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A Technique for Abrupt Load Disturbance Detection in Process Control Systems ⋆

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Abstract: A simple technique for the detection of abrupt load disturbances occurring in process control systems is proposed in this paper. The technique is based on the computation of an index using routine operating data, after a simple experiment is performed initially, and it can be employed usefully in the context of performance assessment and adaptive control. Simulation and experimental results confirm its effectiveness.

1. INTRODUCTION

Nowadays, process monitoring and control system performance assessment play a more and more important role in industry due to the need of increasing the quality of the products and of reducing the overall costs at the same time. Since in large plants there are hundreds of control loops and it is almost impossible for operators to monitor each of them manually and since an unsatisfactory performance can be caused by different factors (Patwardhan and Shah (2002)), it is important to have tools that are first able to automatically determine if an abnormal situation occurs and then to help the operator to understand the reason for it and possibly to suggest the way to solve the problem (for example, if a bad controller tuning is detected, then new appropriate values of controller parameters are determined) (Jelali (2006)). Thus, there is the need to integrate different techniques, each of them devoted to deal with a particular situation (Visioli (2006a)).

In the context of assessing the performance of a Proportional-Integral-Derivative (PID) controller, different techniques have been devised recently. With respect to the set-point following task, a method based on the determination of the integrated absolute error and of the settling time has been proposed in (Swanda and Seborg (1999)). It requires the knowledge of the dead time of the process. For the detection of an aggressive controller, both for set-point following and load disturbance rejection task, a statistically-based approach (which consists of calculating the autocorrelation of either the controlled variable or the control error) has been presented in (Miao and Seborg (1999)). Conversely, with the aim of detecting a sluggish controller, in the context of rejection of load disturbances, the use of the so-called Idle Index has been devised in (Hägglund (1999)) and further improved in (Kuehl and Horch (2005)). Again in the context of rejection of load disturbances, the Area Index has been presented in (Visioli (2006b)). By using it in conjunction with the Idle Index, an assessment of the tuning of a PI controller can be performed.

In any case, these latter methodologies rely on the occurrence and on the correct detection of an abrupt (i.e., step-like) load disturbance. This is also an essential requisite in adaptive control. In fact, the model of the process can be updated correctly (in order to determine new controller parameters) only if the process dynamics is sufficiently excited by the process input signal. As a consequence, if the set-point is kept constant during the routine operations of the process, as it is often the case, the estimation of a new process model can be performed only if an abrupt load disturbance occurs and it is detected correctly (Hägglund and Åström (2000)).

Actually, despite for these reasons it is highly desirable that techniques for an abrupt load disturbance be available, this aspect has been somewhat overlooked in the literature. A notable exception is that described in (Hägglund and Åström (2000)), which consists in high-pass filtering the control variable and the process variable signals and verifying if the obtained signals exceed a given threshold. The technique requires the selection of the high-pass filter frequency (which can be fixed as the inverse of the integral time constant) and of the threshold value.

An alternative technique is proposed in this paper. By following a reasoning similar to the one exploited in (Petersson et al. (2003)) for evaluating the usefulness of a feedforward action, we propose to determine if a load disturbance excites sufficiently the dynamics of the closed-loop system by comparing it with a fictious one that has to be applied to the control system at the beginning of the process operations. A suitable index is proposed in order for the comparison to be meaningful. The need of an additional experiment is counterbalanced by the absence of parameters to be selected by the operator.

The paper is organised as follows. The methodology is explained and motivated in Section 2. Practical issues are addressed in Section 3. Simulation results are given in Section 4, whilst experimental results are presented in Section 5. Conclusions are drawn in Section 6.

2. METHODOLOGY

Consider a unity-feedback closed-loop control system where a process P is controlled by a (PID) controller C (see Figure 1). When a load disturbance occurs, it is described

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by a signal d added to the controller output. In order to describe different dynamics of the load disturbance, we suppose that signal d is the step response of a first-order filter F, namely,

$$F(s) = \frac{1}{T_f s + 1}. \quad (1)$$

It is worth stressing that the transfer function from the disturbance d to the process output y is

$$T(s) = \frac{P(s)}{1 + C(s)P(s)}. \quad (2)$$

It turns out that the more the filter time constant T_f is small (with respect to the dominant time constant of $T(s)$), the more the load disturbance is abrupt (i.e., it excites more the dynamics of the process).

In order to detect if an occurring load disturbance is abrupt, the following somewhat trivial consideration can be done. When T_f increases the load disturbance peak response decreases and the settling time increases. In order to illustrate this fact, consider the following example, where the dynamics of $T(s)$ is assumed to be of second order, namely,

$$T(s) = \frac{s}{(s+1)(0.5s+1)}, \quad (3)$$

and different values of T_f from 0 to 6 have been selected. The resulting unit step responses are shown in Figure 2, where the above consideration emerges clearly. Note that the same rationale is valid even when the response is underdamped.

It is worth stressing at this point that, since the proposed technique aims to be useful in the context of controller performance assessment and adaptive control, the employed controller can be poorly tuned and therefore very different dynamics of $T(s)$ have to be considered. For this reason, a technique similar to that employed in (Petersson et al. (2003)) in the context of feedforward control is suggested here. It consists in comparing the obtained load disturbance response with the one obtained by applying a step (i.e., by setting $T_f = 0$). Then, an index is calculated, which determines if the occurring load disturbance signal d can be considered like a step.

More specifically, the technique consists in applying the following procedure. Without loss of generality, we will always assume null initial conditions and positive disturbances ccurring at time $t = 0$ hereafter.

(1) Apply a step signal of amplitude A_s to the control variable and measure the value of the peak response Δ_s and of the 2% settling time $\bar{t}_s$. The 2% settling time is defined as the minimum time after that the output remains withing a two percent range of A_s, i.e.,
$$\bar{t}_s := \min\{\tau \in \mathbb{R}^+ : |y(t)| < 0.02A_s \ \ \forall t > \tau\}. \quad (4)$$
(2) When a load disturbance occurs during process routine operations, measure the amplitude A_d of the step, the value of the peak response Δ_d and of the 2% settling time $\bar{t}_d$. Similarly to the previous case, $\bar{t}_d$ is defined as:
$$\bar{t}_d := \min\{\tau \in \mathbb{R}^+ : |y(t)| < 0.02A_d \ \ \forall t > \tau\}. \quad (5)$$
(3) Calculate the abrupt disturbance index (ADI) as
$$\text{ADI} := \frac{\Delta_d}{A_d \bar{t}_d} \frac{A_s \bar{t}_s}{\Delta_s}. \quad (6)$$

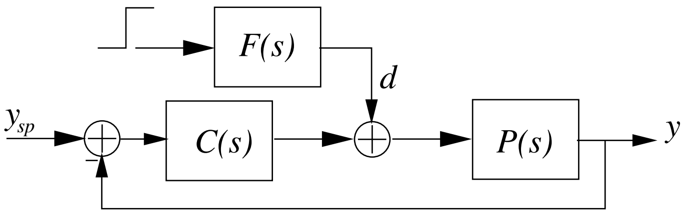

Fig. 1. The considered control scheme.

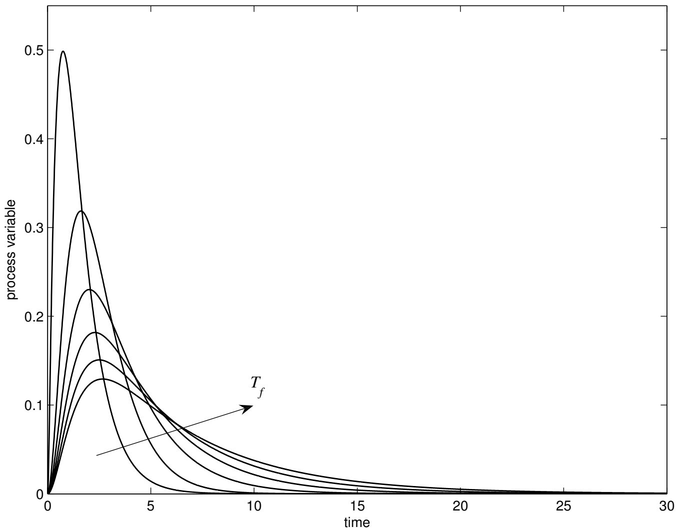

Fig. 2. Step responses for different values of T_f.

It is straightforward to verify that ADI $\in (0, 1]$ and a value of ADI close to one means that the disturbance occurred during routine process operations has been abrupt. Conversely, values of ADI close to zero mean that the disturbance signal has been smooth and it has not been sufficiently exciting for the process dynamics.

It is worth noting that the amplitudes of the disturbances are employed in order to normalised the index. The value of A_d can be easily derived from the difference of the steady-state values of the controller output before and after the occurrence of the disturbance. Further, the threshold value of 2% can be arbitrarily modified without impairing the results.

3. PRACTICAL ISSUES

In order to apply successfully the proposed technique, a few practical issues have to be taken into account. First, the presence of measurement noise has to addressed. Since the method has to be applied off-line, a standard filtering technique can be applied. For a more effective determination of the settling time, a possible alternative approach is to consider the integrated absolute error instead of the process variable. The integrated absolute error is defined as

$$\text{IAE}(t) := \int_0^t |y(v) - y_{sp}| dv \quad (7)$$

where the set-point value y_{sp} has been assumed to be zero. The settling times are then calculated as

$$\bar{t}_s := \min\{\tau \in \mathbb{R}^+ : |\text{IAE}(t)| > (A_s - 0.02A_s) \ \ \forall t > \tau\}. \quad (8)$$

and

$$\bar{t}_d := \min\{\tau \in \mathbb{R}^+ : |\text{IAE}(t)| > (A_d - 0.02A_d) \quad \forall t > \tau\}. \tag{9}$$

Being based on the integration of a (noisy) signal, this approach is more robust to the measurement noise.
Similarly, if a PID controller is employed as a feedback controller, the value of A_d (i.e., the difference of the steady-state values of the controller output before and after the occurrence of the disturbance) can be derived according to the following formula (Åström et al. (1998)):

$$A_d = -\frac{K_p}{T_i}\int_0^\infty (y_{sp} - y(t))dt \tag{10}$$

where K_p is the proportional gain and T_i is the integral time constant of the PID controller. Note that, in practice, the integration time interval of the control error $y_{sp} - y(t)$ can be selected as $[0, \bar{t}_d]$. Also in this case the approach is based on the integration of a (noisy) signal, and therefore it is more robust to the measurement noise.
Regarding the choice of the amplitude of the inital step signal (see step 1 of the procedure outlined in Section 2), this has to be selected in order to provide a sensible result (that is, it has to be sufficiently large with respect to the measurement noise) but, at the same time, it should perturb the process as less as possible. These are actually the same considerations that are done for example when an open-loop step response has to be evaluated for the purpose of system identification.
It is also important to stress that it is necessary to exploit a technique for the detection of a load disturbance (before evaluating if it is sufficiently abrupt or not). For this purpose, those described in (Hägglund (1995)) and (Salsbury (2005)) can be employed.
Finally, it is worth noting that the overall methodology is based on the assumption that the set-point signal does not change during the routine operations of the process. Actually, this is often the case in industrial settings and it is obviously indeed the case where it is important to assess the performance of the controller with respect to the load disturbance rejection task. In this context, it has also implicitly been assumed that the integral action is employed in the controller in order to set the steady-state error to zero in the presence of a constant disturbance.

4. SIMULATION RESULTS

Simulation results are given in order to demonstrate the effectiveness of the proposed technique in different situations. In all the considered examples the amplitude of the load disturbance step is selected equal to one.

4.1 Example 1

As a first example, consider the first-order plus dead-time process

$$P_1(s) = \frac{1}{10s+1}e^{-5s} \tag{11}$$

and an output-filtered PID controller

$$C(s) = K_p\left(1 + \frac{1}{T_i s} + T_d s\right)\frac{1}{T_o s + 1} \tag{12}$$

where the proportional gain K_p, the integral time constant T_i and the derivative time constant T_d have been initially tuned according to the Ziegler-Nichols formulas: $K_p = 2.4$, $T_i = 10$ and $T_d = 2.5$ The PID output filter time constant has been selected so that its dynamics does not influence significantly the overall response, i.e., $T_o = 0.01$. The step responses for the three cases $T_f = 0$, $T_f = 1$ and $T_f = 10$ are shown in Figure 3. The resulting values of the abrupt disturbance index are ADI=0.92 for $T_f = 1$ and ADI=0.65 for $T_f = 10$, indicating correctly that the disturbance is step-like when $T_f = 1$ and it is not step-like when $T_f = 10$. For the sake of comparison, the method devised in (Hägglund and Åström (2000)) and described also in (Visioli (2006b)) has been also applied. Both the process variable and the control variable has been high-pass filtered according to the expressions (for simplicity, the Laplace transform of the signals is employed):

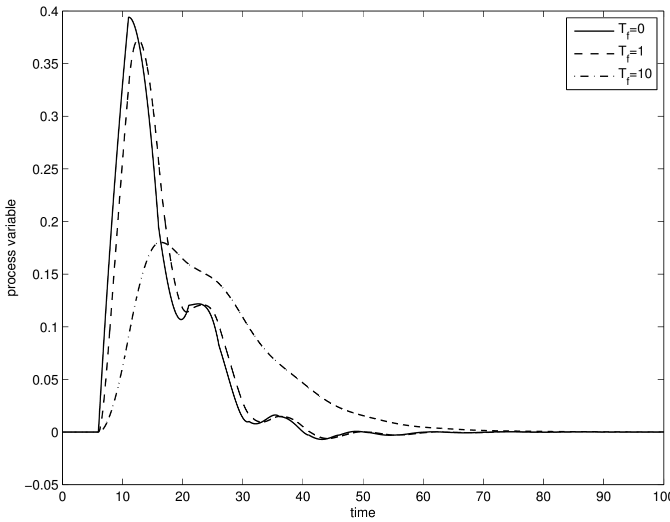

Fig. 3. Step responses for example 1 with $K_p = 2.4$, $T_i = 10$ and $T_d = 2.5$.

$$U_{hp}(s) = \frac{s}{s+\omega_{hp}}U(s) \qquad Y_{hp}(s) = \frac{1}{K}\frac{s}{s+\omega_{hp}}Y(s) \tag{13}$$

where K is the process gain (equal to one) and the frequency ω_{hp} is chosen to be inversely proportional to the integral time constant T_i, i.e., $\omega_{hp} = 0.1$. The resulting signals exceed the given threshold of 3% only when $T_f = 0$ and $T_f = 1$, indicating also in this case correctly that the load disturbance is abrupt.
If the PID parameters are modified by setting $K_p = 3$, $T_i = 7.5$ and $T_d = 2.5$, results are shown in Figure 4. The resulting values of the abrupt disturbance index are similar to the previous case, namely, ADI=0.92 for $T_f = 1$ and ADI=0.64 for $T_f = 10$. Also in this case these results are coherent with those found by applying the technique based on the high-pass filters ($\omega_{hp} = 0.13$).
Finally, the PID controller has been significantly detuned by setting $K_p = 1$, $T_i = 25$ and $T_d = 2.5$. The corresponding load disturbance responses are shown in Figure 5. Once again similarly to the previous cases, it results ADI=0.92 for $T_f = 1$ and ADI=0.67 for $T_f = 10$. Note, however, that in this case, according to the method based on the high-pass filters ($\omega_{hp} = 0.04$), all the disturbances are considered to be abrupt.

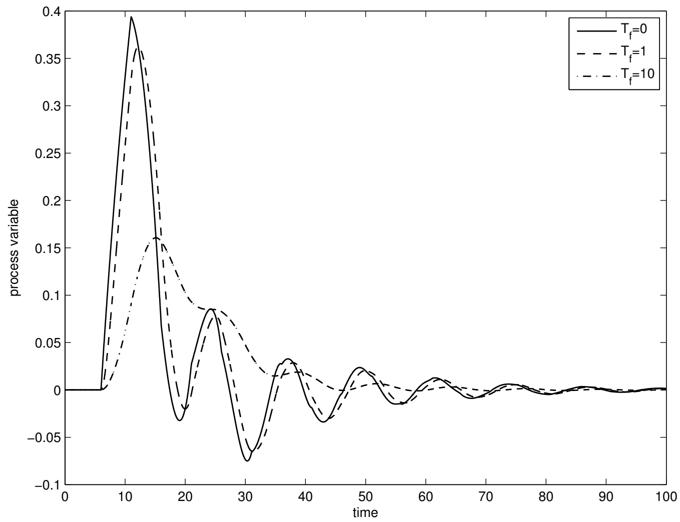

Fig. 4. Step responses for example 1 with $K_p = 3$, $T_i = 7.5$ and $T_d = 2.5$.

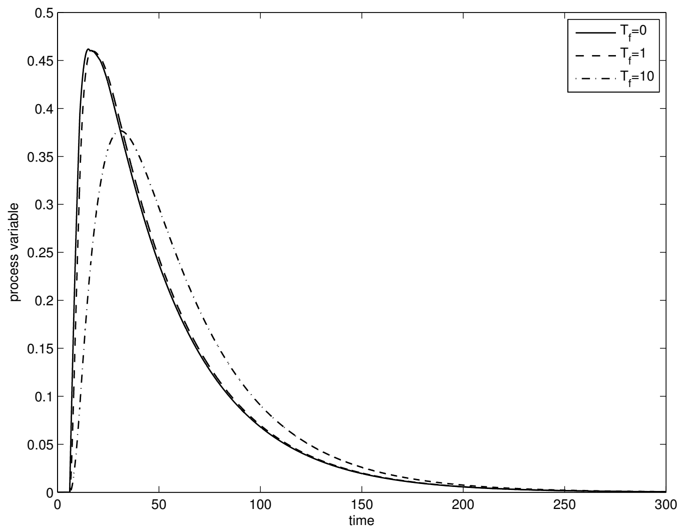

Fig. 5. Step responses for example 1 with $K_p = 1$, $T_i = 25$ and $T_d = 2.5$.

4.2 Example 2

As a second example, we first consider the high-order process

$$P_2(s) = \frac{1}{(s+1)^8} \tag{14}$$

controlled by an output-filtered PID controller (12) with $K_p = 0.7$, $T_i = 10$ and $T_d = 2.5$ (again, $T_o = 0.01$). The same values for T_f of example 1 have been considered, namely, $T_f = 0$, $T_f = 1$ and $T_f = 10$ and the step responses are shown in Figure 6. The resulting values of the abrupt disturbance response are ADI=0.91 for $T_f = 1$ and ADI=0.66 for $T_f = 10$, indicating that for $T_f = 10$ the load disturbance signal is not step-like. Conversely, the technique based on the high-pass filters classifies all the disturbances as abrupt.

If the proportional gain is raised to $K_p = 1.7$, the resulting process variables are those plotted in Figure 7 and in this case we obtain ADI=0.91 for $T_f = 1$ and ADI=0.64 for $T_f = 10$. Also in this case the technique based on the high-pass filters classifies all the disturbances as abrupt. Finally, the PID controller is detuned by setting $K_p = 0.4$, $T_i = 30$ and $T_d = 2.5$. The obtained results are plotted in Figure 8 and the values of the resulting abrupt disturbance index are similar to the previous cases, namely, ADI=0.91 for $T_f = 1$ and ADI=0.67 for $T_f = 10$. Note again that the technique based on the high-pass filters classifies all the disturbances as abrupt.

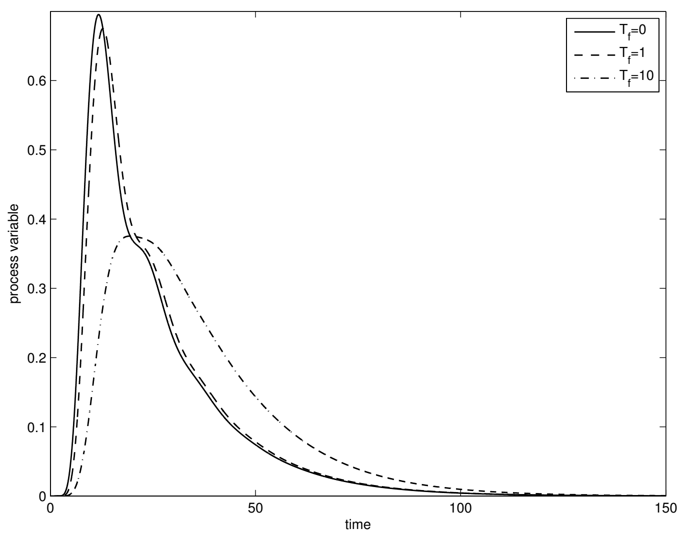

Fig. 6. Step responses for example 2 with $K_p = 0.7$, $T_i = 10$ and $T_d = 2.5$.

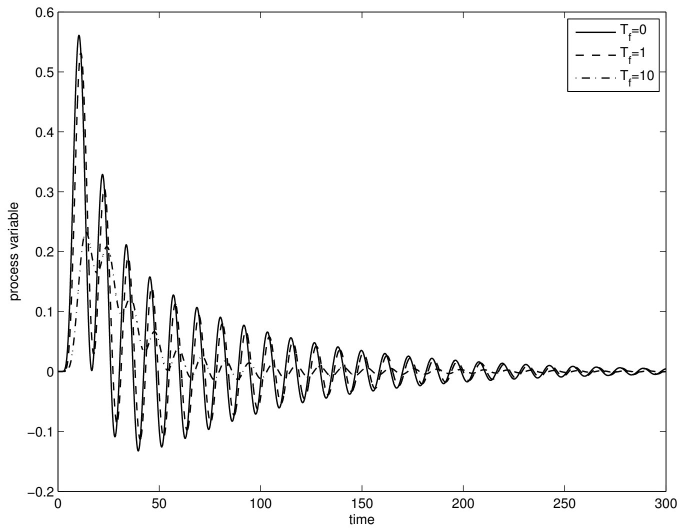

Fig. 7. Step responses for example 2 with $K_p = 1.7$, $T_i = 10$ and $T_d = 2.5$.

5. EXPERIMENTAL RESULTS

In order to show the effectiveness of the devised technique also in practical applications, a laboratory experimental setup (made by KentRidge Instruments) has been employed (see Figure 9). Specifically, the apparatus consists of a small perspex tower-type tank (whose area is 40 cm^2) in which a level control is implemented by means of a PC-based controller. The tank is filled with water by means of

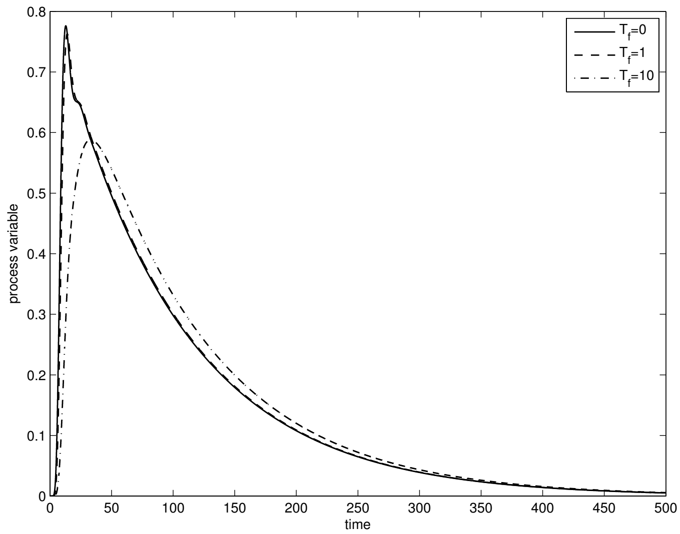

Fig. 8. Step responses for example 2 with $K_p = 0.4$, $T_i = 30$ and $T_d = 2.5$.

a pump whose speed is set by a DC voltage (the manipulated variable), in the range 0-5 V, through a PWM circuit. The tank is fitted with an outlet at the base in order for the water to return to a reservoir. The measure of the level of the water is given by a capacitive-type probe that provides an output signal between 0 (empty tank) and 5 V (full tank). A second inflow (driven by a second pump) is adopted as a disturbance input as shown in Figure 10. Note that the system is nonlinear because the output flow rate depends on the square root of the level. However, it can be approximated by a first-order dynamics with a good accuracy (Visioli (2006a)). A PI controller with $K_p = 4$ and $T_i = 10$ is employed as a feedback controller.
Initially, the system is led to the steady-state with the process output sensor at 2 V. The response of a system to a (software) step of 1 V is shown in Figure 11 and the corresponding controller output signal is plotted in Figure 12. The following values are determined: $A_s = 1$ V, $\Delta_s = 0.18$ V and $\bar{t}_s = 23.1$ s. Then, in a second experiment, the second pump is activated by applying a step signal from 0 to 1.9 V. The obtained process variable and controller output are shown in Figures 13 and 14 respectively. The values $A_d = 1.9$ V, $\Delta_d = 0.38$ V and $\bar{t}_d = 28.1$ s results, yielding to ADI = 0.91. Thus, an abrupt disturbance is detected, confirming the results obtained by using the high-pass filter (Visioli (2006b)).

6. CONCLUSIONS

In this paper we have presented a simple technique for determining when a load disturbance occurring in a process control system can be considered as abrupt, namely, it excites significantly the dynamics of the control system. It has to be remarked that no parameters have to be selected by the user. This is paid by the need of performing a simple experiment in the initial phase.
The technique is based on the determination of the value of an index which provides a quantitative measure of the smoothness of the disturbance. The correct value of a threshold that discriminates if the load disturbance response can be employed in the context of adaptive control or performance assessment obviously depends on the application. However, from the presented simulation and experimental results, it appears that a value of ADI=0.8 can be considered as a sensible default value in a wide range of situations. The advantages of the proposed technique with respect to another one presented previously in the literature have also been clarified.
The overall procedure appears therefore to be suitable to implement in Distributed Control Systems in order to integrate methodologies for the purpose of performance monitoring and control systems performance assessment.

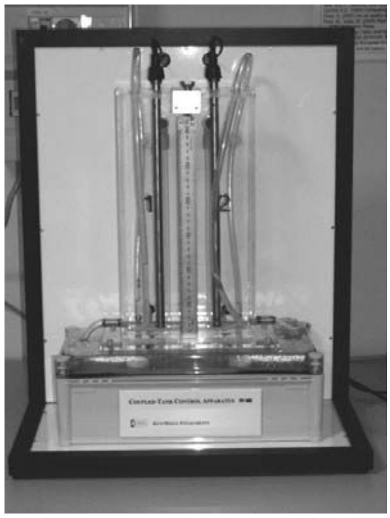

Fig. 9. A picture of the experimental setup.

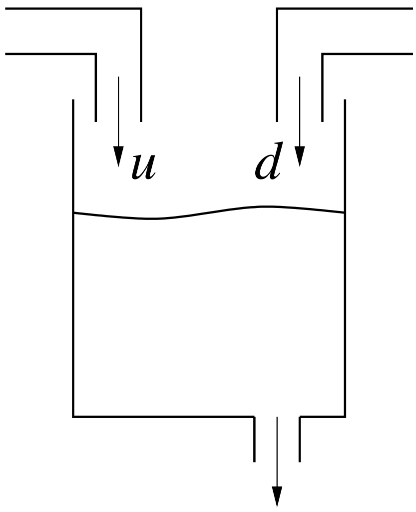

Fig. 10. A sketch of the experimental setup showing the kind of disturbance.

REFERENCES

K. J. Åström, H. Panagopoulos, and T. Hägglund. Design of PI controllers based on non-convex optimization. *Automatica*, 34(5):585–601, 1998.
T. Hägglund. Automatic detection of sluggish control loops. *Control Engineering Practice*, 7:1505–1511, 1999.
T. Hägglund. A control-loop performance monitor. *Control Engineering Practice*, 3:1543–1551, 1995.

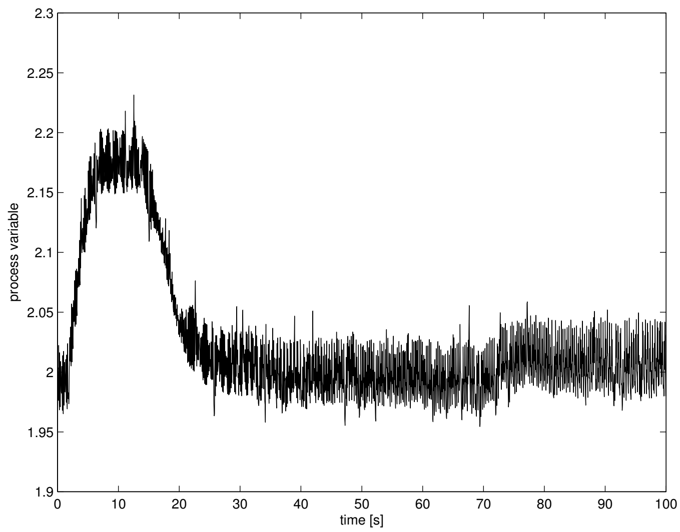

Fig. 11. Experimental process response when a software step is applied to the control variable.

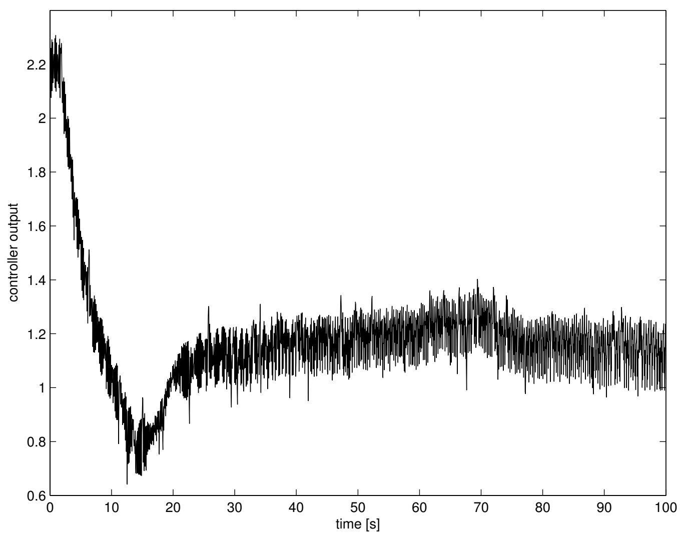

Fig. 12. Experimental controller output when a software step is applied to the control variable.

T. Hägglund and K. J. Åström. Supervision of adaptive control algorithms. *Automatica*, 36(2):1171–1180, 2000.

M. Jelali. An overview of control performance assessment technology and industrial applications. *Control Engineering Practice*, 14:441–466, 2006.

P. Kuehl and A. Horch. Detection of sluggish control loops - experiences and improvements. *Control Engineering Practice*, 13:1019–1025, 2005.

T. Miao and D. E. Seborg. Automatic detection of excessively oscillatory feedback loops. In *Proceedings IEEE International Conference on Control Applications*, pages 359–364, Kohala Coast, HW, 1999.

R. S. Patwardhan and S. L. Shah. Issues in performance diagnostics of model-based controllers. *Journal of Process Control*, 12:413–417, 2002.

M. Petersson, K.-E. Arzen, and T. Hägglund. A comparison of two feedforward control structure assessment methods. *International Journal of Adaptive Control and Signal Processing*, 17:609–624, 2003.

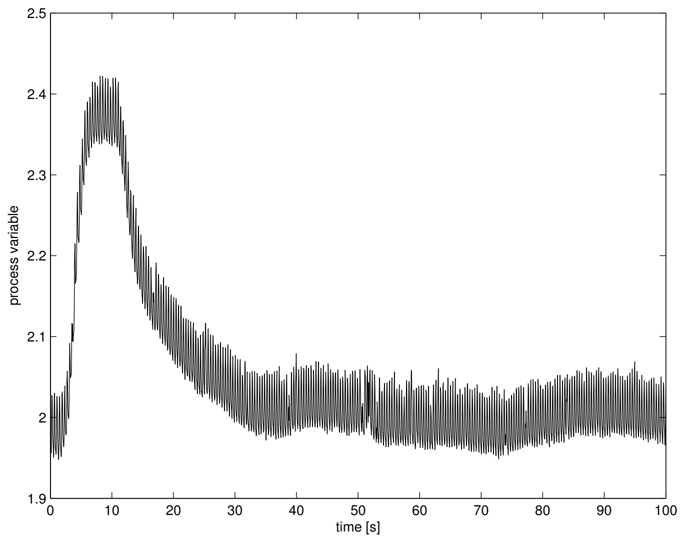

Fig. 13. Experimental process response when a load disturbance is applied.

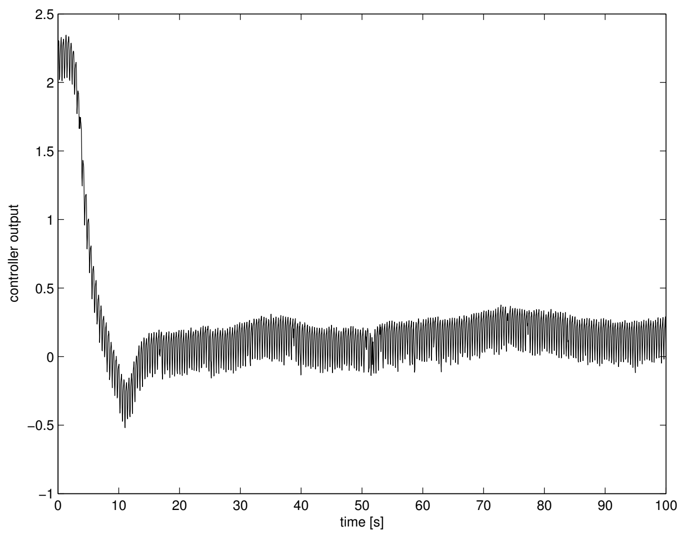

Fig. 14. Experimental controller output when a load disturbance is applied.

T. I. Salsbury. A practical method for assessing the performance of control loops subject to random load changes. *Journal of Process Control*, 15(4):393–405, 2005.

A. P. Swanda and D. E. Seborg. Controller performance assessment based on set-point response data. In *Proceedings American Control Conference*, pages 3863–3867, San Diego, CA, 1999.

A. Visioli. *Practical PID Control*. Springer, 2006a.

A. Visioli. Method for proportional-integral controller tuning assessment. *Industrial and Engineering Chemistry Research*, 45:2741–2747, 2006b.