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Design of electronic throttle valve position control system using Learning Feed-Forward based on Model Reference Adaptive Systems controller

Que Son Tran, Thi Ngoc Anh Dang

***Abstract*— In recent years, the use of electronic throttle valve systems has been very popular in the automotive industry. However, there are still many difficulties in controlling the electronic throttle valve because of multiple nonsmooth nonlinearities, including stick–slip friction, backlash, and a discontinuous nonlinear spring involved in the system. To alleviate these difficulties in controlling the angle of a throttle plate and to make a highly robust controller with limited cost, this paper proposes the new approach using the PD controller and a Model Reference Adaptive System-based Learning Feed-Forward Controller algorithm to the electronic throttle valve. Firstly, the LFFC is applied together with the PD controller to compensate the nonlinearities in the system, and then, the Lyapunov approach is used to find stable adaptive laws for the feed-forward parameters when the parameters of the system changes while the throttle valve is working. The performance of the proposed controller is evaluated by performing some simulations on the Matlab-Simulink software.**

***Index Terms*—Model Reference Adaptive Systems (MRAS); Learning Feed-Forward Control (LFFC); Electronic Throttle Valve system; Multi-Input Multi-Output (MIMO) System.**

I. INTRODUCTION

Electronic Throttle Control (ETC) is the automobile industry's "Fly by Wire" system. In ETC systems, a vehicle's electronic control unit uses feedback signal from the throttle position sensor (TPS), accelerator pedal position sensor (APP sensor), wheel speed sensors, vehicle speed sensor and a set of other sensors to determine how to adjust throttle position.

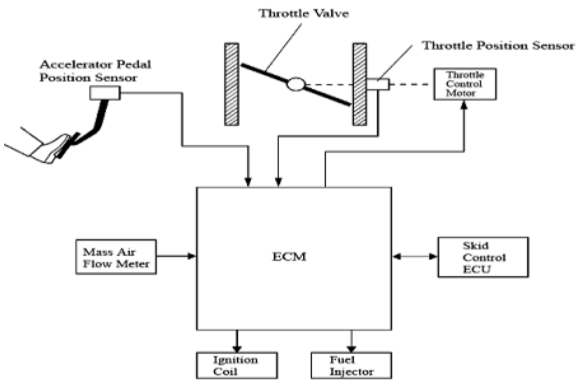

Figure 1. The electronic control unit

Que Son Tran, Department of International Training, Thai Nguyen University of Technology, Thai Nguyen, Viet Nam, +84988039336, (e-mail: tranqueson.ktdt@tnut.edu.vn).

Thi Ngoc Anh Dang, Department of Electronics Engineering, Thai Nguyen University of Technology, Thai Nguyen, VietNam, +841645980721.

Controlling the throttle valve is the control of the open angle of the valve plate controlling the air amount that enters to the combustion engine. The electronic control unit (ECU) determines the precise amount of fuel delivered to the engine. This amount is just enough to obtain an ideal air fuel ratio (A/F) (stoichiometry, about 14.7:1). The Figure 1. The electronic control unit electronic throttling valve, as shown in Figure 2, consists of a dc motor, a motor pinion gear, an intermediate gear, a sector gear, a valve plate, and a nonlinear spring.

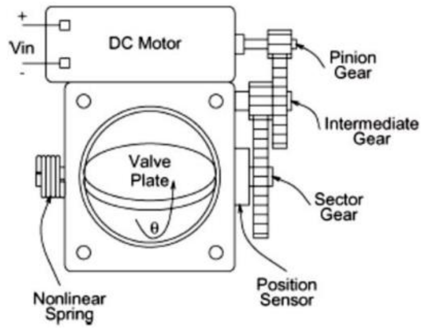

Figure 2. The electronic throttle valve

The motor is connected to the throttle plate through a set of gears. The rotational angle φ of the plate is measured with the help of throttle position sensor. The electromechanical throttle actuators are equipped with springs. In case of a failure in controlling, the springs forces the plate to the so called limp home position φ_0 enabling the emergency operation of the engine. The task of the controller is to provide the control signal u to the motor so that the position of the valve plate tracks the reference signal.

As mentioned later, the model of the plant includes the nonlinear components. The paper discusses a control approach with nonlinear compensation using LFFC based on MRAS to control the position of the valve plate.

The paper is organized as follows: The modelling a throttle valve system is outlined in Section II. The procedure to design the LFFC based on MRAS controller for the electronic throttle valve are discussed in Section III. Section IV is dedicated to the discussion of simulation results and Section V concludes this paper.

II. THE FULL MODEL OF THE ELECTRONIC THROTTLE VALVE

The rotor angular velocity is defined as φ, and the valve plate position is defined as φ. The total inertia and total damping coefficient are respectively determined by [2]

$$J_{tot} = J_m + K_{g1}^2 J_{int} + \left(K_{g1}K_{g2}\right)^2 \left(J_{ps} + J_{set}\right) \tag{1}$$

$$B_{tot} = B_m + K_{g1}^2 B_{int} + \left(K_{g1}K_{g2}\right)^2 B_{ps} \tag{2}$$

Considering the friction and nonlinear spring torque, the dynamic equation is obtained:

$$J_{tot}\dot{\omega} = -B_{tot}\omega + K_t z - T_f(\omega) - T_{sp}(\varphi) \quad (3)$$

Where: $T_f(\omega)$ and $T_{sp}(\varphi)$ are Coulomb fiction and spring nonlinear functions as described below:

The Coulomb fiction function:

$$T_f(\omega) = \begin{cases} F_s, \omega > 0 \\ 0, \omega = 0 \\ -F_s, \omega < 0 \end{cases} = F_s sgn(\omega) \quad (4)$$

where F_S is a positive constant.

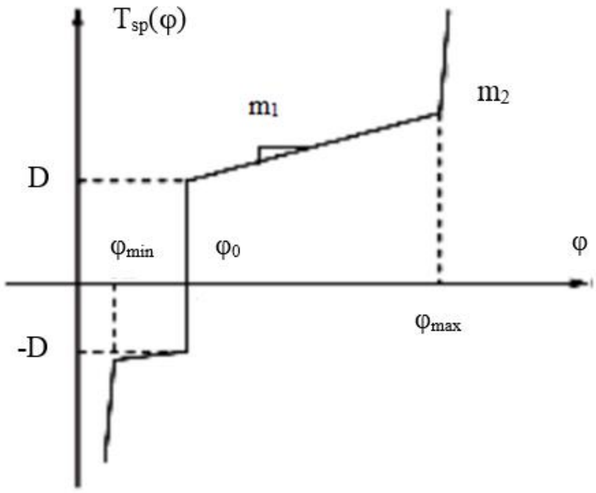

Figure 3. Nonlinear Spring

So, the Spring function:

$$T_{sp}(\varphi) = \begin{cases} D + m_1(\varphi - \varphi_0) if\ \varphi_0 < \varphi < \varphi_{max} \\ -D - m_1(\varphi_0 - \varphi) if\ \varphi_{min} < \varphi < \varphi_0 \end{cases}$$

Or: $T_{sp}(\varphi) = m_1(\varphi - \varphi_0) + D\mathrm{sgn}(\varphi - \varphi_0)$ (5)

Because the nonlinearity coming from backlash phenomenon is insignificant, so we ignored it in the throttle valve mathematical model.

And *z*: is the current through the dc motor windings.

The relationship between the valve plate position and the rotor angular velocity is described by the following relation:

$$\dot{\varphi} = (K_{g1}K_{g2})\omega \quad (6)$$

Finally, the model of throttle system:

$$\dot{\varphi} = (K_{g1}K_{g2})\omega$$

$$\dot{\omega} = -\frac{B_{tot}}{J_{tot}}\omega + \frac{K_t}{J_{tot}}z - \frac{1}{J_{tot}}T_f(\omega) - \frac{1}{J_{tot}}T_{sp}(\varphi)$$

$$\dot{z} = \frac{-K_v}{L}\omega - \frac{R}{L}z + \frac{1}{L}u \quad (7)$$

Where *u*: is the input voltage to the dc motor. Because the motor inductance *L* is ignored,

So $L \approx 0$ and we have: $z = \frac{-K_v}{R}\omega + \frac{1}{R}u$ (8)

From Equation (7) and (8) we can express the dynamic of the electronic throttle valve by Equation (9) as

$$u = \frac{1}{B}\ddot{\varphi} + \frac{A}{B}\dot{\varphi} + \frac{C}{B}\varphi + \frac{\mu}{B}\mathrm{sgn}(\dot{\varphi}) + \frac{k}{B}\mathrm{sgn}(\varphi) \quad (9)$$

Where: $A = \left(\frac{B_{tot}}{J_{tot}} + \frac{K_t}{J_{tot}}\frac{K_v}{R}\right)$,

$B = \frac{K_{g1}K_{g2}K_t}{RJ_{tot}}$, $k = \frac{K_{g1}K_{g2}D}{J_{tot}}$,

$\mu = \frac{F_S}{J_{tot}}$, $C = \frac{K_{g1}K_{g2}m_1}{J_{tot}}$

Now, we design proposed controller in section III.

III. A MRAS – Based Learning Feed – Forward Control

The structure of the controller is shown in Fig 4 [6]

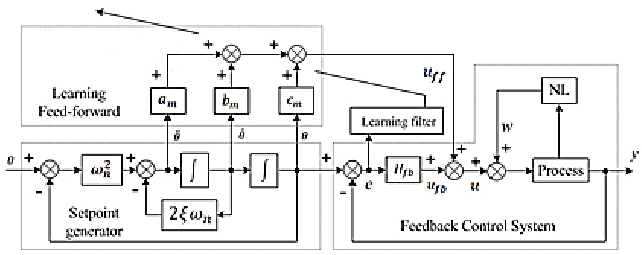

Figure 4. MRAS based on LFFC

As shown in Figure 4, the learning signal is the difference between the output of the setpoint generator (the reference model) and the process. The feedback path, is for compensating for random disturbances, it also generates the learning signal for the system a_m, b_m and c_m are adjustable parameters. The design problem is thus: Find (stable) adjustment laws for the adjustable parameters to make the error between the setpoint generator and the process as well as the errors in the feed-forward parameters asymptotically go to zero.

The form of the adjustment laws [6]:

$$a_m = \alpha_a \int [(p_{21}e + p_{22}\dot{e})\ddot{\varphi}]dt + a_m(0);$$

$$b_m = \alpha_b \int [(p_{21}e + p_{22}\dot{e})\dot{\varphi}]dt + b_m(0);$$

$$c_m = \alpha_c \int [(p_{21}e + p_{22}\dot{e})\varphi]dt + c_m(0); \quad (10)$$

In Equation (10), α_a, α_b, α_c are called the adaptive gains, and $\ddot{\varphi}$, $\dot{\varphi}$, φ, e, and $\dot{e}$ are described in Figure 4, p_{21}, p_{22} are elements of the P matrix – which can be obtained by solving the equation: $A_p^T P + PA_p = -Q$ - follow the method of Liapunov [4].

So the controller is described step by step as follows:

Step 1: **Choose the reference model**: The reference model chosen is second-order function:

$$H_{ref} = \frac{\omega_n^2}{s^2 + 2\gamma\omega_n s + \omega_n^2}$$

Step 2: **Design the feedback controller:**

The feedback controller is designed such that it features robust stability for closed loop when used alone. It has the form of PD-type: $C(s) = K_p + K_d s$

Step 3: **Determine the inputs of the feed-forward part:**

The Table 1 shows the feed-forward components with corresponding input and output signals, form of the adjustment laws, and the target functions that they have to learn.

Table 1: Feed-forward components with corresponding input and output signals.

	Inputs	Output adjust laws	Target function
F_1	$\ddot{\varphi}$	$u_1 = \alpha_1 \int [(p_{21}e + p_{22}\dot{e})\ddot{\varphi}]dt + u_1(0)$	$\frac{1}{B}\ddot{\varphi}$
F_2	$\dot{\varphi}$	$u_2 = \alpha_2 \int [(p_{21}e + p_{22}\dot{e})\dot{\varphi}]dt + u_2(0)$	$\frac{A}{B}\dot{\varphi}$
F_3	φ	$u_3 = \alpha_3 \int [(p_{21}e + p_{22}\dot{e})\varphi]dt + u_3(0)$	$\frac{C}{B}\varphi$
F_4	$\mathrm{sgn}(\dot{\varphi})$	$u_4 = \alpha_4 \int [(p_{21}e + p_{22}\dot{e})\mathrm{sgn}(\dot{\varphi})]dt + u_4(0)$	$\frac{\mu}{B}\mathrm{sgn}(\dot{\varphi})$
F_5	$\mathrm{sgn}(\varphi)$	$u_5 = \alpha_5 \int [(p_{21}e + p_{22}\dot{e})\mathrm{sgn}(\varphi)]dt + u_5(0)$	$\frac{k}{B}\mathrm{sgn}(\varphi)$

Step 4: **Determine the structure of the feed-forward part:** The proposed feed-forward controller is shown in figure 4.

Step 5: **Solve Lyapunov Equations:** We solve Liapunov equations to find the elements of P matrix.

Step 6: **Choose adaptive gains:** In principle, the adaptive gains can be chosen freely.

Step 7: **Training the LFFC:** One component in the feed-forward part should be trained at a time.

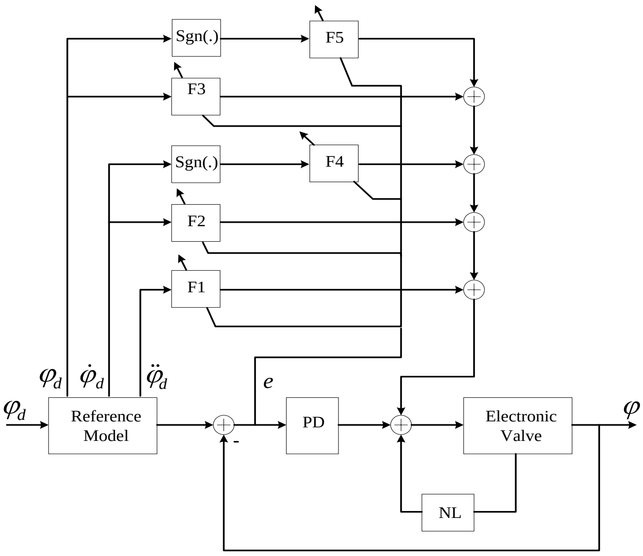

Figure 5: Structure of proposed controller

IV. SIMULATION EXPERIMENTS

In this section, we perform simulation experiments to confirm the effectiveness of the proposed control. The values of the parameters in the electronic throttle system and the parameters of the controller calculated and adaptive gain chosen are given in Table 2. Figure 5 show the simulation valve system. In this test, the initial condition is $(\varphi,\dot{\varphi}) = (0,0)$. The result is presented in Figure 6 and Figure 7.

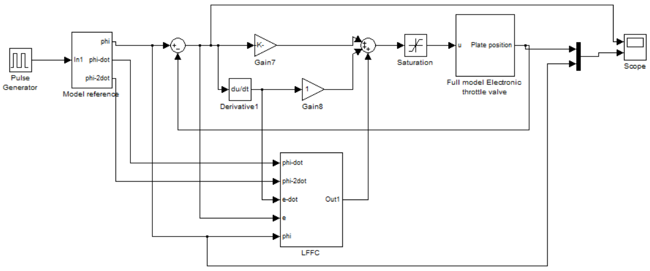

Figure 6: Simulation system

In this simulation, we set the input as square pulse with 1 magnitude. From the simulation results (Figure 6), it can be seen that the output will not follow the reference, because of the effect of nonlinearities in the system. But in the case we use the PD controller in combination with LFFC based on MRAS, the output should track the reference (Figure 7), with the error is sufficiently small.

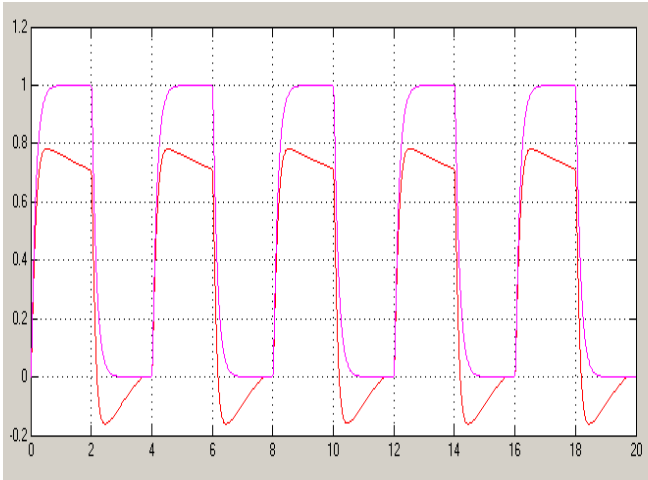

Figure 7. System response with PD controller

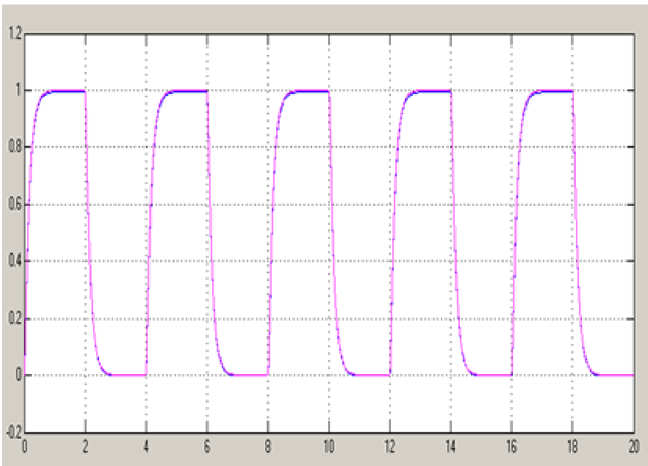

Figure 8. System response with proposed controller

V. CONCLUSION

In this paper, a new algorithm is proposed for designing the controller for the throttle valve as one of the most importance units in an automobile engine. The proposed control approach replaces the conventional PID controller by a PD controller in combination with a Model Reference Adaptive System-based Learning Feed-Forward Controller algorithm. This combination is for overcoming the nonlinearities in the systems for helping the PD controller to control position of the valve plate tracks the reference signal. The result of the proposed control approach is demonstrated through a set of simulation experiments in Matlab – Simulink, in which, all the nonlinearities in the system are compensated, and the PD controller makes the open angle of the throttle valve track the desired reference even when the parameters of the system change in operation.

APPENDIX

Table 2: The parameters value of the electronic throttle valve

Parameter	Value	Parameter	Value
C	1.68e3	P	[0.04 1;500 0.2]
A	128.64	α_1	0.2
B	3.91e4	α_2	0.0032
k	4.6139e3	α_3	0.1
μ	2.1073e3	α_4	0.02
K_p	328	α_5	0.01
K_D	2.5		

Table 3: The parameter names and their definitions

Parameters	Definition
J_m	Inertia of rotor
J_{int}	Inertia of intermediate gear
J_{sect}	Inertia of sector gear
J_{ps}	Inertia of plate and shaft
B_m	Viscous damping constant of motor
B_{int}	Viscous damping constant of intermediate gear
B_{ps}	viscous damping constant of plate and shaft
L	Motor inductance
R	Motor resistance
K_t	Motor torque constant
K_v	Motor back emf constant
K_r	Reset integrator gain
φ_0	Spring default position
D	Spring offset
m_1	Spring gain

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MSc Que Son Tran working at Faculty of International Training, Thai Nguyen University of Technology, Thai Nguyen city, Viet Nam. Research interests: Electronics Engineering, Automatic Control.

MSc Thi Ngoc Anh Dang working at Faculty of Electronics Engineering, Thai Nguyen University of Technology, Thai Nguyen city, Viet Nam. Research interests: Electronics Engineering, Automatic Control.