DESIGN OF ON – LINE FAULT TOLERANT CONTROLLER

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Abstract

A new control strategy is implemented on a heat exchanger model using fault tolerant control (FTC) based on fault detection and isolation (FDI) techniques. The approach is used in implementing this strategy, namely on-line fault tolerant control. This approach is based on using state feedback technique in the design of the gain matrix. A heat exchanger, which represents a subsystem of many industrial systems is used to verify the ability of the proposed fault tolerant methods to compensate for all faults that may take place. The proposed FTC indicates that once FDI is applied, then effect of the fault on the system is reduced, thus preventing the need for any sudden stoppage of the system. The FDI unit is usually contained within the Fault tolerant control, hence enabling the continuous operation of the system close to nominal operating conditions.

تصميم مسيطر ضمني لتحمل الخطأ

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الخلاصة

تم تطبيق استراتجية جديدة على نموذج لمبادل حراري بالأعتماد على (سيطرة تحمل الخطأ) والتي يعتمد على اسلوب اكتشاف الخطأ وعزله. ان الاسلوب المقترح يعتمد على التغذية العكسية للحالة ضمن تصميم مصفوفة الكسب. تم اعتماد المبادل الحراري لكونه يمثل منظومة ضمنية لعديد من المنظومات الصناعية وذلك لغرض تأكيد قدرة طرق تحمل الخطأ المقترحة لتجاوز كل الاخطاء التي يمكن ان تحدث. ان استعمال طريقة كشف الخطأ وعزله يؤدي الى التقليل من تأثير الخطأ مما يؤدي الى انتفاء الحاجة للتوقف الفجائي للمنظومة ولكن اكتشاف الخطأوعزله هو جزء من سيطرة تحمل الخطأ لذا يصبح من الممكن استمرار عمل المنظومة بالرغم من وجود الخطأ وذلك بمستوى قريب جدا من حالة العمل المقبولة.

Keywords: Fault detection and isolation, Fault tolerant control

1. INRODUCTION

A conventional feedback control design for a process plant may result in unsatisfactory performance (even instability), in the event of malfunctions in actuators, sensors or other components of the plant. In order to overcome the limitation of conventional feedback, new controllers are being developed which are capable of tolerating component malfunctions whilst still maintaining desirable and robust performance and stability properties. [1]

Over the past two decades, the growing demand for reliability in industrial processes has drawn increasing attention to the problem of fault detection and isolation (FDI), but only a few studies have been dedicated to the related fault-tolerant control (FTC) problem. A fault (abrupt or incipient) is any kind of malfunction or degradation in the plant that can lead to a reduction in performance or loss of important functions, impairing safety. Therefore, FTC can be motivated by different goals depending on the application under consideration; for instance, safety in power plant control or reliability, or quality improvements in industrial processes. [2, 3, 4]

Fault -tolerant control systems are characterized by their capabilities after fault occurrence to recover performance close to the nominal design performance? In addition, their ability to react successfully (stable) during a transient period, between the fault occurrence and the performance recovery, is an important feature. Accommodation capability of a control system depends on many factors such as the severity of the failure, the robustness of the nominal system, and the actuator redundancy. [2.5,6]

The goal of FTC is to determine a new control law that takes the degraded system parameters into account and, drives the system to a new operating point, such that the main performance parameters (stability, accuracy, etc.) are preserved (i.e., are as close as possible to the initial parameters). It is, therefore, important to define precisely the degraded modes that are acceptable with regard to the required performance parameters, since after the occurrence of faults, conventional feedback control design may result in unsatisfactory performance such as tracking error, instability, and so on. To overcome the limitations of conventional feedback control, new controllers have been developed with accommodation capabilities or tolerance to faults. [6, 7]

Various approaches for fault tolerant control have been suggested in the survey by Ron J. Patton, [7], this paper outlines the state of the art in a field which remains largely a theoretical topic with most application studies based upon aerospace systems. The directions in which the subject is going are summarized and some pointers are given as to the likely future issues and where new research effort is required. The paper provides a basic literature review covering most areas of fault-tolerant control,

H. Noura, and et al., [8], proposed a method to compensate for such faults were illustrated by applying it to a winding machine, which represents a subsystem of many industrial systems. The results show that once the fault is detected and isolated, it is easy to reduce its effect on the system, and process control is resumed with degraded performances close to nominal ones. Thus, stopping the system immediately can be avoided.

2. Design of On-line Fault-Tolerance Controller.

Fig. (1) Shows the general schematic arrangement appropriate to many fault tolerant control systems with four main components: the plant itself (including sensors and actuators) the fault detection and isolation (FDI) unit, the feedback (or feed-forward) controller, and the supervision system. The plant is considered to have potential faults in sensors, actuators (or other components). The FDI unit is responsible for providing the supervision system with information about the onset, location and severity of any faults. Based on the system inputs and outputs together with fault decision information from the FDI unit, the supervision system will reconfigure the sensor set and/or actuators to isolate the faults, and tune or adapt the controller to accommodate the fault effects [7]

Fault - tolerant control is a strategy for reliable and highly efficient control law design. To achieve these requirements, it is also a systematic problem. Fault - tolerant control system should be designed to retain some portion of its control integrity in the event of a specified set of possible component faults or large changes on the system operating conditions that resemble these faults. This can only be done if the control system has built in an element of automatic reconfiguration, once a malfunction has been detected and isolated. Fault diagnosis plays an important role in the fault - tolerant control, as before any control law reconfigure is possible, the fault must be reliably detected, isolated and identified, and the information should be passed to a supervision module to make proper decision, as can be seen in figure (1) [7,8].

The principle of this method is to modify the constant feedback gain so that the reconfigured system approximates the nominal system in some sense, this method uses no FDI mechanism and certain fault models are assumed.

The open-loop model is given by

$$\dot{x}(t) = A_p x_p(t) + B_p u_p(t)$$
$$y(t) = C_p x_p(t) \qquad (1)$$

Where

$A_p \in R^{n\times n}, B_p \in R^{n\times m}, x_p \in R^{n\times m}$,
$C_p \in R^{q\times n}, u_p \in R^{m\times l}$, and q<m. it is assumed that the plant matrices A_p and B_p and the Initial states are unknown. Assume further that the closed-loop system is designed using state-feedback with control law:

$$u(t) = -K_p x_p(t) \qquad (2)$$

With $K_p \in R^{m\times n}$ the nominal closed - loop plant system is thus:

$$\dot{x}_p(t) = (A_p - B_p K_p) x_{p(t)} \qquad (3)$$
$$y_p(t) = C_p x_p(t)$$

Suppose that the model of the system, in which faults are assumed to have occurred, is given by:

$$\dot{x}_f(t) = (A_f - B_f K_f) x_f(t)$$
$$y_f(t) = C_f x_f(t) \qquad (4)$$

Where K_f is the new feedback gain matrix to be determined. Hence, we can require that the two closed - loop system matrices (A_p – B_p K_p.) and (A_f – B_f K_f) are equated so that an approximate solution for K_f is given by:

$$K_f = B_f^+ (A_p - A_f + B_p K_p) \qquad (5)$$

Where B_f^+ denotes the pseudo-inverse of B_f which can be defined using a "singular value decomposition" of B_f [9]. K_f can be calculated from equation (5) for many anticipated faults and be stored in computer.

The main idea of pseudo-inverse modeling (PIM) method is to modify the constant feedback gains of the nominal system, A measure of closeness between systems before and after a fault is the Frobenius norm of the difference between the closed 'A' matrices, and by minimizing this norm, the bound in the variations of closed-loop eigenvalues due to faults is minimized.

The stability of the impaired system is not guaranteed and this may lead to undesirable effects in certain fault scenarios. To attempt to overcome this stability problem a modified pseudo inverse method (MPIM) in which the difference between the closed-loop 'A' matrices is minimized subject to stability constraints, whilst recovering the performance as much as possible.

It is first assumed that (A_f, B_f) form a stabilized pair. If this assumption is not valid, stabilization can be achieved using an inner-loop stability augmentation. The modification is based upon a consideration of structured uncertainty in the state-space model, i.e. by considering the perturbed state-space model, with perturbation matrix ΔA_p, such that:

$$\dot{x}_p(t) = \left(A_p + \Delta A_p\right)x_p(t) + B_p u_p(t)$$
$$y_p(t) = C_p x_p \qquad (6)$$

It is assumed that a stability bound can be found such that if

$$\left|\overline{K}_f\left(i,j\right)\right| < \delta, (i = 1,2...m \;\&\; j = 12...n) \qquad (7)$$

Then the system in eq. (4) will be stable.

The algorithm for the MPIM reconfigurable control system is as follows:

Step 1: Calculate K_f from equation (5)

Step 2: Check the stability of equation (4) for the K_f obtained in step 1.

Step 3: If (4) is stable, stop; otherwise calculate K_f using

$$K_f = \begin{cases} \overline{K}(i,j) & if\left|\overline{K}(i,j)\right| \le \delta \\ \mathrm{sgn}\left|\overline{K}(i,j)\right|)\delta & otherwise \end{cases} \quad \ldots(8)$$

The objectives of PIM in reconfigurable control are to:

1. Maintain as much simplicity as possible in the controller design,
2 Reconfigured system made to approximate nominal system closely, and.
3. Provide graceful degradation in performance, subsequent to a fault.

3. On - Line Fault-Tolerant Controller Results

Consider the heat exchanger shown in figure (2). A linear model for the system can be represented by [10]

$$G(s) = \frac{\exp(-5s)}{(10s+1)(60s+1)} \qquad (9)$$

Where the term e^{-5s} is defined the pure transportation lag transfer function. In some instances in feedback systems for example, in process control, whether in systems controlled by a human operator in the loop or in computer controlled systems -there is a pure time delay or transportation lag in the system. As a result of the distributed nature of these systems, the response remains identically zero until after some time period λ.

We can represent an overall transfer function of a SISO system with time delay as

$$G_I(s) = G(s)e^{-\lambda s} \qquad (10)$$

Where G (s) has no pure time delay. Since G_I (s) does not have a finite state description, standard use of state variable methods is impossible. The result is a closed - loop transfer function with delay λ and otherwise the response of a closed loop design based on delay.

Figure (3) illustrates a single input single output block diagram of the heat exchanger with feedback gain matrix.

A suitable set of state - space equations is

$$\dot{x}(t) = \begin{bmatrix} -0.017 & -0.017 \\ 0 & -0.1 \end{bmatrix} x(t) + \begin{bmatrix} 0 \\ 0.1 \end{bmatrix} \mu(t-5) \qquad (11)$$

$$y(t) = [1 \;\; 0]x(t) \qquad \lambda = 5$$

Suppose we wish to place the closed loop poles at

$$\alpha_c(s) = s + 0.05 \pm j0.087\,;$$

Then the state feedback gain Matrix (ignoring the delay) is

K= [-1.2 - 0.1]

The output response of the closed loop system due to perturbation of a unit step input (with the system being free of the presence of any fault signal) is given in fig.4. This response indicates that the system is stable with reasonably acceptable performance which settles down to zero steady error in less than 75 secs.

The introduction of a severe fault signal into the system, with all other operating condition kept unchanged, as given above, (i.e Gain Matrix, input and FTC being employed) result in the response shown in Fig.(5). The response indicates that the present gain Matrix (K), could not force the system to be stable, and it becomes unstable after the elapse of ($\approx$150 secs). The introduction of fault tolerant control, helps to compute a more suitable gain Matrix [-5.2 – 0.17] which result in a stable system despite the presence of a sever fault signal [see fig.6]. The response show that the system will always retain stability after the elapse of acceptable time for up going and down going unit step inputs, it can therefore be realized that fault tolerant control can ensure the design of a new controller for different severity of fault signals.

4. Conclusions

Fault – tolerant control is a strategy for reliable and highly efficient control law design. To achieve these requirements, two methods are described in this paper.

These methods are on – line fault tolerant control design and dual control mode. For the first method, the constant feedback is modified so that the reconfigured system approximates the nominal system. In this approach, a matrix containing various gain values is pre – computed and saved in the computer memory. This method uses no FDI mechanism and certain fault models are assumed. In addition to providing information operators concerning the system operating conditions, the fault diagnosis module is especially important in fault tolerant control systems where one needs to know exactly which element is faulty in order to react safely. The results obtained indicate that the application of fault tolerant technique to an industrial system such as heat exchanger, enables the compensation of any disturbance due to the presence of any fault signal, however sever it may be. The results also show that once the fault is detected and isolated, then it is easy to reduce its effect on the system, and process control is resumed with degraded performances close to nominal ones. Thus avoiding the need for sudden stoppage of the process

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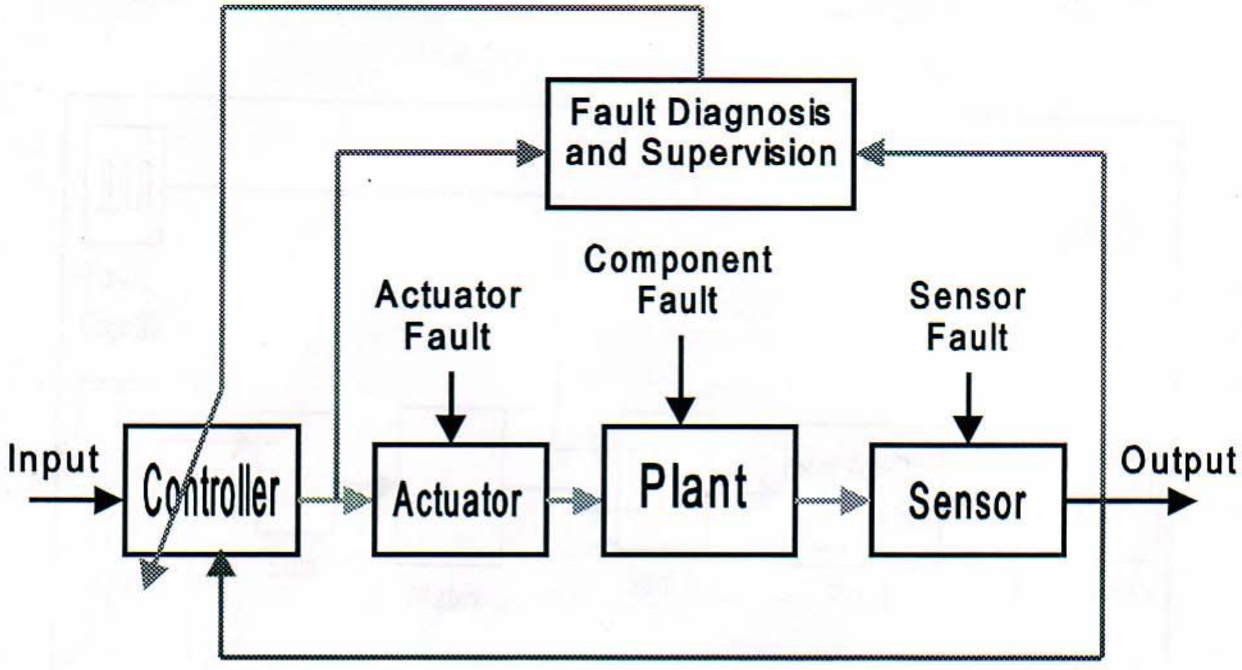

Fig. (1): Scheme of fault – tolerant control system with supervision subsystem

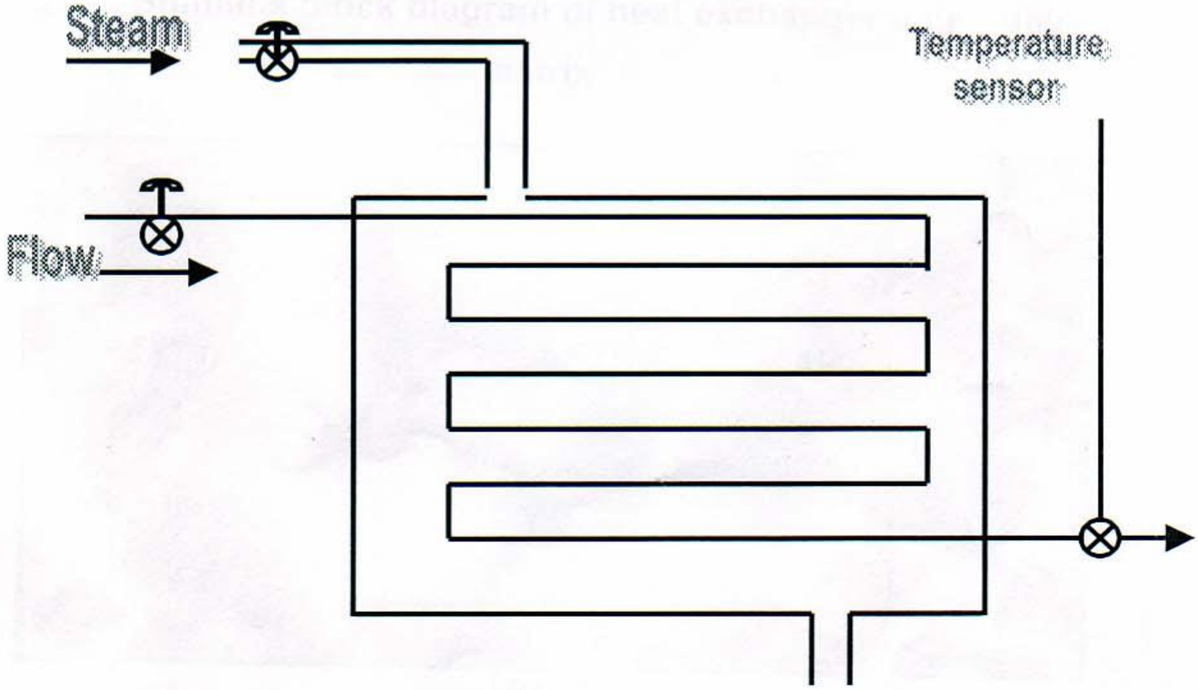

Fig.(2): A heat exchanger.

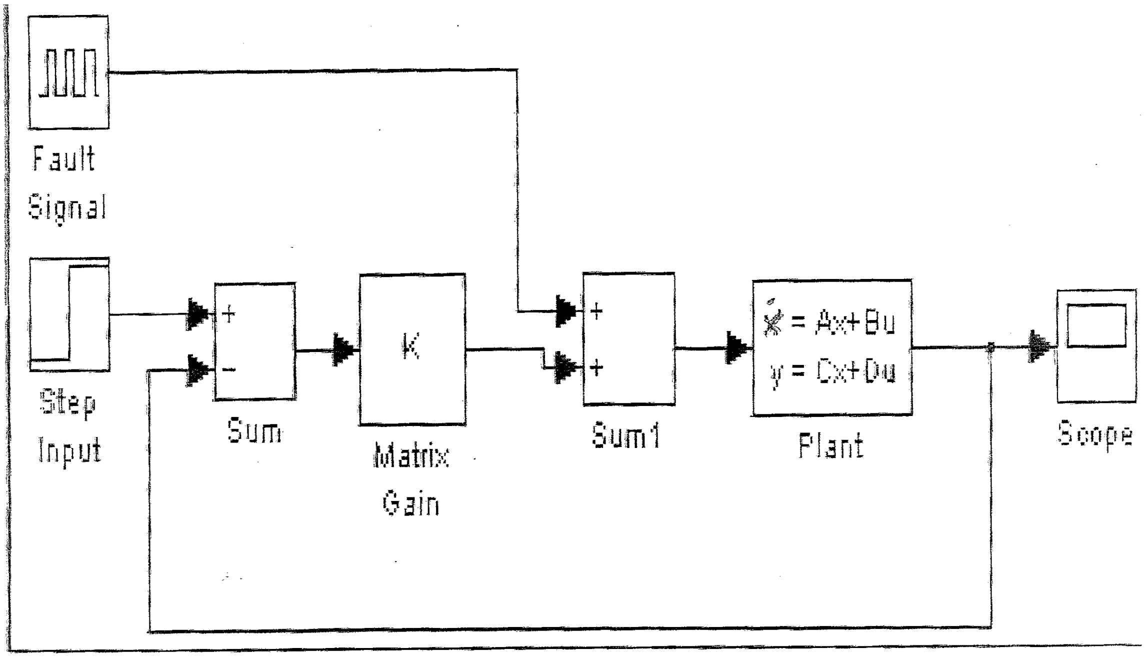

Fig.(3): Simulink block diagram of heat exchanger using gain matrix

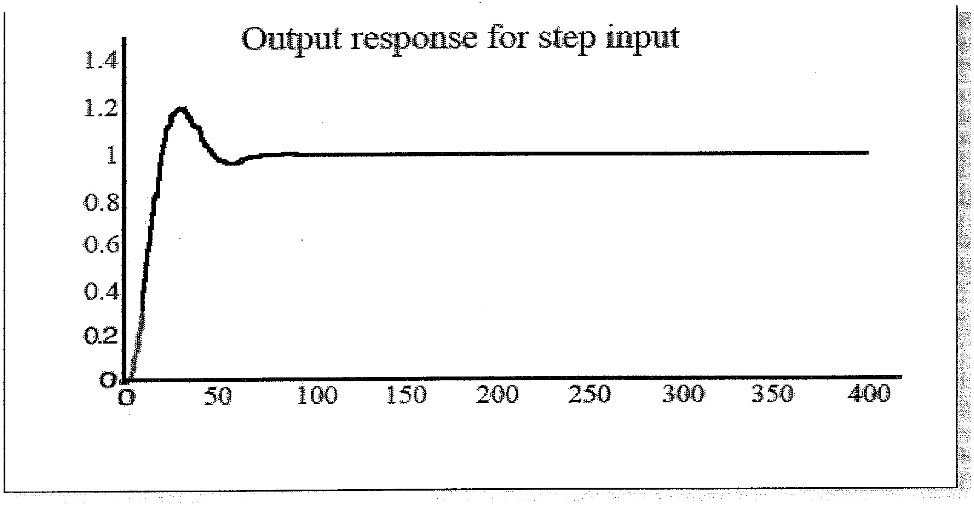

Fig (4)Step Response for Heat exchanger Using gain Matrix

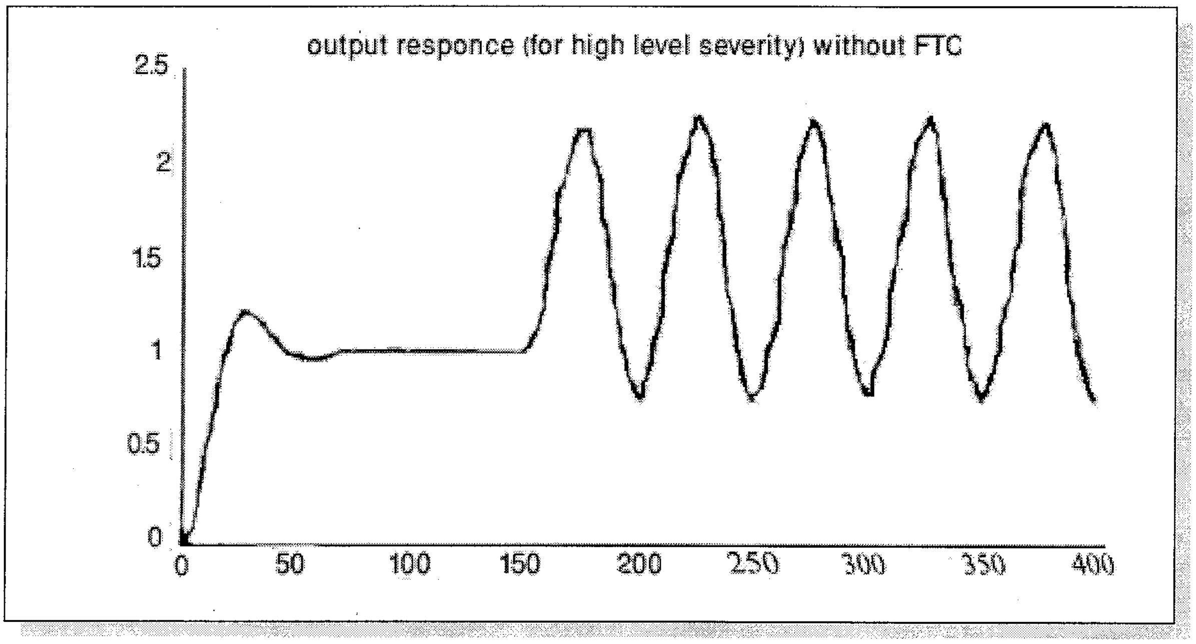

Fig (5) output Response at high Level of Severity without fault tolerant control

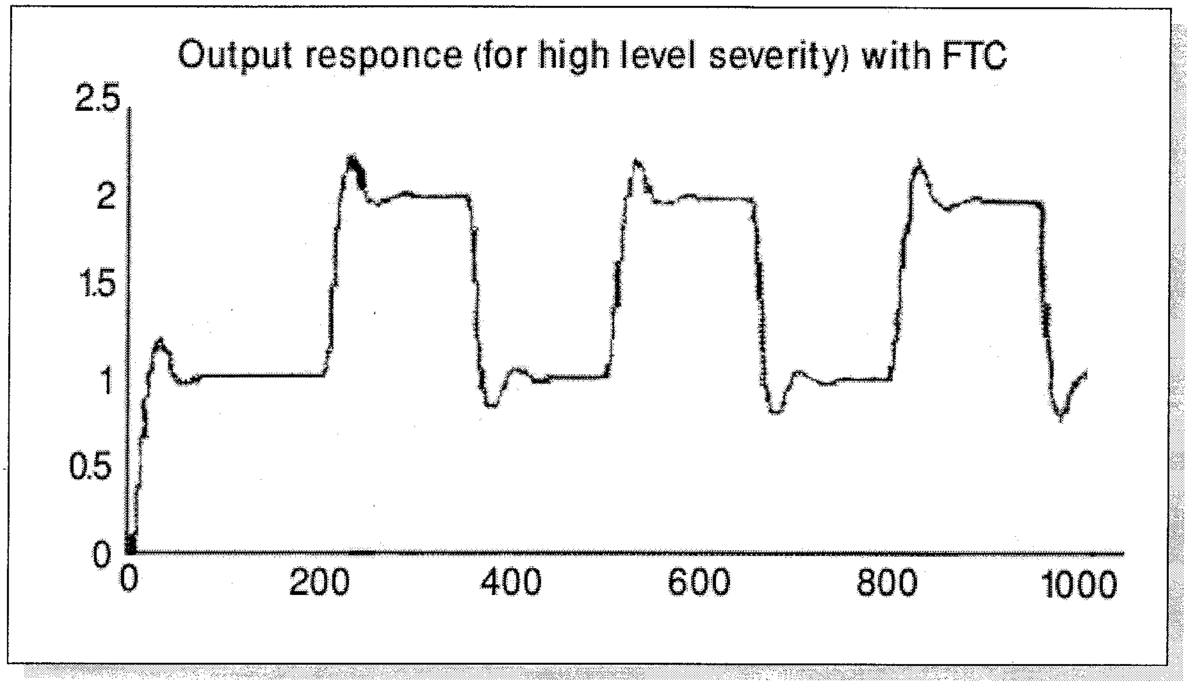

Fig (6) output Response at high Level of Severity with fault tolerant control