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Optimization of fuzzy PID controller's parameters

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Abstract

The paper describes an effective method for determining the optimal parameters of a linear fuzzy PID controller with the use of MATLAB services, referred to as Fuzzy Logic Toolbox and Response Optimization

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Keywords: optimal parameters, linear fuzzy PID controller, MATLAB

1. Introduction

At present, more and more applications are applied for fuzzy proportional-integral-derivative (PID) controllers, which have much more flexible setting than their linear analogues. Methods for determining the optimal parameters of fuzzy PID controllers are quite complex and time consuming, that significantly restrains their application.

In this paper we propose a simple method of fuzzy PID controller's settings with the use of MATLAB and certain provisions of fuzzy linearization method as set forth in[1].

2. Fuzzy controllers

Fig.1 considers one of the most common scheme of fuzzy discrete controller, which has two inputs: control error

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$e(k)$ and its variation $\Delta e(k) = e(k) - e(k-1)$ or velocity $\Delta\dot{e}(k) = \Delta e(k)/\Delta t$ and one output $u(k)$ - control at the moments $k\Delta t$, $k = 1, 2, ..., N$, where Δt - sampling step.

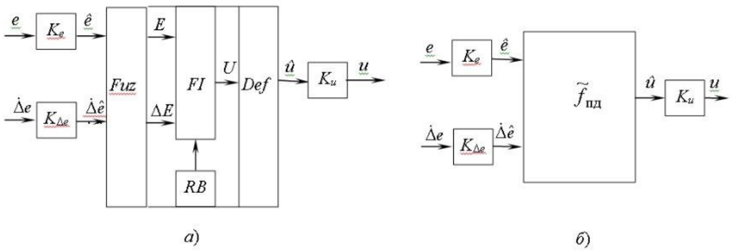

Fig. 1. Simplified (a) and the operators (b) diagrams of the fuzzy controller.

Actual values of the inputs e, Δe using the normalizing coefficients K_e, $K_{\Delta e}$ are converted to normalized $\hat{e}$, $\Delta\hat{e}$ $\in[-1, 1]$. Central element of fuzzy controller is the fuzzy operator $\tilde{f}_{pd}$ (Fig. 1b) performing operations of fuzzification fuzzy inference *FI* and defuzzification *Def* and containing base of rules *RB*.

Operation of fuzzification *Fuz* converts normalized inputs $\hat{e}$ into fuzzy E, ΔE.Fuzzy inference *FI* (Fuzzy for example by Mamdani's method, finds a fuzzy output U basing on fuzzy inputs E, ΔE and rule base RB) of a type

$$R_p^\theta \text{ if } \hat{e} \text{ is } E^\theta \text{, if } \Delta e \text{ is } \Delta E^\theta \text{then } \hat{u} \text{ is } U^\theta \quad \theta = 1, 2, \cdots, q \tag{1}$$

where E^θ, are fuzzy sets, having term of set characterizing the values of the corresponding variables $\hat{e}$, $\Delta\hat{e}$, $\hat{u}$ is negative, Z is zerocharacterizing the values of the corresponding variables $\hat{e}$, $\Delta\hat{e}$, $\hat{u}$ (N negative, Z zero, P - positiveor (*NB* large negative, *NM* is an average negativeclose to zero, *PM* is an average positive, large positive).

Operation of defuzzification of output *Def (Defuzzyfication)* converts fuzzy output U, for example, by the median (Bisector) or the center of gravity (Centroid) methods, into the normalized value $\hat{u} \in [L, -L]$, $L = 1, 2$, which is being multiplied by the coefficient K_u and turns into real u.

3. Coefficients estimation of fuzzy controllers

Simplified method of determining the parameters of fuzzy P, PI, PD and PID controllers consists in linearization and optimization of fuzzy controllers.

In order for fuzzy operator (controller) $\hat{u} = \tilde{f}$ $(\hat{e}, \Delta\hat{e})$ to become equivalent to fuzzy linear $\hat{u} = \hat{e} + \Delta\hat{e}$, we need to perform the following basic conditions, determined in[1]:

1) to use in precondition the triangular membership function (Fig. 2intersecting at value 0.5, and in conclusion singletone functions (Fig. 2b, c);

2) to construct a rule base that contains all possible desirable $\wedge$ - combinations of terms in precondition.

Let's consider the linearization of the fuzzy PD controller and find the ratios, defining its coefficients.

Fuzzy PID controller, which contains a fuzzy PD and a linear I components as well as two inputs e, $\Delta\dot{e}$, are shown in Fig. 3[2]. In this scheme, the integrated error e_i is computed as the sum of incremental controls, obtained at the adder C_1 and a delay element on 1 cycle of Setting Element (SE).

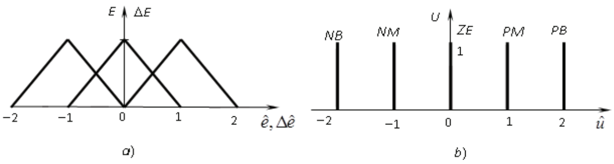

Fig. 2. Triangular (a) and singletone (b) membership functions

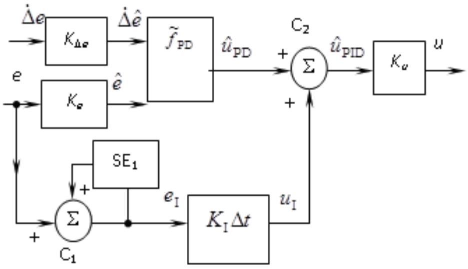

Fig. 3. Fuzzy PID controller

Then the controller's output, formed by adding the fuzzy PD $\hat{u}_{PD}$ and the clear integral (I) u_I components in the adder C_2 will be defined as

$$u(k) = K_u[\tilde{f}_{PD}(K_e e(k), K_{\Delta e}\dot{\Delta}e(k)) + K_I e_I(k)\Delta t] \tag{2}$$

Linearization of an expression (2) looks like

$$\begin{aligned} u(k) &= K_u[K_e e(k) + K_I e_I(k)\Delta t + K_{\Delta e}\dot{\Delta}e(k)] = \\ &= K_e K_u[e(k) + \frac{K_I}{K_e}\sum_{i=1}^{k} e(i)\Delta t + \frac{K_{\Delta e}}{K_e}\dot{\Delta}e(k)] \end{aligned} \tag{3}$$

Comparing (3) with the expression of a linear discrete PID controller

$$u(k) = K_P[e(k) + \frac{1}{T_I}\sum_{i=0}^{k} e(i)\Delta t + T_D\dot{\Delta}e(k)] \tag{4}$$

we obtain rather simple relations

$$K_e K_u = K_{\Pi} K_u = K_p \tag{5}$$

$$\frac{K_I}{K_e} = \frac{1}{T_I} \tag{6}$$

$$\frac{K_{\Delta e}}{K_e} = T_{\mathrm{D}} \tag{7}$$

connecting the parameters of linear and fuzzy PID controllers.

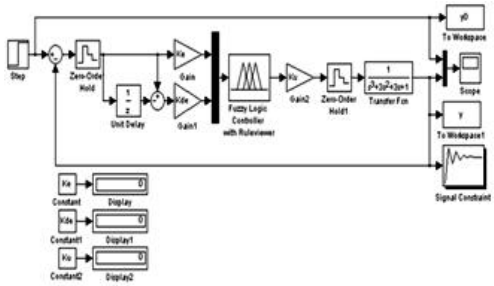

Fig. 4. Digital fuzzy control system's diagram.

Based on equations (2) - (6) we can set in the table 1 the correspondence between the coefficients of traditional linear and fuzzy PID controllers.

Table 1. Coefficients of a fuzzy PID controller.

Fuzzy controller	K_p	$1/T_1$	T
PID	K_eK_u=4.8	KI/Ke=0.51	$K_{\Delta e}/K_e$= 3.7

Identifying by the method of Takahashi[3] the settings of linear PID controllers (K_P = 4.8, T_I = 1.9 T_D = 3.7) and substituting them in the table 1, we can obtain the ratios (4) - (6) to calculate the coefficients $K_e, K_u, K_{\Delta e}, K_I, K_{\Delta u}$ of equivalent linear fuzzy PID controllers. Let us start with a brief description of the procedures of construction, modeling and optimization in MATLAB - SIMULINK of digital control system containing fuzzy PID controller and an object of control with the transfer function

$$W\ (s) = \frac{1}{s^3 + 3s^2 + 3s + 1} \tag{8}$$

4. Constructing a digital control system

For constructing a model of a digital control system with fuzzy PID controller in the modeling package *SIMULINK* we shall transfer from the subcategories *Sources* to the model's window two blocks *Constant* and a block *Step*, generating a unit step function; *Math Operations* - block of comparison *Sum* and two blocks *Gain*; *Discrete* - two blocks *Zero - Order Hold*; *Continuous* - block *Transfer Fcn*, implementing the transfer function of the object (7); *Fuzzy Logic Toolbox* – block of fuzzy controller *Fuzzy Logic Controller with Ruleviewer*; *Sink* - two block *To Workspace*, subcategory *Commonly Used Block* - block *Mux* of multiplexor of signals and oscilloscope's block *Scope* with two inputs; *Simulink Response Optimization* - block of dynamic optimization *Check Step Response Characteristics* etc. Connect the blocks as shown in Fig. 4, enter the required data and obtain the digital control system with fuzzy PID controller.

Let's start construction of the fuzzy PID controller with an editor of fuzzy inference system *FIS Editor*. Replacing ê with *e1*, $\Delta\dot{e}$ with *de1*, û with *u1*, we can write the rules of the fuzzy linear PD controller as follows[1]

R^1_{PD} : if *e1* is *N*, *de1* is *N*, then *u1* is *NB*,

R^2_{PD} : if e1 is N, de1 is Z, then u1 is NM,

R^3_{PD} : if e1 is N, de1 is P, then u1 is ZE,

R^4_{PD} : if e1 is Z, de1 is N, then u1 is NM,

R^5_{PD} : if e1 is Z, de1 is Z, then u1 is ZE, (5)

R^{6}_{PD} : if e1 is Z, de1 is P, then u1 is PM,

R^{7}_{PD} : if e1 is P, de1 is N, then u1 is ZE,

R^{8}_{PD} : if e1 is P, de1 is Z, then u1 is PM,

R^{9}_{PD} : if *e1* is *P*, de1 is *P*, then *u1* is *PB*.

In dialogue windows of a *FIS* editor we enter the input (Fig. 2a) and output (Fig. 2b) membership functions, the mechanism of fuzzy inference *Bisector*, and fuzzy rules (5). We set K_e and K_u, satisfying the constraints K_e K_u = 4.8, for example - K_e = 2; K_u = 2.4, and run the simulation of control system process, manually changing the coefficients K_e and K_u .The best response to the unit step was obtained at K_e = 4; K_u = 1.2, but herewith all restrictions were violated. In the parameters optimization block of fuzzy controller *Check Step Response Characteristics* we set the boundaries of an output signal: time rise (*Rise time*) - not more than 6 s and duration of a transitional process (*Setting time*) - not more than 15 s, and overshoot (*Settling time*) - not more than 10%.

Let's choose a simplex search as a method of optimization(*Simplex Search*) and start the process of optimizing the parameters of the PID controller. We obtain the graph of the transition process (Fig.5), satisfying all the given constraints.

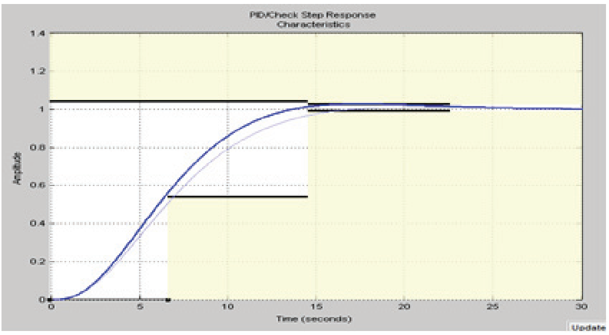

Fig. 5. The optimal transition process.

Thus, the overshoot is absent, i.e. is equal to 0, the time rise is not greater than 6 s, and duration of the transitional process – 15 s at the following values of the parameters of a fuzzy PID controller: *K*de = 2.82 e-4; *Ke* = 5.57; K_i = 0.053; K_u = 2.69.

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