PASSIVITY BASED PROCESS CONTROL

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Abstract:

The concept of passive systems and associated stability conditions have been one of the corner stones of nonlinear control theory. This paper summarises recent developments of process control techniques based on passivity. This includes passivity based robust control, fault tolerant control, and controllability analysis.

Keywords: passive systems, robust control, fault tolerant control, controllability analysis

1. INTRODUCTION

The concept of passivity plays an important role in modern control theory. It originated from studying input-output properties of electric circuits in the 1960s. In terms of circuit theory, a passive network has a positive resistance. That is, the network will dissipate energy or at least not generate energy while moving from one state to another.

A gravity tank is an example of passive process system. Consider the tank system illustrated in Figure 1. Assume the input is the inlet flowrate (F_i) and the output and state variables are the liquid level (h). Suppose the outlet is flowing out without an exogenous force, i.e., $F_o = C_v\sqrt{h}$ where C_v denotes the valve coefficient. The mass balance is given by:

$$\dot{h} = \left(F_i - F_o\right)/A = \left(F_i - C_v\sqrt{h}\right)/A, \tag{1}$$

where A is the cross sectional area of the tank. The energy stored in the tank is the potential energy:

$$S(h) = \tfrac{1}{2}Ah\rho gh = \tfrac{1}{2}A\rho gh^2, \tag{2}$$

which is called the storage function in passivity theory. The inlet flow into the system increases the potential energy in the tank. The increment of potential energy per unit time can be represented by a function of input and output $w(t) = \rho gF_i(t)h(t)$. This is called the supply rate. The rate of change of the storage function is given by the following equation:

$$\begin{aligned}\frac{dS}{dt} &= \frac{\partial S}{\partial h}\frac{dh}{dt} = A\rho gh\left[\frac{1}{A}(F_i - C_v\sqrt{h})\right] \\ &= -C_v\rho gh\sqrt{h} + \rho gF_i h = -C_v\rho gh\sqrt{h} + w.\end{aligned} \tag{3}$$

Note that in the range of definition of h, the first term is always negative. Therefore the rate of change of the stored energy in the tank is less than the power supplied to it. Therefore this process is said to be strictly passive. If $C_v = 0$, that is the outlet valve is completely shut off, then the energy flow into the tank is totally stored. In this case, this process becomes *lossless.*

If we generalise the concept of energy to any non-negative function of the states, then we can define a class of nonlinear processes:

Definition 1. Passive systems (Willems, 1972a)
A system Σ is said to be passive if there exists a nonnegative real function $S(x)$: $S(x) = X \rightarrow R^+$ (called the storage function), and a supply rate $w(t) = y^T(t)u(t)$ such that, for all $t_1 > t_0 \geq 0, x_0 \in X$ and $u \in U$,

$$S(x_1) - S(x_0) \leq \int_0^{t_1} w(t)dt. \tag{4}$$

The passivity of a control affine process can be determined using the following KYP Lemma:

Theorem 1 (Hill and Moylan 1976) Consider the following process:

$$\begin{aligned}\dot{x} &= f(x) + g(x)u \\ y &= h(x),\end{aligned} \tag{5}$$

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where x, u and y are the state, input and output vectors respectively. The process is passive if the following conditions are satisfied:

$$L_f S(x) = \frac{\partial S^T(x)}{\partial x} f(x) \le 0, \tag{6}$$

and $L_g S(x) = \dfrac{\partial S^T(x)}{\partial x} g(x) = h^T(x).$

A linear time invariant system is passive if and only if its transfer function matrix is positive real. In this case Condition (6) is reduced to the following condition:

A system with a state space representation (A, B, C, D) is passive if and only if there exists a positive definite matrix P such that:

$$\begin{bmatrix} A^T P + PA & PB - C^T \\ B^T P - C & -D - D^T \end{bmatrix} < 0 \,. \tag{7}$$

Obviously, a passive system is Lyapunov stable (when u=0). The passivity property can be used to determine the stability of interconnected systems.

Theorem 2 Passivity Theorem (van der Schaft 1997)

Consider the closed-loop system of G_1, G_2 (as shown in Figure 2) with $e_2 \equiv 0$ so that:

$$\begin{aligned} u_1 &= e_1 - G_2(u_2) \\ u_2 &= G_1(u_1), \end{aligned} \tag{8}$$

with G_1, G_2: $L_{2e}^m \to L_{2e}^m$. Assume that for any $e_1 \in L_{2e}^m$ there are solutions u_1, $u_2 \in L_{2e}^m$. If G_1 is passive and G_2 is strictly passive, then $u_2 = G_1(u_1) \in L_2^m$. That is, the closed-loop system is asymptotically stable.

Passive processes are minimum phase. Linear passive systems are phase bounded (within $[-90^\circ, +90^\circ]$). As a result, a strictly passive process is very easy to control – it can be stabilized by any passive controller (provided that the process is zero state detectable). Such controllers include multi-loop PI/PID controllers with any positive controller gains. This motivates control design based on passivity. The basic idea is to "passify" the process first and then design a passive controller to control the passified system. Furthermore, the excess or shortage of "passivity" of a given process can also be used to analyse whether this process can be easily controlled and the achievable performance under feedback control.

Recent development of passivity based process control is summarised in this paper, including feedback / feedforward passification, robust control, decentralized

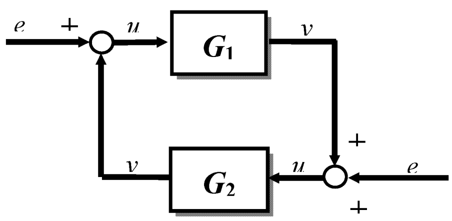

Figure 2. Passivity Theorem

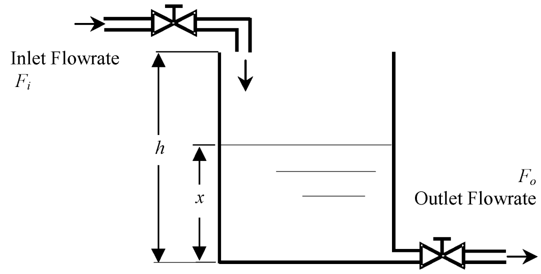

Figure 1. A gravity tank system

fault tolerant control and process controllability analysis.

2. PASSIFICATION OF PROCESS SYSTEMS

As illustrated in Figure 3, a non-passive process (**G**) can be rendered passive by using an output feedback system (**G**$_{fb}$) and/or an input feedforward system (**G**$_{ff}$).

One necessary condition for the existence of an *output feedback* controller that passifies a process is that the process is weakly minimum phase. For *input feedforward* passification, the process needs to be stable. For linear systems, the passifiers can be obtained by solving a matrix inequality problem such that the overall system (with the feedback or feedforward system) satisfies the linear version of the KYP Lemma (Inequality (7)). In this approach, one will encounter bilinear matrix inequality constraints as both matrices A and P are decision variables. Variable transformations are required to convert the bilinear constraints to linear constraints (e.g. Sun et al 1994). For input feedforward passification, the bilinear matrix inequality problem can be avoided by assuming the passified system has the same matrices A and B as the original process (Suryodipuro et al 2004). Passification of control affine nonlinear systems can also be performed based on the nonlinear version of the KYP lemma (e.g., Byrnes et al 1991).

The excess or shortage of passivity for a given process can be quantified by an input feedforward passivity (IFP) index or an output feedback passivity (OFP) index (Sepulchre et al 1997). These indices measure how much feedforward/feedback is required (or is in excess) for a process to be passive. If a stable process **G** is not passive, and a minimum feedforward νI (ν>0) is required such that (**G**+ νI) is passive then **G** is said to be IFP(-ν). If (**G**- νI) is passive, then **G** is IFP(ν), having excessive IFP.

It is noted that the concept of passivity was generalised to dissipativity (e.g., Hill and Moylan 1980), where the supply rate was extended to a quadratic weighted form of the input and output vectors. Clearly, for a process to have the above passivity indices is equivalent to being

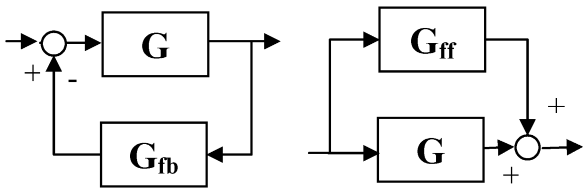

Figure 3. Feedback and feedforward passification

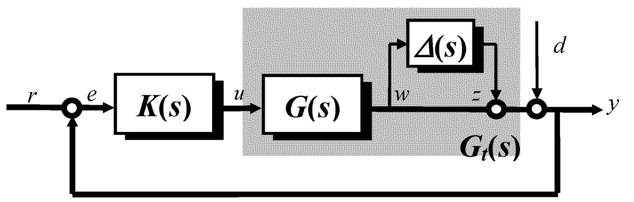

Figure 4. Block diagram of feedback control

dissipative with the following quadratic supply rates:

- A system of IFP (ν) is dissipative with respect to $w(u,y)=u^T y-\nu u^T u$.
- A system of OFP (ρ) is dissipative with respect to $w(u,y)=u^T y-\rho y^T y$.

The Passivity Theorem can be extended using the notion of IFP and OFP:

Condition 1. For the feedback configuration shown in Figure 3, if $\mathbf{G}_1$ is IFP(ν) and $\mathbf{G}_2$ is OFP(ρ), then the closed-loop system is stable if $\rho+\nu>0$.

3. PASSIVITY BASED ROBUST CONTROL

Robustness is an important issue in process control. Since uncertainties in process models are inevitable and could be significant in many cases, it is important that the controller designed based on these models be robust. Consider the control problem illustrated in Figure 4, where $G(s)$ is the process model and $\Delta(s)$ is the multiplicative uncertainty. A robust controller $K(s)$ should be able to stabilise the closed-loop system with the presence of the uncertainty. As shown in Figure 5, the feedback system can be regrouped into two blocks - $\Delta(s)$, the uncertainty, and $T(s)$, the subsystem "seen" by the uncertainty (including $G(s)$ and $K(s)$). Currently, most robust control designs, such as H_∞ control, are based on the small-gain theorem (Zames 1966). These approaches assume the uncertainty is bounded by its norm and lead to control designs which guarantee the closed-loop stability when $\|\Delta\|<\gamma$.

The Passivity Theorem provides a new avenue for robust control. If the uncertainty is passive, then the controller is only required to render system $T(s)$ strictly passive to achieve robust stability even if $\|\Delta\|$ is very large. Although uncertainties are often non-passive, they can be characterised based on their IFP and OFP. If the uncertainty is estimated to have a maximum shortage of IFP of ν, i.e., being IFP(-ν), then the controller K can

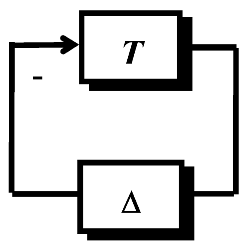

Figure 5. Robust Control

guarantee the robust stability if T has excessive OFP of at least ν.

Motivated by the above observation, we have developed a passivity based approach to robust control. First, we have extended the IFP index such that it is a frequency dependent index. Given a system transfer function matrix $G(s)$, its frequency dependent input feedforward passivity is defined as:

$$\nu_F[G(s),\omega] \overset{\Delta}{=} \left\{\lambda_{\min}\left(\frac{1}{2}[G(j\omega)+G^*(j\omega)]\right)\right\}, \tag{9}$$

which indicates how much excessive passivity the process has at different frequencies. A system's ν_F index is the real part of its frequency response and comprises both the gain and phase information. For a multivariable linear system $G(s)$, we have:

$$\nu_F[G(s),\omega] \le \bar{\sigma}(G(j\omega)) \quad \forall \omega \in R. \tag{10}$$

If the uncertainty's passivity index is bounded:

$$\nu_F(\Delta(s),\omega) \ge -\nu_F(W(s),\omega) \quad \forall \omega \in R, \tag{11}$$

where $W(s)$ is a minimum phase transfer function, then a controller that renders the closed-loop system $T(s)$ to have excessive OFP of $\nu_F(W(s),\omega)$ at frequency ω can achieve robust stability. That is, $T(s)$ should satisfy the following condition:

Condition 2: $T(s)[I-W(s)T(s)]^{-1}$ is strictly passive.

The above condition assumes that the uncertainty can be unbounded. (A passive system can be L_{2e}. e.g., system $G(s)=1/s$ is passive.) The conservativeness of the above condition can be further reduced if the uncertainty does not have unlimited gain. As any stable bounded system will have excessive OFP, a revised IFP index can be obtained with a given OFP index (as shown in Figure 6). In this case, $T(s)[I-W(s)T(s)]^{-1}$ does not need to be strictly passive.

A control synthesis method was developed by the authors such that the closed-loop system satisfies Condition 2. This work is based on the Positive Real Lemma and Semi-Definite Programming. Details are reported in Bao et al (2000, 2003a).

Most physical processes have smaller phase (and thus "more passive") at low frequencies than at high frequencies. Therefore we also developed a robust

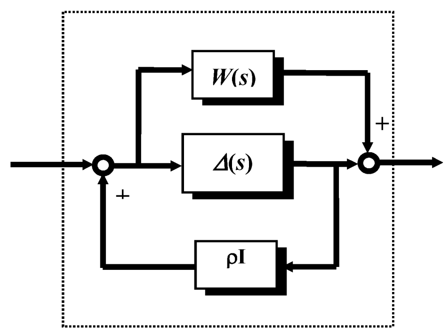

Figure 6. Revised passivity index.

control approach that combines both the Small Gain Theorem and the Passivity Theorem. The uncertainty is characterised by its passivity at low frequencies and by its gain at high frequencies. A "blended" stability condition was derived. A robust control design method was developed based on the Cayley transformation which converted the blended passivity/small gain problem into an H_∞ control problem. Details of this approach are reported in Bao et al (1998).

As the passivity based robust control approach utilises both the gain and phase bounds of the uncertainty, it is often less conservative than the small gain based methods. This was confirmed by the case studies we have conducted.

4. DECENTRALIZED FAULT TOLERANT CONTROL

In process control applications, failures of control components such as actuators, sensors or controllers are often encountered. These problems not only degrade the performance of the control system, but also may induce instability, which could cause serious safety problems. With the increasing reliance on automatic control systems, fault tolerant control becomes an important issue in the process industries. At present, most fault-tolerant control systems are built based on the technique of having redundancy in key controllers. The backup controller is employed once the failure of the main controller is detected. However, the control loop failure may not be detected swiftly and accurately. Sometimes the fault detection system itself could be a possible source of failure (Vidayasagar and Viswanadham 1985). It also requires a significant number of redundant control components, which may increase the system cost to an unacceptable level.

Consider the decentralized control problem of an $n \times n$ linear time-invariant process $G(s)$ with control input u, actuator input u_a, process output y and sensor output y_s (as shown in Figure 7). The model of actuator and sensor failures can be represented as follows (Bao et al 2003b):

$$\begin{aligned} u_a &= E_a u + f_a \\ y_s &= E_s y + f_s \end{aligned} . \qquad (12)$$

where $E_a = diag\{\varepsilon_{a,i}\}$, $E_s = diag\{\varepsilon_{s,i}\}$ are actuator and sensor fault matrices with $0 \le \varepsilon_{a,i}, \varepsilon_{s,i} \le 1$ (i=1,…,n). Vectors $f_a = [f_{a1}, \cdots, f_{a,i}, \cdots, f_{a,n}]^T$ and $f_s = [f_{s1}, \cdots, f_{s,i}, \cdots, f_{s,n}]^T$ represent the constant components of actuators' and sensors' outputs when they fail. This model addresses the following typical failure scenarios (assuming the i-th channel of the control system fails, $1 \le i \le n$):

- Sensor outage: $\varepsilon_{s,i} = 0,\ f_{s,i} = 0$;
- Controller/actuator outage: $\varepsilon_{a,i} = 0,\ f_{a,i} = 0$;
- Sensor partially functioning: $0 \le \varepsilon_{s,i} \le 1$;
- Actuator partially functioning: $0 \le \varepsilon_{a,i} \le 1$;

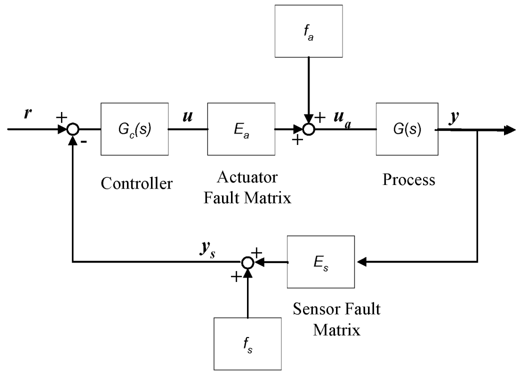

Figure 7. Representation of sensor/actuator failures

- Frozen sensor output: $\varepsilon_{s,i} = 0,\ f_{s,i}$ = constant output from the i-th sensor;
- Frozen controller output and/or actuator stickiness: $\varepsilon_{a,i} = 0,\ f_{a,i}$ = constant output from the i-th controller/actuator.

For the linear feedback system under consideration (as shown in Figure 7), constant vectors f_a and f_s do not affect the closed-loop stability. Consequently, for stability analysis under the control failure scenarios listed above, only the effects of actuator and sensor faulty matrices E_a and E_s need to be considered. In addition, as controller $G_c(s)$ is decentralized, matrices E_a and E_s are permutable. Therefore, control system stability under the above circumstances can be achieved if the controller maintains closed-loop stability when one or more of its output channels are arbitrarily detuned or switched off. Closed-loop stability under this condition is called controller is called decentralized unconditional stability (DUS).

Based on the passivity based stability conditions, we have developed a decentralized fault tolerant approach which requires zero or very low level redundancy. The idea is simple: a strictly passive multivariable plant can be stabilized by any decentralized passive controller. The decentralized passive controller remains passive when one or more of its sub-loops are arbitrarily detuned or taken out of service. If the process is not passive (i.e., IFP(-ν)) then the decentralized controller should have excessive OFP (being OFP(ν)) to maintain closed-loop stability. The decentralized controller will still be OFP(ν) when one or more of its sub-loops are arbitrarily detuned or switched off. Therefore decentralized unconditional stability can be achieved by passivity based decentralized control. A DUS condition was derived by the authors:

Theorem 3 (Zhang et al 2002) For an interconnected system (as shown in Figure 7) comprising a stable subsystem $G(s)$ and a decentralized controller $K(s)$=diag$\{k_i(s)\}$, i=1, ..., n, if a stable and minimum phase transfer function $w(s)$ is chosen such that $\nu_F(G^+(s), \omega) > -\nu_F(w(s), \omega)$ then the closed-loop system will be decentralized unconditionally stable (DUS) if for any loop i=1, ..., n, $k'_i(s) = k_i^+(s)[1 - w(s)k_i^+(s)]^{-1}$ is passive. Matrix U is diagonal with elements of either 1 or –1. The signs of U elements are determined such that the diagonal elements of $G^{+}(s)=G(s)U$ are positive at steady state, i.e. $G_{ii}^{+}(0)\geq 0$, i=1, ..., n. $k'^{+}_{i}(s)$ is the i-th element of transfer function $K^{+}(s)=U^{-1}K(s)=UK(s)$.

Similar to the diagonal scaling treatment for calculating maximum stability gain margins, the conservativeness of the sufficient stability condition given in Theorem 3 could be reduced by using a constant, real and positive-definite diagonal rescaling matrix. A rescaled IFP index was proposed for determining DUS:

$$\nu_s\left(G(s),\omega\right)=\max_{D}\nu_F\left(D^{-1}G^{+}(s)D,\omega\right). \quad (13)$$

Such an index can be obtained by solving a complex Linear Matrix Inequality problem for each frequency ω. Details can be found in Zhang et al (2002).

Based on Theorem 3 and the rescaled IFP index, we have developed a decentralized fault tolerant control that maintains closed-loop stability when any number of loops fails. For stable processes, this control approach does not require any redundant control element. Control design algorithms have been derived for controllers that achieve H_2 performance and also meet the DUS condition in Theorem 4 (Bao et al 2002b). The successive Semi-Definite Programming and controller parameterization techniques were implemented in developing these methods.

This control approach was further developed to cope with unstable processes (Bao et al 2003b). An unstable process is first stabilized via a multi-loop proportional-only feedback controller. A DUS controller is then designed for the stabilized process based on the passivity condition. Redundancy is only required for the stabilizing proportional-only controllers as the passive DUS controller itself is inherently fault tolerant. A numerical method was developed to find the stabilizing controller with the minimum number of loops. This leads to a control system design with the least redundancy and more reliability.

5. CONTROLLABILITY ANALYSIS

As process control is playing an increasingly important role in the process industries, processes should be designed such that they can be easily controlled by feedback control systems to achieve effective disturbance rejection (for reduced product variability) and reference tracking (for fast and smoothly transition from one operating condition to another). Process controllability can be quantitatively measured by the best achievable dynamic control performance. As a process design fundamentally determines the process' controllability, a controllability measure which can be used in early stages of process design will be very useful.

Certain open-loop factors, such as minimum singular values, right-half-plane zeros, time delays and condition numbers were found to be related to controllability (e.g., Morari 1983). However, the above analysis methods suffer from the following weaknesses: (1) they are based on linear models and thus are only suitable to linear or mildly nonlinear processes; (2) they only suggest the likely effect of each attribute on the closed-loop performance but fail to indicate the overall effect of the characteristics on controllability.

As mentioned in Section 1, passive systems (both linear and nonlinear) represent a class of minimum phase systems, which are very easy to control, even if they are highly nonlinear and/or highly coupled. Intuitively, the IFP index of an open loop process can be used to infer the best achievable performance under feedback control. Based on this idea, we have been developing a passivity based framework for analysing process controllability.

Decentralized Integral Controllability

Decentralized control is a widely used strategy in industrial process control. For decentralized designs, an important issue is Decentralized Integral Controllability (DIC). DIC analysis determines whether a multivariable plant can be stabilized by multi-loop controllers, whether the controller can have integral action to ensure zero steady-state error, and whether the closed-loop system will remain stable when any subset of loops is detuned or taken out of service.

Large loop interactions often lead to control performance degradation and even instability in decentralized control of closed-loop systems. Therefore, most existing DIC conditions imply "generalized diagonal dominance" (GDD) (Skogestad and Morari, 1988). As shown by recent studies, GDD is not necessary for closed-loop stability under decentralized control and thus those conditions can be very conservative. Based on the concept of passivity, we have found a new sufficient condition for DIC (Bao et al 2002):

Theorem 4. A stable linear MIMO plant $G(s)$ with a non-singular steady-state gain matrix $G(0)\in R^{n\times n}$ is DIC if a real diagonal matrix D=diag$\{d_1,...,d_i,...,d_n\}$ ($d_i\neq 0$, i=1...n) can be found such that:

$$G(0)D+DG^{T}(0)\geq 0 \quad (14)$$

The above condition is equivalent to the process having a scaled IFP of 0 at the frequency of ω=0. Highly coupled systems may be passive and thus the large interactions they possess do not necessarily destabilize the closed-loop systems under decentralized control. The passivity index is not an explicit measure of interactions but an indicator of the *destabilizing* effect of the interactions.

Decentralized Integral Controllability analysis for nonlinear processes

As the concept of passivity applies to both linear and nonlinear systems, we have extended the above results to nonlinear processes and developed a DIC analysis method for nonlinear processes. It was found that a multivariable nonlinear process $P: u\rightarrow y$ ($u\in U\subset R^n$, $y\in Y\subset R^n$) is DIC for an equilibrium steady state operating point (u_e,y_e) if the following steady-state passive condition is satisfied (together with other conditions for rigorousness) :

$$\left(y-y_e\right)^T\left(u-u_e\right)>0 \;\; \forall u \in U \text{ and } y \in Y \,. \tag{15}$$

The details of this condition and the numerical method for testing the condition are reported in Su et al (2004).

Block decentralized integral controllability

Modern chemical plants generally consist of multiple processing units. Intuitively, a single multivariable controller can be designed for each process unit and a block diagonal controller is thus obtained for the overall plant (decentralized multi-unit control). However, it was often found that such a block diagonal control structure, based on the plant physical decomposition, might not lead to the control system with the best achievable performance, due to the high coupling between different units. Compared with multi-loop control, the number of possible pairing schemes involved in block decentralized control is much higher. Therefore, pairing studies of block decentralized control systems are of great practical importance.

We have extended the concept of DIC and defined the process property of Block Decentralized Integral Controllability (BDIC): For a given multivariable process and certain block diagonal control structure, if there exists a stabilizing controller that has integral action to achieve offset free control and maintains closed-loop stability when any one or more controller blocks are arbitrarily detuned, then this process is said to be BDIC with the particular block diagonal structure.

Based on the same passivity framework, we have derived a sufficient BDIC condition which can be used to test alternative control configurations (Zhang et al 2003a). This analysis was applied in control structure selection of a Supercritical Fluid Extraction (SFE) process. Its was found that due to the high coupling and complicated dynamics, a cross-unit pairing scheme for manipulated variables and controlled variables will lead to a much better achievable control performance than a pairing scheme based on the physical decomposition (Zhang et al 2003b).

Dynamic Controllability Analysis

The frequency dependent input passivity index also reflects the limitations caused by process dynamics. Large time delays in the process or/and RHP zeros will lead to a larger passivity index (at corresponding frequencies) and thus requires controllers to have smaller gains. Passivity based dynamic controllability analysis is being studied by the authors using an Internal Model Control framework (Suryodipuro et al 2004).

6. CONCLUSION

Passivity based techniques have shown to be promising in serval process control areas, including robust control, fault tolerant control and controllability analysis. Our current research focuses on passivity based nonlinear control and controllability analysis for nonlinear dynamic processes.

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