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by

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RESEARCH REPORT

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ANALYZING COMPOSITION CONTROL SCHEMES FOR HEAT INTEGRATED DISTILLATION TOWERS USING THE RELATIVE DISTURBANCE GAIN

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"Analysing Composition Control Schemes For Heat Integrated Distillation Towers Using The Relative Disturbance Gain"

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ABSTRACT: The relative disturbance gain (RDG) is a recently introduced index that can be used to assess control loop operability. It is applied to the problem of controlling composition at both ends of heat integrated towers. Using the RDG the ability of the towers to respond to set point changes, feed flow, feed composition and heat input upsets is assessed. A general approach to calculating the RDG is given.

1. Introduction

Distillation towers are significant energy consumers in a typical chemical plant. Rising energy costs have lead to increased use of energy efficient process designs. For distillation one such approach involves the use of heat integrated towers shown in Fig. 1. The latent heat given up in condensing the overhead from the first tower is used to reboil the second tower. With this scheme approximately one half of the energy required per mole of product can be saved. Although heat integration improves energy efficiency, it also brings with it the potential for problems in control system performance. Upsets occurring in either tower can affect the other tower via the common condenser/reboiler. In this paper a new technique for analysing for control problems, the relative disturbance gain (RDG), is discussed. The RDG is used to analyse the performance of the composition control loops for a spectrum of heat integrated towers. It is shown that the nature of the upset affecting the composition loops has a profound effect on performance. First, a brief introduction to the RDG is given. Then the application of the RDG to heat integrated distillation is presented.

2. Relative Disturbance Gain

To include disturbances in an operability analysis of multiloop PI control systems, Stanley et. al. (1985) defined the relative disturbance gain (RDG). Several additional papers on the RDG have also appeared (Marino Galarraga et. al. (1985, 1986a, 1986b and Marlin et. al. (1986)). The RDG can be applied to nxn systems. To explain the RDG a 2x2 case, shown in Fig. 2, is treated. A disturbance, d, enters the control system and the effect that d has on the response of loop-1 is calculated for two cases for loop-2. These are when loop-2 is a) perfect and b) off. Mathematically the RDG β_1 is defined as:

$$\beta_1=(\partial m_1/\partial d\ x_1|x_2)/(\partial m_1/\partial d|x_1,m_2) \qquad (1)$$

The RDG is similar to the relative gain (RGA) in that it involves a dimensionless ratio of perfect closed loop effects to open loop effects. Since the RDG is a ratio it possesses the same desireable properties as the RGA. The RDG is scale independent and it should be insensitive to nonlinearities. While the RGA is a fixed number for a particular control system, the RDG is different for each disturbance that affects a system. The RDG for loop-2, β_2, can be calculated by interchanging the subscripts in Eqn. 1.

The most significant property of the RDG is its relationship to area under the transient that results if d is a step upset. Suppose that loop-2 is off and a step in d occurs. The area under the resulting transient in the error in x_1 is designated as A_{SISO}. Suppose further that loop-2 is closed and the same step upset occurs in d. The error area for this case is designated as A_{MV}, where the subscript indicates multivariable control. It can be shown that β_1 is proportional to the ratio of the area as

$$\beta_1=(A_{MV}/A_{SISO})\ (1/f_1) \qquad (2)$$

The proportionality factor, $1/f_1$, is determined by how much the feedback controller in loop-1 has to be detuned due to interaction when loop-2 is closed. A simple method of estimating f_1 from steady state data has been developed (Marino Galarraga et. al. (1986a)). These authors also found that for many systems f_1 is in the range of

1. to 3. In order to explain the significance of β_1 it is convenient to take f_1 as 1. In actual applications f_1 should be estimated. If f_1 is 1.0, then is equal to the area ratio for the multiloop and single loop responses.

A necessary condition for a loop to have a good multiloop response, i.e. a small response area, is that the absolute value of its RDG be small. The size of the absolute value of the RDG can be used to decide if the loop under study needs to be decoupled from other loops in the system (Marino Galarraga et. al. (1985, 1986b)). One difficulty that arises in interpreting the RDG is that it involves net areas and cancellation of positive and negative areas is possible. In spite of this limitation, the RDG gives a new dimension to the analysis of classical control schemes using only steady state data. The RDG is not a substitute for the RGA, but rather it should be used in conjunction with the RGA.

3. Heat Integrated Towers

In this paper the RDG is applied to composition control of heat integrated towers shown in Fig. 1. Perfect base and accumulator level and pressure control are assumed. Frey et. al. (1984) calculated the RGA for 10 different control schemes for heat integrated towers with base case properties shown in Table 1.

TOWER PROPERTIES				
x_F	x_{Di}	x_{Bi}	R_i	α_i
.5	.95	.05	2.03	2.0

TABLE 1

They also studied perturbed cases with high distillate purity, high bottoms purity, and low α. The same towers are studied here. Only results for the base case are given. Additional results for the perturbed cases can be found in Wang (1986). Takamatsu et. al. (1982) studied heat integrated towers and found that ratioing manipulated flows produced excellent results, especially for feed flow upsets. Shinskey (1982) also recommends the use of ratios for manipulated variables. Based on these findings, 4 additional control schemes are added to the 10 studied by Frey et. al. (1984). The 14 schemes studied here are given in Table 2.

	MANIPULATED VARIABLES			
Scheme	X_{D1}-Loop	X_{B1}-Loop	X_{D2}-Loop	X_{B2}-Loop
1	L1	V1	L2	F1/F2
2	L1	B1	L2	F1/F2
3	D1	V1	D2	F1/F2
4	L1/D1	V1	L2/D2	F1/F2
5	L1/D1	B1	L2/D2	F1/F2
6	D1	V1	L2	F1/F2
7	D1	V1	D2	V2/F2
8	D1/V1	V1	D2/V2	V2/F2
9	L1/D1	V1	L2/D2	V2/F2
10	L1/V1	V1	L2/V2	V2/F2
11	$\frac{D1}{L1+D1}$	$\frac{B1}{B1+V1}$	$\frac{D2}{L2+D2}$	B2/V2
12	$\frac{L1}{L1+D1}$	$\frac{B1}{B1+V1}$	$\frac{L2}{L2+D2}$	B2/V2
13	$\frac{D1}{L1+D1}$	B1	$\frac{D2}{L2+D2}$	B2/V2
14	$\frac{L1}{L1+D1}$	B1	$\frac{L2}{L2+D2}$	B2/V2

TABLE 2

The upsets studied are: set point changes in one loop, feed flow, feed composition, and heat input. It has been shown (Stanley et. al. (1985)) that the RDG equals the RGA for a setpoint change occurring in one loop. The steady state model for the towers is given by McAvoy (1983). It consists of material balances

$$F = D + B \tag{3}$$

$$x_F F = x_D D + x_B B \tag{4}$$

and an approximate operating equation published by Eduljee (1977)

$$\frac{N-N_m}{N+1} = .75\left[1 - \left(\frac{R-R_m}{R+1}\right)^{.5668}\right] \tag{5}$$

with the minimum reflux ratio given as

$$R_m = \frac{1}{(\alpha-1)}\left[\frac{x_D}{x_F} - \frac{\alpha(1-x_D)}{(1-x_F)}\right] \tag{6}$$

and the minimum number of trays given as

$$N_m = \frac{\ln\left[\frac{x_D}{1-x_D} \cdot \frac{1-x_B}{x_B}\right]}{\ln \alpha} \tag{7}$$

Constant molal overflow is also assumed. This model is differentiated analytically to develop expressions for the process gains needed in Eqn. 1 (Wang (1986)).

4. RDG Results

Due to space limitations only results for schemes I and II are given here and these are shown in Tables 3 and 4. Additional results are given by Wang (1986).

A_{mv} / A_{siso} and f_i Values for Scheme I

Loop	Set Point One Loop	Feed Flow	Heat Input	Feed Comp.	RGA	f_i
1	5.04	6.44	0	.189	2.80	1.80
2	3.32	4.11	1.7	1.56	1.95	1.70
3	5.18	6.48	0	.190	2.86	1.81
4	1.09	0	0	0	.81	1.35

TABLE 3

A_{mv}/A_{siso} and f_i Values for Scheme II

Loop	Set Point One Loop	Feed Flow	Heat Input	Feed Comp.	RGA	f_i
1	1.67	0	0	.806	1.19	1.40
2	1.67	0	0	1.15	1.19	1.40
3	1.67	0	0	.806	1.19	1.40
4	1.67	0	0	1.15	1.19	1.40

TABLE 4

For the best results the RDG should be a small number indicating a small multiloop response area, A_{MV}. There is no significance to the sign of the RDG as there is for the RGA. In interpreting the RDG's it should be noted that A_{MV} is given as product of the RDG, A_{SISO}, and f_i. For many systems, the f_i factor depends primarily on the steady state RGA (Marlin et. al. (1986)). Schemes with RGA's close to 1.0 have f_i's close to 1.0. Schemes with large RGA's > 1 have f_i's near 3. The steady state approach of Marino Galarraga et. al. (1986a) is used to estimate f_i for the cases discussed below. Equal loop speeds are assumed. Also Shinskey (1985) has pointed out that A_{SISO} can differ substantially from scheme to scheme. In the discussion below only the area ratio, A_{MV}/A_{SISO}, is considered. In a final evaluation A_{SISO} needs to be estimated. How to estimate A_{SISO} will be the subject of a future paper. Each of the upsets is considered separately.

4.1 Set Point Change in One Loop

In this case the areas in Eqn. 2 are relative to the final steady state. Since the RDG equals the RGA in this case, schemes with small RGA's will have the best RDG's. The results in Tables 3 and 4 show that scheme II is much better than scheme I for this type of upset. In general schemes that use ratio manipulative variables have RGA's > 1.0. Since the RDG equals the RGA and f_i goes up as the RGA differs from 1.0, the area ratio (f_i RDG) increases faster than the RGA itself. Thus the best schemes for this upset are those with RGA's as close to 1.0 as possible. Schemes 11 through 14 all had equal RGA's that were closest to but greater than 1.0. There is not much of an advantage to schemes with RGA's less than 1.0 in this case. Although there is a favorable effect in lowering the RDG when the RGA is <1.0, the tuning factor, f_i, increases toward 3 as the RGA approaches .5. Thus the area ratio actually goes up relative to schemes with RGA's close to 1.0. The results in this case have important implications in terms of online optimization where set points can be changed independently by a hierarchial optimizer. The RDG shows which control systems will give the best performance under such an optimizer.

4.2 Feed Flow

The results in Tables 3 and 4 show that scheme II is significantly superior to scheme I for this type of upset. In general, schemes ratioing flows have RDG's of 0. for feed flow upsets and they handle such upsets much better than schemes not using ratios. This result is in agreement with the earlier conclusions of Takamatsu et. al. (1982) and Shinskey (1982).

4.3 Heat Input

Upsets in heat input were modeled as having gains proportional to those for vapor boilup. For such upsets Wang (1986) has shown that the RDG's will be either 1.0 or 0. The 1.0's result when vapor boilup is a manipulated variable. In all other cases 0's result. The zero RDG value is the result of level loops which respond in such a manner as to counteract the effect of the upset in the steady state.

4.4 Feed Composition

In calculating the RDG's for feed composition it was noted that in most cases they were fractions. In the few cases where they were not the values were not large relative to 1.0. The results in Tables 3 and 4 show that for this upset scheme I is better than scheme II in three of the four loops. Thus, if one knew that set points would not be changed, and feed flow changes were unlikely, scheme I could perform better than scheme II in practice. This conclusion would be especially true if

the most important products were the distillates from each tower, with the area ratios given by the 1st and 3rd entries in Tables 3 and 4. In this case the two distillate loops can be tightly tuned giving f_i values close to 1.0. This would allow the control system designer to take advantage of the small RDG's. The bottom loops would be detuned.

5. Summary

This paper has discussed the application of the RDG to composition control of heat integrated distillation towers. It has been shown that the type of disturbance affecting the system strongly affects its performance. In configuring control systems it is important to know what significant upsets can be expected in practice. The RDG can be used in conjunction with short-cut models to estimate the effects of various upsets on loop performance and and thus, allow one to screen control schemes in a timely manner. For many types of upsets schemes that use a ratio of manipulative variables perform very well. This conclusion agrees with that of earlier authors. The results presented in this paper should be qualified by that fact that they are based on net areas and cancellation of positive and negative areas is possible. The results presented are relative to A_{SISO} which can differ substantially from scheme to scheme. This parameter needs to be estimated to draw final conclusions.

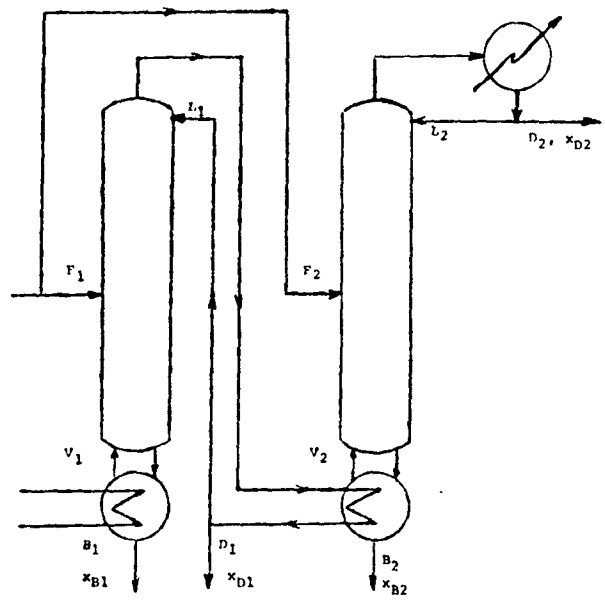

FIGURE 1

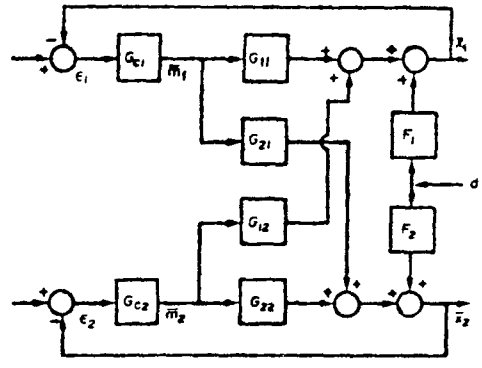

FIGURE 2

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