PERFORMANCE ENVELOPES OF PROCESS INTENSIFIED SYSTEMS

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Abstract: Intensified processes may have response times orders of magnitudes faster than conventional units. Thus, the dynamics of control loop elements such as valves and measurement devices may no longer be negligible. This paper presents the results of an investigation into how the dynamics of control loop components influence the performances of controlled intensified processes. By adopting a particular controller design methodology, it was found that only the process delay and the time-constant of the feedback transmitter affect closed-loop performances. Further analysis showed that there are threshold values for these two parameters, beyond which closed-loop behaviour can be severely degraded, even in the nominal case. In terms of operability, the degree to which a process is intensified may therefore be limited. The results also reveal that advanced control techniques may be necessary if acceptable control of intensified systems is to be achieved.

Keywords: process intensification, control schemes, dynamics, control equipment, control system analysis

1. INTRODUCTION

Advances in Process Engineering have led to numerous new findings and technologies that concentrate on minimising the sizes of unit operations as well as improving the overall speed of production whilst maintaining the throughput of the processes. This concept of "process intensification" was pioneered by ICI in the late 1970's and has since developed rapidly, particularly over the last decade.

Process intensification (PI) is loosely described as a strategy that aims to achieve dramatic reductions in plant volume whilst maintaining production objectives (Ramshaw, 1999). This radical approach to process design is gaining momentum because of drivers that include improved intrinsic safety, increased energy efficiency, reduced plant fabrication costs and easier scale up (Ramshaw, 1983; Jachuck, *et al.*, 1997; Fell, 1998; Ramshaw, 1999; Stankiewicz, and Moulijn, 2000).

Currently, work on advancing PI technologies seems to focus mainly on proving the feasibility of concepts and ideas, as well as attempting to establish key design parameters of various process units. To the best of our knowledge, little investigations have been carried out to study the operation and control of intensified process units.

Minimising the sizes of unit operations inevitably means that process residence times will be much less than conventional sized units. To realise the perceived benefits of PI technology, it is essential that intensified units are coupled with process monitoring and control systems that can cope with the very fast response times so that regulation of environmental variables, product quality, and operational safety can be ensured.

2. STATEMENT OF THE PROBLEM

Reducing the physical sizes of process units whilst maintaining the same throughput means that these units will have shorter residence times, i.e. the dynamics of the systems will be much faster than those encountered in conventional scale units. Adopting the PI design philosophy could lead to an order of magnitude change in equipment capacity, and would probably bring the response times of intensified systems down to milliseconds rather than the more usual tens of minutes encountered in conventional units. Under such circumstances, current instrumentation may be too slow for intensified processes to be controlled by conventional feedback strategies. Measurement delays that may be tolerable in conventional units may be too large and unacceptable for intensified systems, making the control problem more difficult. Hence, fast responding process sensors are needed in order to achieve automatic feedback control. As the philosophy of process intensification is to reduce equipment sizes without compromising on throughputs, actuators of the same size as those employed in conventional units will continue to be utilised. Thus, actuator dynamics could present problems, as they could be orders of magnitude slower than those of the manufacturing unit. Furthermore, interactions between process states and between process units are also aspects that could lead to further difficulties. There are therefore many factors to be considered in realising automatic control of intensified systems.

Components that make up the control loop must be dynamically compatible with the controlled process for acceptable closed-loop performance. This issue has been largely neglected when designing controllers for conventional process systems, since the time-constants of such processes are significantly larger than those of associated actuators and instrumentation. Nonetheless, given a particular strategy, a deep appreciation of the influences of each component of an intensified system control loop is crucial before good control performances can be assured. Apart from time-delay to time-constant ratios, there also appears to be no published accounts of measures that will indicate when a particular mix of dynamic characteristics could lead to unacceptable closed-loop performances.

This paper presents the results of the preliminary stage of a programme of studies into the control and operation of intensified units. One of the objectives is to attempt to define the "performance envelopes" of fast responding processes under different sensor and actuator conditions. If this can be achieved, then guidelines for the selection of control loop components and control strategies for process intensified systems could be extracted. Knowledge of performance limitations can also be used to determine the extent to which a process should be intensified or miniaturised. The work reported here investigates the effects of instrumentation and actuator dynamics on conventional closed-loop performances.

The paper, which focuses on SISO systems, is structured as follows. First, a controller is designed via the "synthesis equation" method. Note that it is not the aim of this contribution to explore new controller designs. Rather, the synthesis equation method was adopted because it is intuitive, but more importantly, the methodology reveals explicitly, the parametric contributions of the loop components on closed-loop behaviour. The Integral of Absolute Error (IAE) between set-point and controlled output is then analytically defined for the corresponding closed-loop system. For simplicity, all components are taken to be linear. Results are then presented, followed by discussions and conclusions.

3. CONTROLLER DESIGN

Consider the closed-loop system shown in Figure 1.

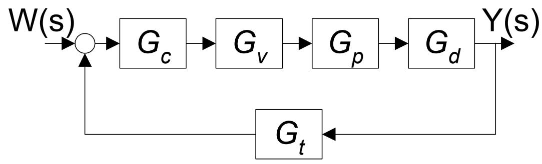

Fig. 1. Closed-loop System

G_c, G_v, G_p, G_d and G_t represent the controller, valve, process, process delay and the feedback transmitter respectively. For simplicity, these components of the closed-loop are assumed linear and G_v, G_p, G_t and G_d have the following forms:

$$G_v = \frac{k_v}{\tau_v s + 1}, \; G_p = \frac{k_p}{\tau_p s + 1}, \; G_t = \frac{k_t}{\tau_t s + 1}, \text{ and}$$

$$G_d = e^{-\theta s}$$

A standardised controller design methodology is used to develop a general form of the controller. The approach adopted here is based on the Synthesis Equation. It uses the closed-loop expression to determine the controller that will yield a specified closed-loop response. A reason for adopting this approach is to ensure that controllers used under different scenarios are designed from the same basis.

The closed-loop transfer function of the above system is

$$\frac{Y}{W} = \frac{G_c.G_v.G_p.G_d}{1 + G_c.G_v.G_p.G_d.G_t} \qquad (1)$$

Rearrangement yields

$$G_c = \frac{1}{G_v.G_p.G_d}.\frac{\frac{Y}{W}}{\left(1 - G_t \frac{Y}{W}\right)} \qquad (2)$$

The control objective is to have the closed-loop behave according to:

$$\frac{Y}{W} = \frac{e^{-\theta s}}{\lambda s + 1} \qquad (3)$$

It can be seen that the controller comprises the inverses of the valve and process models, and, λ, which is the user specified closed-loop time-constant.

Without loss of generality, the gains of the process, the valve and the transmitter, k_p, k_v and k_t, can be set equal to 1. Substitution of equation (3) into equation (2) and approximating the delay as $G_d \approx 1-\theta s$, yields

$$G_c = \frac{(\tau_v s+1)(\tau_p s+1)(\tau_t s+1)}{\lambda\tau_t s^2 + (\lambda+\tau_t+\theta)s} \quad (4)$$

Expanding equation (4) and re-arrangement produces a controller of the form:

$$G_c = G_f . K_c \left(T_{d^2} s^2 + T_d s + \frac{1}{T_i s} + 1 \right) \quad (5)$$

where $G_f = \dfrac{1}{\left(\dfrac{\lambda\tau_t}{\lambda+\tau_t+\theta}s+1\right)}$, $K_c = \dfrac{\tau_v+\tau_p+\tau_t}{(\lambda+\tau_t+\theta)}$,

$T_{d^2} = \dfrac{\tau_v\tau_p\tau_t}{\tau_v+\tau_p+\tau_t}$ $T_d = \dfrac{\tau_v\tau_p+\tau_v\tau_t+\tau_p\tau_t}{\tau_v+\tau_p+\tau_t}$ and

$T_i = \tau_v + \tau_p + \tau_t$

It can be seen that the controller settings take into account actuator and transmitter dynamics.

Notice too that when transmitter dynamics are negligible, the controller reduces to the normal Proportional-Integral-Derivative (PID) form. Otherwise, the design yields an algorithm equivalent to a Proportional-Integral-Derivative-Derivative (PIDD) controller in series with a first-order filter. This leads to an interesting interpretation. When the dynamics of the transmitter are significant, then further anticipatory action is required, leading to the second-order derivative term. In this case, a low-pass filter would be required to mitigate the effects of high order derivative action.

4. SIMULATION WORK

Evaluation of the performances of the controller under different transmitter and valve dynamics were initially carried out via numerical simulation, using SIMULINK™. The IAE between the set-point and controlled output was used as the measure of control performances. The results were very inconsistent however, especially when the time-constants of the valve and/or transmitter were significantly different from that of the process. With hindsight, this should have been expected; under these conditions, the set of equations describing the system becomes "stiff". Therefore, performance investigation of the above closed-loop system was eventually carried out analytically, with the help of the Symbolic toolbox in the MATLAB™ environment, thus avoiding numerical problems.

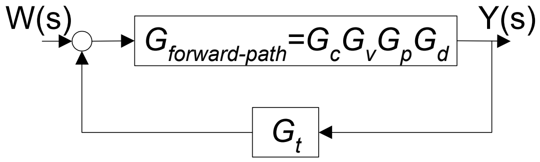

Fig. 2. Simplified diagram of the closed-loop system

From Figure 2, the error response transfer function was established for a unit step change in the input, *W(s)* as:

$$error(s) = \frac{W(s)}{1+G_{forward\text{-}path}.G_t} \quad (6)$$

where

$$G_{forward\text{-}path} = \frac{(\tau_t s+1)(1-\theta s)}{\lambda\tau_t s^2 + (\lambda+\tau_t+\theta)s} \quad (7)$$

Equation (7) shows that the specified closed-loop time-constant, the transmitter time-constant and the process delay are the only parameters that have significant influence on overall control performance. It follows from equation (4) that the controller cancels the poles of G_v and G_p, resulting in equation (7) above. In other words, the effects of process and the valve time-constants on closed-loop behaviour have been removed as a result of the controller design adopted.

Substituting equation (7), G_t and $W(s) = \dfrac{1}{s}$ into equation (6) yields

$$error(s) = \frac{\lambda\tau_t s + (\tau_t+\lambda+\theta)}{(\lambda s+1)(\tau_t s+1)} \quad (8)$$

The IAE can then be determined by integrating the absolute value of the inverse Laplace transform of equation (8), from time 0 to time *t*, which yields

$$\text{IAE} = \left| \frac{\lambda(\lambda+\theta)}{\lambda-\tau_t}\left(1-\exp\left(-\frac{t}{\lambda}\right)\right) - \frac{\tau_t(\tau_t+\theta)}{\lambda-\tau_t}\left(1-\exp\left(-\frac{t}{\tau_t}\right)\right) \right| \quad (9)$$

5. RESULTS AND DISCUSSION

To study the effects of λ, τ_t and θ on closed-loop performances, different τ_t and θ values were considered for three desired closed-loop responses (λ = 0.5, 1.0 and 1.5). In each case, the closed-loop had to track a unit step change in set-point, and the IAE was determined using equation (9).

The performance evaluation results are summarised in the 3-D plot shown in Figure 3 below, where $1/\tau_t$ and $1/\theta$ were used to identify the "performance envelope" for the system under investigation.

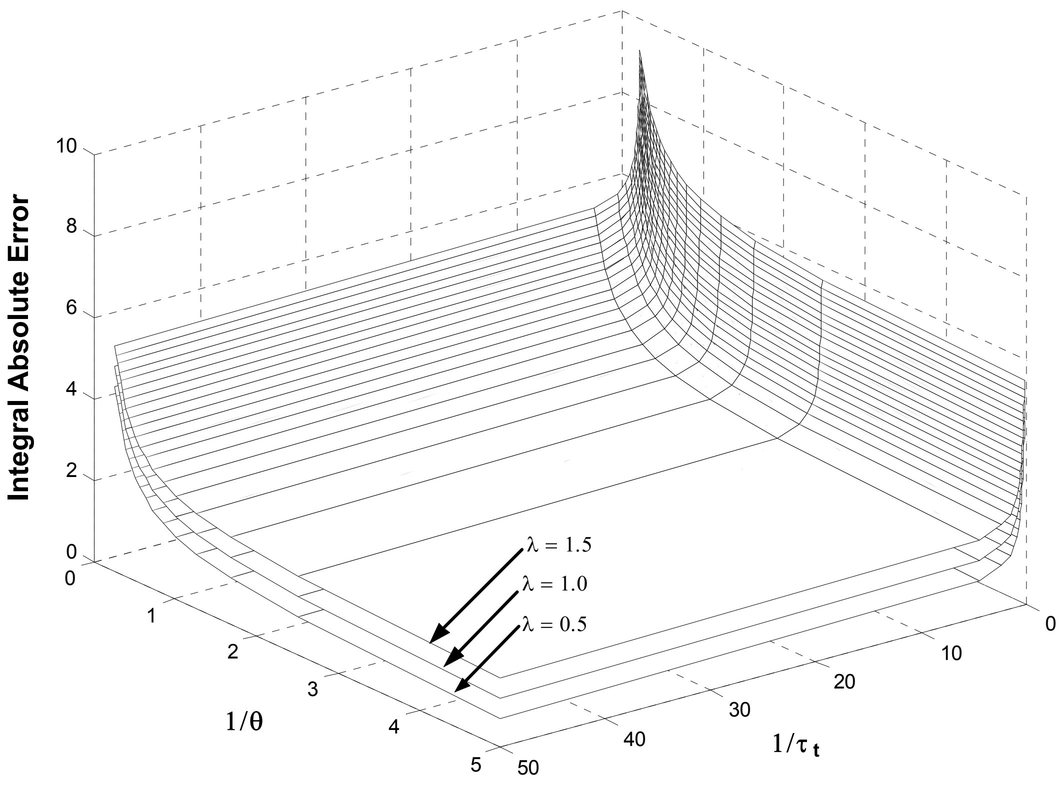

Fig. 3. IAE values for different $1/\tau_t$ and different $1/\theta$ at λ = 0.5, 1.0 and 1.5

As expected, smaller values of the closed-loop time-constant, λ, produce better overall control performances as indicated by the lower IAE values.

A particular consequence of using the controller given by equation (5) is that closed-loop performance is independent of actuator dynamics and the dynamics of the controlled process (see equation (8)). This is because the controller cancels the forward path dynamics and, as a result, the response speeds of the closed-loop components (relative to the time-constant of the process) have no bearing on performance.

The presence of process time-delays will however degrade control performance, and this can be clearly seen from the IAE values in Figure 3. In the case of this example, overall controller performance degrades rapidly when θ becomes greater than 1. Recall that the approximation $G_d \approx 1\text{-}\theta s$ was used in the formulating the controller, so that the resulting structure bears some resemblance to the familiar PID controller. If this requirement is relaxed, it is possible that the detrimental effects of time-delays will not be as marked. There is definitely scope for improving control performances, in particular, by incorporating time-delay compensation into the control system. Nevertheless, it does point to the fact that advanced control algorithms would be necessary.

The solution to the problem of large transmitter response times is not so straightforward, however. Typically, transmitter time-constants range between 0.2s - 2.0s. Figure 3 shows that, for any particular value of θ, control performance may deteriorate severely even if the fastest transmitter is used. If the controller design outlined in this paper is employed, the problem of slow dynamics in the feedback path will be compounded if the measurement device has an associated delay. Then, effective control may only be achieved through the use of "soft-sensors" (e.g. Tham, *et al.*, 1989). Again, advanced techniques may be necessary.

Finally, it is also interesting to observe that for $1/\tau_t > 5$ and $1/\theta > 1$, control system performances were almost identical. This indicates that the controller is relatively insensitive to variations in transmitter time-constant and process delay, provided $\tau_t < 0.2$ and $\theta < 1$. Beyond these thresholds however, overall control performance deteriorated exponentially, as $1/\tau_t$ and $1/\theta$ become smaller, i.e. when the time-constant of the transmitter and the time-delay become larger.

6. CONCLUSION

The results presented here provide further insights into how the dynamics of control loop components influence closed-loop performance, with particular reference to intensified systems. The small volumes and large throughputs of such systems lead inescapably to smaller residence times. In some cases, their response times are of the same order of magnitude as those of actuators and measurement transmitters, perhaps even faster. At first, it was thought that this could potentially cause control problems.

However, with the example system studied, it was found that the process delay and transmitter dynamics were the only parameters that influence control performance. This is because the Synthesis Equation design methodology yields controllers that cancel the dynamics of both the process and the actuator. Since forward path dynamics no longer feature, the result applies not only to intensified systems, but also to all closed-loop systems with controllers designed via the same approach. This dispels, to a certain extent, initial reservations about the ability of existing actuators to cope with the demands of controlling intensified systems.

As for the influence of process delay and time-constant of the transmitter, the study identified threshold values beyond which closed-loop performances were severely affected. Therefore, with regard to operability, there are limits to the degree of intensification, especially if high throughputs are to be maintained.

One particular difficulty was experienced while performing this study. Due to the stiffness of the resulting set of system equations, brought about by loop components with very different time-constants, numerical simulation results were very inconsistent. Therefore, it is suggested that studying the dynamic behaviour of intensified systems be best done analytically, aided by symbolic mathematical tools.

The work presented in this paper assumes no process-model mismatch and the results were obtained using a non-conventional PIDD type controller. It would be interesting to assess the robustness of the strategy when there are uncertainties associated with the parameters of the loop components used for controller design; and when the controller is constrained to have the standard PID structure. These are the subjects of current work.

ACKNOWLEGEMENTS

The financial support provided by Universiti Sains Malaysia granted to Syamsul Rizal Abd Shukor is gratefully acknowledged.

REFERENCES

Fell, N. (1998). Innovation Offers A New Spin On Drug Production. *Chemical Engineer,* 23-25.

Jachuck, R. J., C. Ramshaw, K. V. K. Boodhoo, and J. C. Dagleish. (1997). Process Intensification: The Oppurtunity Presented By Spinning Disc Reactor Technology. *Institution of Chemical Engineers Symposium Series*. (141), 417-424.

Ramshaw, C. (1983). HIGEE - An Example of Process Intensification. *Chemical Engineer,* 13.

Ramshaw, C. (1999). Process Intensification And Green Chemistry. *Green Chemistry,* 15-17.

Stankiewicz, A. I. and J. A. Moulijn (2000). Process Intensification: Transforming Chemical Engineering. *Chemical Engineering Progress,* 22-34.

Tham, M. T., A. J. Morris, and G. A. Montague (1989). Soft-Sensing: A Solution To The Problem of Measurement Delays. *Chemical Engineering Research & Design,* **67** (6), 547-554.