Adaptive control of air temperature through spraying of water

José Antônio Riul
Frederico Antônio Melo do Vale
Simplício Arnaud da Silva
Universidade Federal da Paraíba - Centro de Tecnologia - Departamento de Tecnologia Mecânica
Paulo Henrique de Miranda Montenegro
Curso de Pós-Graduação em Engenharia Mecânica - Universidade Federal da Paraíba

Abstract

The use of electric energy for acclimatization is increasing in the entire world, what encourages the interests for researches in alternative sources of energy, in development of new equipment. Nowadays, acclimatization by absorption, evaporative cooling and desiccant cooling researches are accomplish aiming the reduction in the use of electric energy. In this paper, air cooling of an environment is proposed by spraying of water. This system, named simulator, is made of two parts. The first aim is to production of air under determinate condition and the second has the objective of reduce the air temperature of a recipient through spraying of water. In the proposed adaptive temperature controller, the system parameters are estimated in real time such as the controller design and its parameters. As experimental results are shown: temperature response, the system parameters estimates, the controller parameters, control variable and estimation error.

Keywords

Acclimatization, Identification, Adaptive Control.

Introduction

The use of eletric energy for acclimatization is increasing in the entire world. In the USA, is estimated that 50% of all residential electric energy is used for acclimatization, ventilation and heating. Concerning about the increasing of the use of electric energy intensifies the interests for researches in some areas, like alternative sources of energy, improvement of electrical equipment profits and development of new equipments. Researches with acclimatization systems by absorption, evaporative cooling and desiccant cooling are being accomplished more and more. This cycles provide the reduction of electric energy use and do not damage the environment with harmful gases.

The direct spraying of water in a running mass of air is based in the mass and heat transfer principles (Kreith, 1977). The water is sprayed directly in the air, through a water pump with controlled outflow, aimming at the variation of the air temperature (Benjan, 1988). In this paper, we propose the air cooling of the environment by spraying water. The system analysed, named simulator is made of two parts. The first aims at the production of air under determinated conditions and the second has the objective of reducing the air temperature of a recipient through spraying of water. The controllers are very usefull to reduct the air temperature and to keep the wanted values. We propose the use of a self-tuning PI controller, which system parameters are estimated in real time as well as the controller design and its parameters. The experimental results are shown as: temperature response, parameters of the system and controller estimates, control variable and estimation error.

Description of the system

The analysed system named simulator, as we can see in Fig. 1, is made of two parts. The first has the objective of producing air in determinated conditions and is formed by an evaporator, a condenser, a ventilation system and a refrigerator system by steam compression. The ventilation system is constituted of an electric motor, an electric switch, a ventilator and a duct for the air flowing. To make a simulator works, at first is necessary to activate the ventilation system (motor and ventilator), through the electric switch. The ventilator is connected to a duct of air, where there is a switch that regulates the air flowing to the evaporator. The evaporator is connected to a condenser.

The cooling system works with a compressor that fills up the condenser with R–22 fluid in high pressure and temperature. After passing by the condenser, the fluid R–22 is expanded in a cappillary tube and then goes to the condenser, where it will be overheated before returns to the compressor.

The air that flows through the duct impulsed by the ventilation system passes over the cooled condenser and looses sensitive heat and absolute humidity, then it arrives in the condenser, where its temperature is raised and its absolute humidity is reduced.

The second part of the simulator, that has the objective of reducing the air temperature is formed by a recipient with water for spraying, a recipient with four pulverizers, two water pumps of 12 volts, a tank of 200 l to simulate the environment whose temperature has to be controlled.

IDENTIFICATION OF THE SYSTEM

The parametric models which are responsible for the identification of the systems are very important because they make possible the acquirement of a parametric vector that represents approximately the analysed system. The identification can be made in an off line system, by collecting and saving the input/output measures for a subsequent process, or in an on line system. In this, the data are processed in a recursive way in agreement with each sample time without needing to stop the process, characterizing the identification in real time. The identification in real time is the essence of the design of an adaptive control. A applicable algorithm in the identification of the systems is the least squares (LS), according to Aguirre (2000), Ljung (1982), Hemerly (1996) and Rúbio & Sanchéz (1996).

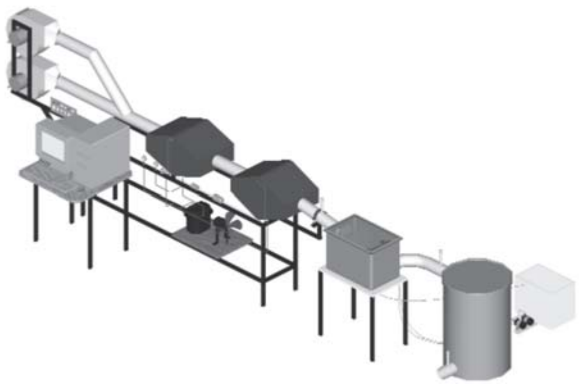

Figure 1- Climatic simulator

An appropriate situation to the adaptive control is when the data of the process are obtained and available in sequence according to each sample time, allowing the estimation of the parameters in real time through the recursive algorithms.

The recursive algorithms use the q(k) calculated before the k instant to obtain the new estimates q(k+1), according to the Eq. (1), and Rúbio & Sanchéz (1996), present in eight steps the algorithm of the Recursive Least Squares (RLS).

$$\hat{\theta}(k+1) = \hat{\theta}(k) + updating \qquad (1)$$

The parametric model of the system in analysis is the ARX. This kind of representation and the system order were chosen after verifying the accomplished tests, where were obtained with less work of the computer. The Eq. (2), shows the SISO ARX model, used in the system, represented by the difference equation and the parameters a_1, a_2, b_1 and b_2 to be estimated.

$$y(k) = a_1 y(k-1) + a_2 y(k-2) + b_1 u(k-1) + b_2 u(k-2) + e(k) \qquad (2)$$

The mathematics model is obtained with the technic of parametric identification in real time, through the collected data directly in the system. To obtain the data, a serie of tests was organized, using the simulator, a temperature transducer, a PC - Pentium 100Mhz computer, with 16Mb of RAM memory, as showed in Fig. 1. The system parameters that will be used in the design and in the establishment of the adaptive controller are estimated in function of the control variable u(k) sent to the system and the response y(k) received from it.

ADAPTIVE CONTROLLER

The main types of adaptive controllers are: the controller by scheduling gain, the adaptive controllers by reference model and the self-tuning regulator (STR). (Astrom, 1995). The STR aims at the automation of the mathematics modelling works, design and the establishment of the control law. In the STR, the estimate parameters of the system are atualized and the controller parameters are obtained by the solution of a design that uses the estimated parameters of the system. A scheme of a STR is presented in Fig. 2.

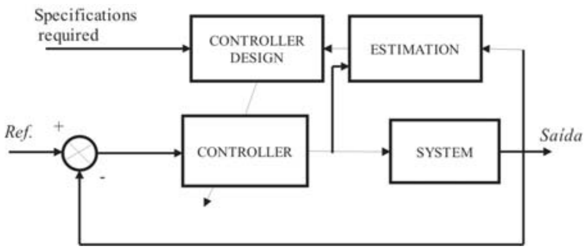

Figure 2- Block diagram of a self-tuning (STR)

Two loops are emphasized in the scheme. The inner loop is composed by the output feedback and by the system. The outer is composed by the estimator, by the control law project and by the tuning controller. The first has the function of estimating the system parameters and for this is used a recursive estimator; the second is a mechanism of adaptation that executes in real time the controller design, using the performance specifications; and the third is a controller of tuning parameters. This control framework is suboptimal and is based on the separation of the identification and control. According to Coelho & Coelho (2004), it is a significant benefit in relation to the other types of controllers, because the variations of the system are followed by the estimator and by the controller in each sample time.

The STR is very flexible considering the choice of the design method of the controller and of the algorithm for the estimation of the system parameters. This approach is based on the certainty equivalent principle (Hemerly, 1996). Various methods of adaptive control can be used in the design stage: the Minimum Variance controller (MV), the General of Minimum Variance controller (GMV), the General Predictive controller (GPC), the Linear Quadratic Gaussian (LQG) and the PID, PI, PD controllers. In this paper will be designed and implemented a self-tuning PI controller by the placement of the poles, using the RLS for the estimation of the system parameters.

Isermann et al (1992) presents the General Linear controller in a z-plane. Rúbio & Sanchéz (1996) presented the z-plane PI controller according to the Eq. (3).

$$G_c(z^{-1}) = \frac{Q(z)}{P(z)} = \frac{q_o + q_1 z^{-1}}{1 - z^{-1}} \quad (3)$$

The technic used to find the controller parameters is the pole placement. The purpose of the method is to design the controller so that all poles of the closed-loop system, assume prescribed values (Isermann et al, 1992). Using the performance specifications imposed to the system, the position of the dominants poles to the closed-loop are determined. The system in analysis is represented by a second order discrete transfer function, as showed in Eq. (4).

$$G_p(z) = \frac{B(z)}{A(z)} = \frac{b_1 z + b_2}{z^2 + a_1 z + a_2} \quad (4)$$

Using the Eq. (3), and the Eq. (4), we have the transfer function of the controller-system in closed-loop (Quiles et al, 2002), showed in the Eq. (5).

$$M(z) = \frac{B(Z)Q(Z)}{A(Z)P(Z) + B(Z)Q(Z)} = \frac{(b_1 z + b_2)(q_0 z + q_1)}{(z^2 + a_1 z + a_2)(z-1) + (b_1 z + b_2)(q_o z + q_1)} \quad (5)$$

The denominator of the Eq. (5), is the characteristic polynomial $P_c(z)$ of the controller-system, as shows the Eq. (6).

$$P_c(z) = z^3 + (a_1 - 1 + b_1 q_0) z^2 + (a_2 - a_1 + b_1 q_1 + b_2 q_0) z + b_2 q_1 - a_2 \quad (6)$$

Defining $z_1 = \nu + j\omega$ e $z_2 = \nu - j\omega$ as the discrete poles wanted for the system in closed-loop, we have the polynomial $P_d(z) = (z - z_1)(z - z_2)$ and the observer polynomial of first order $P_o(z) = (z - p)$, and if they are multipliyed we have the Eq. (7).

$$P_c(z) = \left[(z-\nu)^2 + \omega^2\right](z - p) = z^3 - (2\nu + p) z^2 + (\nu^2 + \omega^2 + 2\nu p) z - \nu^2 p - \omega^2 p \quad (7)$$

Equaling the terms of the same order from the algebric result showed in Eq. (7) to the characteristic polynomial from the Eq. (6), we have:

$$p = \frac{b_1 b_2 \left[(a_2 - a_1) - (\nu^2 + \omega^2)\right] - b_2^2 (a_1 + 2\nu - 1) b_1^2 a_2}{b_1^2 (\nu^2 + \omega^2) + 2\nu b_1 b_2 + b_2^2} \quad (8)$$

$$q_0 = \frac{1 - 2\nu - p - a_1}{b_1} \quad (9)$$

$$q_1 = \frac{a_2 - p(\nu^2 + \omega^2)}{b_2} \quad (10)$$

With the parameters p, q_0 and q_1, the control variable is determined according to the Eq. (11).

$$u(k) = q_0 e(k) + q_1 e(k-1) + u(k-1) \quad (11)$$

Specifications for the system performance

The specifications of performance imposed to the controller-system are: overshoot and time of establishment. The desired poles are determined by this specifications and it is considered that the controller-system follows the characteristic behaviour of the continuous polynomial showed in the Eq. (12).

$$P(s) = s^2 + 2\zeta\omega_n s + \omega_n^2 \quad (12)$$

Where: ω_n - natural angular frequence (rad/s)
ζ - damping factor (...)

The performance specifications in transitory regulations that are required are:

- overshoot (ss) of 20%
- establishment time (t_s) of 240 s, up to ±2% of the final value.

Through the specifications below and using the Eq. (13), we have the required continuous poles in closed-loop, according to Eq. (15).

$$ss = \exp\left(\frac{-\zeta\pi}{\sqrt{(1-\zeta^2)}}\right).100\% \quad (13)$$

$$t_s = \frac{4}{\zeta\omega_n} \quad (\pm 2\%) \quad (14)$$

$$s_{1,2} = -\zeta\omega_n \pm \omega_n\sqrt{(1-\zeta^2)} = \sigma \pm \omega_d i \quad (15)$$

Using the determined values for $s_{1,2}$, we have the equivalent poles to the z-plane, and in consequence, n = 0,9830 and w = 0,0320, which applied in the Eq. (8), Eq. (9), and Eq. (10), in association with the estimated parameters of the system, results in the control variable given in Eq. (11).

The self-tuning PI controller was implemented experimentally through a computer program developed in LabVIEW. Its operation occurs according to the Fig. 3.

With the system parameters given in sample times of 1s, the design by pole placement is executed for the perfomance specifications imposed to the system through the real and imaginary parts of the discrete poles $z_{1,2} = 0,9830 \pm 0,0320i$, in association with the system parameters given by the RLS. Using this values, the program culculates the parameters p, q_0 e q_1, which are used in the calculation of the control variable, that is sent to the physical system and to the RLS estimator that also receives the temperature information from the transducer.

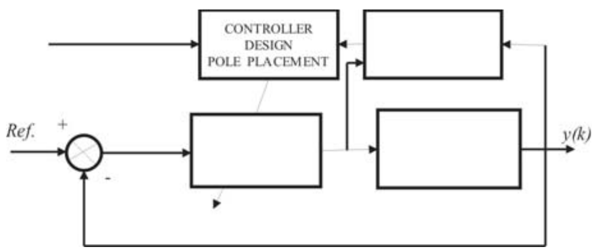

Figure 3 – Self-tuning PI Controller and system

Results

In this paper it was design and implemented a self-tuning PI controller for a non-linear air cooling system a through spraying of water. In this way, the design and implementation are restricted to a conventional PI controller, in much as this system is restricted to one set point. The system performance was estimated for a period of 400s, but the MQR was implemented with a forgetting factor λ=0,99, with the objective of keeping the alert estimator (higher weight for the actualized measures),what helps a permanent estimation of the system dynamics, without wasting the control action.

In the experiment, the temperature of 29,9 °C was adopted as reference signal. The temperature of the test recipient in the start of the cooling process was 33,0 °C, and it was reduced to 29,9 °C, after 350s as showed in Fig. 4. In a period of 240s, the temperature of this recipient approaches to the reference value, with an error of 0,3 °C, that corresponds to a relative error of 1,3%, that is an acceptable value according to the stipulated ones. The Figure 5 shows the control variable and, as we can see, in the period of 125s, it has saturated with the value of 8,1 volts, the maximum of the water pump. The Figure 6 shows the evolution of the estimated parameter of the system. We notice that in the start of the process, these estimated values suffer a variation, and it occurs because the RLS starts with void values. In Figure 7, the evolution of the controller parameter is showed. In the start of the process, this parameters varies for the same fact indicated in the system parameters. The Figure 8 shows the estimation error given for the difference between the real temperature of the process during the air cooling, and the temperature estimated for the RLS. The maximum value of the estimation error is 0,44 °C.

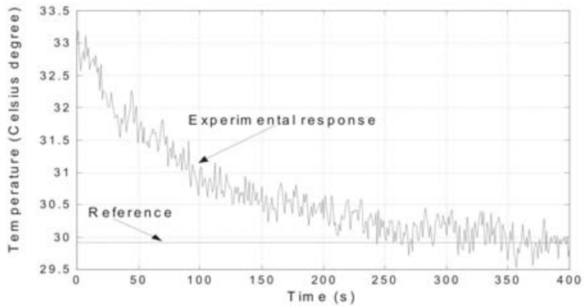

Figure 4 - Experimental response to a reference degree using the self-tuning PI controller

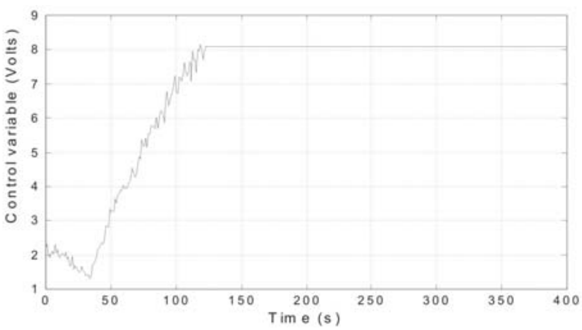

Figure 5 - Control variable of the system by the action of self-tuning PI controller

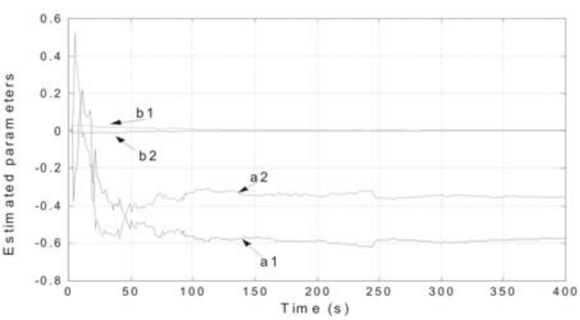

Figure 6- Estimated system parameters

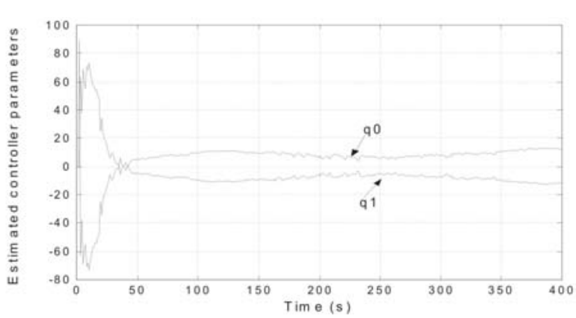

Figure 7- Controller parameters

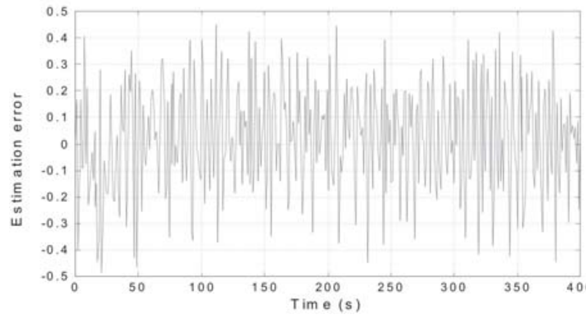

Figure 8 - Estimation error

Conclusion

In this paper, it was designed a self-tuning controller by pole placement to controlling the air temperature through spraying water. The experiments was accomplished by using a proportional controller of parameter $k_p = 5$ in the interval of 0 and 35s, to facilitate the estimation of the system, avoiding an unsuitable action of the adaptive control, and after 35s, the self-tuning PI was activated. According to Fig. 4, the specifications of performance imposed to the system in closed loop were verified. It was observed that after 240s the experimental response approaches to the reference, with a relative error that is an acceptable value according to the stipulated ones. Then, this system obtained the desired performance by using the self-tuning controller by pole placement.

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