Automatic Tuning of Electronic Throttle Control Strategy

Joško Deur, *Member, IEEE*, Danijel Pavković, *Student Member, IEEE*, Martin Jansz, and Nedjeljko Perić, *Member, IEEE*

***Abstract*--Electronic throttle is a DC servo drive which provides precise, drive-by-wire positioning of the throttle plate. The electronic throttle body (ETB) parameters can significantly vary due to production deviations, variations of external conditions (e.g. temperature), and aging. In order to avoid the influence of ETB parameters variations to the electronic throttle control performance, an electronic throttle auto-tuning procedure is proposed in the paper. The auto-tuner tunes the parameters of electronic throttle control strategy based on the results of on-line identification of linear and nonlinear process dynamics. The main characteristics of the auto-tuner are good tuning accuracy, short tuning interval (about 1.5 seconds), and simple implementation. In addition, it does not require any prior knowledge of ETB parameters. The auto-tuner is verified experimentally.**

***Index terms* -- electronic throttle, control, auto-tuning, friction, limp-home nonlinearity.**

I. Introduction

The use of electronic throttles in modern automotive engines provides implementation of engine-based vehicle dynamics control systems, and improve vehicle emissions, fuel economy, and drivability. A nonlinear electronic throttle control strategy has been developed and experimentally verified recently [1,2]. The strategy includes a PID feedback controller, a lead-lag feedforward controller, and a nonlinear compensator of friction and limp-home effects. Most of the control strategy parameters are calculated directly from the known or estimated parameters of the electronic throttle body (the process), while only a couple of nonlinear compensator parameters are tuned empirically. The conventional, off-line calculation of the control strategy parameters has been carried out in [1,2] based on the results of off-line process identification given in [3]. This is the common tuning approach used also in other electronic throttle control papers (e.g. [4,5]).

The main process parameters (such as the limp-home position, friction, and the DC motor armature resistance) can significantly vary due to production deviations, variations of external conditions (e.g. temperature), and aging. In order to avoid the influence of process parameters variations to the electronic control system performance, a control strategy auto-tuning procedure is proposed in this paper. The auto-tuning procedure can be executed for every single vehicle in the stage of vehicle production and/or in some specific intervals of vehicle exploitation (e.g. each time when engine is turned off). The main requirements on the auto-tuning procedure are that it should be accurate, fast, and simple. In addition, it should not require any a priori knowledge of process parameters.

II. Problem Formulation

A. Assumptions on process model structure

The schematic of a typical electronic throttle control system is shown in Fig. 1. The electronic throttle body (ETB) represents a low-power DC servo-drive which needs to provide precise positioning of the throttle plate. The following ETB design characteristics are assumed [3]:

(i) the drive does not include an inner current control loop,

(ii) the drive motion is constrained by a dual-return spring, which returns the throttle plate into the so-called limp-home position in the case of power supply failure, and

(iii) the DC motor armature and chopper dynamics may be neglected.

Taking into account these assumptions, the ETB with embedded chopper (i.e. the process) may be described by the model shown in Fig. 2 [3,6]. The model includes the well-known linear model of DC-drive, extended with the friction and limp-home nonlinearities $m_f(\omega_m)$ and $m_s(\theta)$, respectively.

It is also assumed that

(iv) the return spring for the region above the limp-home position ($\theta > \theta_{LH}$, Fig. 2) is quite weak (the slope of $m_s(\theta)$ is low), so that its influence to the process dynamics may be neglected [6].

The above assumptions are quite mild. The assumptions (i)-(iii) are basic ETB design assumptions, which are satisfied for many ETBs of different suppliers. The additional assumption (iv) should also be satisfied for many ETBs; otherwise, the armature voltage required to overcome the return spring torque m_s around the wide open throttle position $\theta <\approx 90^{\circ}$ would be unnecessarily large, which would lead to motor overheating and low control authority.

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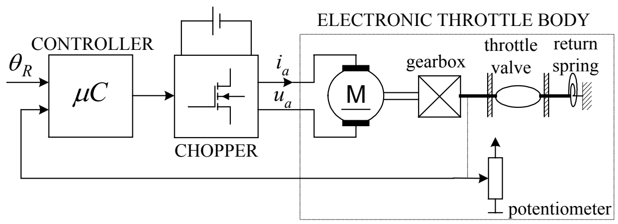

Fig. 1. Functional scheme of electronic throttle.

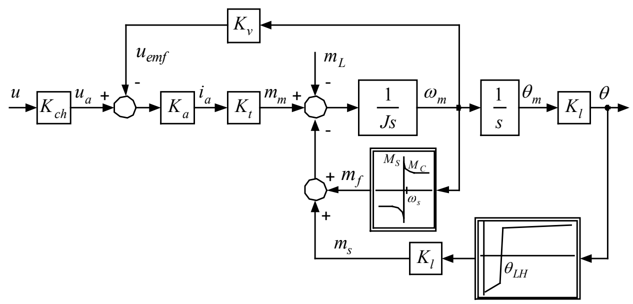

Fig. 2. Block diagram of process model.

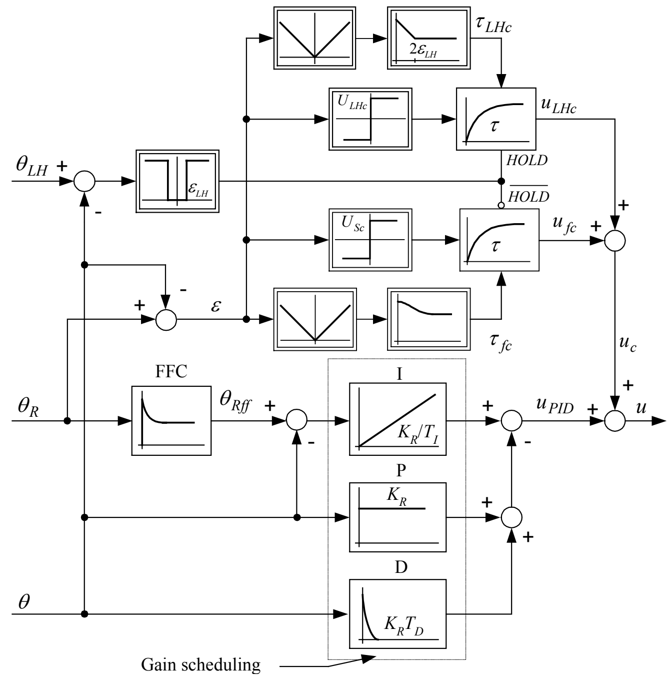

Fig. 3. Block diagram of electronic throttle control strategy.

B. Requirements on auto-tuner performance

The auto-tuner should satisfy the following requirements on its performance:

(i) high accuracy of auto-tuning, which includes high accuracy of on-line process parameter estimation,

(ii) short auto-tuning period (less than 1-2 seconds), so that it can be executed quickly in some specific intervals of vehicle exploitation (e.g. when engine is turned off), and

(iii) simplicity of the auto-tuning algorithm, so that it can be implemented on a low-cost automotive microcontroller system with integer arithmetic.

These requirements can be regarded as stringent, especially in the view that no prior knowledge of any process parameter has been assumed.

C. Auto-tuner specification

The auto-tuner is aimed to tune an electronic throttle control strategy based on the process parameters determined by on-line estimation.

The control strategy used in this work is shown in Fig. 3 [1,2]. The core of the strategy is a PID controller extended with a lead-lag feedforward controller. In order to improve the control system performance in the small-signal operating mode, the linear controller is extended with a nonlinear feedback friction compensator with the output u_{fc}. The compensator includes the Coulomb friction-like relay term, which output signal is filtered to avoid the chattering effect and a response overshoot in the presence of static friction (stiction) dynamics. Since the return spring static curve has similar relay form as the friction static curve (see Fig. 2), the limp-home compensator has the same structure as the friction compensator. The limp-home compensator is activated if the throttle position θ is inside the limp-home region $\theta_{LH} \pm \varepsilon_{LH}$; otherwise the friction compensator is active.

The on-line-estimated process parameters include: (i) the parameters of dominant linear process dynamics (Section IV), which are used for linear controller tuning, and (ii) the parameters of the nonlinear process static curve (Fig. 4, [3]), which are used for nonlinear compensators tuning. The control strategy parameters that are tuned by the auto-tuner are (Fig. 3): two sets of PID controller parameters K_R, T_I, and T_D (for $\theta > \theta_{LH}$ and $\theta < \theta_{LH}$), the feedforward controller zero z_{ff}, the limp-home position θ_{LH}, and the friction and limp-home compensation voltages U_{Sc} and U_{LHc}, respectively. Other parameters of the control strategy are set to fixed values [1,2].

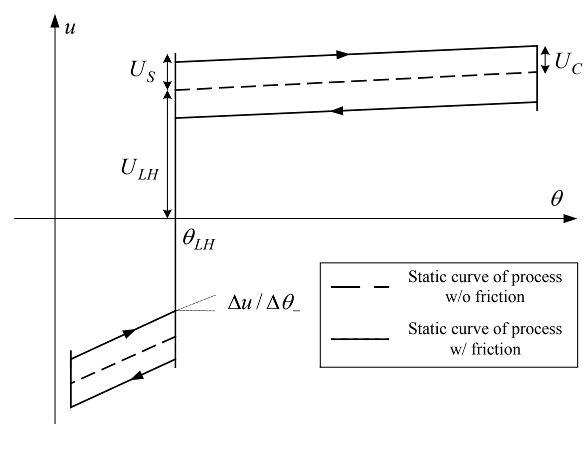

Fig. 4. Process static curve ($U_{S,C}=K_{ch}K_aK_tM_{S,C}$).

III. AUTO-TUNER OUTLINE

The schematic representation in Fig. 5 outlines how the auto-tuner works. There are six characteristic phases of auto-tuner operation, which are denoted in Fig. 5 by encircled numbers and arrows. Each phase relates to either a single point or a portion of the process static curve, and can be executed in open loop (ol) or closed loop (cl). Fig. 5 also shows which type of the commanded signal u or the reference signal θ_R is applied in each phase.

In initial phase 0, the auto-tuner determines the limp-home position θ_{LH}. The commanded signal u is then ramped-up (phase 1) until the breakaway from the limp-home position is detected. The commanded signal is then reset to zero, and increased again toward the detected breakaway voltage u_{ba}. In this way, the throttle is positioned (at the end of phase 1) to the upper edge of the static curve at $\theta = \theta_{LH}$, i.e. to the left most operating point of the approximately linear operating region $\theta > \theta_{LH}$ of the static curve.

At the beginning of phase 2, a step change of the commanded signal u is applied. Based on the throttle position response during phase 2, the parameters of dominant linear process dynamics are estimated. Using the estimated process parameters, the basic set of PID controller parameters (for the region $\theta > \theta_{LH}$) is determined at the beginning of phase 3. The throttle is then brought (under the PID control) to the position θ_0 which is somewhat larger than the limp-home position θ_{LH}.

In phase 4, the ramp change of the throttle position reference θ_R through the static curve region $\theta \leq \theta_0$ is commanded. In this way, the main parameters of the process static curve are estimated. Based on these estimates, final tuning of the control strategy is carried out in phase 5.

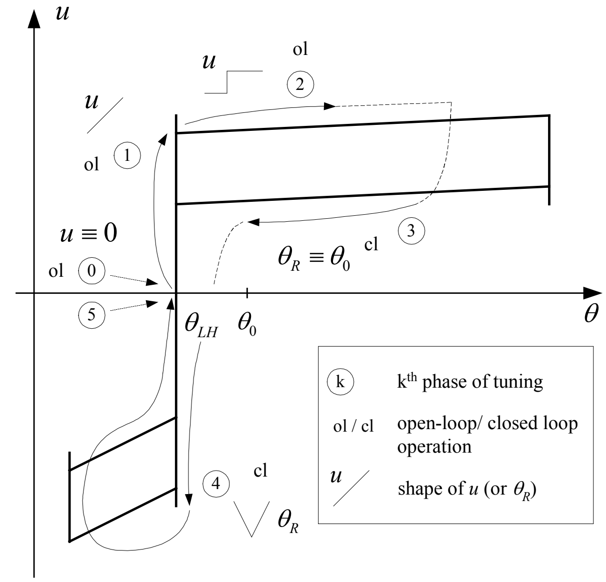

Fig. 5. Illustration of auto-tuning operations.
(0 - Limp-home position estimation, 1 - Breakaway from limp-home position, 2 - Identification of linear process dynamics, 3 - Basic tuning of controller and closing control loop, 4 - Identification of process static curve, 5 - Final tuning of control strategy)

IV. PROCESS IDENTIFICATION

The auto-tuning operations during the process identification phases 0, 1, 2, and 4 are described. The description is illustrated by the experimental auto-tuning response shown in Fig. 6. The overall auto-tuning procedure lasts about 1.5 seconds.

A. Phase 0 – Limp-home position estimation

The limp-home position θ_{LH} is simply determined as the average throttle position during the first several instants of auto-tuner execution (when $u \equiv 0$).

B. Phase 1 – Breakaway from limp-home position

The main task of the auto-tuner during phase 1 is to bring the throttle to the upper point of the limp-home region (Fig. 5). According to the auto-tuning requirements (Section II), this needs to be done in a relatively short period, using the open-loop control only, and having no prior knowledge of the process static curve parameters. Phase 1 is divided in two stages. In the first stage, the commanded signal u is ramped-up until the breakaway from the limp-home position is detected (the interval $t = 0$-0.35 s in Fig. 6). The reached commanded signal u is saved as the breakaway voltage u_{ba}. In order to avoid slow throttle transition through the region $\theta > \theta_{LH}$ and possible excess of the right stop position, the throttle is returned to the limp-home position in the second stage by setting $u = 0$. It is then brought close to the breakaway operating point u_{ba} (but without breakaway) by applying an exponential form of the commanded signal u [7].

There are two practical aspects of auto-tuner implementation for phase 1 [7]: (i) choice of the rate of change of the commanded signal u during the first stage, and (ii) the breakaway detection. The u-rate is chosen to a maximum value that still provides an accurate estimation of u_{ba}. The breakaway instant k_{ba} is found as the first sampling instant after which the sum of three consecutive throttle speed samples is greater or equal to $5\Delta_\omega$ (Δ_ω - the speed measurement quantization level), i.e.

$$k_{ba} = \min\{k_s\} \ , \tag{1a}$$

where k_s satisfies the relation

$$\omega(k_s+1) + \omega(k_s+2) + \omega(k_s+3) \geq 5\Delta_\omega \ . \tag{1b}$$

Note that the breakaway voltage is given by

$$u_{ba} = u(k_{ba}) \ , \tag{1c}$$

and that the speed signal ω is reconstructed by time-differentiation of the measured throttle position signal θ (T - sampling time):

$$\omega(k) = \left[\theta(k) - \theta(k-1)\right]/T \ . \tag{2}$$

Inserting (2) in (1b), and rearranging yields the simpler form of the condition (1b):

$$\theta(k_s+3) - \theta(k_s) \geq 5\Delta_\theta \ , \tag{3}$$

where $\Delta_\theta = T\,\Delta_\omega$ is the throttle position measurement resolution (in this application: $\Delta_\theta = 0.106^\circ$ and $T = 4$ ms).

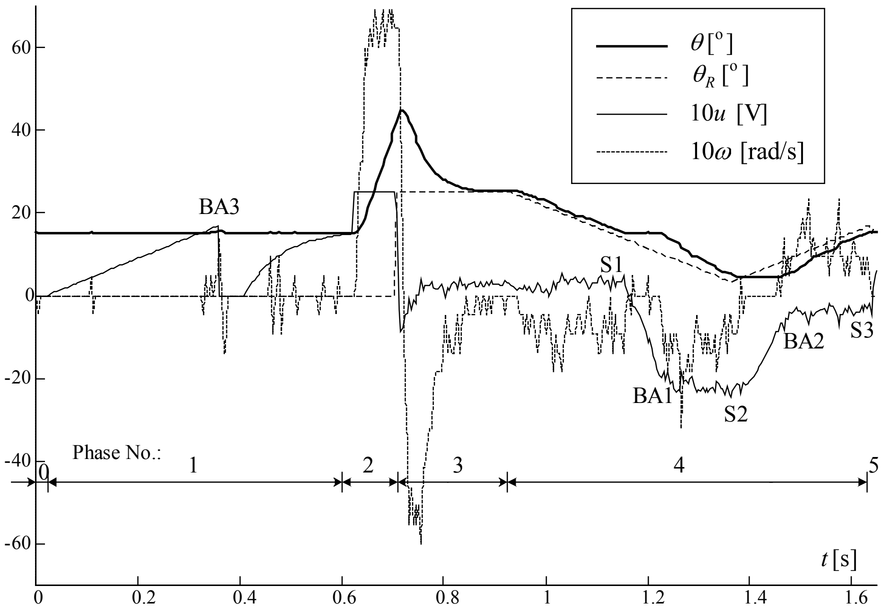

Fig. 6. Experimental response of electronic throttle during auto-tuning procedure.

C. Phase 2 – Identification of linear process dynamics

According to the process analysis presented in [6], the return spring influence on the process dynamic behavior may be neglected in the region $\theta > \theta_{LH}$ (see also assumption (iv) in Section II), so that the linear process model (Fig. 2 with $m_f = m_s = 0$) may be approximated by the integral+lag term

$$G_p(s) = \frac{\theta(s)}{u(s)} = \frac{1}{s}\frac{\omega(s)}{u(s)} = \frac{K_p}{(T_{em}s+1)s} \ , \tag{4}$$

where the process gain K_p and the electromechanical time constant T_{em} are defined as

$$K_p = K_{ch}K_l / K_v \ , \qquad T_{em} = J/(K_a K_t K_v) \ .$$

Hence, the throttle speed step response is given by

$$\omega(t) = \omega_{ss}\left(1 - e^{-t/T_{em}}\right) . \tag{5}$$

The process gain K_p is estimated as $K_p = \omega_{ss}/\Delta u$ [3], where ω_{ss} is the speed response steady-state value, and Δu is the commanded signal step change. In order to avoid time-consuming numerical optimization of T_{em} (applied in [3] for off-line process identification), it is convenient to integrate the speed response and find a relation between the speed integral (i.e. the displacement $\theta_{fin} - \theta_{init}$) and T_{em}:

$$\int_0^{T_{fin}} \omega dt = \theta_{fin} - \theta_{init} = \omega_{ss}\int_0^{T_{fin}}\left(1 - e^{-t/T_{em}}\right)dt =$$
$$= \omega_{ss}\left[T_{fin} - T_{em}\left(1 - e^{-T_{fin}/T_{em}}\right)\right] . \tag{6}$$

Since the identification interval T_{fin} is larger than $3T_{em}$ (the steady-state condition), the exponential term on the most right-side of Eq. (6) is less then 0.05 and may be neglected. Hence,

$$T_{em} \approx T_{fin} - \frac{\theta_{fin} - \theta_0}{\omega_{ss}} \ . \tag{7}$$

In order to calculate the steady-state speed ω_{ss} and determine T_{fin}, it is necessary to detect the steady-state portion of the speed response. The steady-state instant k_{ss} is determined as the first sampling instant after which the absolute value of the sum of N consecutive throttle speed differences is less than or equal to the speed quantization level Δ_ω, i.e.

$$k_{ss} = \min\{k_r\} \ , \tag{8a}$$

where k_r satisfies the relation:

$$\left|\sum_{i=1}^{N} \omega(k_r + i) - \omega(k_r + i - 1)\right| \le \Delta_\omega \ . \tag{8b}$$

The final throttle position θ_{fin} and the steady-state speed ω_{ss} are then determined as

$$\theta_{fin} = \theta(k_{ss}) \ , \tag{9}$$

$$\omega_{ss} = \frac{1}{N_1 + M}\sum_{i=N-N_1+1}^{N+M} \omega(k_{ss} + i) \ , \tag{10}$$

where $N_1 < N$ is the number of last several samples inside the sampling window used in (8b), and M is the number of additional subsequent samples used to calculate the average steady-state speed ω_{ss}.

D. Phase 4 – Identification of process static curve

The required process static curve parameters U_S, U_{LH}, and $\Delta u / \Delta\theta_{-}$ (Fig. 4) can be reconstructed from the relatively narrow portion of the overall static curve, which includes the limp-home region and the region below the limp-home position ($\theta \leq \theta_0$ in Fig. 5). The static curve is recorded as the closed-loop response with respect to ramp form of the position reference θ_R [3]. The ramp slope is set to a maximum value which still provides a reasonably accurate prediction of the static curve. The recorded static curve is shown in Fig. 7 (solid line).

Estimation of the static curve parameters in [3] was based on off-line straight-line interpolations of the static curve. This technique is not suitable for on-line estimation, because of the high computational requirements and certain inaccuracy of the on-line recorded static curve (cf. static curves in Fig. 7). Therefore, another identification method based on the characteristic points of the static curve is proposed. There are six characteristic points (Fig. 7), which can be divided in two characteristic groups: the breakaway points BA1-BA3, and the sliding-regime points S1-S3. The breakaway point BA3 was already identified in phase 1 ($u_{BA3} = u_{ba}$), and the other two breakaway points BA1 and BA2 are identified in the similar way [7]. The voltage levels of the sliding-regime points S_j, $j = 1, 2, 3$ are estimated by averaging the commanded signal u over a narrow sliding interval:

$$u_{Sj} = \frac{1}{L}\sum_{i=1}^{L} u(k_{Sj} + i) \ . \tag{11}$$

Averaging starts at the sampling instant k_{Sj} which is determined based on the following conditions (Fig. 6):

$$\begin{aligned} &\theta_R(k_{Sj}) < \theta_{LH} \ , \ \text{for } j = 1 \ , \\ &\theta_R(k_{Sj}) > \theta_R(k_{Sj} - 1) \ , \ \ \text{for } j = 2 \ , \\ &\theta_R(k_{Sj}) > \theta_{LH} \ \wedge u_{BA2} \text{ already estimated}, \quad \text{for } j = 3 \ . \end{aligned} \tag{12}$$

Once the characteristic voltage levels u_{BAi} and u_{Si} are estimated (see * and o-marks in Fig. 7), the required static curve parameters U_S, U_{LH}, and $\Delta u / \Delta\theta$ (Fig. 4) are readily calculated as:

$$\begin{aligned} U_S &= \frac{1}{2}\left[\frac{u_{BA3} - u_{S1}}{2} + \frac{1}{2}\left(\frac{u_{S3} - u_{BA1}}{2} + \frac{u_{BA2} - u_{S2}}{2}\right)\right] , \\ U_{LH} &= \frac{1}{2}\left(\frac{u_{BA3} + u_{S1}}{2} - \frac{u_{BA1} + u_{S3}}{2}\right) , \\ \frac{\Delta u}{\Delta\theta_-} &= \frac{1}{2}\left(\frac{u_{S3} - u_{BA2}}{\theta_{LH} - \theta_{\min}} + \frac{u_{BA1} - u_{S2}}{\theta_{LH} - \theta_{\min}}\right) . \end{aligned} \tag{13}$$

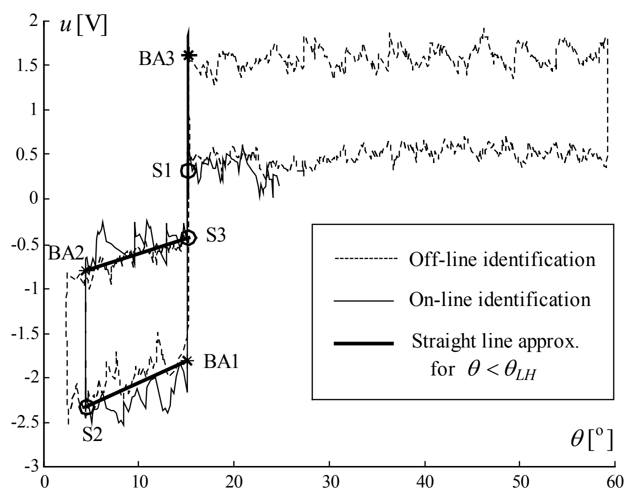

Fig. 7. Process static curves recorded by off-line and on-line experiments, and results of on-line identification

V. CALCULATION OF CONTROL STRATEGY PARAMETERS

A. Phase 3 – Calculation of basic set of controller parameters

The basic set of PID controller parameters (for the region $\theta > \theta_{LH}$) is calculated based on the estimated parameters K_p and T_{em} of the simplified linear process model (4). The controller parameters are optimized according to the damping optimum design method [8]. By equating the closed-loop system characteristic polynomial (obtained from (4) and Fig. 3, [6]) with the damping optimum characteristic polynomial

$$N(s) = D_2^3 D_3^2 D_4 T_e^4 s^4 + D_2^2 D_3 T_e^3 s^3 + D_2 T_e^2 s^2 + T_e s + 1 \ ,$$

the following equations for the PID controller parameters are obtained [6]:

$$\begin{aligned} K_{R+} &= \frac{1}{K_p}\frac{T_{em} + T}{D_2^2 D_3 T_e^2} \ , \\ T_{I+} &= T_e \ , \\ T_{D+} &= D_2 T_e\left(1 - \frac{D_2 D_3 T_e}{T_{em} + T}\right) , \end{aligned} \tag{14}$$

where D_2 and D_3 are the damping optimum characteristic ratios (with optimal values of 0.5, [8]), and T_e is the equivalent time constant of the closed-loop system.

The lead-lag feedforward controller discrete-time zero is determined off-line as [6]:

$$z_{ff} = \exp(-2.04 T / T_e) \ . \tag{15}$$

B. Phase 5 - Calculation of other control strategy parameters

The return spring is significantly stiffer in the region $\theta < \theta_{LH}$ than in the region $\theta > \theta_{LH}$ (Figs. 2 and 7). Thus, the control system tuned according to (14) would have slower response in the region $\theta < \theta_{LH}$ compared to the desired response for the region $\theta > \theta_{LH}$ [1,6]. In order to provide the same control performance for the both regions, the PID controller design must take into account the return spring influence, i.e. a second-order lag process model must be used instead of the integral+lag model (4). The final equations for the optimal controller parameters can be conveniently presented in the following form [6] (as a modification of the basic equations (14)):

$$\begin{aligned} K_{R-} &= K_{R+} - \Delta K_R \ , \\ T_{I-} &= T_{I+}(1 - a) \ , \\ T_{D-} &= \frac{T_{D+} - aT}{1 - a} \ , \end{aligned} \tag{16}$$

with the correction factors ΔK_R and a defined as

$$\Delta K_R = \frac{\Delta u}{\Delta \theta_-} \ ,$$

$$a = \frac{D_2^2 D_3 T_e^2}{T_{em} + T} K_p \frac{\Delta u}{\Delta \theta_-} \ . \tag{17}$$

The parameter θ_{LH} of the control strategy (Fig. 3) is set to the limp-home position value estimated in phase 0. Similarly, the parameters U_{Sc} and U_{LHc} of the control strategy can be equated with the estimated values of friction and limp-home voltages U_S and U_{LH}, respectively. However, it may be convenient to correct these relations somewhat according to:

$$U_{Sc} = \kappa_S U_S \ ,$$

$$U_{LHc} = \kappa_{LH} U_{LH} \ , \tag{18}$$

where κ_S and κ_{LH} are the correction factors with values close to 1.

C. Choice of design parameters

A detailed discussion on the choice of the design parameters T, T_e, D_2, D_3, κ_S, and κ_{LH} is presented in [7,6]. Only the main recommendations are given here.

The sampling time T influences the control system bandwidth and the auto-tuner robustness. It should be set in the range from 3 to 6 ms.

The characteristic ratios D_2 and D_3 are set to values below the optimal value 0.5 ($D_2 = 0.37$ and $D_2 = 0.4$), in order to provide the boundary aperiodic step response of the control system. The closed-loop system equivalent time constant T_e can be set to an arbitrary value above [6]

$$T_{e\min} = \frac{2}{D_2 D_3} \frac{T}{1 + T/(T_{em} + T)} \ . \tag{19}$$

VI. Experimental Verification of Tuned Control Strategy

More than hundreds auto-tuning experiments have been executed, and the estimated process parameters have always taken similar on values. This points out to the robustness of the auto-tuning strategy. The estimated parameters agree well with the results of off-line identification (see e.g. Fig. 7).

In order to additionally test the on-line identification method, as well as the controller calculation method, the auto-tuning procedure has been extended with an interval of control strategy verification. The control system response during this interval is shown in Fig. 8. This response confirms that the controller is well tuned. The control system step response has the desired aperiodic form for all the tested operating modes, and the settling time is approximately 70 ms. The limp-home compensator practically eliminates the standstill interval for throttle passing through the limp-home region.

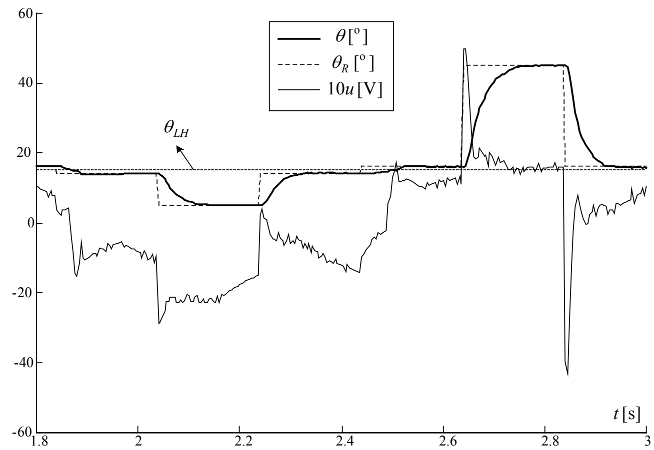

Fig. 8. Experimental response of tuned electronic throttle control system.

VII. Conclusion

An auto-tuner for the recently proposed electronic throttle control strategy has been developed and experimentally verified. The auto-tuner application provides that all electronic throttles from a vehicle production series have similar (desired) control performance, regardless of variations of electronic throttle body parameters due to production deviations, external conditions variations, and aging. The auto-tuner does not require any prior knowledge of the process parameters. It is characterized by simple implementation and fast execution.

Acknowledgment

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