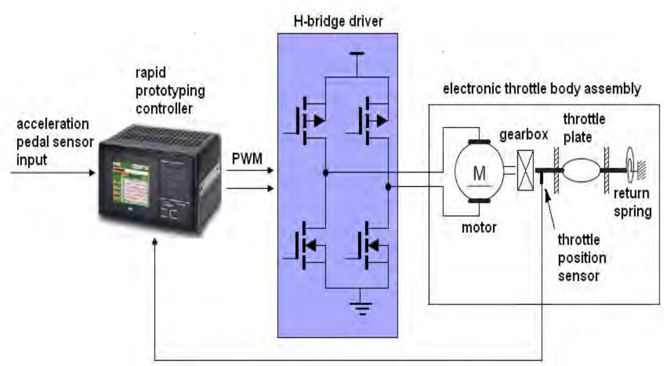

Figure 1. ETC Hardware

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.

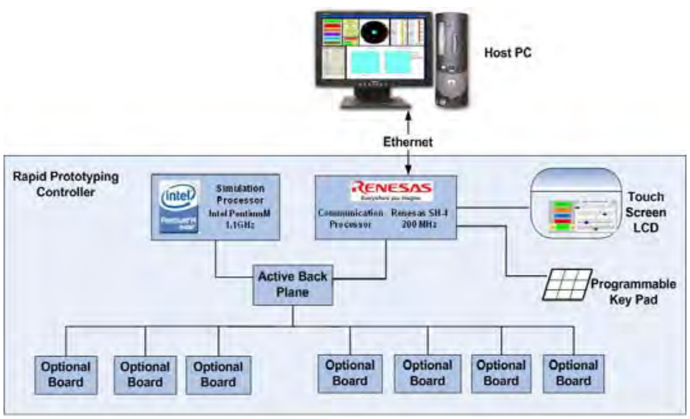

Figure 2. Hardware Architecture of the Rapid Prototyping Controller

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.

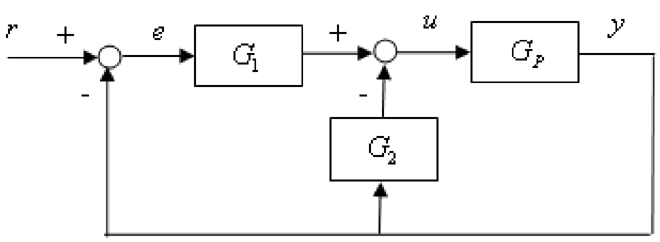

Figure 3. 2-DOF Controller Structure

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:

$$u = G_1 r - (G_1 + G_2) y \tag{1}$$

$$y = G_P u \tag{2}$$

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

$$J(\rho) = \frac{1}{2T_f} \int_0^{T_f} e^2(t,\rho) dt \tag{3}$$

where T_f is the time to reach equilibrium, and ρ 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:

$$\frac{\partial J(\rho)}{\partial \rho} = \frac{1}{T_f} \int_0^{T_f} e(t,\rho) \frac{\partial e(t,\rho)}{\partial \rho} dt \tag{4}$$

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

$$\rho(k+1) = \rho(k) - \gamma_k H_k^{-1} \frac{\partial J(\rho)}{\partial \rho}(k) \tag{5}$$

where γ is the step size, and H is the Hessian of J for which the following approximation is used:

$$H = \frac{1}{T_f} \int_0^{T_f} (\frac{\partial e}{\partial \rho})(\frac{\partial e}{\partial \rho})^T dt \tag{6}$$

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

$$u' = G_1' r - (G_1' + G_2') y - (G_1 + G_2) y' \tag{7}$$

$$y' = G_P u' \tag{8}$$

Rewrite (7) as follows:

$$u' = G_1 (\frac{G_1'}{G_1} r - \frac{G_1' + G_2'}{G_1} y) - (G_1 + G_2) y' \tag{9}$$

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 $(\frac{G_1'}{G_1} r - \frac{G_1' + G_2'}{G_1} y)$ is used as reference, the output from the plant will be y'. This is shown in Figure 4.

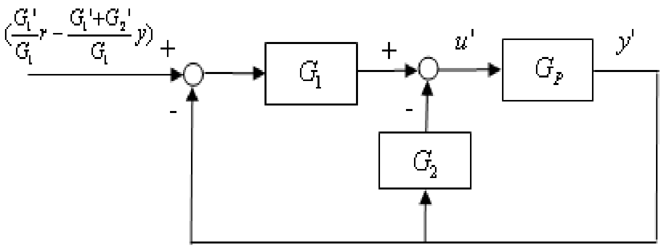

Figure 4. Illustration of Pair of Equations (9) and (8)

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.

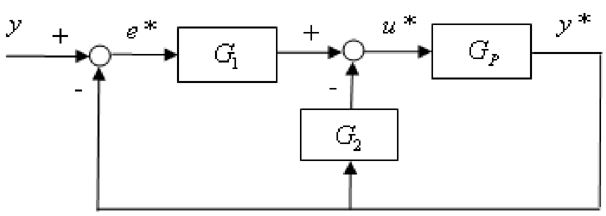

Figure 5. Gradient Experiment

Since $(\frac{G_1'}{G_1}r - \frac{G_1'+G_2'}{G_1}y)$ 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:

$$y' = \frac{G_1'}{G_1}y - \frac{G_1'+G_2'}{G_1}y^* \tag{10}$$

Because $e' = r' - y' = -y'$, it leads to:

$$e' = \frac{G_1'+G_2'}{G_1}y^* - \frac{G_1'}{G_1}y \tag{11}$$

This is illustrated in Figure 6.

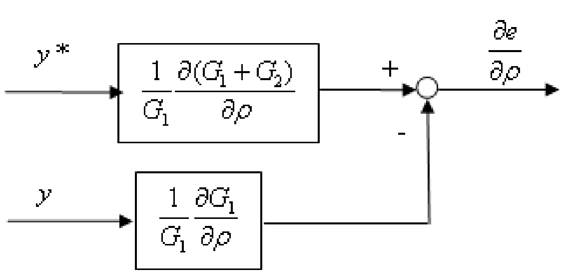

Figure 6. Calculation of $\partial e / \partial \rho$

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:

$$G_1(\rho) = K_P + \frac{K_I}{s} \tag{12}$$

$$G_2(\rho) = \frac{K_D s}{100(0.001s+1)} \tag{13}$$

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:

$$\frac{1}{G_1}\frac{\partial(G_1+G_2)}{\partial\rho} = \begin{bmatrix} \frac{s}{K_P s + K_I} \\ \frac{1}{K_P s + K_I} \\ \frac{s^2}{100(K_P s + K_I)(0.001s+1)} \end{bmatrix} \tag{14}$$

$$\frac{1}{G_1}\frac{\partial G_1}{\partial\rho} = \begin{bmatrix} \frac{s}{K_P s + K_I} \\ \frac{1}{K_P s + K_I} \\ 0 \end{bmatrix} \tag{15}$$

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:

$$K_P = 0.39\,,\ K_I = 8.55\,,\ K_D = 0.44$$

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.

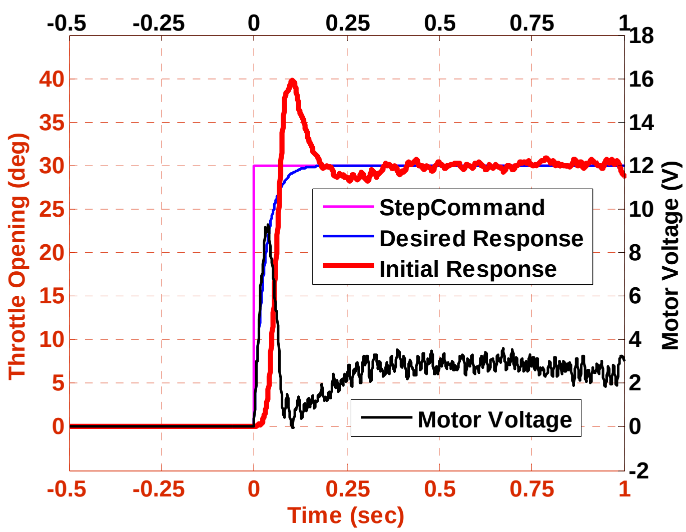

Figure 7. Results of Normal Experiment

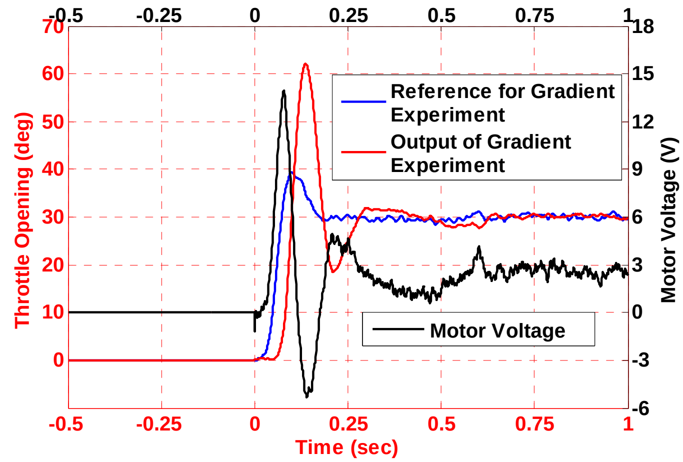

Figure 8. Results of Gradient Experiment

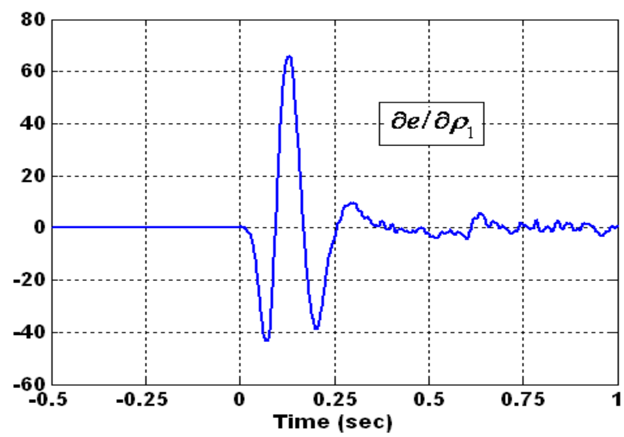

Figure 9(a). $\partial e/\partial \rho_1$ **for the First Iteration**

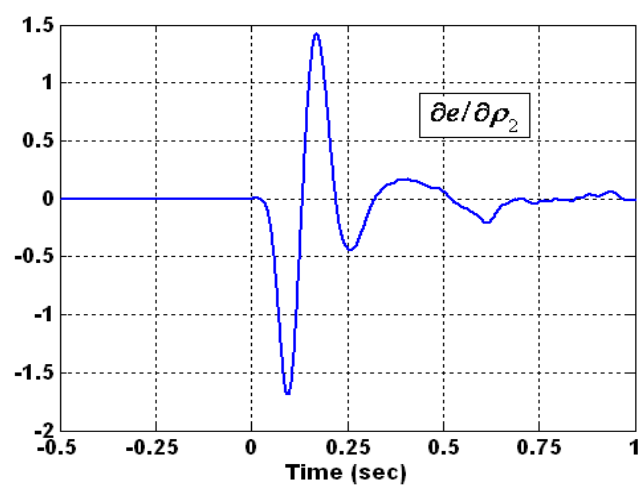

Figure 9(b). $\partial e/\partial \rho_2$ **for the First Iteration**

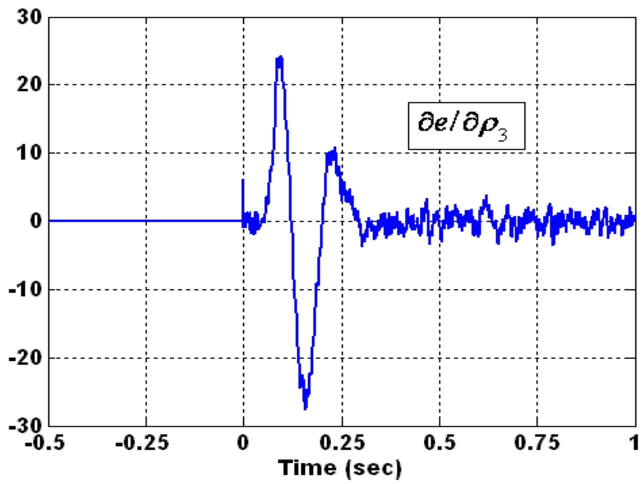

Figure 9(c). $\partial e/\partial \rho_3$ **for the First Iteration**

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:

$$K_P = 0.7292,\ K_I = 7.4019,\ K_D = 0.7824$$

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.

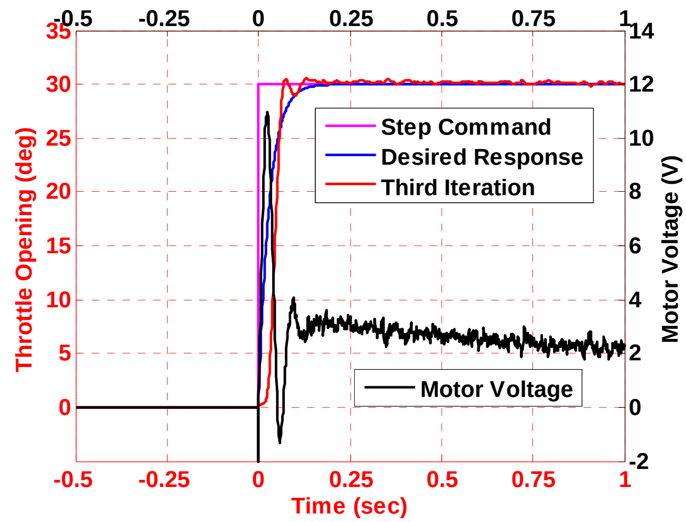

Figure 10. Results of the Last Iteration

Table 1. Results of the IFT Process for ETC Optimization

Iteration	Starting Gains $[K_P\ K_I\ K_D]'$	J	$\partial J(\rho)/\partial \rho$	H	γ	New Gains $[K_P\ K_I\ K_D]'$
1	$\begin{bmatrix}0.3900\\8.5500\\0.4400\end{bmatrix}$	4.0847	$\begin{bmatrix}-11.5777\\0.2542\\-2.0895\end{bmatrix}$	$\begin{bmatrix}140.2929 & -0.0699 & -17.4669\\-0.0699 & 0.1059 & -1.3342\\-17.4669 & -1.3342 & 24.2001\end{bmatrix}$	1.00	$\begin{bmatrix}0.4813\\7.1662\\0.5159\end{bmatrix}$
2	$\begin{bmatrix}0.4813\\7.1662\\0.5159\end{bmatrix}$	2.8161	$\begin{bmatrix}-5.7344\\0.0740\\-0.1777\end{bmatrix}$	$\begin{bmatrix}42.1881 & -0.0198 & -7.5738\\-0.0198 & 0.0432 & -0.3975\\-7.5738 & -0.3975 & 8.6862\end{bmatrix}$	1.00	$\begin{bmatrix}0.6442\\6.9179\\0.6671\end{bmatrix}$
3	$\begin{bmatrix}0.6442\\6.9179\\0.6671\end{bmatrix}$	1.9813	$\begin{bmatrix}-2.2871\\0.0232\\-0.5034\end{bmatrix}$	$\begin{bmatrix}19.1583 & -0.0094 & -4.1641\\-0.0094 & 0.0191 & -0.1739\\-4.1641 & -0.1739 & 5.9831\end{bmatrix}$	0.50	$\begin{bmatrix}0.7292\\7.4019\\0.7824\end{bmatrix}$
Final	$\begin{bmatrix}0.7292\\7.4019\\0.7824\end{bmatrix}$	1.7344				

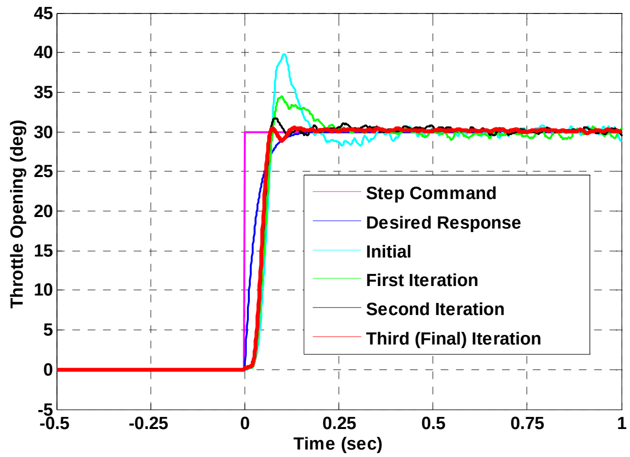

Figure 11. Comparison of the Responses of All Iterations

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.

REFERENCES

1. Daniel McKay, Gary Nichols and Bart Schreurs, Delphi Electronic Throttle Control Systems for Model Year 2000; Driver Features, System Security, and OEM Benefits. ETC for the Mass Market, SAE 2000-01-0556
2. Mark Costin, Robert Schaller, Mario Maiorana, et.al., An Architecture for Electronic Throttle Control Systems, SAE 2003-01-0098
3. Andreas Pechlaner and Bjorn Steurich, Electronic Throttle Control with Contactless Position Sensor and Smart Power Full-Bridge, SAE 2001-01-0984
4. Josko Deur, Danijel Pavkovic, Nedjeljko Peric, et.al., An Electronic Throttle Control Strategy Including Compensation of Friction and Limp-Home Effects, IEEE Transactions on Industry Applications, Vol. 40, No. 3, 2004
5. Josko Deur, Danijel Pavkovi, Nedjeljko Peri, et.al., An Adaptive Nonlinear Strategy of Electronic Throttle Control, SAE 2004-01-0897
6. Danijel Pavkovic, Josko Deur, Martin Jansz, et.al., Adaptive Control of Automotive Electronic Throttle, Control Engineering Practice 14 (2006), page 121–136
7. Lars Eriksson and Lars Nielsen, Non-Linear Model-Based Throttle Control, SAE 2000-01-0261
8. Salem Al-Assadi, Jens Breitinger and Nathan Murphy, Model-Based Friction and Limp Home Compensation in Electronic Throttle Control, SAE 2006-01-0857
9. Danijel Pavkovic, Josko Deur, Martin Jansz, et.al., Experimental Identification of an Electronic Throttle Body, European Conference on Power electronics and Applications 2003
10. Josko Deur, Danijel Pavkovic, Nedjeljko Peric, et.al., Analysis and Optimization of an Electronic Throttle for Linear Operating Modes, European Conference on Power electronics and Applications 2002
11. Chang Yang, Model-Based Analysis and Tuning of Electronic Throttle Controllers, SAE 2004-01-0524
12. Salem Al-Assadi, Jens Breitinger and Nathan Murphy, Tuning an Electronic Throttle Controllers Using Computer-Aided Calibration Method, SAE 2006-01-0307
13. Hakan Hjalmarsson, Svante Gunnarsson, and Michel Gevers, A Convergent Iterative Restricted Complexity Control Design Scheme, Proceedings of the 33rd IEEE Conference on Decision and Control
14. Hakan Hjalmarsson, Michel Gevers, Svante Gunnarsson, et.al., Iterative Feedback Tuning: Theory and Applications, IEEE Control Systems 1998
15. Hakan Hjalmarsson, Iterative Feedback Tuning — an Overview, Int. J. Adapt. Control Signal Process, 2002(16), page 373–395
16. Hakan Hjalmarsson and Thom Birkeland, Iterative Feedback Tuning of Linear Time-Invariant MIMO Systems, Proceedings of the 37th IEEE Conference on Decision and Control
17. Hakan Hjalmarsson, Efficient Tuning of Linear Multivariable Controllers Using Iterative Feedback Tuning, Int. J. Adapt. Control Signal Process, 1999(13), page 553-572
18. Hakan Hjalmarsson, Control of Nonlinear Systems Using Iterative Feedback Tuning, Proceedings of the American Control Conference, 1998
19. Benoit Codronst, Franky De Bruynet, Michel De Want, et.al., Iterative Feedback Tuning of a Nonlinear Controller For an Inverted Pendulum With a Flexible Transmission, Proceedings of the 1998 IEEE International Conference on Control Applications
20. J. Sjoberg, F. De Bruyne, M. Agarwal, et al., Iterative Controller Optimization for Nonlinear Systems, Control Engineering Practice, 2003(11), page 1079–1086
21. K. Hamamoto, T. Fukuda, T. Sugie, Iterative Feedback Tuning of Controllers for a Two-Mass-

Spring System With Friction, Control Engineering Practice, 2003 (11), page 1061-1068
22. Franky De Bruyne and Leonardo C. Kammer, Iterative Feedback Tuning With Guaranteed Stability, Proceedings of the American Control Conference, 1999
23. Sandor Veres and Hakan Hjalmarsson, Tuning for Robustness and Performance Using Iterative Feedback Tuning, Proceedings of the 41st IEEE Conference on Decision and Control
24. R. Hildebrand, A. Lecchini, G. Solari, et.al., Asymptotic Accuracy of Iterative Feedback Tuning, IEEE Transaction on Automatic Control, Vol. 50, No. 8, 2005
25. Gabriel Solari and Michel Gevers, Unbiased Estimation of the Hessian for Iterative Feedback Tuning (IFT), 43rd IEEE Conference on Decision and Control, 2004
26. Henrik Jansson and Hakan Hjalmarsson, Gradient Approximations in Iterative Feedback Tuning for Multivariable Processes, Int. J. Adapt. Control Signal Process, 2004(18), page 665–681
27. R. Hildebrand, A. Lecchini, G. Solari, et.al., Optimal Prefiltering in Iterative Feedback Tuning. IEEE Transaction on Automatic Control, Vol. 50, No. 8, 2005
28. Kai-Ming Tsang, Ahmad B. Rad, Wai-Lok Chan, Iterative Feedback Tuning for Positive Feedback Time Delay Controller, International Journal of Control, Automation, and Systems, vol. 3, No. 4, 2005, page 640-645
29. Oliver Lequin, Michel Gevers, Magnus Mossberg, et.al., Iterative Feedback Tuning of PID Parameters: Comparison with Classical Tuning Rules. Control Engineering Practice, 2003(11), page 1023–1033
30. F. De Bruyne, Iterative Feedback Tuning for Internal Model Controllers, Control Engineering Practice 11 (2003), page 1043–1048

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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