QFT CONTROL OF A ROTARY DRYER

D. Jiménez, F. Castaño and F.R. Rubio

Escuela Superior de Ingenieros, Universidad de Sevilla.
Camino de los Descubrimientos s/n, 41092-Sevilla (Spain).
Tlf: +34 954487386, Fax: +34 954487340
e-mail:(danieljj,fernando,rubio)@cartuja.us.es

Keywords: Industrial Processes, Robust Control, Rotary Dryer.

Abstract

This paper describes the design of a multivariable robust controller for a drying process. The plant consists of a co-current rotary dryer to evaporate moisture from a waste product. A methodology to design a multivariable QFT controller and prefilter is shown. The performance obtained with this control strategy has been validated under simulation.

1 Introduction

This paper presents the control of a drying process. This process uses a continuous rotary dryer in which the material is tumbled, or mechanically turned over with extremely hot air which is continuously flowing in the same direction.

The primary control requirement is to maintain the outlet moisture of the product at a constant value, but it is also interesting to control the output temperature if the exhaust air is used by another process.

A robust controller is needed to keep a good performance of the temperature and moisture values due to the system behavior which depends on the operating point.

One approach to designing robust control systems is through the use of Quantitative Feedback Theory (QFT), which was developed by I.M. Horowitz [2]. A multivariable QFT controller is proposed, which will be robust enough to work in an appropriate mode according to the performance of the controlled variables. In previous papers, [4] and [5], other approaches have been used to control this very same plant. A H_∞ controller was presented in paper [4] and a classical PID control in paper [5]. This paper presents a different approach (QFT) to control the plant.

A feedback loop is useful in a control system when dealing with uncertainties and disturbances in the plant. However, the introduction of these feedback loops raises several secondary effects commonly known as "feedback costs" referring to the severity of the control signal needed in order to face the aforementioned problems, including the possible noise in measuring the output signals.

The QFT technique is based on quantifying these effects in order to determine its relative importance in a particular situation. This technique is solved, both for SISO (Single Input Single Output) and MIMO (Multiple Inputs Multiple Outputs), in the classical frequency domain.

The article is organized as follows. In section 2, a description of the system is presented. Section 3 describes the MIMO QFT control strategy that is used. The results obtained by simulation are presented in section 4. Finally, in section 5, the major conclusions to be drawn are given.

2 System Description

The system considered corresponds to a *co-current rotary dryer*, as seen in figure 1, which is located at the laboratories in the School of Engineering of the University of Seville, with a distributed control system that allows the control and integral monitoring of the dryer. The main objective of a rotary dryer is to reduce the moisture of the product at a desired value by heating the product with the air passing through the dryer.

Figure 1: Co-current rotary dryer

Furthermore, the exhaust air generated can be used by another auxiliary process or application. A dryer plant, as shown in Fig. 2, includes, in addition to the drum, many auxiliary elements needed for feeding the product and generating the necessary heat.

In a rotary dryer the wet material is continually transported by the rotation of the drum, and dropped through a hot air current that circulates throughout the dryer. The cylinder has a continuous series of blades inside, so that while it is turning, these blades take the material and throw it in waterfall within the

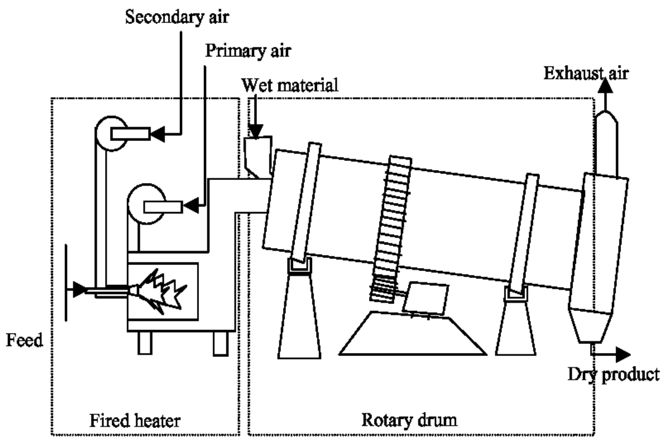

Figure 2: Schematic Diagram

gaseous current. Generally, the drum turns to a speed between 3 to 7 rpm, and the speed of the air varies between 1.5 to 4 m/s, depending on the size of the particles to dry and on the quantity of fine powder formed during the process. The speed of rotation, angle of elevation and air velocity determine the material delay time.

The system can be described by a set of nonlinear equations describing mass and energy balances. A detailed model can be seen in [5].

In order to obtain a robust controller working in all range of operations, a linear model of the system is obtained by linearization at a nominal and for other operating points [5]. Figure 3 shows the nominal operating point (PN) and the working space (before the scaling process). In this case, the plant can be modelled like a multivariable system where the control variables are the mass flow of fuel and the mass flow of wet material. The controlled variables are the moisture of the dry product and the exhaust air temperature, see figure 4. The plant happens to be extremely coupled and ill conditioned. However, the coupling effect can be reduced with the introduction of a decoupling matrix.

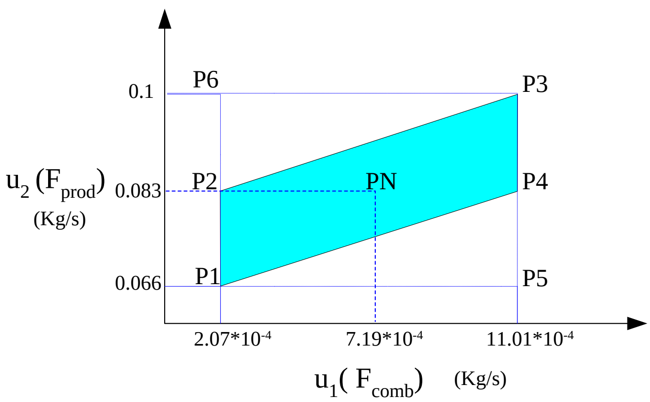

Figure 3: Working area of control variables

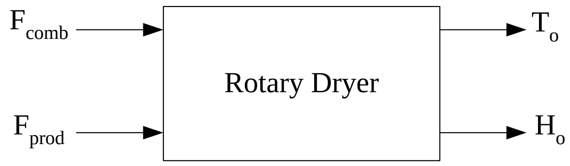

Figure 4: MIMO system

3 Control Strategy

The main problem when dealing with multivariable plants is the existence of coupling effects. If these are non-existing or very small the problem can be solved by treating each loop separately, but most of the times this is not possible so a multivariable design is needed. Amongst the several approaches in multivariable QFT (for instance [3] and [7]), the one followed in this paper is the one explained in Yaniv and al. [8].

The feedback controller design problem can be formulated as two degrees of freedom QFT multivariable problem with tracking specifications, which can be posed under the general configuration shown in figure 5.

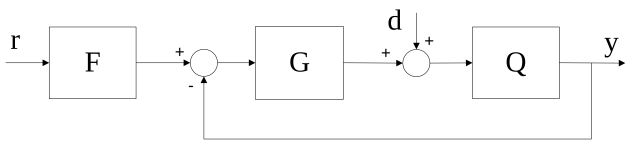

Figure 5: MIMO problem definition

where Q is an LTI system belonging to a set **Q** which includes a variety of possible operating points. A diagonal controller ($G = diag(g_1, g_2)$ for the 2x2 case) and a pre-filter **F** are designed, in such a way that the system remains stable and fulfills the closed loop tracking specifications.

The design process transforms the problem under consideration, figure 5 into the design of two sequential MISO systems [8], as seen in figures 6 and 7 where $\pi_{ij} = [Q^{-1}]_{ij}$ and d_{11}, d_{12}, d_{21}, d_{22} are the disturbances in which the coupling terms are converted to.

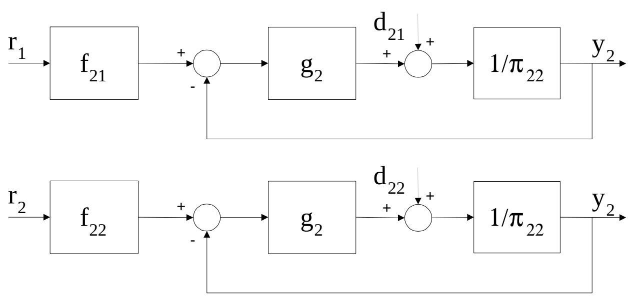

Figure 6: First of the MISO problems to solve

Once the controller g_{22} and pre-filter are designed, the equiva-

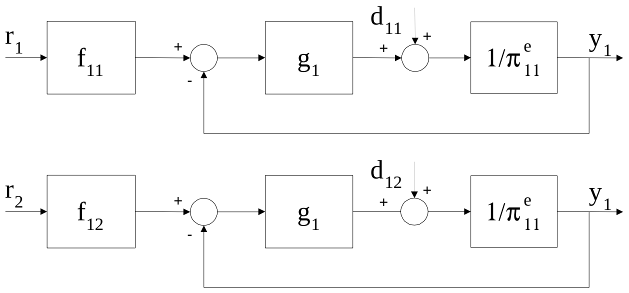

Figure 7: Second of the MISO problems to solve

lent plant $\frac{1}{\pi^e_{11}}$ can be obtained by closing the moisture loop. In this case

$$\pi^e_{11} = \pi_{11} - \frac{\pi_{12}{\cdot}\pi_{21}}{\pi_{22} + g_2}$$

Then, the other controller and pre-filter can be designed as well.

Scaling the plant is important as it makes the process of analyzing and designing controllers easier. To carry out the scaling it is necessary to determine the expected magnitude of the maximum changes of control signals over each input and the maximum variations allowed of the outputs. In this application the following values obtained as maximum variations, before the scaling is done are:

- $\triangle F_{comb\ _{max}} = 5{\cdot}10^{-4}$Kg/s
- $\triangle F_{prod\ _{max}} = 0.02$ Kg/s
- $\triangle T_{o\ _{max}} = 2$ºC
- $\triangle H_{o\ _{max}} = 0.2$ %

Applying the scaling method described in [6], a scaled plant can be obtained.

Several models have been obtained around the nominal operating point to estimate uncertainty as were shown in figure 3. The controller designed must be robust enough so as to assure the fulfillment of all the desired specifications for each of the operating points in the uncertainty set.

Although the method followed here is by itself capable of reducing the coupling effects it has been found under simulation that if first decoupled, the results are even better. So, in the case described in this paper, the transfer matrix Q, shown in figure 5, is the result of applying a decoupling matrix to the open loop plant.

For the 2x2 process, the open loop transfer function is of the form,

$$P(s) = \begin{pmatrix} P_{11} & P_{12} \\ P_{21} & P_{22} \end{pmatrix}$$

A static decoupling matrix is suggested and obtained as follows. It has the form,

$$D = \begin{pmatrix} d_{11} & d_{12} \\ d_{21} & d_{22} \end{pmatrix}$$

For each of the operating points one such matrix can be obtained in the form [1],

$$D_i = P^{-1}(0) = \frac{1}{detP(0)} \begin{pmatrix} g_{22}(0) & -g_{12}(0) \\ -g_{21}(0) & g_{11}(0) \end{pmatrix}$$

where $P(0)$ is non-singular. The transfer function of the decoupled system is $Q(s) = P(s){\cdot}D$. Among this set of matrices the one that reduces the most the coupling effects in all the operating points is chosen.

For both the humidity and temperature loops, the tracking specifications are determined from the requirements of $\pm 10\%$ steady state error, peak overshoot $< 2\%$. and a rise time as fast as possible (less than 5000 seconds for the humidity loop, and less than 500 seconds for the temperature loop). Additionally, robust stability margins for both loops of 4.25 dB gain and 37ºC phase are assumed, which are satisfied when all the perturbed loop gain plots due to uncertainties exist outside of the 4 dB M-Circle. The humidity loop of the system is to be designed to meet the following upper and lower tracking boundary specifications:

$$a_{22}(j\omega) \leq \left|\frac{y_2}{r_2}\right| \leq b_{22}(j\omega)$$

where b_{22} and a_{22} are the maximum and minimum desired values for the response:

$$b_{22}(s) = \frac{5.5{\cdot}10^{-5}s + 2.75{\cdot}10^{-7}}{s^2 + 0.0008s + 2.5{\cdot}10^{-7}}$$

$$a_{22}(s) = \frac{2.25{\cdot}10^{-7}}{1000s^3 + 2s^2 + 0.00125s + 2.5{\cdot}10^{-7}}$$

In the same form, the temperature loop of the system is to be designed to meet the following upper and lower tracking boundary specifications:

$$a_{11}(j\omega) \leq \left|\frac{y_1}{r_1}\right| \leq b_{11}(j\omega)$$

where b_{11} and a_{11} are the maximum and minimum desired values for the response:

$$b_{11}(s) = \frac{0.0002816s + 7.04{\cdot}10^{-5}}{s^2 + 0.0128s + 6.4{\cdot}10^{-5}}$$

$$a_{11}(s) = \frac{3.802{\cdot}10^{-5}}{2s^3 + 1.026s^2 + 0.01308s + 4.225{\cdot}10^{-5}}$$

The main part of the QFT system consists in the shaping of the controller and pre-filter to fulfill the specifications given before (in the form of contour bounds). These bounds come from the graphic analysis of the inequations representing each of the MISO problems, such as:

$$a_{21}(\omega) \leq \left|\frac{g_2{\cdot}f_{21} - \pi_{21}{\cdot}t_{21}}{\pi_{22} + g_2}\right| \leq b_{21}(\omega)$$

$$a_{22}(\omega) \leq \left|\frac{g_2{\cdot}f_{22} - \pi_{21}{\cdot}t_{12}}{\pi_{22} + g_2}\right| \leq b_{22}(\omega)$$

$$a_{11}(\omega) \leq \left| \frac{g_1 \cdot f_{11} - \pi_{12}^e \cdot f_{21}}{\pi_{11}^e + g_1} \right| \leq b_{11}(\omega)$$

$$a_{12}(\omega) \leq \left| \frac{g_1 \cdot f_{12} - \pi_{12}^e \cdot f_{22}}{\pi_{11}^e + g_1} \right| \leq b_{12}(\omega)$$

where

$$\pi_{12}^e = \frac{\pi_{12} \cdot g_2}{\pi_{22} + g_2}$$

By replacing the elements of the closed loop transfer function (t_{ij}) with the maximum desired values (b_{ij}) and also taking into account the inequations describing robust specifications for each of the four problems, the complete set of specifications bounds can be obtained. In figure 8 the bounds for the humidity loop and the representation of the nominal open loop functions are shown . As can be seen, the specifications are fulfilled at lower frequencies but not so at the highest.

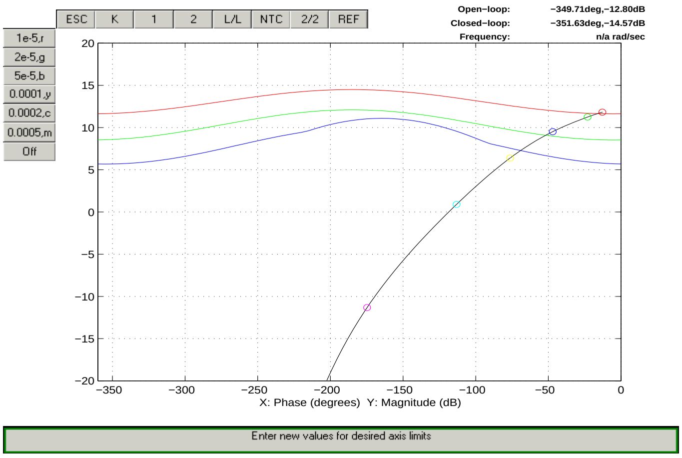

Figure 8: Controller shaping for the moisture loop

Figure 9 shows the shaping of the pre-filter for the humidity loop. As can be seen, the ill conditioning effect can not be avoided entirely around the bandwidth frequency.

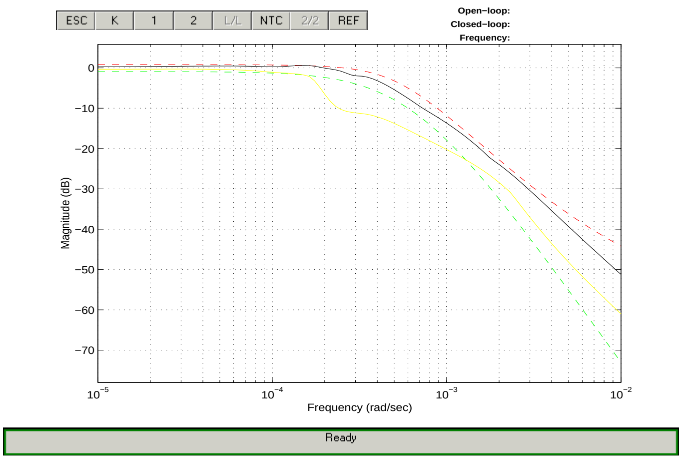

Figure 9: Pre-filter shaping for the moisture loop

Since the more important signal to be controlled is the moisture, a pre-filter for the later loop has not been considered.

The multivariable controller is obtained, pre-multiplying the diagonal one by the decoupling matrix. This controller has also been designed so the effect of possible noise in the measuring of the moisture signal is rejected.

4 Simulation Studies and Results

After translating the specifications from the time domain to the frequency domain, they have been relaxed at high frequencies, even more for the temperature loop. The resulting controller for the system is given by the equations:

$$G = \begin{pmatrix} \frac{2.54 \cdot 10^{-7}}{s(s^2+0.02813s+0.00012204)} & 0.02675 \\ \frac{1.103 \cdot 10^{-6}}{s(s^2+0.02813s+0.00012204)} & 4.389 \end{pmatrix}$$

Although no specification has been imposed for the control signals it can be seen afterwards that the results obtained for these signals are under the maximum allowed limits for each of the operating points.

In figure 10, simulation results are shown (for the nominal and the other four operating points considered), for the humidity response when an input reference step in humidity is applied. In it, the dashed line represents the maximum desired specification for the humidity response, while the dotted one is the minimum.

The reduced coupling effect of the moisture loop in the temperature loop is shown in figure 11. Although it may appear that the oscillations are important, it is not so taking into account the peak values of less than 0.1 °C.

In figures 12 and 13 the results for the two control signals are presented, verifying that the maximum peak values are under the saturation values for these signals. Notice that the fuel control signal is measured in seconds. This is the time the valve must be opened for the necessary amount of fuel to pass.

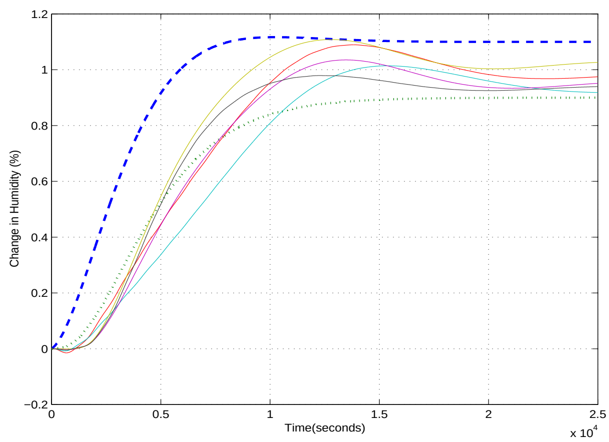

Figure 10: Simulation result for the moisture loop

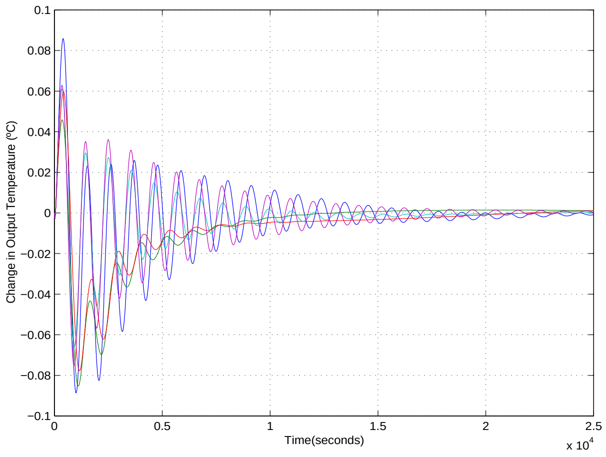

Figure 11: Effect of a step reference in humidity in the temperature loop

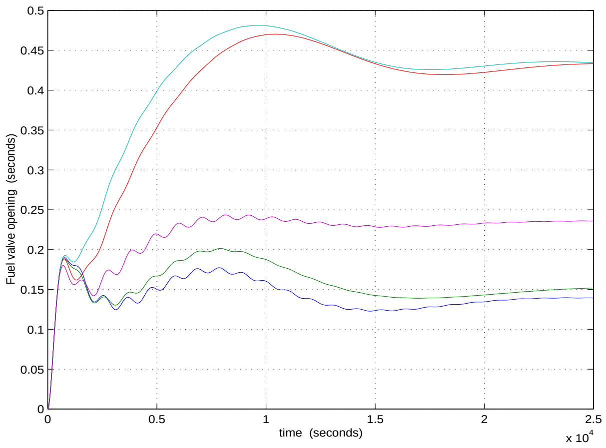

Figure 12: Time response of the first control signal (Fuel feed)

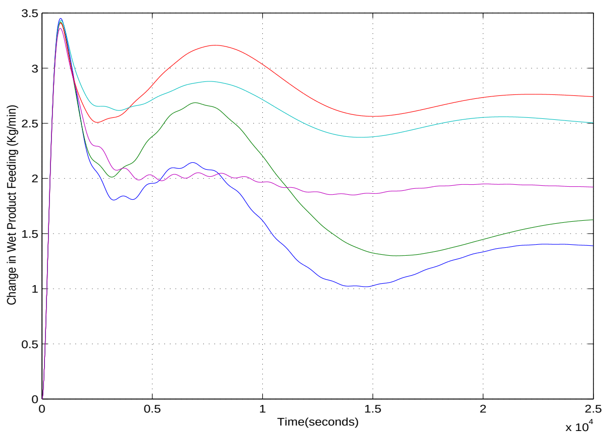

Figure 13: Time response of the second control signal (Product feed)

Simulation results without the decoupling matrix

In order to demonstrate that the former strategy by itself is not good enough to diminish the coupling effect of the plant, some results without the decoupling matrix are presented.

In this case, the design process is the same, but the decoupling matrix is not present. In figures 14 and 15 the time responses for the two loops when an input reference step in humidity is applied are given. Although the coupling effect is reduced, it is not as good a result as it is with the coupling matrix.

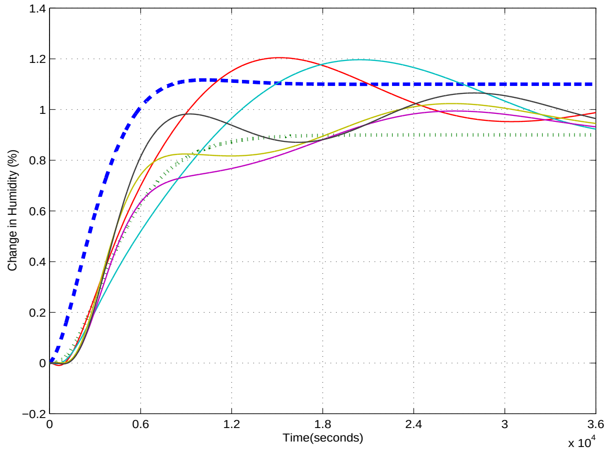

Figure 14: Simulation result for the moisture loop without the pre-decoupling matrix

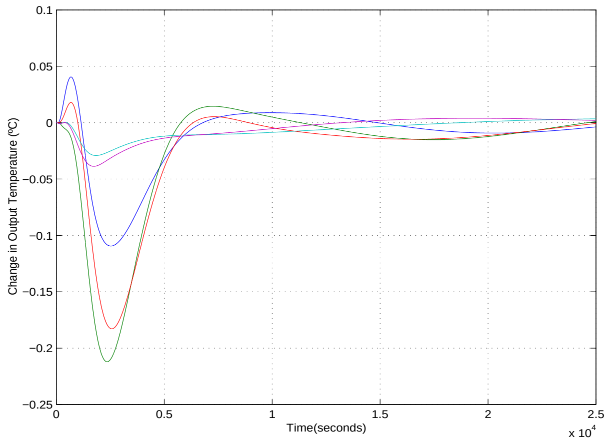

Figure 15: Effect of a step reference in humidity in the temperature loop without the pre-decoupling matrix

5 Conclusions

Control strategies and applications of Multivariable QFT controller to a co-current rotary dryer have been presented. In order to handle the interactions of the system, a decoupling matrix has been proposed to obtain a reduction in the coupling effects. The controller has been tested by simulation and some of the results of these tests are shown. This controller is currently being implemented in a SCADA system used to control a real plant located at the laboratories in the School of Engineering of the University of Seville.

Acknowledgements

The authors would like to acknowledge CICYT for funding this work under grant DPI2001-2424-C02-01.

References

[1] K.J Aström, K.H Johansson and Q.G. Wang. "Design of decoupled PID controllers for MIMO systems", (2001).

[2] I.M. Horowitz. "Survey of Quantitative Feedback Theory (QFT)", International Journal of Control, Vol. 53-2, pp 255-291 (1991).

[3] C.H. Houpis and S.J. Rasmussen. "Quantitative Feedback Theory. Fundamental and Aplications", Marcel Dekker Inc, New York (1999).

[4] F. Castaño, M.G. Ortega and F.R. Rubio. "A Multivariable H_∞ Controller for a Rotary Dryer.",15th World Congress International Federation of Automatic Control (IFAC-02), 21-26 July, Barcelona, España, 2002. .

[5] F.R. Rubio, C. Bordons, J. Holgado and R. Arjona. "Modelling and PID Control of a Rotary Dryer." . PID'00 IFAC Workshop on Digital Control: Past, present and future of PID control. Terrassa (Spain), 5-7 April 2000.

[6] S. Skogestad and I. Postlethwaite. "Multivariable feedback control: Analysis and design", Wiley-Sons, New York, (1996).

[7] I.E. Santamarina and M.G. Sanz. "Diseño de Controladores Multivariables QFT de Matriz Completa", Ph.D (In Spanish) (2001).

[8] Oded Yaniv. "Quantitative Feedback Design of Linear and Nonlinear Control Systems". Kluwer Academics Publishers, (1999).