Modified Ratio Control Configurations for Distillation Composition Control

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Abstract: A class of new distillation composition control configurations, modified ratio control configurations, are proposed in this paper. These modified ratio control configurations are obtained by augmenting standard ratio control configurations with some design parameters. By properly selecting these design parameters, disturbance sensitivities and control loop interactions can be reduced. Methods for selecting these design parameters are described in this paper. The proposed approach has been tested in a methonal-water separation column and nonlinear simulation results demonstrate the superiorities of these modified ratio control configurations.

Keywords: distillation control, distillation control configuration, ratio control configuration, disturbances rejection.

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Introduction

Distillation is the most widely used separation process in chemical and petroleum industry. A distillation column control system is a typical multi-input multi-output (MIMO) system in that there are several controlled variables and several manipulated variables. For a binary distillation column, the controlled variables are product compositions, levels in reboiler and condenser, and pressure in the column. The possible manipulated variables are reflux rate, vapour boil up rate, condenser duty, product flow rates, and their combinations. It is possible to design a 5x5 multivariable controller for binary distillation column. However, such a multivariable controller is difficult to tune and maintain. In practice, distillation columns are controlled by decentralised control systems which are easy to tune and fault- tolerant. Therefore, there exist many possible control configurations, i.e. the pairing between controlled variables and manipulated variables. The conventional control configuration is the LV configuration where the top composition is controlled by manipulating the reflux rate and the bottom composition is controlled by manipulating the vapour boil up rate. The LV configuration is also called energy balance configuration. Another frequently used control configuration is the DV configuration where the top composition is controlled by manipulating the top product flow rate and the bottom composition is controlled by manipulating the vapour boil up rate. The DV configuration is also called material balance configuration.

Apart from the energy balance and material balance configurations, there is also a group of frequently used configurations where ratios among reflux rate, vapour boil up rate, and product flow rates are used as composition manipulators. These configurations are called ratio control configurations, which have been used in practice for a long time (Radmaker et al, 1975). Skogestad et al (1990) compare several control configurations including LV, DV, and $L/DV/B$ configurations. They are very strongly in favour of the $L/DV/B$ configuration and suggest that it is the best choice for all modes of operation. Ryskamp (1980) proposes a new strategy, $D/(L+D)V$ configuration, where the ratio $D/(L+D)$ is used to control the top composition and the vapour boil up, V is used to control the bottom composition. It is found that this new strategy works well at moderate reflux ratios and at high reflux ratios. The discussions of Skogestad and Morari (1987a) point out that ratio configurations have the effect of introducing multi-variable control via SISO design. Some ratio configurations can also improve disturbance rejection ability for certain disturbances. This can be analysed using the method presented in (Zhang and Tham, 1991). In this paper, we propose to add some design parameters into ratio configurations to improve their property. By properly selecting these parameters, the modified ratio configurations will have better disturbance rejection ability and decoupling effect.

This paper is arranged as follows. The next section will describe the relationships between the models of different control configurations. Based on these relationships, given the model of one configuration, the model of another configuration can be obtained. These relations are used to determine the design parameters in modified ratio configurations. Section 3 will describe a methanol-water separation column, which is used as an example to demonstrate the modified ratio control configurations. Section 4 will describe the modified ratio control configurations. The way how to determine design parameters will be presented. Robustness of such modified ratio control configurations is assessed through μ – analysis. Nonlinear simulation results are provided to demonstrate the superiorities of these modified ratio control configurations over standard ratio control configurations. The last section contains some concluding remarks.

2. Relations Between Different Control Configurations

To systematically study different distillation control configurations, it is necessary to have the models of these configurations. These models can be obtained through experimental methods, e.g. step test. Since the number of possible configurations is large, it will be very time consuming and costly to obtain these models through experimental methods. There exist certain relations between those configurations and by using these relations it is possible to obtain the model of one configuration from that of another configuration. Several researchers have investigated the transformation of distillation control configuration models (Skogestad and Morari, 1987b; Hagblom and Waller, 1988; Yang et al, 1990; Zhang and Tham, 1991). In this section, the method presented in (Zhang and Tham, 1991) is briefly described.

Let the base configuration used be the *LV* configuration having the following transfer function models:

$$\begin{pmatrix}\Delta y\\ \Delta x\end{pmatrix} = G\begin{pmatrix}\Delta L\\ \Delta V\end{pmatrix} + G_d\begin{pmatrix}\Delta d_1\\ \bullet\\ \bullet\\ \bullet\\ \Delta d_n\end{pmatrix} \tag{1}$$

$$= \begin{pmatrix}g_{11} & g_{12}\\ g_{21} & g_{22}\end{pmatrix}\begin{pmatrix}\Delta L\\ \Delta V\end{pmatrix} + \begin{pmatrix}g_{d11} \cdots g_{d1n}\\ g_{d21} \cdots g_{d2n}\end{pmatrix}\begin{pmatrix}\Delta d_1\\ \bullet\\ \bullet\\ \bullet\\ \Delta d_n\end{pmatrix}$$

where G and G_d are process model and disturbance model respectively, y and x are top and bottom product compositions respectively, $d_1, \ldots, d_n$ are disturbances.

In the *LV* configuration, the condenser level and the reboiler level are controlled by manipulating the top and bottom product flows respectively. There exists a relation between the inventory manipulators, composition manipulators, and disturbances. This relation can be expressed as follows:

$$\begin{pmatrix}\Delta D\\ \Delta B\end{pmatrix} = M\begin{pmatrix}\Delta L\\ \Delta V\end{pmatrix} + M'\begin{pmatrix}\Delta d_1\\ \bullet\\ \bullet\\ \bullet\\ \Delta d_n\end{pmatrix} \tag{2}$$

$$= \begin{pmatrix}m_{11} & m_{12}\\ m_{21} & m_{22}\end{pmatrix}\begin{pmatrix}\Delta L\\ \Delta V\end{pmatrix} + \begin{pmatrix}m'_{11} \ldots m'_{1n}\\ m'_{21} \ldots m'_{2n}\end{pmatrix}\begin{pmatrix}\Delta d_1\\ \bullet\\ \bullet\\ \bullet\\ \Delta d_n\end{pmatrix}$$

where M and M' are 2 x 2 and 2 x n dynamic matrices respectively. Since the level control loops are much faster than the composition control loops and, further, by assuming perfect level control, the dynamics in M and M' can be neglected. Therefore, only the static elements of M and M' should be determined. The elements of M and M' can be calculated from steady state column data and steady state gains in Eq(1). Let the first two disturbances be feed rate and feed composition disturbances, i.e. $\Delta d_1 = \Delta F$ and $\Delta d_2 = \Delta z$, then the elements of M and M' can be calculated as follows (Zhang and Tham, 1991).

$$m_{11} = -m_{21} = -\frac{\overline{D}g_{11}(0) + \overline{B}g_{21}(0)}{\overline{y} - \overline{x}} \tag{3}$$

$$m_{21} = -m_{22} = -\frac{\overline{D}g_{12}(0) + \overline{B}g_{22}(0)}{\overline{y} - \overline{x}} \tag{4}$$

$$m'_{11} = 1 - m'_{21} = \frac{\overline{z} - \overline{x} - \overline{D}g_{d11}(0) - \overline{B}g_{d21}(0)}{\overline{y} - \overline{x}} \tag{5}$$

$$m'_{12} = -m'_{22} = \frac{\overline{F} - \overline{D}g_{d12}(0) - \overline{B}g_{d22}(0)}{\overline{y} - \overline{x}} \tag{6}$$

$$m'_{1i} = -m'_{2i} = -\frac{\overline{D}g_{d1i}(0) + \overline{B}g_{d2i}(0)}{\overline{y} - \overline{x}} \tag{7}$$

$$(i = 3,4,\ldots,n)$$

In the above equations, the overlined variables represent the nominal values of these variables at steady state.

Suppose that the composition manipulators in the new configuration are Δu_1 and Δu_2, which could be ΔL, ΔV, ΔD, ΔB, and their functions. Through linearisation, if Δu_1 and Δu_2 are nonlinear functions of ΔL, ΔV, ΔD, and ΔB, the composition manipulators Δu_1, and Δu_2 can be expressed as linear combinations of ΔL, ΔV, ΔD, and ΔB as follows

$$\begin{pmatrix} \Delta u_1 \\ \Delta u_2 \end{pmatrix} = G_1 \begin{pmatrix} \Delta L \\ \Delta V \end{pmatrix} + G_2 \begin{pmatrix} \Delta D \\ \Delta B \end{pmatrix} \tag{8}$$

where G_1 and G_2 are 2x 2 coefficient matrices. Composition manipulators for the *DV* configuration, for example, can be represented as

$$\begin{pmatrix} \Delta D \\ \Delta V \end{pmatrix} = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} \Delta L \\ \Delta V \end{pmatrix} + \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} \Delta D \\ \Delta B \end{pmatrix} \tag{9}$$

while those for the *L/DV/B* configuration can be represented as

$$\begin{pmatrix} \Delta L/D \\ \Delta V/B \end{pmatrix} = \begin{pmatrix} 1/\overline{D} & 0 \\ 0 & 1/\overline{B} \end{pmatrix} \begin{pmatrix} \Delta L \\ \Delta V \end{pmatrix} + \\ + \begin{pmatrix} -\overline{L}/\overline{D}^2 & 0 \\ 0 & -\overline{V}/\overline{B}^2 \end{pmatrix} \begin{pmatrix} \Delta D \\ \Delta B \end{pmatrix} \tag{10}$$

Eliminating ΔD and ΔB from Eq(2) and Eq(8) gives

$$\begin{pmatrix} \Delta L \\ \Delta V \end{pmatrix} = \left(G_1 + G_2 M\right)^{-1} \begin{pmatrix} \Delta u_1 \\ \Delta u_2 \end{pmatrix} - \\ - \left(G_1 + G_2 M\right)^{-1} G_2 M' \begin{pmatrix} \Delta d_1 \\ \bullet \\ \bullet \\ \bullet \\ \Delta d_n \end{pmatrix} \tag{11}$$

Substitute Eq(11) into Eq(1) gives

$$\begin{pmatrix} \Delta y \\ \Delta x \end{pmatrix} = G\left(G_1 + G_2 M\right)^{-1} \begin{pmatrix} \Delta u_1 \\ \Delta u_2 \end{pmatrix} + \\ + \left[G_d - G\left(G_1 + G_2 M\right)^{-1} G_2 M'\right] \begin{pmatrix} \Delta d_1 \\ \bullet \\ \bullet \\ \bullet \\ \Delta d_n \end{pmatrix} \tag{12}$$

Therefore the process model and the disturbance model for the new configuration are

$$G\left(G_1 + G_2 M\right)^{-1}$$

and

$$G_d - G\left(G_1 + G_2 M\right)^{-1} G_2 M'$$

respectively. It can be seen that different control configurations will have different disturbance sensitivities and control loop interactions.

To obtain the model of a new configuration, the first step would therefore be to find G_1, G_2, M, and M' from steady state operating data and this step is very easy. Once G_1, G_2, M, and M' are obtained, the process model and the disturbance model are readily obtained from Eq(12).

3. A Methanol-Water Separation Column

3.1 The Distillation Column

The distillation column studied in this paper is a simulated methanol-water separation column.

A nonlinear tray by tray dynamic model has been developed from mass and energy balances (Simonsmier, 1977). The column data are presented in Table 1. The following assumptions are imposed: negligible vapour holdup, perfect mixing in each stage, and constant liquid holdup.The steady state conditions for this column are listed in Table1.

3.2 Models for the LV Configuration

The process model and the disturbance model of the *LV* configuration are obtained through step tests. Step changes in reflux flow, steam flow to the reboiler, feed flow rate, and feed composition are imposed on the column individually and the resulting process data are recorded. The process and disturbance models are approximated by first order lag plus delay models. First order difference equations corresponding to the models can be obtained via inverse *z*-transformation. The parameters of the difference equations are estimated through the *LS* (least squares) algorithms and are changed back to the parameters of the transfer functions. Since the distillation column is nonlinear, both positive and negative step changes are applied and their results are averaged.

The identified process model is

$$G(s)=\begin{pmatrix} \frac{1.09}{1+4.3s} & -\frac{1.27}{1+6.2s} \\ \frac{2.15}{1+14.2s} & -\frac{6.4}{1+15.7s} \end{pmatrix} \tag{13}$$

The identified disturbance model is

$$G_d(s)=\begin{pmatrix} \frac{0.17}{1+25.2s} & \frac{0.126}{1+9.8s} \\ \frac{2.9}{1+15.8s} & \frac{0.583e^{-2.5s}}{1+17.6s} \end{pmatrix} \tag{14}$$

4 Modified Ratio Control Configurations

4.1 Modified Ratio Control Configurations and Their Models

Modified ratio control configurations are obtained by introducing some design parameters into the standard ratio configurations. For example, the *L/DV/B* configuration can be modified into L/(D+α)V/(B+β) configuration by introducing the design parameters α and β. Standard ratio configurations can be understood as special cases of modified ratio control configurations. The *L/DV/B* configuration can be obtained by setting α and β to zero. The model for this new configuration can be obtained using the method presented in Section 2 as follows.

$$\Delta\frac{L}{D+\alpha}=\frac{\Delta L}{D+\alpha}-\frac{L\Delta D}{(D+\alpha)^2} \tag{15}$$

Table 1. Steady State Data for the Distillation Column

Column data:	
No. of theoretical stages: (including reboiler and condenser)	N=10
Feed tray:	NF=5
Feed composition:	z=0.5
Feed flow rate:	F=18.23 g/s
Operating variables:	
y:	0.95
x:	0.05
D:	9.13 g/s
B:	9.1 g/s
L:	10.0 g/s
V:	13.8 g/s

$$\Delta\frac{V}{B+\beta}=\frac{\Delta V}{B+\beta}-\frac{V\Delta B}{(B+\beta)^2} \tag{16}$$

Therefore,

$$G_1=\begin{pmatrix} 1/(D+\alpha) & 0 \\ 0 & 1/(B+\beta) \end{pmatrix} \tag{17}$$

$$G_2=\begin{pmatrix}-L/(D+\alpha)^2 & 0\\ 0 & -V/(B+\beta)^2\end{pmatrix} \tag{18}$$

The process gain for the new configuration is

$$G=G_{LV}\left(G_1+G_2M\right)^{-1} \tag{19}$$

The disturbance model for the new configuration is

$$G_d=G_{dLV}-G_{LV}\left(G_1+G_2M\right)^{-1}G_2M' \tag{20}$$

Clearly, it can be seen that, by properly selecting α and β, disturbance sensitivity can be reduced and control loop interaction can also be reduced. Therefore, proper selection of α and β can improve the properties of ratio control configurations.

4.2 Determination of Design Parameters

The design parameters can be so selected as to reduce disturbance gains. That is

$$\min_{\alpha\beta} \sum \omega_j \left|g_{dij}\right| \tag{21}$$

where ω_j is the weight for the jth disturbance. Disturbance weights should be selected such that disturbance gains of all the disturbance considered are of comparable magnitudes. Disturbance weights can also be used to specify the relative importance of each disturbance. The design parameter can also be chosen to reduce control loop interactions. That is

$$\min_{\alpha\beta} \left|g_{21}/g_{11}\right|+\left|g_{12}/g_{22}\right| \tag{22}$$

The design parameter can be selected to reduce both disturbance gains and control loop interactions. In this case, Eq(21) and Eq(22) are combined as follows:

$$\min_{\alpha\beta} \sum \omega_j \left|g_{dij}\right|+\left|g_{21}/g_{11}\right|+\left|g_{12}/g_{22}\right| \tag{23}$$

4.3 Comparison of the *L/(D+α) V/(B+β)* Configuration and the *L/DV/B* Configuration

In the $L/(D+\alpha)$ $V/(B+\beta)$ configuration, α and β are determined according to Eq(23) so as to reduce both disturbance gains and control loop interactions. The weight for feed rate disturbance is set to 1.8 and that for feed composition disturbance is set to 10. The optimum α and β are found to be

$$\alpha = -0.9391$$

$$\beta = 1.3752$$

The process gains and disturbance gains for this new configuration can then be obtained using the method presented in Section 2. The new process gains are

$$G=\begin{pmatrix}5.5971 & -3.2251\\ 5.35 & -29.9456\end{pmatrix} \tag{24}$$

The disturbance gains are

$$G_d=\begin{pmatrix}0 & 0.2872\\ 0.001 & 1.1763\end{pmatrix} \tag{25}$$

The process gains and disturbance gains for the *L/DV/B* configuration can also be calculated and they are as follows

$$G_{L/DV/B}=\begin{pmatrix}6.23 & -2.85\\ 5.28 & -24.42\end{pmatrix} \tag{26}$$

$$G_{dL/DV/B}=\begin{pmatrix}-0.08 & 0.286\\ -0.34 & 1.205\end{pmatrix} \tag{27}$$

It can be seen that disturbance gains of the modified configuration are smaller than these of the *L/DV/B* configuration, especially the disturbance gains with respect to the feed flow disturbance.

Open loop responses of the *L/DV/B* configuration and the modified configuration to a 10% decrease in feed flow rate are shown in Figure 1. It can be seen that the modified configuration is less affected by feed flow disturbance. Closed loop responses of the two configurations to a 40% increase in feed rate are shown in Figure 2. The controllers used are diagonal PI controllers and are tuned to optimise the achievable robust performance as described in (Zhang et al, 1994). Figure 2 indicates that closed loop response of the modified configuration is better than that of the *L/DV/B* configuration.

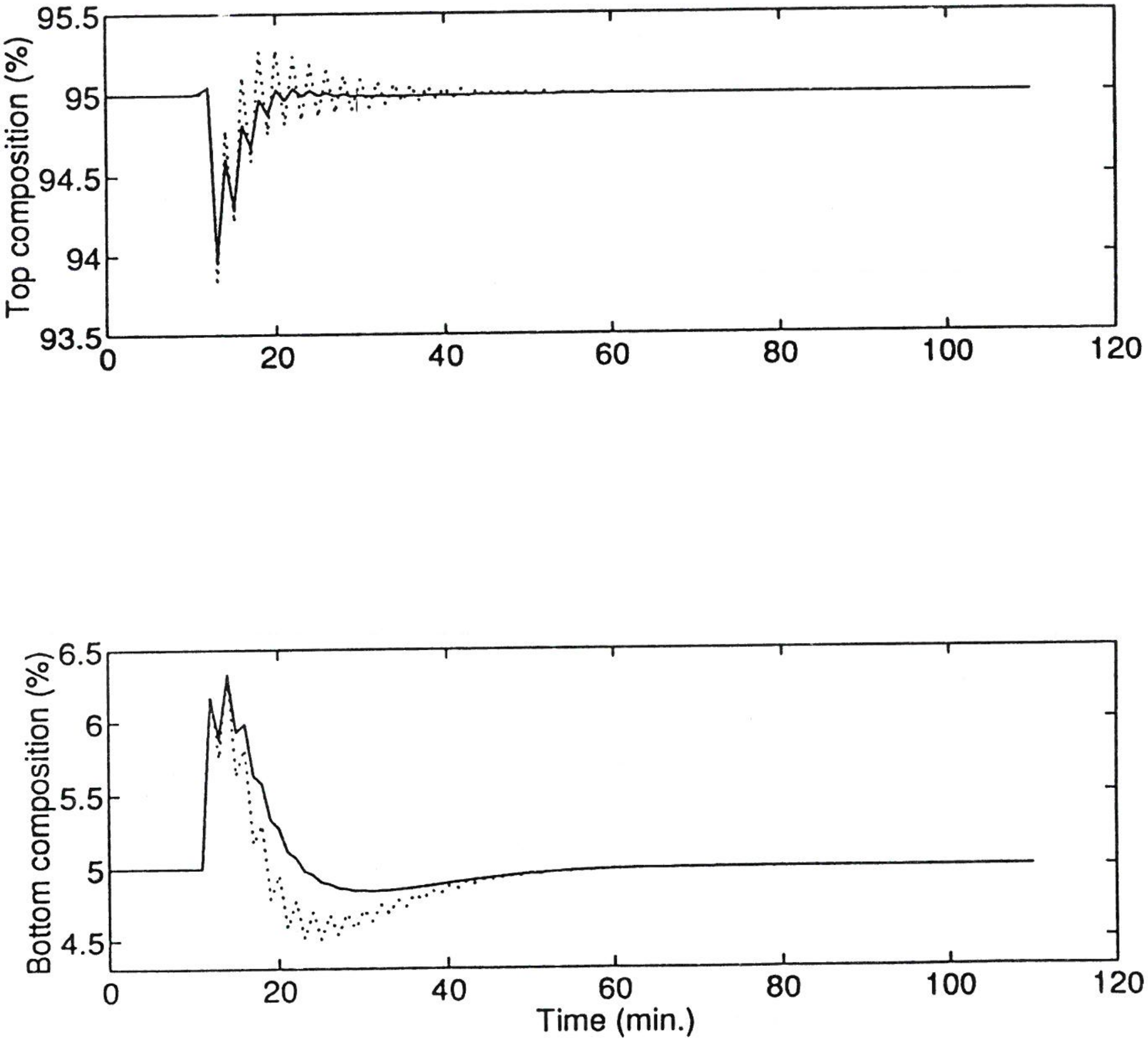
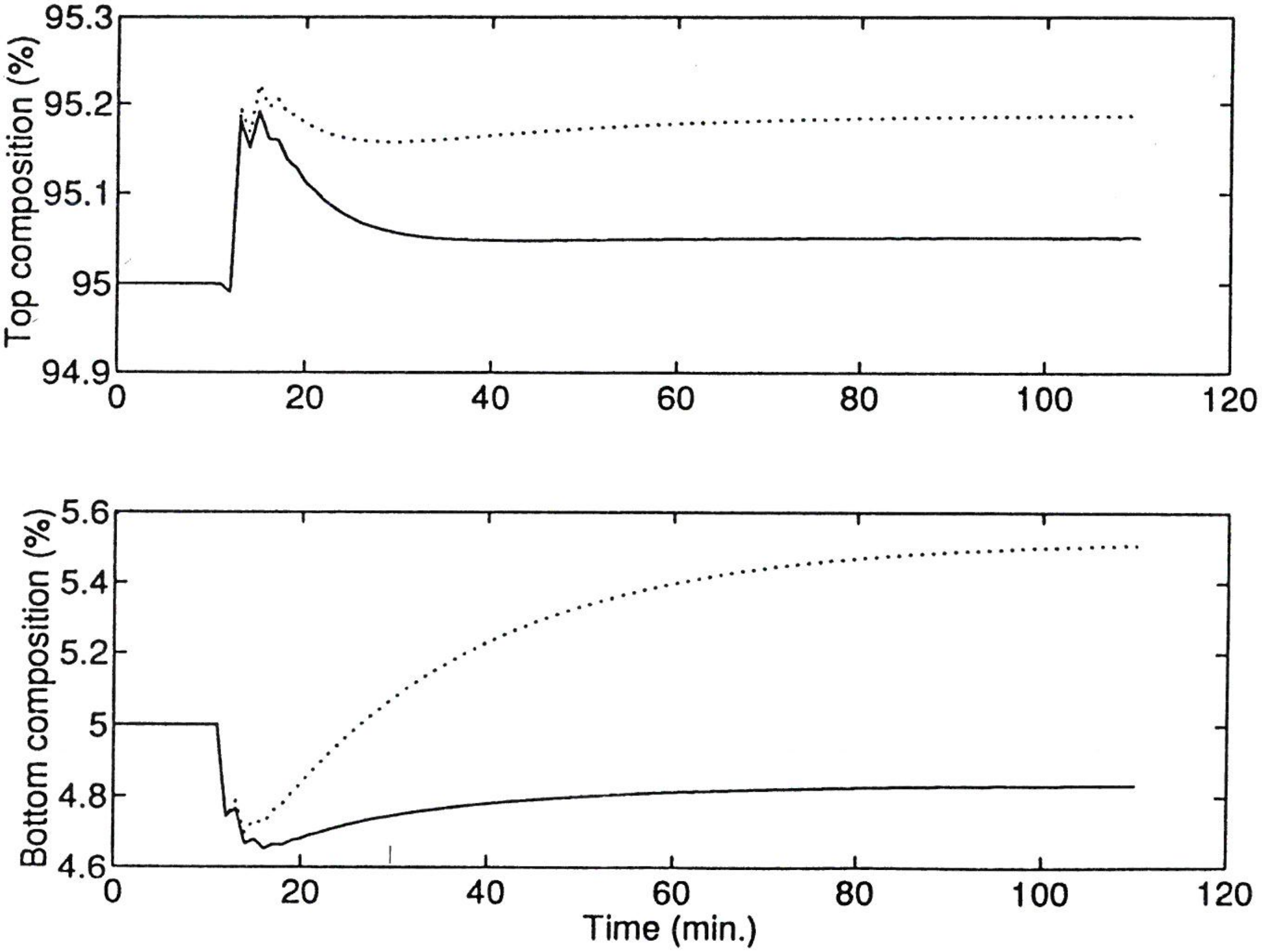


Figure 1. Open Loop Responses of L/DV/B and L/(D+α)V/(B+β) Configurations to a 10% Decrease in Feed Rate (Solid line: L/(D+α)V/(B+β); Dots: L/DV/B)



Time (min.)

Figure 2. Closed Loop Responses of L/DV/B and L/(D+α)V/(B+β) Configurations to a 40% Increase in Feed Rate (Solid line: L/(D+α)V/(B+β); Dots: L/DV/B)

Robustness of the modified control configuration can be assessed through the structured singular value analysis (Doyle, 1982, 1985). Uncertainties in the distillation column model are lumped into a full block output multiplicative uncertainty. The uncertainty weight is determined by studying the relative model differences of the distillation column under different operating conditions, and is as follows (Zhang et al, 1994)

$$W(s)=0.4\frac{1+4.5s}{1+0.8s} \tag{28}$$

With such a model uncertainty description, robust stability can be obtained iff

$$\sup_{\omega} \mu(-WSGC) < 1 \tag{29}$$

and robust performance can be achieved iff

$$\sup_{\omega} \mu \begin{pmatrix} -WSGC & -WSGCGdWd \\ -WpS & -WpSGdWd \end{pmatrix} < 1 \tag{30}$$

where $S = (I+GC)^{-1}$, W_p is the performance weight, and W_d is the disturbance weight. The performance weight is chosen as

$$W_p(s)=0.5\frac{1+5s}{5s} \tag{31}$$

which indicates that integral control action is required at low frequency and an amplification of disturbance at high frequency of up to a factor of two is allowed. Such a performance weight is chosen based on the discussions of Skogestad and Lundstrom (1990). The disturbance weight is chosen as

$$W_d = \mathrm{diag}\,\{0.09, 0.5\} \tag{32}$$

The result of μ–analysis for the $L/(D+\alpha)V/(B+\beta)$ configuration and the $L/DV/B$ configuration are shown in Figure 3 and Figure 4 respectively. It can be seen that through introducing the modified ratio control configuration better robust performance is obtained.

The design parameters are determined based on the models of the column under a specific operating condition. When operating condition changes, the design parameters may no longer be optimum and the modified ratio configuration may not be better than the corresponding standard one. To assess the impact of changing operating conditions on the modified ratio control configurations, disturbance gains of the *L/DV/B* and the *L/(D+α) V/(B+β)* configuration, designed for the nominal operating condition, under different operating conditions are calculated and listed in Table 2. It can be seen from Table 2 that the modified ratio configuration designed for the nominal operating condition is generally less sensitive to disturbances than the *L/DV/B* configuration under other operating conditions. This indicates that the modified ratio control configuration is better than the standard ratio control configuration for a variety of operating conditions.

4.4 Comparison of the $LV/(B+\alpha)$ Configuration and the LV/B Configuration

In the $LV/(B+\alpha)$ configuration α is chosen according to Eq(23) so as to reduce both disturbance gains and control loop interactions. The optimum α is found as

$$\alpha = 4.5557$$

The process gains for the $LV/(B+\alpha)$ configuration is

$$G=\begin{pmatrix} 0.8541 & -9.7201 \\ 0.961 & -48.98 \end{pmatrix} \tag{33}$$

The disturbance gains for this configuration is

$$G_d=\begin{pmatrix} -0.4127 & 0.2195 \\ -0.0362 & 1.0542 \end{pmatrix} \tag{34}$$

Table 2. Disturbance Gains Under Different Operating Conditions

Operating conditions	L/DV/B		L/(D+α)V/(B+β)	
A	-0.1062	0.267	-0.0141	0.2178
	-0.3359	1.249	0.0846	1.3201
B	-0.0726	0.2689	-0.015	0.2704
	-0.2071	1.2369	0.0567	1.2143
C	-0.0679	0.2776	-0.0054	0.2755
	-0.2763	1.5153	0.1506	1.4651
D	-0.0836	0.2781	-0.0065	0.2758
	-0.3573	1.52	0.1636	1.4646
E	-0.0502	0.2771	0.0016	0.2753
	-0.2285	1.5123	0.1279	1.4661
F	-0.0397	0.1147	0.0008	0.116
	-0.3066	1.5112	0.0819	1.4964
G	-0.044	0.1017	-0.1246	0.0944
	-0.2959	1.5168	-0.2997	1.4749

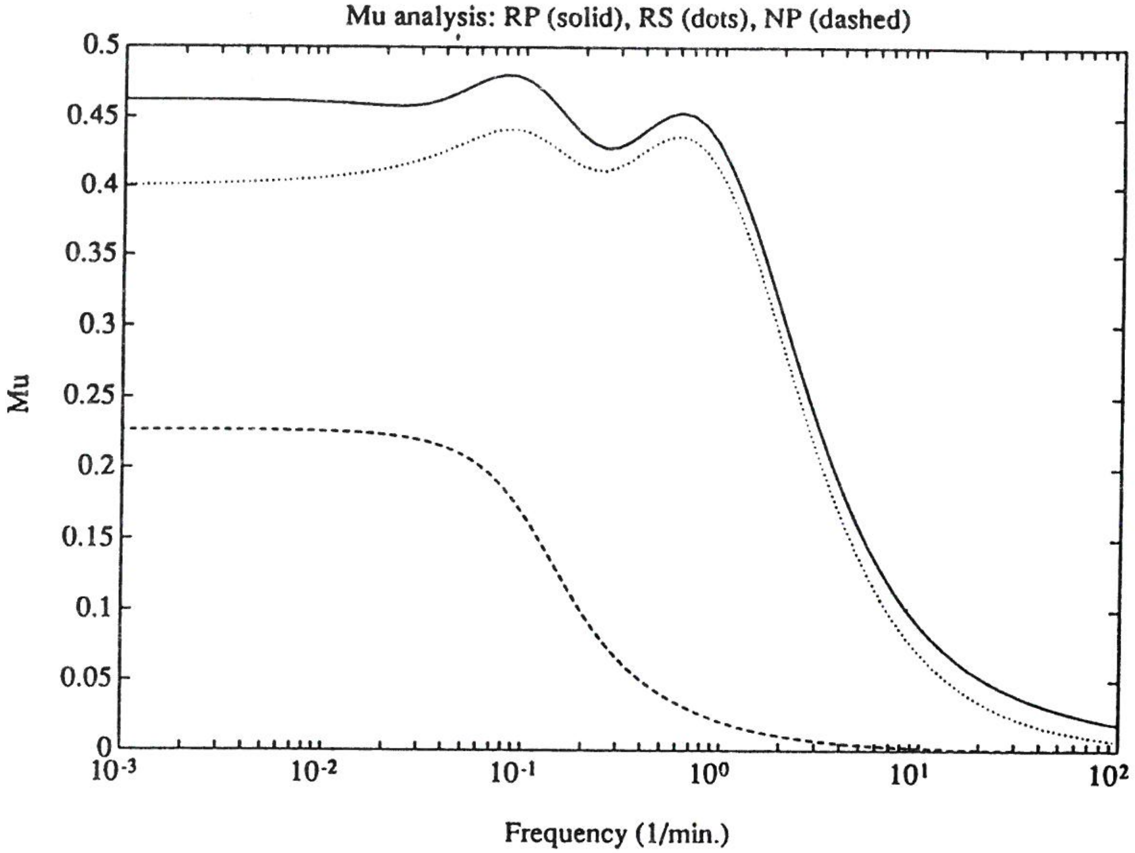


Figure 3. μ **Analysis for** $L/(D+\alpha)V/(B+\beta)$ **Confoguration**
(Solid line: robust performance; dots: robust stability; dashed line: nominal performance)

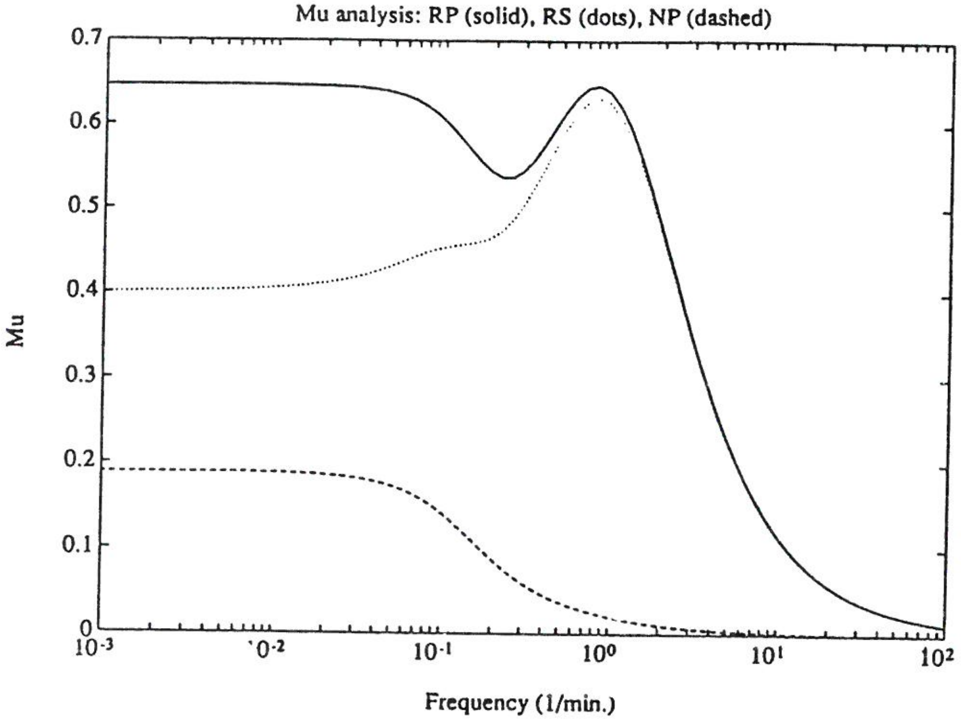


Figure 4. μ **Analysis for L/DV/B Confoguration**
(Solid line: robust performance; dots: robust stability; dashed line: nominal performance)

The process gain and the disturbance gain for the *LV/B* configuration are

$$G_{LV/B}=\begin{pmatrix}0.8 & -5.25\\ 0.67 & -26.46\end{pmatrix} \tag{35}$$

$$G_{dLV/B}=\begin{pmatrix}-0.55 & 0.24\\ -0.74 & 1.17\end{pmatrix} \tag{36}$$

It can be seen that disturbance gains are significantly reduced by introducing this modified configuration. The disturbance gain from feed rate to bottom composition is reduced by more than 20 times.

Open loop responses of the *LV/B* configuration and the *LV/(B+α)* configuration to a 10% decrease in feed rate are shown in Figure 5. It can be noticed in Figure 5 that the modified ratio configuration is insensitive to feed rate disturbance, especially the bottom composition.

In the above examples, disturbance gains for feed rate disturbance can be substantially reduced by introducing the modified ratio control configurations. However, the reduction in disturbance gains for feed composition disturbance is moderate. The modified control configurations are still more sensitive to feed composition disturbance than the *LV* configuration. This can be explained by the qualitative analysis presented in (Zhang and Tham, 1991) which shows that ratio control configurations are always sensitive to feed composition disturbance.Therefore, ratio control configurations are mainly for rejecting feed rate disturbances. Modified ratio control configurations can be used to further reduce disturbance sensitivities to feed rate disturbances.

5 Conclusions

Modified ratio control configurations for distillation composition control are proposed in this paper. These configurations are obtained by introducing adjustable design parameters into standard ratio control configurations. These design parameters can be selected so as to reduce disturbance sensitivities and control loop interactions. A method for selecting these parameters is described in this paper. These modified ratio control configurations are not more difficult to implement than the corresponding standard ones.

The modified ratio control configurations are tested in a methonal-water separation column. Nonlinear simulation results show that these modified ratio control configurations can significantly reduce disturbance sensitivities. Therefore, they are superior to standard ratio control configurations. Since ratio control configurations are widely used in practice, the modified ratio configurations will also have practical potentials.

Acknowledgments

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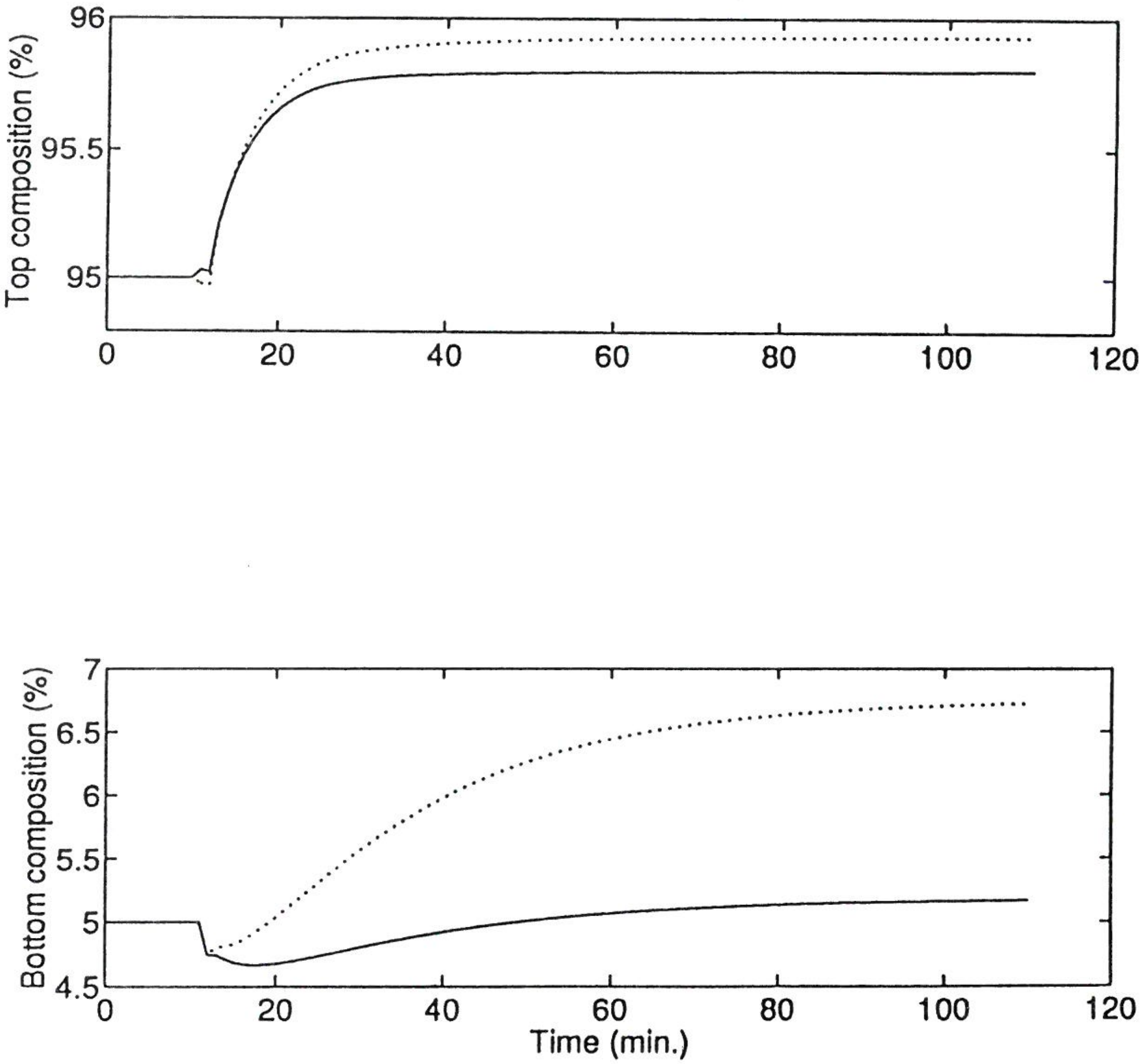

Figure 5. Open Loop Responses of LV/B and LV/(B+α) Configurations to a 10% Decrease in Feed Rate (Solid line: LV/(B+α); Dots: LV/B)

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