FUZZY CONTROL FOR PITCH CONTROL OF AN AERO-DYNAMICAL SYSTEM. DESIGN AND TUNING

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Abstract: In this paper fuzzy controller for pitch control of an aero-dynamical system is discussed. For initial tuning classical PID control obtained in accordance to the Ziegler-Nichols method is used. On its base the coefficients of a linear fuzzy controller obtained. In the last step the fuzzy controller is made nonlinear and it is fine tuned for the aero-dynamical system. The experiments are carried out with a laboratory set-up. The set-up represents real life system with nonlinearities.

Key words: PID controller, Fuzzy controller, Tuning, Aero-dynamical system, Pitch 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 commonly used proportional–integral–derivative (PID) controller as well as design procedure and tuning of nonlinear fuzzy controller is addressed.

2. Aero-dynamical System.

The two rotor aero-dynamical system (Fig.1) is a laboratory set-up designed for control experiments [1]. In certain aspects its behaviour resembles that of a helicopter. The used laboratory set-up is manufactured by Inteco®.

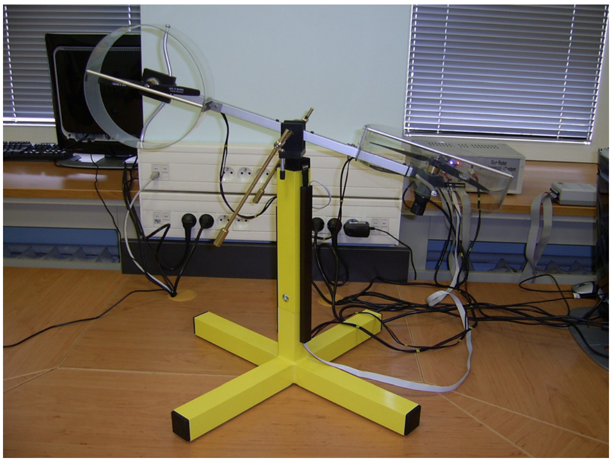

Fig. 1 Aero-dynamical system

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.

3. PID controller design.

A PID controller is the most commonly used feedback controller in industry. The control is computed by the formula

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

where $e(t)$ is the error of the system ($e(t) = r(t) - y(t)$ cf. Fig.2).

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). One way of tuning those parameters is according to the Ziegler-Nichols rule [2]. The coefficient of the PID controller are given in Table 1, where Ku is the ultimate gain the oscillations are with period Tu.

Table 1. Computation of the K_p, T_i and T_d parameters.

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.2.

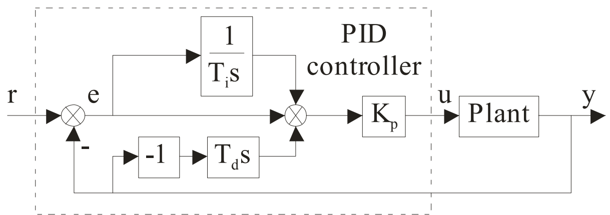

Fig. 2 Modified PID controller.

For the laboratory set-up the obtained ultimate gain is $Ku = 0.823$ and the oscillation period is $Tu = 4$ s. Then the coefficients for the PID controller (according to Table 1) are $K_p = Ku/1.7 = 0.4992$, $T_i = Tu/2 = 2$ and $T_d = Tu/8 = 0.5$.

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. 3. 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 2, is used.

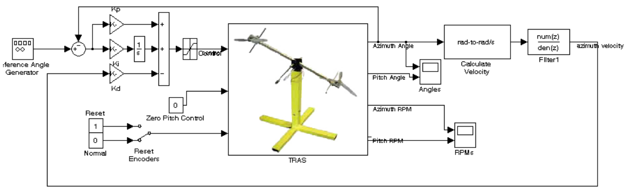

Fig. 3 Simulink block-diagram

For experimental purpose the input signal has been chosen. It is a pulse with period 50 s. and amplitude 0.25 rad. The reference signal has been chosen with relatively small amplitude (0.25 rad) in order to prevent saturations in the laboratory set-up.

The response of the laboratory set-up is presented in Fig.4. On top of Fig.4 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).

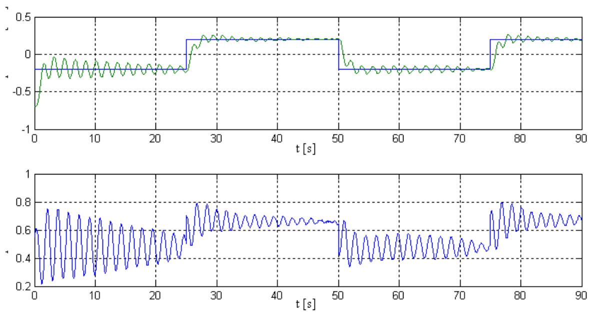

Fig. 4 Response of the laboratory set-up

The same experiments are carried out with the linear model of the system. For the liner system the classical PID controller is showing satisfactory performance. However from Fig. 4 it can be noticed that the response with the laboratory set-up is oscillatory. This is caused by the nonlinearities of the set-up. This shows that classical PID control has some limitations and in the case of nonlinear systems it is better to be used nonlinear controller.

4. 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 existing 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 can be made nonlinear. This can improve performance in certain control regions.

5. Types of fuzzy controllers

The simplest fuzzy controller is ***Fuzzy Proportional (FP)*** controller (cf. Fig 5). The input to this controller is the error and the output is the control signal. The difference with the standard P controller is that it has two gains instead of just one.

Fuzzy proportional-derivative controller (FPD) (cf. Fig 5). This controller has two inputs – the error and the derivative of the error.

Derivative action helps to predict the error and the proportional-derivative controller uses the derivative action to improve closed-loop stability. There is optimal value of the derivative gain. If the derivative part is increased (starting form zero – pure proportional controller) the oscillations will be dampen, however if the gain is too big the system becomes overdamped and it will start to oscillate again.

Fuzzy incremental controller (FInc). If there is a sustained error in steady state, integral action is necessary. A controller with integral action will always return to zero in steady state. It is possible to obtain a fuzzy PI controller using error and change in error as inputs to the rule base. Experience shows, however, that it is rather difficult to write rules for the integral action. It is common solution to design FInc controller in almost the same configuration as the FPD controller except for the integrator on the output. Problems with wind up also have to be dealt with. It is often a better solution to configure the controller as an incremental controller. An incremental controller adds Δu to the current control signal u. A disadvantage is that it cannot include D-action well.

The weight coefficients of the linear fuzzy controller can be obtained form classical ones. The relationship between their coefficients is presented in Table 2.

Table 2. 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}

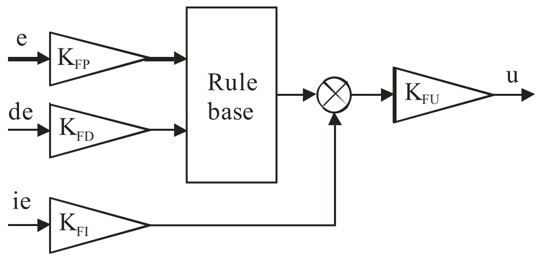

Fig. 5 Fuzzy proportional-derivative + integral controller

Fuzzy proportional, integral and derivative controller (FPID). It is straight forward to envision a PID controller with three input terms: error, integral error, and derivative error. A rule base with three inputs, however, easily becomes rather big and, as mentioned earlier, rules concerning the integral action are troublesome. Therefore it is common to separate the integral action as in the ***Fuzzy PD+I***, (FPD+I) controller in Fig. 5.

6. Tuning of the Fuzzy controllers

The obtained results form Table 2 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 3. By varying the corresponding intervals of the linguistic variables it is also possible to achieve compensation of the nonlinearities in the system.

Table 3. Rules of thumb for hand tuning of a PID controller.

Action	Rise time	Overshoot	Stability
Increase K_{FP}	Faster	increases	get worse
Increase K_{FD}	Slower	decreases	improve
Increase K_{FI}	Faster	increases	get worse

7. Proposed Fuzzy FPD+I controller

The proposed 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 [5]. The defuzzyfication is done by the centre of gravity method. It is proposed that both input and output variables have five linguistic terms. In Fig. 6 and Fig. 7, the proposed membership functions for the input linguistic variables error and derivative of the output signal are presented correspondingly. On Fig. 8, the proposed linguistic terms for the output variable (control) are presented.

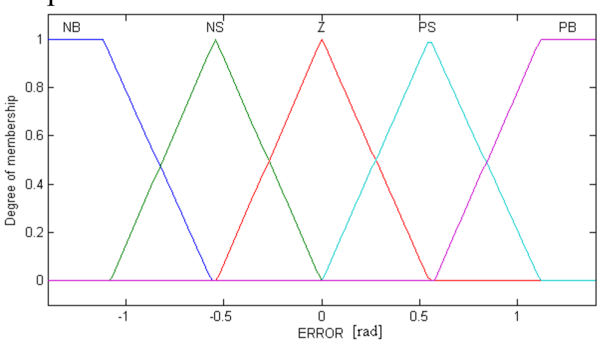

Fig. 6 Linguistic terms for input linguistic variable error.

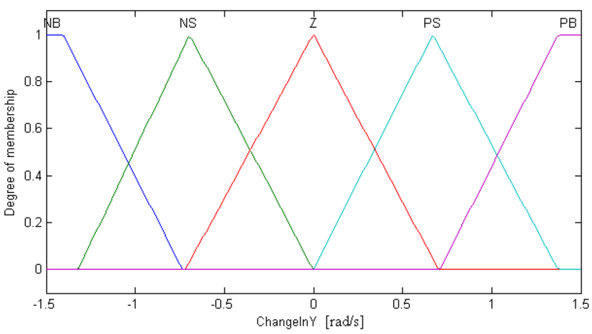

Fig. 7 Linguistic terms for input linguistic variable change of the error.

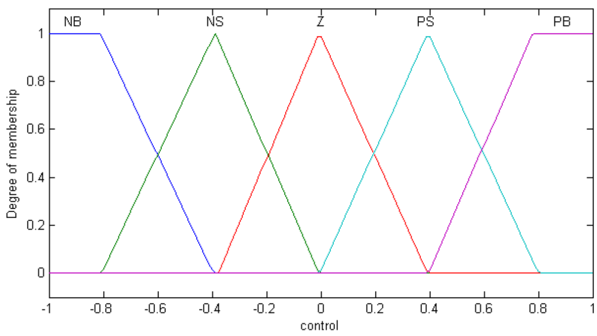

Fig. 8 Linguistic terms for output linguistic variable control.

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.

ERROR \ ChangeInY	NB	NS	Z	PS	PB
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. 9.

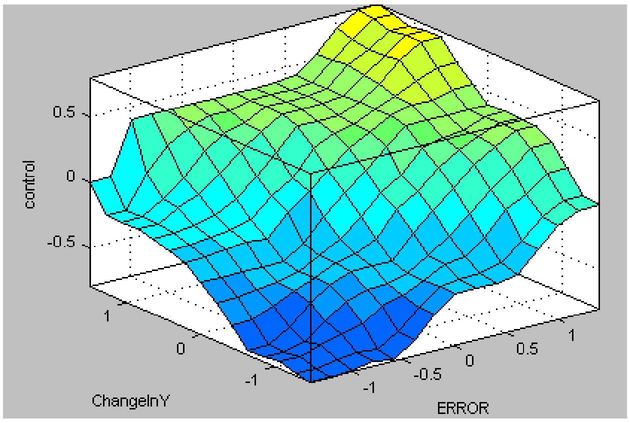

Fig. 9 Control surface of the FPD+I.

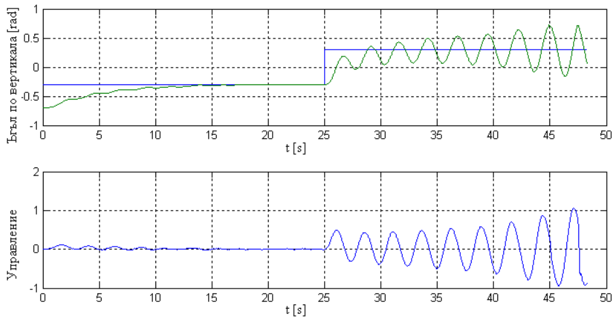

Fig.10 Response of the laboratory set-up

From the response of the FPD+I controller shown in Fig. 10 it can be concluded that the system is unstable. Again it can be checked that response to the linear system is satisfactory. This means that the parameters of the FPD+I controller should be tuned.

The controller is tuned with the rules of thumb form Tab3. In order to decrease the area where the control action is zero the linguistic variable zero is modified as well. Also two additional rules are introduced.

26. If (ERROR is NS) then (control is not NS)
27. If (ERROR is PS) then (control is not PS)

The obtained control surface is presented in Fig. 11 and the response of the system on Fig.12. It can be seen that the response with the tuned FPD+I controller is satisfactory. It eliminated the oscillations, observed with the classical PID controller. Also the overshoot is eliminated.

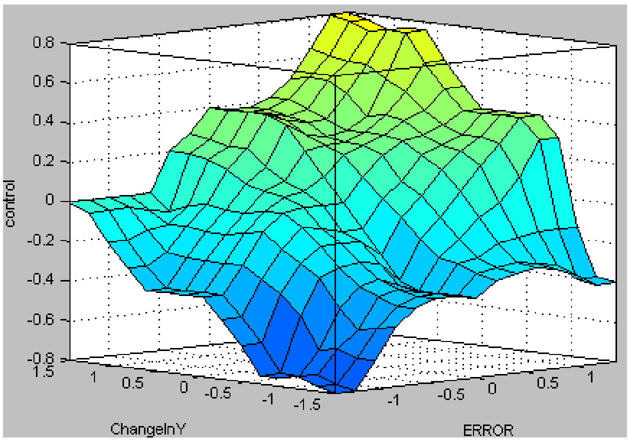

Fig. 11 Control surface of the tuned FPD+I.

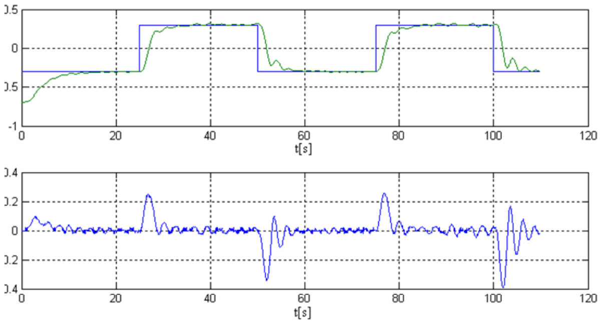

Fig.12 Response of the laboratory set-up

8. Conclusion

In this paper on the base of a classical PID controller, a fuzzy equivalent is obtained. The Fuzzy PD+I controller is also tuned to improve its performance and to work with nonlinearities of the laboratory set-up: aero-dynamical system.

Acknowledgement

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