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GRACEFUL PERFORMANCE DEGRADATION IN ACTIVE FAULT-TOLERANT CONTROL SYSTEMS

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Abstract: In this paper, a new design approach is proposed for active Fault-Tolerant Control Systems (FTCS), which allows one to explicitly incorporate possible graceful performance degradation into the design process. The method is based on explicit model-following and reference input adjustment techniques. The performance degradation is represented through a reference model. Only actuator faults are considered herein. When a fault is detected by the Fault Detection and Diagnosis (FDD) algorithm, the reconfigurable controller will be designed automatically so that the dynamics of the closed-loop system match that of the reference model. The system command input is also adjusted on-line to prevent the actuators from saturating during the initial period of controller reconfiguration. An eigenstructure assignment technique has been used for designing feedback part of the reconfigurable controller. The proposed method has been evaluated using lateral dynamics of an F-8 aircraft subject to actuator failures and constraints on the actuator dynamic ranges. Satisfactory results have been obtained.

Keywords: Graceful Performance Degradation, Actuator Saturation, Model-Following Reconfigurable Control (MFRC), Reference Governor (RG), Fault Detection and Diagnosis (FDD).

1. INTRODUCTION

In FTCS design, an important question is whether one should attempt to recover the original system performance fully or to accept a degraded performance. What is the consequence if the performance degradation is not considered in the reconfiguration process?

As it has been shown in (Gao and Antsaklis, 1992; Noura, *et al.*, 2000; Zhang and Jiang, 2001a; 2001c), it is relatively straightforward to design a post-fault controller to recover the pre-fault system performance. In practice, once a fault occurs, the degree of the system redundancy and the available actuator capabilities can be significantly reduced. If the design objective of FTCS is still to try to achieve the pre-fault performance of the system, this may require the system actuators to provide extra efforts to compensate for the changes caused by the fault, especially, during the initial fault recovery period. This may be undesirable for a practical system due to physical limitations of its actuators. The consequence of the so-designed FTCS may lead to actuator saturation, or worse still, to cause further damage to the system, and even result in lose of the system stability. Therefore, trade-off between achievable performance and available control capability should be carefully examined in all FTCS designs. In other words, one may just have to accept the performance degradation in the design process after all. Unfortunately, this critical issue has not been addressed satisfactorily in the literature. Designing a reconfigurable controller to achieve an achievable performance without violation of actuator capability is therefore the main objective of this paper. Only actuator faults are considered.

Controller design methodology based on model-following principles provides a simple, yet practical way to achieve desired design objectives with consideration of performance degradation. If the dynamic characteristics of the system with performance degradation can be represented by a reference model, a controller can then be synthesized to achieve the above objective.

Currently, there is a lack of a systematic way to design model-following active FTCS with the consideration of performance degradation. Furthermore, almost all existing model-following methods assume that the states and the post-fault system model are available (obtained from a perfect FDD scheme). Therefore, it is highly desirable to develop new techniques that can integrate the FDD scheme and the reconfigurable control law in a coherent fashion with consideration of physical limitations of the impaired system.

When an actuator fault occurs, the actuator capabilities is usually reduced. Possible saturation of the remaining actuators becomes an important factor to consider in FTCS. A significant amount of work has been done to deal with actuator saturation (Bemporad and Mosca, 1998; Bodson and Pohlchuck, 1998; Kothare, *et al.*, 1994; Pachter, *et al.*, 1995). One way is to construct a feedback compensator to satisfy constraints on actuators (Kothare, *et al.*, 1994). The other is to modify the reference input so that the constraints are not violated. This approach is sometimes called *reference governor (RG)* or *reference management* (Bemporad and Mosca, 1998), or *command limiting* in the context of flight control (Bodson and Pohlchuck, 1998). Although several methods are available for command limiting to prevent actuators from saturation, it is relatively straightforward to modify the reference inputs. Furthermore, the reference governor is usually designed separately from the feedback controller. For this reason, the reference governor is employed here. A dynamic scheme for generating time-varying, nonlinearly modified reference input signal is proposed in this paper.

2. PERFORMANCE DEGRADATION IN FTCS

In a typical control system design, there are three main objectives: (1) to maintain stability; (2) to produce desired transient responses; and (3) to reduce steady-state errors. However, the design objectives for FTCS can be very different, because one should not only consider the system performance under normal conditions, but also the system performance under faults. It is important to point out that the emphasis on system behavior in these two modes of operation can be significantly different. During the normal operation, more emphasis is placed on the quality of the system's behavior. In the presence of a fault, however, the robustness of the system to the fault and how the system survives with an acceptable performance degradation become a predominant issue.

To be more precise, one can assign priorities among the design objectives and rank them according to their importance. This priority list can be divided into two groups: primary (high-priority) objectives, and secondary (low-priority) objectives. The primary objectives relate to the most critical system properties while the secondary objectives correspond to the less critical ones.

In many safety-critical systems, one cannot simply shut down the system in the event of a fault. The mission may still need to be completed. Therefore, for those systems, maintaining the closed-loop system stability alone is not enough, some degree of transient and steady-state performance is also very important.

Failures in a system can result in many undesirable behaviors, such as loss of degrees of controllability and observability, excessively large transients, reduction in stability margins, or even loss of stability.

A FTCS should be designed to maintain the highest priority objectives with the limited resources. The ability of a control system, in the event of a fault, to automatically reduce its demand on the level of performance so that the primary objectives can be achieved under the constraints of the available control power is known as *graceful performance degradation*. This is an important feature of FTCS that makes it unique. One of the main considerations in the FTCS design is to determine appropriate *allowable performance degradation* for all possible faults considered. Once the allowable performance degradation is specified, the problem becomes how to design a reconfigurable controller to achieve it.

For the above purpose, some form of performance measures needs to be defined for FTCS. Depending on the specific application or design methods chosen, performance measures can be specified in time and/or frequency domains. Furthermore, depending on different interval during the three intervals of system operation in FTCS, as outlined in (Zhang and Jiang, 2001b), different performance measures may have to be used. The system is linear time-invariant in the pre-fault and post-fault intervals. Therefore, various existing performance measures can be used in these two intervals. However, the system dynamics in the duration of fault occurrence and fault recovery are more complex. Because of the changes caused by fault and the changes initiated by the reconfiguration process, the system behavior in this period depends on the severity of the fault and reaction of the reconfiguration action being carried out. In this interval, time-domain based measures are more suitable since both the evolution of the fault and the controller reconfiguration process are time-varying.

A good measure of the system performance is the relative stability of the system, which can be examined in terms of the locations of the dominant eigenvalues. Under the normal system operation, the real part of the dominant eigenvalues should be in the desired region away from the imaginary axis with a certain minimum distance. When a fault occurs, the degree of the existing redundancy is reduced, and the ability of the system to deal with faults is reduced as well. Without reconfiguration the eigenvalues of the closed-loop system may move closer to or even cross the imaginary axis. If there exists enough actuator redundancy, it is possible to relocate all the eigenvalues of the reconfigured system to pre-fault locations, and hence, recover the original system performance completely (Zhang and Jiang, 1999; Zhang and Jiang, 2001a). By doing so, the closed-loop stability and dynamic performance of the system are maintained. However, as mentioned previously, such design relies heavily on the capability of the remaining actuators and the availability of the accurate post-fault system model. If done improperly, it may lead to unrealistically large control signals which saturate the control actuator, especially during the initial period of reconfiguration. In this regard, one may have to accept some performance degradation by assigning eigenvalues at different locations to avoid possible actuator saturation.

3. GRACEFUL PERFORMANCE DEGRADATION THROUGH REFERENCE MODEL AND REFERENCE INPUT ADJUSTMENT

3.1 *Representation of Performance Degradation*

A simple way to represent system dynamics with prescribed performance levels is through reference models. In general, reference models should represent the desired behaviors of the system in different intervals, i.e. before and after fault occurrence. It is important to note that a single reference model may not be enough for FTCS to cover entire system operation. It is desirable to use different models for normal and impaired operating conditions separately.

To select the reference models for FTCS, extra care should be taken to consider:

- performance limitations with reduced actuation capabilities;

- acceptable performance degradation in the transient and steady-state behaviors.

Generally speaking, design of a suitable reference model is not a simple task even for a normal system, not to mention for the system with various type of faults. A satisfactory reference model should be able to capture majority of the transient and steady-state requirements in the closed-loop system design specifications without violating any physical constraints on the system variables and the control devices.

In the context of FTCS, the reference model should depend on the type of faults in the system. The model should be flexible enough to represent the high priority objectives with appropriate discount on the low priority ones under the condition that all system and control variables are within the physical constraints. The model should reflect the graceful performance degradation in both the transient and the steady-state intervals. In general, this is a very difficult problem. However, once we restrict ourselves to faults in actuators only, the problem becomes much more solvable. In this paper, the reference model is a function of the control effectiveness factors which are readily available through FDD scheme on-line in real-time (Zhang and Jiang, 1999; 2001b).

Once the design objectives and reference models are determined, the problem becomes how to synthesize reconfigurable control laws to follow the reference model.

3.2 *Dynamic Reference Governor*

In addition to representing performance degradation using reference models, it is also important to modify the reference input in the presence of a fault. The dynamic reference governor will be used to change the set-point of the system and prevent the actuators from saturating during the initial period of reconfiguration. Therefore, combination of reference model and command input adjustment will make it possible to design a FTCS with consideration of performance degradation. The steady-state control signals are determined by the reference model and the reconfigurable controller, while the control signals during the reconfiguration interval are mainly decided by the dynamic reference governor.

Let's assume that the desired reference input is $\mathbf{r}_k$. The reference governor generates a modified reference input $\mathbf{r}'_k$ based on

$$\mathbf{r}'_{k+1} = \mathbf{r}'_k + \kappa_k \cdot [\mathbf{r}_{k+1} - \mathbf{r}'_k] \qquad (1)$$

where κ_k $(0 < \kappa_k \leq 1)$ is a parameter to be determined to satisfy the actuator constraints. In the literature, some optimization techniques have been used to find the most suitable value for this parameter (Bemporad and Mosca, 1998).

In FTCS, actuator saturations often occur in the initial period of the reconfiguration due to abrupt changes caused by the fault and absence of an accurate post-fault system model. When more accurate post-fault system model becomes available, the synthesized control signals will settle within a desired range governed by the prescribed reference model. Therefore, the following exponentially-weighted dynamic reference governor is proposed in this paper:

$$\kappa_k = 1 - \rho e^{-\tau(k-k_D)}, \quad k \geq k_D \qquad (2)$$

where k_D is the time at which the fault is detected. $\tau > 0$ and $\rho > 0$ are two design parameters. For large k, κ_k will tend to 1, and therefore, $\mathbf{r}'_{k+1} \rightarrow \mathbf{r}_{k+1}$.

Note that the adjustment to the original reference input starts as soon as a fault is detected at time k_D. This allows the reference governor to modify the reference input before and during the reconfiguration process to prevent actuator saturations without affecting the steady-state performance of the reconfigured system.

3.3 *Configuration of FTCS*

To ensure the closed-loop system to follow the prescribed reference model, a feedback controller alone is not sufficient, it is often necessary to use feedforward controllers as well. The entire system is depicted in Fig. 1.

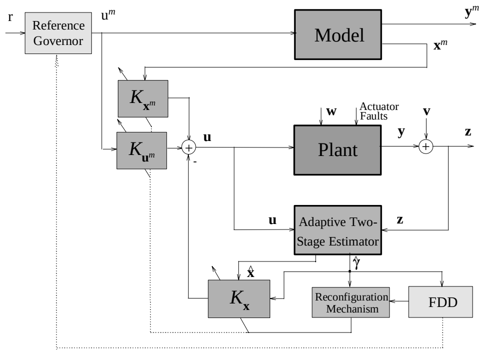

Fig. 1 *Integrated RG, FDD and MFRC configuration.*

In this configuration, three parts of reconfigurable controllers, $\{K_{\mathbf{x}}, K_{\mathbf{x}^m}, K_{\mathbf{u}^m}\}$, need to be synthesized simultaneously.

4. DESIGN OF MODEL-FOLLOWING RECONFIGURABLE CONTROLLER

4.1 *Design of Model-Following Reconfigurable Control*

Let's consider the system modelled by the following linear stochastic difference equations under normal and fault conditions with unknown actuator faults:

$$\begin{cases} \mathbf{x}_{k+1} = F\mathbf{x}_k + G\mathbf{u}_k + \mathbf{w}_k^{\mathbf{x}} & k < k_F \text{ Normal} \\ \mathbf{x}_{k+1} = F\mathbf{x}_k + G^f\mathbf{u}_k + \mathbf{w}_k^{\mathbf{x}} & k \geq k_F \text{ With fault} \\ \mathbf{y}_k = H_r\mathbf{x}_k \\ \mathbf{z}_k = H\mathbf{x}_k + \mathbf{v}_k \end{cases} \qquad (3)$$

where $\mathbf{x}_k \in \Re^n$ is the plant state, $\mathbf{u}_k \in \Re^l$ is the input. $\mathbf{y}_k \in \Re^l$ is the output. $\mathbf{z}_k \in \Re^m$ corresponds to the measurements. $\mathbf{w}_k^{\mathbf{x}} \in \Re^n$ is a zero-mean white Gaussian noise sequence with covariance $Q_k^{\mathbf{x}} \in \Re^{n\times n}$ representing the modelling errors. $\mathbf{v}_k \in \Re^m$ is a zero-mean white Gaussian measurement noise sequence with covariance $R_k \in \Re^{m\times m}$. $H_r \in \Re^{l\times n}$ is a matrix which relates to a subset of outputs that track the reference inputs. $H \in \Re^{m\times n}$ relates the measurements. k_F is the time at which a fault occurs. During the normal operation, the system is represented by $\{F, G, H_r\}$. Once a fault occurs, the matrix G is assumed to become G^f.

In this paper, two reference models are used. One for the system under normal operation (referred to as desired reference model) and the other for the system with actuator faults (referred to as degraded reference model).

$$\begin{cases} \mathbf{x}_{k+1}^m = F_n^m \mathbf{x}_k^m + G_n^m \mathbf{u}_k^m \\ \mathbf{y}_k^m = H_n^m \mathbf{x}_k^m \end{cases}, \quad k < k_F$$
$$\begin{cases} \mathbf{x}_{k+1}^m = F_f^m \mathbf{x}_k^m + G_f^m \mathbf{u}_k^m \\ \mathbf{y}_k^m = H_f^m \mathbf{x}_k^m \end{cases}, \quad k \geq k_F \tag{4}$$

where $\mathbf{x}_k^m \in \Re^{n^m}$ is the model state, $\mathbf{u}_k^m = \mathbf{r}'_k \in \Re^{l^m}$ the input, and $\mathbf{y}_k^m \in \Re^{l^m}$ the output.

Based on the system (3) and the reference models (4), one needs to synthesize the following control gains $\{K_{\mathbf{x}}^n, K_{\mathbf{x}^m}^n, K_{\mathbf{u}^m}^n\}$ to generate the desired control signals:

$$\mathbf{u}_k^n = -K_{\mathbf{x}}^n \mathbf{x}_k + K_{\mathbf{x}^m}^n \mathbf{x}_k^m + K_{\mathbf{u}^m}^n \mathbf{u}_k^m \tag{5}$$

Once the occurrence of a fault is detected, a new controller $\{K_{\mathbf{x}}^f, K_{\mathbf{x}^m}^f, K_{\mathbf{u}^m}^f\}$ will be synthesized so that the closed-loop system follows the degraded reference model with the following control signal:

$$\mathbf{u}_k^f = -K_{\mathbf{x}}^f \mathbf{x}_k^f + K_{\mathbf{x}^m}^f \mathbf{x}_k^m + K_{\mathbf{u}^m}^f \mathbf{u}_k^m, \quad k \geq k_R \tag{6}$$

where k_R represents the controller reconfiguration time.

However, to make these reconfigurable control design possible, the post-fault system model has to be determined and the state variables should be available for feedback. To obtain the required states and the fault parameters, estimation techniques have to be used. In this paper, a two-stage adaptive Kalman filter (Zhang and Jiang, 1999; Wu, *et al.*, 2000) is used.

4.2 *Design Methodology for Reconfigurable Controller*

As mentioned previously, the function of the feedforward control is to make the controlled variables to follow the outputs of the desired and the degraded reference models during normal and fault operations, respectively, i.e. to find a control sequence $\mathbf{u}_k$ that forces the command tracking error $\mathbf{e}_k$ to zero at the steady-state

$$\mathbf{e}_k = \mathbf{y}_k - \mathbf{y}_k^m = H_r \mathbf{x}_k - H^m \mathbf{x}_k^m \tag{7}$$

When this condition is satisfied, the system states and the control signals, $\mathbf{x}_k^*$ and $\mathbf{u}_k^*$, will satisfy:

$$\mathbf{y}_k^* = H_r \mathbf{x}_k^* = H^m \mathbf{x}_k^m \tag{8}$$

and the system dynamics

$$\mathbf{x}_{k+1}^* = \begin{cases} F\mathbf{x}_k^* + G\mathbf{u}_k^*, & \text{Normal operation} \\ F\mathbf{x}_k^* + \hat{G}_k^f \mathbf{u}_k^*, & \text{System with fault} \end{cases} \tag{9}$$
$$\mathbf{y}_k^* = H_r \mathbf{x}_k^*$$

where $\hat{G}_k^f$ is the estimate of G^f at time k.

The solutions for $\mathbf{x}_k^*$ and $\mathbf{u}_k^*$ can be found from:

$$\mathbf{x}_k^* = S_{11}\mathbf{x}_k^m + S_{12}\mathbf{u}_k^m + \Delta(\mathbf{u}_k^m) \tag{10}$$
$$\mathbf{u}_k^* = S_{21}\mathbf{x}_k^m + S_{22}\mathbf{u}_k^m + \Delta(\mathbf{u}_k^m) \tag{11}$$

where $S_{ij}, i, j = 1, 2$, are constant feedforward gain matrices. If we restrict ourselves to step inputs, $\Delta(\mathbf{u}_k^m) = 0$. The solution for $\mathbf{x}_k^*$ and $\mathbf{u}_k^*$ to achieve perfect tracking can be represented as:

$$\mathbf{x}_k^* = S_{11}\mathbf{x}_k^m + S_{12}\mathbf{u}_k^m \tag{12}$$
$$\mathbf{u}_k^* = S_{21}\mathbf{x}_k^m + S_{22}\mathbf{u}_k^m \tag{13}$$

where $S_{ij}, i, j = 1, 2$, are calculated by

$$S_{11} = \Phi_{11}S_{11}(F^m - I) + \Phi_{12}H^m \tag{14}$$
$$S_{12} = \Phi_{11}S_{11}G^m \tag{15}$$
$$S_{21} = \Phi_{21}S_{11}(F^m - I) + \Phi_{22}H^m \tag{16}$$
$$S_{22} = \Phi_{21}S_{11}G^m \tag{17}$$

and $\Phi_{ij}, i, j = 1, 2$, are given by

$$\Phi = \begin{bmatrix} \Phi_{11} & \Phi_{12} \\ \Phi_{21} & \Phi_{22} \end{bmatrix} = \begin{cases} \begin{bmatrix} F - I & G \\ H_r & 0 \end{bmatrix}^{-1} & \text{Normal operation} \\ \begin{bmatrix} F - I & \hat{G}_k^f \\ H_r & 0 \end{bmatrix}^{-1} & \text{System with fault} \end{cases}$$

where I is an identity matrix.

It should be noted that Φ_{ij} depends on the pre- and post-fault plant models, whereas S_{ij} depends on both the plant and the reference models in normal and fault conditions.

To incorporate feedback controller, let's define

$$\tilde{\mathbf{x}}_k = \mathbf{x}_k - \mathbf{x}_k^*, \ \tilde{\mathbf{u}}_k = \mathbf{u}_k - \mathbf{u}_k^*, \ \tilde{\mathbf{y}}_k = \mathbf{y}_k - \mathbf{y}_k^* \tag{18}$$

then,

$$\tilde{\mathbf{x}}_{k+1} = \begin{cases} F\tilde{\mathbf{x}}_k + G\tilde{\mathbf{u}}_k, & \text{Normal operation} \\ F\tilde{\mathbf{x}}_k + \hat{G}_k^f \tilde{\mathbf{u}}_k, & \text{System with fault} \end{cases} \tag{19}$$
$$\tilde{\mathbf{y}}_k = H_r \tilde{\mathbf{x}}_k \tag{20}$$

For a feedback control signals given by

$$\tilde{\mathbf{u}}_k = -K_{\mathbf{x}}\tilde{\mathbf{x}}_k = -K_{\mathbf{x}}(\mathbf{x}_k - \mathbf{x}_k^*) \tag{21}$$

From the definition of $\tilde{\mathbf{u}}_k$ in (18), it follows:

$$\mathbf{u}_k = \mathbf{u}_k^* + \tilde{\mathbf{u}}_k = \mathbf{u}_k^* - K_{\mathbf{x}}(\mathbf{x}_k - \mathbf{x}_k^*) \tag{22}$$

Substituting (12) and (13) into (22), the total control signal can be shown as:

$$\mathbf{u}_k = \underbrace{-K_{\mathbf{x}}\mathbf{x}_k}_{\text{feedback}} + \underbrace{(S_{21} + K_{\mathbf{x}}S_{11})\mathbf{x}_k^m}_{\text{reference model}} + \underbrace{(S_{22} + K_{\mathbf{x}}S_{12})\mathbf{u}_k^m}_{\text{feedforward}} \tag{23}$$

It should be noted that (23) represents the inputs to the actuators for both normal and fault conditions. In the presence of an actuator fault, the control input matrix G will be replaced by $\hat{G}_k^f$, S_{ij} and the three controller gain matrices $\{K_{\mathbf{x}}, K_{\mathbf{x}^m}, K_{\mathbf{u}^m}\}$ need to be re-calculated on-line.

The feedback part of the controller is designed using eigenstructure assignment techniques. The design objective here is to synthesize the feedback part of the controller to achieve not only the same eigenstructure as the desired reference model for normal operation, but also the same eigenstructure as the degraded reference model under the fault conditions. Interested reader is referred to (Jiang, 1994; Zhang and Jiang, 1999; Zhang and Jiang, 2001a) for detail.

5. EXAMPLE AND PERFORMANCE EVALUATION

A fourth-order lateral F-8 aircraft model (Sobel and Kaufman, 1986) with two inputs and two outputs is used to illustrate the design procedure and to test the method.

5.1 *The System and the Reference Models*

The linearized aircraft model can be described as

$$\begin{aligned}\dot{\mathbf{x}}(t) &= A\mathbf{x}(t) + B\mathbf{u}(t)\\ \mathbf{y}(t) &= C\mathbf{x}(t)\end{aligned} \tag{24}$$

where state and input vectors are $\mathbf{x} = [p\ r\ \beta\ \phi]^T$ and $\mathbf{u} = [\delta_a\ \delta_r]^T$, respectively, with p representing the roll rate, r the yaw rate, β the sideslip angle, ϕ the bank angle, δ_a the aileron deflection, and δ_r the rudder deflection.

To maintain the desired sideslip and bank angles during normal and fault conditions, the output matrix H_r is chosen as $H_r = C = \begin{bmatrix} 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\end{bmatrix}$.

Taking into account of the noise and representing the system in the discrete domain, the system can be written as:

$$\begin{aligned}\mathbf{x}_{k+1} &= F\mathbf{x}_k + G\mathbf{u}_k + \mathbf{w}_k^{\mathbf{x}}\\ \mathbf{y}_k &= H_r\mathbf{x}_k\\ \mathbf{z}_k &= H\mathbf{x}_k + \mathbf{v}_k\end{aligned} \tag{25}$$

where $H = C = H_r$ and the sampling period $T = 0.1$ second is used.

Following the design consideration outlined in Section 3, system parameters of the desired and the degraded reference models as well as those of the open-loop system are given in Table 1.

Table 1 The system and the reference models

Models	A	B
Open-loop System	$\begin{bmatrix} -3.598 & 0.1968 & -35.18 & 0\\ -0.0377 & -0.3576 & 5.884 & 0\\ 0.0688 & -0.9957 & -0.2163 & 0.0733\\ 0.9947 & -0.1027 & 0 & 0\end{bmatrix}$	$\begin{bmatrix} 14.65 & 6.538\\ 0.2179 & -3.087\\ -0.0054 & 0.0516\\ 0 & 0\end{bmatrix}$
Desired Ref. Model	$\begin{bmatrix} -10.0 & 0 & -10.0 & 0\\ 0 & -0.7 & 4.5 & 0\\ 0 & -0.5 & -0.7 & 0\\ 1 & 0 & 0 & -0.5\end{bmatrix}$	$\begin{bmatrix} 20.0 & 2.8\\ 0 & -3.13\\ 0 & 0\\ 0 & 0\end{bmatrix}$
Degraded Ref. Model	$\begin{bmatrix} -10.0 & 0 & -10.0 & 0\\ 0 & -0.85 & 4.5 & 0\\ 0 & -0.5 & -0.85 & 0\\ 1 & 0 & 0 & -0.6\end{bmatrix}$	$\begin{bmatrix} 10.0 & 1.4\\ 0 & -1.565\\ 0 & 0\\ 0 & 0\end{bmatrix}$

The desired reference model satisfies all necessary performance requirements of the aircraft during normal operation (Sobel and Kaufman, 1986). In the selection of the degraded reference model, the following two factors have been considered: (1) the selected system outputs track the selected reference model in the presence of actuator faults, and (2) the steady-state closed-loop control signals should not violate the constraints on the actuators for all fault conditions. In this regard, not only the system matrix A, but also the control matrix B are properly selected.

5.2 *Indices for Performance Evaluation*

To evaluate the performance of the proposed approach, the following indices have been used:

$$\epsilon_k = \begin{cases} \dfrac{\left\{\sum_{i=1}^{l}\left(y_k^{desired}(i) - y_k(i)\right)^2\right\}^{1/2}}{\left\{\sum_{i=1}^{l}\left(y_k^{desired}(i)\right)^2\right\}^{1/2}} & k < k_F\\ \dfrac{\left\{\sum_{i=1}^{l}\left(y_k^{degraded}(i) - y_k(i)\right)^2\right\}^{1/2}}{\left\{\sum_{i=1}^{l}\left(y_k^{degraded}(i)\right)^2\right\}^{1/2}} & k \geq k_F\end{cases} \tag{26}$$

where $y_k^{desired}$ and $y_k^{degraded}$ denote the outputs of the desired and degraded reference models at time k, respectively, and y_k denotes the output of the system.

In addition, the average and the maximum values of $\epsilon_k, \forall k \in \{k_F, N\}$ are also used in the overall performance evaluation, i.e.,

$$\bar{\epsilon} = \frac{1}{N - k_F + 1}\sum_{k=k_F}^{N}\epsilon_k; \quad \epsilon_{\max} = \max\{\epsilon_k\},\ \forall k \in \{k_F, N\} \tag{27}$$

where N is the number of data points used.

5.3 *Simulation Results and Performance Evaluation*

To evaluate the performance of the proposed method, a partial loss of 75% of the control effectiveness in the aileron is simulated at time $k_F = 5$ sec. A constant input vector, $\mathbf{r} = [\,2.8558\ \ 17.088\,]^T$, is used as the original reference input to the system and the reference models. The parameters in the reference governor are chosen as $\tau = 0.05$ and $\rho = 1$. The amplitude limits for the two closed-loop control channels are set as: $\delta_a^c = \pm 15$ deg and $\delta_r^c = \pm 10$ deg.

5.3.1. *Performance with reconfiguration using the degraded and the desired reference models*

For comparison purpose, system outputs (y_1: sideslip angle, y_2: bank angle) are illustrated in Fig. 2 with the objective of reconfiguring for the degraded and the desired reference models. The corresponding closed-loop control signals and the modified reference inputs are shown in Fig. 3.

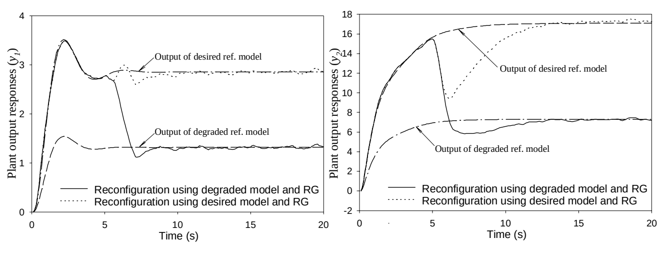

Fig. 2 *System outputs using degraded and desired ref. models.*

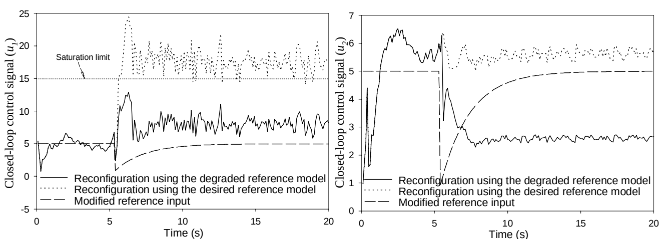

Fig. 3 *Corresponding control signals.*

Results in Fig. 2 have clearly shown that the two outputs of reconfigured system are able to track those of the degraded reference model satisfactorily. The magnitude of the associated steady-state control signal for aileron is slightly larger than that in the pre-fault interval. The magnitude of the steady-state signal for the rudder is even smaller than that in the pre-fault condition because of the reduced performance requirements.

In fact, if the performance degradation had not been considered in the design, the synthesized closed-loop control signal in the aileron channel would have violated the actuator saturation limit soon after the fault occurrence. However, using the degraded reference model and the reference governor, the closed-loop control signals in both channels are well within the constraints of the actuators.

5.3.2. *Performance with and without reference governor*

The system outputs with and without reference input adjustment are illustrated in Fig. 4. The corresponding closed-loop control signals are shown in Fig. 5. It can be seen that with reference governor, smaller control signals have been obtained at the beginning of the reconfiguration process. The corresponding output responses are slightly sluggish with an undershoot in the bank angle, which can be interpreted as a part of the performance degradation. Without the reference input adjustment, the control signal in the aileron channel is slightly over the limit of 15 deg . in the beginning of the reconfiguration process, although the steady-state control signal did not violate the constraint.

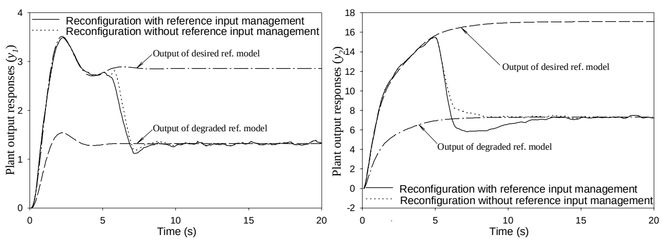

Fig. 4 *System outputs with and without reference governor.*

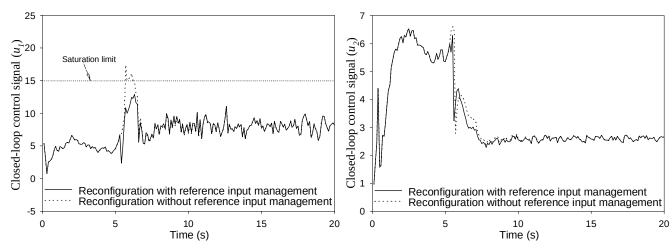

Fig. 5 *Corresponding control signals.*

6. CONCLUSIONS

The design issues for fault-tolerant control systems (FTCS) with explicit consideration of graceful performance degradation have been addressed in this paper. An integrated approach has been proposed based on the concept of reference input adjustment and model-following reconfigurable control strategy. Two reference models are used, one for normal system operation and the other for system under actuator faults. The latter considers the physical limitations of actuator capabilities so that the actuator limits are not violated. A dynamic reference governor has been proposed for such purpose. The reconfigurable controller is designed using an eigenstructure assignment technique based on model-following principles. The FDD scheme is based on a two-stage adaptive Kalman filter for simultaneous state and fault parameter estimation, statistical decisions for fault detection, diagnosis and activation of the controller reconfiguration. Simulation results using an aircraft model have demonstrated the effectiveness of the proposed scheme.

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