Experimental Flight Control Function for Electronic Flight Control System of High Aspect Ratio Light Utility Aircraft

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Abstract. Aircraft technology demonstrator is an aircraft which is used for experimental and demonstration purpose. This type of aircraft has a unique capability, *i.e.* demonstrating the experimental or newly developed system. The consequence is the aircraft not only has to be able to ensure its own safety like a normal aircraft, but also needs to be capable to return the aircraft to safety in case of the experimental system. This article presents a design for Electronic Flight Control System to safely execute experimental Flight Control Laws in flight test. The purpose of this research is to provide a relatively safe way to test newly developed Flight Control Laws in experimental flight. This research uses linear models of the Light Surveillance Aircraft, which have been developed in LAPAN Indonesia since 2014. The simulations that have been done indicate that the Experimental System is able to execute the experimental commands and reduce accidental risk by giving a relatively safer signal whenever the aircraft is going into potentially dangerous maneuver.

INTRODUCTION

Aircraft control systems have evolved rapidly ever since the first aircraft was built. In the first generation of aircrafts, the control systems are very simple with limited capability. Then, as the aircraft's performance increases, simple control systems become incapable to govern the aircraft's handling and performance. The accidents that happened because of failures in flight controls demands for a better safety and thus, more robust and more responsive methods of aircraft flight control are needed.

Since 2014, LAPAN has developed the LAPAN Surveillance Aircraft (LSA), a light utility single engine aircraft for surveillance mission. The second series, LSA-02, is dedicated for technological demonstration purpose. The idea is to make LSA-02 as a test bench for a newly developed flight control systems. If this succeed, LSA-02 will become the first technology demonstrator aircraft in Indonesia.

The LSA series use STEMME S-15-1, which is manufactured in Germany as the basic aircraft. LSA-02 is planned to be supplemented with Electronic Flight Control System (EFCS). This system enables the aircraft to be controlled in two modes, which are mechanical control system and electronic control system. The specification for LSA is given in TABLE 1. The EFCS consists of two systems, which are the Basic Electronic Flight Control System (BEFCS) and the Experimental System (XS). These two systems have their own Flight Control Laws (FCLs) called basic Flight Control Laws (bFCLs) and experimental flight control laws (xFCLs), respectively.

To fulfill its mission as a technology demonstrator, bFCLs have been developed[1]. These bFCLs serve as the basic automatic flight control for the aircraft. The research objective in this paper is to introduce a design to apply the xFCLs as an additional flight function to the Electronic Flight Control System. The purpose of this research is to provide a relatively safe way to test newly developed FCLs in an experimental flight.

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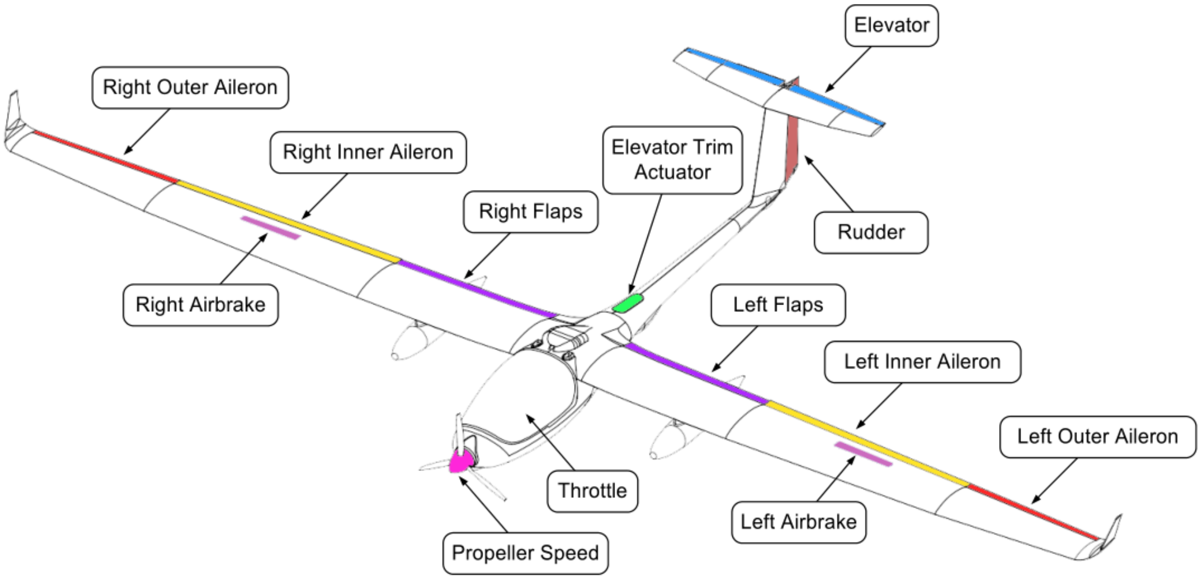

FIGURE 1. Aircraft STEMME ES15 which is modified with EFCS to become LSA-02[1].

TABLE 1. Light surveillance aircraft specification.

Specification	Value	Unit
DIMENSION		
Span	18	m
Length	8.52	m
Height	2.45	m
WEIGHT & PAYLOAD		
Max Take Off Weight	1100	kg
Max Payload	310	kg
Useful Payload	20	kg
Max Fuel	130	L
FLIGHT PERFORMANCE		
Cruise Speed	234	km/h
Ceiling	4.875	m
Rate of Climb	3	m/s
Range	1120	km

FLIGHT CONTROL SYSTEM

Electronic Flight Control System is a control system in aircraft where the movement of flight controls is converted to electronic signals. The control algorithms are called Flight Control Laws and usually are stored in the Flight Control Computer (FCC). Electronics for aircraft flight control systems are part of the field known as avionics. The EFCS is designed to improve the handling and the performance of the aircraft.

Flight Control Laws are sets of laws used in a system to control the aircraft motion. In this research, the FCLs design was based on 9 linear models of the LSA aircraft. The trim points were created by varying the aircraft center of gravity and the flight path speed. These trim points are listed in TABLE 2.

In the previous research, the bFCLs was designed using eigenstructure assignment and advanced PI technique[1]. The eigenstructure assignment keeps the open-loop stable eigenvalues and corresponding eigenspace unchanged[2]. Eigenstructure assignment is a very powerful approach to the design of any linear state-space feedback system, as it can be shown very easily that the closed-loop system structure depends entirely upon the system eigenvalues and the system's left and right eigenvectors[3]. This technique is also explored well in Refs. 4 and 5.

The concept of the advanced PI controller is to make a first order approximation for the desired state variable response. An extended system is then constructed, which consists of the state variables required for designing a tracking controller. The gains are then obtained by solving the problem described using the extended system. It should be noted that the controller is a linear system, hence the variables involved in this system only relevant to particular reference values (trim values). The advanced PI controller is also explored in Refs. 6, 7 and 8.

TABLE 2. Trim point for aircraft model.

Trim Point	h[m]	m[kg]	x_{CG}[m]	V_K[km/h]
1	1000	1000	-2.71	130
2	1000	1000	-2.71	160
3	1000	1000	-2.71	190
4	1000	1000	-2.62	130
5	1000	1000	-2.62	160
6	1000	1000	-2.62	190
7	1000	1000	-2.51	130
8	1000	1000	-2.51	160
9	1000	1000	-2.51	190

DESIGN REQUIREMENTS AND CRITERIAS

The FCLs requirements are divided into several categories, each of which is related to parameters and variables involved in flight control application, *i.e.* modes, input signals, output signals, control loops, characteristic values, control accuracy and performance, and flight envelope protection requirements.

Input Signals Requirements

The FCLs receive input from Flight Control Panel (FCP) and sensors. The input signals requirements for the FCLs are shown in TABLE 3.

TABLE 3. Input signals requirements.

Categories	No	Requirements
FCP commands requirements	1	The FCLs shall receive command of airspeed from the FCP
	2	The FCLs shall receive command of altitude from the FCP
	3	The FCLs shall receive command of vertical speed from the FCP
	4	The FCLs shall receive command of flight path inclination angle from the FCP
	5	The FCLs shall receive command of heading from the FCP
	6	The FCLs shall receive command of tracking from the FCP
	7	The FCLs shall receive command of pre-programmed navigation flight from the FCP
Sensor input requirements	8	The FCLs shall receive the measurement data of altitude from sensor
	9	The FCLs shall receive the measurement data of geodetic position from sensor
	10	The FCLs shall receive the measurement data of angle of attack from sensor
	11	The FCLs shall receive the measurement data of angle of sideslip from sensor
	12	The FCLs shall receive the measurement data of attitude from sensor
	13	The FCLs shall receive the measurement data of surfaces deflection from sensor
	14	The FCLs shall receive the measurement data of ground speed from sensor
	15	The FCLs shall receive the measurement data of vertical speed from sensor
	16	The FCLs shall receive the measurement data of angular rate from sensor
	17	The FCLs shall receive the measurement data of acceleration from sensor

Output Signals Requirements

The FCLs produce commands for actuators. The requirements for the output commands are given in TABLE 4.

TABLE 4. Output Signals Requirements

Categories	No	Requirements
FCL commands requirements	1	The FCLs shall command the actuator of aileron
	2	The FCLs shall command the actuator of elevator
	3	The FCLs shall command the actuator of rudder
	4	The FCLs shall command the actuator of throttle
	5	The FCLs shall command the actuator of propeller speed
	6	The FCLs shall command the actuator of flaps
	7	The FCLs shall command the actuator of airbrake
Entry point requirements	8	The xFCLs shall receive airspeed command from the bFCL
	9	The xFCLs shall receive altitude command from the bFCL
	10	The xFCLs shall receive heading command from the bFCL

Command Protection Requirements

To ensure that the aircraft stays safe during the experimental flight, the command signals are protected according to the requirements in TABLE 5.

TABLE 5. Command protection requirements.

Categories	No	Requirements
Commands protection requirements	1	The xFCLs shall limit pitch attitude deviation outside the range of $\pm 4^0$
	2	The xFCLs shall limit bank angle outside the range of $\pm 25^0$
	3	The xFCLs shall limit pitch airspeed outside the range 140 to 180 km/h
	4	The xFCLs shall limit altitude outside the range 500 m to 2500 m

DESIGN ARCHITECTURE

The FCLs in general receive commands from the FCP and measurement data from aircraft's sensors. The FCLs produce the commands to the control elements of the aircraft. The aircraft later produces dynamic responses representing its characteristic which will be measured by the aircraft's sensors, and the information from the sensors will be fed back to be processed for producing corrections for the commands from the FCP. The interaction between FCL, FCP and aircraft is depicted in FIGURE 2.

The FCP is the interface between pilots and the EFCS. The FCP provides the pilot access to the EFCS to control the aircraft, for example selecting automatic modes, defining test parameters, and entering flight plan. The FCP also informs the pilot about active and available automatic modes, the status system error, and the aircraft flight state. The command from FCP is shown in FIGURE 3.

The FCLs structure adopt cascade structure that consists of two types of Laws, the bFCLs and the xFCLs. The bFCLs further consist of outer loops part and inner loops part, whereas the xFCLs only have the outer loops part. Each loop possesses their own control modules with specific input-output variables. The modularity and cascade structure of FCLs allow maintainability and flexibility for future development[9,10]. Another type of structure for FCLs known as the fault-tolerant flight control is used in Refs. 11 and 12. This architecture focuses on fault handling and redundancy managing[13]. The FCLs require information from 30 kinds of variables as seen in TABLE 6TABLE 6.

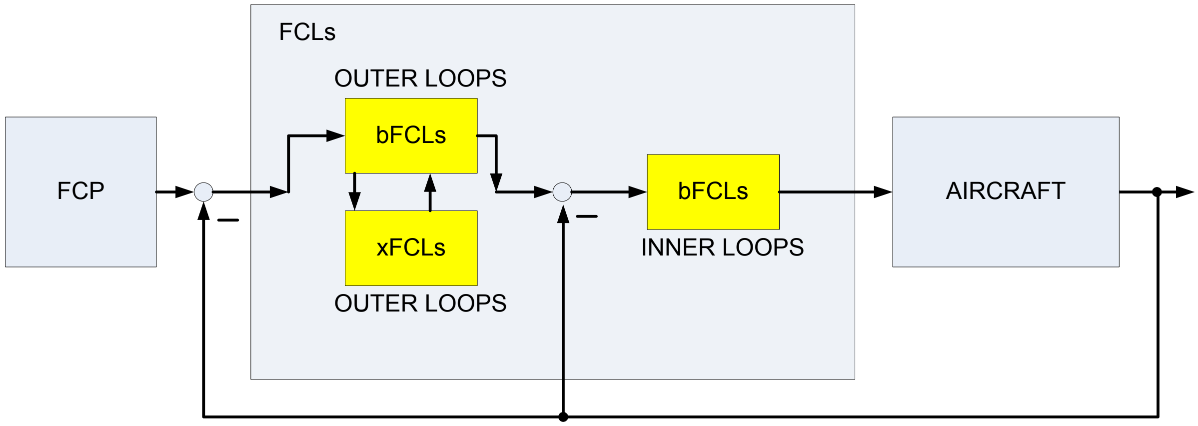

FIGURE 2. General structure of FCLs

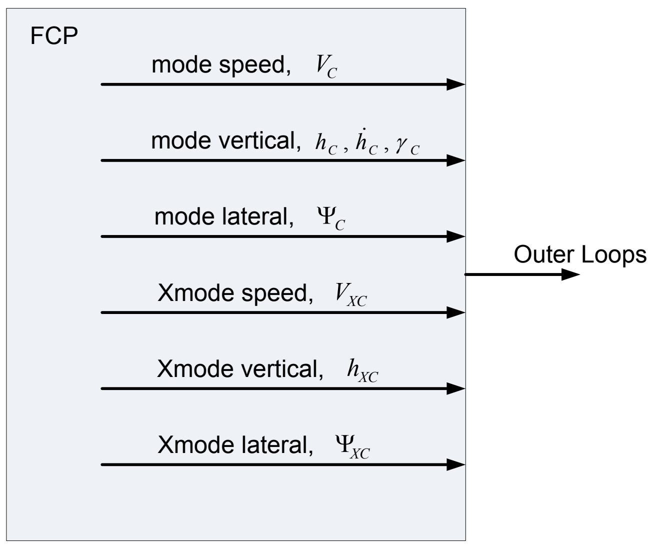

FIGURE 3. Flight Control Panel (FCP) structure

TABLE 6. Output variables produced by FCLs.

No	Variable	Symbol	No	Variable	Symbol
1	Distance in x axis	x_g	16	Rudder	ζ
2	Distance in y axis	y_g	17	Throttle	η_F
3	Distance in z axis	z_g	18	Propeller speed	ω_P
4	Altitude	h	19	Flaps	η_K
5	Bank angle	Φ	20	Airbrake	η_S
6	Pitch angle	Θ	21	Flight path velocity	V_K
7	Azimuth angle	Ψ	22	Airspeed	V
8	Angle of attack	α	23	Wind speed	V_W
9	Angle of sideslip	β	24	Vertical speed	$\dot{h}$
10	Flight path inclination angle	γ	25	Roll rate	p
11	Flight path azimuth angle	χ	26	Pitch rate	q
12	Wind inclination angle	γ_w	27	Yaw rate	r
13	Wind azimuth angle	χ_W	28	Load factor in x axis	n_x
14	Aileron	ξ	29	Load factor in y axis	n_y
15	Elevator	η	30	Load factor in z axis	n_z

The basic FCLs are implemented to provide basic control functions. The XS enables the deployment of experimental flight control laws (xFCLs) into aircraft flight control system. The experimental FCLs may experience failures during the flight, hence the basic FCLs shall be able to monitor xFCLs commands and the aircraft behavior during experimental flight and take over control whenever a failure occurs or when the maneuver is deemed to be dangerous.

The bFCLs outer loops have three modes of control, which are the heading control, the vertical control and the speed control. The vertical control contains further three different selections, which are altitude control, vertical rate control and flight path inclination angle control.

The xFCLs parts are expected to have capability to control these three modes as well, but it does not necessarily need to have the exact modes as the bFCLs. For example, the vertical control may only have altitude control mode. The xFCLs authority to govern aircraft is limited via certain entry point as shown in FIGURE 4.

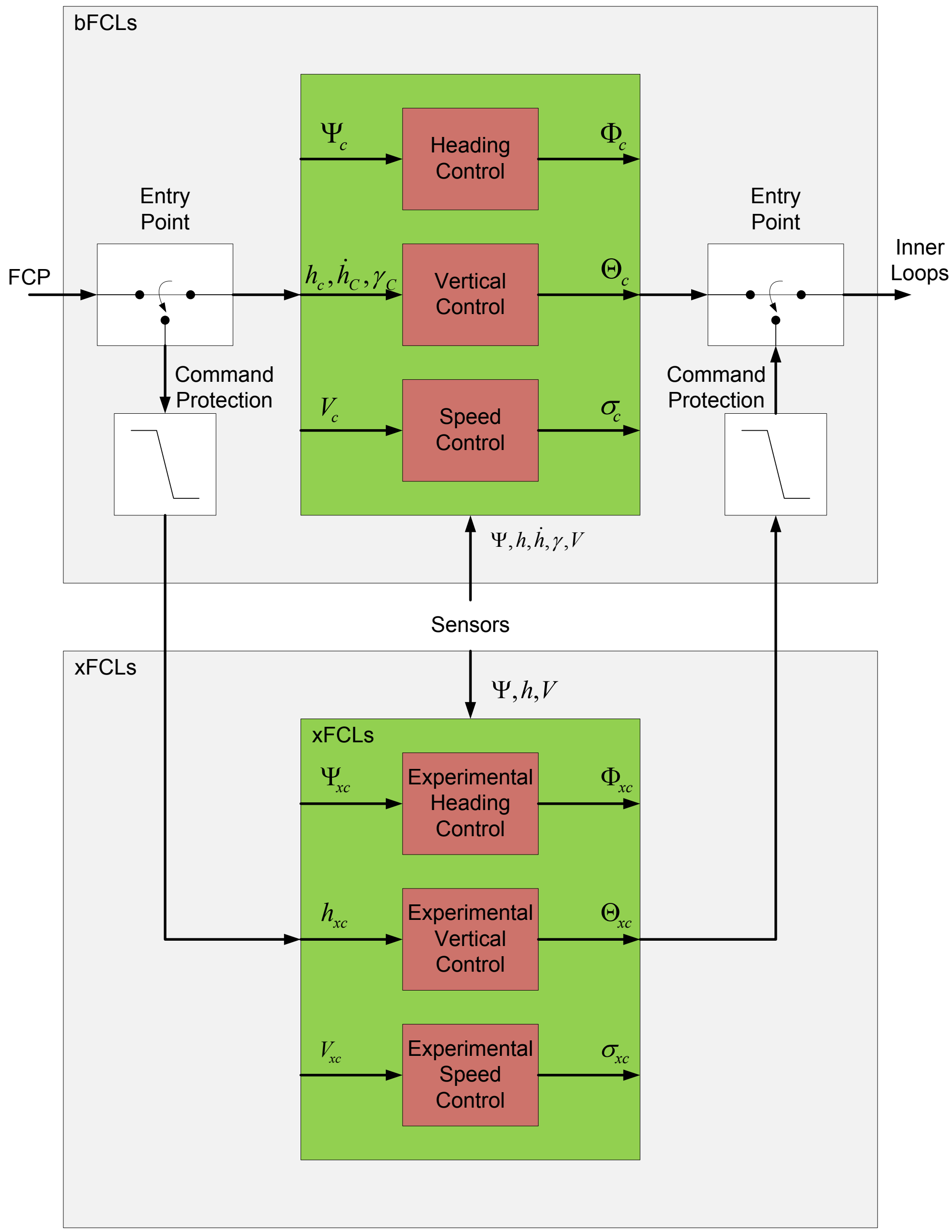

FIGURE 4. Controller structure of bFCLs and xFCLs in outer loops

The inner loops comprise six control modules, *i.e.* roll/roll damping, pitch/pitch damping, yaw/yaw damping, engine, flaps, and airbrake control modules. The inner loops command the control element devices of the aircraft, which are aileron, elevator, rudder, throttle, propeller speed, flaps and airbrake. The inner loops receive inputs from the outer loops, which are commands for bank angle, pitch angle, angle of sideslip, and throttle. The inner loops structure is shown in FIGURE 5.

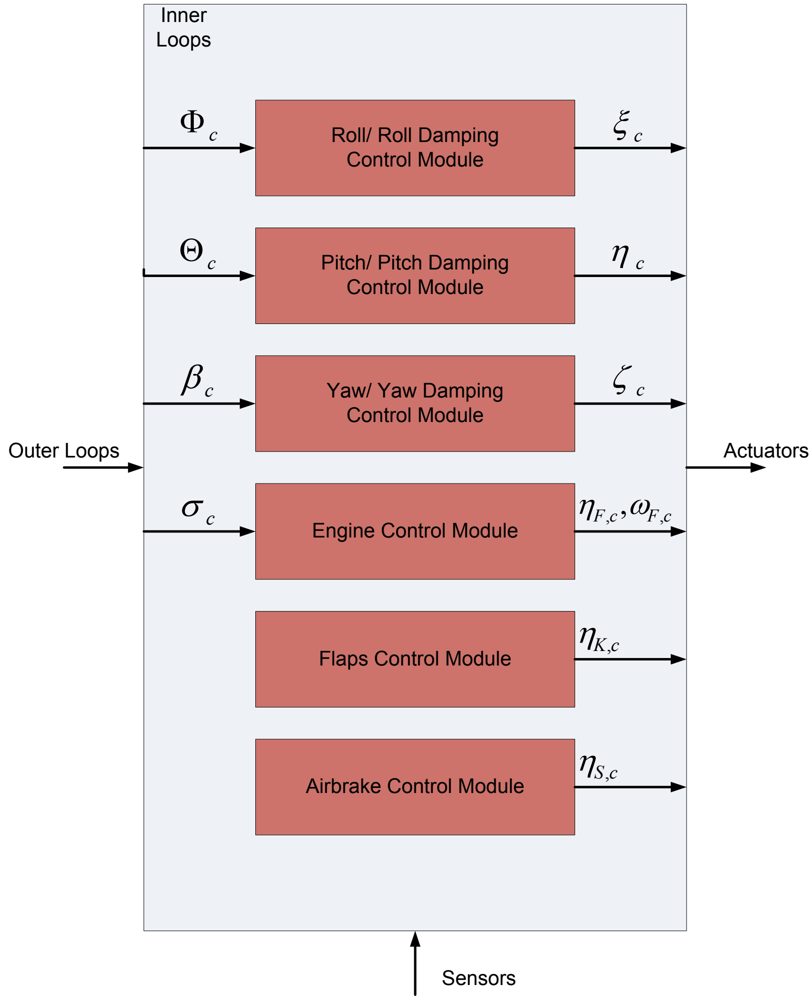

FIGURE 5. Inner loops structure of bFCLs

AIRCRAFT SIMULATION

Some simulations were conducted to verify the Experimental System that has been designed. For simulation purpose, second FCLs were created with structure resembled the bFCLs but with different gain control values. These FCLs acted as the experimental FCLs. The simulations were conducted in trim points as described in TABLE 2. For each case, the simulation was conducted for 100 seconds.

Case 1

The first simulation was to test the input entry point. This entry point was in charge of managing the input signals from the FCP and determined whether the signals go to the BEFCS or the XS. The scenario in the first simulation is as follows. First, the pilot gives two different speed commands to the FCP. The pilot then set which control modes is active. In this case, the pilot activates the XS mode and deactivates the BEFCS mode. If no error occurred, the aircraft should follow the speed command from the XS instead of the BEFCS.

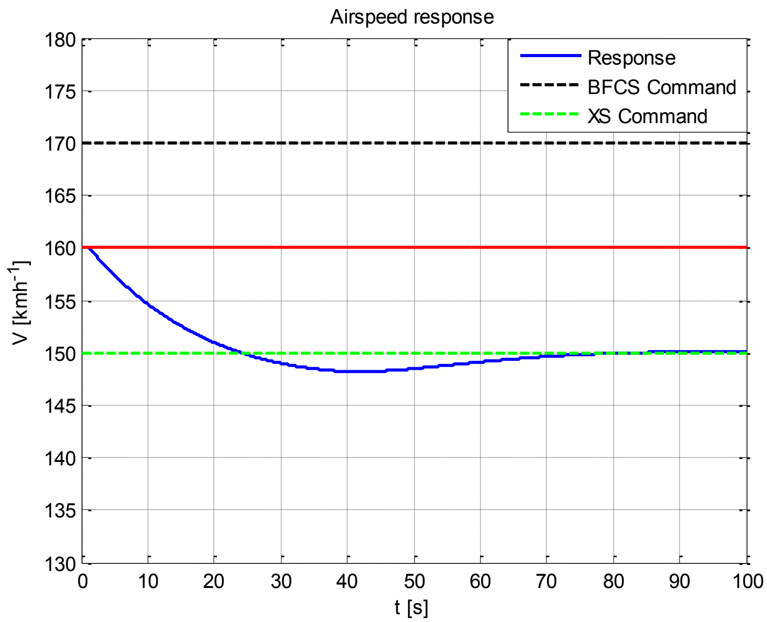

FIGURE 6. Example of aircraft responses for case 1, trim point 5, with $\boldsymbol{V_C}$ = 170 km/h and $\boldsymbol{V_{XC}}$ = 150 km/h

At the beginning of the simulation, the aircraft was trimmed at trim point 5, as shown by table 1. The pilot gave two airspeed commands. The BFCS airspeed command was set at 170km/h and the XS airspeed experimental command was set at 150 km/h. The simulation showed that the aircraft correctly follows the XS command, not the BEFCS command.

Case 2

The second simulation is to test the command protection function. In this simulation, the XS control mode was turned on and the BFCS mode was turned off. The pilot was then deliberately giving a dangerous command by setting the airspeed in the XS mode over the safety limit. Below is the result of the simulation.

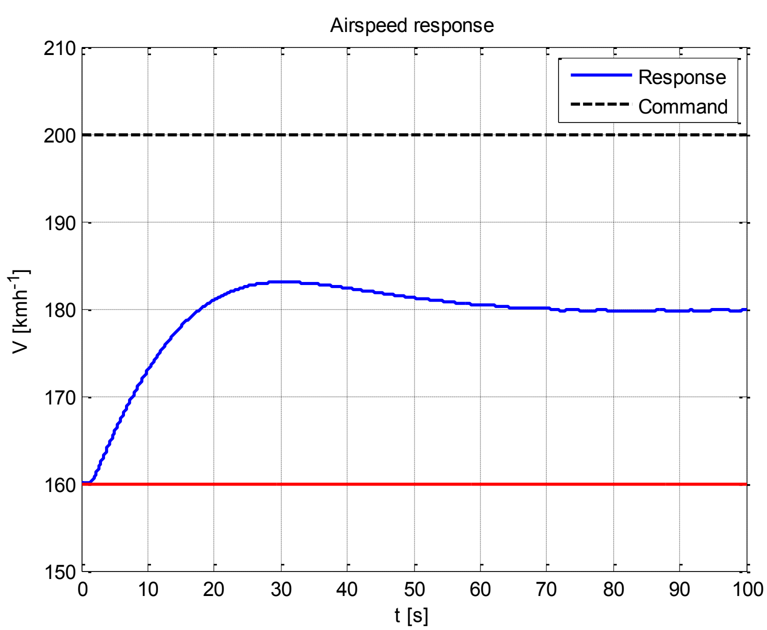

FIGURE 7 Example of aircraft responses for case 2, trim point 5, with $\boldsymbol{V_{XC}}$ = 200 km/h

At the beginning of the simulation the aircraft was trimmed at trim point 5, as shown by TABLE 2. The pilot activated the XS control mode and set the airspeed command at 200 km/h. Considering that the safety limit was set maximum at 180 km/h, the FCLs should protect this dangerous command and keep the airspeed in safety range. From the FIGURE 7 we can see that the aircraft briefly exceeded 180 km/h but then going down and stable at 180 km/h because of the applied command protection.

Case 3

The third simulation is also to test the command protection function. In this simulation, the XS control mode was turned on and the BFCS mode was turned off. At the beginning of the simulation, the aircraft was trimmed at trim point 5, as shown by TABLE 2. In this simulation, the XS was supposed to have inadequate capacity to manage the heading/tracking command. In the beginning, the aircraft had steady heading angle of 30^0. The pilot then gave command to the aircraft to change the heading to 90^0. With poor heading control, the aircraft would have extreme bank angle. The command protection was expected to protect this extreme bank angle and gave more appropriate command to the aircraft.

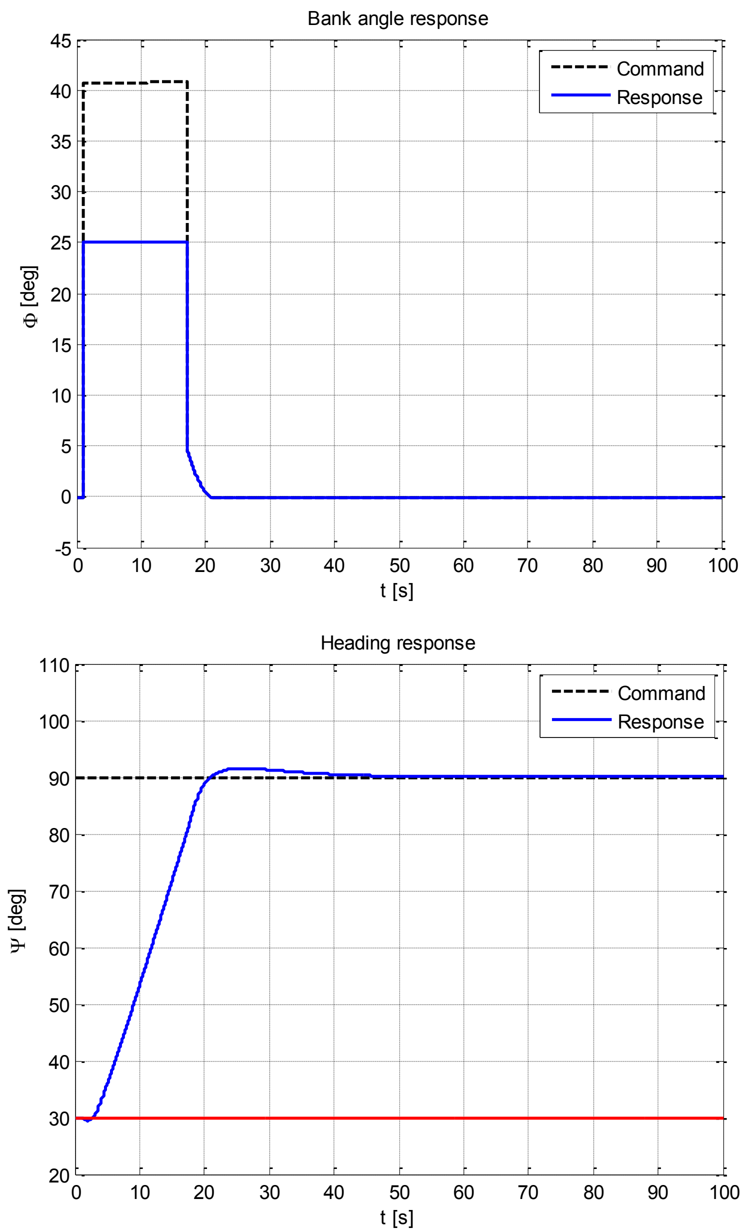

FIGURE 8. Example of aircraft responses for case 3, trim point 5, with $\boldsymbol{\Psi}_{XC}$= 90^0

In this simulation, the command protection limited the bank angle up to 25^0. From FIGURE 8, it can be seen that the xFCLs installed in the XS was inadequate to ensure the safety of the aircraft. The command protection was able to reduce the bank angle command from the XS. Even though the aircraft bank angle response was still undesirable but the command protection applied would reduce the risk occurred from extreme bank angle.

CONCLUSION

A design for Electronic Flight Control System to safely execute an experimental Flight Control Laws in a test flight has been successfully developed. This research can provide a relatively safe way to test a newly developed Flight Control Laws in an experimental flight. The simulations that has been done indicate that the Electronic Flight Control System was able to execute the experimental commands and reduce accidental risk by giving a relatively safer signals whenever the aircraft was going into potentially dangerous maneuver. The first simulation case shows that the entry point was able to manage the FCLs command. The second case shows that the command protection function prevented the airspeed from exceeding the limit, which was set at 180 m/s. In third case, the command protection function prevented the bank angle from exceeding the limit, which was set at 25^0.

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