IDENTIFICATION AND ROBUST CONTROL IMPLEMENTATION FOR AN AIR HEATING PLANT

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Abstract. *This paper presents the system identification process of an air heating and flux control plant, followed by closed-loop robust control designs. The plant consists of a PVC tube with a fan in the air entrance (that forces the air through the tube) and a mass flux (or pressure) sensor in the output. A heating resistance warms the air as it flows inside the tube. The plant is multivariable, with two inputs (the angular velocity of the fan and the current in the heating resistance) and two outputs (air temperature and air mass flux or pressure).The identified mathematical model is nonlinear, mainly because of the air mass sensor. The model combines transfer functions with delays and nonlinear elements (the sensor). The model is then linearized and the delays are properly approximated by non-minimum phase transfer functions. Finally, the resulting model is transformed to a state-space model, which is used for control design purposes. Robust control design techniques are used in order to control temperature and mass flow / air pressure. The techniques used are LQG/LTR (for the mass flow control) and H infinity Loop Shaping (for pressure control). The controllers are validated in simulation software. Finally, the controllers are implemented in MATLAB/Simulink with Real Time Windows Target, in order to provide real time characteristics to the controllers. This control program is then compiled and executed at the same priority level as the very operating system, in order to guarantee real time. Finally, the experimental results are compared to evaluate the controller's performance.*

Keywords: *Air Heating Plant, Robust Control, System Identification*

1. INTRODUCTION

The closed loop control design for multivariable processes (that is, when all the plant inputs affects all the outputs) is in general more complicated than the simple single loop design, most commonly adopted in process control systems. In general, when the plant is truly multivariable, that is, it is not possible to model it as a bunch of single input single output system (SISO), the mathematical model must predict the coupling between all the inputs and outputs. Modern and highly mathematical intensive techniques are then necessary in order to guarantee closed loop stability and performance.

Some classes of plants are even more challenging, as for example the *thermo fluidic* ones, which are described by Partial Differential Equations (PDE). In the case of compressible fluids, the problem is even worse. Theoretically, the Navier-Stokes equation should be used to model the process, which is very difficult to solve even numerically, which means that the analysis would be very time-consuming, let alone the closed loop control, that must be in real time.

In those cases, in order to obtain manageable models, one has to appeal to System Identification, as described in (Ljung, 1999). If one assumes that the process to be controlled is linear ant time invariant, there are lots of techniques and experimental procedures to obtain models of this kind (that are, of course, only approximations). Frequently, however, the identification process is expensive and time consuming, and in order to have models (even the simple ones) in practical times, one has to accept great uncertainties in the model's parameters. Robust control techniques, which guarantee stability and performance in the presence of those uncertainties, must then be used.

In this work, some robust and multivariable controllers are presented for an air heating and air flux/pressure control mechatronic plant (that is, the air temperature and air flux or pressure are the controlled variables) in which the control inputs are the resistance's voltage and the fan's velocity. As this plant's mathematical model is very difficult to obtain analytically (Navier-Stokes PDE should be obtained), the System Identification methodology will be used. Also, the plant has two inputs and two outputs, and there is a high degree of coupling between, which means that four transfer functions must be determined. A picture of the plant is presented in Figure 1, which consists of a pipe conducting the air, which is forced by a controlled fan. At one of the pipe extremities, there is a heating resistance (also controlled) and at the other a mass flux sensor (or pressure sensor), used most commonly in cars (Bentley, 1988).

The designed controller must be implemented in a computerized system, and the control signal must be delivered to the plant in analog form, between 0 to 10V, which are proportional to the heating voltage and the fan's angular velocity.

Another difficulty associated to this plant is the delay (dead time) present in each control channel. Those delays are generally associated to the physical distances between the sensors and the actuators. In fact, it will be shown that the more distant the sensor is from the actuator, the greater the associated delay. It is well known that in such systems, the phase lag in the loop transfer function is very high, and high loop gains are severely restricted in order to have closed loop stability. Several design techniques were developed in recent years in order to cope with delays, and the most famous and utilized is the Smith predictor (Zhong, 2006).

In this work, on the other hand, the dead time terms in the transfer functions will be approximated by rational transfer functions, known as Padé approximation. Those simplifications introduce non-minimum phase behavior in the plant, which increases the difficulty in designing efficient controllers. It will be shown, however, that very satisfactory controllers are obtained. The objectives of this work are then: 1) apply system identification techniques in order to obtain a model for the air heating and air flux control, 2) apply robust control design techniques by using the mathematical model obtained, and 3) compare the performance of the designed controllers in the real plant.

The remaining material is organized as follow: in section 2, the controlled plant is presented in more detail, as well as the system identification process. In section 3, the designs of robust controllers are presented: LQG/LTR technique for the control of temperature and air mass flow, and H infinity Loop Shaping for control of temperature and air pressure. In section 4, simulations and experimental results are presented for the closed loop systems designed above, and in section 5, conclusions and future works are indicated. This paper was presented in COBEM 2013 (Colón *et al*, 2013).

2. MODELING AND IDENTIFICATION

The plant/process controlled in this work is the kit LTR 701 from the manufactures Amira/Elwe, which is in the Control Laboratory at the Sorocaba Campus – São Paulo State University (UNESP). A picture of the plant is in Figure 1. This kit consists of an air conducting pipe, in which the air is forced by a proportionally controlled fan (which dynamic is deliberately ignored). The fan's velocity is varied between 0 to 100 per cent, which corresponds to 0 to 10 V in the analog input signal. A heating resistance is right after the fan, which also can be varied from 0 to 100 per cent. There is a manual butterfly entrance valve, right before the fan, which can be used to generate disturbances in the system.

There is a thermo couple sensor to measure the air temperature, which can be put in four different places along the tube. At the other end of the tube, an air mass flux sensor or a pressure sensor can be connected. Those signals are internally converted in analog voltage signals, which are also accessible in the front panel (or in a connector to the computer system to be used in the control function).

The acquisition board is the MF-614 from Humusoft, which has seven analog inputs and two analog outputs (the digital inputs and outputs will not be used in this work). The analog inputs can be configured to accept signal from -10 to 10 V, which in compatible to the voltage levels of the kit. The software used for control / system identification used is a real time software (real time Windows target, that is a toolbox of MATLAB/Simulink). This tool generates a simulation / control executable file that runs with higher priority than the operational system (kernel) and takes control of the hardware (and of the interrupt request management), guaranteeing the hard real time demands.

The thermo couple sensors are of the type NiCr-Ni, with time lag constants of 0.3 or 3.0 seconds, depending on which sensor is used (this constants will be ignored). The more distant the sensor is put away from the heating resistance, the greater is the dead time in the corresponding transfer function.

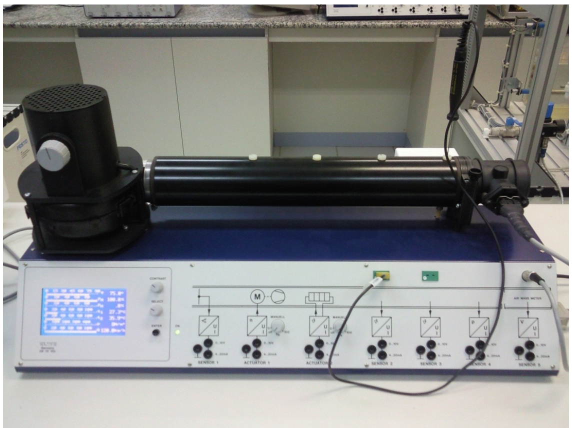

Figure 1. Didactical plant LTR701.

All the inputs are voltage signals, that ranges from zero to 100 per cent (0 to 10 V): 1) the heating signal, that is proportional to the current applied in the resistance; 2) fan signal, that is proportional to the fan's velocity (the motor dynamics is negligible and between zero to 100 per cent). All the output signals, that is, the signals generated by the plant's sensor, are also voltage signals between 0 to 10 V. Those signals are: 1) thermo-couple temperature, which can be put in different positions along the tube; 2) The mass flow measurement, which is measured by the sensor presented in Figure 2, and pressure sensor, also at the tube's end.

Figure 2. Mass flow sensor

The flap signal measures the angle for the butterfly valve (that is varied manually). Both the actuators receive command signals ranges from 0 to 10 V (that corresponds to maximal power) and the increment in power is 0.1 per volt. The thermocouple measures temperatures between 20 to 120°C, and the increment is 10°C per volt. The butterfly angle varies between 0 to 100°, and the increment is 10° per volt. Finally, the mass flow sensor measures flows between 0 to 120 kg per hour, but it is nonlinear, and its characteristic curve was determined experimentally and are presented in Figure 3.

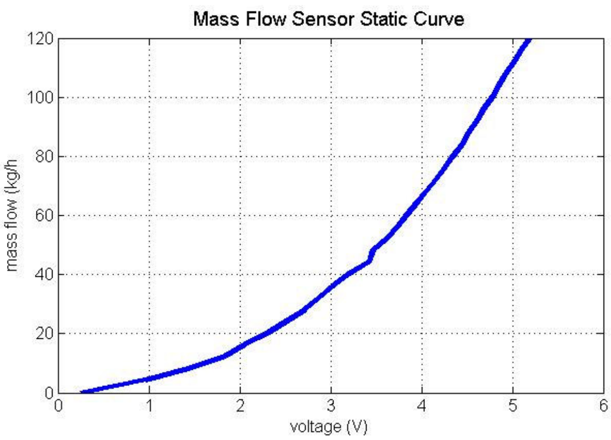

Figure 3. Mass flow sensor characteristic (static) curve

In order to linearize the system (if we use the mass flow sensor), we have to invert this curve (that is, we have to find the inverse function and use it in series with the block that receives the mass flow signal in the Simulink control diagram). We proceeded to the identification of the several transfer functions (relating the inputs and outputs) and interpolated the output signals by using a curve fitting tool. The general structure of the transfer functions identified is second order (with real poles) with dead-time. As the thermocouple can be put in four different positions along the tube, we chose to put in the most distant point (from the resistance). The transfer functions relating pressure and actuator signals were extracted from the manufacturer manual.

The following transfer functions were obtained by system identification: between resistance and temperature (the thermo couple was put in the most distant position):

- Between resistance and temperature: $G_{1,4}(s) = \dfrac{0.1358}{(3.7599\,s+1)(0.0379\,s+1)} e^{-0.096\,s}$
- Between voltage in the fan and temperature: $G_{2,4}(s) = \dfrac{0.1132}{(4.4903\,s+1)(0.5896\,s+1)} e^{-0.5s}$
- Between voltage in the fan and mass flow (voltage): $G_3(s) = \dfrac{12.6470}{(0.3621\,s+1)(0.068\,s+1)} e^{-0.24\,s}$
- Transfer function between flap and temperature: $G_{4,4}(s) = \dfrac{1.107}{(7.675\,s+1)(0.1528\,s+1)} e^{-0.78\,s}$
- Transfer function between flap and mass flow sensor: $G_5(s) = \dfrac{0.8117}{(0.0322\,s+1)(0.0319\,s+1)} e^{-0.08\,s}$

The five dead-time factors above can be approximated by Padè approximations (rational functions), which are:

$$e^{-0.096\,s} = \frac{-s+20.83}{s+20.83};\; e^{-0.5s} = \frac{-s+4}{s+4};\; e^{-0.24s} = \frac{-s+8.333}{s+8.333};\; e^{-0.78s} = \frac{-s+2.564}{s+2.564};\; e^{-0.08s} = \frac{-s+25}{s+25}$$

The transfer matrix of the complete system (relating the two inputs and the two outputs) can be calculated based on the identified transfer functions. By using MATLAB, it is possible to find the state space representation of the complete system, which results in:

$$A = \begin{bmatrix} -47.48 & -17.57 & -2.284 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 \\ 32.00 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 \\ 0.000 & 2.000 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 \\ 0.000 & 0.000 & 0.000 & -5.918 & -2.013 & -0.755 & 0.000 & 0.000 & 0.000 \\ 0.000 & 0.000 & 0.000 & 4.000 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 \\ 0.000 & 0.000 & 0.000 & 0.000 & 0.500 & 0.000 & 0.000 & 0.000 & 0.000 \\ 0.000 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 & -25.80 & -11.63 & -5.288 \\ 0.000 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 & 16.00 & 0.000 & 0.000 \\ 0.000 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 & 4.000 & 0.000 \end{bmatrix}$$

$$B = \begin{bmatrix} 0.500 & 0.000 \\ 0.000 & 0.000 \\ 0.000 & 0.000 \\ 0.000 & 0.250 \\ 0.000 & 0.000 \\ 0.000 & 0.000 \\ 0.000 & 8.000 \\ 0.000 & 0.000 \\ 0.000 & 0.000 \end{bmatrix} \quad C = \begin{bmatrix} 0.000 & -0.0596 & 0.6204 & 0.000 & -0.0428 & 0.3421 & 0.000 & 0.000 & 0.000 \\ 0.000 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 & -4.0127 & 8.3599 \end{bmatrix} \quad D = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}$$

The state-space representation for the system with pressure sensor (which has a different dynamic) is not presented here.

3. ROBUST CONTROL DESIGN

In order to design robust controllers for the system, we have to estimate the frequency response of the system, by means of the singular value decomposition (Sanchez-Pena *et al*. 1998), which is presented in Figure 4. In a certain sense, the uppermost plot represents the superior limit to the maximum gain in each frequency.

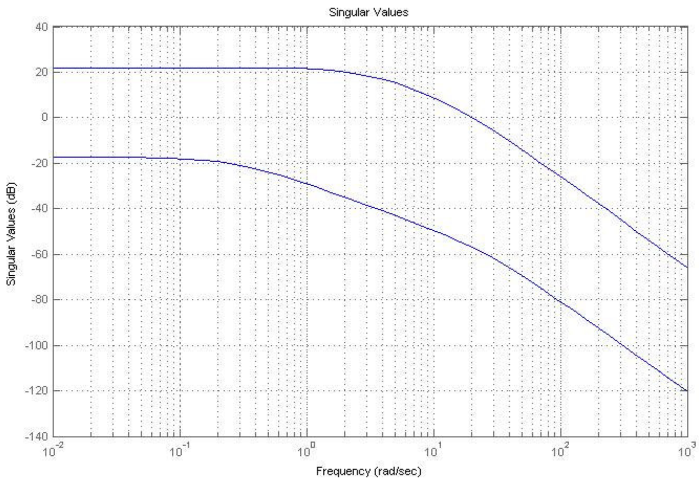

Figure 4. Singular value diagrams for the complete system

The two design techniques used in this paper are: 1) LQG/LTR (linear quadratic Gaussian /Loop Transfer recovery) and H Infinity Loop Shaping, which will be presented in the following section.

3.1. LQG/LTR

This control design technique is presented in (Cruz, 1996) and the controller will be a transfer matrix $K(s)$ with the same number of inputs and outputs as the plant itself, which is 2 x 2. The inputs are temperature and mass flow sensor measurements and the outputs are the control signals that must reach the actuators, that is, the resistance signal and the fan signal (both in volts). The controller, as said, was implemented in MATLAB/Simulink software, with the real time extension. The controller is a state feedback controller, where the states are estimated by a Kalman Filter. Both the state feedback gain matrix and the output injection gain matrix of the Kalman filter must be designed according to the prescriptions in (Cruz, 1996). We have to adjust only one parameter μ, which the square root is inversely proportional to the low frequency gain of the open-loop system. This control design technique produces a robust controller. For a similar plant, with different sensors, a design example is presented in (Colón *et al*., 2009). In order to compensate for stationary errors (for step reference inputs), we must introduce one integrator in each plant input (these integrators are in fact put in the output of the controller $K(s)$). In Figure 5, we have the singular values for the extended plant (with the integrators). If we calculate the transmission zeros of the system, we will conclude that this system have non-minimal phase, which complicates but not invalidate the design technique.

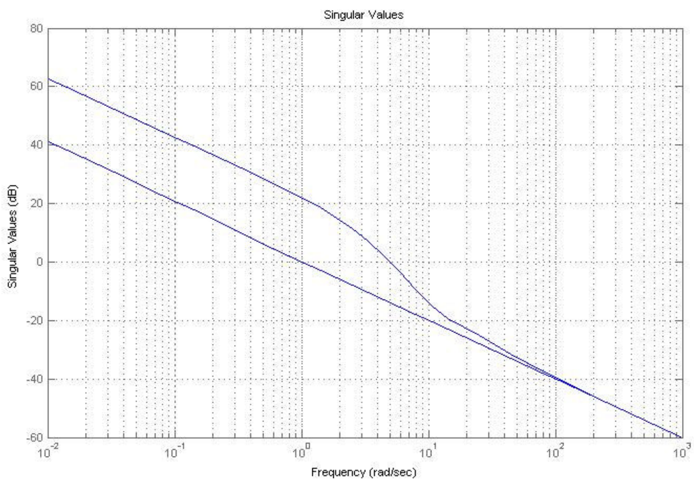

Figure 5. Singular values for the extended plant (with integrators).

The method for obtaining the controlled in more detail will not be presented (Cruz, 1996).

3.1 H Infinity Loop Shaping

The second controller design technique to be applied to this plant is the H∞ loop shaping, which is described in (MacFarlane and Glover, 1992). In this technique, the performance requirements are also specified in the open loop singular values plots. The robustness index γ for this design technique have the same role as the phase margin for a SISO classical design, but does not suffer from the same drawbacks. We have to fix this parameter in order to start the design. The chosen robust stability index must satisfy:

$$\left\| \begin{bmatrix} K_L(s) \\ I \end{bmatrix} (I - G(s)K_L(s))^{-1} M_L^{-1}(s) \right\|_\infty \le \gamma$$

The plant's transfer matrix $G(s) = M_L(s)^{-1} N_L(s)$ must be decomposed in a product of two co-prime transfer matrices, and it must be multiplied by the weight transfer function $W_1(s)$ and $W_2(s)$, which give the desired shape for the open loop singular values plots. Then the following constant is calculated:

$$\gamma_{\min} = \left(1 - \left\| \begin{bmatrix} N_L(s) & M_L(s) \end{bmatrix} \right\|_H^2 \right)^{\frac{1}{2}}$$

and if γ_{min} is too high, the open loop singular value plots are unattainable (at the same time that robustness is guaranteed) so that the weight functions have to be modified. The less the value of γ, the better the robust stability margin, and if the minimum value is achieved, we have optimal robust H infinity control.

Typical closed loop specifications for loop shaping design are in terms of the sensibility function $S(s)$ and complementary sensibility function $T(s)$, which is equal to one when added. As we want good disturbance rejection properties, the low frequency gain of $S(s)$ must be low and as we want good tracking (of reference signals) properties and rejection of noise, the $T(s)$ at low frequencies must be around one. Also, the roll-of frequency must be -20 dB/dec. The weight functions chosen were

$$W_1\ (s) = (1/s) I_{2x2}$$
$$W_2\ (s) = 2\ ,\ W_2\ (s) = 5$$

The singular values plot for the augmented plant (with pressure sensor) are presented in Figure 6.

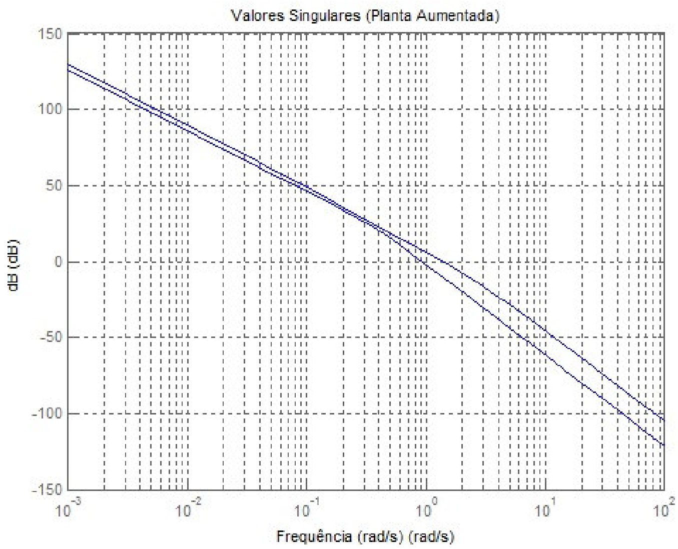

Figure 6. Singular values plot for the augmented plant.

4. SIMULATION AND EXPERIMENTAL RESULTS

In the following, the results of simulation and experimental implementation are presented. Initially, we will control the temperature and mass flow by using the LQG/LTR controller. After that, the H infinity controller is used (to control temperature and pressure).

4.1 Simulation and control using LQG/LTR

In any control design technique, the less the number of parameters, the easier the process is. For this plant, the only parameter to be varied is μ, which square root is inversely proportional to the low frequency gain, so that, the lower this parameter is, the better will be tracking and disturbance rejection properties of the closed-loop system. In Figure 7 we see the mass flow and temperature control (reference signals, simulation and experimental) for μ=0.05. We can see that the simulation (using the same controller but controlling the plant's model) produces better performance than the real plant, as this last one is nonlinear (due to the mass flow sensor) and little mismatches in the identified model. In Figure 8 we see the control signals for the real plant control. One can see that in order to have this performance, the control signals almost reach the maximum values, that is, 10 V. In Figure 9 and Figure 10 we have the same plots for another controller (the one corresponding to μ=0.5). In this case, the performance is worse, and the reference tracking capability is unsatisfactory. The delay in the flow signal, probably due to a neglected dynamic, is the very cause of the overshoot in the temperature signal. In Figure 11and Figure 12, that is, for μ=1, this effect is even worse, which indicates that the best value is μ=0.05. For smaller values of this parameter, the closed-loop system resulted unstable in the experimental apparatus, which could be predicted by the oscillatory behavior in the first case. The temperature signals in those plots are the difference between the ambient temperature (estimated in 25 C) and the real (sensor) temperature.

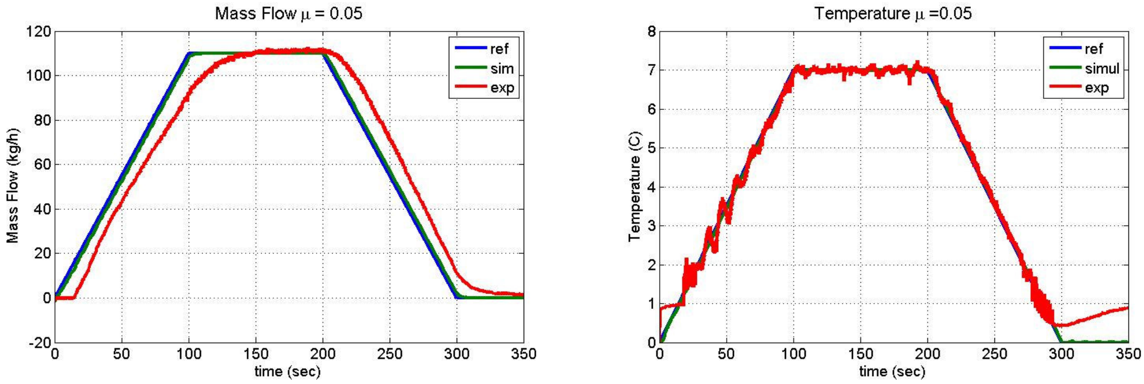

Figure 7. Reference, simulation and experimental mass flow and temperature for μ=0.05.

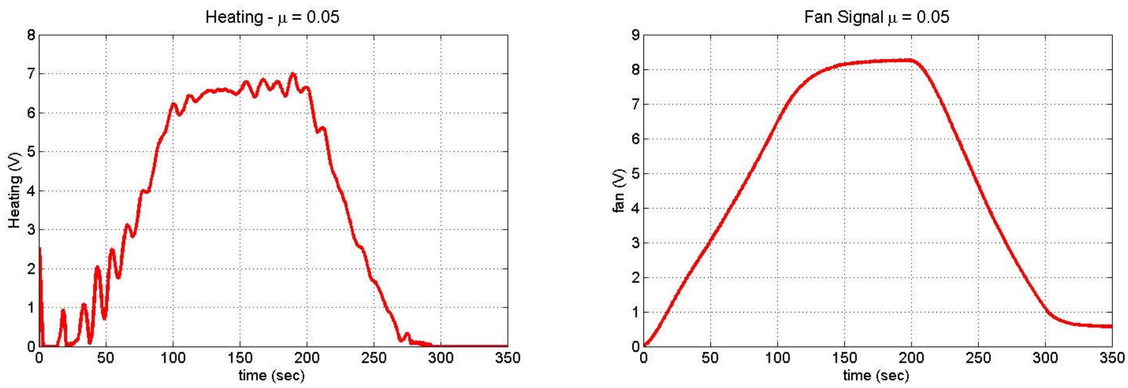

Figure 8. Heating and fan (control signals) for μ=0.05.

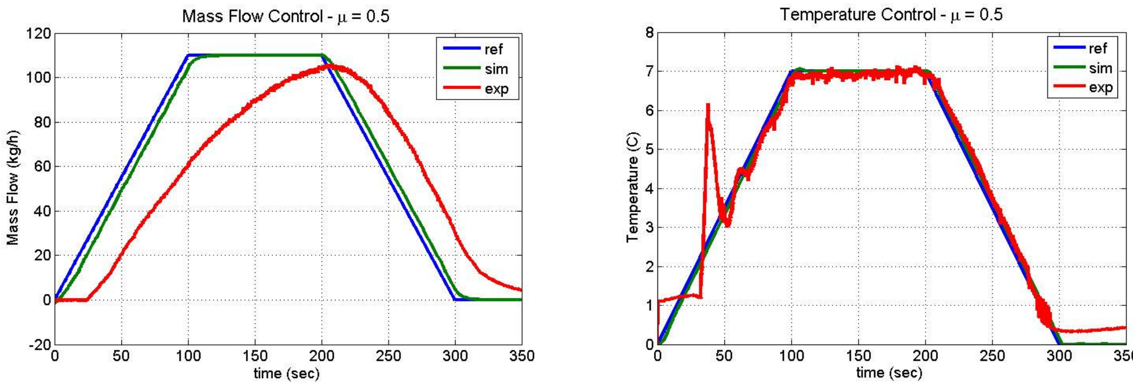

Figure 9. Reference, simulation and experimental mass flow and temperature for μ=0.5.

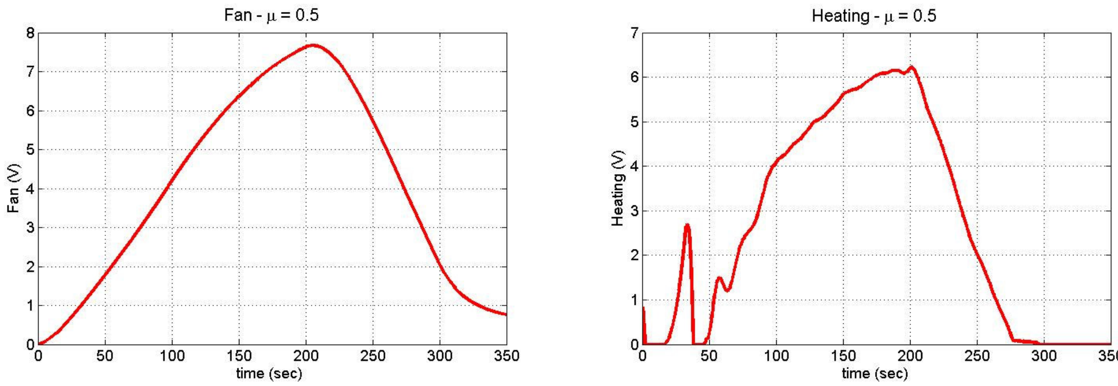

Figure 10. Heating and fan (control signals) for μ=0.5.

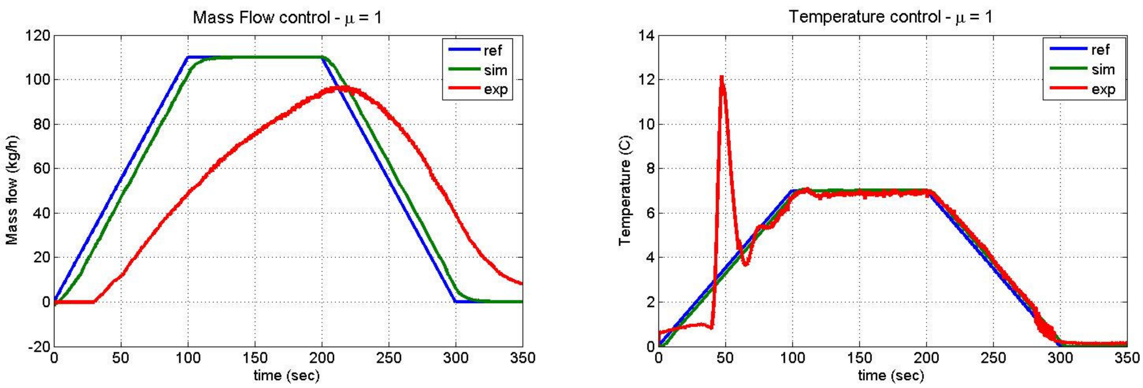

Figure 11. Reference, simulation and experimental mass flow and temperature for μ=1.

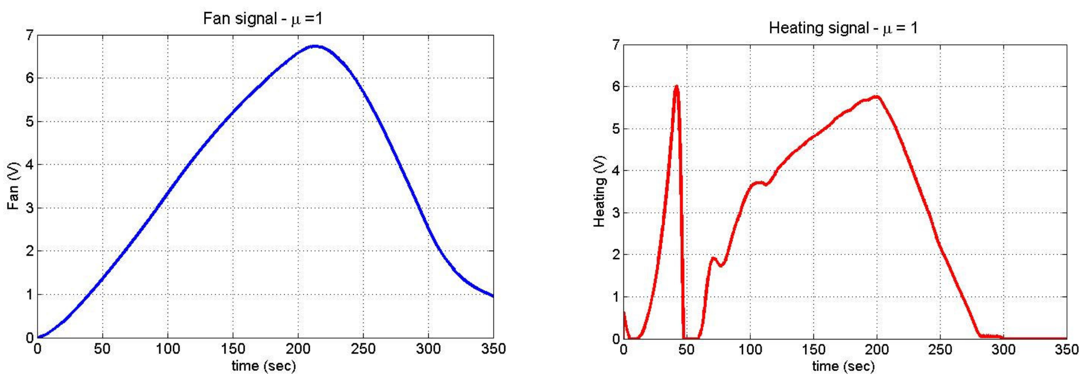

Figure 12. Heating and fan (control signals) for μ=1.

In order to evaluate the performance for abrupt signal variations, the step responses for the mass flow control were plotted in Figure 13. It is easily seen that the best response, in terms of settling time, is for μ=0.05. In this situation, there is a little overshoot. The temperature reference signal was 2 degrees (that is, 27 degrees in reality).

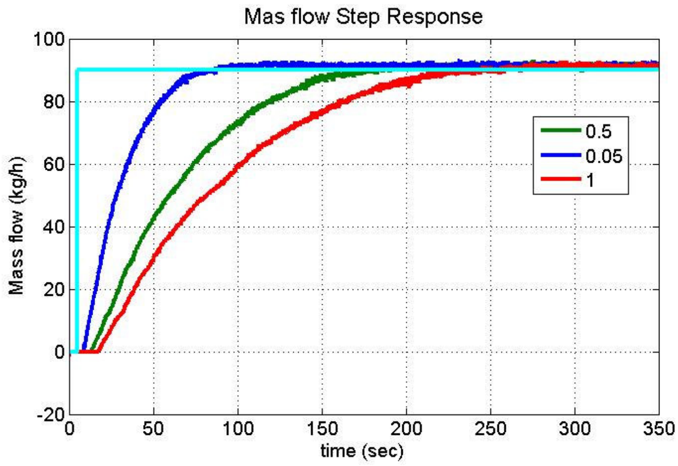

Figure 13. Step responses for μ=0.05, 0.5 and 1

In order to evaluate the disturbance rejection performance of the controller, a sudden variation of the manual valve were generated, as shown Figure 14. In Figure 15 we can see the effect of the flap manual variation in the mass flow and in Figure 16, the fan signal imposed by the controller in order to compensate the effect in the mass flow. It is clear the immediate effect of the flap in the mass flow, but the controller reaction is a bit slower. The temperature reference signal was constant and equal to 27 degrees.

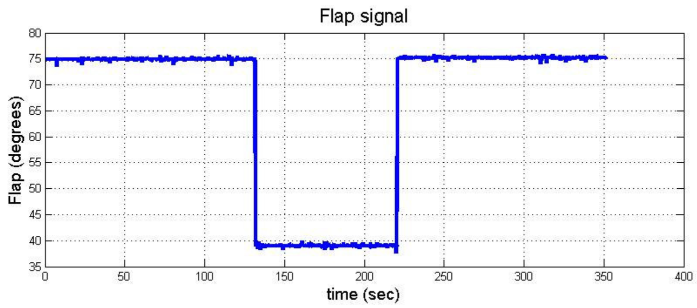

Figure 14. Flap disturbance signal.

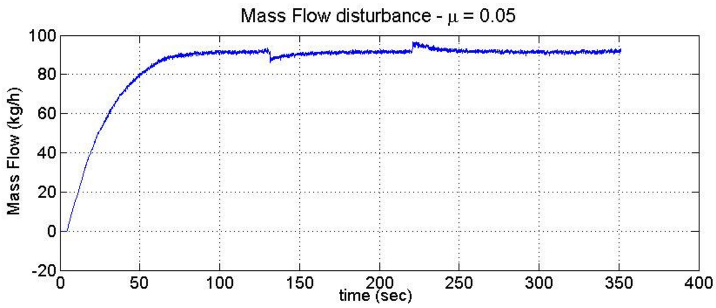

Figure 15. Mass flow disturbance caused by the flap variation.

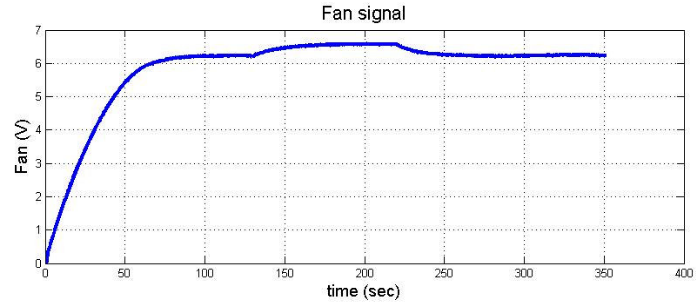

Figure 16. Control signal to compensate the mass flux disturbance.

4.2 4.2 Experimental Results for the H Infinity Loop Shaping

Another sensor that can be used for control purposes is the pressure sensor. The pressure grows monotonically with the mass flux, and sometimes it can be advantageous to control this variable in spite of mass flow. In fact, it will be shown, by simulations, that the controller designed for pressure produced smooth results. The design technique used here was H infinity loop shaping. In Figure 17, we see the pressure signal reference (light blue), simulation (dark blue) and experimental (red). In Figure 18 it is presented the temperature, in Figure 19 the fan signal (in volts) and in Figure 20 the heating signal. This first case is for the weight functions equals to simple integration, $W_2(s) = 5$ and $\gamma = 15$. One can clearly see that the control is more efficient, as there is little deviation from the reference, and the temperature control requires less control effort, as compared to the mass flow control. One possible explanation is that the high flow reference signal in the above examples dissipates much more heat in the resistance, which implies that more power is required to follow the signal temperature. In Figure 21, Figure 22, Figure 23 and Figure 24 it is shown the same signals, but for a different controller. In this case, the performance is poorer, but the control effort is lower.

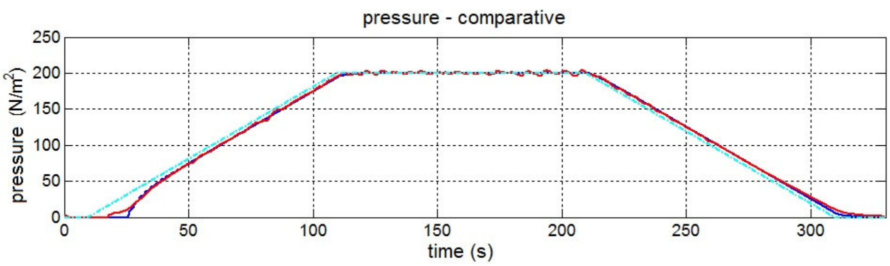

Figure 17. Reference signal, simulation and sensor signal for pressure control with $W_2(s) = 5$ and $\gamma = 15$.

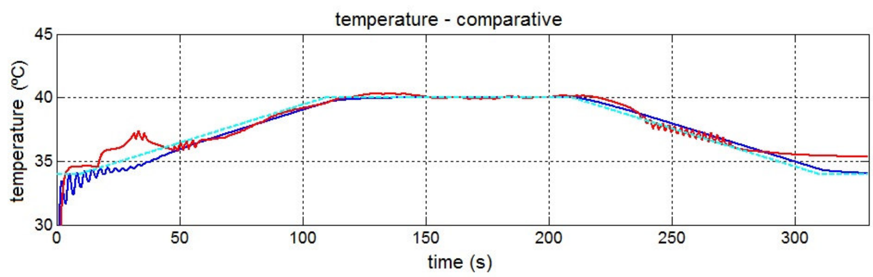

Figure 18. Reference signal, simulation and sensor signal for pressure control with $W_2(s) = 5$ and $\gamma = 15$.

The control problems, in the case of mass flux control and pressure control, are different, despite the similarities. So it is not sensible to compare those controllers in all aspects. But we can conclude that the measurement of the mass flow signal produces a more complicated system, in which a good control performance is more difficult to obtain (perhaps due to the sensor nonlinearity, or the neglected sensor dynamic).

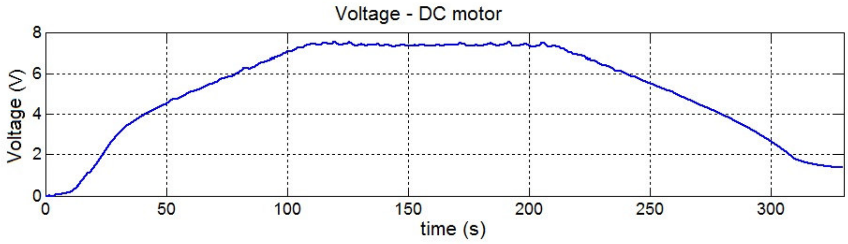

Figure 19. Reference signal, simulation and sensor signal for pressure control with $W_2(s)=5$ and $\gamma=15$.

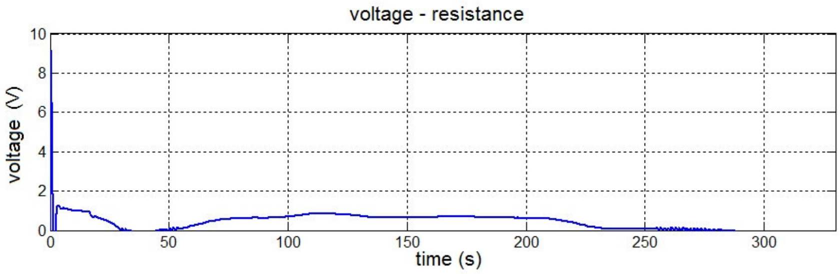

Figure 20. Control signal (voltage) applied in the heating resistance for $W_2(s)=5$ and $\gamma=15$.

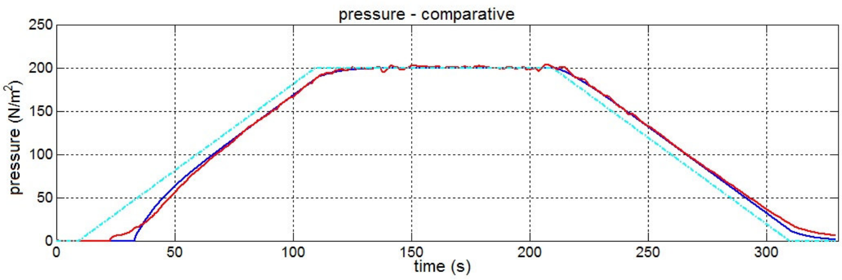

Figure 21. Reference signal, simulation and sensor signal for pressure control with $W_2(s)=2$ and $\gamma=15$

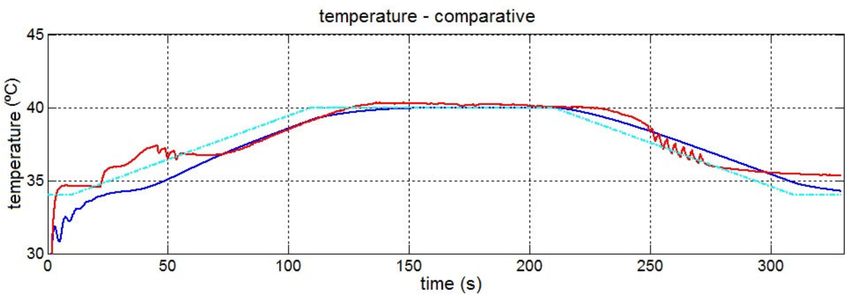

Figure 22. Reference signal, simulation and sensor signal for temperature control with $W_2(s)=2$ and $\gamma=15$

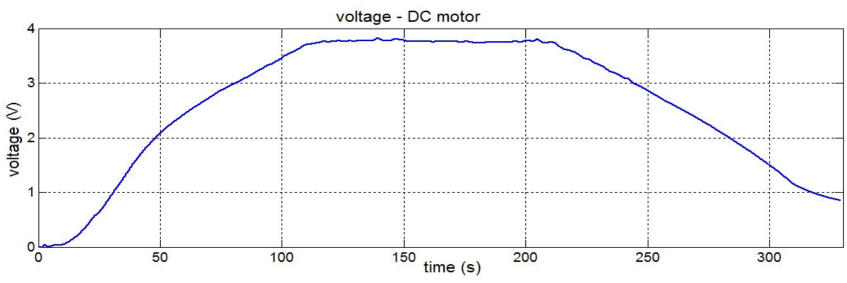

Figure 23. Reference signal, simulation and sensor signal for pressure control with $W_2(s)=2$ and $\gamma=15$.

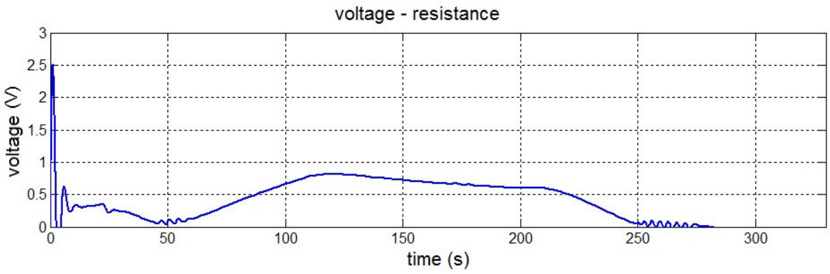

Figure 24. Reference signal, simulation and sensor signal for temperature control with $W_2(s) = 2$ and $\gamma = 15$.

5. CONCLUSIONS

Two different robust controllers were designed, simulated and compared. The first one controls temperature and air mass flow, and the mathematical model for the system, for this case, was obtained by system identification techniques. The second controller was for control of temperature and pressure (different sensor) and was designed in a previous mathematical model. This plant is in general difficult to model precisely, as it involves compressible fluids (air). A precise model would need partial differential equations, which is difficult to analyze and control (computational requirements). Robust control design techniques were used in order to compensate the model uncertainties due to the system identification techniques.

Future works will evaluate the possibilities of nonlinear modeling techniques (which produce nonlinear models) and more detailed models of the fan, the mass flow sensor and the thermo couple (temperature sensor). Also, the robustness properties of the controllers will be evaluated by using the technique of Polynomial Chaos, which considers the plant's parameters as random variables, and estimates the response of this stochastic system by simulating an equivalent deterministic system.

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7. RESPONSIBILITY NOTICE

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