FROM PID TO FUZZY CONTROL. APLICATION FOR AZIMUTH CONTROL OF AN AERO-DYNAMICAL SYSTEM

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Abstract: In this paper the tuning of a proportional–integral–derivative (PID) controller for azimuth control of an aero-dynamical system is discussed. The PID control is obtained in accordance to the Ziegler-Nichols method. Then the coefficients of the controller are fine tuned for the aero-dynamical system. On the base of this PID controller, a fuzzy equivalent controller is obtained and tuned. The latter controller is nonlinear and with it help the nonlinearities of the plant are eliminated.

Key words: PID controller, Fuzzy controller, Tuning, Aero-dynamical system, Azimuth control.

1. Introduction

Control theory provides a variety of methods for controller design. During their education, students are encouraged to get acquainted with all of them and on the later stage to make a reasonable choice of the controller type. This is done on the basis of comparison between the different methods. In this paper a discussion regarding tuning of a commonly used PID controller as well as design procedure and tuning of nonlinear fuzzy controller is addressed.

2. PID controller design.

A proportional–integral–derivative (PID) controller is the most commonly used feedback controller in industry. It uses an "error" value ($e(t)$), which is the difference between a measured process variable and a desired setpoint ($e(t) = r(t) - y(t)$) in order to calculate the control signal. The design of the controller is generic and there are only three parameters K_p, T_i and T_d (proportional gain, integral time and derivative time correspondingly) which must be tuned in accordance to the particular controlled system. The control signal ($u(t)$) is computed from the equation

$$u(t) = K_p\left(e(t) + \frac{1}{T_i}\int_0^t e(\tau)d\tau + T_d\frac{de(t)}{dt}\right) \qquad (1)$$

One way of tuning those parameters is according to the Ziegler-Nichols rule [1]. It is performed by setting the T_i and T_d gains to zero. The K_p gain is then increased (from zero) until it reaches the ultimate gain Ku, at which the output of the control loop oscillates with a constant amplitude Ku and oscillation period Tu. These parameters are used to set the P, I, and D gains (Table 1) depending on the type of controller used.

Table 1. The font size and appearance for the styles.

controller	K_p	T_i	T_d
P	$Ku/2$		
PI	$Ku/2.2$	$Tu/1.7$	
PID	$Ku/1.7$	$Tu/2$	$Tu/8$

In case of abrupt changes in the reference signal the controller will perform better if the derivative part do not depend on the error, but depends on the change in the output of the system. Such a scheme is used in this paper for simulation purposes and is presented on Fig.1

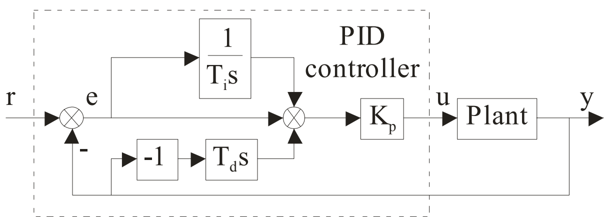

Fig. 1 Modified PID controller.

The obtained results should be regarded as initial tuning of the controller. If the result is not satisfactory the parameters can be further tuned. This is done by applying rules of thumb. Some of them are summarised in Table 2.

Table 2. Rules of thumb for hand tuning of a PID controller.

Action	Rise time	Overshoot	Stability
Increase K_p	Faster	increases	get worse
Increase K_D	Slower	decreases	improve
Increase $1/T_I$	Faster	increases	get worse

3. Aero-dynamical System.

The two rotor aero-dynamical system (Fig.2) is a laboratory set-up designed for control experiments [2]. In certain aspects its behaviour resembles that of a helicopter. The used laboratory set-up is manufactured by Inteco®.

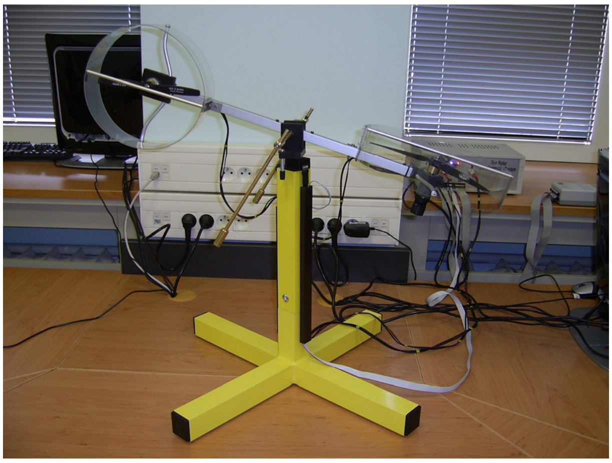

Fig. 2 Aero-dynamical system

The laboratory set-up consists of a beam pivoted on its base in such a way that it can be rotated freely both in the horizontal and vertical planes. At both ends of the beam there are DC motors connected with propellers, which pivot the beam in the horizontal and vertical plane correspondingly (simulating main and tail rotors). A counterbalance arm with a weight at its end is attached to the beam at the pivot point. It provides shift in the centre of gravity.

From the control point of view the laboratory setup exemplifies a relatively high order (sixth order) non-linear system with significant cross-coupling. There are four measurable variables. Two of them are the outputs of the system. They are horizontal and vertical angles measured by position sensors (incremental encoders) fitted at the pivot. For control purposes are also used their angular velocities. The other two are the angular velocities of the rotors, measured by tacho-generators coupled with the driving DC motors. These variables are additional and are not used by the proposed controllers.

In the real life helicopters, the control of the aero-dynamic forces are controlled with the change of the angle of attack of the blades, while in the laboratory set-up the speed of the blades is changed. That's why as a control signal the voltage applied to the DC motors is used. The voltage is controlled with pulse width modulator (PWM). By varying the coefficient of the PWM the effective voltage is changed according to the formula $u(t) = v(t)/\mathrm{v}_{\max}$. The maximum voltage is $\mathrm{v}_{\max} = 24\ \mathrm{V}$ and the control is in the range $[-1 \quad 1]$ (the sign of the PWM coefficient determines the rotational direction). The control of the speed of the corresponding propeller has an effect on the position of the beam.

4. PID control for azimuth control of the aero-dynamical set-up.

The oscillations on Fig. 3 are obtained, based on linearlized model of the laboratory set-up due to limitations with physical system. This regime of the system is obtained for $T_i = T_d = 0$ and $Ku = 0.536$. From Fig. 4 it can be found that oscillation period is $Tu = 6.3$ s.

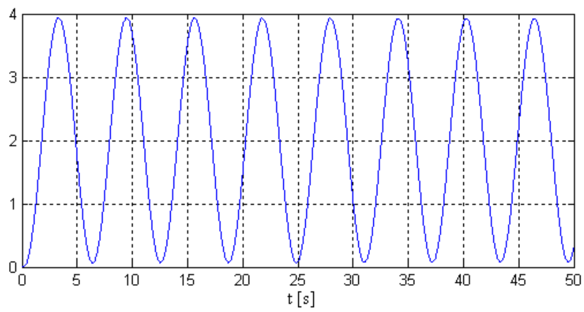

Fig. 3 Oscillatory regime of the aero-dynamical system (azimuth)

Then in accordance to the last row of Table 1, the coefficient of the PID controller can be calculated

$$K_p = Ku/1.7 = 0.3216 \quad (2)$$

$$T_i = Tu/2 = 3.15 \quad (3)$$

$$T_d = Tu/8 = 0.79 \quad (4)$$

The experiments with the set-up are carried out in Matlab/Simulink® environment, with Real Time Workshop®. The block diagram of the system is presented in Fig. 4. In the middle of the figure is shown the driver for connection to the two rotor aero-dynamical laboratory set-up. It is provided by the manufacturing company Inteco®. The modified PID controller, presented in Fig 1, is used.

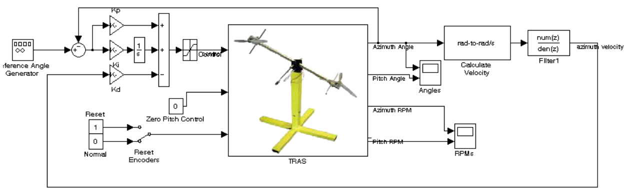

Fig. 4 Simulink block-diagram

For experimental purpose two input signal are selected. The first one is a pulse with period 50 s. and amplitude 0.5 rad. The reference signal has been chosen with relatively small amplitude (0.5 rad) in order to prevent saturations in the laboratory set-up. The second testing signal is sine wave with the same amplitude (0.5 rad) and frequency 0.02 Hz.

The response of the laboratory set-up to the first test signal is presented in Fig.5. On top of Fig.5 the measured rotation of the laboratory set-up and the reference signal are shown. On the bottom half of the figure the calculated control signal is presented (the coefficient of filling of the PWM).

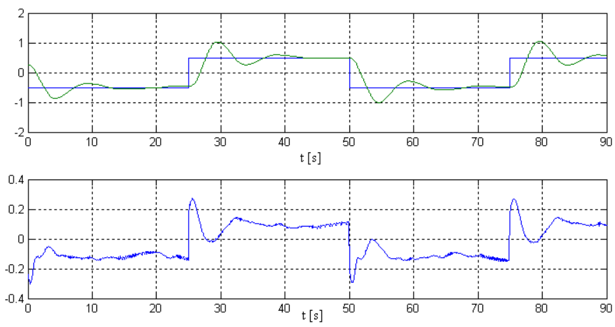

Fig. 5 Response of the laboratory set-up

The results for the second test signal are presented in Fig 6. The organization of the signals and their presentation in the subfigures are the same signals as in Fig. 5.

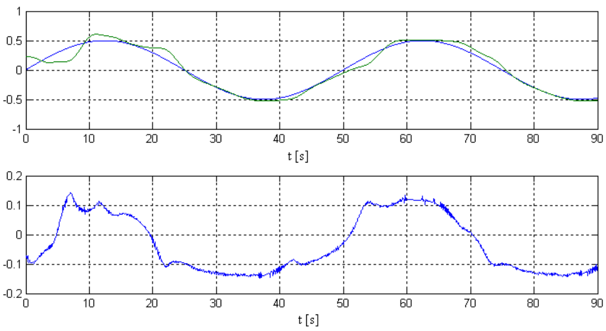

Fig. 6 Response of the laboratory set-up

Especially from the Fig. 6 it can be seen that the laboratory set-up is nonlinear. Around the zero the dead zone effect can be observed. This is due to the fact that the set-up is insensitive to small control signals, i.e. due to the friction, slow rotation of the blades do not result in a movement of the horizontal beam of the set-up. The same experiments are performed with the linear model of the set-up. For the linear model there is no such effect.

5. Linear fuzzy controllers

Since fuzzy controllers are nonlinear, it is more difficult to set the controller gains compared to PID controllers. One possible way for tuning of the fuzzy controller is to use already tuned PID controller and to design linear fuzzy controller. This is done by replacing the summation in PID control by a linear fuzzy controller acting like a summation. The closed loop system should thus show exactly the same step response [3]. Then the fuzzy controller is made nonlinear. This improves the performance in certain control regions.

6. Fuzzy proportional-derivative + integral (FPD+I) controller

The simplest fuzzy controller is Fuzzy Proportional (FP) controller. This controller is often very simple, i.e. with not satisfactory performance. In Practice it is common to use Fuzzy PD (FPD) controller. This controller improves stability of the close loop system. If the system has steady stay error Fuzzy PI (FPI) controller is needed. This controller is often designed as a FPD controller and the output of the controller is then integrated. In order to overcome the problem with wind up an incremental control (FInc) can be used. This controller computes the change of the control signal. Fuzzy PID controller is complicated, with large numbers of rules and the control action can not be visualized. One way to use the potential of the PID control action is to use FPD controller and to add separate (non-fuzzy) integral action (Fig. 7). The weight coefficients of the linear fuzzy controller can be obtained form classical ones. The relationship between their coefficients is presented in Table 3.

Table 3. Relationship between classical and fuzzy controllers.

controller	K_p	$1/T_i$	T_d
FP	$K_{FP}K_{FU}$	-	-
FInc	$K_{FD}K_{FU}$	K_{FP}/K_{FD}	-
FPD	$K_{FP}K_{FU}$	-	K_{FD}/K_{FP}
FPD+I	$K_{FP}K_{FU}$	K_{FI}/K_{FP}	K_{FD}/K_{FP}

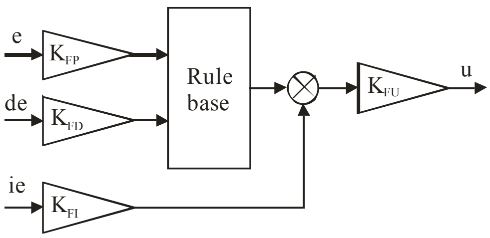

Fig. 7 Fuzzy proportional-derivative + integral controller

The proposed fuzzy part (FPD) of the FPD+I controller has two inputs and one output (linguistic variable). It consists of twenty five rules. The rules are designed on the base of max-min (Mamdani) inference [4]. The defuzzyfication is done by the centre of gravity method. It is proposed that both input and outputs variables have five linguistic terms. During the transition from linear to nonlinear fuzzy controller the tuning around the area with large nonlinearities (around the zero) is carried out. In this way the negative effect from the nonlinearities of the laboratory set-up are eliminated. On Fig. 8 and 9, the proposed membership functions for the input linguistic variables error and derivative of the output signal are presented correspondingly. On Fig. 10, the proposed linguistic terms for the output variable (control) are presented.

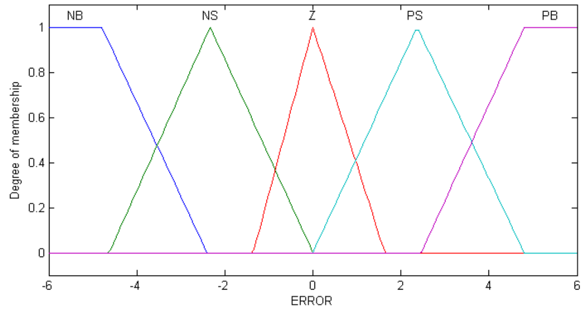

Fig. 8 Linguistic terms for input linguistic variable error.

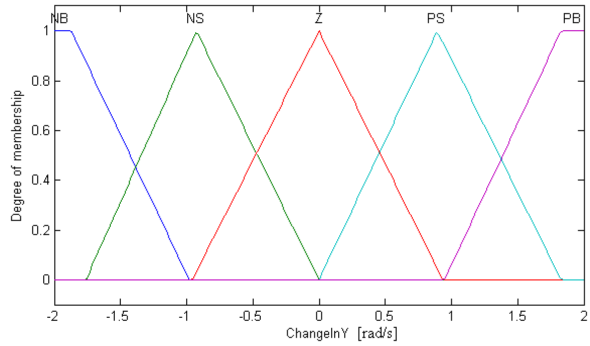

Fig. 9 Linguistic terms for input linguistic variable change of the error.

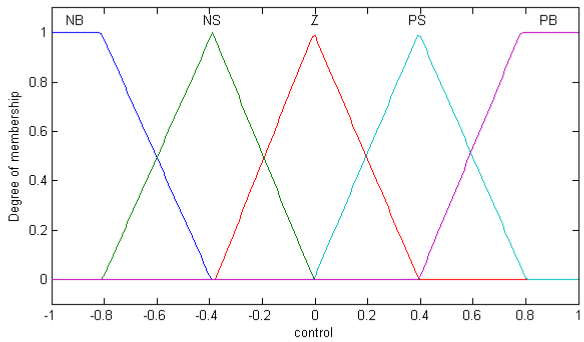

Fig. 10 Linguistic terms for output linguistic variable control.

The rule basis for the proposed PD controller is presented in Table 4. This controller can be seen as a diagonal controller. As stated in [5], the number of the rules can be reduced. This is not done in this paper, because the proposed controller will be used for illustrative purposes in laboratory exercises with students.

Table 4. Rule base for the FPD controller.

		ChangeInY				
		NB	NS	Z	PS	PB
ERROR	NB	1.NB	6.NB	11.NS	16.NS	21.Z
	NS	2.NB	7.NS	12.NS	17.Z	22.PS
	Z	3.NS	8.NS	13.Z	18.PS	23.PS
	PS	4.NS	9.Z	14.PS	19.PS	24.PB
	PB	5.Z	10.PS	15.PS	20.PB	25.PB

The rules correspond directly to the intuitive idea for control. For example, rule 13 states that if the beam is in the desired position and is not moving then it is not necessary to apply any control to the propellers. At the other positions on the secondary diagonal, the deviation and the angular velocity are with opposite signs (rules 5, 9, 17 and 21), the beam is not in the desired location but it is moving towards it and thus again it is not necessary to apply any control (Zero). When we have positive deviation and the beam is not moving (rules 14 and 15) the control action should be positive small (PS). The same control is applied in case of zero deviation, but with positive change of the output signal. Otherwise the beam will overshoot the set-point (rule 13). When both deviation and the angular velocity are positive, not only the beam is off the desired position, but it also deviates from it and the deviation increases in time. In such case it is necessary to apply a larger control action, which will drive the beam of the setup towards the desired location (rules 19, 20, 23, 24 and 25). The top part of the Table 4 is filled in a similar way, but there the necessary movement is to the opposite direction. The proposed FPD controller has a control surface as shown in Fig. 11.

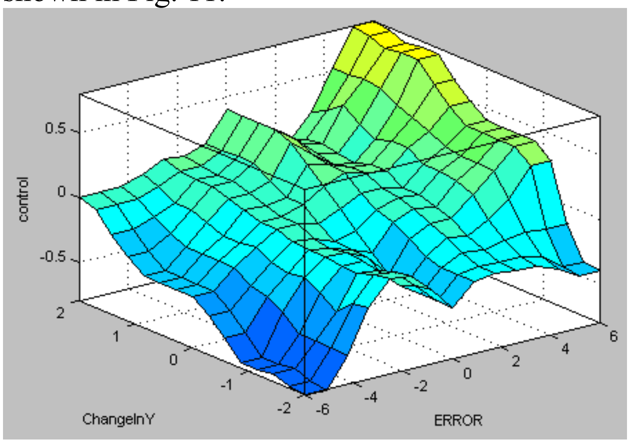

Fig. 11 Control surface of the FPD.

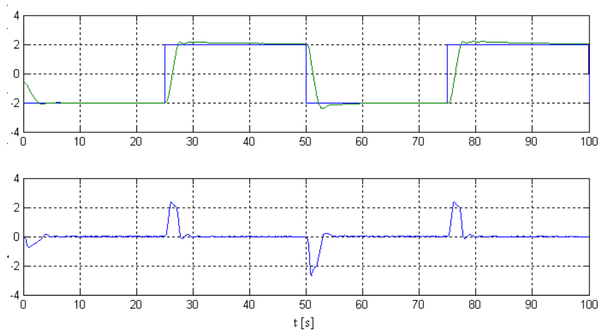

Fig.12 Response of the laboratory set-up

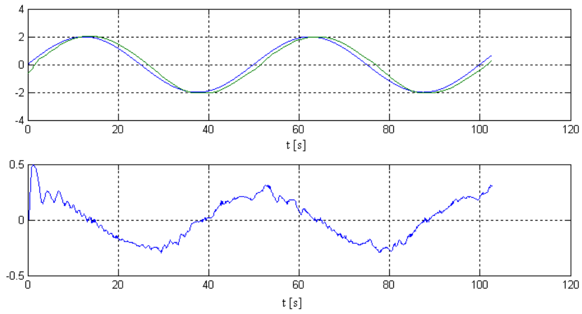

Fig.13 Response of the laboratory set-up

From the response of the FPD+I controller shown in Fig. 12 it can be seen that the overshoot and the settling time are significantly reduced in comparison with the classical PID controller (Fig. 5). From Fig. 13 it is also evident that the effect of the nonlinearities is also removed.

7. Conclusion

In this paper the design and tuning of the classical PID controller as well as fuzzy equivalent is presented. The Fuzzy PD+I controller is also tuned. The control is applied for azimuth angle tracking of an aero-dynamical system (laboratory set-up). The problems caused by the nonlinearities of the set-up are eliminated by the tuned fuzzy controller.

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