Proceedings of the 17th World Congress
The International Federation of Automatic Control
Seoul, Korea, July 6-11, 2008

PERFORMANCE INDICES BASED SELF TUNING FOR SI-ENGINE CONTROL OPTIMIZATION

T. Jeinsch*, G. Yang**, S.X. Ding**, N. Weinhold* and M. Schultalbers*

*Powertrain Mechatronics Development Gasoline Engines, IAV GmbH
38518 Gifhorn, Germany (torsten.jeinsch@iav.de).
**Institute for Automatic Control and complex Systems, University of Duisburg-Essen
Bismarckstrasse 81BB, 47057 Duisburg, Germany

Abstract: The calibration of today's spark ignition (SI) engine control systems is a complex and cost-intensive procedure. To cope with increasing demands in performance issues on the one hand and lowering costs on the other hand, a design procedure combining an approximate simulation model with a self tuning algorithm has been developed. In this paper a performance indices based self tuning method for SI-Engine control optimization is presented. This method has been implemented in an Electronic Control Unit (ECU) for tuning controller parameters in the rail pressure control loop. Results from the validation on an engine test bench at IAV GmbH are shown.

Keywords: calibration, engine management, performance indices, self-tuning regulators, PI controllers

1. INTRODUCTION

Today's SI-Engines are controlled by an ECU with a large number of embedded sensors and actuators. In order to meet the continuously rising demands of lower emissions and fuel consumption, increasing number of functions and parameters are added into the engine control system. In the calibration procedure of today's SI-Engines, more than 5000 parameters should be optimized in order to get the satisfactory control performance (Fischer, 2000). To reduce the time required for calibration, the Design of Experiments (DoE) methods were developed in recent years (Röpke, 2005). Besides DoE, the method based on physical simulation models is proposed currently by Millich (2006) and Tomforde (2007). Compared with DoE, the advantage of using physical simulation models is saving measurements in calibration procedure in case of moderate variations in SI-Engines. The main drawback of this method is that the performance of calibration is determined by the accuracy of the simulation model. Due to the complexity and nonlinear behavior of SI-Engines, it will take a lot of time and effort to build accurate process models for all operating conditions.

The idea to overcome this drawback is the combination of the simulation model based calibration with an online self tuning algorithm. This procedure consists of two steps: firstly, a rough parameterization of the process is obtained through a physical model based simulation. Note that this model is only required to provide the initial values for self tuning, hence it does not need to be very accurate. Secondly, an online self tuning procedure with initial values obtained from the simulation model is used to fine-tune the parameters. Through this combination, the time and effort needed for calibration can be significantly reduced without loss of calibration quality. For the sake of the successful implementation in an ECU, the used self tuning algorithm has to fulfill the requirements on low computational effort and limited storage capacity. Therefore a control performance indices based, full-automated online self tuning method has been developed and verified in the rail pressure control loop.

2. OVERVIEW OF COMMON RAIL SYSTEM

Fig. 1 shows the structure of the common rail system in a direct injection spark ignition engine (Blath, 2006). The fuel is delivered by a high pressure pump into the rail, which serves as storage of the fuel, and then the fuel is injected through the fuel injector into the cylinders.

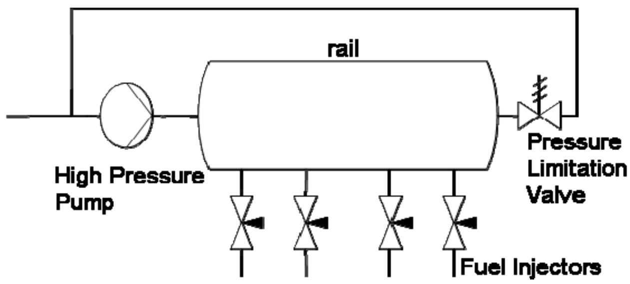

Fig. 1 Structure of common rail system

The high pressure pump is controlled by a feedforward and a feedback controller in ECU, so that the rail pressure p_{rail} is adjusted in order to follow the reference value p_{ref}, which depends on the operating conditions of the engine, as shown in Fig. 2. The feedforward controller F improves the tracking performance when the reference value changes, while the feedback PI controller C compensates disturbances for robust purpose. The common rail system P has a strong nonlinear behavior, i.e. process parameters are changing with operating conditions. For this reason, the use of gain scheduled controllers is state of the art. In calibration process, the parameters of both controllers should be tuned separately under all possible operating conditions and stored in operating condition dependent look-up table to ensure a defined control performance. Due to the page limit, we only focus on the self tuning of feedback controller parameter for disturbance rejection in section 3.

3. SELF TUNING PROCEDURE

The PI feedback controller (see Fig.2) can be described as

$$u(s) = K_P(1 + 1/T_i s)e(s)$$

where *Kp* and *Ti* depend on the operation condition. Due to the uncertainty in the simulation model, the initial values of controller parameters are set very conservative for the "worst case". The goal of the online self tuning in engine test bench is to improve the load disturbance rejection performance, such as the settling time. To guarantee a good stability performance after retuning, the controller parameters have to be retuned to ensure that a) the manipulated variable *u* has no large overshoot and b) the control loop has no oscillations.

The self tuning procedure based on the classical performance indices, and the indices which are normally used in process industry for performance monitoring. Due to the noise and oscillations in the SI-Engine system, the performance indices which are not robust against noise, such as idle index (Hägglund, 1999), are not considered here.

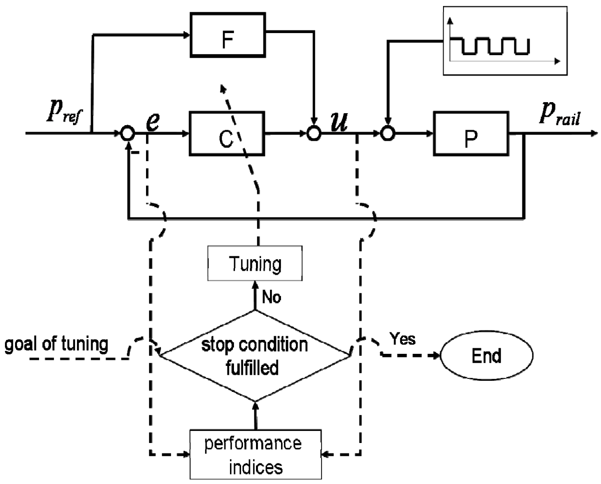

Fig. 2 Flowchart of self tuning procedure

The flowchart of the self tuning procedure is shown in Fig 2. The closed control loop is excited by a set of step functions as load disturbances. The performance indices to evaluate the disturbance rejection performance can be calculated from the signal of *u* and *e*. Unlike the classic controller design the proposed self tuning procedure does not need to identify the process parameters. That means the performance indices do not decide directly how large *Kp* and *Ti* should be, but rather give the information whether *Kp* and *Ti* are too large or too small. Due to the conservative controller design strategy the self tuning procedure begins in each operation condition with small *Kp* and large *Ti*. The detailed tuning procedure consists of 3 stages:

The 1st stage:

a) When next excitation comes, compute area index (Visioli, 2005) and overshoot.
b) If the performance requirement (no oscillation and no large overshoot in *u*) is fulfilled, increase *Kp* and go back to step a), otherwise go to stage 2.

The 2nd stage:

c) When next excitation comes, compute area index, overshoot and settling time.
d) If the performance requirement is not fulfilled, reduce *Kp*, otherwise reduce *Ti.*
e) Check the stop condition, which is determined by the goal of tuning, if it is not fulfilled then go back to step c), otherwise go to stage 3.

The 3rd stage:

f) Set *Kp* and *Ti* to the values corresponding to the optimal settling time and stop the tuning.

Remark: in the beginning of the self tuning, decreasing *Ti* leads to significant reduction of the settling time with little sacrifice of the overshoot, which can be compensated by decreasing *Kp* if necessary. When *Ti* is reduced to the stage that the overshoot can not be compensated, then the stop condition is activated and the procedure ends. Note that at the stage, oscillation may occur which leads to the increasing of settling time.

4. RESULT FROM ENGINE TEST BENCH

The proposed self tuning method has been implemented in an ECU and validated on an engine test bench for calibration of controller parameters for many operating conditions. The tuning process at the operating condition with 4000 [1/min] engine speed and 20% air charge is shown in Fig. 3. At around *660s* the settling time has the minimum value, and further decreasing of *Ti* can not improve the settling time anymore. The stop condition is activated at around *770s* and the self tuning procedure stops.

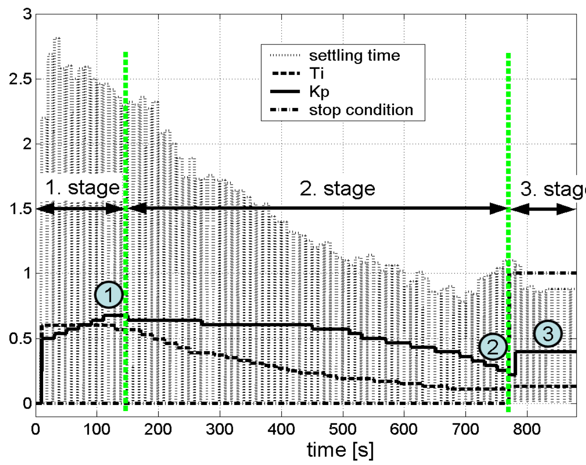

Fig. 3 Self tuning at one operation condition

Three pairs of *Kp* und *Ti* during the tuning process are marked in Fig. 3. The rail pressure responses to the load disturbance with these three pairs of *Kp* and *Ti* are shown in

Fig. 4. It is clear that the solid line with tuned $Kp=0.39$ and $Ti=0.13$ shows the best performance regarding the tuning aim.

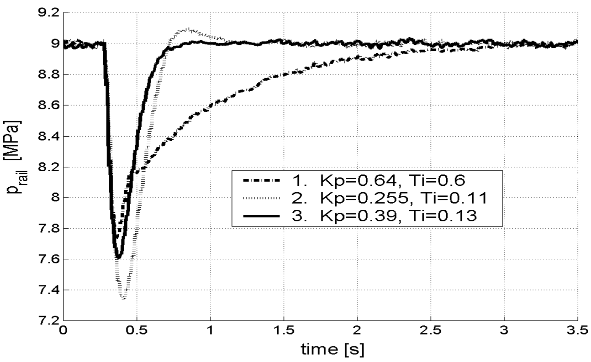

Fig. 4 Comparison of the disturbance rejection performance

With 40% air charge, tuning results of five operating conditions at engine speed from 1000 to 5000 [1/min] are shown in Fig. 5 and Fig. 6.

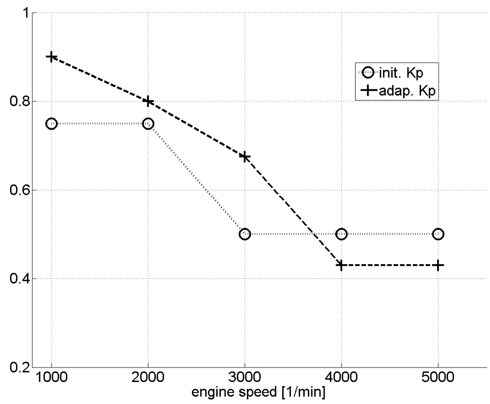

Fig. 5 Initial and adapted *Kp*

The comparison between the settling times is shown in Fig. 7. Without any engagement of application engineers the controller parameters for many operating conditions could be online in a short time automatically calibrated, which means that the human and physical resources are saved.

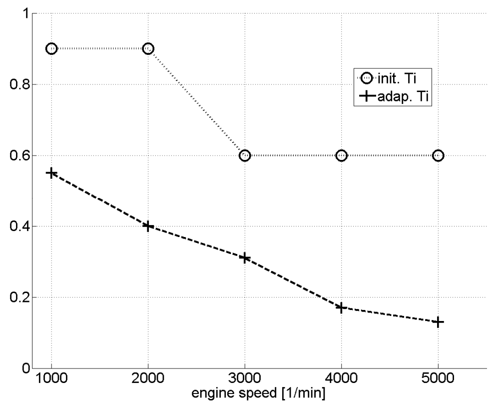

Fig. 6 Initial and adapted *Ti*

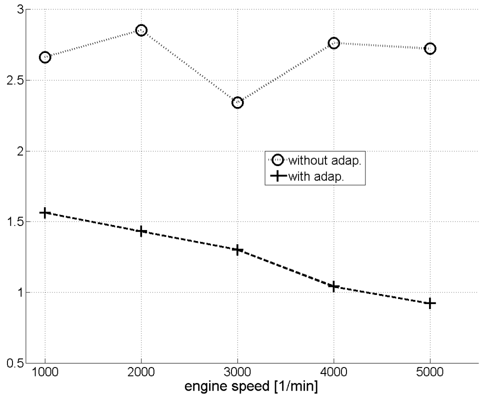

Fig. 7 Comparison between settling times

5. CONCLUSIONS AND PROSPECTS

The self tuning method presented in this paper is also used for other process in SI-Engine with a similar control structure in calibration process. If the excitation exists under normal driving condition, the controller parameters in the ECU can also be online adapted to compensate ageing effects of components in order to ensure the defined control performance.

REFERENCES

Blath, J.P. (2006). Modelling of fuel pressure dynamics. *3. ASIM Workshop – Modelling, control und simulation in automotive and process automation*, Wismar, pp. 67-75.

Fischer, M. and K. Röpke (2000). Effiziente Applikation von Motorsteuerungsfunktionen für Ottomotoren. *MTZ (Motortechnische Zeitschrift) 61*, pp. 562-570

Hägglund, T. (1999). Automatic detection of sluggish control loops. *Cont. Eng. Prac.* **7**, 1505–1511.

Millich, E., W. Gottschalk, M. Köller, H. Braun and M. Schultalbers (2006) Calibration of torque structure and charge control for SI engines supported by physical simulation models. *SAE 2006-01-0854.*

Röpke, K. (Ed.) (2005). Design of Experiments (DoE) in Engine Development II, expert verlag, Germany.

Tomforde, M., H.P. Dünow, J.P. Blath and T. Jeinsch (2007). Modellierung eines mengengesteuerten Hochdruck-Kraftstoffsystems für Ottomotoren mit Benzin-Direkteinspritzung. *VDI-Berichte* Nr. **1971**, pp. 803-810.

Visioli, A. (2005). Assessment of tuning of PI controller for self-regulating processes, Proc. *IFAC World Congress, 2005,* Prague.