Independent Design of Multivariable Controllers for A 24-Tray Separating Mixture of Methanol and Water

Elham Sareban[1], Amir Torabi[2], Seyed Kamal-e-ddin Mousavi Mashhadi[3]
1- Department of Electrical Engineering, Khorasan Institute of Higher Education, Mashhad, Iran
Email: Elham.Sareban@gmail.com
2- Department of Electrical Engineering, Khorasan Institute of Higher Education, Mashhad, Iran
Email: Amirtorabi1@gmail.com
3- Department of Electrical Engineering, Iran University of Science and Technology, Tehran, Iran
Email: sk_mousavi@iust.ac.ir

Received: February 2014 Revised: June 2014 Accepted: August 2014

ABSTRACT
Most industrial processes are characterized with large uncertainties. To deal with these kinds of processes and achieve fast and accurate control in a stable fashion, the multiple-model control methods have been demonstrated to be very effective. It is difficult to build the precise mathematic model of the object and to accurately control the object with the traditional control methods. This paper applies H-infinity robust control strategies to a 24-tray separating a mixture of methanol and water. The idea has favorable controls on control targets (rise time, settling time, overshoot and undershoot, the interaction between input and output) and help on stability of the system output. Then in order to show that the proposed controller affords a good robust performance consistently we have implemented four controllers.Performance analysis of the H-infinity robust controller, Model Predictive Control (MPC), conventional PID controller and also LQG/LTR has been done using MATLAB. The comparison of various time domain parameters was done to prove that the H-Infinity robust controller has best time characteristics and in face with uncertainties has better reacts as compared to other controllers. Beside this, MPC controller has satisfied result in robust stability.

KEYWORDS: H-Infinity Robust Controller, PID Controller, Model Predictive Control, LQG/LTR Controller, Uncertainty.

1. INTRODUCTION

The process of designing a control system usually makes many demands of the engineer or engineering team. These main demands emerge in two steps design procedure as follows:
1- Design a controller.
2- Analyze the resulting controlled system to see if the specifications are satisfied; and if they are not satisfied modify the specifications or the type of controller [1].
Most of chemical processes are fundamentally multi-input/multi-output (MIMO) systems. In spite of increasing advanced multivariable controllers, the multi-loop PI/PID control using multiple single-input/single-output (SISO) PI/PID controllers stays the standard for controlling MIMO systems with modest interaction because of its simple and failure tolerant structure and appropriate operation [2-3]. Moreover, due to process and loop interactions, the design and tuning of multi-loop controllers is much more hard compared with that of single-loop controllers. Since the controllers interact with each other, the tuning of one loop cannot be done individually. Using the tuning models for a SISO system to multi-loop systems mostly leads to poor operation and stability. Many of researches have been focused on how to efficiently take loop interactions into account in the multi-loop controller design. Much model have been proposed, that contain the detuning method, sequential loop closing (SLC) approach, relay auto-tuning method, and independent loop method.
At first Mayne [4] introduced the well-known SLC approach for the design of multi-loop controllers and later studied by Hovd and Skogestad [5]. In this approach, the controllers are tuned sequentially, wherein the fastest loops controller should be tuned first by considering a selected input–output pair; this loop is then closed and then the controller of the lower loops is tuned for a second pair while the first control loop remains closed and so on. The sequential loop closing approach (SLC) is simpler than the detuning approach as each controller is designed using SISO design approaches.

Authors in [6–9] used the relay feedback method to the design of each corresponding SISO controller, in relay auto-tuning for the multi-loop control system. The control loops are tuned sequentially or simultaneously. Moreover, based on sequential algorithm, the multi-loop control system is designed in a series of SISO design problems and the interaction taken into account in a consecutive fashion.

Luyben proposed the biggest log modulus tuning (BLT) method that is a typical example of the detuning method [10], wherein by ignoring process interactions from other loops, each individual controller is first designed based on the Ziegler–Nichols (Z–N) tuning rules [11]. Then, the interactions are taken into account by detuning each controller until the multivariable Nyquist stability is satisfied.

Although, a disadvantage is that the controller settings are made more conservative, the advantage of this approach is due to the easiness in operation and comprehensibleness for control engineers.

It is easy for SISO processes to tune PID controller parameters, such as Ziegler-Nichols (Z-N) method, internal model control (IMC) based method, optimization method, gain-phase margin method and so on. But for multivariable system because between the input and output has the coupling relations, therefore the PID parameters tuning is complex.

There are a number of reported studies in the literature [12–16] introduced the concept of an effective open-loop transfer function (EOTF) to take into account the loop interactions in the new design of a multi-loop controller. Appling this concept, the design of a multi-loop controller can be wisely converted to the design of a single-loop controller.

In [12], based on structure decomposition, the multi-loop control system is absolutely separated into equivalent independent SISO loops, as a result, the effects of the method and controller on the loop interaction and subsequent system properties, such as right half plane (RHP) zeros and poles, integrity, and stability, are explained. For an individual control loop, researchers have proposed the dynamic relative interaction to derive the multiplicative model factor (MMF) [13]; then the equivalent transfer function is achieved by multiplying the main loop transfer function with the estimated MMF within the vicinity of the individual control loop critical frequency.

The effective open-loop transfer function (EOTF) is formulized without previous knowledge of controller dynamics in other loops and the controller is individually planned for equivalent single loops [14]. With the same objective, authors in [15] proposed the EOTF supplies both gain and phase information for multi-loop controller design in four ways.

Authors In [16] presented the benefits of the EOTF including decreased modeling requirements and ease of implementation, while the potential disadvantage is decrease in achievable control performance due to limited controller structure.

The control operation of the multi-loop systems is also closely related to the control loop pairing.

Applying the steady-state gain and bandwidth of the process transfer function element, the relative effective gain array (REGA) has been suggested in [17] that combines the benefits of both the RGA and DRGA.

Relative normalized gain array (RNGA) is applied for loop interaction measurements [18]. Considering both the steady-state and transient information of the process transfer function into account, it provides more accurate interaction assessment than the conventional RGA based loop paring criterion.

In the last decade, model predictive control (MPC) has become an increasingly popular control technique used in petrochemical industries and is beginning to attract interest from other process industries [19-23]. For example authors in [20] reports more than 4,500 applications spanning a wide range from chemicals to aerospace industries are reported. Also many theoretical and implementation issues of linear MPC theory have been studied so far [24-25].

In this paper, we utilize robust control strategies to design multivariable H-infinity controllers.

Then, using the principles of modern control we designed four controllers consideration following control targets:

1- Eliminate the oscillations frequency (speed)
2- Reduce the amplitude of *overshoot and undershoot*
3- Reduce the rise time or descent time and *settling time*
4- Eliminate the interaction between inputs and outputs

The designed controllers are implemented to verify their performance and finally despite uncertainty H-infinity robust control method shows better response.

2. THE CONTINUOUS-TIME LINEAR QUADRATIC GAUSSIAN FORMAT

The system model is assumed to be as follows:

$$\dot{x} = Ax + Bu + Gw \tag{1}$$

Where X is the random state variable with the mean and variance at time zero, the system matrices A and B and the system input u and w are Gaussian noise process w ≈ N (0, Q) and G is a matrix-weighted noise, Quadratic performance index as follows:

$$J[X(t_0),t_0] = \frac{1}{2}X^T(T)S(T)X(T) + \frac{1}{2}\int_{t_0}^{T}(X^T QX + u^T Ru)\,dt \tag{2}$$

Where S (T) ≥ 0 is a symmetric weighting matrix R> 0, Q ≥ 0 and weight matrix input mode and Plant and weighting matrices can be functions of time.
Setting the control signal u*(t) in the interval [t_0, T] is a promising way to minimize the cost function j (t_0) = E {J [x (t_0), t_0]}, where x (T), free T is constant in time. This issue is known as the linear quadratic Gaussian LQG control. The general structure of this controller is shown in Fig. 1.

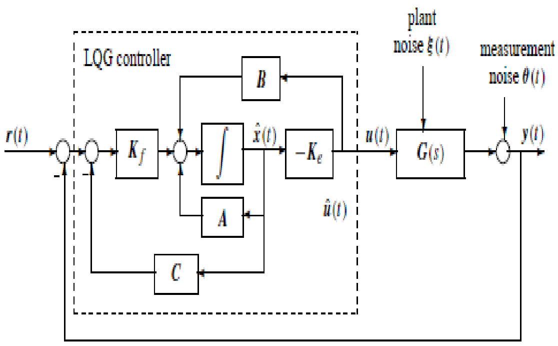

Fig. 1. General structure of LQG controller [26]

2.1. Known States

First, we assume that the state x(T) is exactly measurable. The linear feedback control law as follows:

$$u(t)=-K(t)x(t) \tag{3}$$

The relationships that minimize the performance index, is as the following that feedback gain vector is defined as follows:

$$K(t)= R^{-1} B^T S(t) \tag{4}$$

Due to this, $-\dot{S} = A^T S + SA - SBR^{-1} B^T S + Q$ (5)

The cost function j(t_0) Comes to the optimal mode j*(t_0) that:

$$j^* (t_0)=\frac{1}{2} E[X^T(t_0)S(t_0)X(t_0)]+ \frac{1}{2} \text{trace}\int_{t_0}^{T}(SGQ' G^T)dt \tag{6}$$

The optimal control signal u*(t) is obtained as follows:

$$u^*(t)= R^{-1} B^T S_\infty \tag{7}$$

That S_∞ is a limit and positive definite solution of the Riccati equation. ($\dot{S} = 0$)

2.2. Uncertain States

It is assumed that all states x(t) are not exactly measurable, Instead, the measurement vector Z (t) is defined by the following equation:

$$Z(T)= Hx+v \tag{8}$$

Where v ≈ N (0, R_V) is a Gaussian noise measurements. The control signal u (t) is only an estimate of x(t), which is derived from the measurements, is dependent. By optimizing the cost function j (t_0) = E {J [x (t_0), t_0]} and swept backward by using two sets of matrix Riccati equations gets for control and estimates process. Estimating equation is as follows:

$$\dot{P} = AP+ GQ'G^T - PH^T(R_v)^{-1} HP \tag{9}$$

$$P(t_0)= P_0 \tag{10}$$

$$L= PH^T(R_v)^{-1} \tag{11}$$

$$\dot{\hat{x}}= A\hat{x}+ Bu = L(z- H\hat{x}) \tag{12}$$

Kalman filter Gain and L (t) are the state estimate of the error covariance matrix P . In these conditions, Gain optimal control $\hat{x}(t)$ is the estimated signal $x(t)$, that instead of applying to the $K(t)$ linear feedback control law, it is as follows:

$$u(t)= -K(t)\hat{x}(t) \tag{13}$$

The equations for K (t) will be the above equations. Using the equations above and paste it in cost function, cost function for optimal control and optimal estimation can be achieved as follows:

$$j^*(t_0)= \frac{1}{2} E[X^T(t_0)S(t_0)X(t_0)] + \frac{1}{2}\text{trace}\int_{t_0}^{T}(SGQ' G^T)dt + \frac{1}{2}\text{trace}\int_{t_0}^{T}(K^T R_V KP)dt \tag{14}$$

It should be noted that the first sentence of the LQ regulator has been confirmed. The second term represents an increase in costs due to uncertainty in the perturbation signal x(t) which is due to the noise process. The last sentence represents an increase in costs due to the uncertainty in the measurements.
LQG regulator design to the reference input signal r(t)

3. H-NFINITY ROBUST CONTROLLER DESIGN

In this section, the robust control algorithms are introduced, and applied to design H-infinity controllers to provide the maximum stability bound for a 24-tray separating a mixture of methanol and water system.
Formulation of design problem H-infinity is shown in a general framework in Figure 2. Standard Performance characteristics and uncertainty multiplied augmented are specified. The input weights W_c and W_s play an important role in control performance. The weights are determined by the physical nature of the problem, finally by trial and error, the exact amount weight will be determined.

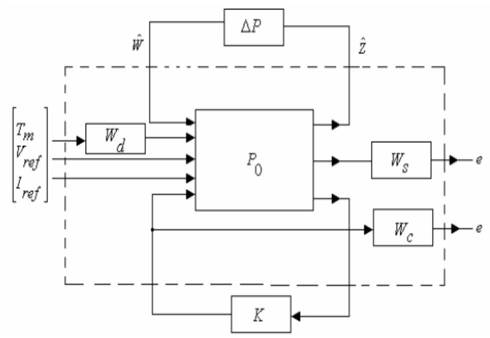

Fig. 2. Standard form of robust control problem [27]

$$P:\begin{cases} \dot{x}=Ax+B_u u_c+B_w w \\ z=C_z x+D_{zu} u_c + D_{zw} w \\ y=C_y x + D_{yw} w \end{cases} \quad (16)$$

Where $x \in R^{n_x}$ is State variable, $w \in R^{n_w}$ is external input (noise, disturbance and reference input), $u_c \in R^{n_u}$ is Control input, $z \in R^{n_z}$ is Controlled output and $y \in R^{n_y}$ is Output. Necessary Assumptions for the control of H_2, H-infinity are true.

Display state space controller and the closed-loop system as follows:

$$\begin{cases} \dot{x}_c = F x_c + G y \\ u_c = H x_c + J y \end{cases} \quad (17)$$

$$\begin{cases} \dot{x}_{cl} = A_{cl} x_{cl} + B_{cl} w \\ z = C_{cl} x_{cl} + D_{cl} w \end{cases} \quad (18)$$

$$\begin{bmatrix} A_{cl} & B_{cl} \\ C_{cl} & D_{cl} \end{bmatrix} = \begin{bmatrix} A + B_u J C_y & B_u H & B_w + B_u J D_{yw} \\ G C_y & F & G D_{yw} \\ C_z + D_{zu} J C_y & D_{zu} H & D_{zw} + D_{zu} J D_{yw} \end{bmatrix} \quad (19)$$

$T_i(s) = L_i T(s) R_i$ is the function of external input , $w_i = R_i^{-1} w$, To the controlled output, $z_i(s) = L_i z$, which is used to quantify various functional purposes. Realization of $T_i(s)$ state Space , like this $\begin{pmatrix} A_{cl} & B_i \\ C_i & D_i \end{pmatrix}$ is where:

$$B_i = \begin{pmatrix} B_{wl} + B_u J D_{ywl} \\ G D_{ywl} \end{pmatrix} \quad (20)$$

$$B_{w_1} = B_w R_i \quad (21)$$

$$C_i = (C_{z_1} + D_{z_l u} J C_y D_{z_l u} H) \quad (22)$$

$$C_{z_l} = L_i C_z \quad (23)$$

$$D_i = D_{z_l w_l} + D_{z_1 u} J D_{yw_l} \quad (24)$$

$$D_{z_l w_l} = L_i D_{zw} R_i \quad (25)$$

$$D_{yw_l} = D_{yw} R_i \quad (26)$$

$$D_{z_l u} = L_i D_{zu} \quad (27)$$

Standard performance benchmarks are H_2, H_∞. To express the problem into linear matrix inequalities Lyapunov matrix, $I \in I = \{H_2, H_\infty\}$ P_i, is divided into the following:

$$P_i = \begin{bmatrix} Y_i & N_i \\ N_i^T & * \end{bmatrix}, P_i^{-1} = \begin{bmatrix} X_i & M_i \\ M_i^T & * \end{bmatrix} \quad (28)$$

Applying Y_i, X_i, N_i, M_i in the above relation, it will choose N_i, M_i so that:

$$M_i N_i^T = 1 - Y_i X_i \quad (29)$$

Condition for the closed-loop system stability by controlling design, $P_i > 0$, in this way comes:

$$\begin{bmatrix} X_i & I \\ I & Y_i \end{bmatrix} > 0 \quad (30)$$

Design variables , F_i, G_i, H_i, J_i, (the space state controller) change by using the relationship $\hat{F}_i, \hat{G}_i, \hat{H}_i, \hat{J}_i$:

$$\hat{F}_i = N_i F_i M_i^T + N_i G_i C_y X_i, Y_i B_u H_i M_i^T + Y_i (A + B_u J_i C_y) X_i \quad (31)$$

$$\hat{G}_i = N_i G_i + Y_i B_u J_i \quad (32)$$

$$\hat{H}_i = H_i M_i^T + J_i C_y X_i \quad (33)$$

$$\hat{J}_i = J_i \quad (34)$$

4. ROBUST PID CONTROLLER DESIGN

Because the H-infinity controllers designing by using two Riccati equations are of the same order as that of the generalized plant, so the final controller may be high. About 90% of industrial controllers are of PID-type. So it is useful if the high-order controllers can be reduced to PID control structure.

The principle structure of the conventional PID controlled system consists of PID controllers and plant as shown in Fig. 3.

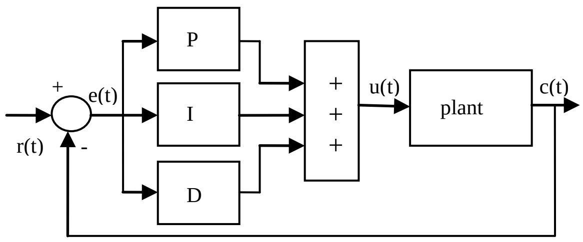

Fig. 3. The conventional PID control system [28]

In the state-space domain consider a controller $K(s)$, given by a state-space realization of the form

$$\begin{cases} \dot{x} = A_k x + B_k y \\ u = C_K z + D_k \end{cases} \quad (35)$$

Find a similarity transformation T such that

$$TA_k T^{-1} = \begin{bmatrix} 0 & 0 \\ 0 & a_2 \end{bmatrix} \quad (36)$$

Where a_2 is nonsingular. This transformation can be computed using the eigenvalues decomposition of A_k . With this T , C_k and B_k are decomposed as follows:

$$C_k T = \begin{bmatrix} c_1 & c_2 \end{bmatrix}, T^{-1} B_k = \begin{bmatrix} b_1 \\ b_2 \end{bmatrix} \quad (37)$$

A high PID approximation of the form

$$K_{PID}(s) = K_P + K_i/s + K_d s \quad (38)$$

That $K_i = \dfrac{1}{T_i}$ (39)

And $K_d = \dfrac{T_d}{1 + s/p_d}$ (40)

It can be obtained by truncating the Maclaurin expansion of the controller with respect to the variables*:*

$$\begin{aligned} K(s) &= C_k \left(sI - A_k\right)^{-1} B_k + D_k \\ &= \begin{bmatrix} c_1 & c_2 \end{bmatrix} \left(sI - \begin{bmatrix} 0 & 0 \\ 0 & a_2 \end{bmatrix} \right)^{-1} \begin{bmatrix} b_1 \\ b_2 \end{bmatrix} + D_k \quad (41) \\ &= \frac{c_1 b_1}{s} + (D_k - c_2 a_2^{-1} b_2) - c_2 a_2^{-2} b_2 s + O\left(|s|\right) \end{aligned}$$

Since we are most interested in the low frequency band, so we have

$$K_p = D_k - c_2 a_2^{-1} b_2, K_i = c_1 b_1, K_d = -c_2 a_2^{-2} b_2 \quad (42)$$

It is then clear that the resulting PID controller achieves good approximation at low frequencies, especially the integral action, so we can expect that the resulting PID controller will retain the disturbance rejection performance of the high-order controller.

4.1. Model Predictive Control

Predictive control has been known by several names over the years: Model Based Predictive Control (MBPC), Generalized Predictive Control (GPC), Dynamic Matrix Control (DMC) and Sequential Open-Loop Optimizing Control (SOLO), among others [29-37].

Block diagram of the Model Predictive Control (MPC) show in Fig. 4.

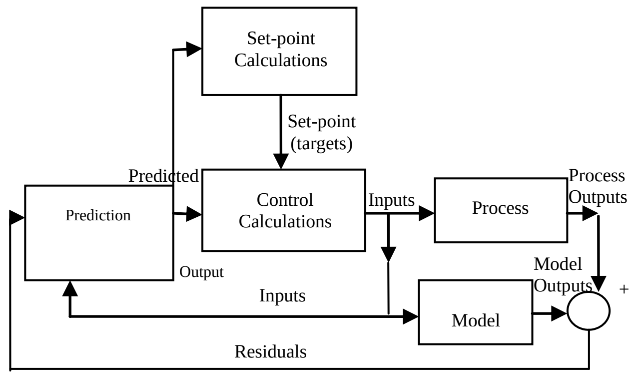

Fig. 4. The Model Predictive Control (MPC) block diagram [38]

Matlab's Model Predictive Control Toolbox was chosed that gathers software capable of design, analyses and implement the desired control system, and provides a convenient graphical user interface that supports customization.

5. THE SIMULATION RESULTS

A 24-tray tower separating a mixture of methanol and water, examined by Luyben [10], has the following transfer function matrix [39]:

$$G(s) = \begin{bmatrix} \dfrac{-2.2e^{-s}}{7s+1} & \dfrac{1.3e^{-0.3s}}{7s+1} \\ \dfrac{-2.8e^{-1.8s}}{9.5s+1} & \dfrac{4.3e^{-0.35s}}{9.2s+1} \end{bmatrix} \quad (59)$$

To investigate the nature of system, the output step response of the system is shown in Figure 5, According to the response, it can be found that the interaction between the input and the output is high and the system is not damped optimal response.

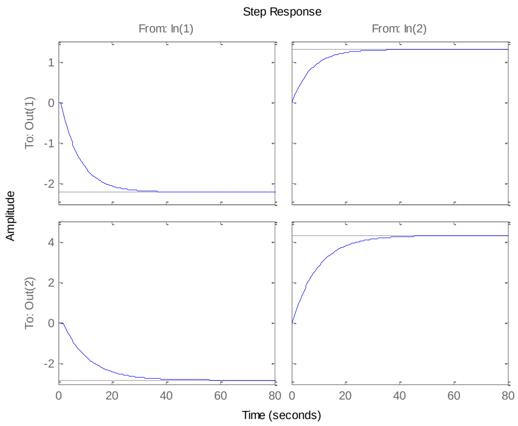

Fig. 5. Output system for Step input

The PID controller parameters are shown in Table I.

Table 1. PID controller parameters

K_p	T_i	T_d	P_d
10.4357	0.40933	0.060617	0.5988

The step response for PID controller is shown in Figure 6. We see that the response for the PID controller has zero steady-state error although the settling time is great.

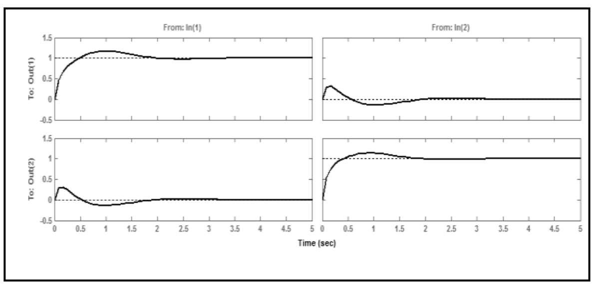

Fig. 6. Step response for PID controller

Fig. 7 shows the multistep response system of the PMC controller. Although applying the multi-step inputs of the system in various times, the robust stability is satisfied.

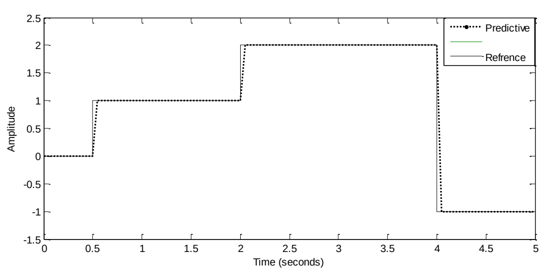

Fig. 7. Multistep response for PMC controller

By applying three separate controllers without and with using the uncertainty as shown in Figures 8 and 9, H-infinity Robust control works best in against of uncertainty.

As seen from Figures 8, H-infinity controller has the best response because the interaction between input and output is much smaller and the response is faster.

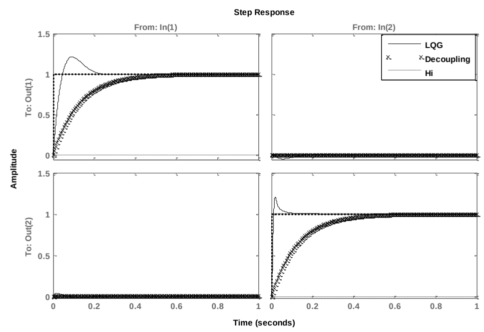

Fig. 8. Compared output system to a step input with LQG, Decoupling and H-infinity controller without uncertainty

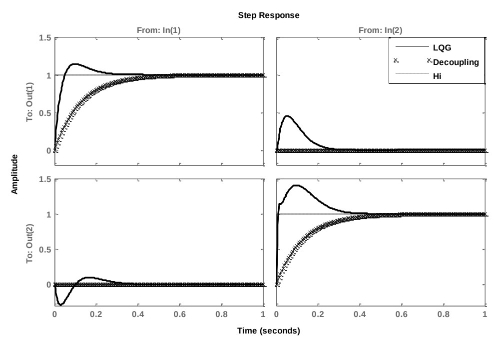

Fig. 9. Compared output system to a step input with LQG, Decoupling and H-infinity controller with uncertainty

6. CONCLUSIONS

The interplay between input/output variables is a usual phenomenon and the principal obstacle faced with the designing of multi-loop controllers for interacting multivariable processes.

In this paper, the robust control algorithms are applied to design H-infinity controllers to provide the maximum stability bound for a 24-tray separating a mixture of methanol and water. In order to establish control purposes such as reduce the amplitude of overshoot and undershoot, Frequency oscillations system, the interaction between input and output model and a faster step response system, we design a H-infinity robust controller by using the principles of modern control.

Then in order to show that the proposed controller affords a good robust performance consistently we

have implemented LQG/LTR, Decoupling controllers. The first design method is LQG/LTR, that proposes eigenvalue for closed loop LQG design and then in LTR method. These eigenvalues will be re-adjusted by gain adjusting in LQR method. The other method is decoupling in which a PI-controller is combined with this case. The third controller is PID controller, that on the other hand, are simple, easy to implement, and comparatively easy to re-tune on line. Finally we applied H-infinity robust controller because its setting of controller is higher than LQG/LTR method. To obtain robust stability by using dynamic output feedback, H_2 and H-infinity robust controllers for a class of indefinite linear systems are proposed. Uncertainties are of limited norm.
The results showed that when there is no uncertainty in the system and also by considering the system with uncertainty, however the system stability is maintained and the proposed H_∞ control schemes have good effect, fast response strong adaptability and the best step response. However, Model Predictive Control (MPC) has also acceptable result in robust stability.

REFERENCES

[1] S. Skogestad, I. Postlethwaite, "**Multivariable feedback control Analysis and design",** [Online]. Available:http://www.kjemi.unit.no/pub/che/Control.Group/Skogestad/bo .

[2] P.J. Campo, M. Morari, **"Achievable closed-loop properties of systems under decentralized control: conditions involving the steady-state gain,"** IEEE *Trans.Automat. Control*, Vol.39, No.5, pp.932–943, 1994.

[3] J. Lee, W. Cho and T.F. Edgar, **"Multi-loop PI controller tuning for interacting multi-variable processes,"** *Compute. Chem. Eng*. Vol.22, No.11 , pp. 1711–1723, 1998.

[4] D.Q. Mayne, "**The design of linear multivariable systems",** *Automatically*, Vol.10, No.4 pp.207-201, 1973.

[5] M. Hovd, S. Skogestad, **"Sequential design of decentralized controllers,"** *Auto metical*, Vol.30, No.10, pp.1601–1607, 1994.

[6] K.J. Åström, T. Hägglund, ***Automatic Tuning of PID Controllers,*** *Instrument Society of America, Research Triangle Park, NC*, 1988.

[7] A.P. Loh, C.C. Hang, C.K. Quek and V.U. Vasnani, **"Auto-tuning of multi-loop proportional-integral controllers using relay feedback,"** *Ind. Eng. Chem. Res*, Vol32, No.1, pp.1102-1107, 1993.

[8] S.H. Shen, C.C. Yu, **"Use of relay-feedback test for automatic tuning of multivariable systems,"** *AIChE J*, Vol.40, No.2, pp/ 627–646, 1994.

[9] Y. Halevi, Z.J. Palmor and T. Efrati, **"Automatic tuning of decentralized PID controllers for MIMO processes,"** *J. Process Control*, Vol.7, No.2, pp.119–128, 1997.

[10] W.L. Luyben, **"Simple method for tuning SISO controllers in multivariable systems,"** *Ind. Eng. Chem. Process Des*. Vol.25, No.3, pp.654–660, 1986.

[11] J.G. Ziegler, N.B. Nichols, **"Optimum settings for automatic controllers,"** *Trans*. *ASME*, Vol.64, No.1, pp.759–768, 1942.

[12] Z.X., Zhu, **"Structural analysis and stability conditions of decentralized control systems,"** *Ind. Eng. Chem. Res*, Vol.35, No.3, pp.736–74, 1996.

[13] M.-J., He, W.J., Cai, B.F., Wu and M., He, **"Simple decentralized PID controller design method based on dynamic relative interaction analysis,"** *Ind. Eng. Chem. Res*. Vol.44, No.1 , pp.8344-8334, 2005.

[14] H.P. Huang, J.C. Jeng, C.H. Chiang and W. Pan, **"A direct method for multi-loop PI/PID controller design,"** *J. Process Control*, Vol.13, No.2, pp. 769–786, 2003.

[15] Q. Xiong, W.-J. Cai, **"Effective transfer function method for decentralized control system design of multi-input multi-output processes",** *J. Process Control*, Vol.16, No.1, pp.784- 773 , 2006

[16] H. Cui, E.W. Jacobsen, **"Performance limitations in decentralized control,"** *J. Process Control*, Vol.12, No.4, pp.485–494, 2002.

[17] Q. Xiong, W.J. Cai and M.J. He, "**A practical loop pairing criterion for multivariable process",** *J. Process Control*, Vol.15, No.7, pp. 741–747, 2005.

[18] M.J. He, W.J. Cai, W. Ni and L.H. Xie, **"RNGA based control system configuration for multivariable processes,"** *J. Process Control*, Vol.19, No.6, pp. 1036–1042, 2009.

[19] S.J. Qin, T. Badgwell, **"An Overview of Nonlinear Model Predictive Control Applications,"**. *Nonlinear Predictive Control, Birkhäuser*, p. 369 , 2000.

[20] S.J. Qin, T. Badgwell, **"A Survey of Industrial Model Predictive Control Technology,"** *Control Engineering Practice*, Vol.11, No.6, 2003.

[21] C. García, D. Prett, and M. Morari, **"Model Predictive Control: Theory and Practice–A Survey,"** *Automatica*, Vol.25, No.3, p.335, 1989.

[22] M. Morari, J.H. Lee, **"Model Predicitve Control: Past, Present, and Future,"** *Comput. Chem. Eng.*, Vol.23, No.4, pp. 667, 1999.

[23] J.B. Froisy, **"Model Predictive Control: Past, Present, and Future,"** *ISA Transactions*, Vol.33, No.1, pp. 235, 1994.

[24] J. Lee, B. Cooley, **"Recent Advances in Model Predictive Control and Other Related Areas,"** *in J. Kantor, C. Garcia, and B. Carnahan, Eds., 5th International Conference on Chemical Process Control. CPC V, American Institute of Chemical Engineers*, p. 201, 1996.

[25] D.Q. Mayne, J.B. Rawlings, C.V. Rao, and P.O.M. Scokaert, **"Constrained Model Predictive Control: Stability and Optimality,"***Automatic*, Vol.26, No.6, p.789, 2000.

[26] *J.M. Maciejowski*, **Multivariable Feedback Design**, *Addison- Wesley*, 1989.

[27] H. Khaluzadeh, M. Akbari Sani, **"Dyzbad nonlinear wind turbine modeling and control it based on stochastic optimal feedback controller,"** *Journal of Control*, Vol.8, No.3, 1387.

[28] D. Yang Quan Chen, D. Atherton, ***Linear Feedback Control***, this book is available for purchase at www.siam.org/catalog. Chapter 6, 2007.

[29] M.M. Kale, A.J Chipper field. **"Stabilized mpc formulations for robust reconfigurable flight control,"** *Elsevier Science*, Vol.13, No.6, pp.771-788, 2005.

[30] Elling W. Jacobsen. **"Model predictive control-control theory and practice,"** *Automatic Control*, Vol.4, No.2, February 2005.

[31] J.M. Maciejowski **"Fault-tolerant aspects of mpc,"** *IEE, Department of Engineering, University of Cambridge*, 1999.

[32] J.M. Maciejowski. **"Modelling and predictive control: Enabling technologies for reconfiguration,"** *Annual Reviews in Control*, Vol. 23, No.12, pp. 13–2, 1999.

[33] M.M. Kale, A.J., Chipper field. **"Reconfigurable flight control strategies using model predictive control,"** *Proceedings of the 2002 IEEE International Symposium on Intelligent Control*, pp.43-48 , 2002.

[34] M. Huzmezan , J.M., Maciejowski **"Reconfigurable flight control of a high incidence research model using predictive control,"** *In UKACC International Conference Control* '98, 1998.

[35] E.C. Kerrigan, J.M., Maciejowski and P.J., Goulart **"Constrained Control Using Model Predictive Control,"** *Advanced strategies in control systems with input and output constraints*, Vol.346, No.3, pp. 273-291 2006.

[36] J.M. Lemos, J.M. Maciejowski, ***Predictive methods in fault-tolerant control,*** *Prentice Hall*, 2002.

[37] A. Bemporad, M. Morari and N. Lawrence Ricker, ***Model Predictive Control Toolbox for use with Matlab,*** The *mathworks*, 2004.

[38] Seborg et al., ***Model Predictive Control,*** online v*ersion of book on process Dynamics and Control*, Chapter 20, 2011.

[39] T.N. Vu, M. Lee, **"Independent design of multi-loop PI/PID controllers for interacting multivariable processes,"** *J. Process Control*, Vol.20, No.3, pp. 922–933, 2010.