15th Triennial World Congress, Barcelona, Spain

FAULT-TOLERANCE ANALYSIS FOR MAJOR ACTUATOR FAILURES: APPLICATION TO A WINDING MACHINE

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Abstract: This paper deals with the analysis of the fault-tolerant control (FTC) design in the presence of major actuator failures. In the presence of a complete loss of an actuator which is a major failure, the nominal control objectives cannot be reached anymore. Thus, degraded performances are re-defined in order to avoid huge loss in the system security and productivity. The discussion is conducted through the application to a winding machine. This analysis and the fault-tolerant method presented here could be applied to a wider range of industrial systems. *Copyright© 2002 IFAC.*

Keywords: Fault-tolerant control, Major actuator failure, Winding machine.

1. INTRODUCTION

A conventional feedback control design may result in unsatisfactory performances, in the event of malfunctions in actuators, sensors or other components of the system. In high automated industrial systems where maintenance or repairing cannot be always achieved immediately, fault-tolerance has become of paramount importance. Hence, to preserve the safety of operators and the reliability of processes, the presence of faults must be taken into account during the system control design.
Much effort has been done in the field of fault-tolerant control (FTC) systems within the nuclear and avionics industries, chemical or petrochemical plants, etc. The various studies dealing with this problem are based on hardware or analytical redundancy.
In industrial processes, hardware redundancy is rare and even non-existant, because of an expensive financial cost. Redundant sensors, usually much easier and less expensive than actuators are generally installed. Thus, in the event of a major actuator failure, it is impossible to maintain the damaged system at some acceptable level of performances. It becomes of prime importance to lead it to its optimal operating order, with respect to desirable performances and their degrees of priority. Thus, the main feature is to minimize the loss of productivity (to produce with a lower quality) or/and to operate safely without danger to human operators or to equipment. The system can continue to operate with decreased performances as long as it remains in acceptable limits.
The use of analytical redundancy allows us to reduce the cost and the maintenance of the instruments. Most of these studies are based on the linear-quadratic control methodology given by (Huang and Stengel, 1990), (Joshi, 1987), adaptive control systems presented by (Morse and Ossman, 1990), (Noura *et al.*, 1994), eigenstructure assignment (Gavito and Collins, 1987), (Jiang and Zhao, 1998) and knowledge-based systems (Ballé *et al.*, 1997), (Chang *et al.*, 1990), (Taylor and Lubkeman, 1990).
The fault tolerant operation can be achieved either passively through the use of a control law insensitive to some faults, or actively through a failure detection and

isolation mechanism and the redesign of a new control law. In this paper, the possibility and the necessity of designing a fault-tolerant control system in the presence of a major actuator failure is analyzed. Indeed, previous work have dealt with minor actuator faults, like biases or a decrease in the actuator effectiveness (Noura *et al.*, 2000*b*). Here, major failures such as, an actuator is blocked or completely lost are considered. For these kinds of failures, the use of multiple-model techniques is appropriate, since the number of the failures is not too big. Some recent studies have used these techniques (Rago *et al.*, 1998), (Yang *et al.*, 2000), (Zhang and Jiang, 1999).

It is important to notice that the strategy to implement and the level of achieved performances in the event of failures differ according to the type of process, the allocated degrees of freedom and the severity of the failures. The fault-tolerant control method described here is analyzed through an application to a winding machine.

The control system performances versus the severity of the failure are illustrated by figure 1. The analysis presented in this paper shows the limits of fault-tolerant strategies. The failure addressed here, leads to a big decrease of performances. Thus, it is necessary to restructure the control objectives with degraded performances.

This paper is organized as follows: in section 2, the identification and the nominal control of the winding machine used to illustrate the aim of the paper are given. Section 3 is devoted to the discussion about the actuator failure effects on the system and how to accommodate for these failures. The results are then given and commented. Finally concluding remarks are given.

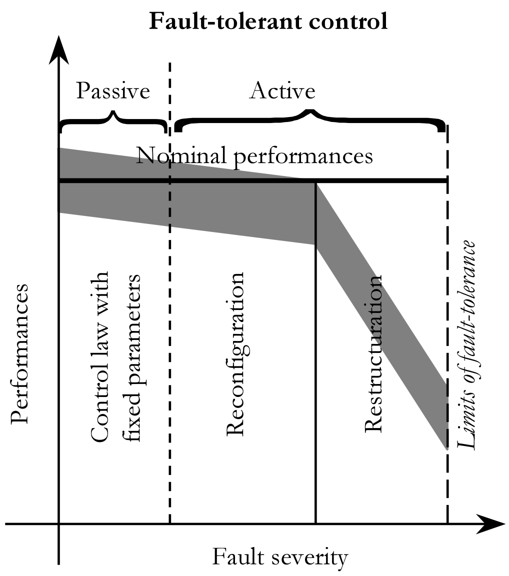


Figure 1. fault-tolerant control strategies.

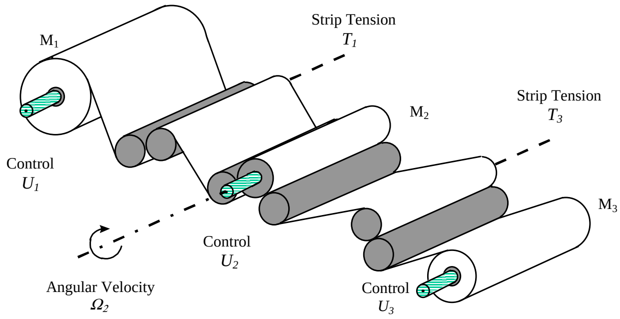


Figure 2. Winding machine.

2. WINDING MACHINE

2.1 *Process description*

The method proposed in this article is applied to a winding machine representing a subsystem of many industrial systems as sheet and film processes, steel industries, and so on. The system is composed of three reels driven by DC motors (M_1, M_2, and M_3), gears reduction coupled with the reels, and a plastic strip (Fig. 2). Motor M_1 corresponds to the unwinding reel, M_3 is the rewinding reel, and M_2 is the traction reel. The angular velocity of motor M_2 (Ω_2) and the strip tensions between the reels (T_1, T_3) are measured using a tachometer and tension-meters, respectively. Each motor is driven by a local controller. Torque control is achieved for motors M_1 and M_3, while speed control is realized for motor M_2. For a multivariable control application, a dSPACE board associated with $Matlab^{TM}/Simulink$ software is used.

The control inputs of the three motors are U_1, U_2, and U_3. and correspond to the current set points I_1 and I_3 of the local controller. U_2 is the input voltage of motor M_2. In winding processes, the main goal usually consists of controlling tensions T_1 and T_3 and the linear velocity of the strip. Here the linear velocity is not available for measurement, but since the traction reel radius is constant, the linear velocity can be controlled by the angular velocity Ω_2. Figure 3 illustrates a simplified multivariable block-diagram of the winding machine.

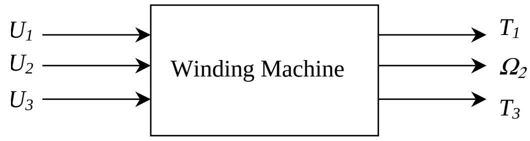


Figure 3. Inputs/Outputs of the Winding Machine.

2.2 *Identification of the nominal system*

The system is considered to be linear around a given operating point, and the corresponding analytical model is obtained using an ARX structure. This model describes the dynamical behavior of the system in terms of input/output variations Δu and Δy around the operating point (U_0, Y_0). For simplicity of notation, (u, y) are used instead of (Δu, Δy). The data set used for the parameter identification step is composed of pseudo-random binary sequence signals applied to the system and their corresponding outputs. The sampling interval is $T_s = 0.1\ s$. The signals collected via the dSPACE board are given in the interval [-1, 1] corresponding to [$-10\ V$, $10\ V$]. The linearized model of the winding machine around the operating point (U_0, Y_0) is given by the following discrete state-space representation:

$$\begin{aligned} U_0 &= \begin{pmatrix}-0.15 & 0.6 & 0.15\end{pmatrix}^T \\ Y_0 &= \begin{pmatrix}0.6 & 0.55 & 0.4\end{pmatrix}^T \end{aligned} \tag{1}$$

$$\begin{aligned} x(k+1) &= Ax(k) + Bu(k) \\ y(k) &= Cx(k) \end{aligned} \tag{2}$$

with:

$$x = \begin{pmatrix} T_1 \\ \Omega_2 \\ T_3 \end{pmatrix} \qquad u = \begin{pmatrix} U_1 \\ U_2 \\ U_3 \end{pmatrix}$$

$$A = \begin{pmatrix} 0.4126 & 0 & -0.0196 \\ 0.0333 & 0.5207 & -0.0413 \\ -0.0101 & 0 & 0.2571 \end{pmatrix} \tag{3}$$

$$B = \begin{pmatrix} -1.7734 & 0.0696 & 0.0734 \\ 0.0928 & 0.4658 & 0.1051 \\ -0.0424 & -0.093 & 2.0752 \end{pmatrix}$$

C is the identity matrix I_3. The system described by these matrices is completely observable and controllable.

2.3 *Nominal control*

The nominal control law is set up according to a tracking control design. The tracking control problem requires that the number of outputs that have to follow a reference input vector, y_r, must be less than or equal to the number of control inputs. This is the case for the winding machine: three control inputs are available, thus the three outputs T_1, Ω_2, and T_3 can be tracked. The feedback controller to be designed has to cause the output vector y to track the reference input vector in the sense that in steady state:

$$y_r(k) - y(k) = 0 \tag{4}$$

For this purpose, a comparator and integrator vector z is added to satisfy the following relation:

$$\begin{aligned} z(k+1) &= z(k) + T_s(y_r(k) - y(k)) \\ &= z(k) + T_s(y_r(k) - Cx(k)) \end{aligned} \tag{5}$$

where T_s is the sampling interval.

The open loop system is then governed by the augmented state space equations:

$$\begin{aligned} \begin{pmatrix} x(k+1) \\ z(k+1) \end{pmatrix} &= \begin{pmatrix} A & 0 \\ -T_sC & I_3 \end{pmatrix} \begin{pmatrix} x(k) \\ z(k) \end{pmatrix} + \begin{pmatrix} B \\ 0 \end{pmatrix} u(k) \\ &\quad + \begin{pmatrix} 0 \\ T_sI_3 \end{pmatrix} y_r(k) \\ y(k) &= \begin{pmatrix} C & 0 \end{pmatrix} \begin{pmatrix} x(k) \\ z(k) \end{pmatrix} \end{aligned} \tag{6}$$

The nominal feedback control law of this system can be computed by:

$$u(k) = -KX(k) = -\begin{pmatrix} K_1 & K_2 \end{pmatrix} \begin{pmatrix} x(k) \\ z(k) \end{pmatrix} \tag{7}$$

The feedback control gain matrix $K = \begin{pmatrix} K_1 & K_2 \end{pmatrix}$ is computed using the LQI technique such that the following cost function is minimized:

$$J = \frac{1}{2} \sum_{k=0}^{\infty} (X^T(k)QX(k) + u^T(k)Ru(k)) \tag{8}$$

Weighting matrices Q and R are respectively non-negative symmetric and positive definite symmetric matrices, $Q = 0.05I_6$ and $R = 0.1I_3$.

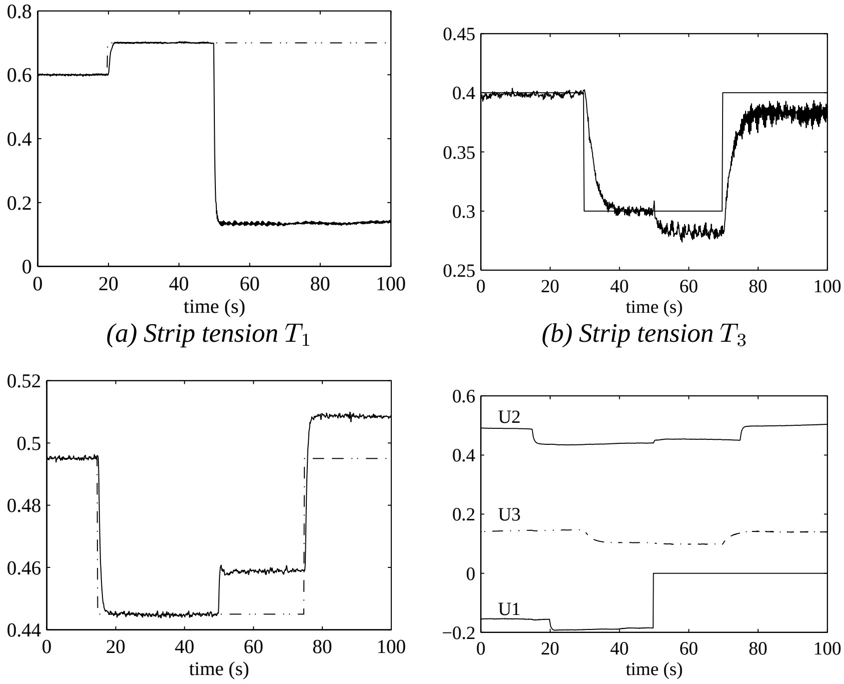
3. FAULT-TOLERANT CONTROL

3.1 *Failure effect*

The actuator faults considered in previous work correspond to biases, drifts or a loss in the effectiveness of the actuator. For this kind of fault, it is still possible to track all the outputs of the system. This was achieved using another control law, added to the nominal one in order to compensate for the faults. This additive control law is based on the estimation of the fault magnitude. The limits of this method are reached in case of an actuator has got stuck or completely lost (Noura *et al.*, 2000*a*). In this paper, the possibility to continue operating with degraded performances is analyzed in the case of a critical failure such as the complete loss of an actuator.

In the winding machine, the strip has to be rolled up in a correct way, that is strip tensions T_1 and T_3 have to be maintained to a certain level. In this application, this is achieved by maintaining a negative (resistant) torque on motor M_1 and a positive torque on motor M_3. Due to the strong coupling in this system, the angular velocity Ω_2 of the traction reel M_2 influences the strip tensions.

The failure considered here is that motor M_1 is out of order at time instant $t_f = 49.5\ s$; i.e. motor M_1 runs as if its control input $U_1 = 0$. This failure leads to a big decrease of strip tension T_1 which cannot be controlled anymore. With the nominal control law, the coupling in the system leads the angular velocity Ω_2 to increase trying to compensate for strip tension T_1; Ω_2 increases of about 20%. Not only, it is impossible to compensate for T_1, but also this has the opposite effect on strip tension T_3, which decreases of almost 20% from its reference value. That makes the strip rolled up badly. Figure 4 illustrates the failure effect on the



(a) Strip tension T_1 *(b) Strip tension T_3*

(c) Angular velocity Ω_2 *(d) Control inputs U_1, U_2, and U_3*

Figure 4. Faulty Inputs/Outputs of the Winding Machine.

system inputs and outputs.

It can be seen that for this failure, the system operates badly in terms of the product quality but not in terms of the system security. It is also easy to understand that if this failure occurs on one of the other motors, the system cannot be able to run anymore. That is to say that it is not always possible to accommodate for all failures occurring on the system. It always depends on the available hardware or analytical redundancy.

With the knowledge of the system operating conditions in mind, the objective of this paper is to propose a method able to cope with the failure occurring on motor M_1.

3.2 *Failure accommodation*

This failure is a severe failure because it leads to a huge loss in the closed-loop system performances. As one of the system control inputs is out of order, it becomes impossible to track the three system outputs. Hence, according to the system operation requirements, these outputs have to be divided into priority outputs to be maintained to their reference inputs with the detriment of other secondary outputs.

In equivalent industrial application, the objective is to roll up the strip in a correct way. This can be achieved, if tension T_3 and the angular velocity Ω_2 are mainly maintained to their reference inputs. These outputs are considered as priority outputs to be maintained with the detriment of strip tension T_1 considered as a secondary output.

Thus, the method proposed here is based on the knowledge of the system model where strip tension T_1 is considered as a perturbation. The system control inputs are U_2 and U_3, and the outputs to be tracked are Ω_2 and T_3.

There is no hardware redundancy available on this system. In addition it is impossible to build such a hardware redundancy here. In (Dardinier-Maron *et al.*, 1999), a fault-tolerant control method for critical actuator failure has been addressed. This method is based on the computation of a new operating zone in degraded mode. The whole outputs are still able to be tracked but at modified reference inputs. It has been applied to a three-tank system, where the objective is to track the levels in the tanks. The modified reference inputs are lower than the nominal ones. The computation of the new reference inputs requires the nonlinear model of the system. Unfortunately, this is seldom the case in the real industrial systems.

In the case where the nonlinear system is not available, one way to cope with these critical failures is to get a model of the faulty system. For these kinds of critical failures, the number of faulty models is limited. It is easy, from the knowledge one has of the system, to define which failures could be compensated for and which ones require to stop the system immediately.

In the winding machine, there are three actuators driven by the control inputs U_1, U_2 and U_3. Motor M_2 has to impose the velocity of the strip. If this motor is out of order, it is obvious that the strip cannot be rolled up and the system must be stopped immediately. It is also the case if motor M_3 is out of order, because strip tension T_3 cannot be maintained to its reference value anymore. Thus, the only critical failure to deal with in this system is the loss of motor M_1.

3.3 *Faulty system Model and Results*

Since two control inputs are only available after the failure has occurred, it is impossible to continue the tracking control of the three system outputs. Therefore, a tracking control law using the same principal as described previously , based on the faulty system model, has been achieved to track two system outputs Ω_2 and T_3 which are considered as priority outputs. It has been noted previously that strip tension T_1 is considered as a perturbation. With this restructuration, the identification of the faulty system has been achieved off-line. The system is running with $U_1 = 0$, a set of excitation signals, U_2 and U_3, has been applied to the winding machine. The obtained model is the following:

$$
\begin{aligned}
x_f(k+1) &= A_f x_f(k) + B_f u_f(k) + F_f T_1(k) \\
y_f(k) &= C_f x_f(k)
\end{aligned}
\tag{9}
$$

$$
x_f = y_f = \begin{pmatrix} \Omega_2 \\ T_3 \end{pmatrix} \qquad u_f = \begin{pmatrix} U_2 \\ U_3 \end{pmatrix}
$$

$$
A_f = \begin{pmatrix} 0.4995 & -0.0262 \\ 0.0723 & 0.4314 \end{pmatrix} \quad F_f = \begin{pmatrix} 0.2149 \\ -0.0490 \end{pmatrix}
$$

$$
B_f = \begin{pmatrix} 0.53 & 0.0236 \\ -0.0782 & 1.2865 \end{pmatrix}
$$

Once the failure is detected and isolated, the fault-tolerant control module switches from the nominal control law to the new one. This control law guarantees the fact that the strip continues to be rolled up in a correct way and avoids stopping the machine due to a bad quality of the final product.

Figure (5) shows the results obtained when switching from the original model to the new one after the failure has been detected and isolated. The fault diagnosis module is not achieved here, but a delay of 10 sampling periods is considered before switching to the new control law. This delay corresponds to the detection and isolation task. It can be seen that strip tension T_1 is still far from its reference value because it is not tracked, while strip tension T_3 and the angular velocity Ω_2 follow their respective reference inputs after the switching process and the strip is rolled up in a correct way.

4. CONCLUSION

In this paper, a fault-tolerant control design in case of major actuator failure has been analyzed. This analysis has been conducted through the application to a real pilot plant. This plant represents subsystems of real industrial systems. It has been shown that the design of a fault-tolerant control system depends on the plant itself and the degrees of freedom in terms of hardware redundancy. In the case where it is possible to design such a fault-tolerant control method for this kind of major failure, the model corresponding to this failure is achieved off-line. The supervision module at the upper level decides to switch to the accurate control law according to the isolated failure. It should be noted, that whatever the importance of the fault-tolerant control system designed, it is never obvious to compensate for all kinds of failures. In the system used here, there is no problem of security, but the system is still able to continue its operation which avoids the loss in the productivity and the quality of the product.

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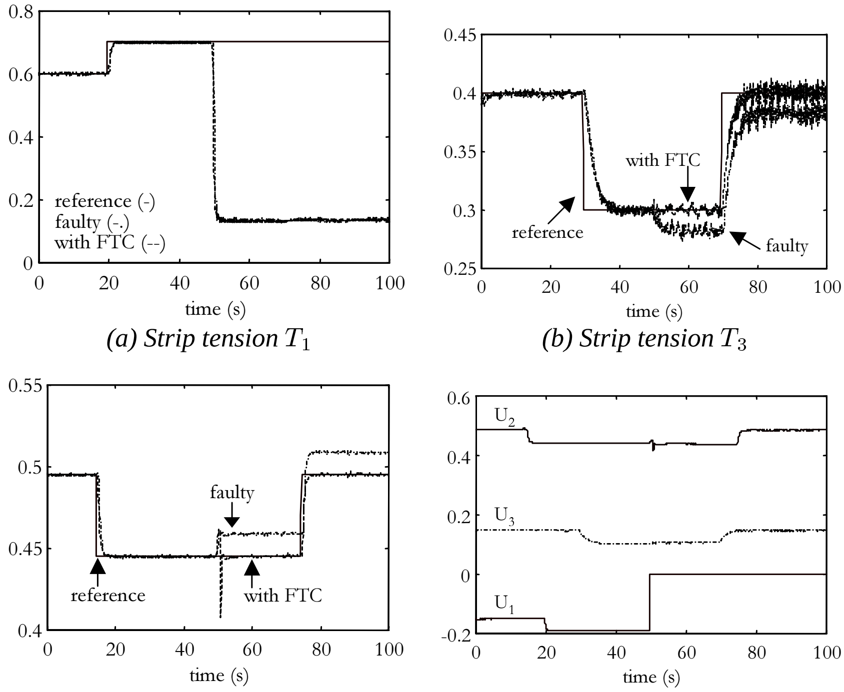

(a) *Strip tension* T_1 (b) *Strip tension* T_3

(c) *Angular velocity* Ω_2 (d) *Control inputs with FTC*

Figure 5. Faulty Inputs/Outputs of the Winding Machine with fault-tolerant control.

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