Int. J. Appl. Math. Comput. Sci., 2008, Vol. 18, No. 4, 553–560
DOI: 10.2478/v10006-008-0048-1

ACTUATOR FAULT TOLERANT CONTROL DESIGN BASED ON A RECONFIGURABLE REFERENCE INPUT

DIDIER THEILLIOL [*], CÉDRIC JOIN [*,**], YOUMIN ZHANG [***]

[*] Centre de Recherche en Automatique de Nancy (CRAN)
Nancy-Université, CNRS, BP 239, 54506 Vandoeuvre Cedex, France
e-mail: didier.theilliol@cran.uhp-nancy.fr

[**] ALIEN-INRIA, Lille-Saclay, France
e-mail: cedric.join@inria.fr

[***] Department of Mechanical and Industrial Engineering
Concordia University, 1455 de Maisonneuve Blvd. W., Montreal, Quebec H3G 1M8, Canada
e-mail: ymzhang@encs.concordia.ca

The prospective work reported in this paper explores a new approach to enhance the performance of an active fault tolerant control system. The proposed technique is based on a modified recovery/trajectory control system in which a reconfigurable reference input is considered when performance degradation occurs in the system due to faults in actuator dynamics. An added value of this work is to reduce the energy spent to achieve the desired closed-loop performance. This work is justified by the need of maintaining a reliable system in a dynamical way in order to achieve a mission by an autonomous system, e.g., a launcher, a satellite, a submarine, etc. The effectiveness is illustrated using a three-tank system for slowly varying reference inputs corrupted by actuators faults.

Keywords: fault tolerant control (FTC), actuator fault accommodation, reconfigurable reference input.

1. Introduction

Sensor or actuator failures, equipment fouling, feedstock variations, product changes and seasonal influences may affect the controller performance in as many as 60% of industrial control problems (Harris *et al.*, 1999). The objective of a fault tolerant control system (FTCS) is to maintain current performances close to the desirable ones and preserve stability conditions in the presence of component and/or instrument faults. In some circumstances a reduced performance could be accepted as a trade-off (Zhang and Jiang, 2003a). In fact, many FTC methods have been recently developed (Blanke *et al.*, 2003; Noura *et al.*, 2000; Patton, 1997). Almost all the methods can be categorized into two groups (Zhang and Jiang, 2003b): passive and active approaches. Passive FTC deals with a presumed set of system component failures based on the actuator redundancy at the controller design stage. The resulting controller usually has a fixed structure and parameters. However, the main drawback of a passive FTCS is that as the number of potential failures and the degree of system redundancy increase, controller design could become very complex, and the performance of the resulting controller (if it exists) could become significantly conservative. Moreover, if an unanticipated failure occurs, passive FTC cannot ensure system stability and cannot reach again the nominal performance of the system. Controllers switching underlines the fact that many faulty system representations had to be identified so as to synthesize off-line pre-computed and stabilized controllers. These requirements are sometimes difficult to meet. An active FTCS is characterized by an on-line FDI process and a control reconfiguration mechanism. According to the FDI module, a control reconfiguration mechanism is designed in order to take into account the possibility of fault occurrence (Theilliol *et al.*, 2002). Advanced and sophisticated controllers have been developed with fault accommodation and tolerance capabilities, in order to meet pre-fault reliability and performance requirements as proposed by (Gao and Antsaklis, 1991; Jiang, 1994) for model matching approaches or by (Gao and Antsaklis, 1992) to track a trajectory, but also with degraded ones as suggested by (Jiang and Zhang, 2006). Moreover, the importance of improving the system behaviour during the fault accommodation delay has been, recently, considered by (Staroswiecki et al., 2007) in order to reduce the loss of performance. This paper addresses a new approach in order to increase the performance of an active fault tolerant control system. This novel technique consists in taking into account a modified recovery/trajectory control system when performance degradation occurs in the system due to faults in actuator dynamics. The developed method preserves the system performance through an appropriate reconfigurable reference in order to preserve the output dynamic properties and to limit the energy of control inputs as well. The paper is organized as follows: Section 2 recalls the actuator fault representation and the controller synthesis for LTI systems. Section 3 is devoted both to remind a classical fault tolerant controller considered in this paper and to define the novel reconfigurable reference input technique. A simulation example of a well-known three-tank system with slowly varying reference inputs subject to actuator faults is used in Section 4 to illustrate the effectiveness and performance of the active fault tolerant control system. Conclusions and further work are discussed in Section 5.

2. Basic concept

2.1. Control system synthesis. Consider the discrete linear system given by the following state space representation:

$$\begin{cases} x_{k+1} = Ax_k + Bu_k, \\ y_k = C_r x_k, \\ w_k = Cx_k, \end{cases} \tag{1}$$

where $A \in \mathbb{R}^{n\times n}$, $B \in \mathbb{R}^{n\times p}$, $C \in \mathbb{R}^{m\times n}$ and $C_r \in \mathbb{R}^{h\times n}$ are the state, control, output and tracking output matrices, respectively. $x \in \mathbb{R}^n$ is the state vector, $u \in \mathbb{R}^p$ is the control input vector, $w \in \mathbb{R}^m$ corresponds to the measured output vector and $y \in \mathbb{R}^h$ represents the system outputs that will track the reference inputs. Note that, in order to maintain controllability, the number of outputs h that can track a reference input vector r cannot exceed the number of control inputs $p \geq h$.

The study considered in this paper is suitable not only for regulation, but also for the tracking control problem. The eigenstructure assignment (EA) or the linear quadratic regulators (LQR) are among the most popular controller design techniques for multi-input and multi-output systems. Since the feedback control, $-K^{\mathrm{nom}}_{\mathrm{feedback}} x_k$, can only guarantee the stability and dynamic behaviour of the closed loop system, a complementary controller is required to cause the output vector y to track the reference input vector r in the sense that the steady state response is

$$\lim_{k\to+\infty} y = r. \tag{2}$$

To achieve steady-state tracking of the reference input, various techniques have been developed. Among them, a feedforward control law based on a command generator tracker (Zhang and Jiang, 2002) can be considered such that

$$u^{\mathrm{nom}}_k = -K^{\mathrm{nom}}_{\mathrm{forward}} r_k - K^{\mathrm{nom}}_{\mathrm{feedback}} x_k, \tag{3}$$

where the feedforward gain $K^{\mathrm{nom}}_{\mathrm{forward}}$ is synthesized based on the closed-loop model-following principle. As proposed by D'Azzo and Houpis (1995), another solution to track the reference input consists of adding a vector comparator and integrator ($z^{\mathrm{nom}} \in \mathbb{R}^h$) that satisfies

$$\begin{aligned} z^{\mathrm{nom}}_{k+1} &= z^{\mathrm{nom}}_k + T_s(r_k - y_k) \\ &= z^{\mathrm{nom}}_k + T_s(r_k - C_r x_k). \end{aligned} \tag{4}$$

Therefore, the state feedback control law is computed by

$$u^{\mathrm{nom}}_k = -K^{\mathrm{nom}}_{\mathrm{forward}} z^{\mathrm{nom}}_k - K^{\mathrm{nom}}_{\mathrm{feedback}} x_k, \tag{5}$$

where the feedforward gain $K^{\mathrm{nom}}_{\mathrm{forward}}$ (different from (3)) is synthesized based on an augmented state space representation with desired behaviour of a plant in closed loop.

In the following, matrix C is assumed to be equal to an identity matrix: the outputs are the state variables. However, the control law could be computed using the estimated state variables.

2.2. Actuator fault model. In most conventional control systems, controllers are designed for fault-free systems without taking into account the possibility of fault occurrence. Let us recall the faulty representation.

Due to abnormal operation or material aging, actuator faults may occur in the system. An actuator can be represented by additive and/or multiplicative faults as follows:

$$u^f_j = \alpha^j_k u_j + u_{j0}, \tag{6}$$

where u_j and u^f_j represent the j-th normal and faulty control actions. u_{j0} denotes a constant offset when the respective actuator is jammed and/or $0 \leq \alpha_k \leq 1$ denotes a gain degradation of the j-th component $\forall j \in \{1, \dots, p\}$ (constant or variable). In this paper, only the reduction in effectiveness is considered, i.e.,

$$u^f_j = \alpha^j_k u_j \quad \text{with } 0 < \alpha^j_k \leq 1. \tag{7}$$

Such modelling can be viewed as multiplicative faults which affect matrix B as

$$\begin{aligned} B \begin{pmatrix} u^f_1 & u^f_j & u^f_p \end{pmatrix} &= B \begin{pmatrix} \alpha^1_k & 0 & \cdots & 0 \\ 0 & \alpha_k & \ddots & 0 \\ \vdots & \ddots & \ddots & \vdots \\ 0 & 0 & \dots & \alpha^p_k \end{pmatrix} u \\ &= B^f u. \end{aligned} \tag{8}$$

Matrix B^f represents the actuator fault distribution matrix related to the nominal constant control input matrix B. Therefore, the discrete state space representation defined in (1) with actuator faults modelled by control effectiveness factors becomes

$$\begin{cases} x_{k+1} = Ax_k + B^f u_k, \\ w_k = Cx_k, \end{cases} \tag{9}$$

or, in a faulty case, if $j \in \{1 \dots p\}$, Eqn. (7) is rewritten as $u_j^f = u_j + (1 - \alpha_k^j)u_j$ with $0 < \alpha_k^j \le 1$. According to (8), Eqn. (1) is described based on an alternative representation following an additive representation:

$$\begin{cases} x_{k+1} = Ax_k + Bu_k + F_a f_k^a, \\ w_k = Cx_k, \end{cases} \tag{10}$$

where $F_a \in \mathbb{R}^{n\times p}$ represents the actuator fault distribution matrix ($F_a = B$) and $f \in \mathbb{R}^p$ is the faulty vector.

In the presence of actuator faults, the faulty actuators corrupt the closed-loop behaviour. Moreover, the controller aims at cancelling the error between the measurement and its reference input based on fault-free conditions. In this case, the controller gain is away from the 'optimal' one and may drive the system to its physical limitations or even to instability.

Under the assumption that an efficient fault diagnosis module is integrated in the reconfigurable control to provide sufficient information, an active fault tolerant control system based on the fault accommodation principles is developed in the next section in order to preserve the output dynamic properties and to limit the energy of control inputs.

3. Actuator fault tolerant control design

3.1. Actuator fault accommodation: Reconfigurable control gain synthesis or the fault compensation principle. In order to annihilate the actuator fault effect which appears at sample $k = k_f$ on the system, various methods have been proposed to recover as close as possible the performance of the pre-fault system according to the fault representation considered. Among these methods, two main classical approaches have been developed. One is based on a model matching principle where the control gain is completely re-synthesised on-line, and the other method is based on fault compensation added to the nominal control law.

Based on multiplicative fault representation, defined in (9), some extensions of the classical pseudo-inverse method (PIM) have been proposed to guarantee both the performance and the stability of the pre-fault system. Using constrained optimization, in (Gao and Antsaklis, 1991; Staroswiecki, 2005) a suitable feedback control $K_{\text{feedback}}^{\text{accom}}$ was synthesized. Moreover, (Zhang and Jiang, 2002; Guenab *et al.*, 2006) proposed to compute a reconfigurable feedforward gain $K_{\text{forward}}^{\text{accom}}$ controller in order to eliminate the steady-state tracking error in a faulty case. Therefore, the control signal applied to the system at sample $k = k_r > k_f$ is represented as

$$u_k^{\text{FTC}} = -K_{\text{feedback}}^{\text{accom}} r_k - K_{\text{forward}}^{\text{accom}} x_k. \tag{11}$$

However, under an additive faulty representation, defined in (10), (Noura *et al.*, 2000; Theilliol *et al.*, 2002; Rodrigues *et al.*, 2007) proposed to add a new control law u^{acc} to the nominal control law synthesised as presented in Sec. 2.1. The total control signal to be applied to the system at sample $k = k_r > k_f$ is represented as follows:

$$\begin{aligned} u_k^{\text{FTC}} &= (u_k^{\text{nom}}) + u_k^{\text{acc}} \\ &= (-K_{\text{feedback}}^{\text{accom}} z_k - K_{\text{forward}}^{\text{accom}} x_k) + u_k^{\text{acc}}. \end{aligned} \tag{12}$$

According to the new control law in (12), the discrete state space representation defined in (10) becomes

$$\begin{cases} x_{k+1} = Ax_k + Bu_k^{\text{nom}} + Bu_k^{\text{acc}} + F_a f_k^a, \\ w_k = Cx_k, \end{cases} \tag{13}$$

where the additional control law u^{acc} must be computed such that the faulty system is as close as possible to the nominal one. Therefore

$$Bu_k^{\text{acc}} + F_a f_k^a = 0. \tag{14}$$

Using the estimation of the fault magnitude $\hat{f}_k^a$ obtained from the fault diagnosis module, the solution to (14) can be obtained by the following relation if matrix B is of full row rank:

$$u_k^{\text{acc}} = -B^+ F_a \hat{f}_k^a, \tag{15}$$

where B^+ is the pseudo-inverse of matrix B.

In both cases, a fault tolerant controller was designed to compensate faults by computing a new control law in order to minimize the effects on the system performance and, consequently, to achieve the desired dynamic and stability performance of the faulty closed-loop system. Furthermore, the reconfigurable control mechanism requires some adjustments of the control inputs and, consequently, reduces the 'lifespan' of various components from a reliability point of view.

3.2. Actuator fault accommodation: Recovery/trajectory control system. From a control point of view, in the tracking assumption, the reconfigurable control mechanism requires more energy to reach the target and to guarantee steady-state performance. Thus, the energy variable E_k associated with the accommodated control law is defined as

$$E_k = \sum_{\tau=0}^{k} u_\tau \times (u_\tau)^T = \sum_{\tau=0}^{k} u_\tau^{\text{FTC}} \times (u_\tau^{\text{FTC}})^T. \tag{16}$$

In order to reduce E_k, the proposed technique is to modify, during the reconfiguration transient, the reference input vector r. To achieve this goal, when the fault is detected and reconfigured at sample $k = k_r$, the error ϵ_{k_r} between r_{k_r} and the output vector y_{k_r} is considered as an impulse which excites a non-periodic system. The dynamic behaviour of this system is chosen according to the criteria to reach the nominal reference as well as to reduce E_k. This recovery/trajectory control reference r^{acc} is defined as follows:

$$r_k^{\mathrm{acc}} = r_k - g_k(\epsilon_{k_r}), \quad \forall k \geq k_r, \tag{17}$$

where $g_k(\epsilon_{k_r})$ signifies an impulse response according to the error ϵ_{k_r} between r and the output vector y at sample $k = k_r$. When the fault is detected and the controller is reconfigured, the new reference r^{acc} is considered. For $k > k_r$, the fault accommodation control signal applied to the system based on the reconfigurable gain synthesis is computed as

$$u_k^{\mathrm{RFTC}} = -K_{\mathrm{forward}}^{\mathrm{accom}} r_k^{\mathrm{acc}} - K_{\mathrm{feddback}}^{\mathrm{accom}} x_k \tag{18}$$

or, if the fault compensation principle is considered, the fault accommodation control signal, defined in (12), becomes

$$\begin{aligned} u_k^{\mathrm{RFTC}} &= (u_k^{\mathrm{recon}}) + u_k^{\mathrm{acc}} \\ &= (-K_{\mathrm{forward}}^{\mathrm{accom}} z_k^{\mathrm{acc}} - K_{\mathrm{feddback}}^{\mathrm{accom}} x_k) + u_k^{\mathrm{acc}}, \end{aligned} \tag{19}$$

where z^{acc} corresponds to the integrator vector defined as

$$z_{k+1}^{\mathrm{acc}} = z_k^{\mathrm{acc}} + T_s(r_k^{\mathrm{acc}} - y_k). \tag{20}$$

A reconfigurable control mechanism has been proposed to limit the drawback of a fault accommodation strategy which requires more energy to reach the target and to guarantee steady-state performance. To demonstrate the effectiveness of the prospective work, the well-known three-tank system (Join *et al.*, 2005) was considered around one operating point. In the presence of an actuator fault, the nominal controller (NL), the fault accommodation principle without (FTC) and with (RFTC) a reconfigurable reference input were evaluated and compared.

4. Illustrative example

4.1. Process description. The process is composed of three cylindrical tanks with an identical cross section S. The tanks are coupled by two connecting cylindrical pipes with a cross section S_n and an outflow coefficient μ_{13}. The nominal outflow is located at Tank 2. It also has a circular cross section S_n and an outflow coefficient μ_2. Two pumps driven by DC motors supply Tanks 1 and 2. The flow rates through these pumps are defined by the calculation of flow per rotation. All the three tanks are equipped with sensors for measuring the levels of the liquid (l_1, l_2, l_3).

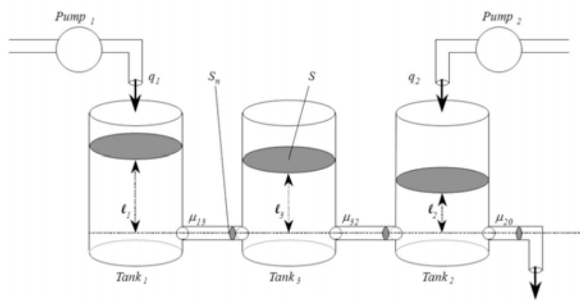

Fig. 1. Synoptic of the three-tank-system.

4.2. Plant modelling. The non-linear system can be simulated conveniently using Matlab/Simulink by means of non-linear mass balance equations.

As all the three liquid levels are measured by level sensors, the output vector is $y = \begin{pmatrix} l_1 & l_2 & l_3 \end{pmatrix}^T$. The control input vector is $u = \begin{pmatrix} q_1 & q_2 \end{pmatrix}^T$. The purpose is to control the system around an operating point. Thus, it was linearized around an operating point which is given by $y_0 = \begin{pmatrix} 0.4 & 0.2 & 0.3 \end{pmatrix}^T$ [m] and $u_0 = \begin{pmatrix} 0.35 & 0.33 \end{pmatrix}^T 10^{-4}$ [m^3/s]. Using the Torricelli rule, for $l_1 > l_3 > l_2$, the linearized system can then be described by a discrete state space representation with a sampling period $T_s = 1$ s with

$$A = \begin{pmatrix} 0.988 & 0.0001 & 0.0112 \\ 0.0001 & 0.9781 & 0.0111 \\ 0.0112 & 0.0111 & 0.9776 \end{pmatrix},$$

$$B = \begin{pmatrix} 64.568 & 0.0014 \\ 0.0014 & 64.22 \\ 0.3650 & 0.3637 \end{pmatrix}$$

and C an identity matrix.

Levels l_1 and l_2 have to follow the reference input vector $r \in \mathbb{R}^2$. These outputs are controlled using the multivariable control law described previously. The control matrix pair of the augmented plant is controllable, and the nominal tracking control law, designed by an LQ+I technique, leads to feedback/forward gain matrices:

$$\begin{aligned} K_{\mathrm{feedback}}^{\mathrm{nom}} &= \begin{pmatrix} 21.6 & 3 & -5 \\ 2.9 & 19 & -4 \end{pmatrix} 10^{-4}, \\ K_{\mathrm{feedback}}^{\mathrm{nom}} &= \begin{pmatrix} -0.95 & -0.32 \\ -0.3 & -0.91 \end{pmatrix} 10^{-4}. \end{aligned} \tag{21}$$

4.3. Results and comments. The validation of the tracking control with the linearized model is shown in Fig. 2, where step responses with respect to set-point changes are considered for a range of 3000 s. Reference inputs r are step changes of 12.5% for l_1 (and l_2 not presented here) of their corresponding operating values. The dynamic responses demonstrate that a tracker is synthesized correctly (NL means the fault-free case in

Fig. 2). Then, in a similar way, an actuator fault was applied. A gain degradation of Pump 1 (a clogged or rusty pump, etc.) is considered and appears abruptly at sample $k = k_f = 1000$ s on the system during the steady-state operation. To do so without breaking the system, the control input applied to the system is equal to the control input computed by the controller multiplied by a constant system ($\alpha_1 = 0.2$ and $u_{10} = 0$). Since an actuator fault acts on the system as a perturbation, and due to the presence of the integral error in the controller, the system outputs reach again their nominal values (NL means the faulty case in Fig. 2).

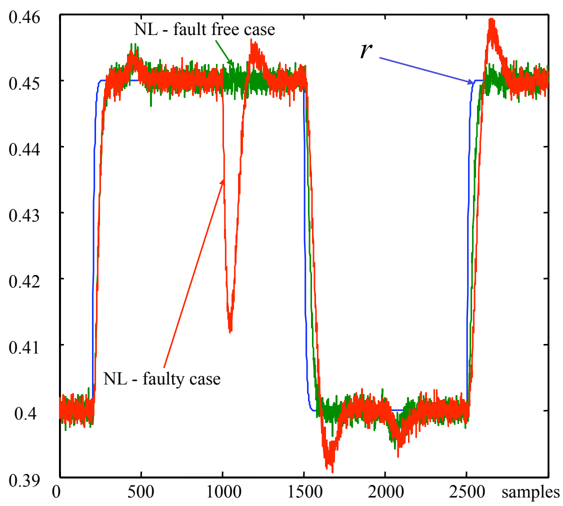

Fig. 2. Level l_1 in a fault-free case and with a fault on Pump 1.

Under the assumption that a fault detection, isolation and estimation module will provide to the FTC system the information about the occurrence of the actuator fault at sample $k = k_r > k_f = 1010$ s, the re-adjusted control reference r^{acc} is defined following the technique proposed in Section 3.2. A second-order impulse response is chosen to modify the initial reference r on level l_1. This level is corrupted by the faulty pump associated with Tank 1. The second-order impulse response is considered with a natural frequency ω and damping ratio ξ calculated in a discrete form with a sampling period $T_s = 1$ s based on the following classical transfer function:

$$G(s) = \frac{\omega^2}{s^2 + 2\xi\omega s + \omega^2}, \tag{22}$$

where s is the Laplace variable.

As shown in Fig. 3 for specific $\xi = 10.5$, the re-adjusted control reference input r^{acc} is 'revised' just after the occurrence of the fault and finally returned to the initial reference input r after a short period.

The compensation control law is computed in order to reduce the fault effect on the system. Indeed, since

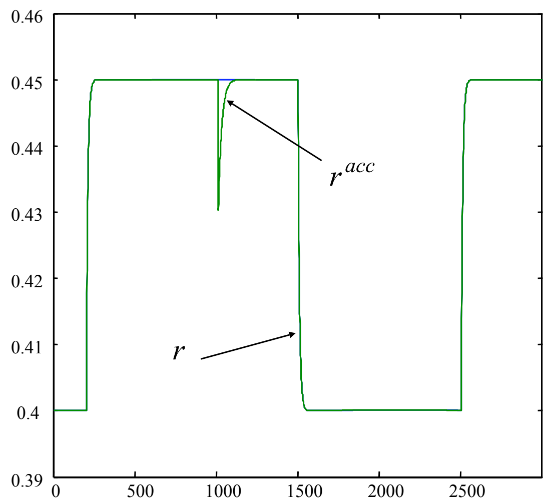

Fig. 3. Reference input for level l_1 in a fault-free case and the recovery principle.

an actuator fault acts on the system as a perturbation ($k = k_f = 1000$ s), the system outputs reach again their nominal values, as illustrated in Fig. 4. With the fault accommodation methods (FTC or RFTC with $\xi = 10.5$), the outputs decrease less than in the case of a classical control law (NL), and then they reach the nominal values quicker because the fault is estimated and the new control law is able to compensate for the fault effect at instant $k = k_r > k_f = 1010$ s when the fault is isolated. It can be easily seen that, after the fault occurrence, the time response and the dynamic behaviour of the compensated outputs in both FTC and RTFC cases are not similar and completely different from the fault-free case.

These results can be confirmed by the examination of the control input q_1 (Fig. 5). In the classical law (NL), the control input increases slowly trying to compensate for the fault effect on the system. In the accommodation approach, the RTFC control input increases quickly and enables rapid fault compensation on the controlled system outputs in a way similar to the case with the FTC control input.

The computation of the tracking error norm ($\|e_l\|_2 = \|r - y\|_2$) emphasizes the performance of the approach as presented in Table 1. With two fault accommodation methods (RFTC and FTC), tracking error norms for outputs l_1 and l_2 are very close and slightly lager than the nominal one, but still significantly smaller than in the case with the classical control law (NL) under the fault condition.

The effectiveness of the reconfiguration strategy based on a novel recovery/trajectory control is highlighted in Table 2, where the energy (16) associated with the flow rate δq_1 around the reference r on level l_1 is calculated between $k = 2000$ s and $k = 2400$ s. In view of the

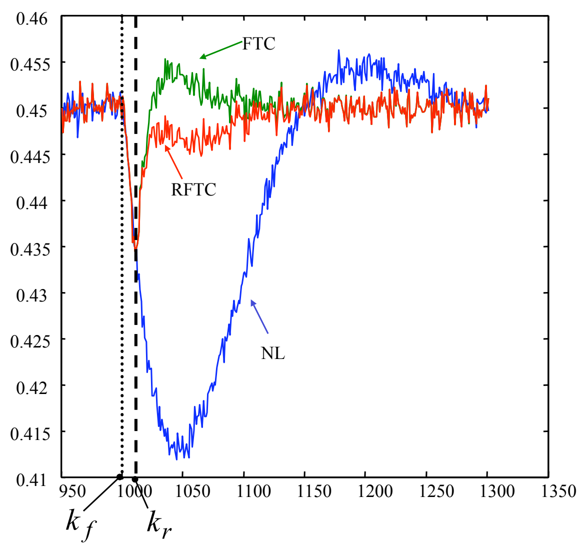

Fig. 4. Zoom on level l_1 with a fault on Pump 1 with the nominal control law (NL), fault accommodation without FTC and with RFTC recovery reference input.

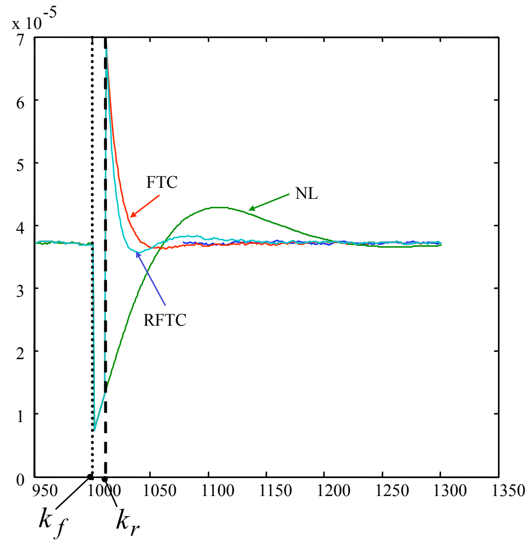

Fig. 5. Zoom on flow rate q_1 with a fault on Pump 1 and with the nominal control law (NL), fault accommodation without FTC and with RFTC recovery reference input.

above figures and the energy computation illustrated in Table 2 for the experiments, it appears clearly that RFTC preserves the output dynamic properties and limits the energy of control inputs when compared with the classical FTC.

As discussed previously, the performance of the new recovery/trajectory control is linked to the damping ratio ξ. As illustrated in Fig. 6, the tracking error norm $\|e_{l_1}\|_2$ and the energy associated with the first actuator Φ_{q_1} are established with a different damping ratio ξ.

Table 1. Norms of the tracking error computed between $k = 2000$ s and $k = 2400$ s.

with	Fault-free case NL	Faulty case NL	Faulty case FTC	Faulty case RFTC
$\|e_{l_1}\|_2$	0.0211	0.2989	0.0514	0.0540
$\|e_{l_2}\|_2$	0.0197	0.1087	0.0223	0.0219

Table 2. Variation in energy computed between $k = 2000$ s and $k = 2400$ s.

with	Fault-free case NL	Faulty case NL	Faulty case FTC	Faulty case RFTC
$\Phi \times 10^{-4}$	0	1.3048	1.1432	1.0624

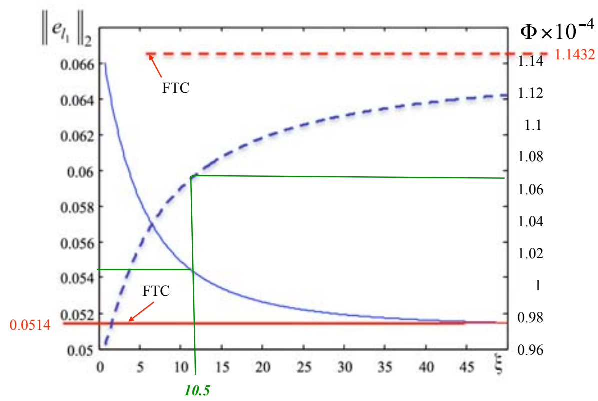

Fig. 6. Performance indices $\|e_{l_1}\|_2$ (solid line) and Φ_{q_1} (dashed line) vs. the damping ratio ξ for RFTC.

The computation of the two performance indices is realized for a time period around the fault occurrence started at $k = 2000$ s and finished at $k = 2400$ s. The data provided in the two previous tables are included in Fig. 6 ($\xi = 10.5$). It is interesting to note that for a large value of the damping ratio ξ the performance indices are close to a classical fault accommodation (FTC): the second order impulse response is close to zero when the damping ratio ξ increases. Consequently, an optimal damping ratio has to be found in order to preserve the output dynamic properties and to limit the energy of control inputs.

5. Conclusion

This paper presented an active fault tolerant control system design strategy which takes into account a modified trajectory/reference input for system reconfiguration. Classical fault accommodation methods were considered to design the fault tolerant controller. The design of an appropriate recovery/trajectory control reference input provides the fault accommodation controller with the capabilities to simultaneously reach their nominal dynamic and steady-state performances and to preserve the reliability of the components (Finkelstein, 1999). The application of this method to the well-known three-tank system example gives encouraging results. Future work will concern the theoretical definition of the optimal impulse response for flatness control (Fliess *et al.*, 1995) in the FTC framework (Mai *et al.*, 2006).

References

Blanke M., Kinnaert M., Lunze J. and Staroswiecki M. (2003). *Diagnosis and Fault-Tolerant Control*, Springer-Verlag, Berlin.

D'Azzo J. and Houpis C.H. (1995). *Linear Control System Analysis and Design: Conventional and Modern, 4-th Revised Edition*, McGraw-Hill, New York, NY.

Finkelstein, M. S. (1999). A note on some aging properties of the accelerated life model, *Reliability Engineering and System Safety* **71**(1): 109–112.

Fliess M., Lévine J., Martin P., Rouchon P. (1995). Flatness and defect of non-linear systems: Introductory theory and examples, *International Journal of Control* **61**(6): 1327–1361.

Gao Z., and P.J. Antsaklis (1991). Stability of the pseudo-inverse method for reconfigurable control systems, *International Journal of Control* **53**(3): 717–729.

Gao Z., and P.J. Antsaklis (1992). Reconfigurable control systems design via perfect model following, *International Journal of Control* **56**(4): 783–798.

Guenab F., Theilliol D., Weber P., Ponsart J.C. and Sauter D. (2005). Fault tolerant control method based on costs and reliability analysis, *Proceedings of the 16th World IFAC Congress*, Prague, Czech Republic, CD-ROM.

Harris T.J., Seppala C., Desborough L.D. (1999). A review of performance monitoring and assessment techniques for univariate and multivariate control systems, *Journal of Process Control* **9**(1): 1–17.

Jiang J. (1994). Design of reconfigurable control system using eigenstructure assignments, *International Journal of Control* **59**(2): 395–410.

Jiang J. and Zhang Y. (2006). Accepting performance degradation in fault-tolerant control system design, *IEEE Transactions on Control Systems Technology* **14**(2): 284–292.

Join C., Ponsart J.-C., Sauter D. and Theilliol D. (2005). Nonlinear filter design for fault diagnosis: Application to the three-tank system, *IEE Proceedings Control Theory and Applications* **152**(1): 55–64.

Patton, R.J. (1997). Fault-tolerant control: The 1997 situation, *Proceedings of the IFAC Symposium SAFEPROCESS*, Kingston-upon-Hull, UK, **2**: 1033–1055.

Mai P., Join C. and Reger J. (2006). An example of flatness based fault tolerant control using algebraic derivative estimation, *Proceedings of the Advanced Control Diagnosis Workshop*, Nancy, France, CD-ROM.

Noura H., Sauter D., Hamelin F. and Theilliol D. (2000). Fault-tolerant control in dynamic systems: Application to a winding machine, *IEEE Control Systems Magazine* **20**(1): 33-49.

Rodrigues M., Theilliol D., Aberkane S. and Sauter D. (2007). Fault tolerant control design for polytopic LPV system, *International Journal of Applied Mathematics and Computer Science* **17**(1): 27-38.

Staroswiecki M. (2005). Fault tolerant control: The pseudo-inverse method revisited, *Proceedings of the 16th IFAC World Congress*, Prague, Czech Republic, CD-ROM.

Staroswiecki M, Yang H. and Jiang B. (2007). Progressive accommodation of parametric faults in linear quadratic control, *Automatica* **43**(2): 2070–2076.

Theilliol D., Noura H. and Ponsart J.C. (2002). Fault diagnosis and accommodation of a three-tank system based on analytical redundancy, *ISA Transactions* **41**(3): 365–382.

Wu N.E., Zhang Y.M. and Zhou K (2000). Detection, estimation and accommodation of loss of control effectiveness, *International Journal of Adaptive Control and Signal Processing* **14**(7): 775–795.

Zhang Y.M. and Jiang J. (2002). Active fault-tolerant control system against partial actuator failures, *IEE Proceedings – Control Theory and Applications* **149**(1): 95–104.

Zhang Y. M. and Jiang J. (2003a). Fault tolerant control cystem design with explicit consideration of performance degradation, *IEEE Transactions on Aerospace and Electronic Systems* **39**(3): 838–848.

Zhang, Y.M. and Jiang J. (2003b). Bibliographical review on reconfigurable fault tolerant control systems, *Proceedings of the IFAC Symposium SAFEPROCESS*, Washington, D.C., USA, pp. 265–276.

Received: 15 January 2008
Revised: 23 May 2008