Fuzzy self-tuning PID controller for hypersonic wind tunnel pressure regulation

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Abstract: This article refers to the design of a new controller to regulate the pressure in the setting chamber of a hypersonic wind tunnel. By inheriting, then developing the mathematical model of the hypersonic wind tunnel pressure process, firstly the paper presents the design of the traditional PID by the Skogestad method. And then, a new fuzzy self-tuning PID controller by combining traditional PID and fuzzy logic calculation block is presented in this article. These blocks are responsible for online tuning of the traditional PID parameters. Simulation results on Matlab, indicate that the proposed new fuzzy self-tuning PID controller improves the quality of the hypersonic wind tunnel pressure control system with small overshoot, fast response time, small-steady-state-error.

Keywords: Wind tunnel, flying vehicle, PID, fuzzy logic, pressure regulation, adaptive control, Matlab.

1. INTRODUCTION

Nowadays, flying vehicles are increasingly popular in the transportation, especially in freight and passenger transport. Along with the development of science and technology, flying vehicles are constantly being studied to improve and modernize: from shape, application of new materials, to developing modern control algorithms. It is therefore necessary to have a test facility to assess the aerodynamic characteristics of the aircraft under different flight conditions. The flying vehicles test facility creates stream flow in tunnel with controlled pressure and velocity, corresponding to the actual space pressure conditions of the flying vehicle, and called wind tunnel. Wind tunnels are categorised as subsonic, supersonic and hypersonic, depending on the mach number.

In this paper, the author concentrate on studying hypersonic wind tunnel. Hypersonic wind tunnel is used in aerodynamic research, simulating flight environments, studying the effect of air stream through solid objects at times much greater than the speed of sound, for example Mach 5. Hypersonic wind tunnel helps to define performance and eliminate technical errors on a new design of flying vehicle to minimize the risk of pilot and lower the cost of flying vehicle. From experiments on flight conditions, new materials, new shapes of large wings, small wings, tail, torso, legs, energy system and engine structure will be completed to manufacture a flying vehicle.

In the world, countries with developed aerospace industries such as the US, Russia, France, England, Germany and Japan have built science and technology centers with many hypersonic wind tunnels with great speed, can reach Mach 30 (30 times the speed of sound) to study and test flying objects such as spacecraft, missiles, airplanes, warheads or extremely velocity movements but it is not possible to carry out experiments by practical means, all need to simulate in the test environment of the supersonic wind tunnel. Some hypersonic wind tunnels like as LENS-X, be owned by Calspan University at Buffalo Research Center, NASA-USA used to test space launchers, missiles, airplanes; Hypersonic wind tunnel in Ames National Full Scale Aerodynamic Complex, NASA-USA used to check and simulate space shuttle and space vehicles; Hypersonic wind tunnel AT-303 in Central Aerohydrodynamic Institute, Moscow, Russia with great velocity from Mach 8 to March 20, to simulate jets in clean air conditions, perform aerodynamic tests with different mixing gases; The Japan Aerospace Exploration Agenc owns the hypersonic wind tunnel with velocity from Mach 5 to Mach10, used to simulate special environments with airflow, studying aerodynamic properties and the phenomenon of air flow around aircraft or spaceship.

The researches in the world in hypersonic wind tunnel is varied. The paper [1] presents the hypersonic facility used for aerothermo dynamic investigations of entry flows in terms of Mach and Reynolds numbers, using carbon dioxide as the test gas. The paper [2] deals principally with the wind tunnels built at ONERA during the last century and concerns for energy saving, encourages manufacturers of ground vehicles to perform aerodynamic tests. The article [3] presents the design of static pressure probes to significantly improve the accuracy on the free-stream quantities and benefits to the characterization of hypersonic wind-tunnel flow fields. These researches [1,2,3] focus on improving the structure and technology of hypersonic wind tunnel and received certain results. Another researches are presented in [4-9]. In this direction, control algorithms have been developed for the wind tunnel hypersonic pressure process to control stably the pressure in hypersonic wind tunnel, according to the setpoint, such as simple PI controller [5], adaptive fuzzy PI controller [6,7], fuzzy assisted PI controller [8], backstepping controller [9], hybrid fuzzy-PID controller [5]. These controllers have basically been effective for the hypersonic

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wind tunnel pressure regulation. However, these controllers apply to a simple wind tunnel hypersonic model, not considering the disturbance.

The paper presents a new controller for regulating the pressure of a hypersonic wind tunnel, based on fuzzy logic, called the fuzzy self-tuning PID controller. The fuzzy self-tuning PID controller combines the advantages of traditional PID (simple, reliable, stable) and the advantages of fuzzy logic (no need for sufficient information about the object, good adaptation when the object-parameter changes). On the basis of inheriting and developing the mathematic model of hypersonic wind tunnel pressure process, the paper firstly presents the design of the PID controller according to Skogestad's method. given in part 3. And then, the paper focuses on designing the fuzzy self-tuning PID controller for hypersonic wind tunnel pressure regulation, shown clearly in part 4. Building simulation model of hypersonic wind tunnel pressure control system using the proposed-controllers on Mallab is conducted in part 5. Finally, the conclusions are presented in part 6.

2. MODEL OF HYPERSONIC WIND TUNNEL SYSTEM

Schematic of hypersonic wind tunnel facility is presented as Fig.1, including three main components: HP - high pressure system, VAC - vacuum system, and wind tunnel system. The main equipment blocks are: PRV – pressure regulating valve, H1 – air heater system, SC – settling chamber, N – nozzle, TS – test section, D – diffuser), and AF – Aftercooler [10,12].

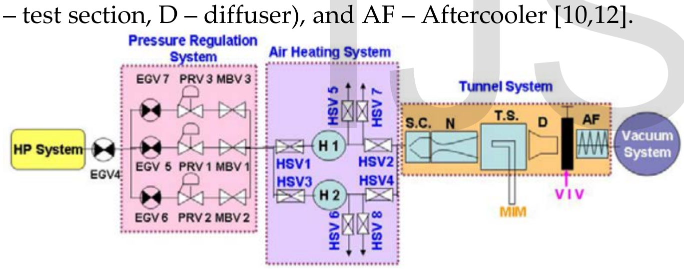

Fig.1. Schematic of hypersonic wind tunnel facility

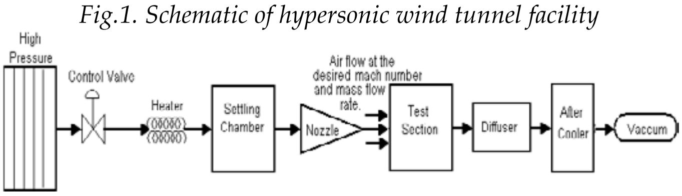

Fig.2. Block diagram of hypersonic wind tunnel

This paper focuses on designing the parameters self-tuning PID based on fuzzy logic to stabilize pressure in the settling chamber of hypersonic wind tunner. Thus the output technology parameter here is the air pressure in the settling chamber P_3, while the input control signal changes the wind tunnel pressure as the valve opening, m. This compressed air pressure comes out of HP compressed air tank (with parameters P_1, V_1, T_1) via control valve (PRV), through H1 air dryer (parameters are P_2, V_2, T_2) and to the settling chamber (SC) with the parameters P_3, V_3, T_3.

Thus, we can consider the process of compressed air pressure in the settling chamber of a hypersonic wind tunnel consisting of three consecutive pressure vessels as shown in Fig.3.

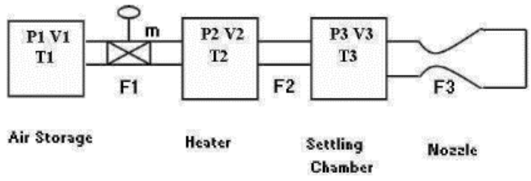

Fig.3. Block diagram of hypersonic wind tunnel pressure

The physical parameters of the actual large scale hypersonic wind tunnel system for Mach 6 operation, as below [7,10]:

+ Total volume of the compresed air storage tank: 132m^3
+ Control valve: 12 inch throttle valve
+ Volume of heater: 18.24m^3
+ Volume of settling chamber and pipelines: 2.7m^3
+ Cross section of nozzle: 0.0130394 m^2

For nominal test condition: $P_1 = 300bar$, $T_1 = 300^oK$, $P_3 = 70bar$, $T_2 = 700^oK$, $T_3 = 300^oK$

To build a mathematical model for the pressure process in the settling chamber of a hypersonic wind tunnel, we assume that compressed air acts as the ideal gas and its mass in the tank at time t is:

$$m_1(t) = \frac{V_1 P_1(t)}{RT_1(t)} \quad (1)$$

where $m_1(t)$ is the mass of air contained in the compressed air storage tank, V_1 is volume of the storage tank. R is the gas constant for air, $P_1(t)$ and $T_1(t)$ are pressure, temperature in compressed air storage tank, n is polytropic index.

The pressure of the remaining air in the storage tank is given as below:

$$P_1(t+1) = P_1(t)\left(\frac{m_1(t+1)}{m_1(t)}\right)^n \quad (2)$$

The continuous equations [10,13,15] for three pressure vessels may be written as follow:

$$C_1\frac{dP_1}{dt} = -F_1 \quad (3)$$

$$C_2\frac{dP_2}{dt} = F_1 - F_2 \quad (4)$$

$$C_3\frac{dP_3}{dt} = F_2 - F_3 \quad (5)$$

Where:

$$C_1 = \frac{V_1}{nRT_1}, C_2 = \frac{V_2}{nRT_2}, C_3 = \frac{V_3}{nRT_3}$$

Flow rate of compressible fluid [10,13] F_1 is given by

$$F_1 = mC_v N_8 P_1 Y\sqrt{\frac{XM}{T_1 Z}} \quad (6)$$

Where m is the stem movement, Cv is the valve coefficient, N_8 is the constant for engineering units, Fp is the constant for pipeline geometry, M is molecular weight of air, Z is the compressibility factor, Expansion factor $Y=1-(X/(3.F_k.XT))$ where XT is critical pressure drop ratio factor and F_k is the ratio of specific heats factor, and $X=(P_1-P_2)/P_1$ where P_2 is the downstream pressure of PRV. These physical parameters of valves [7,10]: $C_v=0.1305$; $N8=0.000948$; $F_p=1$; $XT=0.562$; $M=29$; $Z=1.077$; $F_k=1.4$;

The outflow from heater F_2 is given as [7,10]:

$$F_2 = k(P_2 - P_3) \qquad (7)$$

The mass flow rate through nozzle [7,10], F_3 is given as

$$F_3 = \frac{k_5 P_3}{\sqrt{T_3}} \qquad (8)$$

Where k_5 is the nozzle constant and P_3 is the settling chamber pressure and T_3 is the settling chamber temperature.

From equations (1) to (8), we obtain the following linear differential equations as below:

$$\frac{dP_1}{dt} = \frac{k_1 P_1}{C_1} + \frac{k_2 m}{C_1} \qquad (9)$$

$$\frac{dP_2}{dt} = \frac{k_1 P_1}{C_2} + \frac{k_2 m}{C_2} - \frac{k_3 P_2}{C_2} - \frac{k_4 P_3}{C_2} \qquad (10)$$

$$\frac{dP_3}{dt} = \frac{k_3 P_2}{C_3} + \frac{(k_4 - k_5) P_3}{C_3} \qquad (11)$$

where:

$$k_1 = \left.\frac{\partial F_1}{\partial P_1}\right|_m, k_2 = \left.\frac{\partial F_1}{\partial m}\right|_{P_1}, k_3 = \left.\frac{\partial F_2}{\partial P_2}\right|_{P_3}, k_4 = \left.\frac{\partial F_2}{\partial P_3}\right|_{P_2}$$

Perform Laplace transformation of the (9), (10), (11) equations and note that these vessels are in series, so we get the transfer function of the pressure process in settling chamber as:

$$G(s) = \frac{P_3(s)}{m(s)} = G_1(s)G_2(s)G_3(s) = \frac{P_1(s)}{m(s)}.\frac{P_2(s)}{P_1(s)}.\frac{P_3(s)}{P_2(s)}$$

$$G(s) = \frac{K_3}{C_1 s - K_1}.\frac{C_1C_3 s^2 - (C_1K_4 - C_1K_5)s}{C_2C_3 s^2 - (C_2K_4 - C_2K_5 - C_3K_3)s + K_3K_5}.\frac{K_3}{C_3 s - K_4 + K_5} \qquad (12)$$

Transfer function of the pressure process in the settling chamber as below [7]:

$$G(s) = \frac{P_3(s)}{m(s)} = \frac{7{,}898.10^7 s + 4{,}21.10^5}{s^3 + 16{,}68s^2 + 3{,}367s + 0{,}01937} \qquad (13)$$

3. DESIGN OF PID CONTROLLER

Transfer function of the pressure process can be written as:

$$G(s) = 4{,}21.10^5 \frac{187{,}6s + 1}{(169{,}49s + 1)(5{,}04s + 1)(0{,}06s + 1)}$$

$$G(s) = K\frac{T_{z1}s + 1}{(\tau_{p1}s + 1)(\tau_{p2}s + 1)(\tau_{p3}s + 1)} \qquad (14)$$

where: $K = 4{,}21.10^5$; $T_{z1} = 187{,}6$; $\tau_{p1} = 169{,}49$; $\tau_{p1} = 5{,}04$; $\tau_{p1} = 0{,}06$

We see the object has a high order model. Therefore, in order to determine the PID parameters, we need to approximate the higher order model to the lower order, here we choose the second order model. Applying Skogestad's hafl-rule [15,16] with the overview transfer function (15) as:

$$G(s) = \frac{k\prod_{i=1}^{m}(\tau_{zi}s + 1)}{\prod_{j=1}^{n}(\tau_{pj}s + 1)} e^{-\theta_0 s} \qquad (15)$$

According to Skogestad [16,17], we choose to reduce the model order according to the following approximation rules (T1, T1a, T1b, T2, T3) with the corresponding conditions:

$$\frac{T_0 s + 1}{\tau_0 s + 1} \approx \begin{cases} T_0/\tau_0 & (T_0 \ge \tau_0 \ge \theta) \quad (T1) \\ T_0/\theta & (T_0 \ge \theta \ge \tau_0) \quad (T1a) \\ 1 & (\theta \ge T_0 \ge \tau_0) \quad (T1b) \\ T_0/\tau_0 & (\tau_0 \ge T_0 \ge 5\theta) \quad (T2) \\ \tilde{\tau}_0/\tau_0 & (\tilde{\tau}_0 \overset{\text{def}}{=} \min(\tau_0, 5\theta) \ge T_0) \quad (T3) \end{cases}$$

Applying to (14), we have $T_0 = 187{,}6$; $\tau_0 = 169{,}49$; $\theta_0 = 0$, notice that $T_0 \ge \tau_0 \ge \theta_0$, so we use approximation law (T1):

$$\frac{T_0 s + 1}{\tau_0 s + 1} = \frac{T_{z1}s + 1}{\tau_{p1}s + 1} = \frac{187{,}6s + 1}{169{,}49s + 1} \approx \frac{187{,}6}{169{,}49} = 1{,}1$$

Thus, the transfer function (14) approximates to:

$$G(s) = \frac{K}{(\tau_1 s + 1)(\tau_2 s + 1)} = \frac{4{,}631.10^5}{(5{,}04s + 1)(0{,}06s + 1)} \qquad (16)$$

Also according to Skogestad, the PID controller parameter for the object (16), is defined as follows [15,16]:

$$Kp = \frac{T_1}{K.T_C}; T_I = \min[T_1, k_C T_C]; T_D = T_2 \qquad (17)$$

The coefficients Tc, kc are chosen depending on the object characteristic. The small kc selection will bring faster system response. The smaller the choice of Tc, the faster the system response, but the control signal changes more strongly, the system is less stable, and exists steady-error.

Selected $T_C = 1{,}6$; $k_C = 2$, PID parameters are calculated arcording to Skogestad, as below:

- $K_p = \dfrac{T_1}{K.T_C} = \dfrac{5{,}04}{4{,}631.10^5.1{,}6} = 6{,}81.10^{-6}$
- $T_I = \min[T_1; k_C T_C] = \min[5{,}04; 2.1{,}6] = 3{,}2$

$\Rightarrow K_I = \dfrac{K_P}{T_I} = \dfrac{6{,}81.10^{-6}}{3{,}2} = 2{,}13.10^{-6}$

- $T_D = T_2 = 0{,}06$

$\Rightarrow K_D = K_P.T_D = 6{,}81.10^{-6}.0{,}06 = 3{,}66.10^{-5}$

The parameters of the PID controller are defined as

$$K_p = 6{,}81.10^{-6}; K_I = 2{,}13.10^{-6}; K_D = 3{,}66.10^{-5} \qquad (18)$$

4. DESIGN OF FUZZY SELF-TUNING PID CONTROLLER

The structure block diagram of hypersonic wind tunnel pressure control system using the fuzzy self-tuning PID controller is shown in Fig.5.

The fuzzy seft-tuning PID controller is built based on PID law with the self-tuning parametters by fuzzy calculation blocks. Each fuzzy calculation block has two-inputs: first-input is error (E) between response and setpoint (signal *e*); second-input is differential of error (EC), corresponding to the differential error signal *ec*. Each fuzzy calculation block has one-output: output of Kp-fuzzy calculation block is KP, corresponding to the output value K_{pf}; output of Ki-fuzzy calculation block is KI, corresponding to the output value K_{if}; output of Kd-fuzzy calculation block is KD, corresponding to the output value K_{df}. The values K_{pf}, K_{if}, K_{df} are calculated automatically according to the fuzzy law, based on two-input-signals *e* and *ec*.

Then, each value K_{pf}, K_{if}, K_{df} is multipled by the initial vaule K_{p0}, K_{i0}, K_{d0} thereby giving the online value of PID parameters K_p*, K_i*, K_d* as

$$K_p{*} = K_{pf}.K_{p0}; K_i{*} = K_{if}.K_{i0}; K_d{*} = K_{df}.K_{d0} \qquad (19)$$

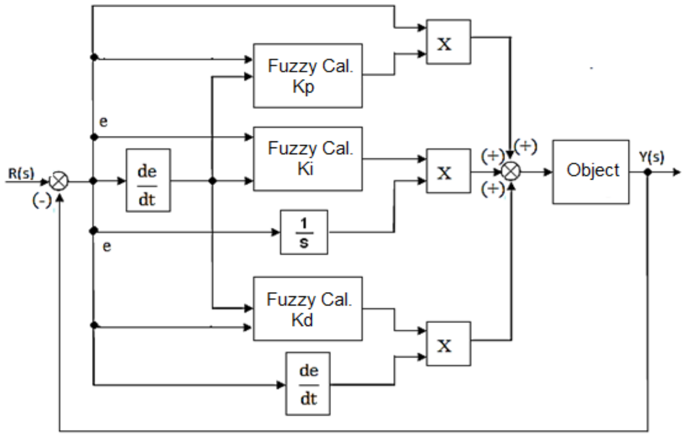

Fig.5. Structure block diagram of hypersonic wind tunnel pressure control system using the fuzzy self-tuning PID controller

Using membership functions are shaped triangular for all variables, fuzzied for all variables by 7 fuzzy sets {PB, PM, PS, Z, NS, NM, NB}. The physical domain of the input & output variables are defined as: E∈[-20;20], EC∈[-2;2], KP∈[0;40], KI∈[0;1.3], KD∈[0,20].

Table 1. Fuzzy rules of K_{pf}, K_{if}, K_{df}

K_{pf} K_{if} K_{df}		E						
		PB	**PM**	**PS**	**Z**	**NS**	**NM**	**NB**
EC	**PB**	PB	PB	PM	PS	Z	Z	Z
	PM	PB	PB	PM	PS	Z	Z	NS
	PS	PB	PM	PS	Z	Z	NS	NM
	Z	PB	PS	Z	Z	Z	NS	NB
	NS	PM	PS	Z	Z	NS	NM	NB
	NM	PS	Z	Z	NS	NM	NB	NB
	NB	Z	Z	Z	NS	NM	NB	NB

The fuzzy rules table for the fuzzy calculation blocks, coressponding to values K_{pf}, K_{if}, K_{df}, is presented in Table 1.

The use of the Max-Min composition rule and the cetroid defuzzification method, we can obtain the clear output value of each calculation block: K_{pf}, K_{if}, K_{df}. Thus, the parameters of PID controller can be calculated on-line by equation (19).

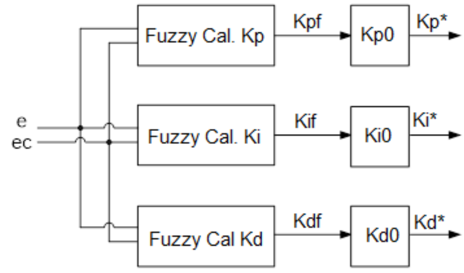

Fig.6. Structure of the fuzzy calculation blocks Kp, Ki, Kd

5. SIMULATION RESULT

In this section, the author build the simulation model of the hypersonic wind tunnel pressure process using three controllers: (a). PID controller by Skogestad, *denoted PID*; (b). Fuzzy self-tuning PID controller, *denoted uPID-Fuzzy*; (c). Adaptive fuzzy PI controller by Varghese [7], *denoted PID-Fuzzy*.

The simulation model of the hypersonic wind tunnel pressure process using PID-Fuzzy [7] presents in Fig.7. From [7], reference model is the first order object [11]:

$$M(s) = \frac{1}{0.05s + 1} \qquad (20)$$

The parameters of the PID controller is selected from (18):

$K_p = 6,81.10^{-6}$; $K_I = 2,13.10^{-6}$; $K_D = 3,66.10^{-5}$

The coefficients adjust the input and output variables of the fuzzy controller K1, K2, K3 where: $K_1 = 0,1$; $K_2 = 0,0095$; $K_3 = 2.5$

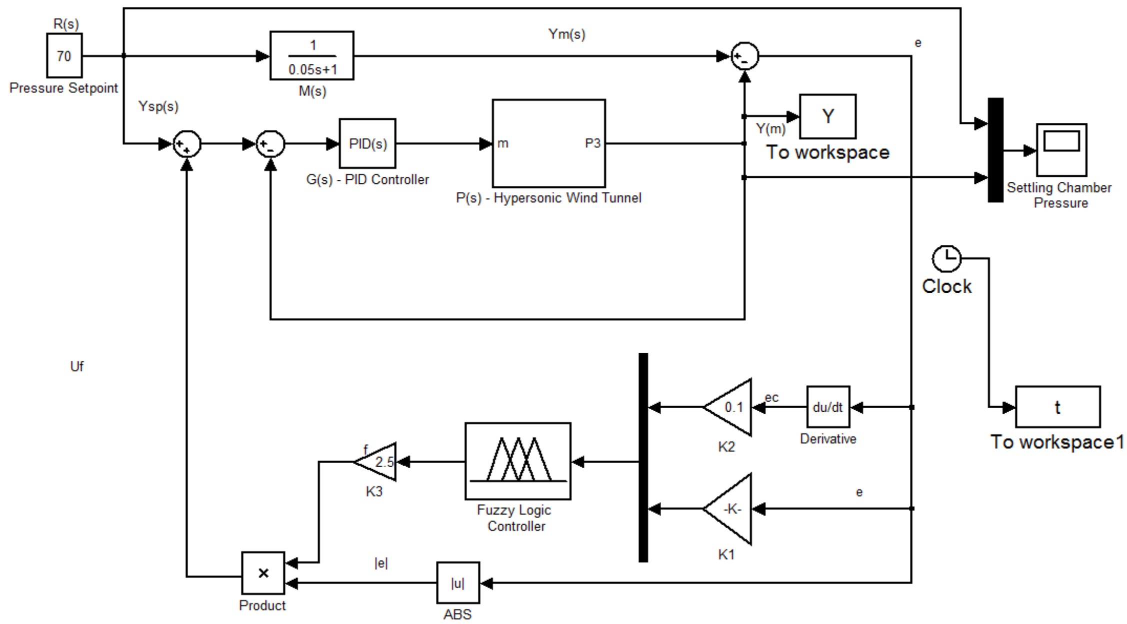

Fig. 7. *Simulation model of the hypersonic wind tunnel pressure control system using PID and PID-fuzzy controllers*

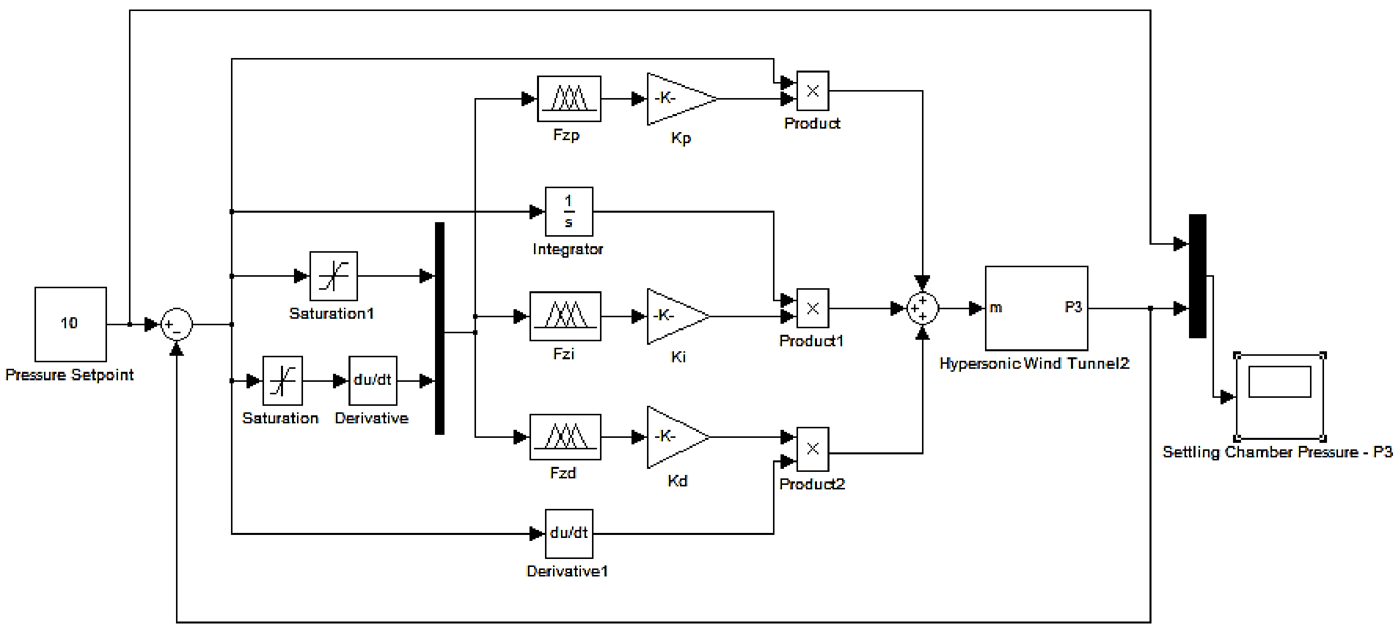

Fig.8. *Simulation model of the hypersonic wind tunnel pressure control system using the fuzzy self-tuning PID controller (uPID-fuzzy)*

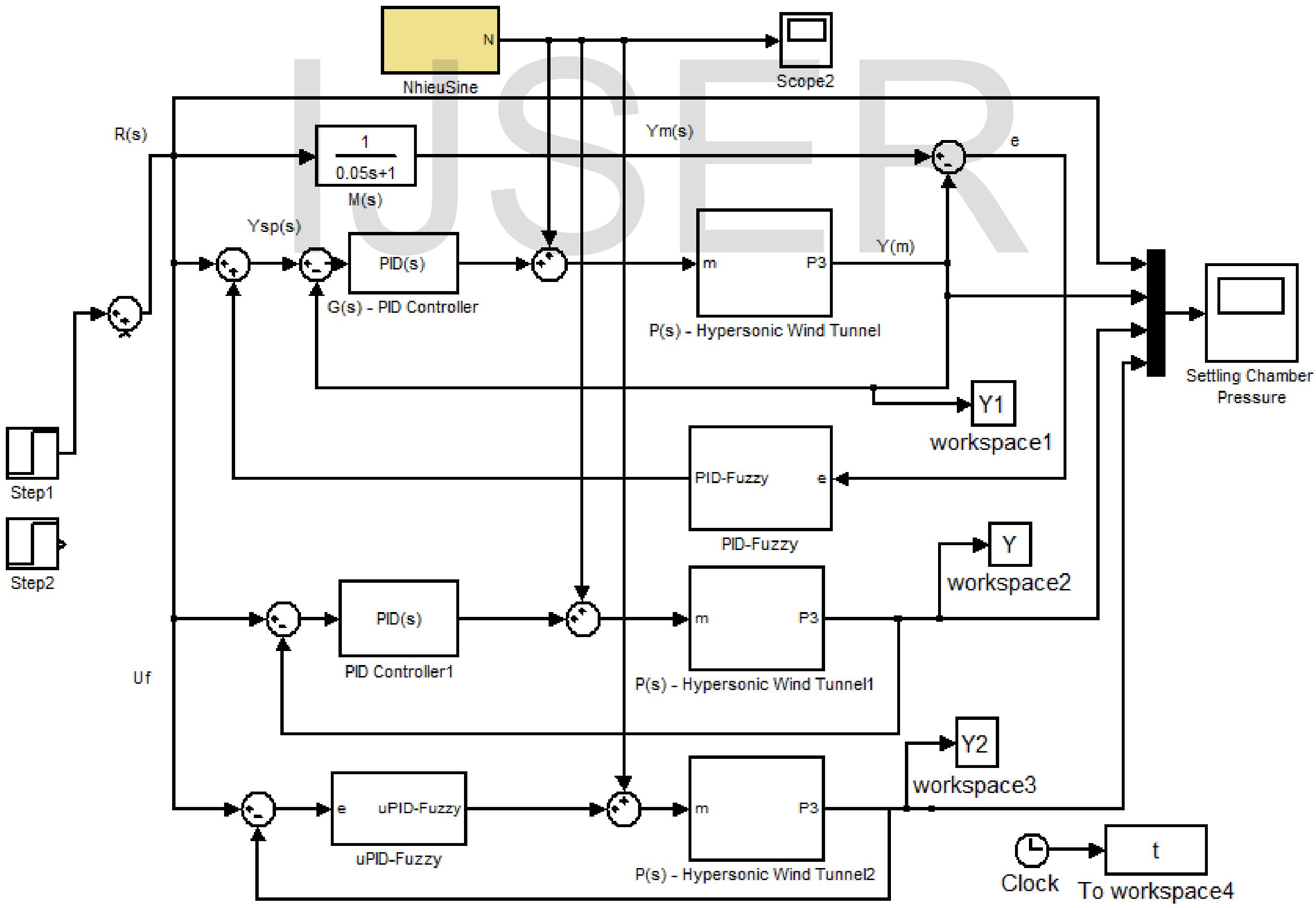

Fig.9. *Simulation model of the hypersonic wind tunnel pressure control system with 3 controllers and disturbance*

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When the setpoint signal changes according to each constant-value-level, the response of the system is shown in Fig.10.

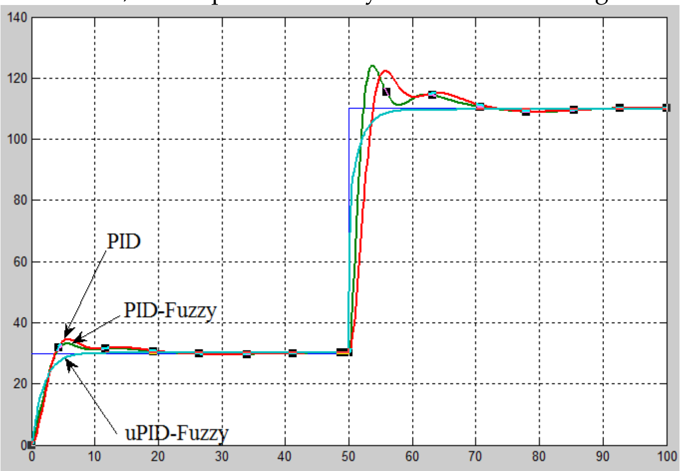

Fig.10. *Response system with the two-level-setpoint*

Table 2. Quality evaluation criteria with two-level-setpoint

Controller / Quality index	PID	PID-Fuzzy	uPID-Fuzzy
Rise time t_r (s)	2,58	2,75	3,85
Settling time t_s (s)	19,96	18,68	6,92
Overshoot, %	15,30	10,95	0,09
Steady state error	~0	~0	0

Based on the response of the system to each controller and the comparison table of the quality evaluation criteria of the system, we have some conclusions as follows:

+ PID controller combined with fuzzy logic have better control quality than traditional PID controller.

+ In the hypersonic wind tunnel pressure control system, with working-characteristic at very high pressure, large flow and time for a test from only a few seconds to a few tens of seconds should require the controller to meet the settling time and overshoot as small as possible. So based on the simulation results, we see the fuzzy self-tuning PID (uPID-Fuzzy) is the best controller with the rise time of 3.85 seconds, the settling time is 6.92 seconds and the overshoot is 0.09%.

When the control object is affected by the sine-disturbance, seeing Fig.11, we obtain the output response of the system as shown in Fig.12.

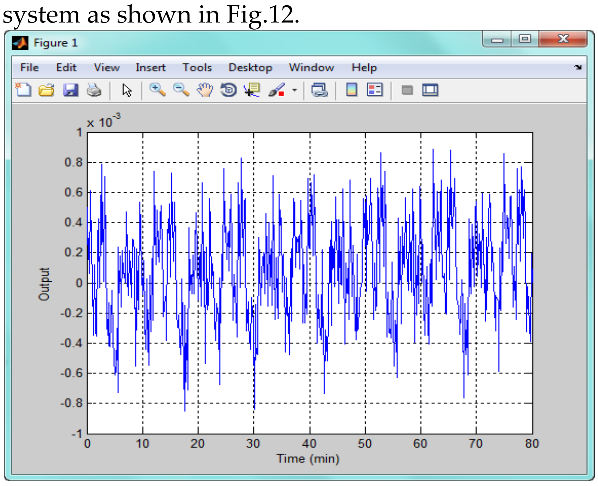

Fig.11. *Input disturbance on the object*

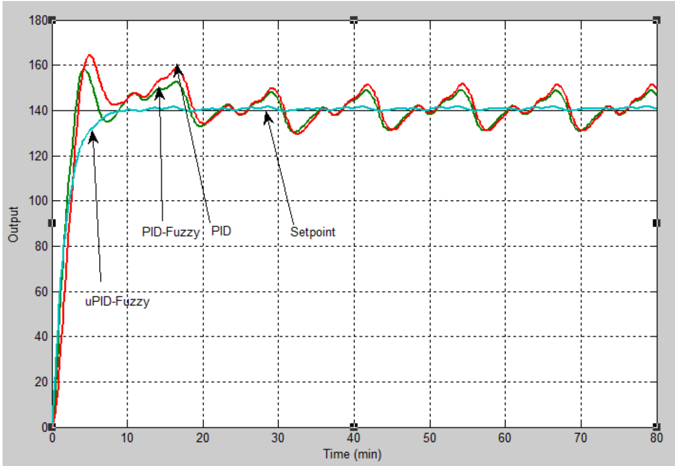

Fig.12. *Response system with the disturbance*

Table 3. Quality evaluation criteria with disturbance

Controller / Quality index	PID	PID-Fuzzy	uPID-Fuzzy
Rise tim, t_r (s)	2,62	2,42	3,85
Settling time, t_s (s)	78,20	76,89	7,32
Overshoot, %	9,94	7,80	0,82
Anti-disturbance	No	No	Yes
Steady state error	Large, may be unstable	Large, may be unstable	Very small

Based on the response of the system when the object is affected by the input disturbance in the sine-form with each controller, such as Fig.11, we have some conclusions as follows:

+ The use of traditional PID controller may be unstable.

+ With the PID-fuzzy controller, designed according to [7] , the system quality is much reduced, and may be unstable with large disturbance.

+ With the fuzzy self-tuning PID controller (uPID-fuzzy) the system quality is also reduced but still ensures stable system with small overshoot (0.09%), fast response time (6.92s), small-steady-error.

6. CONCLUSION

Hypersonic wind tunnel is a very complex system, with many control objects. These objects are nonlinear, often do not have enough parameters needed to build the object model. So the design of traditional controllers, such as PID, is difficult. In this paper, the author has combined the traditional PID controller with fuzzy logic to adjust online the PID parameters, to adapt to the kinetic changes of the object or the effects of noise on the object, thereby improving the quality pressure control system for hypersonic wind tunnel. On the basis of inheriting and developing mathematical model of hypersonic wind tunnel pressure process, the author has designed the traditional PID controller according to Skogestad. And then, the author has designed the fuzzy self-tuning PID controller for the hypersonic wind tunnel pressure regulation.

The simulation results, evaluation results, when comparing the proposed controller in the article with the adaptive fuzzy PI controller [7] in the case two-level-setpoint as well as the impact noise, shown that the fuzzy self-tuning PID controller gives outstanding quality, promising possibilities that can be applied in practice.

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