Fuzzy Assisted PI Controller with Anti-reset wind up for Regulating Pressure in a Hypersonic Wind Tunnel

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ABSTRACT

Wind tunnels are being used to study the aerodynamic properties of race cars, fighter planes etc. It allows us to make a reusable prototype and test it in the tunnel. Hypersonic wind tunnels operate at hypersonic speeds ie, with a mach number greater than 6. For doing experiments, it is necessary to maintain a constant pressure in the settling chamber of the tunnel so that we get the desired Mach number and mass flow rate through the nozzle. Here, a fuzzy assisted PI control system incorporating anti reset wind up is developed for regulating the pressure and hence a constant mass flow rate in the hypersonic intermittent blow down type wind tunnel and the results obtained are analised.

Keywords

Hypersonic wind tunnel, anti reset windup, fuzzy assisted PI controller.

1. INTRODUCTION

Wind tunnel is a facility used to investigate the aerodynamic properties of objects by passing a stream of velocity-controlled air over them. Although the form of a wind tunnel can vary, all wind tunnels have a drive system and a test section where a model is supported in airstream whose characteristics are measured by test instrumentation.

The different subsystems of the system are high pressure system, wind tunnel system which consists of Pressure regulating valve (PRV), Heater, Settling chamber, Nozzle, Test section, the Diffuser, Vacuum isolation valve After cooler and Vacuum Chamber. Air is compressed and stored in the high pressure system. It is released through a pressure regulating valve to create the desired pressure in the settling chamber. Heater is used to heat the air while passing through the heater bed to avoid liquefaction when it is expanded through the nozzle to get high Mach numbers. The pressure in the settling chamber is controlled by the proper operation of the control valve so that flow through test section meets the Mach number and mass flow rate specified for the test conditions.

Conducting experiments in a large-scale blowdown-type wind tunnels is costly and time consuming. The system is highly uncertain and non linear. The set pressure has to be reached within few seconds. So it is a challenging task to develop a controller that should adapt for different set pressure values and inlet pressure values, mass flow and temperature. These limitations and the need for high reliability systems make the role of controller design important.

Obtaining the mathematical models of the wind tunnel process is very complicated since they involve viscous effects and distributed characteristics. Working with simplified nonlinear model control is mainly used to handle the control problems with varying process parameters. Different non linear adaptive techniques are available in literature.

The specifications of the hypersonic wind tunnel system is available in the directory of wind tunnel facilities in India [8]. In 2008 Mr. Eric M.Braun et.al. developed a supersonic blow down wind tunnel control using LabVIEW [1]. The control algorithm was based on numerically integrating the differential equations used to model the tunnel in which the proportional and integral terms were added and tuned in a simulation to determine their appropriate values. Mr. Varghese Jacob et.al. established a lumped parameter mathematical model for the high pressure systems of hypersonic wind tunnel for designing a controller for pressure regulation [2].

The fuzzy controller essentially is a kind of non-linear controller, which are built up based on intuition and experience about the plant to be controlled. The fuzzy controller is designed to impart common sense to the control system thereby improving its performance. Due to reset wind up, if the error returns to zero, the control action will remain saturated. The condition can be eliminated by providing anti- reset wind up. Now, as soon as the error changes sign, the control action can return within the control range in one sampling period. The results obtained are compared with that of the fuzzy assisted PI controller without anti reset wind up[11].

2. SYSTEM MODEL

We consider total system as three pressure vessels as shown below. The continuity equation of the pressure vessels are used to develop the non linear model. Models of different components are developed to obtain the process model of the wind tunnel system for designing a controller. We consider total system as three pressure vessels.

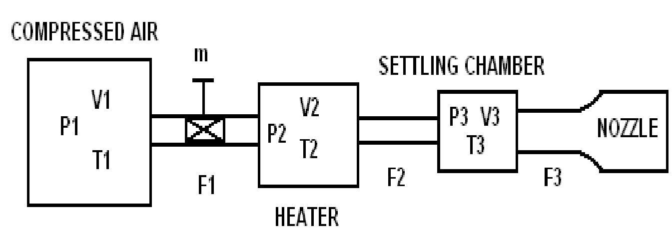

Figure 1. Block diagram of system to be modeled.

The continuity equation of the pressure vessels are used to develop the non linear model. Block diagram of systems to be modeled is given in figure 2. The modeling equations are as given below [2]. Assuming that the compressed air behaves as an ideal gas its mass in the tank at time't' is given by

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

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

Flow rate of compressible fluid [6] F1 is given by

$$F_1 = mC_v N_8 F_p P_1 Y \sqrt{\frac{XM}{T_1 Z}} \text{ ---- (1)}$$

Where 'm' is the position of the valve, C_v 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 $Y = 1 - \frac{X}{3F_k X_t}$

where X_t is critical pressure drop ratio factor and F_k is the ratio of specific heats factor and $X = \frac{P_1 - P_2}{P_1}$, where P_2 is the downstream pressure of PRV.

Heater chamber is considered as one pressure vessel and connected pipelines and settling chamber together considered another pressure vessel. The outflow from heater F_2 is given by

$$F_2 = C_v N_8 F_p P_2 Y \sqrt{\frac{XM}{T_2 Z}} \text{ ---- (2)}$$

Where the Expansion factor $Y = 1 - \frac{X}{3F_k X_t}$ and

$X = \frac{P_2 - P_3}{P2}$ where P_3 is the settling chamber pressure.

For different Mach number simulations we use fixed nozzles with different cross section area. It always maintains a choked flow through nozzle. The mass flow rate through nozzle, F_3 is given by

$$F_3 = \frac{K_n P_3}{\sqrt{T_3}} \text{ ---- (3)}$$

Where k_n is the nozzle constant and P3 is the settling chamber pressure and T_3 is the settling chamber temperature.

The continuity equations for three pressure vessels may be written using equations 1, 2 and 3 as

$$C_1 \frac{dP_1}{dt} = -F_1$$

$$C_2 \frac{dP_2}{dt} = F_1 - F_2$$

$$C_3 \frac{dP_3}{dt} = F_2 - F_3$$

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

For nominal test condition, P_1=300bar, T_1=300 K; T_2=700 K; T_3=529 K [8].

3. CONTROLLER

3.1 PI Controller

For designing a PI controller, we need to know the gain K, Delay time t_d and time constant τ for calculating the controller parameters K_c and τ_i . To select the best values of the controller parameters we use controller tunning. Here we use one of the most popular empirical tuning methods, known as the process reaction curve method or Cohen coon method, developed by Cohen and Coon[10].

In this method, the process reaction curve is drawn and is used for tuning the PI controller. The process reaction curve shown in figure 2, is plotted by giving a step change from 10% opening of the valve to 20% opening. In the initial condition, ie, 10% opening of the valve, the pressure is maintained constant at 45 bar at time of 50 sec. Now, when we apply a step input change of additional 10%, the pressure is maintained constant at 90 bar at time of 100sec. This 's' shaped curve obtained is called the process reaction curve which is as shown below. From the curve, we get the values of proportional gain and integral time, using which we can write the controller transfer function.

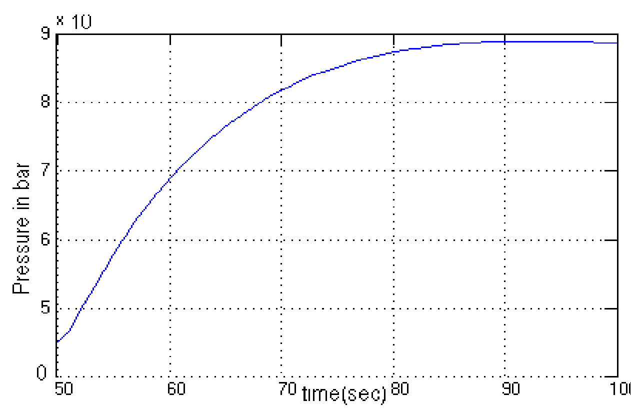

Figure 2. Process reaction curve

The proportional gain is given by

$$K_c = \frac{\tau}{Kt_d}(0.9 + \frac{t_d}{12\tau}) \text{ and}$$

The integral time is given by

$$\tau_i = \frac{30 + 3(t_d/\tau)}{9 + 20(t_d/\tau)}$$

Using these equations, we obtained the proportional gain as K_c=5.3 and integral time as τ_i=1.6 sec.

The transfer function of the PI controller is given by,

$$\frac{U(s)}{e(s)} = K_c + \frac{K_c}{\tau_i s}$$

The integral term of a PI controller causes its output to continue changing, as long as there is a non zero error.

Often, the errors cannot be eliminated quickly, and given enough time, they produce larger and larger values for the integral term, which in turn keeps increasing the control action until it is saturated ie, the valve is completely opened or closed. This condition is called reset wind up, Then even if the error returns to zero, the control action will remain saturated.

The condition can be eliminated by providing anti- reset wind up. Now, as soon as the error changes sign, the control action can return within the control range in one sampling period. Anti reset wind up will stop integrating the error as soon as the controller output saturates.

3.2 Fuzzy Assisted PI Controller

The error(e) and error rate(e_r) are the input variables, f is the output variable. Fuzzy relations between e, e_r and f is formed. Then f can be changed on line according the rules, current error and error rate. The block diagram of the system is shown below.

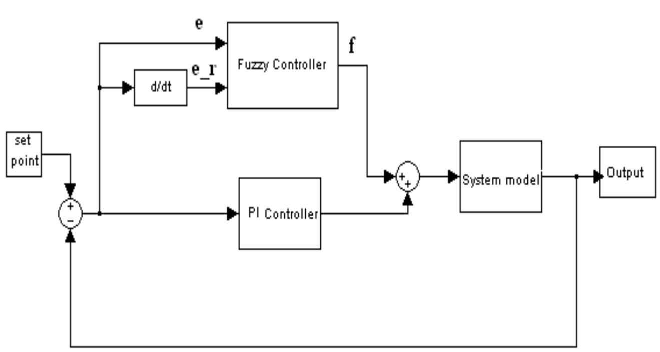

Figure 3. Block diagram of system with Fuzzy assisted PI Controller.

The membership functions are defined based on the two inputs of the fuzzy system, error e and error rate e_r. Seven triangular membership functions are defined for both input and output. The membership function is given below.

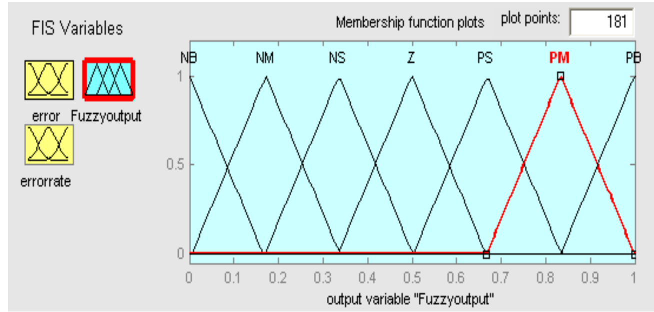

Figure 4. Fuzzy membership function.

The seven fuzzy subsets assigned for input and output variables are Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Medium (PM) and Positive Big (PB). The rule table for fuzzy controller is shown below.

Table 1. Fuzzy rule table.

e_r	e						
	PB	PM	PS	Z	NS	NM	NB
PB	PB	PB	PM	Z	Z	Z	Z
PM	PB	PB	PM	PS	Z	Z	NS
PS	PB	PM	PS	PS	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 defuzzification method used is centroid. The fuzzy controller is designed using fuzzy tool box in Matlab [3]. Figure below shows the simulink block diagram of the system with fuzzy assisted PI controller.

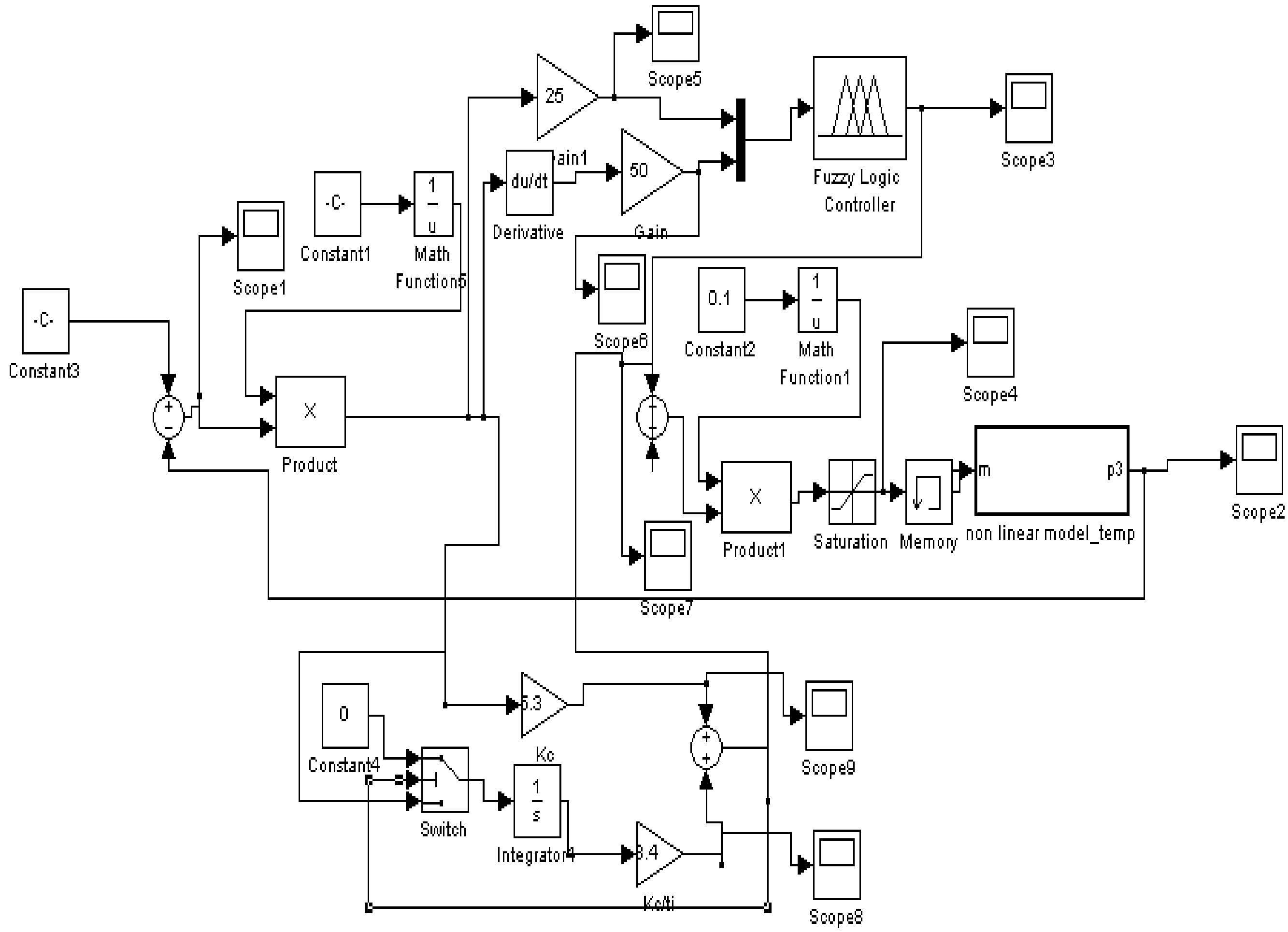

Figure 5. Simulink program of the system with fuzzy assisted PI controller with anti reset windup.

4. SIMULATION RESULTS AND DISCUSSIONS

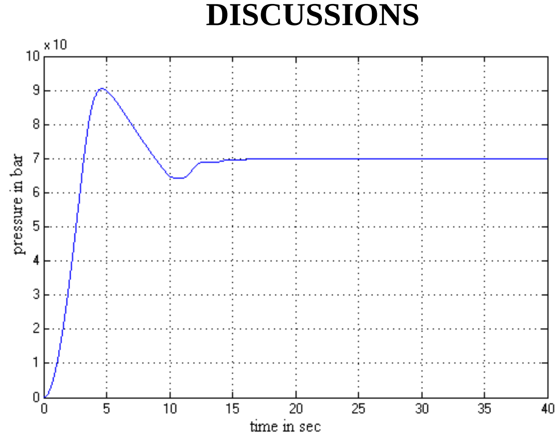

Figure 6. Output response using Fuzzy assisted PI controller with anti-reset windup for set point 70 bar.

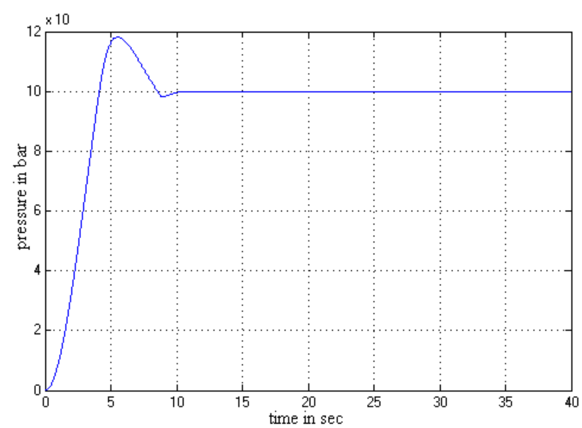

Figure 7. Output response using Fuzzy assisted PI controller with anti-reset windup for set point 100bar

From the simulation graphs, it is seen that for a set point of 100 bar, the settling time for the controller is 10 sec and, for a set point of 70 bar, the settling time is 16 sec. Compared with the controller without anti reset wind up [11], the controller with anti reset wind up is good and the two results are tabulated below. Clearly, we can say that the fuzzy assisted PI controller with anti reset wind up has fast settling time, less overshoot, and reduced IAE and ISE.

Table 2. Result Comparison Table

Controller	Fuzzy Assisted PI Controller with Anti-reset wind up		Fuzzy Assisted PI Controller	
Parameter	Set point		Set point	
	100 bar	70 bar	100 bar	70 bar
Settling Time	**10** sec	**16** sec	**27** sec	**30** sec
Percentage Overshoot	20%	28.5%	81%	97%
IAE	$6.69x10^{8}$	$5.81x10^{8}$	$8.2x10^{9}$	$5.59x10^{9}$
ISE	$5.02x10^{15}$	$2.56x10^{15}$	$4.3x10^{16}$	$2.02x10^{16}$

5. CONCLUSION

The simulation results shows an improvement in the settling time for the fuzzy assisted PI controller with reset wind up compared to the controller without reset wind up. An improvement in percentage overshoot and IAE can be obtained by modifying the rule base of the fuzzy controller. In this work, error and error rate are taken as inputs to the fuzzy controller. Further works is to be carried out by incorporating more inputs to the fuzzy controller like the pressure in the first vessel, intermediate pressures etc. More investigations in this direction are required for improved performance of the Fuzzy assisted PI controller.

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