Selection of Decentralized Control Configurations based on Disturbance Rejection for Plants with Pure Integrators

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Abstract

The paper considers the effect of interactions on the disturbance rejection properties of decentralized control systems. In particular, the problem of selecting the control structure which yields the best disturbance rejection properties under independent tuning of the individual subsystems is addressed. As a special case we consider systems that contain one or more integrators and which give rise to a number of zero elements in the transfer-matrix of the overall system. By assuming that no performance specifications exist for these integrators, we derive a method in which the disturbance sensitivity of the remaining outputs can be minimized. The method is based on closing the integrator loops prior to the evaluation of a performance measure proposed in this paper. The results are particularly relevant to the process industry where plants usually contain a large number of integrators in the form of gas and liquid holdups for which the performance specifications usually are weak. An example from the process industry is used to illustrate the method and it is shown that the developed performance measure correctly predicts the closed loop systems properties for different kinds of disturbances.

1 Introduction

Disturbance attenuation is often the main objective of process control. This paper considers the disturbance attenuation properties of a closed loop system, when the plant is controlled using a decentralized controller. The plant model is given by a general square multivariable $n \times n$ system $G(s)$, i.e., having n inputs and n outputs. Decentralized control implies that the overall system is decomposed into a number of interacting subsystems for which individual controllers are designed, i.e., the overall controller may be written on a blockdiagonal form. Such a decomposition of the control problem is usually preferred due to the inherent robustness of such structures (both with respect to model uncertainty and sensor/actuator failures) and the ease of (re)tuning compared to the case with full multivariable controllers. However, the potential cost of using a limited controller structure is reduced closed loop performance due to the presence of interactions among the subsystems and the possibly strong directionality of the overall multivariable system. Therefor tools are needed, guiding the engineer in the selection of an acceptable control configuration, i.e. a structure of interconnections between measurements and manipulated variables, in order to achieve the desired performance of the closed-loop system. Especially in the area of process control should these tools be able to make use of the fact that several pure integrators are contained in the plant and that there usually are no tight performance specifications for the corresponding inventory loops.

Available tools for the selection of decentralized control configurations addressing the disturbance rejection properties of a closed loop system are very few. Hovd and Skogestad [8] introduced the closed loop disturbance gain (CLDG), which can aid in determining the required open loop gain in each subsystem in order to achieve a specified disturbance attenuation for the overall closed loop system. Skogestad and Morari [15] propose to evaluate the Disturbance Condition Number, or the closely related Relative Disturbance Gain [16], together with the RGA [2] to determine whether decentralized or full multivariable control should be used for disturbance rejection. Other performance related tools are the performance relative gain array (PRGA) [8] and the Relative Sensitivity Asymptotes [1]. Even the RGA [2] is often used as a pairing tool based on performance considerations, e.g. [4]. One important shortcoming of most available tools is, however, the assumption that perfect control up to the bandwidth is a reasonable assumption. Schmidt and Jacobsen [12] showed that this, in general, is not the case for systems larger than 2×2. In particular, for the RGA all available theoretical results concern stability only while performance is addressed only by engineering rules of thumb resting on no theoretical basis whatsoever.

Also the issue of handling (almost) pure integrators has received little attention in the literature so far. However, it is well known that essentially all processes in the process industry contain a large number of integrators in the form of liquid and gas holdups. These integrators need to be stabilized, but otherwise there are usually few performance specifications assigned to these variables. The standard approach in industrial practice, and with available tools, is to close the integrator loops first, without paying any attention to the remaining control structure design problem. Buckley [3] proposes to control levels (integrators) based on the overall material balance control. The main objective thereby is that of production rate control, i.e., to enable changes in the production rate. According to Ogunnaike [10], Buckleys approach is still dominating in industrial practice. Price [11] proposes some guidelines for production rate and inventory control design.

The main weakness of essentially all available methods is that they treat the stabilization problem independently of the remaining control configuration problem. However, it is well known that the decision regarding which inputs to use for stabilization usually has a large impact on the remaining control problem. One commonly studied example is that of composition control in distillation columns, see e.g. [14], for which it is well known that the achievable decentralized control performance depends strongly on which inputs that are used for level control. However, at present there are no tools that can be used to determine the best control configuration, without designing controllers for all possible configurations, even for this relatively simple example.

Another issue to be taken into account, when selecting control configurations, is the fact that the systems transfer matrix might contain zero elements. These zero elements can occur because of the presence of pure integrators and/or because of a certain physical structure of the system. The corresponding relative gains and decentralized relative gains [12] for these elements are by definition zero, and thus yield no information about how the interactions affect the system. However, it is important to find a method of dealing systematically with those zero elements. For example, for the case of distillation it has been found that the best pairing corresponds to pairing on zero elements of the open loop transfer matrix and hence on zero relative gains [14].

In the following we consider independent, decentralized and finite bandwidth control. Based on this we develop a measure for the influence of interactions on the disturbance rejection properties of a given pairing. To avoid a strong dependence on the type of controller used, we simply specify the desired performance of the single loops using a few key parameters such as bandwidth, or cross-over frequency, and phase margin.

It is important to note that, in general, by using dependent, rather than independent, controller design a better disturbance rejection of the overall system can be achieved. However, the restriction to independent controller design has its advantage in the fact that less knowledge about the system is required and thus the controller design can be performed with a much less detailed model of the plant. It is also interesting to note that controllers in the process industry usually are tuned in an independent way.

In order to use the measure developed in this paper also for systems with pure integrators and with zero elements in the systems transfer matrix, a method based on loop closure of the integrator loops, prior to the evaluation of the measure, is proposed. An example from process industry shows the usefulness of this method.

The paper considers mainly single-loop controllers, i.e., scalar subsystems, but an extension to block-diagonal controllers is straightforward.

2 A measure for achievable disturbance attenuation

In this section a measure for the achievable disturbance attenuation of a certain control configuration, or pairing, is derived.

We consider a general, square multivariable $n \times n$ system G and a stable open loop disturbance transfer function G_d

$$\begin{aligned} y &= Gu + G_d d \\ u &= K(r-y) \end{aligned} \tag{2.1}$$

It is assumed that the signals and systems transfer functions are scaled, such that the maximum expected disturbances corresponds to $\|d\|_\infty = 1$ and that an acceptable disturbance rejection is obtained if the outputs satisfy $\|y\|_\infty \leq 1$ for all possible disturbances. K is a diagonal controller. The closed loop equation can be obtained by rewriting the equations in (2.1), to obtain

$$y = SGKr + SG_d d \tag{2.2}$$

where S is given by $S = (I + GK)^{-1}$. As we are only focusing on disturbance rejection, and not on setpoint tracking, we assume in the following $r = 0$. Because K is a diagonal controller the sensitivity S can be rewritten (see, e.g., [5]), as

$$y = SG_d d = S_{\tilde{G}} \left(I + ET_{\tilde{G}}\right)^{-1} G_d d \tag{2.3}$$

where $E = \bar{G}\tilde{G}^{-1}$, $S_{\tilde{G}} = \left(I + \tilde{G}K\right)^{-1}$, $T_{\tilde{G}} = I - S_{\tilde{G}}$ and $G = \tilde{G} + \bar{G}$ with $\tilde{G}$ containing only the diagonal and $\bar{G}$ the off-diagonal elements of G.

Usually the desired closed loop performance in terms of desired cross-over frequency (ω_c) and phase margin (ϕ_m) in the single controlled loops can be determined and therefore the corresponding desired sensitivities $\left[\hat{S}_{\tilde{G}}\right]_{ii}$ can be approximated by appropriately chosen transfer functions $f_i(s)$

$$
\begin{aligned}
\left[\hat{S}_{\tilde{G}}\right]_{ii} &\approx f_i(\omega_{ci}, \phi_{mi}) \quad , \quad i = 1, ..., n \\
F &= diag(f_1, ..., f_n)
\end{aligned} \tag{2.4}
$$

where equality holds at the desired crossover frequency. The desired crossover frequency can, e.g., be chosen as the maximum open-loop disturbance bandwidth in each output. The problem of obtaining the transfer functions $f_i(s)$ is addressed in section 2.2.

Having approximated the desired sensitivities around the cross-over, it is possible to determine the controllers K_{ii} achieving these sensitivities in the independently controlled single loops using an IMC type of controller. However, it is important to stress that whatever controller design method is used, the frequency response of the controller at the desired cross-over ω_c is dependent only on the performance specifications at this frequency.

$$K = \tilde{G}_m^{-1}\left(F^{-1} - I\right) \approx \tilde{G}_m^{-1}\left(\hat{S}_{\tilde{G}}^{-1} - I\right) \tag{2.5}$$

The term $\tilde{G}_m$ results from the separation of the system $\tilde{G}$ into a diagonal minimum phase system $\tilde{G}_m$ and a diagonal allpass transfer matrix $\tilde{A}$.

$$\tilde{G} = \tilde{A}\tilde{G}_m \tag{2.6}$$

By rewriting equation (2.3) we get

$$y = SG_d d = S_{\tilde{G}} X_d d \approx F X_d d \tag{2.7}$$

which yields the ratio X_d as

$$
\begin{aligned}
X_d &\approx F^{-1} S G_d = \\
&= \left[I + \bar{G}\tilde{G}_m^{-1}\left(\left(F^{-1} - I\right)^{-1} + \tilde{A}\right)^{-1}\right]^{-1} G_d
\end{aligned} \tag{2.8}
$$

Here X_d is defined as the ratio between the achieved closed loop disturbance sensitivity (SG_d) and the desired sensitivity in the controlled loops (F) for a given pairing. In the equations above equality holds in the case that the single loops are minimum phase, i.e., if $\tilde{G} = \tilde{G}_m$. It is interesting to note that under the assumption of perfect control, i.e. $F \approx 0$, the ratio X_d becomes equal to the CLDG, proposed by Hovd and Skogestad [8]. The main difference compared to the CLDG lies in the assumption of finite bandwidth control and the fact that they used the CLDG for dependent controller tuning.

2.1 Selecting control configurations

Equation (2.7) suggests that if for a certain pairing the induced infinity norm $\|FX_d\|_{i\infty}$ is smaller than one for all frequencies, independent tuning of the decentralized controller should lead to acceptable disturbance rejection of the closed loop system. In place of the induced infinity norm the maximum singular value of FX_d is used in the following, leading to a slightly more conservative measure.

Based on the above it can be stated that if, for a certain control structure, $\bar{\sigma}(FX_d)$ at the relevant frequencies is much larger than one, unsatisfactory disturbance rejection is to be expected. This leads us to the definition of the ξ_d-measure.

$$\xi_d(\omega) = \bar{\sigma}(FX_d), \quad \omega \in [\alpha\omega_b, \beta\omega_b] \tag{2.9}$$

A reasonable choice for the constants α and β is $\alpha \approx 0.1$ and $\beta \approx 10$. Based on the above, we propose the following pairing rule based on the ξ_d-measure

> *Pairing rule: The pairing, for which the maximum peak of the ξ_d-measure, defined in equation (2.9), is the smallest in the frequency range of its evaluation, should be preferred, when disturbance attenuation is the main issue.*

Note that the measure is evaluated only in some region around the desired cross-over frequency ω_c. The reason for this is that this is the frequency region where the impact of interactions and disturbances expectedly will be most significant, and also the region we have focused upon in the controller design above. For frequencies well below the bandwidth the sensitivity will usually be relatively small, the effect of interactions will be less significant and the disturbance rejection good. Furthermore the cross-over frequency / bandwidth is usually chosen such that the influence of disturbances is small for frequencies above the cross-over frequency.

In order to ensure a stable closed loop system it should always be verified, that $X_d(s)$ in equation (2.7) is stable for the chosen $F(s)$. Furthermore, since the controllers for the single loops are designed without considering the effect of interactions, pairings not being decentralized integral controllable (DIC) (see [6]) should be excluded. DIC might, e.g., be checked using the RGA or the Niederlinski Index [9]. However, note that even if a pairing is DIC, it is not guaranteed that using independent controller tuning will result in a stable closed loop system. A possible approach for dealing with this problem is to consider an interaction measure, e.g. the finite bandwidth PRGA [13], to determine configurations in which the interactions do not risk the stability.

It is important to stress that selecting a pairing by minimizing the above measure does not imply minimization of interactions between the single loops, but rather minimization of the effect of disturbances on the overall closed loop system. The assumption of independent controller tuning has the advantage that control configurations can be chosen which allow the desired performance to be obtained using simple models of the system and simple controller tuning.

2.2 Determination of the performance specifier F

The evaluation of the ξ_d-measure above requires the definition of the performance specifier $F(s)$. This implies, that for each single loop a transfer function $f_i(s)$ has to be found, representing the desired closed loop sensitivity in this loop.

The idea, employed here, is to find the open loop transfer functions $l_i(s)$ fulfilling the performance specifications in terms of cross-over frequency ω_c, phase margin ϕ_m and high-frequency roll-off n_{ro}. Based on the desired open loop transfer functions $l_i(s)$, the performance specifiers $f_i(s)$ are then obtained as

$$f_i(s) = \frac{1}{1+l_i(s)} \tag{2.10}$$

Depending on the desired roll-off the transfer function $l_i(s)$, fulfilling the open loop performance specifications above, can be designed in the following way.

- For a roll-of of $n_{ro} = -1$ (based on lead-compensator design)

$$l_i(s) = \frac{k_i}{s}\frac{s+bN}{N(s+b)} \quad , \quad b = \frac{\omega_c}{\sqrt{N}} \quad , \tag{2.11}$$

$$k_i = \omega_c\sqrt{N} \quad , \quad \frac{\pi}{2} - \phi_m = \arctan(\frac{\sqrt{N}}{2} - \frac{1}{2\sqrt{N}}) \tag{2.12}$$

- For a roll-of of $n_{ro} = -2$ (based on IMC)

$$l_i(s) = \frac{k_i\omega_c}{s}\frac{1}{1+t_i s} \quad , \quad t_i = \frac{\tan(\frac{\pi}{2} - \phi_m)}{\omega_c} \quad , \quad k_i = |1 + jt_i\omega_c| \tag{2.13}$$

The desired cross-over frequency ω_c can be determined by considering the maximum singular value of the scaled open loop disturbance transfer function G_d. The bandwidth should be larger than or equal to the frequency at which the maximum singular value $\bar{\sigma}(G_d)$ is equal to one. The phase margin ϕ_m might, e.g., be chosen by robustness or resonance peak considerations.

The performance specifier $F(s)$, determined as described above, can also be used for the determination of the decentralized relative gain [12] and the finite bandwidth PRGA [13].

3 Example

As an example system we consider a simple two-product distillation column (*column A*), which has been extensively studied, e.g. in [14]. The controlled variables consist of the bottom level M_B, the condenser level M_D, the top product composition y_D and the bottom product composition x_B. The manipulated variables are the reflux L, the boilup V, the distillate flow D and the bottoms flow B. The main disturbances acting on the system are changes in the feed-flow F and the feed-composition z_F. Without any feedback active the plants transfer matrix contains 6 elements which are identically zero. In open loop D and B have no effect on y_D and x_B, D has no effect on M_B and B no effect on M_D.

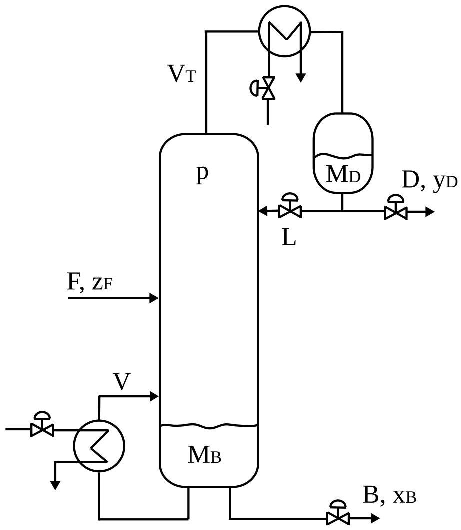

Figure 1: Two-product distillation column with single feed and total condenser.

A widely used control configuration for this plant is the so called LV- configuration. It consists of pairing the inputs and outputs in the following way: M_B/B, M_D/D, y_D/L and x_B/V. Interestingly this is also the pairing the common pairing rule based on the RGA suggests (see table 1). A study

	L	V	D	B
M_B	0	0	0	**1**
M_D	0	0	**1**	0
y_D	**35.9**	-34.9	0	0
x_B	-34.9	**35.9**	0	0

Table 1: Steady state RGA evaluated for the *column A* system. In bold the elements of the LV-control configuration suggested by the RGA.

by Skogestad et al. [14] showed that the best possible pairing in terms of disturbance rejection (in the case that no ratios of manipulated variables are considered as inputs) was to pair y_D/D and x_B/B, the so called DB-configuration, in which the levels were stabilized using the remaining inputs L and V. This control configuration corresponds to closing two loops on zero elements in the systems transfer matrix and, as can be seen from table 1, to all four RGA elements being identically zero. Skogestad et al. [14] used perfect control for the level loops and dependent controller tuning, based on global optimization of single loop PI-controllers, for the remaining loops.

In the following we consider whether the DB configuration is a good configuration even in the case of independent finite bandwidth control of the level loops followed by independent controller tuning of the remaining loops.

To determine the desired crossover frequency in the single loops, the maximum singular value of the open loop disturbance transfer function is evaluated, showing that for frequencies above $0.14 rad/min$ the effect of the disturbances on the system can be neglected. Therefor a desired crossover frequency of $\omega_c = 0.2 rad/min$ is chosen for the single controlled loops. Furthermore a desired phase-margin of $\phi_m = 80°$ is chosen. All controllers are in the following determined such that, without interactions, the chosen crossover frequency and phase-margin is obtained.

Figure 2 shows the ξ_d-measure evaluated for the two considered pairings, *LV* and *DB*. Prior to the evaluation of the ξ_d-measure, the level loops have been closed by independently designed finite bandwidth PI-controllers. The plots in figure 2-left show that in the considered frequency

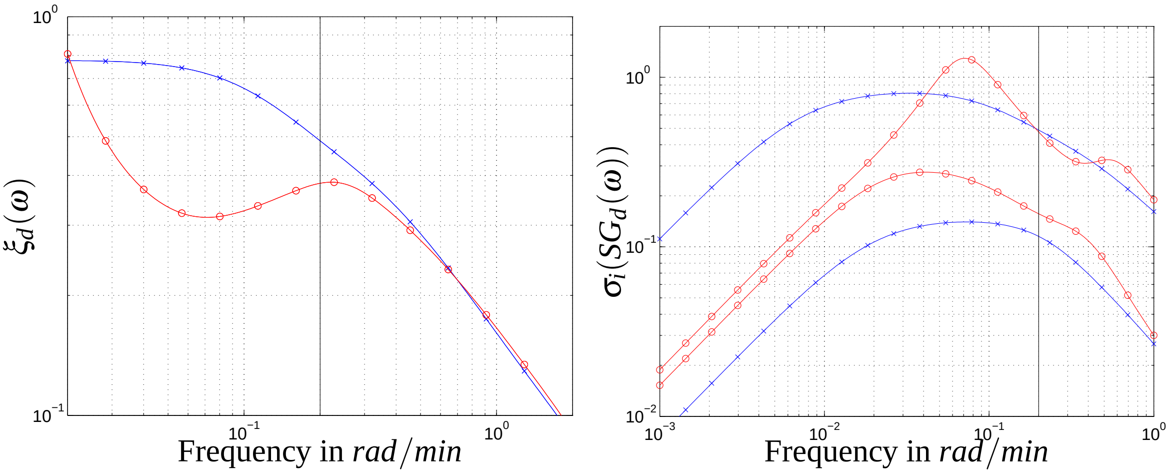

Figure 2: Left: ξ_d-measure for the two different pairings (x) LV-pairing, (o) DB-pairing. Right: Singular values of closed loop disturbance transfer functions for the two different pairings. (x) LV-pairing, (o) DB-pairing. The solid black line indicates the desired crossover frequency $0.2 rad/min$

range the *DB*-pairing is somewhat better than the *LV*-pairing. However, the sharp decrease of ξ_d for smaller frequencies also indicates that the *LV*-configuration seems to be better for frequencies below $0.01 rad/min$. To see if the predictions, based on the ξ_d-measure, are reasonable, lead-lag controllers were designed for the remaining loops.

Figure 2-right shows the singular values of the closed loop disturbance transfer function for the composition loops only (level loops and corresponding inputs have been neglected). As predicted by the ξ_d-measure there is only a slight difference between the configurations at the desired crossover frequency. Furthermore, it can be seen that at low frequencies the *DB*-configuration rejects disturbances much better than the *LV*-configuration. Only in a relatively small frequency range is the *LV* configuration better, while the ξ_d-measure for the *DB*-configuration is slightly larger than one. However, both control configurations seem to allow acceptable rejection of disturbances using independent controller tuning.

An interesting application of the ξ_d-measure is the possibility of finding the pairing which rejects a certain disturbance in the best way. Figure 3-left shows the ξ_d-measure evaluated for the case if only the feed-flow F is considered, while figure 3-right shows the ξ_d-measure, if only the feed-composition z_F is considered. Based on these plots one would select the *DB*-configuration in order to reject disturbances in the feed flow, while the *LV*-configuration seems favorable in the case of disturbances in the feed composition. It is interesting to note that the closed loop disturbance gain, evaluated for the *DB* and the *LV* configuration, clearly favors the *DB*-configuration for both types of disturbances.

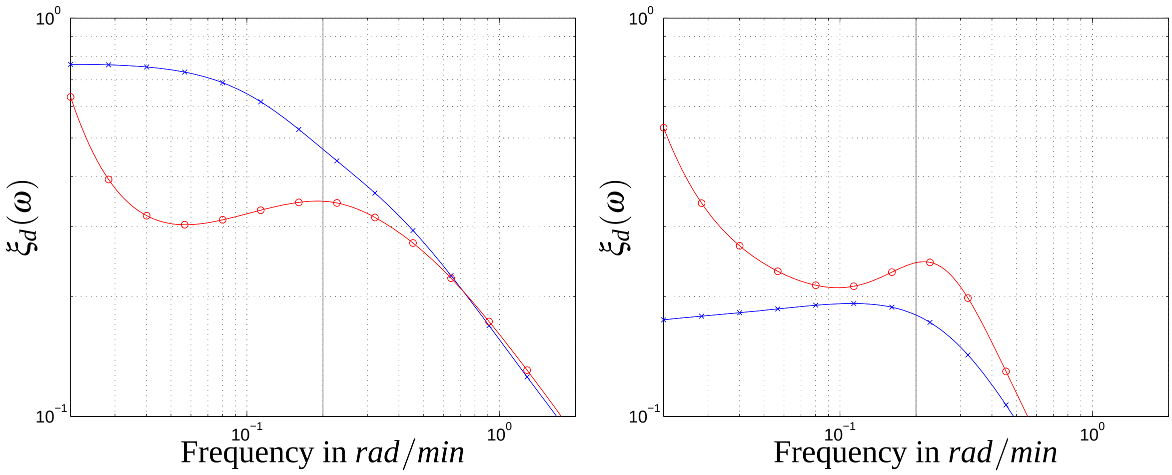

Figure 3: ξ_d-measure for the two different pairings and different disturbances. Left: only the feed-flow is disturbed. Right: only the feed-composition is disturbed. (x) LV-pairing, (o) DB-pairing. The solid black line indicates the desired crossover frequency $0.2 rad/min$

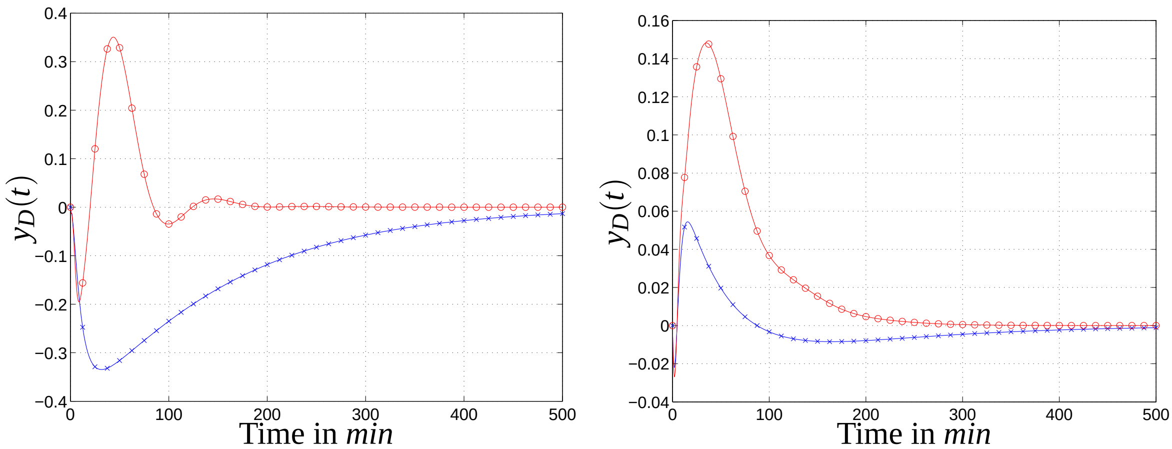

Figure 4: Time response for the top product composition y_D in the case of disturbances. Left: 20% increase in the feed flow. Right: 10% increase in the feed-composition. (x) LV-pairing, (o) DB-pairing.

In order to verify this prediction the system has been simulated (using a linear model) for the two cases (see figure 4).

1. 20% increase in the feed flow F, and

2. 20% increase in the feed composition z_F.

Figure 4 shows the time response of the top composition y_D for the two disturbances. It can clearly be seen that in the case of a flow disturbance the *DB*-configuration is the better choice and in the case of a composition disturbance the *LV*-configuration is preferable.

However, as seen above, the *DB*-configuration is the preferred structure when both disturbances are considered.

4 Selecting control configurations for plants with pure integrators

Above we considered some standard configurations for distillation columns, which were based on closing the level loops in an ad-hoc manner, i.e., without paying attention to the remaining composition control problem. This is also the traditional way of closing level and pressure loops in the process industry.

In this section we describe a method which makes it possible to systematically select the best pairings for systems which contain zero elements in the open loop transfer matrix. Such zeros might occur because of the physical structure of the system and/or because of the existence of pure integrators in the system. The main problem arising through these zeros is, that the measure described above might not be directly applicable for all possible pairings. This is the case if a pairing is chosen such that the diagonal of G (and G_m) contains at least one zero element, because a controller can obviously not be tuned on a zero element.

4.1 The method

The following method circumvents this problem.

1. Reorder the rows of the system transfer matrix G such that the corresponding output vector contains as first entries the outputs of all the integrators (e.g., levels and pressures).

2. Determine the *viable* control configurations. A pairing is *viable* if

   - the pairing does not correspond to any negative steady state RGA elements. It is important to stress that in this way not all non-DIC pairings are rejected, because zero steady state RGA elements are allowed.
   - the integrator loops are independently tuneable, i.e. integrator- pairings on transfer matrix elements identically zero are not allowed. However, zero elements in $G(s)$ are allowed for the other outputs.

   This selection will usually reduce the number of possible pairings and thereby also the computational effort, heavily.

3. For every viable control configuration perform the following tasks

(a) Reorder the columns of the system G such that the diagonal contains the elements to pair on for the given control configuration.

(b) Close the integrator loops by independently designed controllers for the corresponding diagonal elements.

(c) Delete the rows corresponding to the integrators and the columns corresponding to the inputs used for the integrator-control. If the remaining systems transfer matrix contains a diagonal element identically zero, then reject the pairing. Otherwise apply the ξ_d-measure to this remaining system.

4. Select the pairings obtaining the smallest values for the ξ_d-measure and, in order to choose a final configuration, perform an additional controllability analysis on them.

The main idea of this method is to close the integrator loops in a way which is favorable for the remaining subsystem. Here the assumption is made, that the integrator loops do not have tight performance specifications and mainly need to be stabilized. Furthermore, it is assumed that it is not the type of controller, nor its tuning, used to stabilize the integrators, that is important, but rather the inputs used to control them.

The closure of the integrator loops can be done in different ways. One possibility, the computationally fastest, is to consider the behavior of the system only at the desired crossover frequency ω_c. Hereby the controllers for the integrator loops are only determined as their frequency response at ω_c, and the ξ_d-measure for the remaining system is evaluated only at this frequency. Two other possibilities are to use perfect control or to design simple PI controllers for the integrator loops. These have the advantage that the remaining system is dynamic and the measure can take non minimum phase behavior into account. Furthermore, in this way different bandwidths for the integrator loops and the remaining loops can be used, which is closer to the reality.

An interesting variant of this method would be to close the integrator loops in a sequential way, thereby not limiting the viable configurations to independently tuneable ones. In this way many more pairings would become viable. However, in this case not only the integrator-pairing would be an issue, but also the order in which the integrator-loops are closed. Finally, it should be noted that this method also can be used to calculate other measures like, e.g., the decentralized relative gain [12] or the finite bandwidth PRGA [13].

The idea to close certain loops prior to consider the remaining system has been employed before, e.g. in [14] and [7].

5 Example continued

Here the method described in the preceding section is applied to the example system, introduced above. By evaluating the steady state RGA and considering the zero elements of the open loop transfer matrix it is found that only 9 viable pairings exist (out of a total of 24 possible pairings).

In this example it was chosen to do the calculations only for the frequency corresponding to the desired crossover frequency of the single controlled loops ($\alpha = \beta = 1$). The result can be seen in table 2. The LV-configuration is rated 5th-best pairing and only slightly better than the

	$\xi_d(\omega_c)$	M_B	M_D	y_D	x_B
	0.3337	V	L	B	D
	0.4141	L	V	D	B
	0.4485	L	D	B	V
	0.4607	V	D	L	B
LV-configuration:	0.4885	B	D	L	V
DB-configuration:	0.5002	V	L	D	B

Table 2: The ξ_d-measure for the 6 best configurations determined by the method described above. ($\omega_c = 0.2 rad/min$)

DB-configuration (6th-best pairing). However, the best three pairings in table 2 do not result in a stable closed loop system in the case of independent controller tuning. This fact suggests that the selection of a suitable control configuration should not be based on the ξ_d-measure only, but that additionally an interaction measure should be evaluated in order to select a pairing which is able to acceptably reject disturbances, but which has only small interactions between the subsystems. One possible interaction measure is the finite bandwidth PRGA [13].

6 Conclusions

The paper considers closed loop performance, in terms of disturbance rejection, under independent decentralized control. A controller independent model based measure has been proposed which can be used to screen different pairings for their ability of disturbance rejection using independent tuning of the individual loops. The application of this measure to an example from process industry showed that it correctly predicted the systems closed loop behavior for different kinds of disturbances. One interesting result is that the proposed measure can be used in order to tailor the control configuration for the expected disturbances. As a special case we considered systems that contain one or more integrators and which give rise to a number of zero elements in the transfer-matrix of the overall system. Using the assumption that no tight performance specifications exist for these integrators, we derived a systematic method in which the disturbance sensitivity of the remaining outputs can be minimized.

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