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Scientific-Research Article

Designing a Fault-Tolerant Control System for the Boeing 747

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This article examines the fault tolerance control (FTC) system for the Boeing 747. to reach this goal, firstly 6 degrees of freedom equations are simulated and linearized by using dynamic inversion method. Then, the system is controlled by a linear proportional-integral-derivative controller. To control this system, the angular velocity loop (r, q, p) must be closed and use cascade control to achieve this goal. Faults such as actuator and sensor failure are injected into the system, and by adding an integrated gain to the controller, the system resists these faults. Also, a redundancy system has been used in sensors to prevent sensor faults. Moreover, a linear Kalman filter has been used to eliminate noise in the system. If an actuator is locked in the Boeing 747, the faulty actuator is removed from the control system. Then, a healthy actuator or other remaining actuators will eliminate the effects of this fault.

Keywords: *Fault-Tolerant Control System, Dynamic Inversion, Redundancy System, Linear Kalman Filter*

Introduction

A Fault-tolerant control system is a system that can maintain the aircraft's performance against possible faults. The system must have a mechanism to detect, isolation and change the configuration to achieve this purpose. With the feedback received from the output, it is possible to determine whether the system has a fault or not. The detection mechanism specifies the system's part with a fault. Finally, the configuration change mechanism modifies the configuration of the control system if necessary so that the system is free of faults. In some configurations, the robust control method is used to make a fault-free system, and there is no need to change the configuration in this method.

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Review of literature

Zhong (2014) investigated the faults in airplanes such as actuators, sensors, and components faults. Different types of Fault-tolerant control systems are examined, and the actuator fault is corrected online.
Khorasani (2018) described the fault-tolerant control system in general and explained it for different gas turbines and aircraft systems. The article categorized different types of fault-tolerant control system.
Lombart et al. (2009) simulated the fault-tolerant control system for the Boeing 747 and implemented the same system in the simulator of Delph University in the Netherlands. A nonlinear

adaptive control method with dynamic inversion was used.
Blanke et al. (2006) fully described the fault-tolerant control system. In section 7 of this book, different types of fault-tolerant control systems, including active and passive systems, as well as the architecture of the system are explained.
Adîr and Stoica (2013) had the fault-tolerant control for a quadrotor. First, a PD controller was used for the Euler angles and height, which had a good performance without fault. However, with fault occur in the actuator, angles and heights did not reach their desired value. By adding a PI controller before PD in each mode, the fault tolerance was done without fault detection, and the device's output reached the desired value.
Megna and Szalai (1977) have described the hardware redundancy for an FBW aircraft (Fly-By-Wire). Hardware redundancy was used in the FBW aircraft to increase reliability. For example, several flight computers are used to issue control commands to use one flight computer. In the FBW system, the pilot cannot control the surfaces directly, and the pilot's command reaches the surfaces using the flight computer.
For this purpose, instead of using a flight computer, three or four flight computers are used, and also, instead of using one sensor, three or four sensors are used in the flight control system. This reference also describes the fault detection mechanism using the fault tree.
Torres-Pomales (2000) has explained software redundancy. One of the advantages of this method is that there is no need for an additional sensor or system, which in turn reduces costs. In some cases, it is impossible to design a hardware redundancy, so software redundancy is studied. On the other hand, to implement this method, the system must be entirely and perfectly simulated, which requires a complete identification of the system.
Lombaerts et al. (2011) has suggested a configuration change method for the fault-tolerant control system. This method involves online physical detection with inverse nonlinear adaptive control.
Choudhary (2019) has described the voting mechanism between n modules in the redundancy system, which is done according to the importance of each channel (primary or secondary channel).
Collinson (2011) has explained the FBW flight control system and the requirements observed in this control system. The redundancy system must be used in this control system. For this purpose, a quadruple redundancy system has been used in this system. Also, the voting mechanism of sensors allows the second data to be selected from the bottom in the systems.
Kornecki and Hall (2004) have described Boeing and Airbus aircraft's FBW flight control system. This system has been used on missiles and drones. Due to the high security needed for passenger aircraft, this system was used with a slight delay. The article has investigated the safety source required for this system in passenger aircraft.
Mulcare et al. (1988) described the digital flight control system with quadruple redundancy for aircraft. According to this reference, systems with quadruple redundancy can maintain system performance against two faults. The article presents the analysis, implementation, and validation of this system.
Asadi (2013) has designed a nonlinear, robustness multi-input and multi-output fault tolerant control system. By using the potential function method, the author has designed an optimal route so that in the event of a failure, the aircraft will begin to approach and land in its optimal route.

Significance of the study

In this paper, an attempt has been made to simulate the Boeing 747 aircraft equation, and the equations have been linearized using the dynamic inversion method. The aircraft has been controlled using the proportional–integral–derivative controller. The effects of faults of different parts (sensor faults, component and sensor faults) are investigated in this simulation, and an attempt is made to eliminate the effects of these faults in the system using different methods, including adding an integral gain, using a Kalman filter, detecting a failed actuator and removing it from the control system.

Article layout

In the first section, similar works and the general layout of the article are examined. In the second part, the possible faults that may occur in the aircraft are investigated. In the third section, the fault-tolerant system is examined in general. The fourth section describes the simulations performed for the fault-tolerant control system. Finally, in the fifth section, the results are summarized and presented.

Identifying possible faults in the aircraft

In order to design a fault-tolerant control system, the system faults must first be identified. In this section, an attempt has been made to review the faults that led to a Plane and investigate the effects of these faults on the aircraft.

Actuator faults

Actuator faults can be classified into three general categories.

Bias faults: The actuator is applied differently to the control command.

Locking faults: These faults are divided into two categories, lock in the current state and lock in the final state.

Floating faults: If the aircraft hydraulics are lost, the control surfaces have no force and become floating. Figure 1 shows one of the actuator faults that occur in aircraft.
Some actuator faults are listed in Table 1.

Figure 1: Rudder lock in final position on Airbus [1]

Table 1: Examples of actuator faults [1]

Actuator faults	Example
Locking faults in the current state	In 1977, Flight 1080, Lockheed L-1011, the Left elevator was locked in place, and the aircraft made an emergency landing.
	In 2000, the MD-83 plane crashed due to the lock of the elevator. Eighty-eight people were killed.
Locking in the final state.	In 2002, the rudder of a Boeing 747 was locked in its final position, and the plane made an emergency landing, causing no damage.
	In 1994, the rudder of a Boeing 747 was locked in its final position. One hundred thirty-two people were killed.
Floating fault in the trim state	In 1985, the Boeing 747 lost its hydraulics and was out of control. Five hundred twenty people were killed.
	In 2003, the Airbus 300 crashed due to hydraulic loss of all its control surfaces, and the plane made an emergency landing.

Component faults

Component faults are generally divided into three categories: faults at aircraft control surfaces or structures, engines, and flight computers. Some of the component faults that led to the accident are listed in Table 2.

Table 2: Examples of component faults [1]

Component faults	Example
Faults at control surfaces or aircraft structures	In 1985, part of the fuselage was detached, 520 people were killed.
Engine	In 2009, a 320 Airbus lost both engines, and the plane made an emergency landing on the water. There were no casualties in this accident.
	In 2008, the engine of the Boeing 777 did not respond appropriately from the cockpit to the automatic throttle, and the aircraft reduced its uncontrollable altitude.
Flight computer	In 2005, a Boeing 737 crashed due to autopilot failure.
	In 2000, the autopilot of a Boeing 747 gave an incorrect response due to incorrect repairs.

Sensors faults

Sensors faults include bias, noise, loss of accuracy, drift, and freezing.
Bias fault: As in figure 2, bias fault occurs when there is a constant discrepancy between the sensor output and the actual value.

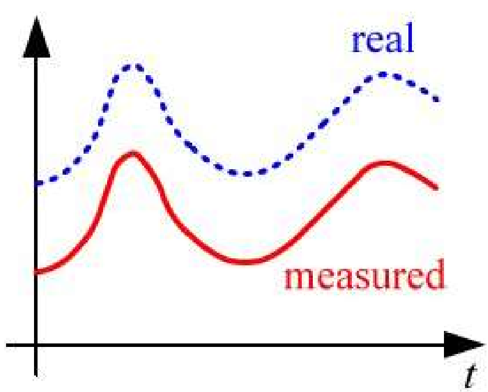

Figure 2: An example of bias fault for sensors [1]

Drift fault: In some cases, the value measured by the sensor slowly exceeds the original value, and as time passes, the fault value increases, which is called the drift fault and is shown in figure 3.

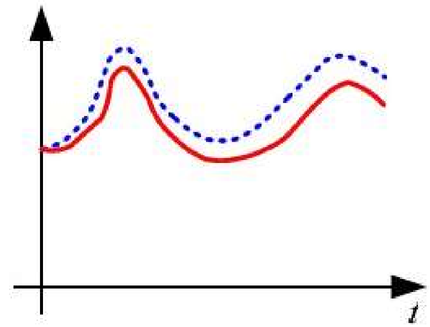

Figure 3: An example of deviation fault for sensor [1]

Loss of accuracy fault: When the measuring device never displays its correct value, as shown in figure 4, loss of accuracy fault occurs.

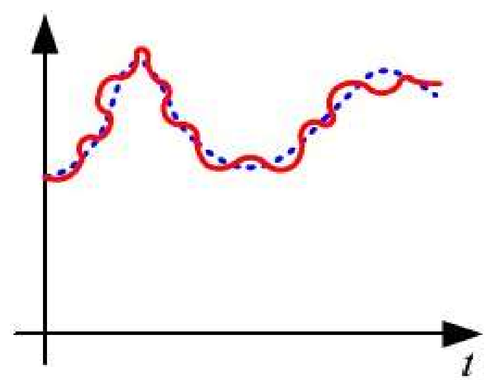

Figure 4: An example of loss of accuracy fault for sensor [1]

Freezing fault: In these cases, the sensor displays a fixed value, regardless of its actual value, as in figure 5.

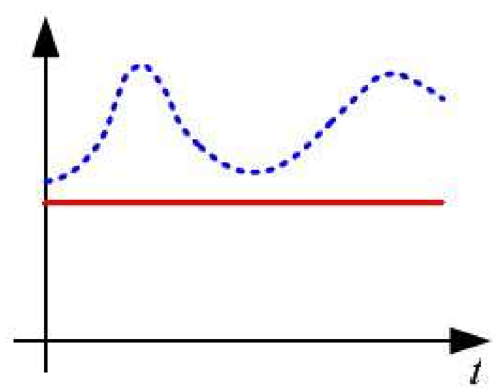

Figure 5: An example of freezing fault for sensor [1]

Noise fault: Data is displayed with some noise in sensors with noise fault. Knowing the amount of standard deviation and frequency of noises is necessary to simulate them in a MATLAB environment. In this paper, by examining the existing sensors, the standard deviation is considered 0.2, and the noise frequency is equal to 500 Hz.

Fault-tolerant control system

A fault-tolerant control system is divided into two general categories: software and hardware. The general structure of these systems for the flight control system is shown in figure 6.

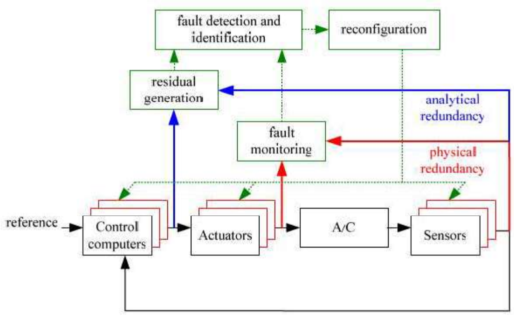

Figure 6: General structure of the Fault-tolerant control system for the flight control system [1]

One of the most critical parts of a Fault-tolerant control system is the fault detection mechanism. This part is shown in figure 7. This section detects faults using additional data generated from analytical and hardware redundancies.

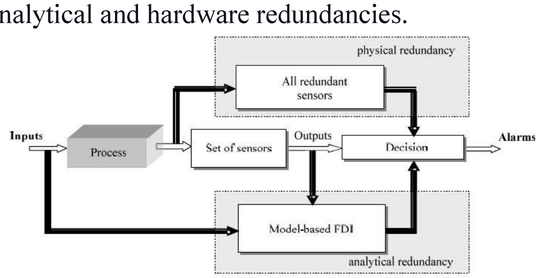

Figure 7: General structure of the fault detection part

As shown in figure 8, the data obtained from the model and the sensors are subtracted in the fault detection mechanism, and the residual value is generated here. By comparing these residues with each other, this mechanism can detect faults in the system.

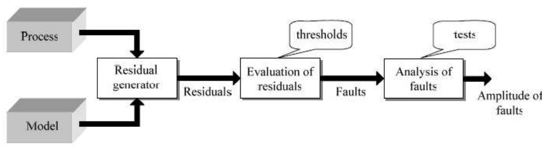

Figure 8: fault detection mechanism using residual output [1]

Hardware fault-tolerant control system

Hardware redundancy is the other Fault-tolerant control system. As in figure 9, four sensors are used in this type of system instead of one. This system applies not only to sensors, but also to flight computers and actuators.

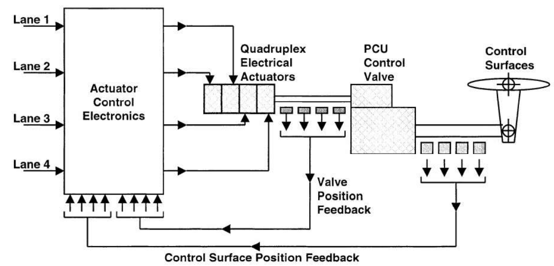

Figure 9: Flight control system with quadruple redundancy [10]

As in figure 10, voting must occur in the system with redundancy. Regardless of how the voting is done, one voter is placed on each channel. These voters determine which channel is connected at each moment.

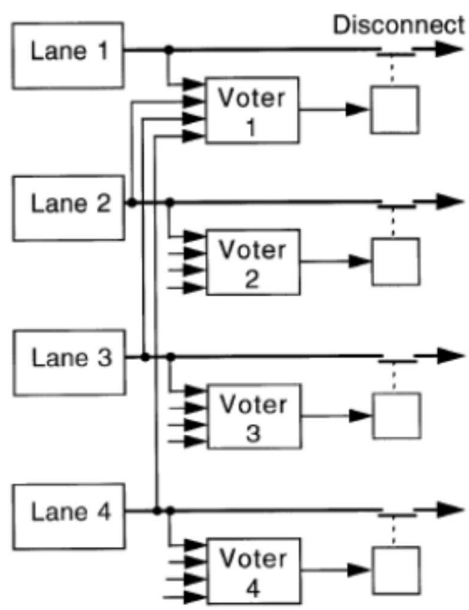

Figure 10: Quadruple redundancy system with voting [10, 11]

Software fault-tolerant control system

This system is divided into two general categories, active and passive, as in figure 11. Various robust control methods are used in the passive method to make the system free of faults. Both the adaptive and multi-model control methods are used in the active method.

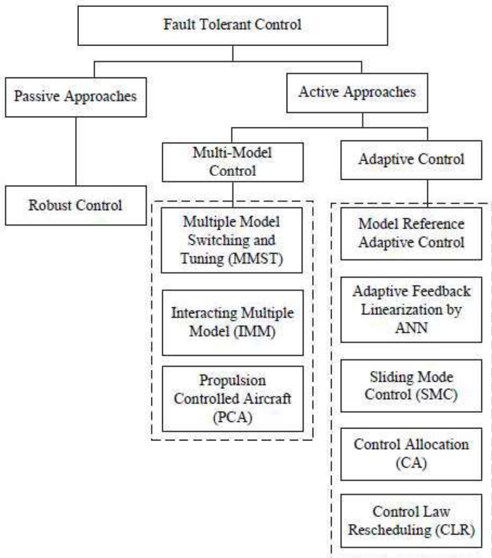

Figure 11: Classification of methods of software fault-tolerant control system [1]

Simulation of fault-tolerant controller system

For simulation of a flight control system, it is necessary to examine it in general. For this purpose, figure 12 shows a flight control system in general. As can be seen from the figure, the flight control system includes:

1. **Pedals and sticks:** Series of motion sensors deliver the pilot's command to the flight computer. Therefore, the flight computer will understand the pilot's command if these components are moved.

2. **Flight computers:** Flight Computers take feedback of the pilot from pedals and stick and control, surface based on pre-defined constraints.

3. **Sensors:** The sensors in the flight control system are responsible for giving feedback to the control system (flight computers).

4. **Actuators:** They move the control surfaces.

5. **Control surfaces:** control surfaces are moved based on the actuators to allow the pilot to use these surfaces to control the aircraft.

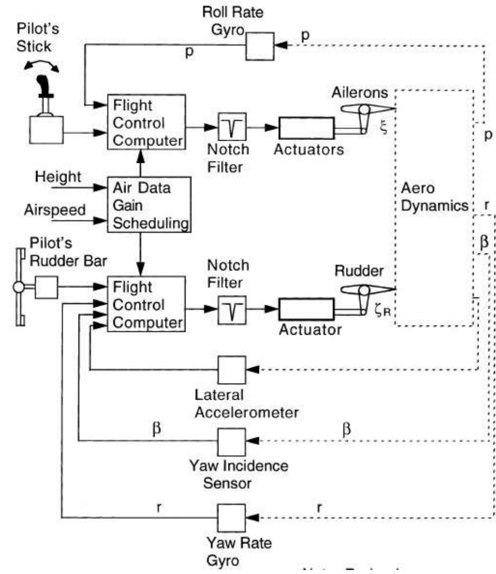

Figure 12: FBW Flight control system [10]

Figure 13 shows a schematic of the fault-tolerant control system implemented in this paper. This system consists of the following blocks.

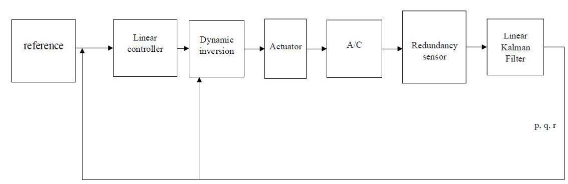

Figure 13: Fault-tolerant control system

1. **Aircraft equation block:** The equations of six degrees of freedom are given for the Boeing 747 aircraft in this block.

2. **Dynamic inversion Block:** This is a dynamic inversion controller block.

3. **Actuator block:** In this block, the function of converting actuators is given, which is generally the function of converting the actuator as a delay. Of course, two points must be considered in this block: the actuator saturation limit and speed, where the actuator saturation limit is 30 degrees and the actuator speed is 30 degrees per second. A fault detection mechanism is implemented in the actuator. If the actuator's output data differs from the actuator input data coming from the flight computer, the actuator fails. Actuator fault is applied in two ways: bias and actuator lock fault. If the actuator has a bias fault, the system can be partially controlled against this fault using the controller integral gain. However, if the actuator is locked in the trim or final mode, it must first be

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determined that this actuator is failed. The detection mechanism is such that if the output of the actuator is constant and this constant value is not the command of the control command, it is detected that the actuator is failed. This faulty actuator must then be removed from the control system because the Boeing 747 has several control surfaces for each channel.

4. **Linear controller block:** A proportional and integral gain is used in this controller. The proportional gain regulates the system's response speed, and the integral gain makes the system somewhat resistant to faults.

5. **Hardware redundancy block:** Multiple sensors are used instead of one in hardware redundancy. This method makes the system itself resistant to sensor faults. It should be noted that when four sensors are used to measure data, voting must be done between these data. According to Reference 10, there are various voting methods that first sort the sensor data in ascending and descending order. As in figure 14, a middle-lower value is selected between these data.

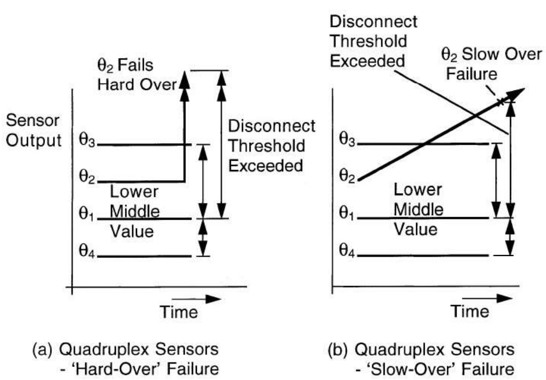

Figure 14: Sensory data with quadratic redundancy [14]

6. **Linear Kalman filter block:** In this block, the input and output of the control system are entered, and also the system must also be implemented in this block as a state space. The output of this block is the output of the sensors without noise. Reference 14 describes the Kalman filter for the linear system. The aircraft equation block and the dynamic inversion are neutralized together. The actuator block, which is a function of converting a delay, can also be ignored. The new block diagram is also shown in the exact figure. This block is drawn assuming that the linear controller is a simple gain with a value of 4. According to the new diagram block drawn, the state space for the system becomes the same as Equation 1.

$$\dot{X} = [4 \quad -4]\begin{bmatrix} u \\ y \end{bmatrix}$$

$$y = [0 \quad 1]\begin{bmatrix} u \\ y \end{bmatrix}$$

Simulation

In this simulation, the following target is considered: Reach the angular velocity ([p q r] = [2 5 1]) degrees per second in different modes

Case 1: The system reaches the desired value without faults and only uses a simple gain.

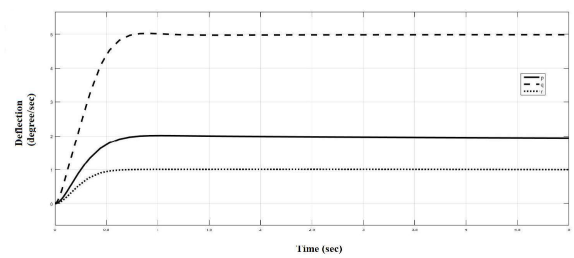

Figure 15: Sensor output in fault-free mode

Case 2: The system has a 5-degree offset fault for actuator. As shown in figure 16, the offset fault check in the control system shows that the system output does not reach the desired value if the actuator has an offset. It may reach the desired value with some difference.

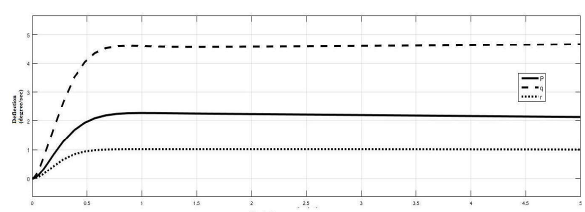

Figure 16: Sensors output when actuators have a bias fault.

Case 3: the actuator bias fault in the system is compensated by adding the integral gain, as shown in figure 17. The system overshoot and then sets to the desired value by adding the integral gain.

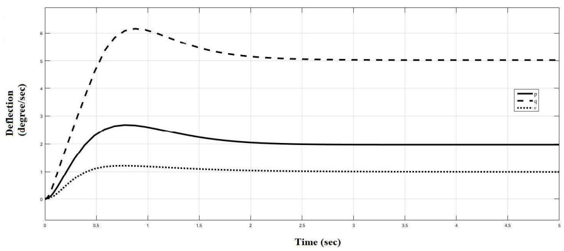

Figure 17: sensors output with bias fault of the actuators and integral gain

Case 4: The sensors have noise. As shown in figure 18, noise with a standard deviation of 0.2 degrees and a frequency of 500 Hz has been entered into the system.

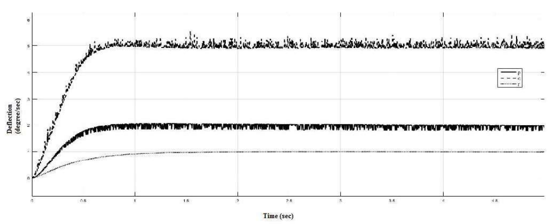

Figure 18: Sensors output after adding noise effect on sensors

Case 5: As shown in figure 19, the noise effects are completely removed using the Kalman filter.

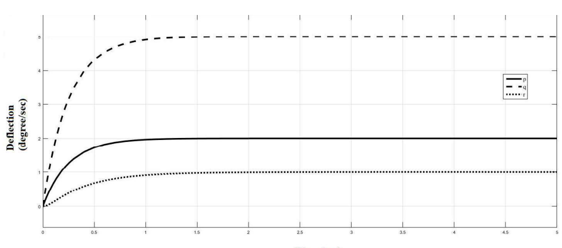

Figure 19: Noise-free sensor output using Kalman filter

Case 6: One of the elevators is locked at 5 degrees. Figure 20 shows the variation of the control surfaces in the case where both control surfaces are well, and figure 21 shows the case in which one of the control surfaces is locked and shows the amount of changes in the intact actuator. As can be seen, when a control surface is locked, the healthy control surface must make further changes to compensate for the effects of the locked control surface.

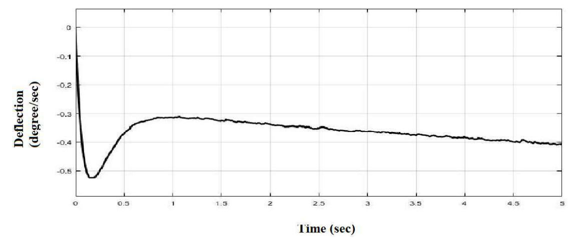

Figure 20: Elevator variation without failure

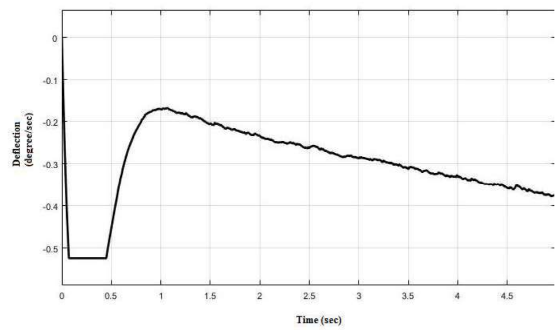

Figure 21: Elevator variation when one of the elevator is locked.

Conclusion

In this paper, a fault tolerant control system is designed for the Boeing 747. Firstly, possible Failure in this aircraft were investigated and a solution was proposed for each failure. In the simulation performed in this paper, actuator and sensor failures were injected and it was tried to make the system resistant to these errors by using various methods such as adding integral gain to the controller and adding redundancy to the system. When actuator failed in this system, firstly these failures must be identified and removed from the control system, and its effects are compensated by using an alternative stimulus.

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