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FUZZY LOGIC IN RESTRUCTURABLE FLIGHT CONTROL SYSTEMS

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Abstract

In this paper, a fuzzy logic controller (FLC) is proposed for restructurable flight control systems. The role of the FLC is to stabilize the aircraft upon a fault occurrence. The FLC derives pitch/roll/yaw controls from a generic knowledge base characterized by 49 *if-then* rules. A linearized model representative of a modern jet fighter provides the basis for the numerical simulation. Simulated faults include various degrees of surface loss at the right stabilator, combined with reduced ailerons and rudder control power. The FLC accomplishes the stabilization task under test conditions without any knowledge of the system parameters. The numerical results demonstrate the potential of the FLC as a suitable control algorithm that bridges the critical gap between the fault occurrence and the full implementation of the new control law.

I. Introduction

With ever-expanding performance envelopes, payloads, and sizes, controlling a modern aircraft has become a difficult task for a pilot without the assistance of flight control systems. However, because flight control laws are written around linearizations, a fault occurrence (loss of control surface, actuator failures, loss of hydraulic, etc.) that alters the system configurations and generates unmodeled dynamics will present major challenges to the baseline controllers. The criticality of a healthy flight control system and vulnerability to such failures were illustrated in the Vietnam War, where more than 20% of the total aircraft loss were attributed to flight control system failures [1]. The need for restructurable flight control systems (RFCS) becomes obvious. Unlike the baseline controller, a RFCS recognizes the changes in the system dynamics and make adjustments accordingly. As a result, the aircraft can still retain a certain performance level, depending on the severity of the fault, and determine whether to continue the mission or abort for repair.

The control restructuring process consists of three major components [2]: fault detection, isolation and estimation (FDIE); trimming/stabilizing the aircraft; and synthesis of a new control law. The FDIE has the critical responsibility of detecting the fault occurrence, suggesting a possible cause and estimating the resultant system parameters, remaining control power and the strategy to allocate them properly. Concurrent to the FDIE activities, the aircraft must be stabilized and trimmed before it diverges beyond recovery. The high degree of interaction between the FDIE and trimming/stabilzing task must yield sufficient time and information to complete the new control law.

Unfortunately, a damaged aircraft presents great difficulties in successfully completing control restructuring for several reasons. First, in the midst of noise, nonlinearity, uncertainty, and rapid dynamics, it is very difficult to accurately estimate system parameters. Although the controller does not possess the knowledge on the most current system parameters, it still has to maintain trimming/stabilizing regardless the status of FDIE. Therefore, the controller must be robust enough to handle a wide range of parameter variations. Although a robust base-line controller can be used, its ability to handle a wide range of fault scenarios is uncertain.

Numerous studies [2-10] have been proposed to solve the RFCS problems. Despite the difference in the techniques they employed, these studies basically follow the 3-stage process aforementioned.

II. Fuzzy Logic in RFCS

The objective of this study is to investigate an alternative approach that seeks direct control upon the detection of a fault occurrence. There are several reasons for selecting fuzzy logic for this application [11-13]. First, fuzzy logic is a knowledge-based system that derives control actions based on input/output relationship; therefore, estimation of the system parameters is not required. Second, the nature of a fuzzy set makes it suitable to process vague and imprecise information, such as uncertain measurement values. Third, fuzzy logic rule base contains control strategies that are applicable to a wide range of qualitatively-similar scenarios. For example, a 20% and 40% loss of a stabilator surface will result in different system parameters (system and control matrices) and dynamic response. Conventional control techniques may require different pole placements to ensure good performance. However, the control strategies for controlling both cases remain the same qualitatively, the

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rule base determines proper control actions based on the magnitudes of the input/output relationship.

2.1 Fuzzy Logic Controller Design

A fuzzy logic controller for a linear aircraft model is designed to stabilize a damaged aircraft. The inputs and outputs of the FLC consist of $\{\theta, q, \phi, p, \psi, r\}$ and $\{\delta_H, \delta_a, \delta_r\}$, respectively. The universe of discourse for the error and error rate is defined as |15| degrees and |18| degrees per second, respectively. The universe of discourse for control surface deflection is defined as |30| degrees, and a constraint of the 60 degrees per second is applied to the deflection rate. Seven fuzzy sets partition the universe of discourse: {NB, NM, NS, ZE, PS, PM, PB}. For simplicity, the same membership functions are used for all control variables as well as controller outputs (Fig. 1).

The FLC employs a series of *if-then* rules that utilize a strategy resembles to that of a PD controller since the rules are predicated on errors and error rates. Examples of the rules in the longitudinal mode are:

If θ is NM and q is NB then δ_H is NB;
If θ is NM and q is NM then δ_H is NB;
If θ is NM and q is NS then δ_H is NB;
If θ is NM and q is ZE then δ_H is NS.

These rules reflect an aggressive control strategy that seeks to apply maximum input whenever applicable so the damping (opposing stabilator deflection) is not applied until the error value is close to zero. Since seven fuzzy sets are used to describe the universe of discourse, and two variables are predicated in the antecedent, a total of 7^2 rules are utilized to cover the complete input/output space (Fig. 2).

Since the qualitative approach is similar, the fuzzy rules from longitudinal mode are readily transferable to the lateral/directional mode without losing generality except for different sign convention. Such a common rule base not only simplifies the design process, but it also greatly reduces the computation burdens.

For implication functions and the compositional rule of inference, Mamdani's minimum-operation is utilized [11]. The relational matrix, R, obtained by min-operation for a discrete universe of discourse is obtained from:

$$R = \Sigma_{u \times v}\, \mu_A(u) \wedge \mu_B(v)/(u, v),$$

where R serves as a bridge between the input and output space, respectively. And $\mu(u)$ is the membership value of u to the fuzzy set A, while $\mu(v)$ is the equivalent part in set B. For defuzzification, the popular center-of-area (COA) technique [11, 13],

$$u_{def} = \frac{\sum_{i=1}^{n} (u_i \times \mu_c(u_i))}{\sum_{i=1}^{n} (u_i)}$$

is utilized, where u_{def} represents the crisp output and u_i is any element that belong to the pertinent fuzzy set C.

III. Fault Simulation

Two fault scenarios are simulated in this study:

I The right stabilator is stuck at the -5 degrees position with a 30% loss of the exposed area
II Complete loss of the right stabilator.

In both cases, a 50% reduction is imposed on both the aileron and rudder effectiveness. The partial loss of the right stabilator effects a new lift curve slope for the stabilators. As a result, longitudinal stability derivatives such as Cm_α are recalculated to reflect the damage. The coupled rolling moment generated by the damage is modeled by the term

$$C_{l_{\delta_H}} = \Delta C_{L_{\delta_H}} \times b$$

where $\Delta C_{L_{\delta_H}}$ is the differential lift between the stabilators and b is the span of the wing. The control effectiveness reduction of the ailerons/rudder is modeled by reducing the values of corresponding control derivatives.

IV. Simulation Results and Discussion

The simulation is assumed to take place at a nominal flight condition of Mach 0.6 at 20,000 ft. Non-zero initial conditions are generated by a 10-degree stabilator step input for an initial period of 0.5 sec. A fault is made to occur at 0.5 sec; whereafter, the FLC activates and assumes the control authority.

Fault I

As a result of 30% loss of the right stabilator, the Cm_α value has raised from -0.29 to -0.17. Although the static margin is retained, proper flight control intervention is needed to restore the original performance level. Especially, when uneven aerodynamic loading due to partial loss and stiction has induced a coupled motion in lateral/directonal modes.

Fig.3.1 shows that the FLC reduces the perturbed α and θ to equilibrium in 3.5 seconds after the damage occurs. The maximum overshoot is about -0.25 rad and -0.20 rad for the θ and α, respectively. Small oscillations are observed for both variables, as well as a small steady state error of about 0.01 rad for the θ. The oscillations and small steady state errors are results of the limited resolution in the level of discretization of the universe of discourse. If a finer discretization level is used, the steady state response will be improved.

Fig. 3.2 shows that δ_H stays within the prescribed limit of 0.52 rad despite the occurrence of Fault I. δ_H oscillates around 0.1 rad and never settles to zero. The non-zero value is necessary to balance the positive pitch moment generated by the stuck right stabilator. Fig. 3.3 shows the lateral/directional dynamics after Fault I. Since the control authorities of the ailerons and rudder have been halved, the time response is slow and overshoots are greater. Similarly, Fig. 3.4 shows that the higher aileron deflection is required to compensate for the smaller control derivatives.

Fault II

Fault II represents a more severe scenario, where the right stabilator is completely lost due to damage. The resultant dynamics are qualitatively similar to the ones in Fault I, but of a greater magnitude. The complete loss of the right stabilator has altered the Cm_α value to 0.0927. The positive Cm_α indicates that the longitudinal stability has been lost as a result of the damage.

Fig 4.1 shows that, despite the loss of stability and much reduced control power, FLC is able to reduce α and θ, and stabilize the aircraft. Compared to Fault I, the time response in Fig. 4.1 is slower and the overshoot is higher as to be expected. A similar situation applies to Fig. 4.2, where the stabilator deflection is noticeably greater than the previous case. The longitudinal response has a settling time of around 5.5 seconds. In Fig. 4.2, small oscillations are observed around 0.0 rad as opposed to 0.1 rad in Fault I. The complete loss of the right stabilator has eliminated the perturbing pitch moment due to a stuck stabilator.

The dynamic response in the lateral/directional modes and the aileron/rudder deflection history after Fault II are depicted in Fig. 4.3 and 4.4, respectively. The combination of stabilator loss and aileron effectiveness reduction has made an obvious impact on the rolling mode performance of the aircraft. Although the FLC applies maximum aileron deflection, the maximum rolling angle still reaches past 1.00 rad. Contrary to rolling, there is very little disturbance in the yaw direction, which is attributed to the lack of fault representation in the yaw mode.

In addition to the nominal flight condition, Fault II is repeated in three other flight conditions (Table 1), and the longitudinal response from these flight conditions is shown in Fig. 5.1 and 5.2. The control objective is met in all flight conditions. The higher overshoots and longer settling time observed in Flight Condition 4 may be attributed to the smaller dynamic pressure at this flight condition. Overall, the nominal FLC design demonstrates good robustness in operations at various flight conditions.

V. Conclusions

This study has shown encouraging results that demonstrate the FLC's ability to stabilize a damaged aircraft without the knowledge of the types of the fault or system parameters. It skips the complicated estimation process and applies direct control based on heuristics. The FLC design also exhibits great flexibility as one generic design accomplishes the design task under different faults and flight conditions. As a result, FLC presents a potential solution that bridges the critical time gap between the fault occurrence and the implementation of the new control law. Although the FLC simulation can be slower than a conventional controller design, proper hardware, such as a fuzzy chip, has great potential to expedite the performance of fuzzy logic controllers.

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	Flt. Cond. 2	Flt. Cond. 3	Flt. Cond. 4
Altitude (ft)	5,000	20,000	40,000
Mach #	0.8	0.8	0.8

Table 1. Other Test Flight Conditions

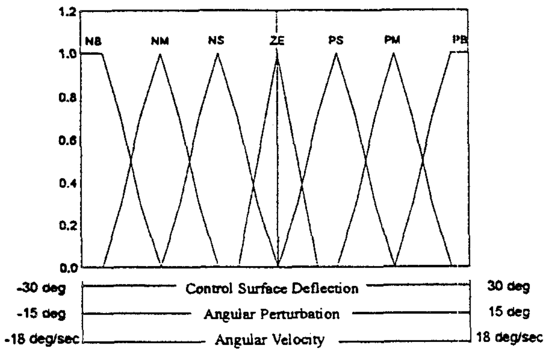

Fig. 1 Membership Functon Distribution

Angular Perturbation

Angular Velocity

	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NM	NM	PS	PM
NM	NB	NB	NM	NM	NS	PS	PB
NS	NB	NB	NM	NS	ZE	PM	PB
ZE	NB	NS	NS		PS	PS	PB
PS	NB	NM	ZE	PS	PM	PM	PB
PM	NB	NS	ZE	PM	PM	PB	PB
PB	NM	NS	PS	PM	PM	PB	PB

Fig. 2 The Generic Rule Base

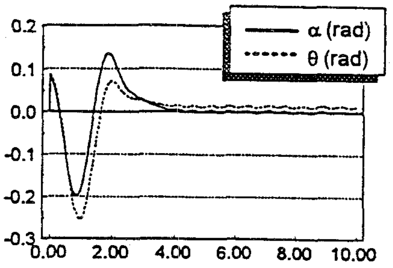

Fig. 3.1 Longitudinal Response of Fault I

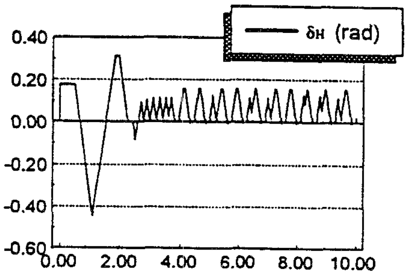

Fig. 3.2 Stabilator Deflection History of Fault I

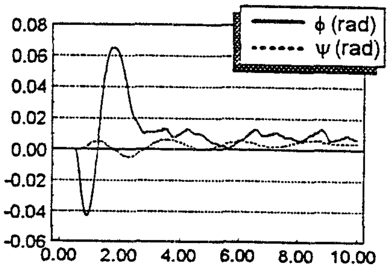

Fig. 3.3 Lateral/Directional Response of Fault I

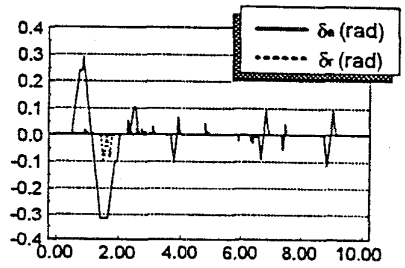

Fig. 3.4 Aileron/Rudder Deflection History of Fault I

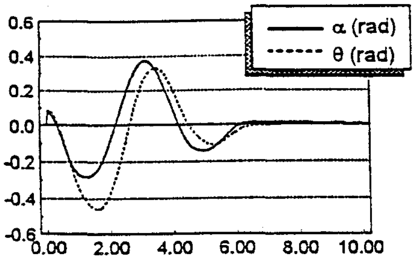

Fig. 4.1 Longitudinal Response of Fault II

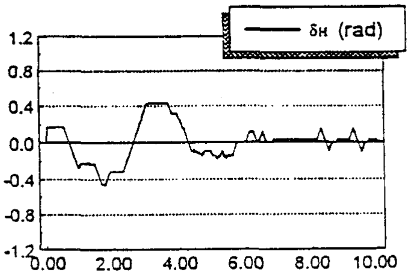

Fig. 4.2 Stabilator Deflection History of Fault II

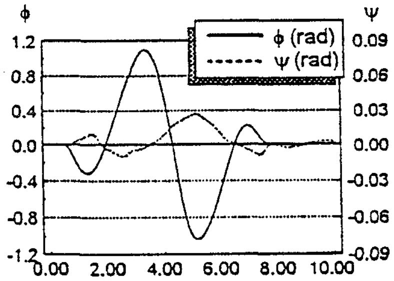

Fig. 4.3 Lateral/Directional Response of Fault II

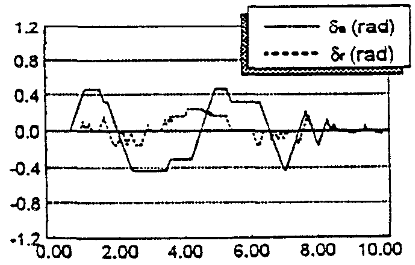

Fig. 4.4 Aileron/Rudder Deflection History of Fault II

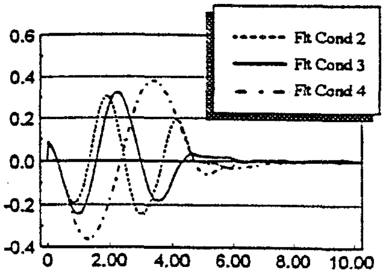

Fig. 5.1 Transient Response of Angle of Attack for Fault II in Different Flight Conditions

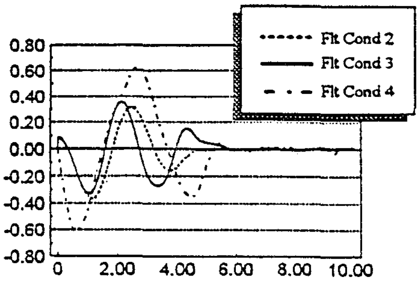

Fig. 5.2 Transient Response of Pitch Angle for Fault II in Different Flight Conditions