Dynamic Operability Analysis of a Fluidized Catalytic Cracker

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In process design problems, the optimal steady state solution hardly becomes the final solution. Other requirements usually force this solution away from the optimal and create alternatives in meeting different objectives. A critical objective is satisfactory transient operation. A particular process design may adversely affect transient operation of the plant (response to process disturbances as well as start-up and shutdown) due to unforeseen limitations on control variables and/or process limitations such as insufficient or overdesigned units. Therefore, an ideal design strategy considers the dynamics of the plant as early as possible in design stages in order to circumvent potential bottlenecking during the actual operation.

Recently, a new design framework has been developed that addresses the issue of process sensitivity to uncertainty emanating from the use of simplified models in controller design (Palazoglu et al., 1985). Based on a dynamic operability measure called the robustness index (RI), it is possible to detect potentially sensitive process designs and analyze design alternatives. The use of the RI facilitates the interaction between the economic and dynamic operability decisions and also helps quantify the impact of different controller structures as well as the extent of modeling on the final process design.

Robustness Indices and Scaling

The mismatch between the actual process and its simplified model can trigger instability, depending on the design of the control system as well as the design of the process itself. The following inequality captures this by establishing a sufficient condition on the robust stability of a feedback system with internal model control (IMC) (Garcia and Morari, 1982) as represented given in Figure 1:

$$(1-\alpha)\frac{1}{\epsilon_1(G)\epsilon_2(G)} + \alpha\frac{1}{[\epsilon_1(G)]^2} > [l_m(\omega)\sigma^*(F)]^2, \quad \forall \omega \epsilon R^+ \quad (1)$$

Here, ϵ_1 and ϵ_2 represent the RI's and α is a constant associated with the uncertainty projection, providing information on the structure of the modeling error in the process. The quantity $l_m(\omega)$ represents an upper bound on the magnitude of the plant/model mismatch (error matrix L). Being a function of the process transfer function model, the RI serves to quantify process-related robustness problems regardless of the particular control strategy. Further details on this result are given elsewhere (Palazoglu et al., 1985).

If the RI's are closer to unity, it usually implies that the process is more tolerant to uncertainty in closed-loop operation. However, it must be noted that uncertainty plays a critical role, in that even with small RI there might exist a sufficiently large uncertainty to cause instability. Therefore, a combination of RI and $l_m(\omega)$ should be utilized in evaluating design alternatives.

Since RI is also scaling-dependent, an optimal scaling procedure has to be carried out to eliminate the effect of scaling on decision making. The following min-max semiinfinite optimization problem is formulated:

$$\min_{S_1,S_2}\left\{\prod_{i=1}^{m}\epsilon_i[S_1G(j\omega)S_2]\right\} \cdot \left\{\max_{\beta\epsilon D}\sigma^*[S_1L(j\omega,\beta)S_1^{-1}]\right\}^m \quad \forall\omega\epsilon R^+ \quad (2)$$

The solution of the optimization problem yields S_1 and S_2. For a case with a single RI as the dynamic operability measure to be used in comparing rival designs, Eq. 2 results in the scaled quantity $\epsilon_1 \cdot l_m(\omega)$ (Palazoglu et al., 1985). This will be illustrated next.

Fluidized Catalytic Cracker (FCC)

An FCC unit is illustrated in Figure 2. Hydrocarbon feed is contacted with hot catalyst in the reactor, causing cracking of the feed to such products as gasoline, middle distillates, and olefins. During this reaction, carbonaceous material deposits on the

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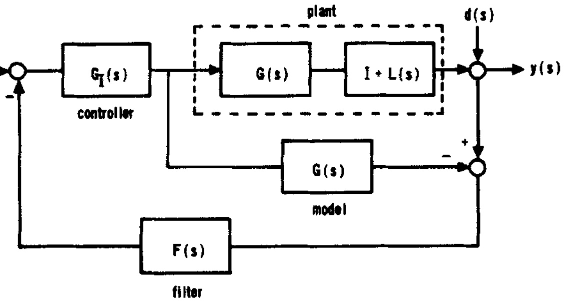

Figure 1. IMC structure.

catalyst surface, which consequently deactivates the catalyst. The regenerator allows the catalyst to be regenerated by partially burning off the deposited carbon. The regenerated catalyst is then recycled back to the reactor. This way, the catalyst also serves as a heat transfer medium that utilizes the exothermic coke burning reaction to provide thermal energy for the endothermic cracking reaction. The integrated nature of the two vessels creates serious operating problems, which have been investigated by many researchers (Kurihara, 1967; Tung and Edgar, 1978; Arkun and Stephanopoulos, 1979).

In this paper, the FCC model developed by Kurihara is studied. The uncertainty $l_m(\omega)$ is calculated based on 10% variation of the Arrhenius rate constants. The steady state operation is restricted by various physical constraints:

$$T_r < 930°\text{F}$$
$$T_g < 1{,}200°\text{F}$$
$$R_{rc} < 60 \text{ tons/min}$$
$$O_{fg} < 0.2 \text{ mol \%}$$
$$R_{ai} < 400 \text{ klb/h}$$

An interactive computer program developed at the University of California, Davis, can build the feasible region and evaluate dynamic operability for analysis as well as design purposes. Figure 3 depicts the feasible region for the FCC. Economic considerations dictate that the uppermost section of the feasible region (limited by R_{ai} constraint) will provide the best oil cracking rate, thus the highest profits. However, the exact location of the operating point is not clearly determined due to the apparent flatness of the constraint bound. Point A has a very slight profit margin over point B and hence dynamic operability considerations might help us to probe the issue further.

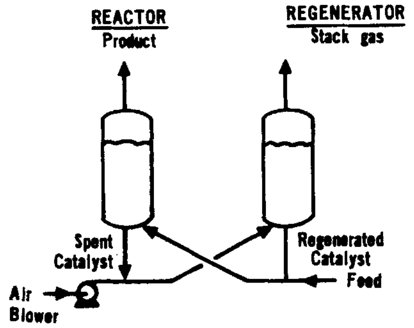

Figure 2. Typical FCC unit.

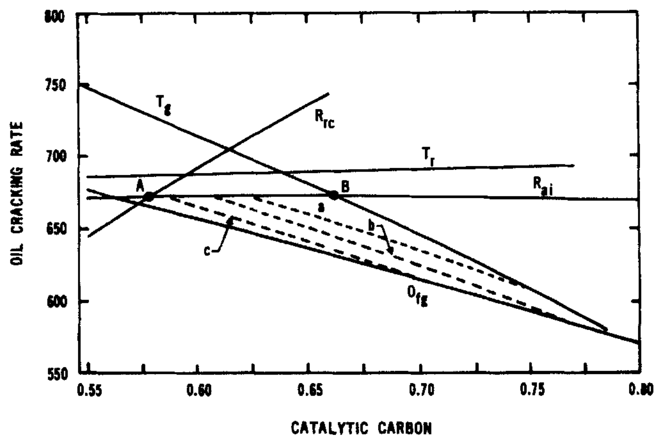

Figure 3. Feasible region of FCC with $\epsilon_1 \cdot l_m(o)$ contours.
a 0.34; *b* 0.35; *c* 0.36

Use of RI as dynamic operability measure

The quantity $\epsilon_1 \cdot l_m(\omega)$ is optimally scaled at steady state ($\omega = 0.0$) for selected points within the feasible region. The controller configuration consists of R_{ai} and R_{rc} as manipulated variables, and T_r and O_{fg} as the controlled variables. The contours of $\epsilon_1 \cdot l_m(o)$ within the feasible region (Figure 3), indicate that point B will have minimum RI; therefore, it is the operating point that is least prone to dynamic operability problems. Point B lies at the intersection of R_{ai} and T_g constraints and can be chosen as the optimum since, when compared with point A, economic sacrifice is minimal. When two locations are compared along the other frequencies, the trend remains the same. This is an interesting case where the dynamic and economic objectives almost do not conflict at all. In other cases, one has to use proper trade-offs to locate an operating point acceptable with respect to both objectives.

Use of RI to determine best control configuration

The results of the previous section are compared with a different controller configuration in which T_g and O_{fg} are now the controlled variables, Figure 4. For this case, the quantity $\epsilon_1 \cdot l_m(o)$ is considerably larger, indicating that the economic opti-

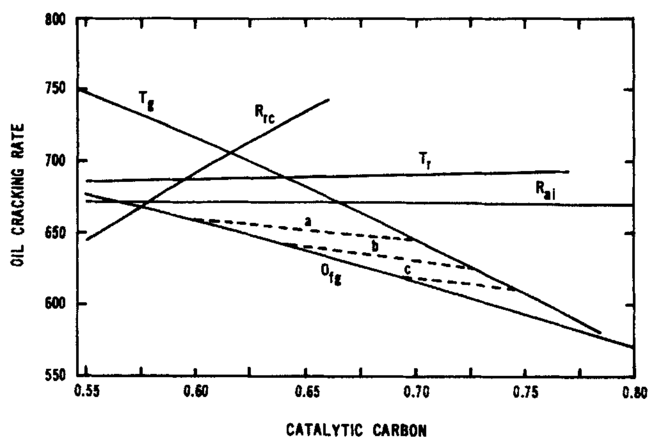

Figure 4. Feasible region of FCC with $T_g - O_{fg}$ as controlled variables.
Contours of $\epsilon_1 \cdot l_m(o)$ are: *a* 1.1; *b* 1.2; *c* 1.3

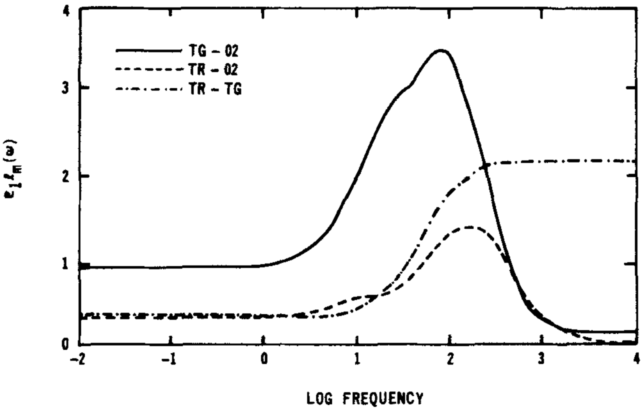

Figure 5. $\epsilon_1 \cdot l_m(o)$ for three controller configurations.
Controlled variables are: *a*, $T_g - O_{fg}$; *b*, $T_r - O_{fg}$; *c*, $T_r - T_g$

mum is now more sensitive to modeling uncertainties. Note that this configuration is also rejected by Tung and Edgar (1978) due to its poor dynamic performance. The contours are also flatter, implying that this controller configuration does not have strong preferences along the R_{ai} constraint in terms of better dynamic operability. An analysis of the quantity as a function of frequency, Figure 5, also confirms the superiority of the previous controller configuration, since it remains significantly low over a wide band of frequencies.

Use of RI to evaluate variations in process and design

Any changes in the variables associated with the design or the operation of the FCC will reflect themselves in modifying the feasible region and thus the optimal operating regime. In addition, the dynamic characteristics of the process will also change and have to be accounted for. Figure 6 demonstrates the movement of the constraints as the feed rate is changed. As expected, the oil cracking rate drops, but the optimum lies at the intersection of T_g and T_r constraints, which is also favored by the lower robustness indices at that location. Compared to a higher feed rate, the indices are also lower, indicating that this regime is less sensitive to uncertainty—possibly due to the lower intensity of the cracking reaction.

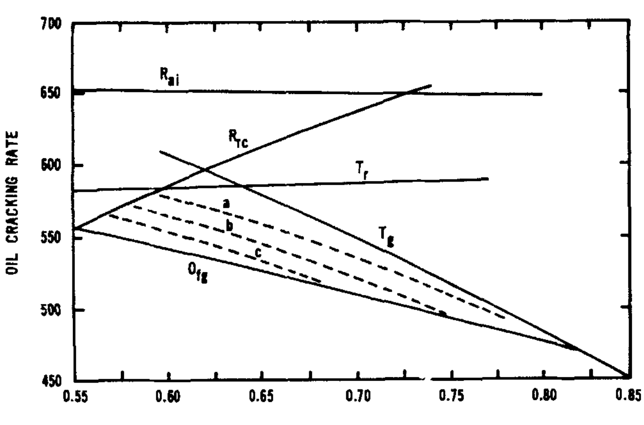

Figure 6. Feasible region for a 15% decrease in feed rate.
Contours of $\epsilon_1 \cdot l_m(o)$ are: *a* 0.30; *b* 0.31; *c* 0.32

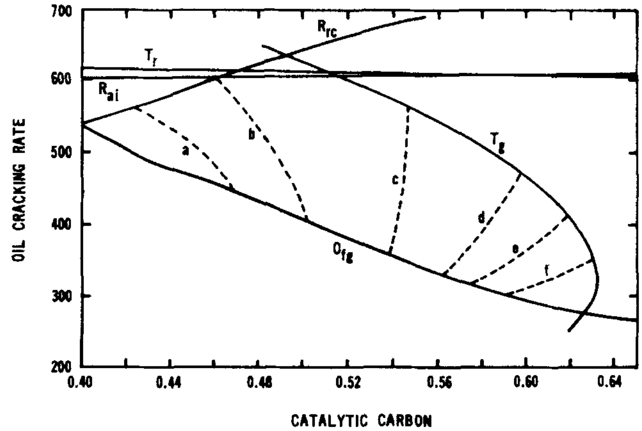

Figure 7. Feasible region for a feed quality factor of 0.08.
Contours of $\epsilon_1 \cdot l_m(o)$ are: *a* 0.30; *b* 0.28; *c* 0.26; *d* 0.24; *e* 0.22; *f* 0.20

The effect of changes in the feed quality is shown in Figure 7, which again points to a lower cracking rate, but this time one also observes a different trend in the robustness index contours. The indication now is that the dynamics will be improved if the oil cracking rate is further reduced, but this obviously conflicts with the economic objectives. The optimum operating point is located at the intersection of T_r and T_g constraints and represents the best trade-off in terms steady state and dynamic operation.

Conclusions

An FCC unit is studied to illustrate the utility of the dynamic operability measures (RI) in helping the designer to assess the relation between economics and dynamics. The results demonstrate the utility of the RI in making design decisions, selecting favorable operating conditions as well as controller configurations. It has to be noted that other dynamic operability measures, if developed, can always be incorporated into the analysis. This work exemplifies the effectiveness and versatility of such dynamic operability measures when employed in process design studies.

Acknowledgment

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Notation

D = region of parametric uncertainty
F = IMC filter
G = process transfer function
G_l = IMC controller
l_m = upper bound on the magnitude of L
L = uncertainty error matrix
m = number of RI's
O_{fg} = O_2 mole fraction at regenerator effluent
R_{ai} = air flow rate
R_{rc} = catalyst circulation rate
R^+ = set of positive real numbers
T_r, T_g = temperature in reactor, regenerator

β = uncertain parameter vector
ϵ_i = ith RI, $\epsilon_i = \sigma^{*,i}/\sigma_*$
σ_*, σ^* = minimum, maximum singular values
ω = frequency

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