Blowdown wind tunnel control using an adaptive fuzzy PI controller

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Abstract: *The paper presents an approach towards the control of a supersonic blowdown wind tunnel plant (as evidenced by experimental data collected from "INCAS Supersonic Blowdown Wind Tunnel") using a PI type controller. The key to maintain the imposed experimental conditions is the control of the air flow using the control valve of the plant. A proposed mathematical model based on the control valve will be analyzed using the PI controller. This control scheme will be validated using experimental data collected from real test cases. In order to improve the control performances an adaptive fuzzy PI controller will be implemented in SIMULINK in the present paper. The major objective is to reduce the transient regimes and the global reduction of the start-up loads on the models during this phase.*

Key Words: *Wind tunnel operation, PI controller, fuzzy PI controller.*

1. INTRODUCTION

A supersonic wind tunnel is an experimental facility used in order to deliver flow at constant stagnation pressure, so that an experiment in a dedicated test section is performed. The stagnation pressure is generally regarded to be constant for the useful duration of the experiment, controlled by one or more pressure regulators in a separate tank upstream of the test section. During a run, the storage tank pressure that supplies plenum chamber pressure decreases continuously and, in order to maintain a constant plenum chamber pressure, the regulator valve must open progressively. A key performance criteria is based on the capability to reduce the transient regime during the opening of the valve and to minimize the pressure overshoot that induces high loads on the model.

In INCAS Supersonic Wind Tunnel [1] the entire process is completed within 15 to 100 seconds, depending on the requested flow regime. The method for controlling the valve opening to maintain a constant plenum chamber for supersonic flow facilities has evolved from manual operation to more moderns active technologies required in order to meet better than 0.1 percent error.

The controller must operate at different stagnation pressures and Mach numbers and has to be robust to accommodate the varying pressure and mass flow requirements safely. New concepts for control are under implementation with the goal to reduce transition phase and overall loads on the models.

There are several models that have been developed for a supersonic blow down wind tunnel control system and some implementations using state of the art software systems (e.g Braun et.al. [3]). The control algorithm is based on 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. Varghese et.al. [4] established a lumped parameter mathematical model for the high pressure systems of hypersonic wind tunnel for designing a controller for pressure regulation.

A classical PI controller is designed and fuzzy controller is added to improve the robustness and performance. Skoczowski et.al [9] proposed an effective method for robust proportional–integral–derivative (PID) control that is easily implementable on commonly used equipment such as programmable logic controller (PLC) and programmable automation controller (PAC).

The method is based on a two-loop model following control (MFC) system containing a nominal model of the controlled plant and two PID controllers.

The fuzzy controller essentially is a kind of non-linear controller, the fuzzy control algorithms are built up based on intuition and experience about the plant to be controlled. The proposed control system for pressure regulation consists of two controllers, the PI controller designed for the nominal plant and the fuzzy controller designed to impart common sense to the control system thereby improving its performance [9].

2. SUPERSONIC WIND TUNNEL MODEL

INCAS Supersonic Blowdown Wind Tunnel is a pressurized aerodynamic tunnel based on two geometrically variable transversal sections that are capable of operating both at subsonic and supersonic speeds (Mach = 0.1…3.5), ensuring a high Reynolds number (over 100 mil/m in transonic regimes). A principle scheme of the installation is presented below:

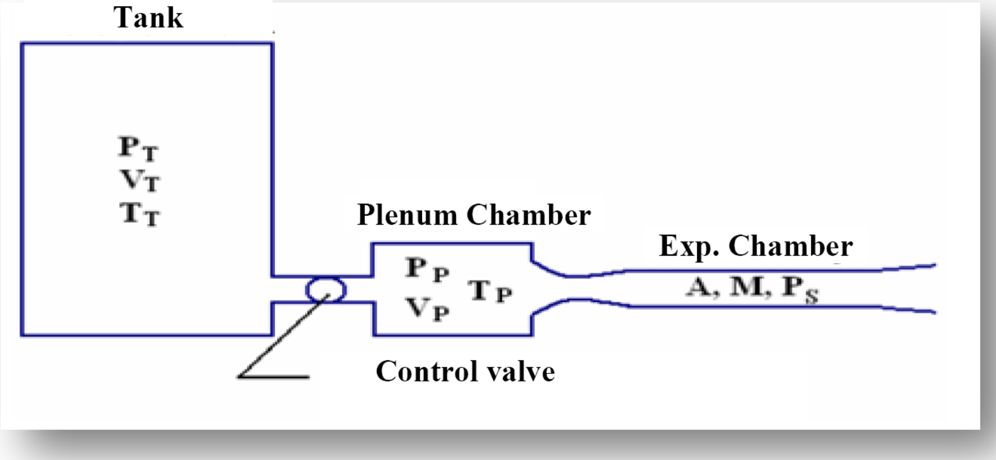

Fig. 1 – General layout for a Blowdown Supersonic Wind Tunnel

The working principle of the installation is based on controlling the airflow using an open geometry while ensuring stabilized flow parameters (pressure, speed, temperature, perturbations) in a specified area, generically called the experimentation chamber. The flow of air starts at high pressure tanks and is fully controlled by a control valve and passes through a silencer system before it’s released into the free atmosphere.

The control valve is the main control actuator of the plant during the active phase, once a global geometry has been defined using dedicated controls for the tunnel geometry. The valve system is utilized during a test in order to ensure proper parameters in the plenum chamber depending on the airflow available in the tank. Thus, the valve operates under special conditions, as the difference in pressure between the two faces of the valve can be extremely high (up to 20 bar) and movement is ample and at high speeds (up to 10 seconds for full opening).

3. PI CONTROL MODEL AND EXPERIMENTAL CONFIRMATION

Because the control valve is the centerpiece in controlling experimental conditions within the experimental chamber, it's most important characteristic is the opening angle. This could be considered as a real theta opening angle of a classical butterfly valve, or equivalent for different regulating valves principles. This paper will use this analogy, but one has to notice that INCAS current physical valve is of a different type [1].

The value upon which pressure stabilization is desired (P0) is one which allows the predetermined (Mach and Reynolds) regime to occur. In the plenum chamber, pressure varies rapidly as the valve is opened, and the pressure can be controlled as long as there is sufficient air remaining in the tank and the theta angle hasn't reached 90 degrees yet. An important aspect is minimizing the shock to which the actuator system is subject to at this particular time.

The main flow parameters (Mach and pressure) alongside the tunnel geometry is qualitatively presented below, for a classical supersonic test configuration.

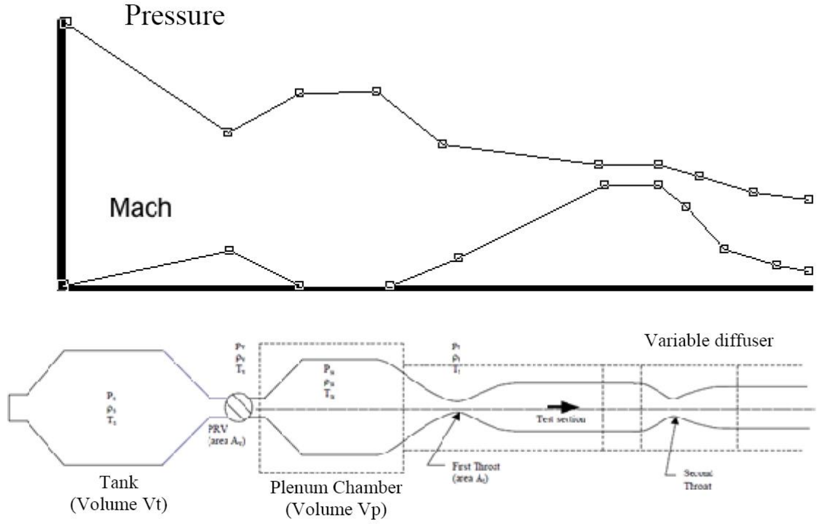

Fig. 2 – Flow parameters variation in the tunnel for a supersonic test

The simplified model of airflow through the installation is based on the model of compressible one dimensional flew. Therefore, the laws of compressible fluid mechanics apply in this case. Geometrical profiling takes into account the fact that parameters are stabilized in the plenum chamber (pressure, temperature) and the speed is zero. In this case, taking into account the critical section:

$$A^* = A_e \cdot M_e \cdot \sqrt{\left[\frac{2}{\aleph + 1}\left(1 + \frac{\aleph - 1}{2} M_e^2\right)\right]^{\frac{1+\aleph}{1-\aleph}}} \tag{1}$$

Pressure in the plenum chamber must be imposed as

$$P_0 = P_e \cdot \left[1 + \frac{\aleph - 1}{2} M_e^2\right]^{\frac{\aleph}{\aleph-1}} \quad (2)$$

Taking into account the use of an pre-existant PI regulator, the valve's angle transfer function is:

$$\Theta(s) = \left(K_P + \frac{K_I}{s}\right)\left(P_0 - P_P(s)\right) \quad (3)$$

After applying inverse Laplace transformation the equation for controlling the opening angle is:

$$\frac{d\,\Theta(t)}{dt} = -K_P \frac{dP_P(t)}{dt} + K_I[P_0 - P_P(t)] \quad (4)$$

Taking into account the flow laws aforementioned, the form used for LabVIEW simulations is:

$$\Delta\Theta = -K_P \frac{\Delta P_P}{\Delta t} + \frac{K_I}{N}\left[P_0 - P_{P,i+1}\right] \quad (5)$$

$$\Theta_{i+1} = \Theta_i + \Delta\Theta \quad (6)$$

The proposed control solution utilizes the principles behind a PI controller, which is largely used in SISO type systems. A bloc diagram of the controller is presented below:

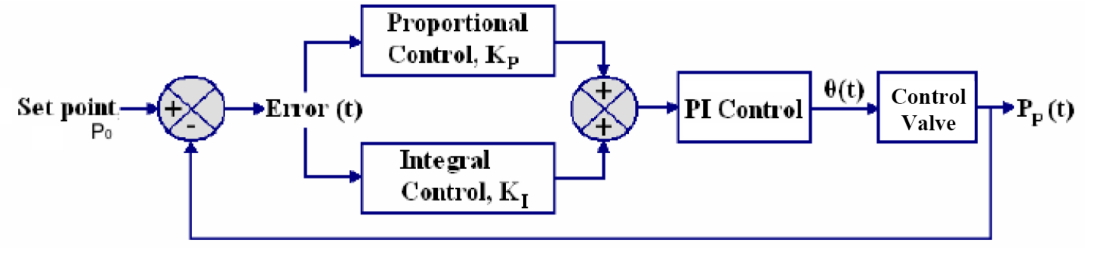

Fig. 3 – Bloc diagram for the PI controller

It's main strong point as a PI controller is it's robustness and simplicity. The set point P_0 represents the imposed pressure in the experimental chamber, while the error between the set point and the instantaneous pressure $P_p(t)$ is used for determining the output (which translates in the increment needed to widen the opening angle theta). A successful control strategy is achieved as stationary error is zero while the transitional period is minimal to allow for a longer useful duration of the test.

Main control parameters are K_p and K_i which can be determined by using experimental data as well.

Validation of the proposed control model is realized with compared with data from the real tests no. 6413 and 6414 in the results section below.

Table 1 – Test runs for PI controller model validation

Test No.	Mach	Reynolds	Pt	Po	T0	Obs.
6413	1.983	8.379 e+06	9.996	2.503	306.3	Sweep
6414	1.982	8.314 e+06	10.014	2.381	303.3	Step

The developed LabVIEW application uses the $K_p = 3.35*10^{-6}$ and $K_i = 5.45*10^{-7}$ determined above and implements the equations for controlling the valve opening angle described above.

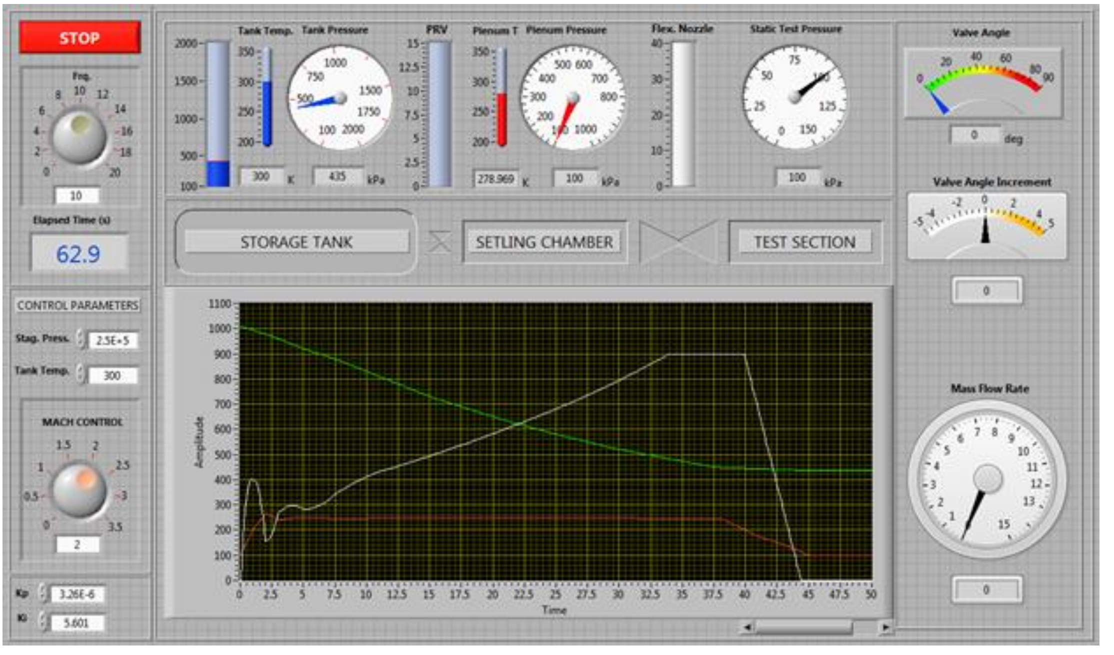

Fig. 4 – LabVIEW application for the PI controller

The LabVIEW application may be used in two different modes. One mode is implemented for the fine tuning of the K_I si K_P parameters, using experimental data from the wind tunnel. This mode is very useful when this experimental data is available and one would like to identify controller parameter that matches the overall evolution of the pressure in the system.

The second mode of operation is based on LavVIEW capability to control the overall tunnel system, using data acquisition system in place at INCAS. This mode is in an experimental phase and is highly dependent on both the sensors used for pressure readings and valve position, as wells as on the technical specifications for the NI data acquisition drivers used for real applications.

The overall model comparison with the experimental data is presented in Fig. 5, for two different operation modes of the tunnel (step and sweep) at Mach 2.0.

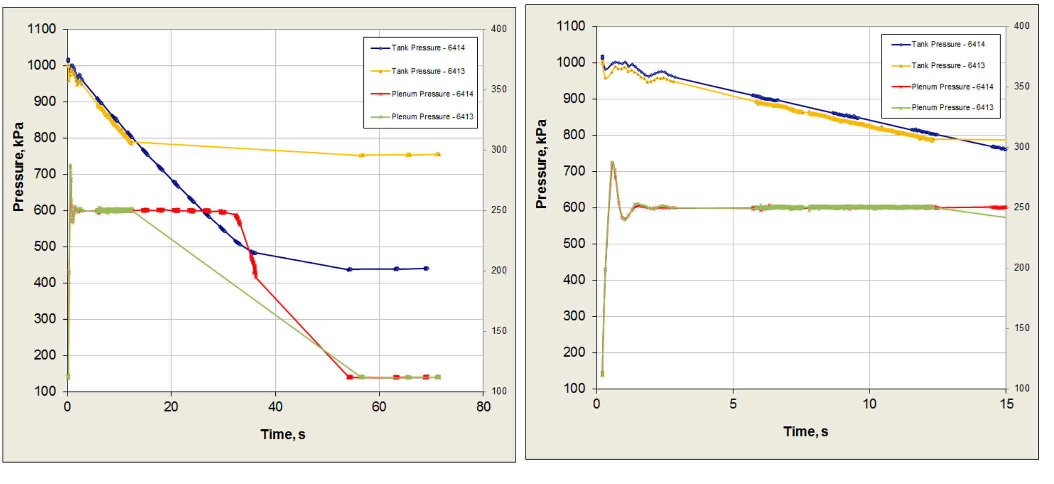

Fig. 5 – PI controller model validation in LabVIEW

4. CONTROL USING PI SIMULINK MODEL

In order to improve the existent control system, the paper now focuses on implementing a PI controller in SIMULINK with similar results to the LABVIEW simulations described above. Therefore we take into account the same transfer function of the fixed part:

$$H_F(s) = \frac{2.54 \cdot 10^7 \cdot s + 5.321 \cdot 10^5}{s^3 + 16.68 \cdot s^2 + 3.367 \cdot s + 0.01937} \tag{7}$$

The new PI parameters of the controller will be calculated using the pole-zero allocation method. This constitutes in allocating the poles and zeroes of the controller transfer function in a satisfactory way so that overshooting is reduced, the duration of the transition time stays below and imposed parameter while still ensuring zero stationary error. A bloc diagram for the implementation of the PI SIMULINK controller is presented below:

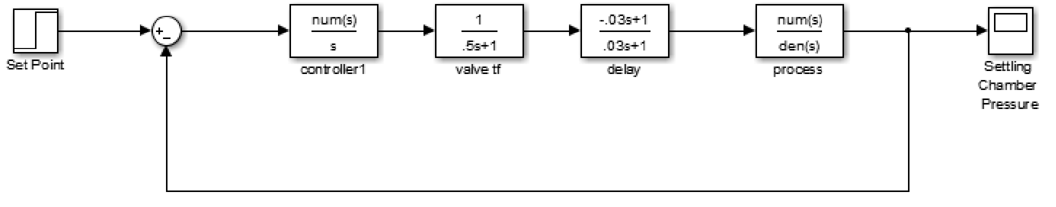

Fig. 6 – SIMULINK implementation for the PI controller

Applying the method while considering that the pole-zero excess is *e = z – p = 2* we arrive at the desired transfer function which is:

$$H_0(s) = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n + \omega_n^2} \cdot \frac{s + z_1}{s + p_3} \cdot \frac{p_3}{z_1}; \tag{8}$$

Where p_3 si z_1 are chose so that $\frac{p_3}{z_1} = 1.01$ and $|z_1| < |p_3|$; with the ulterior condition that $p_3 > 5\ \omega_n$, and for the desired overshootin we impose $\zeta = 0.45$;

After calculations we arrive at the following values for the PI controller:

$$\begin{cases} K_p = 3.26\ \cdot 10^{-6}. \\ K_i = 5.6013 \cdot 10^{-7} \end{cases} \tag{9}$$

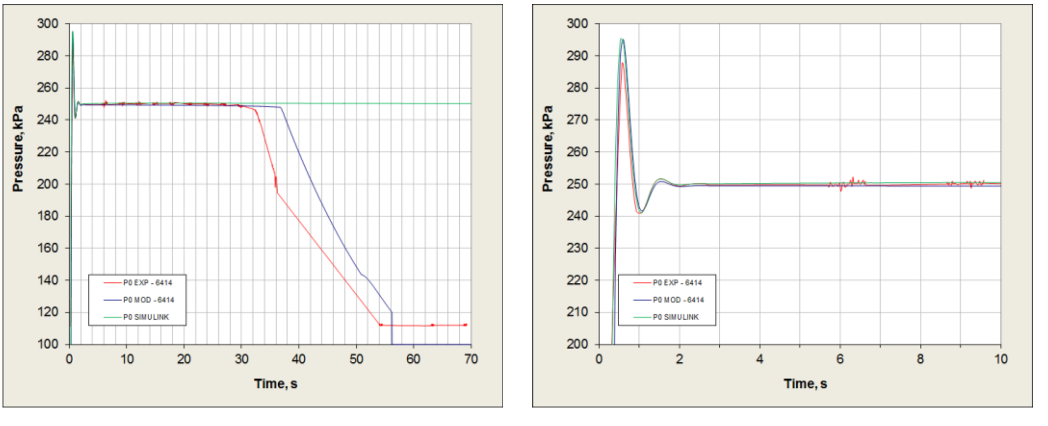

Fig. 7 – PI controller model validation in SIMULINK

5. ADAPTIVE FUZZY PI CONTROLLER MODEL

In order to improve the previously discussed PI controller the paper will implement a control system which will consist of the PI controller, a reference model and a FLC (fuzzy logic controller). The bloc scheme of this implementation is presented in figure 8 below.

The reference model M(s) whose output Ym(s) has the desired characteristic is chosen as:

$$M(s) = \frac{1}{0.05s + 1} \quad (10)$$

The FLC C(s) has Uf as output and the current error (e) and it's time derivative (ec) as input. C(s) is placed between the output of the previously PI controll system and the reference model which insures that the output of the controlled system quickly follows the output of the reference model.

The two inputs of C(s) are scaled by two coeficients, K_1 and K_2 which are required in order to scale the values on the [-1,1] interval where the 7 membership functions are defind for both input and output. The exit is now scaled by a K_3 coeficient. Membership functions are triangulare and are prezented in the figure 9 below.

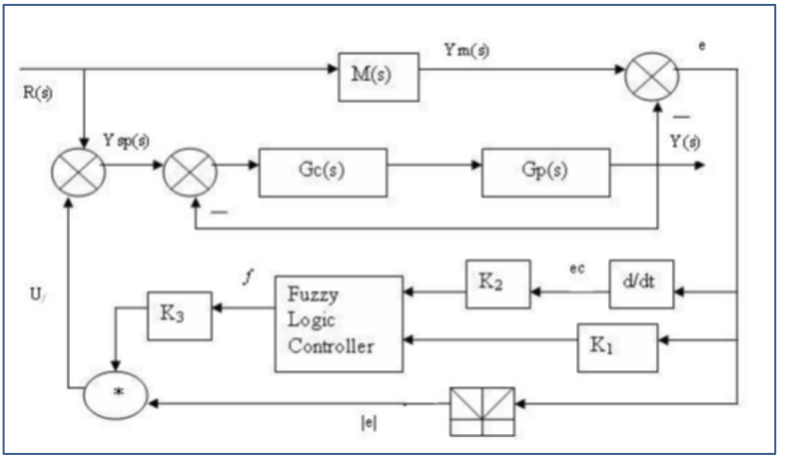

Fig. 8 – Bloc diagram for adaptive fuzzy PI controller

In the fuzzy logic table used, *e* and *ec* are input variables while *f* reprezents the output variable. Acording to the rule table, which consists of 7 linguistic variables for input/output (NB,NM,NS,Z,PS,PM,PB). The external output U_f is determined as $U_f = K_3 f|e|$

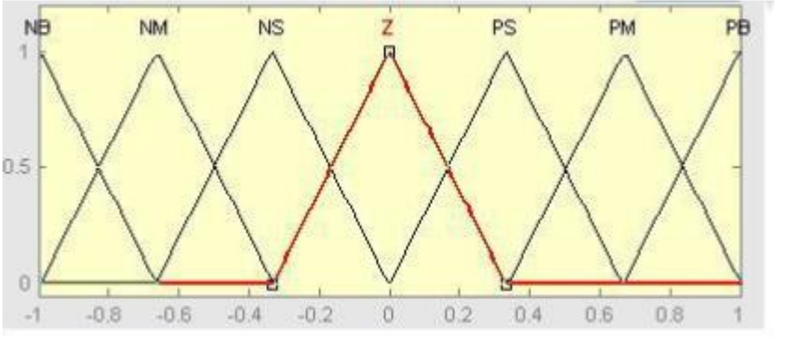

Fig. 9 – Fuzzy membership functions for PI controller

Table 2 – Fuzzy rule table for PI controller

ec	E						
	PB	**PM**	**PS**	**Z**	**NS**	**NM**	**NB**
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 were implemented in MATLAB using fuzzy toolbox and writing 49 type "IF ec AND e…THEN f" type of rules corresponding to the table below. The defuzzification method used is centroid.

The bloc scheme of the implemented adaptive fuzzy PI control in SIMULINK is presented below:

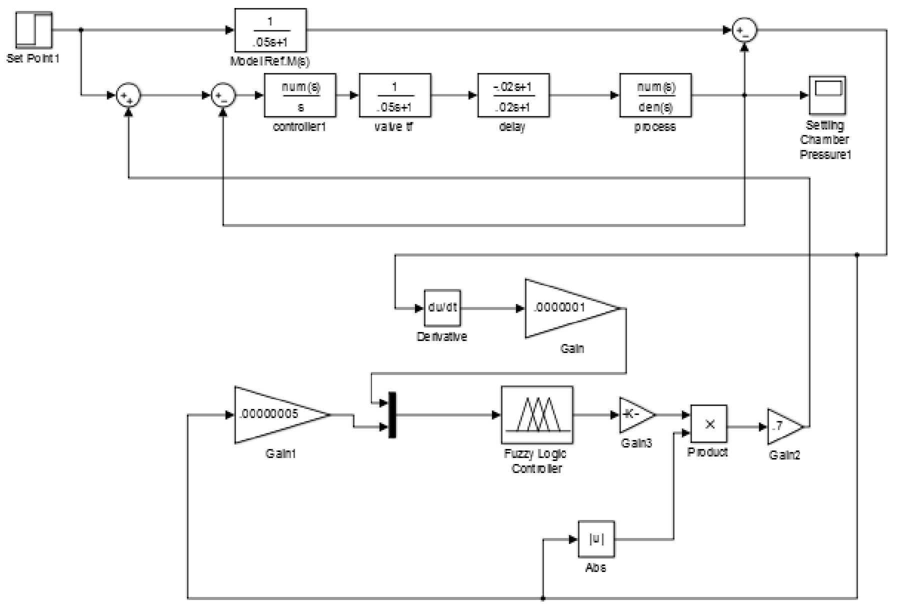

Fig. 10 – Adaptive fuzzy controller in SIMULINK

6. RESULTS FOR ADAPTIVE FUZZY PI CONTROLLER SIMULATION

In order to validate the adaptive fuzzy PI controller model we use the same data as before, using test run 6114 as reference. We use for simulation the following functions and parameters:

- Transfer function : $$H_F(s) = \frac{2.54\cdot 10^7\cdot s+5.321\cdot 10^5}{s^3+16.68\cdot s^2+3.367\cdot s+0.01937} \quad (11)$$

- PI Controller parameters: $$\begin{cases} K_p = 3.26 \cdot 10^{-6} \\ K_i = 5.6013 \cdot 10^{-7} \end{cases} \quad (12)$$

- Reference model $:M(s) = \frac{1}{0.05s+1}$ (13)
- $K_1 = 0.5 \cdot 10^{-7}$ si $K_2 = 10^{-7}$ (14)
- Time constant for valve : 0.05 (15)
- System delay : 0.02 (16)
- Simulation total time : 20 sec. (17)

Simulation results for adaptive fuzzy PI controller are presented in figure 11.

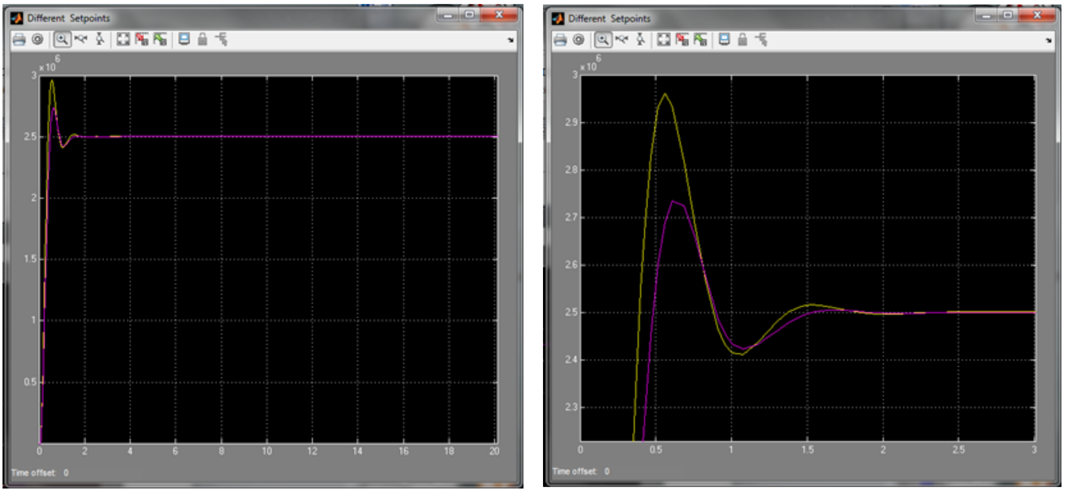

Fig. 11 – Simulation results for adaptive fuzzy controller

7. CONCLUSIONS

In accordance with the desired goal, the present paper has: implemented a LabVIEW model for control and monitoring of the control valve of an blowdown wind tunnel; defined and implemented (in SIMULINK) control schemes using PI and Fuzzy Adaptive PI controllers and it has validated the models using experimental data.

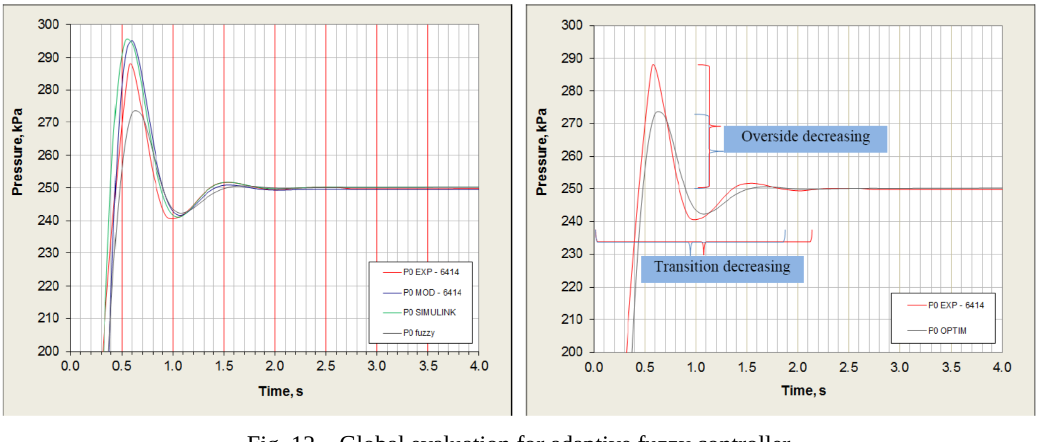

Fig. 12 – Global evaluation for adaptive fuzzy controller

Values of the important K_p and K_i parameters remained similar both while determining them through modeling ($3.26*10^{-6}$, $5.601*10^{-7}$) or through identification by using experimental data ($3.35*10^{-6}$, $5.45*10^{-7}$) which implies that the proposed system can be successfully used in the future for complex simulations.

Table 3 – Global results for PI controller simulations

	Ref	Over	Over_%	t_set		Min_1	delta	delta_%
EXP	250.00	286.58	14.63%	2.10		241.01	45.57	18.23%
MOD	250.00	293.50	17.40%	2.00		242.06	51.44	20.58%
PI	250.00	295.21	18.08%	2.00		241.05	54.16	21.66%
FLC	250.00	273.53	9.41%	1.75		242.28	31.25	12.50%

From the achieved simulations it stands out that the PI controller model has the capacity of accurately simulating the real life experimental conditions but it’s overshooting is too big (compared to the imposed 10%) and it’s rise time is bigger than the ideal one (of 1.5 seconds). After implementing the Fuzzy Adaptive PI controller, a considerable increase in performance is noticed, the overshooting is kept below 10% and the rise time is sufficiently close to 1.5 seconds.

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