FUZZY LOGIC BASED FLIGHT CONTROL SYSTEM FOR THE NIGERIAN AIR FORCE AIR BEETLE AIRCRAFT

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Abstract

This paper reports the design and simulation of a fuzzy logic based Flight Control System (FCS) which could be used to replace or augment the current mechanical control systems on the Nigerian Air Force Air Beetle (ABT-18) aircraft. Four basic controllers were developed, namely, the elevator controller, the speed controller, the bank angle controller and the sideslip controller. Additionally, envelope protection features to limit the angle of attack to 11^0, bank angle to 60^0 and speed to 151 knots were incorporated into the controllers.

Simulation results show that the longitudinal displacement of control stick commands the flight path angle while the lateral stick displacement commands only the bank angles. Also, speed control is achieved using speed lever only. The performance of the Flight Control System, seen from the time history plots, was found satisfactory. The result of the research proved that advanced control systems on the ABT-18 aircraft would simplify aircraft operations, improve handling qualities, safety and reduce pilot work load.

1. Introduction

The Air Beetle aircraft (ABT-18), shown in Fig. 1, is used by the Nigerian Air Force (NAF) for the initial training of pilots as well as for local courier flights. The aircraft belongs to a category of aircraft known in the civil aviation sector as General Aviation (GA) aircraft.

Over the years, there has been a depletion of the ABT-18 fleet due to accidents and incidents. The accidents on the ABT-18 aircraft and indeed most GA aircraft could be attributed to the basic flight characteristics of conventional airplanes whose control responses are coupled.

Fig. 1. The Air Beetle aircraft[1]

The consequence of this coupling interaction is that an apparently simple task, such as direction change in straight and level flight, requires co-ordination between the aileron, elevator and rudder in order to deal with the undesired airplane reaction [1]. The skill(s) required to achieve this co-ordination is relatively complex and difficult to learn. The complex interactions often lead to high pilot workload, especially in adverse weather conditions [1].

In large transport aircraft and modern military aircraft, fly-by-wire technology have been used to improve aircraft handling qualities, safety and direct operating costs. Application of this technology to the ABT-18 aircraft is very desirable if the cost of the technology can be made affordable. Fortunately, recent advances in reliability and capabilities of electronic systems coupled with the fall in prices of

[1] Image is courtesy of Nigerian Air Force

computing systems present an opportunity to develop a low cost, robust system that could be used on the ABT-18 aircraft.

This paper reports the implementation of a fly by wire flight control system using fuzzy logic concept on the ABT-18 aircraft.

2. Literature Review

Several research studies have identified the importance of decoupled controls and fly-by-wire control for aircraft. A Simulation study on a decoupled fly by wire (FBW) control and a pictorial head up display conducted at National Aeronautics and Space Administration (NASA) showed that despite the lack of experience and training, all the pilots in test, who are non-pilots and who had no prior training or practice before the test run, were able to complete complex piloting tasks on the first run [2].

Furthermore, NASA and the Federal Aviation Administration (FAA) concluded from simulator studies that between advanced display concepts and advanced control concepts, control has the largest impact on improving the ability of a novice pilot to operate an aircraft safely [3].

Tomeczyk [3] argued that light airplanes equipped with a mechanical flight control system require full aviation training and comprehensive theoretical knowledge on the part of the pilot. He concluded that the complexity of both control and navigation imposes on the pilot the need to possess certain psychological and physical disposition and proper piloting skills to be able to safely operate the aircraft. This complexity places high demands on pilot skill and experience which are often not met, due to lack of competence, especially in poor weather conditions and complex airspace.

Paul et al [4] noted that light aircraft equipped with mechanical flight control systems have satisfactory handling qualities in smooth air, but these handling qualities are severely degraded by atmospheric turbulence. He concluded that this degradation is attributable to stability and control deficiencies and is most noticeable during instrument landing approach as it often leads to an increase in pilot workload.

The research team of the Department of Avionics and Control, Rzeszow University of Technology Poland, designed, built and tested an experimental fly-by-wire control system on board the PZL-110 Koliber aircraft [3,5,6]. The result of this effort showed that an aircraft equipped with fly-by-wire control is easier to fly, have improved handling qualities and increased safety.

The Raytheon Aircraft Company in partnership with NASA modified a Beech F33C Bonanza by incorporating advanced display and FBW control systems in order to examine the two concepts in flight. Flight tests with the research aircraft showed that after about 15 minutes of instruction, all pilots in test, who were previously non pilots, were able to successfully execute heading, altitude, speed and configuration changes [7].

On the application of fuzzy logic to aircraft flight control system, Wu et al [8] investigated an autonomous flight control system for an atmospheric re-entry vehicle based on fuzzy logic to cover all the re-entry flight regions characterized by different actuator configurations. Simulation results showed that both the thrusters and body surfaces were able to perform their role in appropriate flight regions in nominal trajectory. Also tracking errors and the actuator usage were both well within the appropriate acceptable ranges.

Larkin [9] used a flight simulator to evaluate a fuzzy based autopilot controller capable of maintaining an aircraft along the glide path during final approach to landing. The rule set for the autopilot controller was generated by interviewing an experienced pilot by asking highly structured questions in terms of what control actions he would take given a stipulated set of flight conditions.

Livichitz et al [10] carried out simulation as well as flight tests on a fuzzy logic based automated landing system for an unmanned aircraft. The excellent time response of the nonlinear controller, obtained from simulation, demonstrated the capability of fuzzy logic in providing robust and smooth control of unmanned vehicles.

3. Fly by Wire Flight Control

In an aircraft fly-by-wire system, the mechanical linkages to the flight control surfaces are replaced by electrical signals. A control computer is used to execute the control laws which determine how the pilot's control demands are transmitted into control surface movements. A fly-by-wire control system makes it possible to incorporate some form of protection to ensure that pilot's actions do not exceed the design limit of the airplane. Other advantages of the fly-by-wire system over conventional control systems include the following [11]:

- Reduction in weight and maintenance requirements as mechanical linkages are replaced by electrical wires.
- Turbulence suppression with consequent decrease of pilot work load and increase of passenger comfort.
- Ease of interface with the auto-pilot and other components of the flight management system.
- Increase of stability and handling qualities across the full flight envelope.
- Envelope protection where the computers will reject and tune pilot's commands that might exceed the airframe load factors.

Using advanced control techniques, it is possible to eliminate the complex interactions associated with the mechanical control system. Stewart [2] believes that any control system that will provide single uncoupled responses to input will significantly improve the utility and safety of the airplane.

4. Fuzzy Logic Control Concept

The concept of fuzzy logic was conceived by Lofti Zadeh in 1965 as an extension of classical set theory. The use of fuzzy theory to model human experience and actions has enabled the application of such systems in the design of flight controls. Fuzzy based systems, which require linguistic description of the process rather than its mathematical model, could eliminate the tuning requirements and lend it to use in different airplanes with little or no re-tuning [12].

A Fuzzy Logic Controller (FLC) offers a more flexible and efficient approach especially for the control of non-linear systems by incorporating the ambiguity and abstract nature intrinsic in human decision making into intelligent control systems. The FLC flexibly implements functions in near human terms using the IF-THEN linguistic rules. This intelligent control scheme tends to imitate human decision making and knowledge representation and has proved to be reliable and robust.

Fuzzy logic control involves three related but distinct steps as follows:

- Use of linguistic variables to define the system under consideration.
- The use of fuzzy rule base to specify the control strategy.
- Application of the fuzzy inference process.

A linguistic variable is a variable whose value is represented by words, sentences or artificial language rather than numbers. The set of values taken by a linguistic variable is called a fuzzy set. In order to apply a fuzzy set, fuzzy rule base, which is essentially the control strategy of the system, needs to be specified. Simple, plain language IF ….THEN rules are used to describe the system response relying usually on the operators experience rather than the technical understanding of the system. Rules take the form of IF [premise] THEN [consequence] where premise and consequence are fuzzy relations represented by linguistic variables and consequent linguistic values. The Premise represents a set of conditions to be specified and the Consequence represents the action to be taken.

Fuzzy inference is the process of formulating the mapping from a given input to an output using a fuzzy logic. The mapping then provides a basis from which decisions can be made, or patterns discerned. The fuzzy inference process can be explained as a sequence of four steps: the fuzzification of the input variables, the application of appropriate rules, aggregation of the consequents across the rules, and the defuzzification of the aggregated output [13].

5. Fuzzy Logic Based Flight Control System Design

5.1 Fuzzy Logic Controller Development

A rule based flight controller using fuzzy logic is designed in order to achieve the set objectives. The controller is used to model operators and designers intelligence and was arrived at from interactions with ABT-18 pilots and engineers. MATLAB is used as the development environment with fuzzy logic toolbox for defining the control rules and membership functions.

The fuzzy logic toolbox provides tools for designing system based on fuzzy logic. It uses graphical user interfaces to simplify the development of fuzzy sets. The various fuzzy logic control algorithms are then imported to SIMULINK within the MATLAB environment to simulate the performance of the complete system.

The Aerosim blockset was also used to simulate the aircraft motion and dynamics. The complete ABT-18 aircraft model is composed of aerodynamics model, propulsion model, atmospheric models, inertia model, earth models and the equation of motion models.

5.2 Controller Architecture

The controller architecture consists of the longitudinal controller, lateral controller and the directional controller. The architecture of the fuzzy based flight control system is shown in Fig. 2. The longitudinal controller is made up of the flight path angle control module and the speed control module while the lateral and directional contollers are made up of the bank angle control and sideslip control modules respectively. The inputs to the controllers are the errors (the difference between the desired/ commanded and the current states) and the rate of change of error (usually a first order derivative of the error). The outputs of the controllers are the controlled variable rates such as the elevator rate, aileron rate, throttle rate and rudder rate.

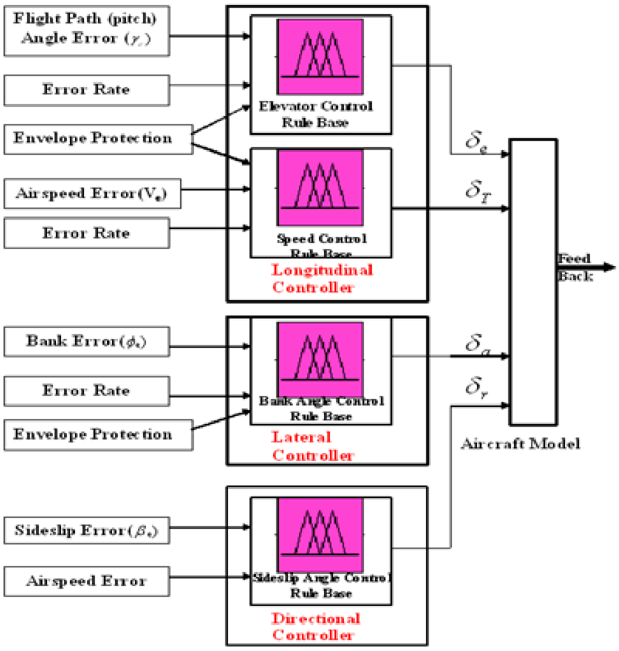


Fig. 2. Fuzzy based flight controller architecture

5.3 Longitudinal Controller

The longitudinal controller controls the longitudinal motion of the aircraft. There are two controllers to control the elevator and the throttle respectively. The elevator controller responds to changes in flight path (or pitch), with respect to the commanded flight path (or pitch), to manipulate the elevator. On the other hand, the throttle controller manipulates the throttle lever with respect to airspeed commands.

5.3.1 Elevator Controller

In designing the elevator controller, the pitch error and pitch error rate were initially used as inputs to the controller. The result although satisfactory, had some drawbacks especially during turns and under turbulence. This resulted in the use of flight path angle error and error rate as inputs to the elevator fuzzy controller. The relationship between the flight path angle and the pitch angle is given by:

$$\gamma_{(\text{flight path angle})} = \theta_{(\text{pitch angle})} - \alpha_{(\text{angle of attack})} \quad (1)$$

Fig. 3 shows the block diagram of the elevator controller. The inputs to the controller are the commanded flight path (FP) angle and the actual FP angle. The difference between the commanded and the actual FP angles is the flight path error. The error rate is obtained by differentiating the error using the differentiator block.

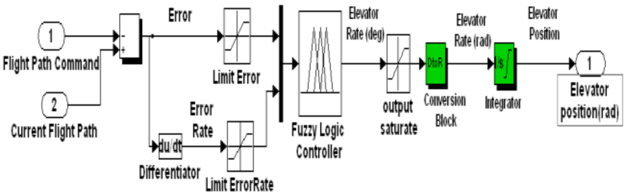
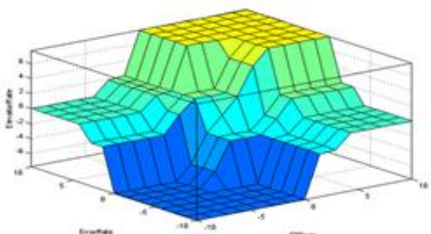


Fig. 3. Elevator Controller

The inputs to the controller, flight path error and error rate as well as the output, elevator rate are described using five membership functions. A total of 25 rules are used to describe the relationship between the error, error rate and elevator rate. Fig. 4 shows the summary of the rule base for the elevator controller and a three dimensional output surface illustrating the relationship between inputs and outputs.

Flight Path Error Rate	Error Rate				
	NB	NS	Z	PS	PB
NB	NB	NB	NB	NS	Z
NS	NB	NS	NS	PS	PS
Z	NB	NS	Z	PS	PB
PS	NS	NS	PS	PS	PB
PB	Z	PS	PB	PB	PB

(a)



(b)

Fig.4. Elevator controller (a) Rule base (b) Three dimensional output surface

The linguistic variables defining membership functions are made up of two letters eg NB. The meaning of the letters are N(negative), B(big), S(small), P(positive) and Z(zero). Others are L(large) and M(medium).

Formation of rules is based on row column combination. For example, rule 1 comes from third row third column of the table in Fig. 4(a). The rule is IF Flight Path error is NB (the current flight path is much smaller than the desired flight path) and error rate is NB (flight path error is decreasing rapidly) THEN elevator rate is NB (large negative deflection).

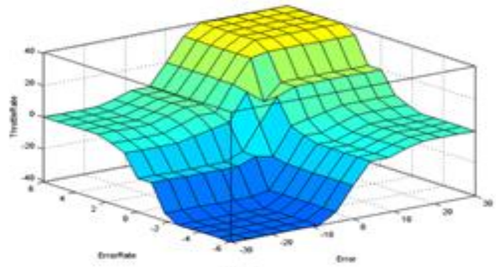
5.3.2 Speed Controller

The construction of the fuzzy logic speed controller follows the same procedure as the elevator controller. The speed controller manipulates the throttle to the desired speed changes. The inputs to the controller are the commanded airspeed and the current airspeed. The output is the throttle rate in percentage. To change the throttle rate to position, the output has to be integrated.

The airspeed error is defined using seven membership functions and a total of 49 rules. A summary of the rule base and the three dimensional output surfaces for the speed controller are given in Fig. 5.

Airspeed Error	Error Rate						
	LN	MN	SN	Z	SP	MP	LP
LN	LN	MN	MN	MN	SN	SN	Z
MN	LN	MN	MN	MN	SN	Z	SP
SN	MN	MN	SN	SN	Z	SP	SP
Z	MN	MN	SN	Z	SP	MP	MP
SP	SN	SN	Z	SP	SP	MP	MP
MP	SN	Z	SP	MP	MP	MP	MP
LP	Z	SP	SP	MP	MP	MP	LP

(a)



(b)

Fig.5. Speed controller (a) Rule base (b) Three dimensional output surface

As an example, rule 2 comes from third row fourth column of the table in Fig. 5(a). The rule is IF Airspeed error is LN (current speed is a lot greater than the commanded speed) and error rate is MN (airspeed error is decreasing moderately fast) THEN throttle rate is MN (Moderately fast reduction in throttle position).

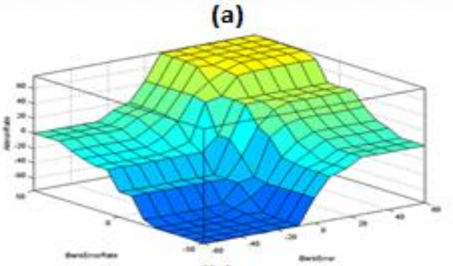
5.4 Lateral and Directional Controllers

The lateral controller controls the lateral motion of the aircraft by manipulating the ailerons through bank angle changes while the directional controller controls the rudder.

The inputs to the bank angle controller are the commanded bank angle and the current bank angle while the output is the aileron position expressed as a percentage of travel. The converter block is used to convert percentage to position (radians). Fig. 6 shows the rule base and the three dimensional output surfaces for the bank angle controller.

Bank Angle Error \ Error Rate	LN	MN	SN	Z	SP	MP	LP
LN	LN	LN	MN	MN	SN	SN	Z
MN	LN	MN	MN	MN	SN	Z	SP
SN	MN	MN	SN	SN	Z	SP	SP
Z	MN	MN	SN	Z	SP	MP	MP
SP	SN	SN	Z	SP	SP	MP	MP
MP	SN	Z	SP	MP	MP	MP	LP
LP	Z	SP	MP	MP	MP	LP	LP

(a)



(b)

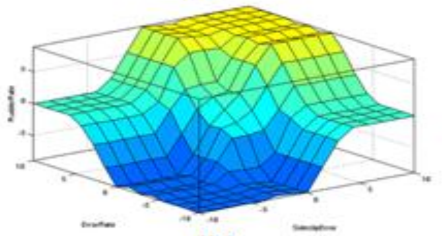
Fig.6. Bank angle controller (a) Rule base (b) Three dimensional output surface

As an example, rule 3 comes from third row fifth column of the table in Fig. 6(a). The rule is IF Bank angle error is LN (current bank angle is a lot less than the commanded bank angle) and error rate is SN (bank angle error is decreasing slowly) THEN aileron rate is MN (Moderately fast reduction in aileron position).

On the other hand, the inputs to the side slip controller are the sideslip command and the current side slip while the output is the rudder position in radians. To obtain the position value, the rudder rate had to be integrated and converted from degrees to radians. Fig. 7 shows the rule base and the three dimensional output surfaces for the rudder controller.

Sideslip Error \ Error Rate	NB	NS	Z	PS	PB
NB	NB	NB	NB	NS	Z
NS	NB	NS	NS	PS	PS
Z	NB	NS	Z	PS	PB
PS	NS	NS	PS	PS	PB
PB	Z	PS	PB	PB	PB

(a)



(b)

Fig.7. Side slip controller (a) Rule base (b) Three dimensional output surface

5.5 Envelop Protection

The envelop protection schemes incorporated into the controllers are the stall protection, the overspeed protection and the overbank protection. Stall protection is achieved by limiting the angle of attack. When an angle of attack above the limit is sensed, the elevator controller would send a command that would move the elevator down until the angle of attack is below the set limit. Simultaneously, the throttle would respond such that the flight path is maintained close to the commanded angle. On the other hand, when an overspeed is sensed, the elevator controller would send a command that would move the elevator trailing edge up while the throttle is reduced to keep the speed close to the limit and also maintain a path close to the desired flight path.

To achieve envelop protection, the elevator controller was modified with two additional inputs, the angle of attack and the airspeed inputs. For the stall protection, the angle of attack limit is set to 11^0. This represents the angle at which the stall warning comes on for the ABT-18 aircraft. The airspeed limit is set to 151 knots. The bank angle controller was also modified by adding a bank angle input. The rules are given relative weights as shown in the example below.

- Rule 25. If (FPError is PB) and (ErrorRate is PB) then (ElevatorRate is PB) (0.1)
- Rule 26. If (AOA is Normal) then (ElevatorRate is Z) (0.0001)
- Rule 27. If (AOA is stall) then (ElevatorRate is PS) (1)
- Rule 28. If (KCAS is Normal) and (PLA is Normal) then (ElevatorRate is Z) (0.0001)
- Rule 29. If (KCAS is Overspeed) then (ElevatorRate is Pro) (1)

The relative weights of the rules, represented by the numbers in bracket, are different. The weight of rules 27 and 29 is ‘1’ signifying a 100 per cent probability of the rules firing. This ensures that once the limits are sensed, the controller ignores any other inputs and executes the envelope protection demands. Using this scheme, conflict is avoided ensuring that normal and envelope protection rules never fire simultaneously.

6. Simulation System and Results

6.1 Simulation System

The complete simulation model showing the connection of the controllers to the aircraft model is shown in Fig. 8. It is made up of the aircraft model, the fuzzy logic controllers and other input and output variables.

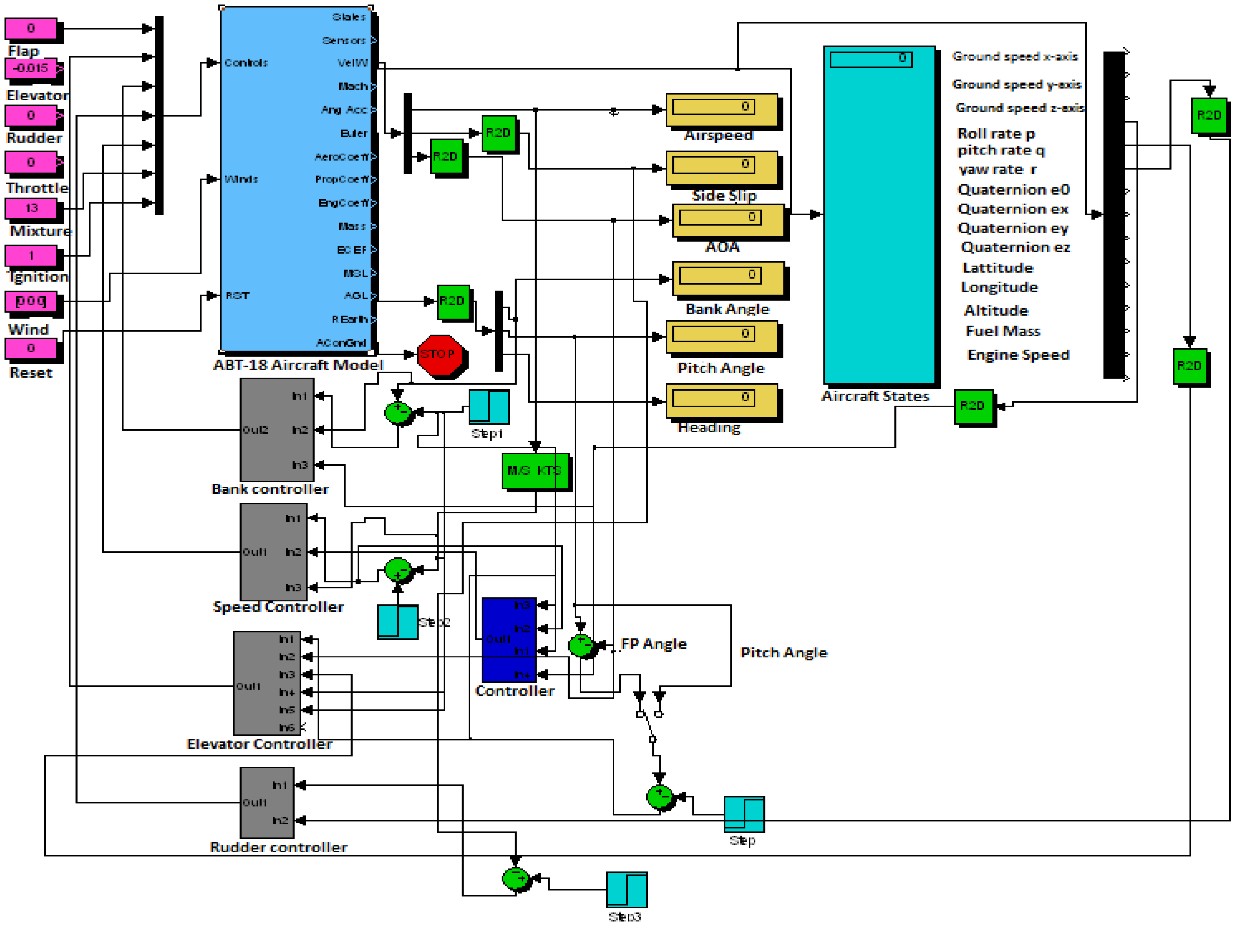


Fig. 8 Complete fuzzy logic flight control system simulation model

The outputs from the bank angle controller, speed controller, elevator controller and rudder controller are fed into the ABT-18 aircraft model as aileron, throttle, elevator and rudder inputs respectively. The aircraft model outputs that are used as input to the controllers are airspeed (converted from m/s to knots), sideslip angle (from radians to degree), angle of attack (radians to degrees), bank angle (radians to degree) and pitch angle (radians to degree).

Others are heading (degree), altitude (feet), pitch rate (rad/s to deg/s), roll rate (rad/s to deg/s) and yaw rate (rad/s to deg/s). The switch SW1 is used to switch between pitch angle and flight path input to the elevator controller.

6.2 Simulation Results

It is intended to demonstrate the versatility and robustness of the controllers by looking at the response time histories of various manoeuvres. The flight manoeuvres considered are level flight, pitch angle acquire and hold to level flight manoeuvre, flight path angle hold to level flight and airspeed hold. Others are steep dive to exercise over speed protection, wind effect, high angle of attack climb to exercise stall protection, bank angle hold to level flight and over bank protection. However due to space constraints, only results from flight path angle hold to level flight, overspeed protection and stall protection are discussed in this paper.

6.2.1 Flight Path Altitude Hold to Level Flight Manoeuvre

Positive flight path command causes the aircraft to climb until the desired altitude is attained. When control is released to command zero flight path angle, the altitude is maintained. The time history is shown in Fig. 9. where the altitude is maintained at 1120 ft. The response of the throttle is such that maximum throttle is commanded to achieve the desired flight path and when level flight command is given (40 s), the throttle adjusts itself to the minimum that will sustain the flight. The elevator also acts to keep the aircraft close to the commanded flight path and altitude.

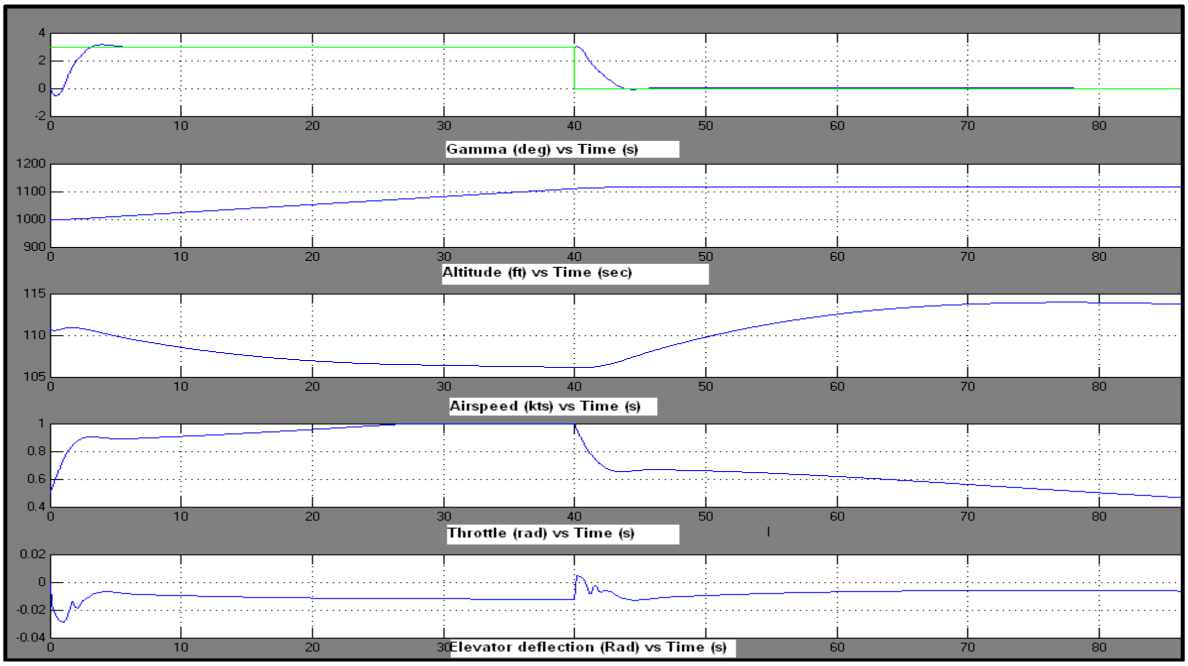


Fig. 9. Time history response of flight path attitude hold to level off manoueuvre

6.2.2 Overspeed Protection

The speed of the aircraft is arbitrarily limited to 151 knots based on the manufacturer's recommendation that a speed of 157 knots should never be exceeded. To exercise the over-speed protection capability of the controller, a deep dive at -8^0 flight path is commanded with the aircraft speed set to 140 knots. The response time history is shown in Fig. 10. When the overspeed occurred at t=14s, the elevator moved in response resulting in a slight oscillation in the flight path trajectory. Eventually, the airspeed and flight path stabilise close to the commanded values. It is possible to adjust the membership functions to obtain a smooth response without the oscillation.

However, in the opinion of the author, this is a necessary indication to the pilot that the aircraft is exercising an overspeed protection function. Since the amplitude and frequency of the oscillation is low, no further iteration is considered.

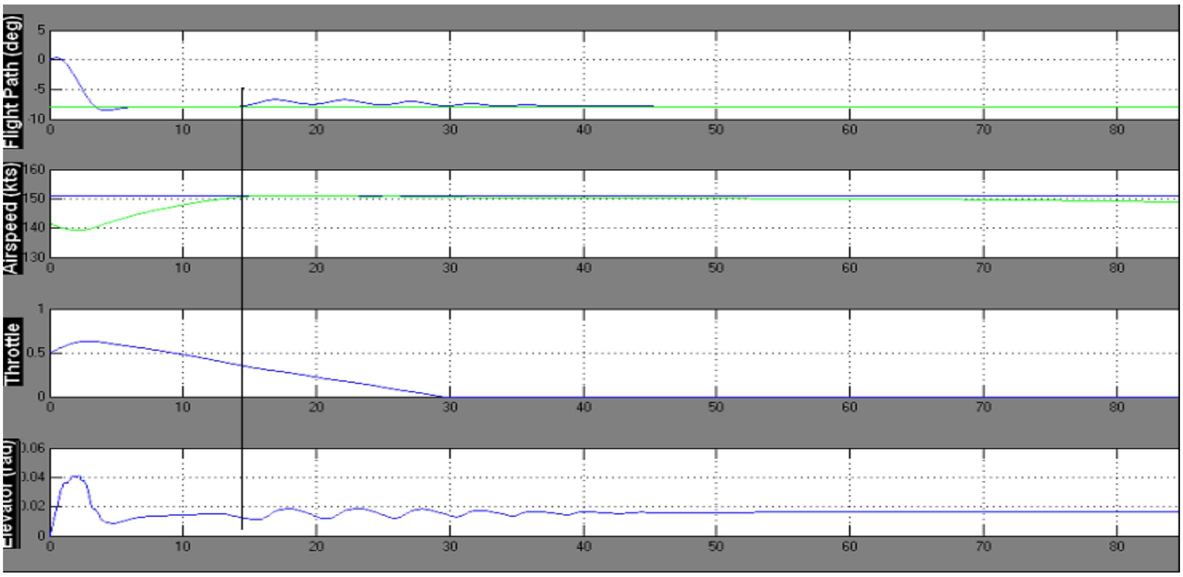


Fig. 10. Time history response for overspeed protection

6.2.3 Stall Protection

To demonstrate the stall protection features of the control system, a steep climb command is issued to ensure that the speed reduces to the stall speed. The angle of attack is limited to 11^0. The time history is as shown in Fig. 11. On the other hand, the airspeed decreases resulting in an increase in the angle of attack.

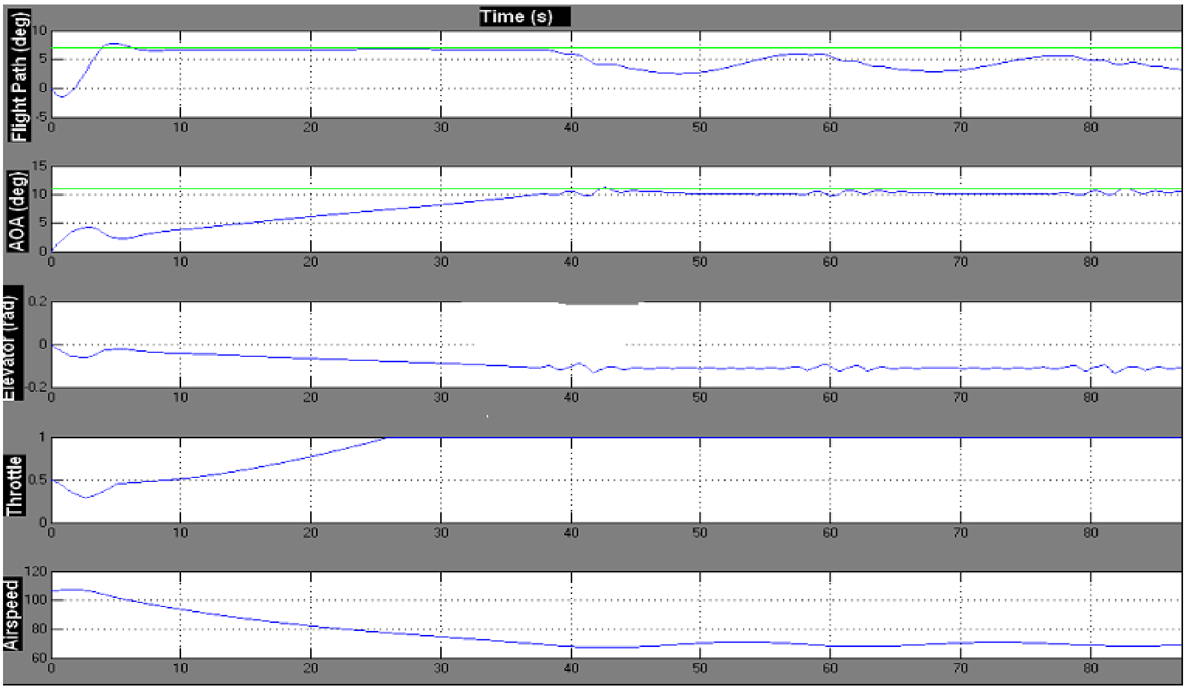


Fig. 11. Time history response for stall protection

When the limit angle of attack is sensed at 11^0, the elevator moves to exercise the stall protection. The angle of attack is maintained close to the limit while the speed stabilises to the minimum speed necessary to maintain both the flight path and the angle of attack.

7. Conclusion

From discussions presented in the preceding sections, it is evident that fuzzy logic could be used to design a decoupled flight control system for the control of the ABT-18 aircraft. Four controllers were developed; the controllers were tested using a six DOF non-linear aircraft model and were found to operate satisfactorily.

The elevator controller consisting of flight path angle and rate feedback provided the required response in the longitudinal axis. Longitudinal movement of the control stick provided the input to this controller. The speed controller consisting of airspeed and acceleration feedback to the throttle provided a satisfactory response.

The speed controller and the elevator controller provided the complete control of the aircraft in the longitudinal axis. The lateral and directional control of the aircraft was achieved using the bank angle controller and the rudder controller. The results seen from the time history plots were considered satisfactory.

The envelope protection scheme incorporated into the longitudinal and lateral controllers would prevent the pilot from carrying out manoeuvres that are beyond the aircraft limits. This would improve the safety of the ABT-18 aircraft and indeed any GA aircraft.

Control decoupling in the ABT-18 aircraft would simplify aircraft operation as well as reduce the time and cost of flying training. It is envisaged that the flight control system when deployed would improve the performance of the ABT-18 aircraft and lead to substantial savings for the Nigerian Air Force.

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