Optimal nonlinear control of flight faults in manned aircrafts in the presence of fault and failure of control actuators

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Abstract*:*

Control actuators' faults are among the major reasons to lose aircraft control while flights. The plane dynamics is severely dependent upon faults and errors in flight control systems and if the reformed control order is not issued by the fault tolerant controller there would be unpleasant outcomes such as inconsistency and the reduction of system performance and some dreadful aerial accidents will occur. This research includes the presentation of a fault tolerant control technique based on nonlinear optimal control method using Rekaty equation related to the state. The characteristics of nonlinear optimal control method entail the possibility of novel aircraft modeling and restructuring of the control systems when a fault occurs and this increases the possibility of flight save. The two scenarios of error and failure include the reduction of elevator efficiency and the exclusion of aileron of a great business aircraft from being controlled and the optimal function of nonlinear method compared with linear optimal control. It is the first time that this technique is used in local research projects as a control method. The results of simulations proved the effectiveness of the proposed approach in consistency retrieval and the preservation of flight route. Several linear and nonlinear controllers have been planned and implemented to control the position and status of flights. During some recent decades and due to lack of ability in linear control systems, there has been extending developments in methods such as linearization with feedback, interest tabling, return to past method, slide mode control, adjustment control, Thus, the goal of the present research is to design a nonlinear controller with a resistant approach for the systems. Also the simulation results showed efficiency of the controllers in flight consistency and system direction. The goal of the present study is to know different aircrafts especially Boeing 100-747, to study about the actuators' failures and to investigate about different types of aerial disasters and their reasons, to know different controlling and comparing techniques with nonlinear control technique and to design active controllers using nonlinear techniques for a Boeing 747 flight aircraft.

Keywords: nonlinear control; fault and failure; control actuators

1. Introduction

Piston motors were along with aircraft wings since the invention of aircrafts by Wright brothers in 1903 to the end of World War II. Here it should be noted that an aircraft needs thrust to move. Meanwhile, piston motor creates power and it is the wing that changes power into thrust. According to the third principle of Newton, each action has a counteract equal to it and in the opposite direction and the wing rotates and gives a certain velocity to certain air particles. Thus, based on F=mc, it enforces a force in the air backwards and the reaction to this force provides a force forwards of thrust. But, the limitation of wing is that it cannot enforce much velocity onto the air. Thus, it is mostly dependent on air.

These points refer to the fact that first the speed of an aircraft with wings is low and its' flight capacity is limited. As we know from aerodynamics, since there is low air mass in high lands, the drag would be low, and we need less thrust and this means less fuel consumption. But as we stressed, wing is not so useful in such heights due to low density. These issues forced the aircraft scientists to find an appropriate alternate for piston motors which finally appeared in jet motor formats. Jet motor also acts based on Newton's third principle and its difference lies in the fact that it enforces great velocity on a small mass of air. Thus, it can achieve high speeds and since it depends less on density, it would be able to work well in high heights. The item jet basically means a pipe or reckoned pipe and jet motor which is basically formed of a set of precisely calculated routes are called so and it is interesting to remind here that some jet motors lacking the rotators such as Ramjet, Pulsejet, Rocket engine. But the jet motors we encounter in aircrafts entail rotating pieces such as turbines and thus they are called Gas Turbine Engines. Also it is because of the term turbine that we deal with different turbine jet motors such as Turbojet, Turboprop, Turbofan, and Turboshalt which will be described in details below.

Here we deal with nonlinear control of the analysis and design of nonlinear control systems. For example, we discuss about nonlinear control systems which at least entail a nonlinear element.

Through appropriate nonlinear control design for a flying vehicle with vertical take off and landing capabilities, we can use this controller to improve the performance and to enhance consistency area in real flying tools. The nonlinear controller should have a more appropriate behavior to resist against indeterminate and nonlinear system phenomena.

Anyway, physical systems are often nonlinear and we can not estimate many systems appropriately through using linear equations. Control theory advances have made us able to enter nonlinear states into a mathematical model and this can lead to achieve more efficient controls for a nonlinear system.

Some of innovative aspects of nonlinear control techniques are as follows: flexibility, adaptability, rapid and active response to the control system in the presence of fault and failures.

In this work it can be observed that the nonlinear control technique to control a flight is utilized in the presence of faults and failure of control actuators actively. Therefore, controlling different types of manned aircrafts is much more flexible in comparison with some other control techniques. It is useful actively in the presence of error and failure of control actuators.

2. Problem statement

Control actuators' damages are among the main reasons why an aircraft becomes uncontrollable while flying. The dynamics of the aircraft is seriously affected by fault and failure elements of flight control system and if a reforming order is not issued by the controller, some undesirable outcomes such as inconsistency and system performance decline will occur and some deadly aerial accidents will happen. This research includes a control technique of fault tolerance based on a nonlinear optimal control method using Rikati equations depending on the state. The characteristics of nonlinear optimal control method make it possible to start a novel aircraft modeling and a restructuring of the control system when a fault occurs and it increases the probability of aircraft saving. Two scenarios of fault and failure including the reduction of elevator efficiency and out of order state of aileron efficiency of a big business aircraft is investigated and the performance of the nonlinear optimal method will be compared with a linear optimal control. It is for the first time that this technique is used as the control method in local research level. The results of simulations approved the efficiency of the proposed approach in restoring consistency and preserving the flight route.

Significance

The overall goal of this research is to investigate about nonlinear control of fault tolerant flights in the presence of fault and failure of control actuators dealing with different practical and theoretical methods. The recognition of centers that can help to progress the present research is among the applied goals of it and these centers can be airlines and air-forces, etc. the final goal of this research is to find out the required weak points and strong points through nonlinear control of fault tolerant flights in the presence of fault and failure of controlling actuators.

The importance of nonlinear control of fault tolerant flights lies in the fact that it is necessary to consider different dimensions of the issue and to identify controlling functions precisely for the airlines.

To do so, the present study tries to investigate about weak points and strong points in passenger carrier aircrafts and this can release the ambiguities and inconsistencies and lead us to achieve methods to alleviate them.

This research is based on a theoretical and practical approach. During data collection, nonlinear control, fault and failure of control actuators will be investigated and the practical work will be conceptualized and then each of these concepts will be dealt with in isolation.

Literature review and background study

The dream of flying has been one of the biggest challenges of human beings for many years and it led to do efforts to realize it and to produce fly instruments. Aerial vehicles are divided into two types: with and without passengers; and each of them are utilized differently due to the specific flying capabilities.

On 17th December 1903two brothers from Ohio (the United States) flew their invented machine. "Wright Brothers" prepared and predicted all required machinery to do a safe and easy flight on 14th December 1903 and tried their very first test flights for their invented aircraft, but unfortunately their first flight was never successful. But finally they were succeeded on 17th December, only 3 days after that, to fly their singly motor aircraft for 4 times in the sky and could record their names for ever as the first human like birds. In year 1901, they could add a horizontal part or an elevator in front of the aircraft and could preserve the equilibrium in the length (or front to rear) of the aircraft. A year later, they also added a vertical part in the back of the aircraft to be able to lean the aircraft downwards and upwards and could fly it in the heights. In this way, they succeeded to preserve the aircraft equilibrium in all three dimensions (including length, width, and height) and could include required controlling tools in the major aircraft sketch. To supply the foregoing force for the aircraft they used a normal four-cylinders gasoline motor with 12 steam horse force and they benefited from aluminum in making its cartel to reduce the weight. Wright brothers selected Outer Banks of northern Carolina, a little distanced from railway lines and land transportation systems and also farther from the ships anchored in the seaside which was a suitable place for the proper winds to do their test flights. Their two-winged aircraft was taken off from a wooden rail with a distance of about 60 feet (more than 18 meters) and in a counter direction to the wind with a speed of more than 20 miles per hour (more than 32 kilometers per hour). In the very first test, Wilber flew a distance about 120 feet during a time period of about 12 seconds. Also the last and the longest flight done by Wilber was a distance of about 852 feet within 59 seconds. About noon in that day, one of the few observers of these flights, who was a young man called "Johnny Moor", boosted in joys, started to run along the seaside after seeing the success of Wright brothers and cried: "they finally succeeded, they finally succeeded, it's great they finally flew". Wilber Wright who had a shorter life died on 30 May 1912 when he suffered from typhoid when he was only 45 years old and his brother "Orwell" passed away on 30th January 1948 when he was 76 years old.

Losing the control of the flight while flying, is one of the most important factors in aerial disasters. Boeing reported in 2013 on aerial accidents of business jet planes with higher than 30 tons of weight during the years between 1959 and 2012. During the years between 1993 and 2012, about 18 air crashes occurred due to losing control while flying and they included 1648 deaths [1].

According to the reports by flight safety organization in England reported in 2013, losing the control of aircraft while flying has been the most common factor in air crashes of business jet aircrafts and turboprops [2].

"Losing flight control" was investigated by a team of specialists from all over the world to investigate about the air crashes related to flight control lose. Losing aircraft control while flying, may occur due to several reasons such as mistakes by the pilot or aircraft damages. Aircraft damage includes technical faults in flight control system- losing trust- damages in body parts, or military attacks, but in the present study we only deal with damages in flight control system, since the actuator often is known as the input in control system. Fault and failure of actuators are much more important factors than sensors or other control system elements in flight control system failures. In 2009 flight 447 of French airline with A330 Airbus crashed. Studies showed that this incident was due to the damages in wing spoilers and therefore the auto-flight system was damaged and the aircraft lost the control. As a result of this damage, the plane crashed Atlantic Ocean and all passengers were dead. This disaster and all other crashes remind us of the necessity of the presence of supplementary and alternative systems to appropriate proper control entries when damage occurs and this issue is posed as fault tolerant flight control systems [5].

Fault tolerant flight control systems refer to control system types that are automatically able to fix the system fault and can retrieve overall consistency and appropriate system performance in critical flight conditions when one or several faults occur. In other words, fault tolerant flight control system is a closed loop control system that can tolerate technical faults and in addition to preserving the system consistency, it enforces a satisfactory performance in control section [6].

During some recent years several control methods have been investigated in the form of active and inactive fault tolerant flight control systems. But few of these methods could be able to guarantee a safe landing in addition to rapid consistency preservation acts after faults occur. For example, in reference [7], sliding mode control method was utilized to follow pilot's entry orders on a military jet. In reference [8], a multiple model variable control theory was utilized through which each of the damages and controls related could be modeled in isolation. In reference [9], a comparative reference model adaptive control approach was applied to fix actuators' damages. The principal problem of most methods mentioned above is the lack of characteristics such as flexibility or adaptability and this challenges the process of control system design especially when we move from a model to another. In this study we have proposed an active fault tolerant control design using a nonlinear technique in order to compensate for the damages in control actuators of the aircraft which is able to react indefinite faults of the actuator actively through control structure change and in this way the consistency and performance quality of the damaged system will be preserved.

The aircraft investigated in this research is Boeing 100-747 known as jumbo jet. This enormous intercontinental aircraft with four turbofan motors has a set of advanced features that change it into a complete sample of a modern business aircraft [10].

Goals

- Acquaintance with different types of aircrafts especially Boeing 100-747
- Studying different damages in actuators and investigating about different air crashes and their reasons
- Acquaintance with different control techniques and comparing them with nonlinear control techniques
- Designing an active controller using a nonlinear technique for a Boeing 100-747 aircraft

Hypothesis

Nonlinear control technique to control a manned aircraft is more flexible in comparison with some control techniques and could be actively utilized in the presence of faults and failures of control actuators.

Research method

We have used the current and valid papers in a library study mode and have used valid and international scientific websites.

Slow and fast flight control channels

To have an efficient air transportation system, aircrafts have been equipped with different control channels. There has been a differentiation between rapid control channels with a dynamic outlook and slow control channels with a dynamic direction. Then, a rapid control channel has been designed for each major axis of the aircraft that could create moments and lets the pilot or autopilot to manage aircraft's rotary speed while slow control channels concern with the aircraft's aerodynamic structuring due to the movements of the aerial motors. A common rapid control channel for the fixed plane wing includes cabin control, computers, electric and mechanical tools connection, several aerodynamic moving panels, and force resources.

The type and size of the number of aerodynamic panels that should be controlled will change based on aircraft categorization. Figure 1.1 represents an old sketch of a big transportation plane with controllable aerodynamic panels. The panels shown in red (elevator, small wing, and helm) are called primary flight controls affected by rapid aircraft dynamics (pitch, roll, yaw). The other panels represented in blue color show secondary flight controls affected by overall aircraft aerodynamic structuring and the slow dynamic could be adjusted through controlling the positions of flops, slides, planes, and the horizontal fixers. The acceptance of such a frame helps the pilot to have a great ability in controlling in addition to ease of the activities of the pilot.

The problem and optimal control resolution method

First the old concepts and methods about fault tolerant flight control were reviewed and new concepts required to analyze them were introduced. Here we try to design a method for fault tolerant flight control through which if there is a partial fault in a stimulator, the aircraft is let to continue its way safely and easily. A two stage control approach also was proposed and utilized to assess the movement and to design fault tolerant flight control.

First, an offline handling movement quality assessment method based on model predictive control has been proposed. Second, a fault tolerant control structure based on a nonlinear inverse control and an online stimulator has been proposed. In both cases, a linear quadratic programming (LQ) has been formed and different fault cases have been taken into consideration when an aircraft does a classic maneuver. Three numeric solutions created in online and offline solutions regarding LQ issues were investigated and utilized.

Categorization of different flying vehicles

As a first step, all flying vehicles made by human beings could be divided into two main categories as follows:

Aircraft: space flying vehicles

Spacecrafts: non-space flying

To divide aircraft into a category we can consider different aspects. Regarding speed, we can divide aircraft into four types below:

Subsonic Aircraft ($0 < M < 0.7$)

Transonic Aircraft ($0.7 < M < 1.2$)

Supersonic Aircraft ($1 < M < 5$)

Hypersonic Aircraft ($5 < M$)

The difference between these aircrafts is due to their speed regarding the speed of sound. M represents the number in an aircraft through which the plane can fly with. This number refers to the ratio of aircraft speed and the speed of the sound in a height where the aircraft flies within. Due to the aircraft type regarding the speed, there would be different dominating rules.

Different types of aircrafts regarding wing types, there are two general categories:

Fixed wing aircraft

Rotary wing aircraft

The first type is called aircraft and the second type is called helicopter.

Aircrafts generally have fixed wings and the wing does not rotate while flying. But helicopter is a type of aircraft whose wing rotates around an axis during the flight.

Different types of aircrafts regarding having passengers

Considering the passengers, aircrafts are divided into two general types:

Manned Aircraft

Unmanned Aircraft

Unmanned aircrafts include directed missiles, rockets, remote piloted vehicles (RPV).

Aircraft movement axes

An aircraft can have other controlled movements in addition to what an automobile can do, and they will be introduced in brief below. It is possible to move round three different axes of the aircraft through certain control panels that can be controlled by a pilot using an aircraft direction lever. Gravity is a force that pulls the aircrafts downwards. Therefore, to fly, the aircraft's wing should create an elevator force stronger than gravity. Aircraft's take off is done through air pressure under and over aircraft's wings. As an aircraft moves forward, the air moving on the wing (the over wing part in convex form) is more than the air moving under the wing. Also, this air moves faster. This leads to enforce air pressure on wings' floor. Then, the stronger pressure under the wing arises the aircraft. The aircraft needs movement to go up. The jet motor causes the aircraft to move forwards in a way that it can take off. To move upwards and go higher, the pilot increases motor force. For landing or moving downwards, the pilot reduces motor force. For rotation, the pilot tilts the aircraft while rotating.

Flight control in aircraft

To control an aircraft while flying, the pilot uses flight control panels. Flight control panels include the followings:

Ailerons

There is an aileron in each side of the wing. By rotating the flight lever towards left and right these layers move. The movement of ailerons changes the form of the wing and there would be a more curvature in one side. Thus, in a side which is bent upwards there would be a more drag force downwards and vice versa, there would be more elevator force in the counterpart. Therefore, the aircraft rotates flank.

Rudder is a control panel on the tail.

The pilot presses on rudder pedals to move it. As he presses the left pedal, the rudder rotates towards left and the tail moves towards right. Pressure on right pedal is followed by the reverse action. The movement of rudder causes an action called yaw.

Elevators

Elevators are placed on horizontal tails. Moving elevators causes the upward or downward movement of the tip of the aircraft and causes ascend or descend of the aircraft. The pilot can pull the flight lever towards him/her or push it forwards to move the elevators. Moving the elevators causes the upward or downward movement of the tail and the aircraft tail follows this movement either. The movement done by the aircraft while moving the elevators is called pitch.

Control process faults

This type of fault is the same as control process or the peripheral systems are affected by control and force signals supplied. Most faults not within the category of sensor and stimulator faults fall within this group. However, they are valid to differentiate and isolate. The fault in a part/unit can be caused by tearing up or sequence of several parts within the control process. It can also refer to a physical damage or fault onto an electric or hydraulic system or the collapse of calculations or due to connection tools. This reduces the ability of the flight control channel to do standard jobs. Practically, this will lead to changes in characteristics of the system itself. The occurrence of faults in an auxiliary system of flight control channel in a transportation aircraft can cause great disasters.

Flight control channel solutions

Today we can encounter using two technologies of major flight control channels. Mechanical flight control channels and fly-by-wire flight control channels. Mechanical flight control channels are utilized in small aircrafts that do not have much aerodynamic forces. The technology posed could not be accessible for a long time and it uses some cables and other mechanical tools to connect pilot levers to hydraulic stimulator control servers connected to movable aerodynamic planes. These cables are connected within the aircraft in cabin area and controllable locations. This system model has several faults, while it is a simple and strong solution to completely control the aircraft and the whole flight area as:

- Necessary long cables, levers, hooks, buffers and supporters, and all these parts create the problem of over weight.
- A costly period of retaining is required for such a mechanical system such as oiling and adjusting different operations
- The merge of principal automatic flight preservation performances with control channels is needed

The use of this method increases flight safety and reduces pilot's work pressure. Meanwhile, it has some other advantages such as: saving the weight, pertaining activity is reduced in comparison with common mechanical flight control channels. However, this solution is to a great extent dependant upon electric force resources that can cause external electromagnetic disturbances whose main reason is the use of composites to construct the body and the frame of the aircraft. During some recent years many advances have been observed in air borne electric resources while few counteracts were carried out to avoid electromagnetic disturbances. Figure (1.3) represents an overall view of the fly-by-wire flight control channel.

Fault and failure

Before considering the possible counter facts in flight control channels, the description of the details of the major terms used in fault management seems necessary. To describe the concepts created in fault tolerant system precisely, some organizations such the technical committee (TFAC) has tried to posse the standard definitions related to fault tolerance system (Rolf Isermann, 2006).

Fault: fault refers to the unauthorized deviation from at least one of the system characteristics of standard, usual, and acceptable conditions. This means that fault is an unusual position that may not affect the proper performance of the system, but finally results in failure or fault. However, faults may be small or hidden and it may be difficult to recognize them.

Failure: decay or failure refers to the permanent stop of a system to perform under certain conditions. Therefore, failure is much more serious than fault. When failure occurs, the performing units do not their jobs properly. For example, when the small wing sticks in a fixed area it is called a failure position and the stimulator is no more able to work. In drivers' license requirements of AMC 25.1309 for giant aircrafts, failure has been defined as an incident which affects the performance of a section, part, or element in a way that it can not continue with the intended goal (and this includes lack of performance and inefficiency).

On the whole it can be claimed that fault is an abnormal behavior of the system that may not affect the performance of the whole system. But finally it may result in system failure. As a result of the occurrence of a fault some structural changes occur in the system which leads to the reduction of the performance or the reduction of the rank of a closed loop system [3]. On the other hand, failure refers to the permanent system stop to administer the expected performance under certain operational conditions [4]. If one or several faults occur, the system unit performance fails. Therefore, failure creates a more severe status in the system compared with the fault.

Types of faults and problems that may occur in an aircraft

In this section we will deal with the faults and inefficiencies that may occur in an aircraft.

Faults related to flight control channel:

In the present study, the faults and errors that occur in flight control channel are investigated through the flight characteristic features' destruction risk and maneuver capability of the aircraft. In the rest of the work the errors and faults will de differentiated repetitively. An overall diagram of flight control system has been represented in figure 1.4. Faults may occur in any unit or subsystem. But here we will deal with faults that occur in stimulators, sensors, and the controlled process.

A glance at flight control stimulator faults

In a physical sense, flight control stimulator faults can be categorized as follows:

1- Faults as a result of overall loss of control stimulator effect include being stock in a location, hard-over and floating.

2- Faults that cause the partial loss or shortage of the effect of control stimulators.

Lock fault in the position which is known as stuck failure occurs when the stimulator freezes in a certain position and does not react to control signals.

This can be due to mechanical problems such as system oiling. This type of fault not only reduces some stimulators, but also it leads to permanent system disturbances. This type of fault has been investigated specifically in some studies (Bajpai et al, 2002; Chang et al, 2008).

Hard-over fault is recognized by stimulator movement upwards or downwards in maximum speed without considering the control signal. Regarding the structural load and aircraft controllability, this type of fault is considered as the most disastrous or the worst fault type. The runaway order can occur as a result of faults in an electronic part and it leads to a big signal sent to the stimulators that can deviate towards maximum deviation. This type of fault has been investigated in several references.

Float failure

Float failure occurs when the stimulator is floating in starting point and it does not pay attention to control effects. An example for float failure is the shortage of hydraulic liquids in elevator stimulators that causes the free movement of the stimulator to adjust the local angle direction. In this case it can not produce an efficient time alongside the earth axis. This type of failure has been investigated here.

This method responds through stimulators that react to control signals where the stimulators to control signals are unusual (low performance, saturation, low reaction time). For example, the presence of a leaked cylinder will lead to lose force and energy and it disturbs the reaction time of the stimulator. Usually force feeding source shortage will lead to an incomplete reaction of the stimulator to the control signal. Li et al 2007; Totah, 1996, have investigated about the issue. The statistics of aerial crashes show that stimulator faults cause deadly crashes.

A glance at sensor failures

- The importance of sensor fault for flight safety

Sensor fault may not be as important as the stimulator fault because it can lead to send wrong control signals. Therefore, it would be very important to avoid sensor fault and when a fault occurs we should recognize it and alternate it with data. Sensor fault may occur due to the failure of a part of the measurement system itself or it can occur due to the state of installing measurement tools (inappropriate position) because of the torn out status or cutting in a certain part of the system which causes lack of precision, or it may not send a signal at all.

The out of order or switched off sensor creates a signal that is more or less related and finally causes the creation of different faults among the real value and the represented value. Therefore, the control system tat receives this incorrect information may create control signals that are completely unrelated to do any performance and may harm the system survival and may have risks.

Statistics show many crashes whose main reason is sensor disorders.

- On 1st August 2005, a serious crash happened in flight aB777 and 124 due to the unlawful maneuvers by incorrect and mistaken signs. ATSB reporter stated that probably a big software fault has let Air Data Inertial Reference Unit (ADIRU) to utilize wrong data in accelerometer. [Australian Transport Safety Bureau, 2007]
- On 1st June 2009, Airbus A330-203 was drawn in Atlantic Ocean and all 216 passengers and 12 crew were dead.
- The latest report of Bureau d'Enquetes etd' Analysis 2012 had claimed that this crash was caused by the temporary contradiction between the measured speed probably because of the stop in putout pipes by the ice crystals which led to the stop and readjustment of the autopilot.
- Sensor fault categorization

Based on adjustment of measurement and the real value, sensor fault can be divided into 5 types below:

Bias: (deviation) when a fixed offset exists between the real signal and the measured signal by the sensor, this fault is known as Bias.

Drift: when the measured signal fades away slowly or retreats, the major signal goes farther and farther, this fault is called drift.

Loss of accuracy: when the measurements never reflect the real value, this fault is called loss of accuracy.

Freezing: it shows sensor signal freezing where the sensor value is permanent without considering the real value.

Calibration error: calibration error represents the error in real physical meaning of electric or electronic signals that go out of the sensor unit and can be seen as a transformer.

Many techniques have been investigated to recognize sensor faults and alleviate the effects. Overall, these techniques merge the physical addition of the sensors as well as other sensors through analytic addition. [Awang et al, 2010; R, Isermann 4 Balle, 1997]

Control process faults

This type of fault is the same as control process or the peripheral systems are affected by control and force signals supplied. Most faults not within the category of sensor and stimulator faults fall within this group. However, they are valid to differentiate and isolate. The fault in a part/unit can be caused by tearing up or sequence of several parts within the control process. It can also refer to a physical damage or fault onto an electric or hydraulic system or the collapse of calculations or due to connection tools. This reduces the ability of the flight control channel to do standard jobs. Practically, this will lead to changes in characteristics of the system itself. The occurrence of faults in an auxiliary system of flight control channel in a transportation aircraft can cause great disasters.

3. Aircraft model

The aircraft investigated in the present research is Boeing 100-747 passenger aircraft known as jumbo jet. This gigantic intercontinental aircraft with 4 turbofan jets has a set of advanced features that have made it a sample of a modern business aircraft.

Using the second rule of Newton, 12 nonlinear first order equations are extracted as the flight equations of aircraft's 6 freedom degree in body coordinates as equations (1) to (6). [11]

Fig.1. Boeng 747 – 100 passenger aircraft[10]

The extraction of flight equations

Force equations

$$\dot{u} = rv - qw - g\sin\theta + \frac{1}{m}\left(\bar{q}sC_{xb} + F_{Tx}\right) \quad (1)$$

$$\dot{v} = -ru + pw + g\sin\phi\cos\theta + \frac{1}{m}\left(\bar{q}sC_{yb} + F_{Ty}\right) \quad (2)$$

$$\dot{w} = qu - pv + g\cos\phi\cos\theta + \frac{1}{m}\left(\bar{q}sC_{zb} + F_{Tz}\right) \quad (3)$$

Cinematic equations:

$$\begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} 1 & \sin\phi\tan\theta & \cos\phi\tan\theta \\ 0 & \cos\phi & -\sin\phi \\ 0 & \dfrac{\sin\phi}{\cos\theta} & \dfrac{\cos\phi}{\cos\phi} \end{bmatrix} \begin{bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} \tag{4}$$

$$\begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} 1 & \sin\phi\tan\theta & \cos\phi\tan\theta \\ 0 & \cos\phi & -\sin\phi \\ 0 & \dfrac{\sin\phi}{\cos\theta} & \dfrac{\cos\phi}{\cos\phi} \end{bmatrix} \begin{bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} \tag{5}$$

Direction equations:

$$\begin{bmatrix} \dot{x}_e \\ \dot{y}_e \\ \dot{z}_e \end{bmatrix} = \begin{bmatrix} c\theta c\psi & s\phi s\theta c\psi - c\phi s\psi & c\phi s\theta c\psi + s\phi s\psi \\ c\theta s\psi & s\phi s\theta s\psi + c\phi c\psi & c\phi s\theta s\psi - s\phi c\psi \\ s\theta & -s\phi c\theta & -c\phi c\theta \end{bmatrix} \begin{bmatrix} u \\ v \\ w \end{bmatrix} \tag{6}$$

In designing the flight control system in an aircraft, it is better to substitute average speed (V_t), attack angle (α), and peripheral slide angle (β), with u, v, w; this is done due to several reasons as described in reference [12]. Therefore, three equations of (7) to (9) are substituted for force equations of (1) to (3) as follows:

$$\dot{\alpha} = \frac{1}{mV_t\cos\beta}\left(-F_x\sin\alpha + F_z\cos\alpha + mV_t\left(-p\cos\alpha\sin\beta + q\cos\beta - r\sin\alpha\sin\beta\right)\right) \tag{7}$$

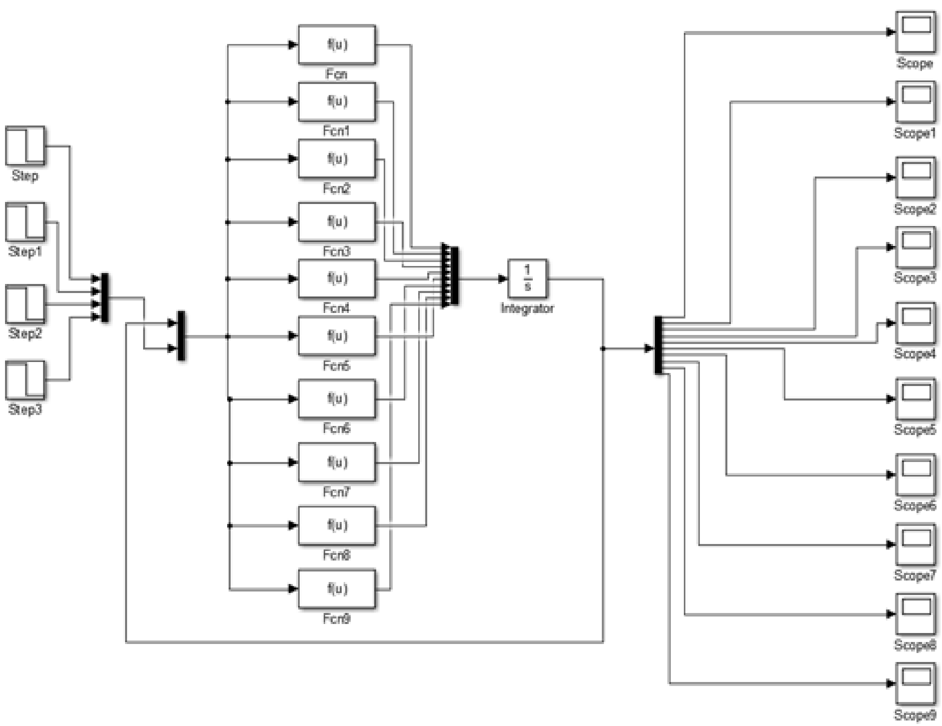
$$\dot{\beta} = \frac{1}{mV_t}\left(-F_x\cos\alpha\sin\beta + F_y\cos\beta + F_z\sin\alpha\sin\beta - mV_t\left(-p\sin\alpha + r\cos\alpha\right)\right) \tag{8}$$

$$\dot{V}_t = \frac{1}{m}\left(F_x\cos\alpha\cos\beta + F_y\sin\beta + F_z\cos\beta\sin\alpha\right) \tag{9}$$

Figure 4: The flowchart as an optimal nonlinear adjustment

$$A(x)=\begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} & 0 & 0 & 0 & a_{18} & 0 & a_{110} \\ a_{21} & a_{22} & a_{23} & a_{24} & 0 & 0 & a_{27} & 0 & 0 & a_{210} \\ a_{31} & a_{32} & a_{33} & 0 & 0 & 0 & a_{37} & a_{38} & 0 & 0 \\ 0 & 0 & a_{43} & 0 & 0 & 0 & 0 & a_{48} & a_{49} & 0 \\ a_{51} & a_{52} & 0 & a_{54} & 0 & 0 & 0 & 0 & a_{59} & a_{510} \\ a_{61} & a_{62} & a_{63} & a_{64} & 0 & a_{66} & a_{67} & a_{68} & a_{69} & 0 \\ a_{71} & a_{72} & 0 & 0 & 0 & 0 & a_{77} & a_{78} & 0 & 0 \\ a_{81} & a_{82} & 0 & 0 & 0 & 0 & a_{87} & a_{88} & 0 & 0 \\ 0 & 0 & a_{93} & a_{94} & 0 & 0 & 1 & a_{98} & a_{99} & 0 \\ a_{101} & a_{102} & 0 & a_{104} & 0 & 0 & 0 & 0 & a_{109} & a_{1010} \end{bmatrix} \tag{10}$$

$$B(x)=\begin{bmatrix} b_{11} & 0 & 0 & 0 & 0 & b_{61} & 0 & 0 & 0 & 0 \\ b_{12} & b_{22} & b_{32} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & b_{73} & b_{83} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & b_{74} & b_{84} & 0 & 0 \end{bmatrix} \tag{11}$$



- The implementation of model in Simulink MATLAB

4. Different methods utilized in aircraft control faults

In this part we will deal with different methods used in aircraft control faults.

Resistant theory

The modern control theory is based on time analysis of differential equation systems. But the consistency of these systems is sensitive to the errors between the real system and its model and this causes inconsistency in itself. To resolve this problem, we utilize the systemic control to consider the possible errors from the first and in this case the system will remain consistent even if an error occurs within the predicted range. This type of designing that uses this method is called resistant control theory. This theory is formed by the merge of frequency reaction method and the time range and is usually studied while postgraduate studies are done at universities due to complicated mathematical operations related to it.

Lack of absoluteness is an important issue in control engineering. Lack of absoluteness can exist both in models and in measurement. The presence of such issues in control systems halts control targets from being realized.

Resistant control is an effort to alleviate such a problem. In fact, resistant control refers to control in the presence of lack of absoluteness in a way that the system behavior and performance could be acceptable in all possible states. One of the sensitive and important issues in encountering the lack of absoluteness is control system consistency. Retaining the consistency in the presence of lack of absoluteness is one of the main challenges in resistant control.

On the whole, there are two approaches towards resistant control:

1) Traditional resistant control: this approach dates back to 1980s and it investigates about the indefiniteness and external chaos within the realm of frequency and reduces their effects on the system.
2) Resistant control using unequal linear matrix tools: since the late 1990s and considering the effective methods to resolve linear matrix inequalities, many of control methods were formularized in a way that we can utilize linear matrix inequalities for designing. During some recent years, linear matrix inequalities have been frequently used to resistant control of dynamic systems and they are developing due to powerful methods of resolving inequalities and also their considerable flexibility. (1)

Optimal control

There have been different common methods to design control systems that were usually trial and error where to identify the design parameters of an acceptable system, different analysis methods were used in an iterative mode. The acceptable performance system is determined based on time characteristics such as ascending time, placement time, maximum rotation, or some frequency characteristics such as phase, range limit, and bandwidth. But when we use this method we should consider different criteria or performances regarding the systems with several inputs or outputs that supply the needs of today's technologies. For example, the control system program of aircraft location which minimizes fuel consumption could not be achieved through well-known methods. The new and direct method of such a complex system is known as optimal control made it possible through digital computers' development.

The goal of an optimal control system is to determine the control signals in a way that they could be applied in limitations and physical conditions and could minimize or maximize certain performances or criteria.

The example that claims: "the good adjustment of a problem is the half of problem resolution", may seem a little exaggerated but it follows a certain problem appropriately.

The entry adjustment of any optimal control issue requires the followings:

1- Mathematical representation or the system model which should be controlled.
2- The statement of physical limitations
3- The identification of system performance

1 Linear control

Control system is among control models used in control engineering vastly. Linear control is known as a prerequisite course for other courses in control engineering.

The backgrounds required about linear control are preliminary math, linear algebra, and differential equations. Linear control includes systems' analysis within the areas of time and frequency. The major issues in linear control are as follows: 1- linear algebra, 2- Lapillus transformation, 3- linear systems representation, 4- studying linear systems consistency through tools: Ruth elements, Hurwitz table, bud figures, Nikuist consistency criterion graphs, Nicole's graphs, roots' geometrical location, 5- pre-phase, post-phase, pre-post-phase control system design.

The linear control deals with studying linear systems and time unchangeable and linearization of unchanging nonlinear systems with time.

Consistency of linear control systems

The concurrent equilibrium response with the temporary response of the system depends on roots of the specific equations. Basically the designing of linear control systems can be considered as the ordering of the location of the poles and the zeros of the closed loop transformation function. In this way the counterpart system works based on the alternate characteristics.

The most important feature of the performance characteristics utilized in designing control systems should be consistent. The definition of consistency regarding different linear, nonlinear, changing with time, and unchangeable with time differ in different systems.

Fundamentally a control system is responsible to control a process. Control systems can utilize different methods to control the process. For example, they can use mechanical, electronic, or electro-mechanic methods, each of which has specific advantages and disadvantages and are used in different locations and to control different processes.

An electronic control system, as it is apparent in the title, is responsible to control a process electronically. This system has 3 main input parts, signal processor and an output. The input of this system is an electrical signal that is formed by the addition of a reference signal and a feedback signal through the output of the sense system.

The signal processor part is responsible to process the signal received through the input based on a set of certain regulations that can be formed of a simple comparing IC to several complicated boards. Results of the processing of the signal processing part are enforced through the output to the process. Also due to the fact that the relationship between the output signal and the input one is linear, this control system is called a linear control system. For more understanding of the issue consider the following example:

Suppose that our goal is to control temperature and moisture in a room. To do so, we need a temperature sensor and a moisture sensor to sense the temperature and moisture of the room and to send appropriate signals related to the temperature and moisture sensed to the processor. In fact, these two sensors are placed at input section of our control system. The signal sent through these sensors to the systems is known as the feedback signal. Also our system output section consists of a heater and a moisture maker activated by the signals sent from the processor. Suppose that we intend to keep the moisture in the room in %50 and the room temperature should be kept fixed at 30 degrees centigrade. Therefore, we have two appropriate amounts of %50 of moisture and 30^0C heat in the processor part. The sensors for temperature and moisture send the sensed amounts to the processor permanently. If the amounts sent have some numbers other than %50 and 30^0C, depending on the amounts being lower or higher than the reference amounts, the heater and the moisture maker processors are switched on or off and this continues until the time when the amounts sent from the sensors becomes the same with the reference amounts (the room temperature should be 30^0C and the moisture should be %50). This was only a sample of the functions of a linear control system. Today, the linear control systems are used to control the required process in all industries (2).

Nonlinear control

Nonlinear control is a field of control engineering which deals with the nonlinear terminals or systems changing with time or both of them. There are many analyses and designing techniques for nonlinear terminals, but the controller or the system under control or both of them may not be a nonlinear terminal and we can not enforce linear control techniques on them directly. The major issue in nonlinear control is that how we can utilize linear control techniques in nonlinear systems. Also new control methods can be used which can not be achieved through linear analysis. Nonlinear controllers do have more interesting features than linear controllers such as speed increase, reduction of energy, and their simple functions. But nonlinear controllers require more complicated mathematical analyses.

Predictive control

Model Predictive Control (MPC) is an advanced process control used in processing industries, chemical industries, and refineries since 1980s. During some recent years, the model predictive control has also been used in balance models of power systems. Model predictive controls based on dynamic models process are mainly experimental linear models achieved through system recognition. The most important advantage of MPC is that it can optimize the current slot time considering future slot times. This is done through the optimization of a limited time range, but its administration can only be carried out during the current slot time. MPC is able to predict future incidents and implement appropriate control acts. PID and LQR controllers do not have prediction capability. MPC is a digital control.

Models used in MPC are usually models to represent the behavior of a complex dynamic system. The prediction control algorithm increases the system complexity and it is not necessary for the simple systems' controls that often are controlled well with PID controllers. Some common dynamic characteristics that are problematic for PID controllers are long time delays and high rank dynamics.

MPC models predict changes in the dependant variables that result from independent variables. In a chemical process, the independent variables that can be changed with the controller are often the set points of PID regulatory controllers (pressure, flow, temperature, ...) or they are the final control sections (valve, damper, ...) of independent variables that can not be regulated through the controller as the disturbances. The dependent variables in these processes are other measurements that show either control goals or control constrains.

MPC uses the current measurements of the system under control, current dynamic processes, MPC models, and goals and constrains of process variable, to calculate the future changes of the dependent variables. These changes are calculated in a way that the dependent variables are kept close to the target and the limitations are observed in independent and dependent variables. Usually MPC sends only the first change in each independent variable for administration and repeats the calculation for the next change.

Although many real processes are not linear, mostly we can consider them within a short linear range. The linear MPC methods are used in most applications with a feedback mechanism in which the prediction errors resulted from lack of adjustment between the model and the process are compensated. In prediction controllers that are formed of only the linear models, the sum of linear algebra rule makes it possible to add the effect of the changes of the multiple independent variables together to predict the response of the dependent variables. Through this, the controlling refers to a set of simple direct matrix algebra calculations that are rapid and resistant.

When linear models are not precise enough to show the nonlinearity of the real model, we can use different methods. In some cases we can use changing the process before or after the linear model to reduce the nonlinearity. We can control the process through a nonlinear MPC that uses a nonlinear model directly. The nonlinear model can be in the form of an experimental curve arrangement (like neural networks) or a precise dynamic model based on a fundamental equilibrium between the mass and energy. We can use the nonlinear model to achieve Cullman filter or use it in linear MPC to linearize it.

Fuzzy control

Fuzzy control (fuzzy logic) was first posed by Lotfizadeh (1965) regarding the devise of fuzzy sets theory in novel calculation era.

The term fuzzy means not precise, not clear, and ambiguous (floating). The function of this part in software sciences can simply be defined as follows: fuzzy logic goes beyond the logic of values "zero and one" in classic software and opens a new gate for the world of software sciences and computers because the floating space and unlimited space between the numbers 0 and 1 are utilized in the logic and the inferences and they are challenged. Fuzzy logic extracts and uses a space between the two values of "let's go" and "let's do not go" into a new era of values of "we might go" or "we will go if" or even "probably we will go".

Conclusion

The resolution of real optimal control systems has certain complexities. In classic control theory, only the input-output- signals and errors are deemed to be important. The unique feature of the classic control theory is that it is based on input-output relationship in systems. The major problem with this theory is that it can only be utilized in independent from time linear systems that have only one input and one output. Therefore, regarding this theory we can not study and analyze systems dependent on time, nonlinear systems, and multiple-input-multiple output systems. Additionally, the classic methods can not be used in optimal control systems with dependent on time nonlinear behaviors. Thus, proposing an appropriate numerical and efficient method to resolve optimal control systems is considerably important.

The nonlinear optimal regulatory control method or Rikati equation depending on the state, resolves an algebraic Rikati equation to produce optimal control rules. The unique feature of this method is that the Rikati equation is resolved due to the dependent on coefficients' feature. This means that feedback control result differs in each stage compared to the previous one. Surely, this can be considered as an optimal feature in designing flight fault tolerant controllers. The control rule is able to adjust itself in response to parametric changes of the aircraft actively. Additionally, due to the presence of non-unitary coefficients and dependent on the state ones, the freedom degrees of controller increases.

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