IDENTIFICATION AND CONTROL OF DISTILLATION COLUMNS

A THESIS

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BY

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an adjustable model was introduced to solve the problem of parameter identification. The two problems are shown in Fig.(1-1).

There are mainly two groups of design methods of MRAS, the first is based on local parameter optimization [4] and the second is based on stability criteria [5-20] ,namely; the direct method of Liapunov and the hyperstability of Popov. The second group was seen to have more general application and more advantages than the first one. In chapter (2),a breif review of the control methods of the second group will be discussed,while chapter(3) will deal with the identification schemes of the same group.

1.2.2 Bilinear Systems

The control theory of linear systems allows the solution of many problems arising to control engineers if the process could be linearized. For the majority of the industrial processes,this linearization is only valuable in a small region of very restricted functions. Research has been done to overcome the analytical difficulties of nonlinear systems. Much effort has been directed towards the study of a class of nonlinear sytems called bilinear,which could be described by differential equations in which quadratic terms appear.

The fundamental interest of this type of modelling is that a large number of natural and industrial processes have intrinsically a bilinear structure [1,2],e.g. the law of mass action in chemistry,the diffusion across a semi-permuable membrain,and the process of heat transfer by coduction and convection. The binary distillation process can be also described by a bilinear model.

1.2.3 Binary Distillation Process

The basic principle of distillation is as simple as : when a solution is boiled,the vapor usually differs in composition from the liquid that remains. Man has long made use of this knowledge to concentrate solutions by boiling them and condensing their vapors. If there are only two components,one concentrate in the condensate and the other in the residual liquid,then the process is called binary distillation. The simplest distillation is the single stage shown in Fig.(1-2). The multi-stage process is established using long columns in which a number of trays are fixed. Each tray represents a single stage (see Fig.(1-3). More details about binary distillation process and its modelling are presented in chapter(6).

1.3 Status of the Field

Regarding MRAS,no attempt was made to deal with the nonlinear systems due to the difficulties arise when dealing with their analysis. Also the adaptive control and identification of bilinear systems have not been considered until now,the reason of directing our attention into looking for a solution of combining the adaptation with bilinear systems.

1.4 Contribution of the thesis

In this thesis,a new formulation of general bilinear systems is presented. It puts the plant in a linear form, while inserting the nonlinearities in the elements of its characteristic matrix,so that making it linear function of plant states and controls. This formulation led to the proposal of two new techniqus for the control and identification of general bilinear systems based on MRAS and the direct method of Liapunov.

The proposed techniques showed a satisfactory response when applied on the binary distillation process as will be seen in chapter(6).

1.5 Thesis Organization

The thesis is organised as follows :

Chapter(2) : contains a general review of control schemes based on MRAS and stability criteria.

Chapter(3) : contains a general review of identification techniques based on MRAS and stability criteria.

Chapter(4) : presents the new control technique of the bilinear systems.

Chapter(5) : presents the new identification technique of the bilinear systems.

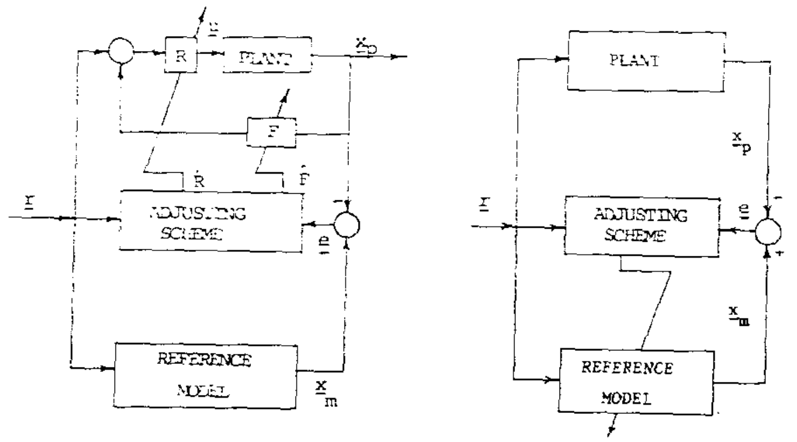
Chapter(6) : includes a bilinear modelization of the binary distillation process and the application of the proposed control and identification techniques on such a model. It also includes some computa-ional aspects.

Chapter(7) : concludes the results of the study in this thesis as well as the recommendation for future research.

Appendix_A : contains some definitions related to stability.

Appendix_B : states Liapunov direct method of stability.

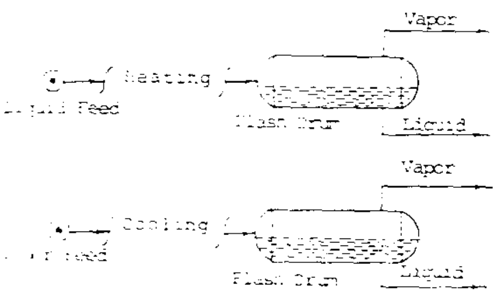
Appendix_C : states the hyperstability theory of Popov.



(a) Control Problem

(b) Identification Problem

Fig.(1-1) Model Reference Adaptive Systems



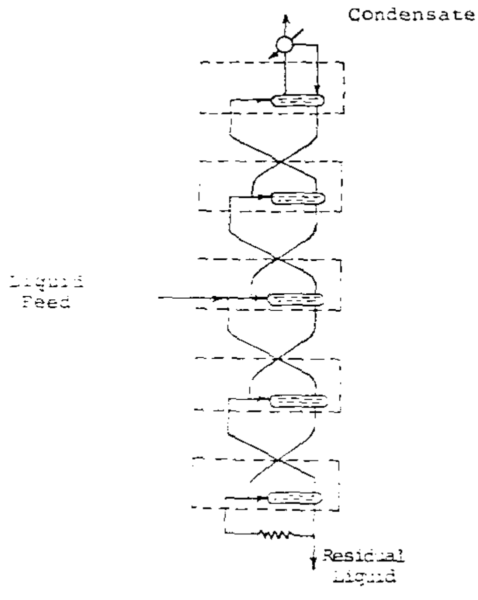


Fig.(1-2) Single Stage Distillation

Fig.(1-3) Multistage Distillation

CHAPTER (2)

A REVIEW OF CONTROL SCHEMES BASED ON MRAS AND STABILITY CRITERIA

2.1 Preliminary

A large number of adaptive control schemes have been proposed during the last twenty years. However, few of them can be considered practically feasible. The difficulties associated with applying such methods to complex real world problems may be attributed to a variety of reasons among which are :

a) The large number of parameters that may have to be adjusted simultaniously.
b) The lack of exact information regarding the unpredictable variations of plant parameters.
c) Noise presented in the output measurements of the plant.

Many developments in model reference adaptive systems (MRAS) using stability criteria; Liapunov direct method and the hyperstability of Popov, have enabled us to overcome many of these difficulties and have resulted in schemes which appear attractive in practical situations.

Using Liapunov direct method, Grayson[5] suggested a bang-bang control for single input-single output plants. He utilized the sgn* fuction to implement the control. Devaud and Caron[6] showed the defects of such functions and proposed another scheme using the sat** function. A continuous control was proposed by Parks[7]. The speed of convergence was improved by Shahein et al [8], using the steepest decsent method in addition with Liapunov. The adjustment of the

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* $\operatorname{sgn}(u)=\begin{cases}-1 & u<0\\ 1 & u>0\end{cases}$

** $\operatorname{sat}(ku)=\begin{cases}-1 & u<-\frac{1}{k}\\ ku & -\frac{1}{k}<u<\frac{1}{k}\\ 1 & u>\frac{1}{k}\end{cases}$

controller parameters,namely;the feedback and feedforward martices was achieved by Narendra and Kudva[9] to control multivariable systems. Hang[10] solved the problem when the number of the adjustable parameters are limited. The effect of noise and the improvement of Liapunov MRAS in a noisy environment were considered by Cate and Verstoep[11]. In a second stage,Landau[12] proposed a technique using Popov hyperstability..

In this chapter,a review of control schemes suitable for different types of processes through MRAS and stability criteria will be presented. No attempt will be made to survey all of the proposed techniques appeared. For interested reader, good surveys are given by Landau [4] and Lindorf and caroll [13]. However,the main features of control techniques of different types of plants will be considered.

2.2 Design Techniques Based on Liapunov

This type of design was firstly introduced by Grayson[5] in 1963 for the control of single input-single output plants. Then a variety of techniques were proposed for the control of multivariable systems. In such techniques,the following procedure was followed :

step(1): Plant and model description and error formulation:

In this step the plant dynamics $\dot{\underline{x}}_p$ as well as that of the reference model $\dot{\underline{x}}_m$ is presented. The reference model is chosen such that it has the required specifications. Then, the dynamics of the state error vector $\underline{e}=\underline{x}_m-\underline{x}_p$ is formulated.

step (2): Introducing Liapunov Function :

A positive definite function in $\underline{e}$ is introduced. The adjusting schemes depend mainly on the choice of this function. This choice is to get finally a negative definite function of $\dot{V}$ when applying the adjusting equations.

step (3): Deducing Liapunov function time derivative $\dot{V}$:

According to the direct method of Liapunov (see appendix B),the convergence of the error vector $\underline{e}$ to the

the ideal unknown matrices
match the model, the dynami
R_o and F_o are required.

The error $\underline{e}$ is formul

$$\dot{\underline{e}} = A_m \underline{e} + B_m \Phi \underline{x}_p + B_m \Psi R$$

where Φ and Ψ are nxn a
between the the unknown i
time-varying matrices R(t

$$\Phi = F^* - F(t) \quad . .$$

$$\Psi = (R^{-1}(t) - R^{*-1})^{-1}$$

step (2) : The Liapunov f
Kodva [9] is as follows :

$$V = 0.5 \left[\underline{e}^T P \underline{e} + tr(\Phi^T \Gamma \right.$$

which is positive definit
$(\underline{e}, \Phi, \Psi)$, where P is an n
matrix which is the uniqu

$$A_m^T P + P A_m = - Q$$

in which Q is a positive
appendix B), and Γ_1 and
matrices.

step (3) :The convergence
tions were proved [9] :

$$\dot{F} = \Gamma_1 B_m^T P \underline{e} \underline{x}_p^T$$

$$\dot{R} = R \Gamma_2 B_m^T P \underline{e} (\underline{r} + F \underline{x}_p$$

null, $\dot{V}$ should be negative definite in $\underline{e}$. Some conditions are introduced to achieve that. These condition are nothing but the required adjusting equations.

In the following sections, the feedback design technique of multivariable plants and those for adjustable plants will be presented.

2.2.1 Feedback Design of Multivariable Systems

In this technique of Narendra and Kodva [9], the parameters of the controller elements, namely; the feedback and the feedforward matrices R and F (see Fig. (2-1)) are adjusted to achieve the required behaviour.

The procedure presented in section 2.2 will be applied now to demonstrate the technique:

step (1): The plant and model are described by:

$$\dot{\underline{x}}_p = A_p \underline{x}_p + B_p \underline{u} \quad . . . . \quad (2-1)$$

$$\dot{\underline{x}}_m = A_m \underline{x}_m + B_m \underline{r} \quad . . . . \quad (2-2)$$

where

$\underline{x}_p$: is an n plant state vector
A_p : is an nxn plant characteristic matrix. It could be unknown and slowly time-varying
B_p : is an nxm plant input matrix. It could be unknown and slowly time-varying as well
$\underline{u}$: is an m control vector
$\underline{x}_m$: is an n model state vector
A_m : is an nxn stable matrix
B_m : is an nxm model input matrix
$\underline{r}$: is the reference input m vector.

Control structure

The control structure is as shown in Fig.(2-2). To reach by which the Liapunov function time derivative $\dot{V}$ becomes:

$$\dot{V} = - 0.5\ \underline{e}^T\ Q\ \underline{e} \qquad \ldots\ldots\ldots\ldots \qquad (2\text{-}8)$$

which is negative definite in the state error $\underline{e}$ and according to the direct method of Liapunov (see appendix B), the error vector $\underline{e}$ is asyptotically stable, i.e. it will converge to the null and the plant output will follow that of the reference model.

It is clear from the adjusting equations(2-7)and(2-8) that there is some computation complexity shown in the large number of the multiplied elements. Moreover, one of the computed parameters dynamics depend on its instantaneous value and the values of the other computed parameters. This makes the computing time significant when compared to the system's time response for some cases. However, this technique could be considered effective for slow systems.

2.2.2 Control of Adjustable Plants

An algorithm [12] was proposed to adjust the plant parameters directly to follow those of the reference model. The block diagram of such algorithm is shown in Fig.(2-3).

The design procedure is identical to that of the previous section in steps (1)and(2) with the exception that the plant is actuated by the reference input vector $\underline{r}$ rather than the control vector $\underline{u}$, i.e. equation(2-1) will be replaced by :

$$\dot{\underline{x}}_p = A_p\ \underline{x}_p + B_p\ \underline{r} \qquad \ldots\ldots\ldots\ldots \qquad (2\text{-}9)$$

and also the error is formulated as:

$$\dot{\underline{e}} = A_m\ \underline{e} + \Phi \underline{x}_p + \Psi \underline{r} \qquad \ldots\ldots\ldots\ldots \qquad (2\text{-}10)$$

while Φ and Ψ are defined here as the parameter misalignment between model and plant, i.e.

$$\Phi = A_m - A_p \quad \ldots\ldots\ldots\ldots\ldots \quad (2\text{-}11)$$

$$\Psi = B_m - B_p \quad \ldots\ldots\ldots\ldots\ldots \quad (2\text{-}12)$$

The Liapunov function is exactly the same as that of equation(2-6) with the new definition of Φ and Ψ.

step_(3): According to the above, the time derivative of the Liapunov function $\dot{V}$ as that of equation(2-8) while the adjusting equations are as follows :

$$\dot{A}_p = \Gamma_1 \, P \, \underline{e} \, \underline{x}_p^T \quad \ldots\ldots\ldots\ldots\ldots \quad (2\text{-}13)$$

$$\dot{B}_p = \Gamma_1 \, P \, \underline{e} \, \underline{r}^T \quad \ldots\ldots\ldots\ldots\ldots \quad (2\text{-}14)$$

A modification was introduced by Hang [10] on the Liapunov function to make this algorithm suitable for the case where the number of plant adjustable parameters are limited. He assumed that there are only v and s adjustable parameters in A_p and B_p respectively. Then equations(2-11)and(2-12) are expressed as :

$$\Phi = \left[f_{ij}(a_{p1}, a_{p2}, \ldots, a_{pv}) \right] \quad \ldots\ldots \quad (2\text{-}15)$$

$$\Psi = \left[g_{ij}(b_{p1}, b_{p2}, \ldots, b_{ps}) \right] \quad \ldots\ldots \quad (2\text{-}16)$$

where f_{ij} and g_{ij} are linear functions of the parameters a_{ph} and b_{ph} respectively, and $\underline{a}_p$ and $\underline{b}_p$ are **v** and **s** vectors forming the adjustable parameters. He introduced the following Liapunov function :

$$V = \underline{e}^T P \, \underline{e} + \sum_{h=1}^{v} \frac{1}{\alpha_h} \left(a_{ph} + \alpha_h \gamma_h x_h \right)^2 + \sum_{h=1}^{s} \frac{1}{\beta_h} \left(b_{ph} + \beta_h \delta_h x_h \right)^2 \quad \ldots\ldots \quad (2\text{-}17)$$

where α, β, γ and δ are positive constants, and M_h and N_h are time-varying functions deduced with the adjusting equations as follows :

$$\left.\begin{aligned} M_h &= \underline{e}^T P \underline{z}_{ah} \\ \dot{a}_p &= \alpha_h (M_h + \gamma_h \dot{M}_h) \end{aligned}\right\} \quad h=1,2,\ldots,v \quad \ldots\ldots \quad (2\text{-}18)$$

$$\left.\begin{aligned} N_h &= \underline{e}^T P \underline{z}_{bh} \\ \dot{b}_{ph} &= \beta_h (N_h + \delta_h \dot{N}_h) \end{aligned}\right\} \quad h=1,2,\ldots,s \quad \ldots\ldots \quad (2\text{-}19)$$

where $\underline{z}_{ah}$ and $\underline{z}_{bh}$ are n vectors obtained by rearranging the elements of $\Phi \underline{x}_p$ and $\Psi \underline{r}$ as :

$$\Phi \underline{x}_p = \left[\underline{z}_{a1} , \underline{z}_{a2} , \ldots , \underline{z}_{av} \right] \underline{a}_p \quad \ldots\ldots \quad (2\text{-}20)$$

$$\Psi \underline{r} = \left[\underline{z}_{b1} , \underline{z}_{b2} , \ldots , \underline{z}_{bs} \right] \underline{b} \quad \ldots\ldots \quad (2\text{-}21)$$

By the above adjusting equations (2-18) and (2-19) for $\dot{\underline{a}}_p$ and $\dot{\underline{b}}_p$, then $\dot{V}$ becomes :

$$\dot{V} = - \underline{e}^T P \underline{e} - 2 \sum_{h=1}^{v} \alpha_h \gamma_h M_h^2 - 2 \sum_{h=1}^{v} \beta_h \delta_h N_h^2 \quad \ldots\ldots \quad (2\text{-}22)$$

from which the overall system asymptotic stability is achieved.

Although it is seen that the computation complexity was reduced using this technique when compared to that of the previous section, it is only valuable when direct adjustment of plant parameters can be done, which is the case of a very small number of industrial systems.

2.3 Design methods Based on Popov Hyperstability

This type of design was firstly introduced by Landau [12] in 1969. A brief discussion of the hyperstability criterion is presented in appendix C.

2.3.1 Continuous Design Techniques

The problem is formulated here as that of section 2.2.2 with one exception that the **r** output vectors $\underline{y}_p$ and $\underline{y}_m$ are the only measurable quantities rather than $\underline{x}_p$ and $\underline{x}_m$ where

$$\underline{y}_p = C\, \underline{x}_p \qquad \ldots\ldots\ldots\ldots\ldots \qquad (2-23)$$

$$\underline{y}_m = C\, \underline{x}_m \qquad \ldots\ldots\ldots\ldots\ldots \qquad (2-24)$$

where C is an **rxn** output matrix

The computing block (see Fig.(2-4)) is actuated by an **r** vector $\underline{v}$ defined by :

$$\underline{v} = D\, \underline{\epsilon} \qquad \ldots\ldots\ldots\ldots\ldots \qquad (2-25)$$

where D is an **rxr** constant matrix,and $\underline{\epsilon}$ is the output error defined by :

$$\underline{\epsilon} = \underline{y}_m - \underline{y}_p \qquad \ldots\ldots\ldots\ldots\ldots \qquad (2-26)$$

The dynamics of the plant parameters are suggested to have the following form [12] :

$$\dot{A}_p(t) = \Lambda(\, \underline{v}(\tau), t\,) \quad , \quad \tau \leqslant t \qquad \ldots\ldots \qquad (2-27)$$

$$\dot{B}_p(t) = \Xi(\, \underline{v}(\tau), t\,) \quad , \quad \tau \leqslant t \qquad \ldots\ldots \qquad (2-28)$$

The following theorem [12] includes the adjusting equations,which are required in the computing block of Fig.(2-4).

Theorem

Necessary and sufficient conditions in order that those model reference adaptive control systems described by equations(2-2),(2-10)and (2-23)to (2-28) be an asymptotically hyperstable system are :