FLIGHT DEMONSTRATION OF FAULT TOLERANT FLIGHT CONTROL SYSTEM

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Abstract

This paper presets flight demonstration of fault tolerant flight control system using a small model plane. Two types of fault tolerant controller based on neural network were developed to maintain automatic flight stability when failures suddenly occured in airframe structure. To simulate the sudden structure failure, a 1/10 scale business jet type model plane with wing-tip separation device was designed and an automatic control system installing fault tolerant controllers was developed. Flight experiments were carried out under the following scenario; the model plane flew automatically aiming four prescribed waypoints, the wing tip was separated suddenly by a command signal from the ground station, and the performance of fault tolerant controllers were investigated. The flight results could demonstrate the effectiveness of the developed controllers which adaptively regulated the serious damage of airframe structure during the flight.

1 Introduction

In many future forecasts, the economic growth and demographic changes in the emerging economic nations can drive the steady increase of air traffic flow over the next 20 years. On the other hand, the fatal accident rate has remained almost constant for the past twenty years [1]. Therefore further reduction of the fatal accident rate is essential to prevent the increasing number of fatal accidents. Airline accident incident statistics [2] shows that the major accidents can be attributed to Loss of Control In-Flight (LOC-I) caused by a piloting mistake, technical malfunctions or unusual upsets due to external disturbances. It is expected that a fault tolerant flight control, or a resilient flight control improve survivability and recovery from adverse flight conditions induced faults, damaged and associated upsets [3].

While many research projects associated with the fault tolerant control have been carried out, it is very difficult to demonstrate the control performance for real airframe structure failure cases since the airworthiness should be satisfied for aircraft operated by a human pilot. One possible demonstration is the use of a scale model as unmanned aircraft. The flight test of a fighter type model plane with wing structure failure was presented [4], but flight tests for a civil type model plane with stricture failure have not been presented. The authors designed a business jet type scale model plane with wing tip separation mechanism as a model of wing structure failure. It is because there are strong indicators of an increasing market for business jet both in developed and developing counties, however it is reported that the fatal accident rate for all business jet civil operations is more than eight times that for large jet passenger aircraft in airline operation between 2000 and 2007 [5]. Therefore, a business jet type scale model was selected in our research project. Additionally, fault tolerant control system based on software algorithms is suitable for a small business jet since the use of expensive hardware devices such as redundant control surfaces is strictly limited through the viewpoint of cost or available space.

Fault tolerant control algorithms based on neural networks (NNs) are investigated in our project [6]. NNs are a mathematical model that is based on biological neural networks. It is recognized that NNs have a high capability to model a complex nonlinear system and they are used in a nonlinear adaptive controller [7]. Two types of controller have been studied. One is a feedback error learning (FEL) method and the other is a nonlinear dynamic inversion (NDI) controller method. In a feedback error learning method, NNs are added parallel to the conventional feedback controller where NNs are modified to minimize the feedback signal. In a nonlinear dynamic inversion method, NNs are used to minimize the error between the mathematical model and the real dynamic model.

2 Adaptive Flight Control Using Neural Networks

When sudden change of dynamic characteristics occurs in airframe structure failure during the flight, a conventional autopilot or autothrottle may be insufficient to maintain stable flight. In these cases, a human pilot has to control the damaged aircraft manually. This increases significantly pilot workloads which may cause serious accidents.

The authors' team has been developing adaptive control systems using neural networks (NNs) which are a mathematical model of biological neural networks. Two types of NNs controller are investigated in this project. One is the online modeling of an error function in a nonlinear dynamic inversion (NDI) controller, and the other is the online learning in a feedback error learning (FEL) controller [6]. NDI realizes the linearlization of the controlled system using system matrices as shown in Fig.1. When the mathematical characteristics change due to failures, NNs are adapted to minimize the error between the model outputs and the sensor outputs during the flight.

FEL which is an analogy of a biological control mechanism utilizes NNs as a feedforward controller attached on a conventional feedback controller. NNs are adapted to minimize the feedback signals as shown in Fig.2. As a result, the NNs will acquire an inverted dynamic model of a system even if the dynamic characteristics change due to failures.

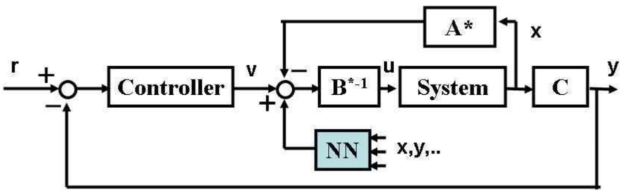

Fig. 1 Basic Concept of NDI Controller with NN

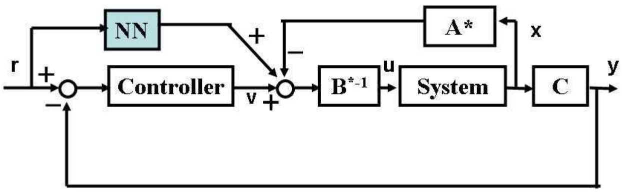

Fig. 2 Basic Concept of FEL Controller with NN

3 Flight Experiment System

3.1 Model Plane

A business jet type model was considered in this project. The outer shape was designed as a 3D CAD model (Fig. 3) by FHI (Fuji Heavy Industry Ltd). The student team at UT (The University of Tokyo) constructed the model plane with 1.4 meter body length and 1.4 m wing span. As shown in Fig. 4, the fuselage and the vertical tail fin were made of CFRP with wood frames. As shown in Fig. 5, the main wing and the horizontal tail were made of balsa with surface film cover. Two electric ducted fan units were mounted on the fuselage. In order to simulate a wing structure failure, 26% of the right wing tip (Fig. 6) can be injected during the flight when a separation signal is sent from a radio controller.

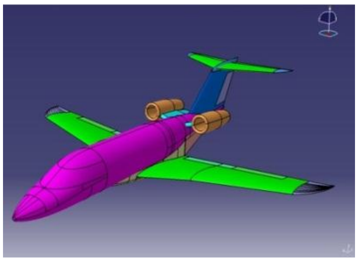

Fig. 3 3D CAD Model of Business Jet

Fig.4 Fuselage and Vertical Tail made of CFRP

Fig.5 Wing Structure and Wing Tip Separation Mechanism

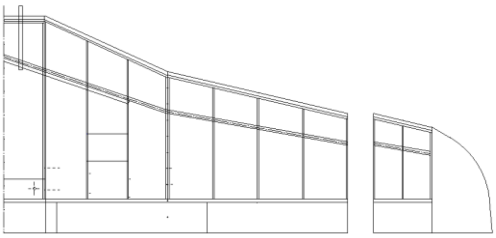

Fig.6 Wing Tip Separation (26% Semi Span)

3.2 Flight Control System

Fundamentally, the plane can fly as a radio control model plane. In the flight tests, takeoff and landing are controlled by a pilot on the ground. When the plane reaches a specified altitude, the pilot sends a command signal which changes flight modes from manual control to automatic control. An automatic control system is installed on the plane. As shown in Figs. 7 and 8 the automatic control system consists of GPS/INS (Global Positioning Systems/Inertia Navigation System), ADS (Air Data System) and Microprocessor. ADS and GPS/INS which integrates GPS signals with MEMS (Micro Electronic Mechanism Systems) accelerometers and gyros are used to estimate the position, the velocities, the angle of attach and the side slip angle by an EKF (Extended Kalman Filter) algorithm [8,9].

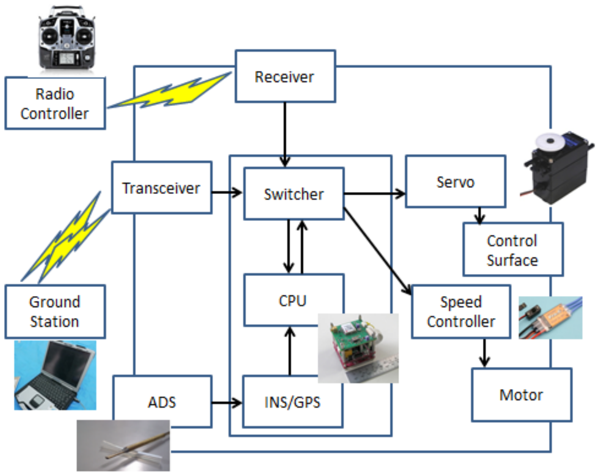

Fig.7 Flight Control System

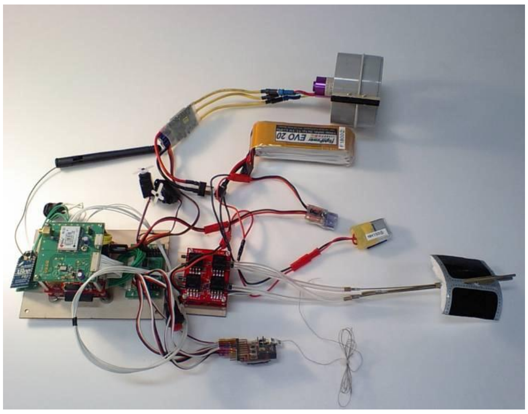

Fig.8 Avionic System

The following software systems are developed;

1) Guidance System

A waypoint tracking system is used as a guidance system. Waypoints are specified as a target point. The command bank angle is defined in proportion to the sight line angle which is the angle between the direction to the target and the ground velocity vector of the plane.

2) Fault Tolerant Flight Control System

Two types of fault tolerant flight control systems, e.g. NDI and FEL are installed on the onboard computer. In each system, the pitch angle, the bank angle, and the flight velocity generated in the Guidance Systems are used as command signals to generate the elevator angle, the aileron angle, the rudder angle and the throttle signal.

4 Wind Tunnel Test

Aerodynamic characteristics were obtained in the wind tunnel at FHI's Utsunomiya Plant. Aerodynamic date of a normal configuration was used for the controller design of the original model without failures. At the wind tunnel testing, aerodynamic characteristics of a failure configuration where a right wing tip was separated were also obtained. Those data were used to estimate the flight dynamics of a damaged model and to evaluate the performance of the fault tolerant controller in the flight simulations. It should be noted that those data was not used in the flight testing.

Since a wind tunnel model was a half scale of the flight model, free stream velocities of this test were 30, 40, 50, 60 m/s to adjust the Reynolds number of the flight test. The separation of the right wing tip causes the change of aerodynamic characteristics. Major changes are observed on lift coefficient, rolling moment coefficient and the yawing moment coefficient [10]. It is estimated that about 10 degrees of the aileron deflection is required to sustain the level flight.

Fig.9 Win Tunnel Model

5 Flight Test

The flight test was carried out at the Makurazaki Airport in Kagoshima Prefecture from 23rd to 27th January in 2011. At the first step, the model plane with normal configuration was tested by ground pilot operation. At the next step, the autopilot system was tested for the normal configuration. Finally, fault tolerant control systems were applied in the flight test where a right wing tip was seperated during the flight. It is noted that takeoff and landing were operated manually by a ground pilot in the autopilot flight and the fault tolerant flight tests.

Fig.10 Flight Model

5.1 Feedback Error Learning

Figure 11 illustrates the flight trajectory in the way point tracking when PID control without FEL (Feedback Error Learning) was applied. Four way points was specified at each corner of a 150x200 m rectangle. The altitude and air speed were specified at 100 m and 22 m/sec, respectively. The plane flies counter clock wise, and a black line, a blue line, and a red line mean manual flight, PID automatic flight before wing tip separation, and PID automatic flight after wing tip separation. This indicates that it was difficult to control the damaged plane when only the conventional PID control was applied.

On the other hand, Fig. 12 illustrates the similar results as Fig. 11 when PID control with FEL was applied. This shows that the plane could continue to track the way points successfully after the wing tip was separated. Figures 13, 14 and 15 show time histories of recorded pitch/bank angles and elevator/aileron deflections. In pitch and bank angles, red and blue lines indicate the command signal from the guidance control and the actual output, respectively. It can be observed that there is a discrepancy in the bank angle just after the wing tip separation. However, the aileron was controlled immediately and the bank angle could track the command signal after that. The bias in the aileron deflection indicates the FEL could generate compensating signals for the rolling moment unbalance due to the wing tip separation.

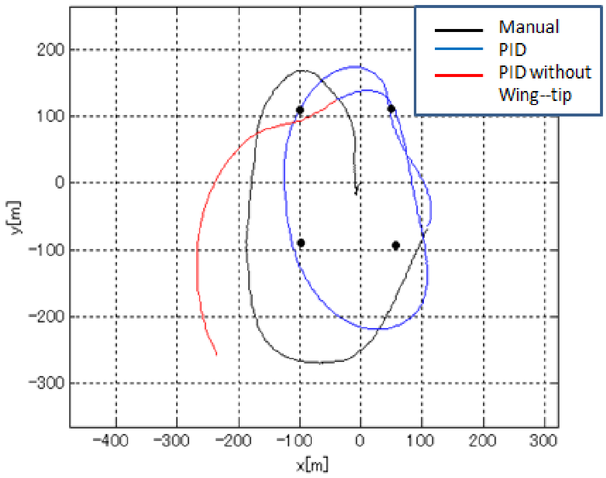

Fig.11 Flight Trajectory (PID control)

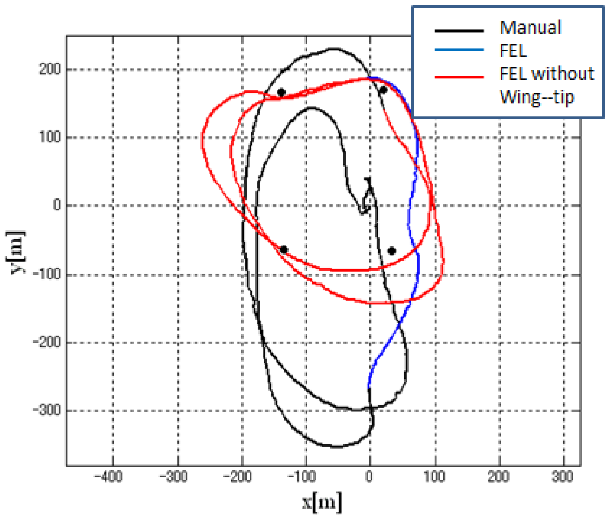

Fig.12 Flight Trajectory (FEL control)

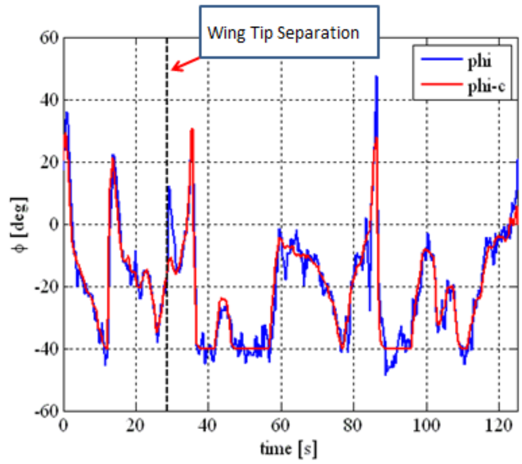

Fig.13 Bank Angle Time History (FEL control)

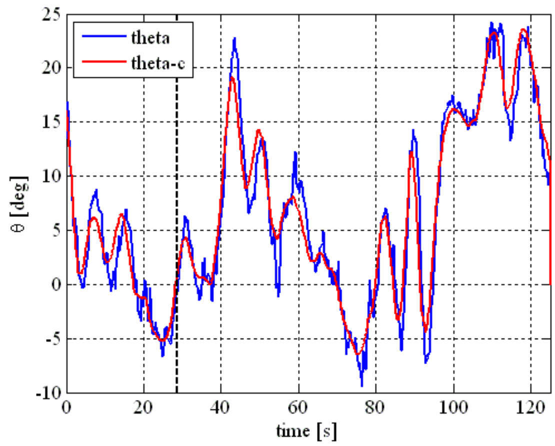

Fig.14 Pitch Angle Time History (FEL control)

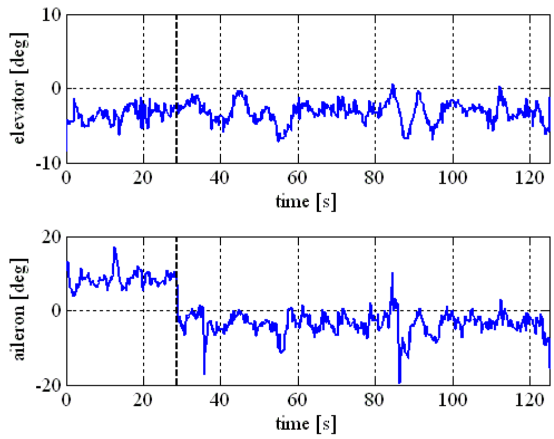

Fig.15 Elevator and Aileron Command Signals (FEL control)

5.2 Nonlinear Dynamic Inversion

The other type of fault tolerant controller NDI (Nonlinear Dynamic Inversion) was also successfully demonstrated in the flight test. Figure 16 shows time histories of states and control signals. When the wing tip separation caused unbalanced rolling moment, the aileron deflection command rose to recover the roll angle by generating a bias command. It can be seen that the pitch and bank angle can successfully track the command signals throughout the automatic flight after the wing separation.

Figure 17 shows video clips which demonstrate the stable flight after the wing tip separation.

6 Conclusions

Although it is very difficult to carry out the flight test of fault tolerant controllers when an airframe structure is actually failed during the flight, it is confirmed that the flight test using the model plane is effective in this project. A business jet type model plane with wing tip separation mechanisms was designed and constructed. An autopilot system including two types of fault tolerant controller based on neural networks was developed and flight test was carried out. The flight test could demonstrate the effectiveness of adaptive characteristics in developed controllers when the wing tip was separated during the flight.

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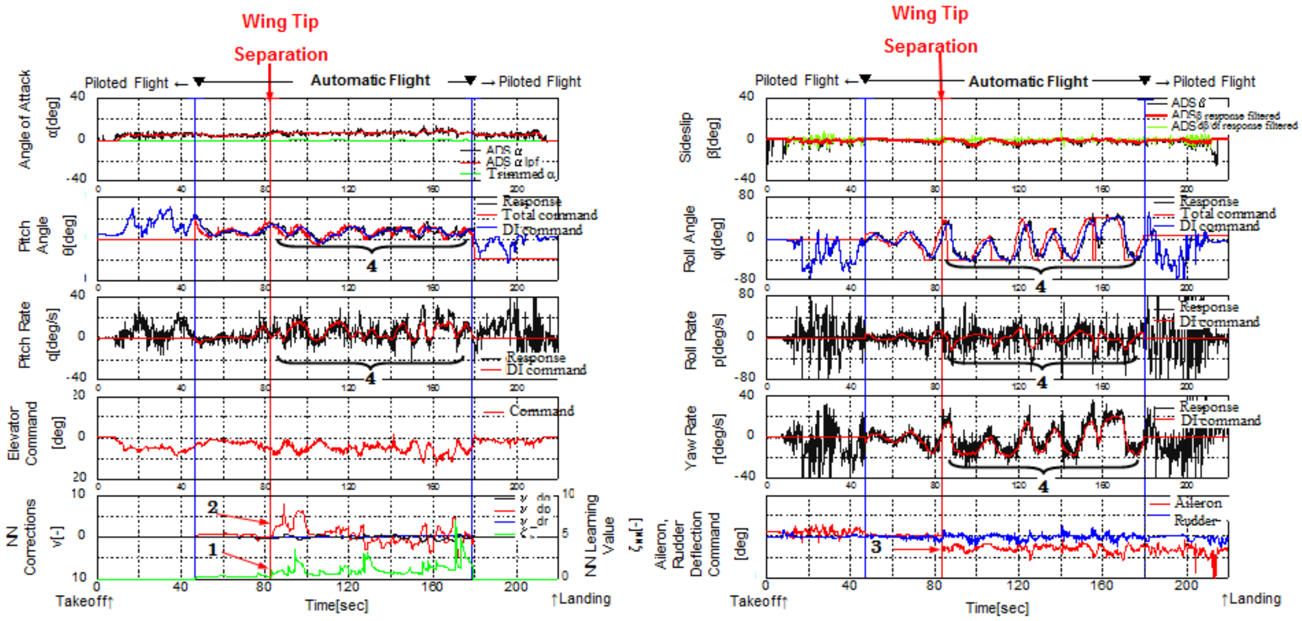

Fig.16 Time Histories of Recorded States (NDI control)

Fig.17 Video Clips of Flight Test at Wing Tip Separation