Chapter 6

Design Modifications for Improved Controllability of Distillation Columns

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Abstract

High-purity distillation columns have several characteristics that make them inherently difficult to control. One of the main control limitations is the strong interactions between the top and bottom of the column. In this paper we study some design modifications of the column which may improve the controllability. These modifications include introducing sidestreams, changing the number of trays and use of a feed preheater for feedback control. It is shown that some of the modifications may yield a significant reduction in the interactions as well as in disturbance sensitivity.

6.1 Introduction

High-purity distillation columns are known to be inherently difficult to control. The main reasons are strong interactions (ill-conditioning) and high disturbance sensitivity (e.g., Skogestad et.al., 1988). The problem of controlling the product compositions of such columns has been studied extensively in the literature over the last decades. However, most authors have considered columns that are close to optimally designed from a steady-state point of view. This reflects common practice in industry; a process unit is designed for steady-state optimality and the control engineer is left with the problem of designing controllers. However, in many cases the operational (dynamic) performance of the column will be poor, even with the "best" possible controller, due to inherent control limitations. That is, the "controllability" is poor. In this paper we discuss possible trade-offs between steady-state optimality and controllability. Relaxing the demands for steady-state optimality may be warranted in terms of improved dynamic performance. The issue of design modifications for improved control in distillation has so far gained little attention in the literature.

In this paper we consider 5 different design modifications: 1) Wachter and Andres (1989) suggested to introduce sidestreams with recycling to the feed to improve controllability of high-purity separations. In this paper we consider the effect of sidestreams with and without recycling to the feed. We find that a sidestream by itself has little effect on controllability, and if it is recycled to the feed as suggested by Wachter and Andres it has almost no effect. 2) Kropholler and Guesalaga (1990) suggested to use a bypass in reflux, i.e., to introduce parts of the reflux further down the column. However, this bypass has essentially no effect on interactions and disturbance sensitivity. Furthermore, when designing controllers for optimized robust performance we found that the optimal controller did not make any use of the bypass. We will therefore not pursue this idea any further. 3) Loe (1976) considered the use of a feed preheater for control. His idea was that manipulation of the feed preheater in a certain way would yield reduced interaction between the top and bottom of the column. In this paper we apply a slight modification of his idea and find that the improvement in controllability may be significant. 4) In addition to the above previously proposed modifications, we analyze the effect of "overdesign" by introducing extra trays in the column. Overdesign is fairly common in industry, mainly to allow for flexibility in the operation and in some cases to overfractionate the products. In this paper we find that overdesign may improve the controllability in some cases. 5) An important issue is the selection of which inputs to use for composition control. This is often specified as a part of the column design, but the decision made here is of vital importance for the remaining control problem. The selection of a proper configuration has been treated quite extensively in the literature during the last decade (e.g., Shinskey, 1984, Häggblom and Waller, 1990, Skogestad et.al, 1990) and is therefore not treated in detail here.

6.2 Example Columns

Data for the "base case" example columns we will use ("Column A and F") are given in Table 6.1. The columns have 40 and 10 theoretical stages, respectively, and both have high-purity products. Column F is somewhat unusual with its large relative volatility and corresponding low reflux. The controllability of both columns have been studied quite extensively in several papers by Skogestad and coworkers (e.g., Skogestad et.al., 1990).

The following modelling assumptions are used: binary separation, constant relative volatility, constant molar flows (neglected energy balance), negligible vapor holdup, and vapor-liquid equilibrium as well as perfect mixing on each stage. Neglecting the vapor holdup implies immediate vapor flow responses throughout the column. The liquid flow-dynamics are described by a linear relation between between liquid flow L_i and liquid holdup M_i;

$$L_i = L_i^0 + (M_i - M_i^0)/\tau_L \tag{6.1}$$

where superscript 0 denotes nominal steady-state values. The hydraulic time-constant τ_L is computed from a linearized Francis weir formula

$$\tau_L = \frac{2}{3}\frac{M_{oi}}{L_i} \tag{6.2}$$

where M_{oi} denotes liquid over weir. We use a liquid holdup on each tray equal to $M_i/F =$ 0.5 min. and assume half the liquid over weir. This yields $\tau_L = 0.063$ min. for column A and $\tau_L = 0.733$ min. for column F. The total lag from a change in reflux to a change in the liquid flow to the reboiler becomes $\theta_L = N\tau_L = 2.46$ min. for column A and $\theta_L = N\tau_L = 6.60$ min. for column F.

The modelling assumptions yield a nonlinear dynamic model with two differential equations per tray; one for composition and one for liquid holdup. This results in a total of $2(N+1)$ states in the full model, with N denoting the number of theoretical trays. In the analysis we will use linear models which are obtained by linearizing the full nonlinear models around the nominal steady-state.

We will in the following mainly consider the LV-configuration, that is, with reflux L and boilup V used for composition control. This may not be the best choice of configuration with respect to control properties (e.g., Skogestad et.al, 1990), but it is the most widespread configuration in industry.

Column	z_F	α	N	N_F	$1-y_D$	x_B	D/F	L/F	V/F
A	0.5	1.5	40	21	0.01	0.01	0.500	2.706	3.206
F	0.5	15	10	5	0.0001	0.0001	0.500	0.227	0.727
•	Feed is saturated liquid								

Table 6.1: Steady-state data for distillation columns A and F.

When considering various design modifications we always adjust the steady-state values of L and V so that the product purities $1 - y_D$ and x_B remain at the values given in Table 6.1, that is, 0.01 for column A and 0.0001 for column F.

6.3 Analysis Tools

6.3.1 The Relative Gain Array

The Relative Gain Array (RGA) was originally proposed by Bristol (1966) as a steady-state interaction measure, and has found widespread applications for selecting single loop pairings in decentralized control. Furthermore, the RGA is closely related to the minimized condition number and so large RGA-values indicate that decouplers will perform poorly on the plant. One of the main advantages of the RGA is that it depends only on the plant model itself, and does therefore not require any preliminary controller design. This is due to an assumption of perfect control. Another advantage of the RGA is that it is scaling independent.

The RGA may easily be extended to a frequency dependent measure (e.g., Bristol, 1978), and will in this case contain more useful information with respect to feedback control. We are here primarily interested in the frequency region around the expected closed-loop bandwidth. The definition of the elements in the RGA is given by

$$\lambda_{ij} = \frac{(\partial y_i/\partial u_j)_{u_{l\neq j}}}{(\partial y_i/\partial u_j)_{y_{l\neq i}}} = g_{ij}(s)[G^{-1}(s)]_{ji} \tag{6.3}$$

As the elements in each row and column sums up to unity in the RGA, we only have to consider the 1,1 element for the 2 × 2 case.

Skogestad et.al. (1990) have successfully used the frequency dependent RGA for selecting control configurations for several distillation columns, and Hovd and Skogestad (1991) have proven its usefulness on a more general basis.

6.3.2 Closed Loop Disturbance Gain

The Relative Gain Array is independent of disturbances. However, the main reason for applying feedback control in distillation is rejection of disturbances that enters the process. In the literature it has been common to consider the open-loop disturbance gains at steady-state when evaluating sensitivity to disturbances. However, one should also for disturbances put emphasis on the dynamic behavior. In addition the direction of the disturbance effect should be considered in the multivariable case. Some disturbances may be easier to reject than others due to a good alignment with the strong input directions of the plant. Stanley et.al. (1985) introduced the Relative Disturbance Gain (RDG) which takes the directions into account. For a particular disturbance z_k the RDG, β_{ik}, is defined for each loop i as the ratio of the change in u_i needed for perfect disturbance rejection in all outputs to the change in u_i needed for perfect disturbance rejection in the corresponding output y_i when all other inputs are kept constant.

$$\beta_{ik} = \frac{(\partial u_i/\partial z_k)_{y_l}}{(\partial u_i/\partial z_k)_{y_i,u_{l\neq i}}} \tag{6.4}$$

Hovd and Skogestad (1991) suggested a measure, the Closed-Loop Disturbance Gain (CLDG), δ_{ik}, based on the RDG but which also takes the disturbance gain g_{dik} into account,

$$\delta_{ik} = \beta_{ik} g_{dik} \tag{6.5}$$

A matrix of CLDG's may be computed from

$$\Delta = \{\delta_{ik}\} = G_{diag} G^{-1} G_d \tag{6.6}$$

where G_{diag} are the diagonal elements of G. Hovd and Skogestad (1991) found that this measure enters nicely into the relation between control off-set e_i and disturbances z_k while the RGA enters in a similar way into the relation between off-set and setpoint changes r_j. We have for the case of decentralized control

$$e_i \approx -\lambda_{ji} \frac{1}{g_{ji} c_i} r_j + \delta_{ik} \frac{1}{g_{ii} c_i} z_k; \quad \omega < \omega_B \tag{6.7}$$

Assume the model is scaled such that the allowed control error, $e_i = y_i - r_i$, is of magnitude 1, and the disturbance model is scaled such that the expected disturbances, z_k, are of magnitude 1. Then (6.7) implies that $|\delta_{ik}(j\omega)|$ is approximately equal to the minimum loop gain, $|g_{ii} c_i(j\omega)|$, needed to reject disturbance z_k. Due to bandwidth limitations the required gain should not be too high. That is, small values of $|\delta_{ik}|$ are preferred. Similar reasoning applies to the RGA for setpoint changes.

In this paper we scale the outputs such that setpoint changes of 0.01 mole-fraction units for column A and 0.0001 mole-fraction units for column F corresponds to magnitude 1 setpoint changes. We consider disturbances in feed flow F and feed composition z_F. For both columns the disturbances are scaled so that a 30 % change in F and a 20 % change in z_F corresponds to magnitude 1 disturbances.

6.4 RGA and CLDG for Example Columns.

The RGA for column A is shown as a function of frequency as the solid line in Figure 6.1a. The RGA starts out at a value of 35 at steady-state but breaks off at intermediate frequencies and reaches a value of 1 at high frequencies. The RGA value of 1 at high frequencies is due to the liquid lag which introduces a one-way decoupling at high frequencies. The frequency where the RGA-value becomes unity is given by $\omega_1 \approx 1/\theta_L$ (Skogestad et.al., 1990), where θ_L is the total liquid lag for the flow-dynamics as defined in Section 2.

The RGA for column F is shown in Figure 6.2a. The RGA starts out at a value of 499 at steady-state, but as for column A it breaks off at intermediate frequencies and reaches a value of 1 at higher frequencies due to the flow-dynamics.

The large RGA-values for the two columns imply that decouplers can not be used as a part of the controller design (Skogestad and Morari, 1987).

The interactions in distillation columns operated with the LV-configuration may be understood as follows: The initial composition responses are dominated by intermixing between adjacent stages as a result of the change in flows L and V. Due to the lag

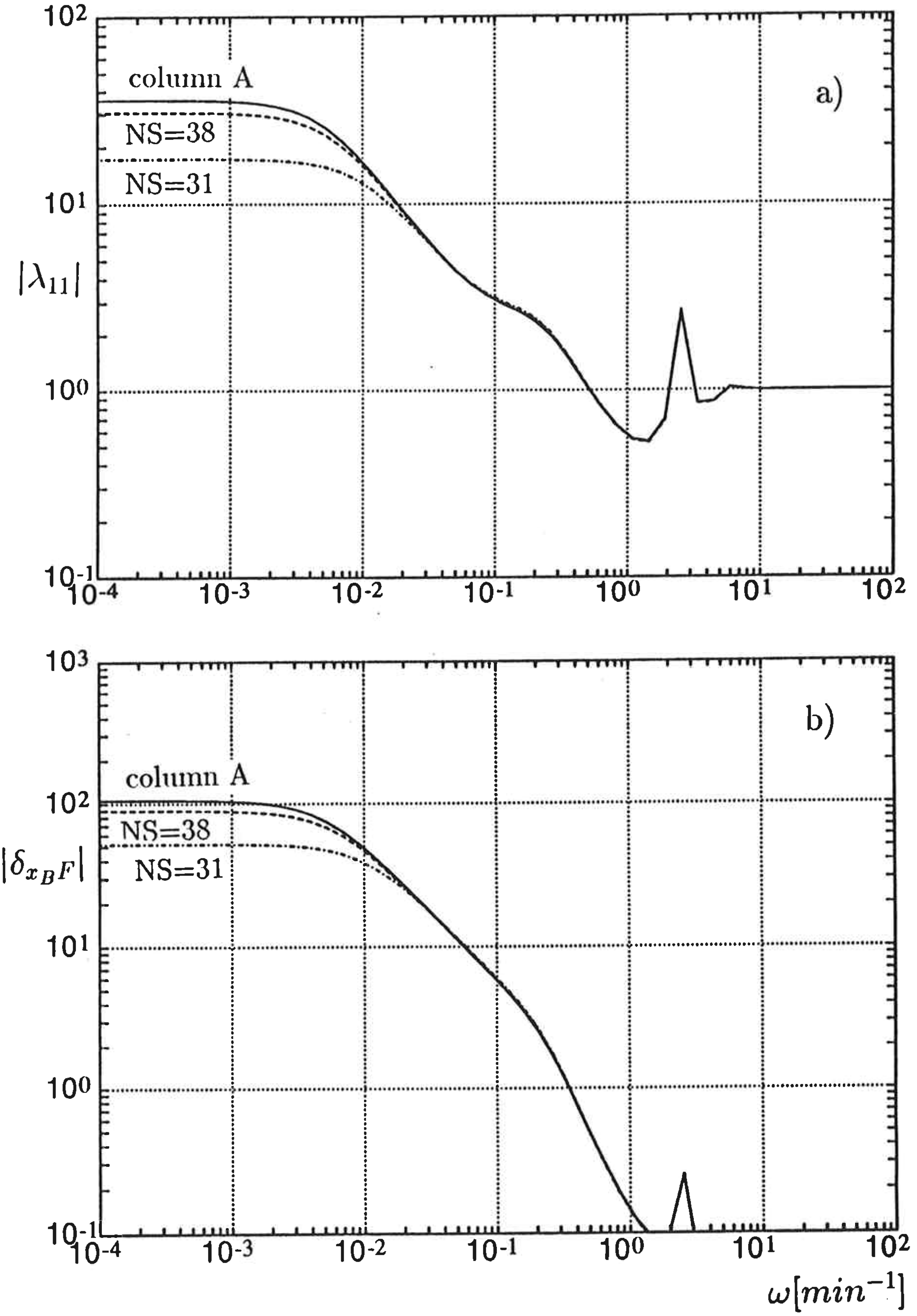

Figure 6.1: (a) RGA and (b) CLDG (effect of F on x_B) as functions of frequency for column A with and without sidestream. Sidestreams $S = 0.1F$ from trays 31 and 38 respectively.

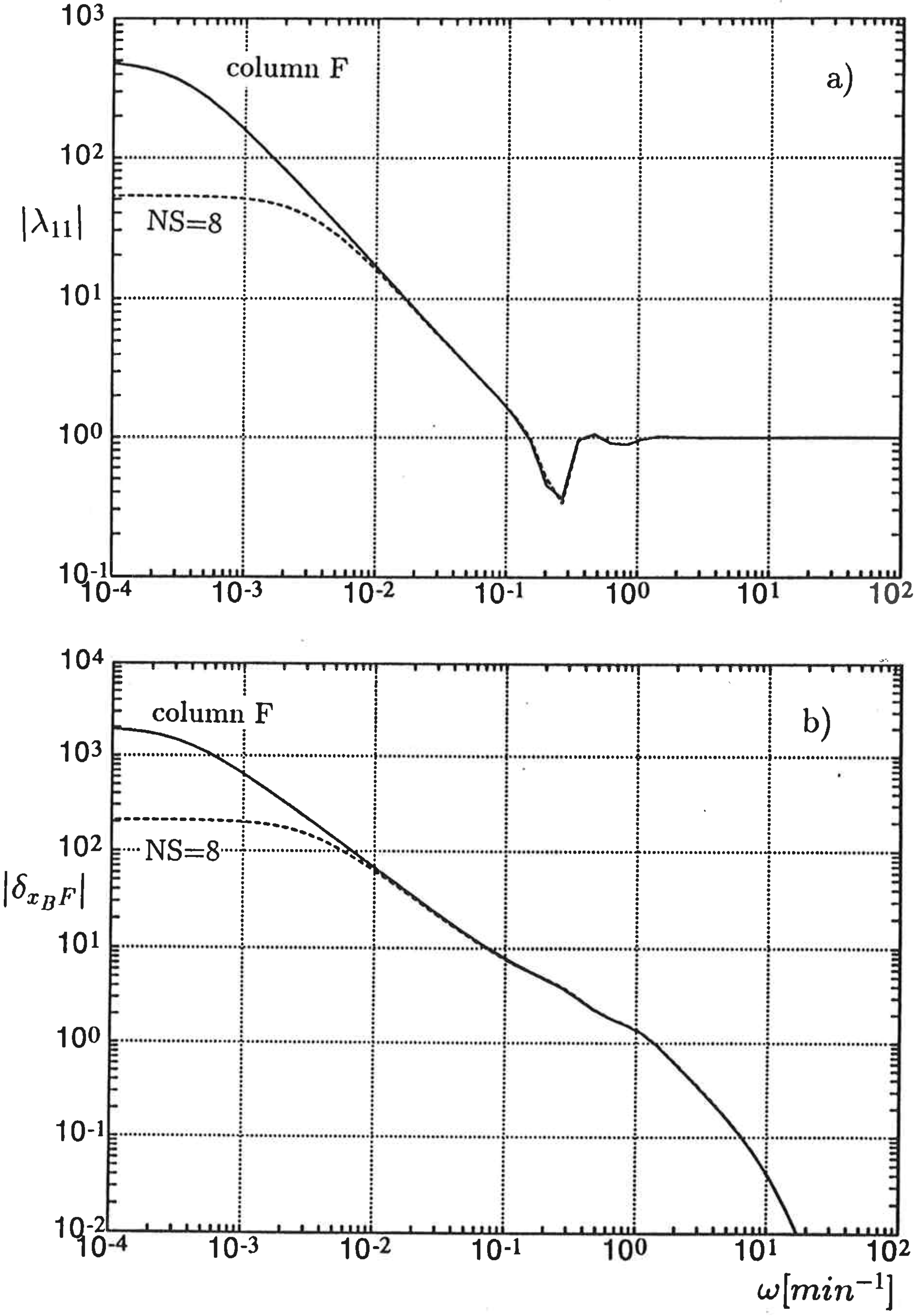

Figure 6.2: (a) RGA and (b) CLDG (effect of F on x_B) as functions of frequency for column F with and without sidestream. Sidestream $S = 0.02F$ from tray 8.

for changes in reflux flow L, the interactions are small initially. The slower part of the responses are dominated by interactions between the compositions on *all* stages (eg, Rademaker et.al, 1975). In a well designed column without any pinch in the composition profile this results in strong interactions between the top and bottom of the column.

Figure 6.1b shows the CLDG as a function of frequency for the effect of a disturbance in feed flow F on bottom composition x_B (worst case disturbance) for column A. We see that the CLDG has its maximum at steady-state and breaks off at the same frequency as the RGA. The CLDG for a disturbance in F on x_B (worst case disturbance) for column F is shown in Figure 6.2b. As for column A the CLDG has its maximum at steady-state and then breaks off at the same frequency where the RGA breaks off.

When analyzing systems for feedback control properties one should emphasize the frequency region around the expected closed-loop bandwidth. The expected bandwidth of most columns will be in the frequency range 0.01 - 0.1 rad/min, depending mainly on the size of measurement delays. We see from Figure 6.1 and Figure 6.2 that the interactions and disturbance sensitivity are worse when the bandwidth is low.

6.5 Effect of Introducing Sidestreams

The high interactions in high-purity distillation (using LV-configuration) is closely related to the fact that the steady-state gains for "changes in internal flows" (change L and V with D and B constant) are significantly smaller than the gains for "changes in external flows" (change in D and B) (e.g., Skogestad et.al., 1988). The reason for the high gains for changes in external flows is easily seen from the overall material balance (e.g, Shinskey, 1984)

$$Dy_D + Bx_B = Fz_F \tag{6.8}$$

For high-purity columns we have $y_D \approx 1$ and $x_B \approx 0$ and thus $D \approx Fz_F$. Any change in D from this value will necessarily lead to an imbalance in (6.8) which will strongly influence the product compositions. One possible way to reduce the effect of external flows on product compositions is to withdraw a small sidestream from a plate inside the column (Wachter and Andres, 1989). The total material balance then becomes

$$Dy_D + Bx_B + Sx_S = Fz_F \tag{6.9}$$

Here S denotes the size of the sidestream and x_S its composition. The compositions inside the column will vary relatively much compared to the product compositions, and one might conjecture that a sidestream will absorb a large part of the imbalance for changes in D and B. Since a sidestream only will have a small effect on the gains for internal flows, we expect the RGA and CLDG to decrease with the introduction of a sidestream, at least at low frequencies. Note that we here use steady-state arguments.

The two dotted lines in Figure 6.1a shows the RGA for column A with a sidestream $S = 0.1F$ on tray 31 and tray 38, respectively. We see that the sidestream reduces the RGA at low frequencies from 35 to 17 and 31, respectively, but has no effect on the RGA at higher frequencies. The reduction in the RGA at low frequencies is expected from the above discussion. The RGA is unchanged at higher frequencies because the initial responses are dominated by the intermixing between adjacent stages due to the change in flows, and as the composition profile is almost unchanged by the sidestream, the initial responses are unaffected. Figure 6.1a shows, as expected, that the effect of a sidestream on tray 31 is significantly larger than for a sidestream on tray 38, which is located only two trays below the top.

A sidestream has a similar effect on disturbance sensitivity as on the RGA. This is illustrated in Figure 6.1b which shows the CLDG for a disturbance in F on x_B for column A with and without sidestreams. We see that the disturbance sensitivity is reduced at low frequencies but is unchanged at higher frequencies. The effect on the other elements of the CLDG-matrix is similar.

Figure 6.2 shows the effect on the RGA and CLDG of introducing a sidestream $S = 0.02F$ in column F. The sidestream is withdrawn from tray 8, which is close to the top. The RGA is reduced from 499 to 53 at low frequency, but as for column A, there is no improvement in the frequency region most important for feedback control. The CLDG is similarly to the RGA significantly reduced at low frequencies but unchanged at higher frequencies.

We conclude from the analysis above that although the RGA and CLDG are reduced at low frequencies by introducing a sidestream, the controllability is almost unaffected as the high-frequency behavior is unchanged. The bandwidth will usually be in the frequency range 0.01 - 0.1 *rad/min*, and in this region there is no improvement in the RGA and CLDG. For manual operation, where "control" will be slow, a sidestream may ease the operation, especially in columns with high purities like column F. For column A, a relatively large sidestream is needed to yield a significant improvement in the low-frequency RGA, and this will be costly as the sidestream will have to be recycled somewhere in the process.

Wachter and Andres (1989) propose to introduce a sidestream and recycle it to the feed. However, then there is no effect on the overall material balance (6.8), and their solution does not yield any noticeable change in the RGA or CLDG.

6.6 Effect of Adding Trays

Industrial columns are often overdesigned in terms of number of trays to increase flexibility with respect to changing feed stocks, and sometimes also to overfractionate the products so that the product specifications are easier to keep when disturbances enter the column. Here we consider overdesigned columns with the product compositions kept at their specifications.

One of the characteristics of an overdesigned column is that is has a pinch in the composition profile. This is seen when plotting $log(x_L/x_H)$ against tray number, where x_L and x_H denotes fraction of light and heavy component respectively. Figure 6.3 shows a plot of $log(x_L/x_H)$ for column A with 40 trays and for column A60 with 60 trays (feed tray at 31). The product specifications are the same for both columns. We see that column A60 has a pinch in the profile around the feed, while column A has no pinch. As one of the main reasons for the interactions in distillation is the interaction between compositions on *all* trays, we expect the pinch zone in the overdesigned column to reduce the interaction between the sections above and below the pinch. Introducing extra trays will also reduce

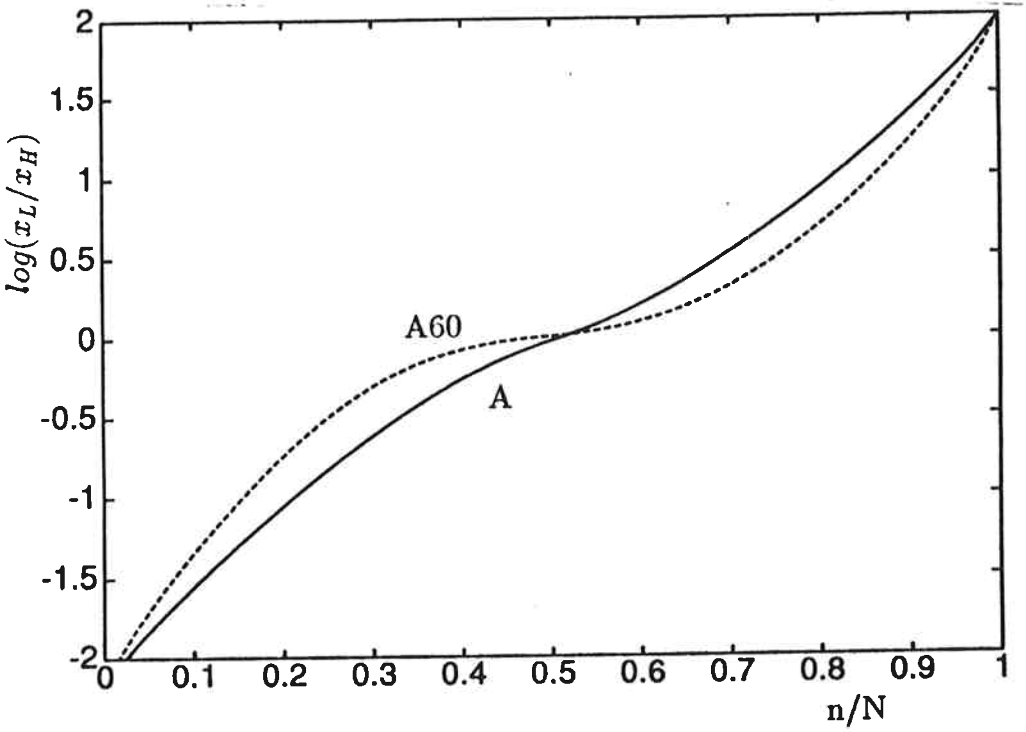

Figure 6.3: Composition profile [$log(x_L/x_H)$ against tray number n/N] for column A and column A60.

the internal flows and thus increase the effect of internal flows on compositions, while the effect of external flows will be almost unchanged.

Figure 6.4a shows the RGA as a function of frequency for column A and column A60. We see that the RGA is significantly reduced both at low and intermediate frequencies. The steady-state value is 35 for column A and 8 for column A60. The initial responses are, as for the case of sidestreams, almost unchanged. However, the lag in liquid flow (θ_L) is larger for column A60 as there are more trays and the liquid flows are smaller compared to the holdups (see (6.2)). This explains why the RGA for column A60 is lower also at high frequencies.

From Figure 6.4b we see that the overdesign also reduces the disturbance sensitivity from F to x_B (which is the largest element in the CLDG-matrix), but the reduction is significantly less than in the RGA for this example. As disturbance rejection usually is the most important in process control, overdesign will in this case not yield significant improvements in performance. However, we find that the improvement in other elements of the CLDG-matrix are significant (e.g., from F to y_D), and the conclusion with respect to overdesign may therefore be different for other columns with similar purities.

Note that we in column A60 introduced the feed at the optimal location $N_F = 31$, i.e. we added 10 trays to each section of column A. By adding the trays non-symmetrically we obtain somewhat different results. By adding 20 trays to the top section we find that y_D is the most sensitive output to disturbances, while adding 20 trays to the bottom section increases the sensitivity of output x_B to disturbances. However, these variations only appear at low frequencies. At intermediate and high frequencies there is almost no difference between the design alternatives; the effect of F on x_B represents the worst case CLDG with nearly the same magnitude for all design alternatives in the most important

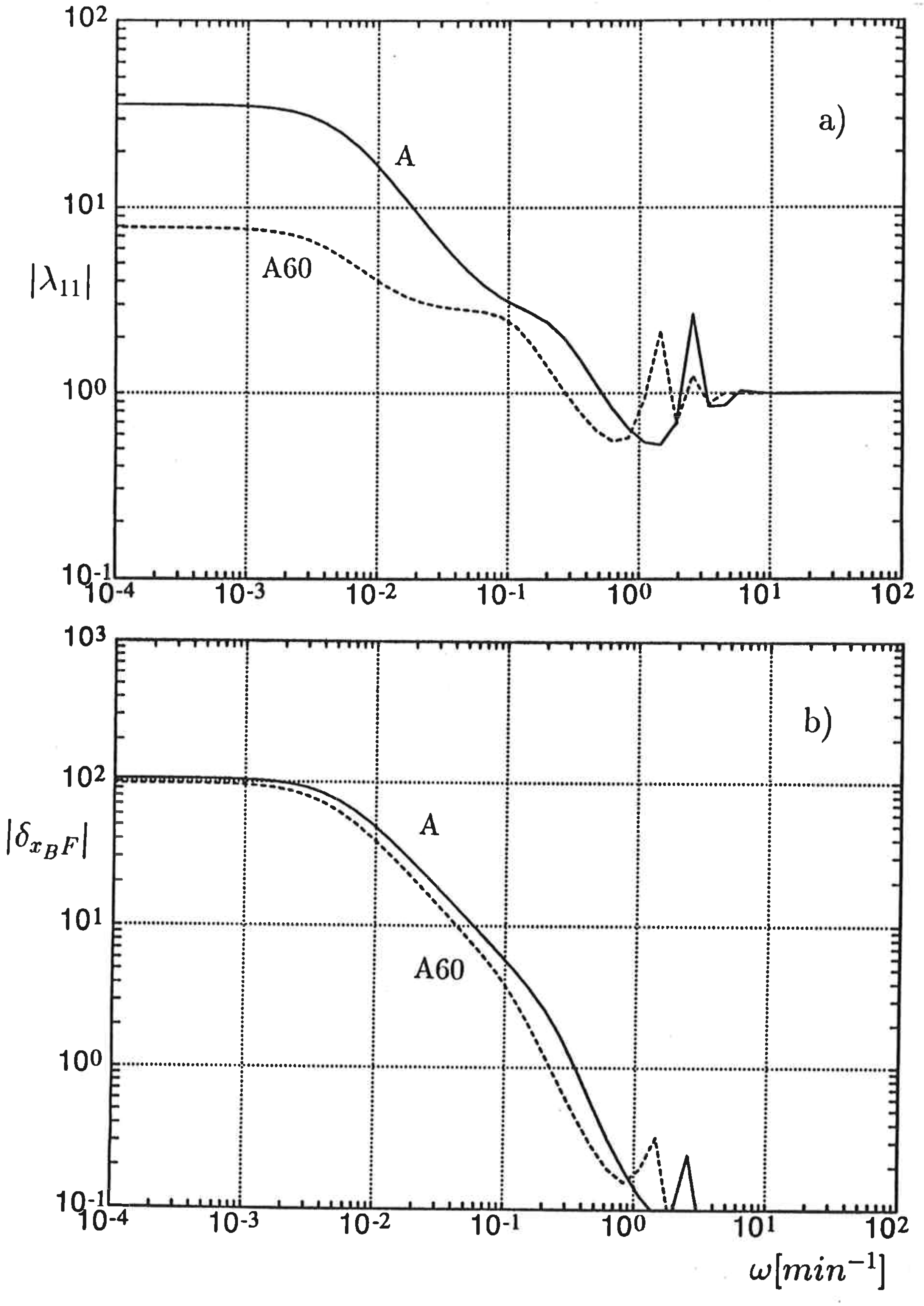

Figure 6.4: (a) RGA and (b) CLDG (effect of F on x_B) as functions of frequency for column A and column A60.

frequency region. Adding the trays symmetrically is the low cost solution in terms of utility consumption, and is therefore the best alternative for column A.

For column F we find that adding 5 extra symmetrically (optimal feed location) yields an improvement in the RGA, but yields a larger CLDG. However, for this column the best alternative seems to be to add the trays in the top section. The effect of this design modification, denoted F15, is shown in Figure 6.5. We see that the RGA is significantly reduced both at low and intermediate frequencies. Figure 6.5b shows the disturbance sensitivity (CLDG) of both y_D and x_B to disturbances in feed flow F. Note that the largest CLDG represents the control limitation at a given frequency. For column F, x_B is the most difficult output at all frequencies. For column F15, on the other hand, we see that y_D is the most sensitive at low frequencies (since we have introduced the extra trays in the top section), while x_B is the most sensitive at higher frequencies. Most important, however, is that the overall disturbance sensitivity is reduced both at low and intermediate frequencies by adding 5 trays to the top section.

The two columns studied here demonstrate that the effect of overdesign on controllability will depend both on the column studied as well as on where the extra trays are introduced. For column A none of the design alternatives considered yielded a significant improvement in controllability. For column F we got better controllability by introducing five extra trays in the top section, i.e., by using a non-optimal feed location. The effect of overdesign on controllability will thus depend on the column at hand, but should be considered for columns that prove hard to control.

With respect to the cost of overdesign, note that adding extra trays reduces the utility consumption needed for a given separation. For column F, the utility consumption in terms of $L+V$, is reduced by approximately 25 % by adding 50 % more trays. Thus, the surface around the steady-state optimal solution may be relatively flat, and the cost of overdesign may be relatively low.

6.7 Use of Feed Preheater for Control

Many columns have a feed preheater which heats the entering feed. Usually the amount of heat added is adjusted to keep the entering feed at a preset temperature, e.g., the bubble point temperature. However, in his thesis, Loe (1976) suggests that the feed preheater may be used more actively in controlling the column in order to reduce the interactions between the top and bottom composition control loops. More specifically, his idea is to counteract a change in boilup (V/F) by an equal change in the liquid fraction of the feed, q_F (such that $\Delta V_F = -\Delta V$ where $\Delta V_F = -F\Delta q_F$). In this way a change in the boilup will have a small effect on the flows in the top section, and one would obtain something close to a one-way decoupling of the column. This will, however, require that the available change in heat input to the feed preheater is almost as large as in the reboiler. Loe also discussed the possibility of using the feed preheater to control the feed-plate composition, but suggested to use a controller with integral action which obviously is not needed nor wanted since it would make the column profile very "stiff".

Here we will modify the idea of Loe somewhat and suggest to use a pure proportional controller between the feed-plate composition (or equivalently, for a binary mixture, the

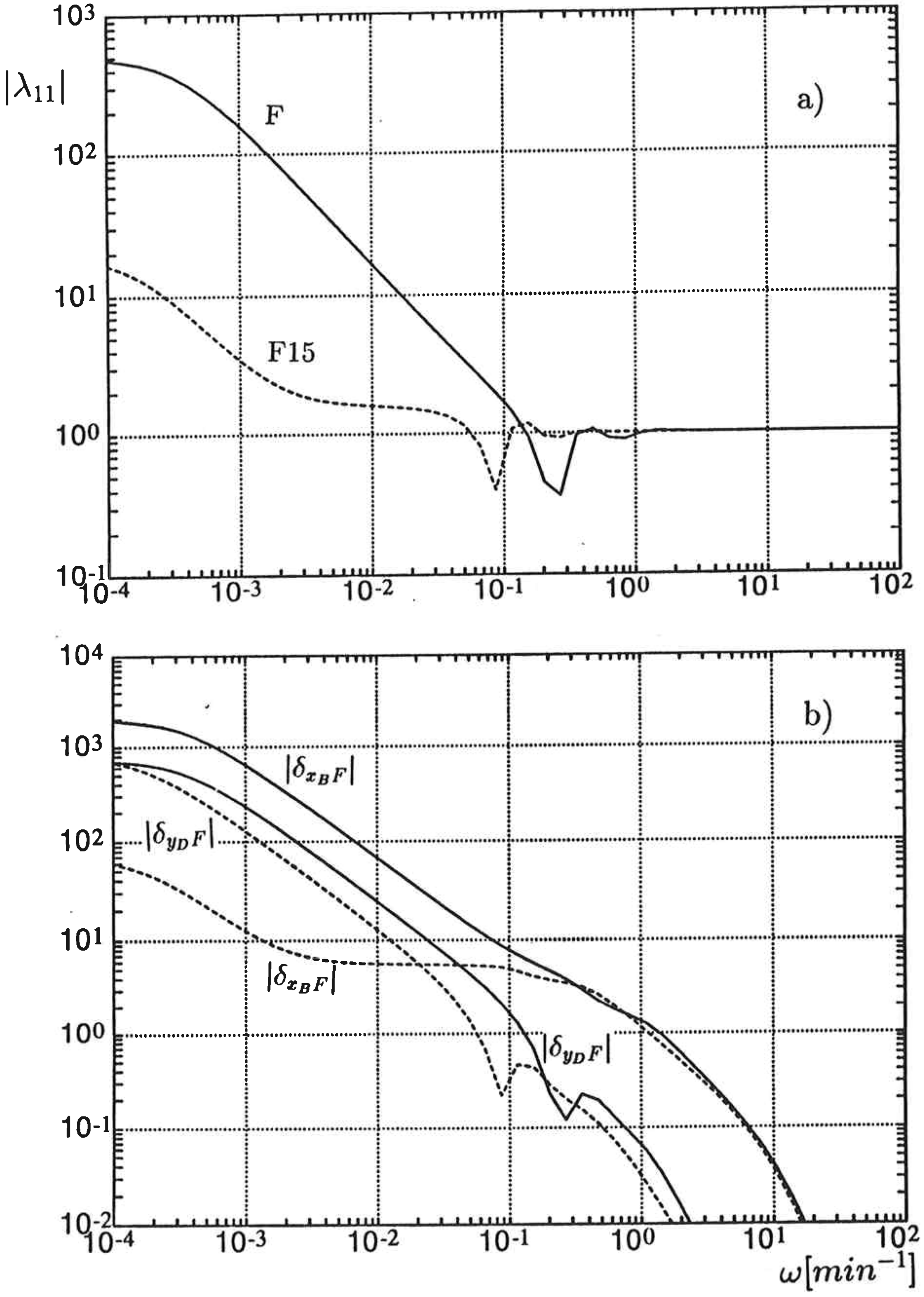

Figure 6.5: (a) RGA and (b) CLDG (effect of F on y_D and x_B) as functions of frequency for column F (solid line) and column F15 (dashed line).

temperature) and the feed preheater

$$dq_F = -k_{qF} dx_{NF} \tag{6.10}$$

By using a pure proportional controller one avoids making the column profile too stiff, and the controller gain may be adjusted so that the requirements for changes in the feed preheating does not exceed the available heating in the preheater. By using a feedback controller we also obtain a degree of two-way decoupling. An increase in reflux will be counteracted by a decrease in q_F and an increase in boilup will be counteracted by an increase in q_F.

Figure 6.6a shows the RGA as a function of frequency for column A using different gains k_{qF} for the feed preheater control. For our example, a gain k_{qF} of 1.0 implies that we for setpoint changes get approximately a 10 % change in Fq_F (feed preheater duty) compared to changes in V (reboiler duty). The largest change in q_F is found for changes in feed composition. A change in z_F from 0.50 to 0.60 yields a change in q_F from 1.0 to 0.91 (keeping y_D and x_B constant). From Figure 6.6a we see that the use of the preheater in control reduces the RGA for the remaining system significantly. The reduction increases with the controller gain used, and with a gain of 1.0 we get a reduction in the RGA at low frequencies from 35.0 to 4.0. The RGA is reduced at frequencies up to $0.1 min^{-1}$, but the reduction is largest at lower frequencies. This implies that we will gain most in terms of improved control performance when the bandwidth of the control system is small, e.g. due to large measurement delays.

The effect of the feed preheater control on disturbance sensitivity is illustrated in Figure 6.6b. We see that we obtain similar reductions in the CLDG as obtained in the RGA.

We do not show results for column F with feed preheater control here. However, similar results are obtained for this column as were obtained for column A, i.e., a significant reduction in both the RGA and CLDG.

Figure 6.7 shows nonlinear responses of column A to a 30 % step increase in feed rate F with and without feed preheater control ($k_{qF} = 2.0$). Single-loop PI-controllers are used for composition control. The controllers were designed for robust performance in both cases, i.e., taking uncertainties into account. A delay of 3 min. in the product composition measurements was included in the design and simulations. In the feed preheater loop a delay of 1 min. was included. The reason for using a smaller delay in this loop is simply that the composition measurement is not critical, and a fast temperature measurement will yield the desired effect. From Figure 6.7 we see that the control performance is improved by using the feed preheater for control. We get smaller overshoot as well as a faster settling to steady-state. This is as expect since the preheater reduces the interactions at low frequencies. Figure 6.7 also shows the response in the feed preheater. We see that the change in q_F only is temporarily, with a maximum change of about 3 %. The changes in reflux and boilup are 30 % with no overshoot for both cases.

We have here only considered using the feed-plate composition to manipulate the feed preheating. However, other strategies are of course possible. For example, one may use compositions at plates some distance away from the feed-plate. For column A, we for instance find that controlling the composition on plate 31, rather than 21, yields a similar

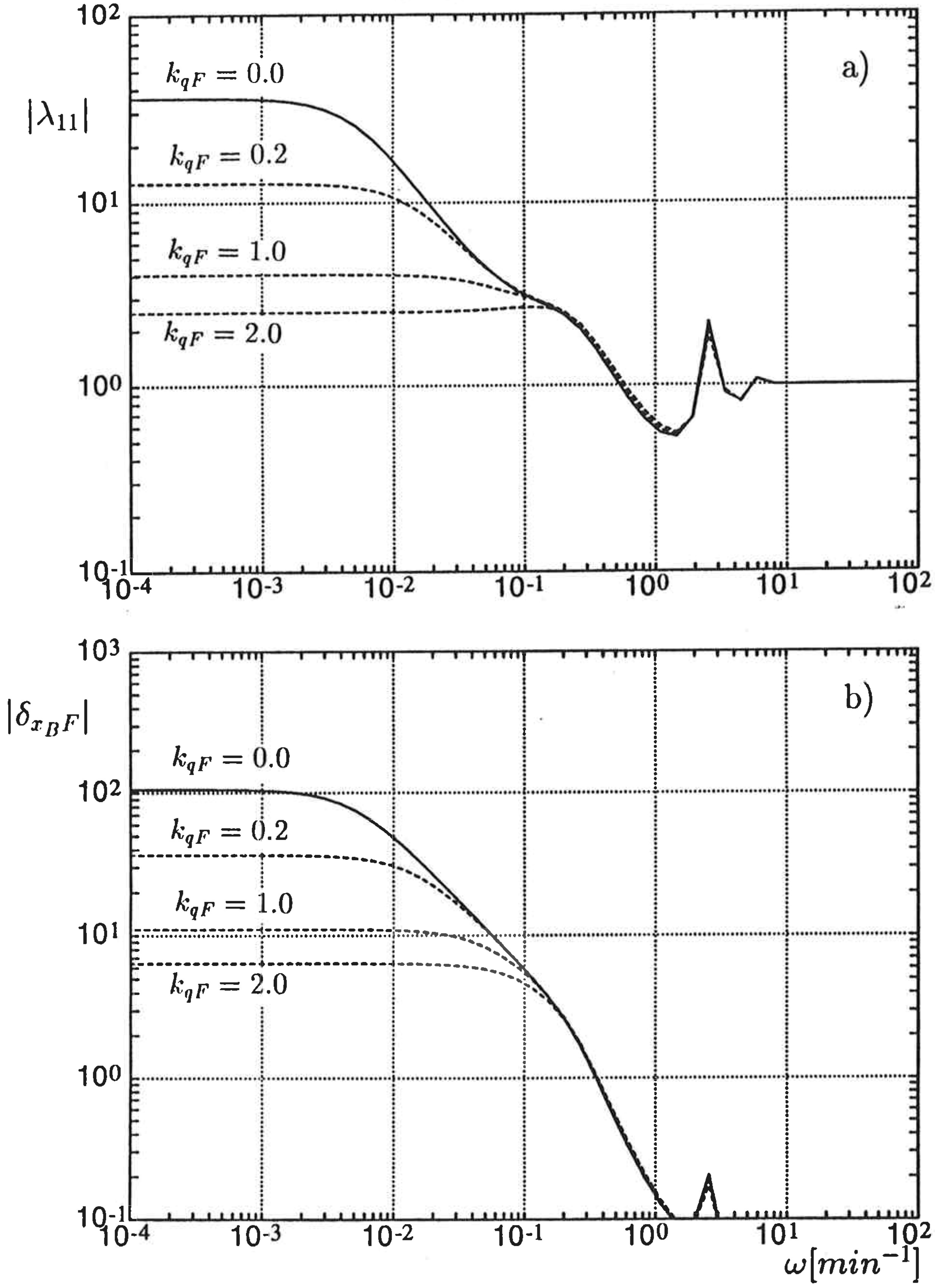

Figure 6.6: (a) RGA and (b) CLDG (effect of F on x_B) as functions of frequency for column A with control of feed preheater. k_{qF} denotes gain for feed preheater controller.

effect on the RGA and CLDG as in Figure 6.6, but with smaller requirements for changes in q_F.

One might believe that the utility consumption is increased significantly by using the feed preheater in control. However, the total change in heat input (i.e., $V - Fq_F$) is not increased significantly. The only exception is for large changes in feed composition. However, the heating of the feed will cost less than the heating used for boilup as we have more light component in the feed. In some cases the active use of a feed preheater in control may be optimal even from a steady-state point of view.

In summary, we have shown that there is a significant potential for improvements in control performance by using the feed preheater actively. In general, it is obvious that one may always improve the control performance by adding an additional manipulated input and/or measurement. For the feed preheater on may consider using other measurements or a multivariable controller. One may also consider adding other manipulated inputs, such as an intermediate reboiler or cooler, or in some cases even the feed rate and feed composition.

6.8 Control Configurations

We have in this paper only discussed the LV-configuration which is the most widespread configuration in industry. The selection of which inputs to use for composition control is made when configuring the level control system. This is often considered as a part of the column design. However, the choice made here is of vital importance for the remaining composition control problem. Different configurations will have different properties with respect to interactions and disturbance sensitivity (e.g., Shinskey, 1984, Häggblom and Waller, 1990, Skogestad et.al., 1990). Skogestad et.al. (1990) studied the control of a number of columns and found that the best choice for most columns were the ratio configuration $(L/D)(V/B)$. In many cases design modifications will not be neeeded if a proper control configuration is chosen. However, the modifications we have considered in this paper will have a similar effect on the $(L/D)(V/B)$-configuration as on the LV-configuration. For other configurations, e.g., the DV-configuration, the conclusions with respect to design modifications may be different.

6.9 Conclusions

We have in this paper considered several possible design modifications for improving the controllability of high-purity distillation columns. The most important conclusions are:

1. A sidestream will reduce interactions and disturbance sensitivity at low frequencies. However, the improvements will not affect the frequency region of the expected bandwidth of the control system. This implies that a sidestream will only be beneficial in high-purity columns which are operated in manual mode.

2. An overdesigned column with additional trays will have a pinch in the composition profile. The pinch zone will reduce the interactions (in terms of the RGA) in the

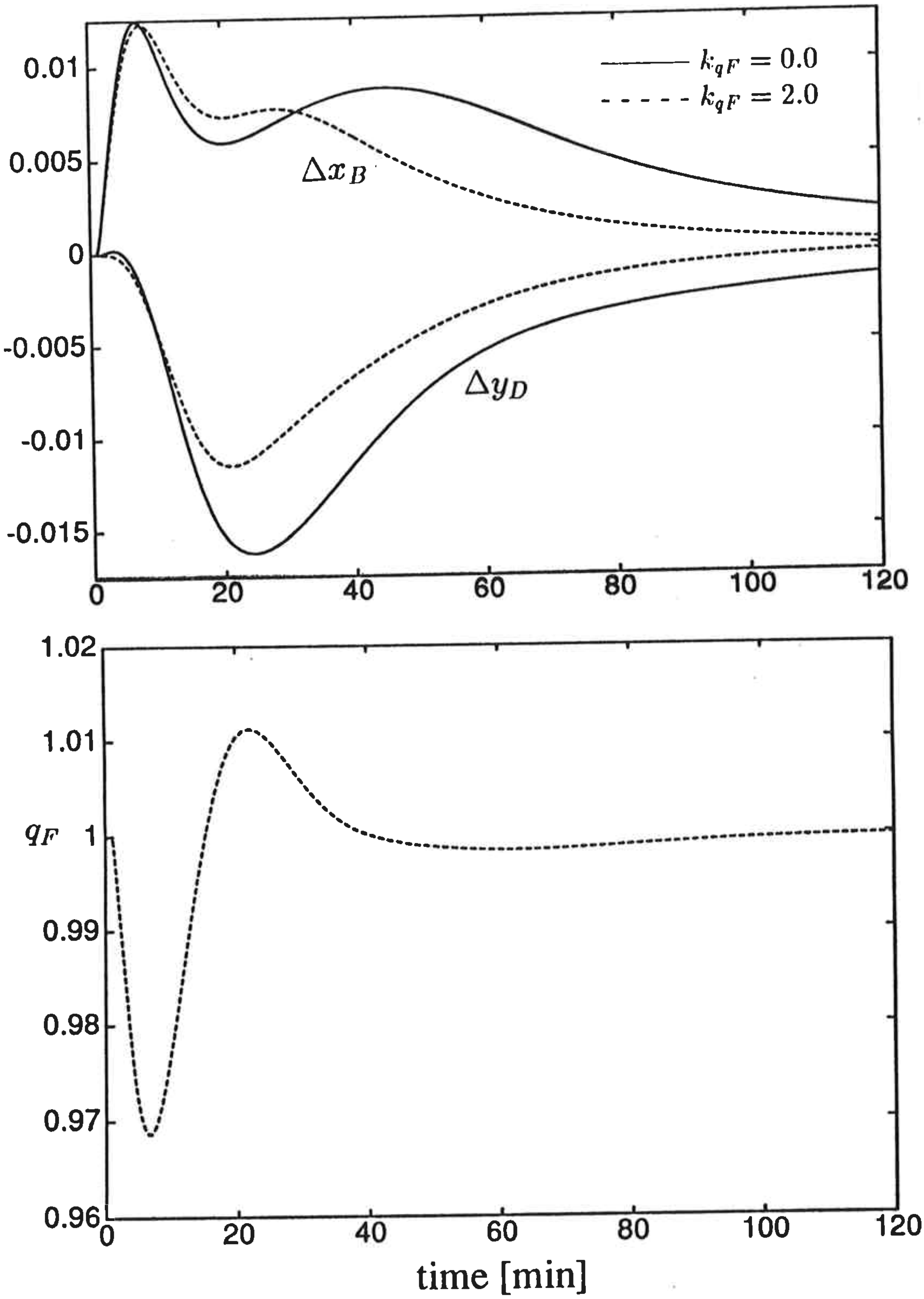

Figure 6.7: Nonlinear response of column A to a 30% increase in feed flow F with and without use of feed preheater for control. Product compositions controlled using single-loop PI-controllers. Lower plot shows response in q_F with feed preheater used for control.

frequency region important for feedback control. However, the reduction in disturbance sensitivity may be small in some cases, while it may be significant in other cases. Thus, the conclusion with respect to the effect of overdesign will depend on the column at hand.

3. Using the feed preheater to control a composition inside the column may yield significant improvements in both the RGA and CLDG, and should be considered as a design modification for columns which prove difficult to control.

We stress that we in this paper only have considered relatively few specific examples, and there is a definite need for additional studies.

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NOMENCLATURE

B - bottoms product rate (kmol/min)
D - distillate product rate (kmol/min)
e_i - control off-set in output i
F - feed flow rate (kmol/min)
$G(s)$ - input transfer matrix
$G_d(s)$ - disturbance transfer matrix
$g_{ij}(s)$ -transfer matrix element
L - reflux rate (kmol/min)
M - liquid holdup (kmol)
N - number of theoretical trays
N_F - feed tray location
q_F - liquid fraction of feed
r_i - setpoint change in output i
S - sidestream rate (kmol/min)
u_i - input i
V - boilup rate (kmol/min)
x_B - bottoms composition
x_{NF} - feed plate composition
x_S - sidestream composition
y_D - distillate (top) composition
y_i - output i
z_F - feed composition
z_k - disturbance k

Greek symbols

α - relative volatility
β_{ij} - element i,j of RDG

Δ - CLDG matrix
δ_{ij} - element i,j of CLDG matrix
λ_{ij} - element i,j of RGA
ω - frequency (min^{-1})
τ_L - hydraulic time constant (min)
$\theta_L = (N-1)\tau_L$ - overall reflux lag (min)

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