# Development of Primary Flight Display Human Machine Interface for Flight Control Panel Model Verification

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**Abstract.** Flight Control Panel (FCP) as an interface between a test pilot and an Electronic Flight Control System (EFCS) provides inputs to Flight Control Computer (FCC). In return, FCC transmits sensor measurement to be displayed on FCP so that the test pilot can examine the aircraft responses concerning command inputs given. The interaction between FCP, FCC, and aircraft is mathematically modeled to verify the FCP functionalities. The verification is performed by defining sets of tests to be executed via Human Machine Interface (HMI) which needs to be previously constructed. The research in this paper shows the development of Primary Flight Display (PFD) as HMI to conduct functionality verification of the FCP model. The PFD provides information on artificial horizon, direction, airspeed, altitude, and vertical speed. In addition, PFD is equipped with virtual knobs to activate commands of airspeed, heading, altitude, vertical speed, and flight path inclination angle. Other flight variables are also displayed on. Results shown in this paper are the design of PFD and compliance of functionality requirements for FCP via model in the loop verification.

## INTRODUCTION

LAPAN Surveillance Aircraft 02 (LSA-02) is a high aspect ratio single-engine light utility aircraft developed for investigation and demonstration of Unmanned Aerial Vehicle (UAV) technology. The basic aircraft of LSA-02 is manufactured in Germany, *i.e*. Stemme ES-15 aircraft. It can be supplemented with an Electronic Flight Control System (EFCS), flight test installations, and additional experimental payloads. To perform its UAV demonstrator mission, LSA-02 shall be firstly operated as a manned aircraft by a safety pilot to cruise flight condition. Later the safety pilot exchanges his/her role as a test pilot and activates automatic flight control modes at EFCS to carry out defined experiments. Here, the test pilot stands by and monitors the aircraft responses which are controlled by EFCS. In case of a dangerous maneuver occurrence, the test pilot promptly deactivates EFCS to return to manual flight. Hence, LSA-02 has two control modes which are basic and electronic control modes. The former refers to manually piloted flight while the latter is automatic flight control employing EFCS.[1,2]

EFCS is engaged by coupling actuators to control elements linkages which belong to the aircraft's basic mechanical control system. The engagement means LSA-02 activates automatic flight control mode. During this mode, the safety pilot acts as a test pilot who selects commands inputs to EFCS via Flight Control Panel (FCP).[3] FCP is a Human Machine Interface (HMI) between the test pilot and the EFCS and is placed on the avionics panel or cockpit in front of the pilot. The FCP has three main functions, *i.e.* to load and send initialization data to the Flight Control Computer (FCC) to be read by Flight Control Laws (FCLs), to allow the pilot to input data or give commands manually to EFCS, and to display information to the pilot.[4] Early version of LSA-02 FCP display has been developed and it continues to comply with more requirements. The layout of indicators on the FCP display is constructed according to regulations and standards such as Federal Aviation Regulations (FARs), European Aviation Safety Agency Certification Specifications (EASA CS), and Civil Aviation Safety Regulation (CASR).

FAR Part 25 and CASR Part 25 are airworthiness standards for transport category airplanes, meanwhile the EASA CS 23 and CASR Part 23 are for normal, utility, acrobatic, and commuter category airplanes. Many sections of FAR

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Part 25, CASR Part 25, EASA CS 23, and CASR Part 23 specify what equipment is required on aircraft and where the equipment is to be placed. Basic instruments such as temperature indicator, clock, and magnetic compass must be installed and be visible from each pilot station. In addition, other instruments must be included such as airspeed indicator, altimeter indicator, vertical speed indicator, gyroscopic rate-of-turn indicator, gyroscopic bank and pitch indicator, and gyroscopic direction indicator. These six indicators are important to aircraft navigation. The flight and navigation instruments required by FAR Part 25 and CASR Part 25.1303 must be grouped on the instrument panel and be centered as nearly as practicable about the vertical plane of the pilot's forward vision. The arrangement of flight displays describes a "T" configuration which is found in the older analog cockpits such as the Boeing 727 or McDonnell Douglas DC-9. Both EASA CS-23 Part and CASR Part 23 mention that when an attitude display is installed, the instrument design must not provide any means, accessible to the flight crew, of adjusting the relative positions of the attitude reference symbol and the horizon line beyond that necessary for parallax correction.[5–8] Although there is a freedom to configure the display presentation in infinite ways, the same basic T configuration is maintained as when individual indicators are used. The altitude is in the center of the display. Airspeed is adjacent to and directly to the left of the attitude display. Altitude is adjacent to and directly to the right of the attitude display. The heading is adjacent to and directly below the attitude display.[9]

This research discusses the development of PFD design as HMI by adopting the basic T configuration and adding some variable instruments based on the requirements of EFCS models such as modes input (speed mode, vertical mode, lateral mode), commands inputs (airspeed, altitude, heading, vertical speed, flight path inclination angle), and other flight variables which will be completely explained in the PFD design chapter in this document. The objectives of this research are to develop PFD software and to verify the functionality of the FCP model. The development process of PFD design follows a very strict process namely the V model.[10] Firstly, PFD design requirements shall be defined as a guideline to construct the PFD design. Later, the constructed PFD design is used to verify the functionality of the FCP model whether it complies with written requirements.

## EFCS CONCEPT AND ARCHITECTURE

With the EFCS installed in the aircraft, there exist two flight control systems. The first one is the conventional mechanical Flight Control System (FCS) that belongs to the unmodified standard certified aircraft. The second one is the EFCS itself which is uncertified. In automatic flight mode, the EFCS uses the mechanical linkages of the mechanical FCS to command control elements via electromechanical actuators. The commands are computed by the FCLs which are implemented in the FCC. Commands to the EFCS are inputted in flight by the test pilot via FCP or on the ground by the flight test engineer via ground control station which is equipped with a data link.

EFCS is developed in such a way as not to generate dangerous maneuvers in flight. Flight safety must be a priority. In case of a critical EFCS failure, a Safety System (SASYS) shall allow switching from the electronic control mode to basic control mode instantly. This switching shall be performed by a Fast Decoupling Device (FDD) that shall be designed simply without software and shall be proved to be qualified. After switching, the test pilot takes over control in manual control mode and becomes the safety pilot. Switching has to be performed in a very short time without transient as required by functional hazard analysis. The most critical failure cases are unlimited runaway when the aircraft is operating close to the ground, *i.e.* during taking-off or landing, and unlimited runaway when the aircraft is operating at airspeeds above the maneuvering speed $V_A$.

The EFCS is designed to be modular and scalable. This design enables easier modification such as changing or adding sensors or payloads. The general architecture of the EFCS can be seen in FIGURE 1. From the figure, the Basic Aircraft (BAC) block is certified and consists of conventional mechanical control linkages and data links. The SASYS with the FDD assures flight safety during automatic flight mode. In case of a failure, the SASYS will automatically disengage the system and warn the test pilot. The FDD is the device which is used to disengage all actuators simultaneously in case of critical error occurs. It shall be designed simply without software but it has to be proven well-performing. In the automatic flight mode (electronic control mode), the EFCS is coupled to the basic mechanical control linkages. For safety reasons, engage-disengage of the system will be realized by the actuator's clutch which is designed to be normally open. When engaging the EFCS, the actuator's clutch is closed or coupled to the mechanical control linkages. In the case of disengaging the EFCS or in the case of power loss, the clutch opens automatically.

To fulfill fail passive behavior, the Basic EFCS (BEFCS) is designed to have dual lanes for control and monitoring functions. The BEFCS handles autopilot function and monitoring of the Experimental System (XS) commands in experimental missions. Therefore, the BEFCS is designed to be reliable to demonstrate flight safety to the certification authority to obtain a flight permit. The XS is considered to be unreliable and only has a single lane system because XS authority to control the aircraft is limited by the BEFCS. Communication between the BEFCS and the XS is done by using Flex Ray data buses.[3]

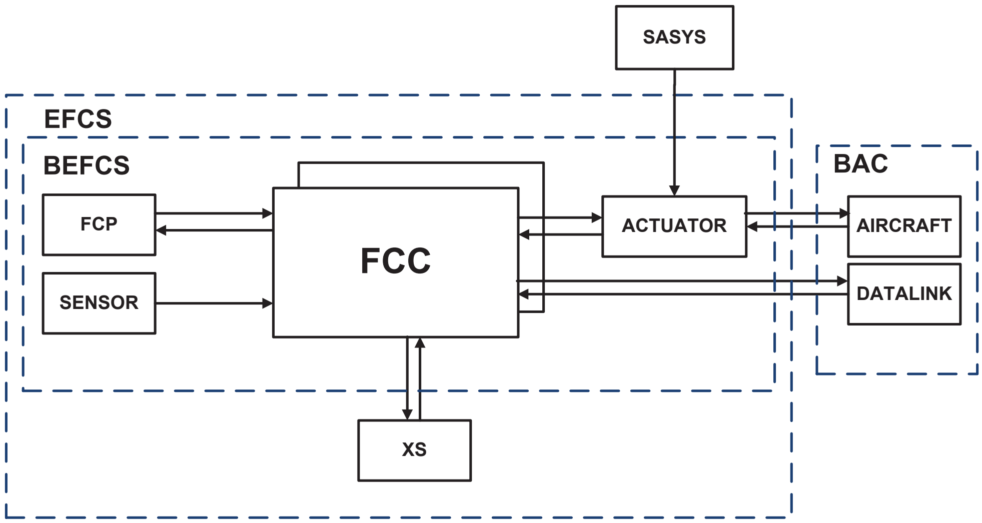



**FIGURE 1**. The architecture of EFCS.

The implementation of EFCS architecture without SASYS and XS is shown in FIGURE 2.

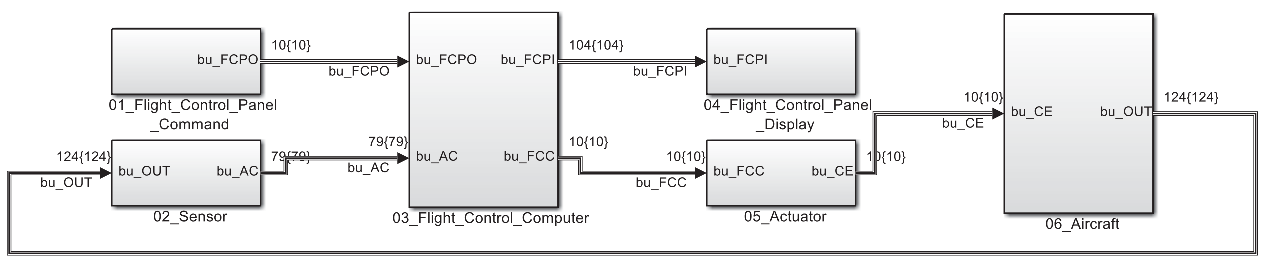



**FIGURE 2**. EFCS model implementation in MATLAB Simulink.

The research focuses on the FCP model which comprises of FCP command subsystem and FCP display subsystem. FIGURE 2 shows that the FCP command has the function of providing commands input to FCC. In return, FCC transmits sensor measurement to be displayed on FCP display. The FCP Command consists of three modes namely speed mode, vertical mode, and lateral mode as displayed in FIGURE 3.

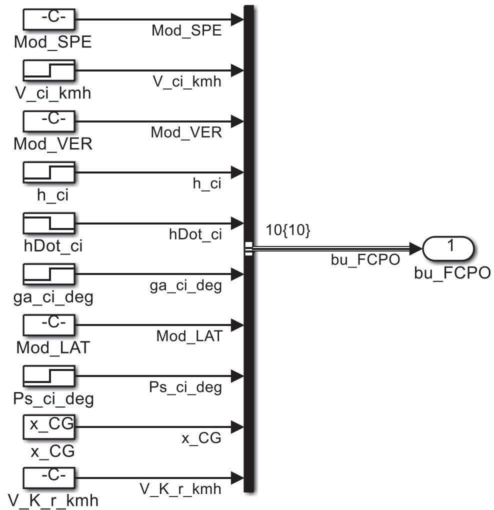



**FIGURE 3.** FCP command model implementation in MATLAB Simulink.

Generally, the speed mode consists of a speed command that controls the forward speed. In addition, the vertical mode conveys altitude command and vertical speed command. The altitude command maintains an assigned barometric altitude. The vertical speed mode allows to perform constant rate of climbs and descents. It must be careful to specify an appropriate vertical speed, as the aircraft will fly itself into a stall if the vertical speed command is greater than the capability of the aircraft's power plant. Lastly, lateral mode covers heading, track over the ground, and turn rate commands.[11,12]

Currently, in EFCS development, speed mode consists of only airspeed command, the vertical mode contains altitude, vertical speed, and flight path inclination angle commands. The lateral mode only covers heading commands but in the future, it is possible to add some more commands *i.e.* track over ground and turn rate commands. Each commands input has a certain range which is displayed in TABLE 1.

**TABLE 1**. Range of EFCS commands input.

| No. | Variable | Range |
|---|---|---|
| 1. | Airspeed command | 130 – 190 km/h |
| 2. | Heading command | 0 – 360 degrees |
| 3. | Altitude command | 600 – 3000 m |
| 4. | Vertical speed command | -2 – 3 m/s |
| 5. | Flight path inclination angle command | -3.5 – 5 degrees |

FCP display has a purpose to show information from sensor measurement, FCP command, flight guidance command, and flight control command. The former is originally the main purpose. However, it is beneficial to display the other three commands. Sensor measurement block includes large numbers of flight variables such as distances, angles, speeds, angular speeds, accelerations, etc. FCP command block is displayed to ensure correct inputs from the FCP command. Flight guidance and flight control command blocks provide output information generated from outer loops and inner loops of FCLs. The implementation of the FCP display is shown in FIGURE 4.

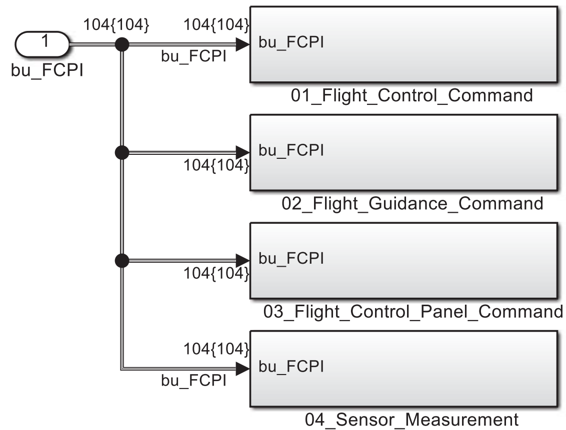



**FIGURE 4**. FCP display model implementation in MATLAB Simulink.

## PFD DESIGN REQUIREMENTS

PFD design requirements shall be firstly defined which are derived from the upper-level requirements *i.e.* navigation instruments regulation and EFCS requirements. The requirements then become the guidelines for developing the PFD design. Later, the developed PFD design is used to verify the functionality of the FCP model whether it complies with written requirements. The whole development process started from the requirement, design, until verification is arranged by adopting the V model into the mini V model which is depicted in FIGURE 5.

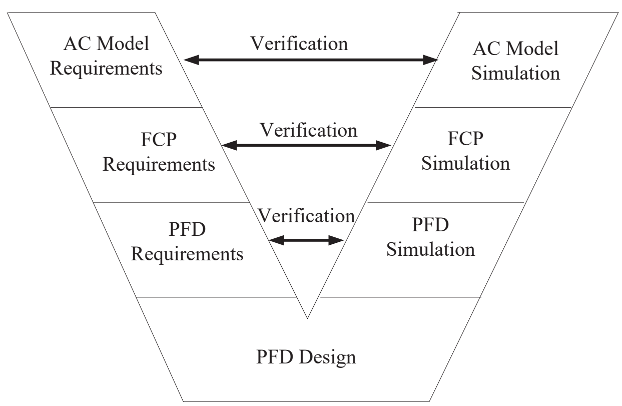



**FIGURE 5.** The mini V model for the PFD design development process.

The PFD design requirement derived from the navigation instruments regulation and the standard is the basic T configuration depicted in FIGURE 6.[9,13]

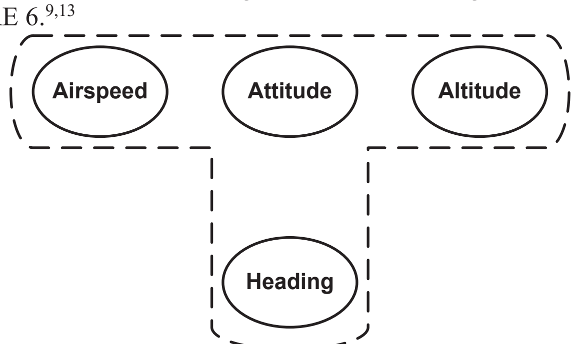



**FIGURE 6**. Basic T configuration for PFD.

The airspeed indicator provides information on indicated airspeed in kilometers an hour of the aircraft. Attitude indicator shows the aircraft pitch and bank angles which are informed using an artificial horizon where sky, ground, and horizon are colored imaged with markings to indicate the pitch and bank angles. The altitude indicator provides information on the indicated altitude in meter of the aircraft. The heading indicator provides heading information independent of the magnetic compass.[14]

Meanwhile, the PFD design requirements are derived from EFCS requirements and are divided into several categories. The categories are related to parameters and variables which are involved in flight control application such as inputs, outputs, and FCP model.[15,16] To accommodate and arrange the variables and parameters to be displayed, the additional requirements are defined, *i.e.* variable indicator types and PFD design layout.

## Input Variables Requirements

According to the EFCS model, FCP sends input to the FCC. To accommodate the FCP function of transmitting commands, the PFD design shall display input variables as written in TABLE 2.

**TABLE 2.** Input requirements.

| No. | Input variable |
|---|---|
| 1. | Speed mode |
| 2. | Vertical mode |
| 3. | Lateral mode |
| 4. | Speed command |
| 5. | Altitude command |
| 6. | Vertical speed command |
| 7. | Heading command |
| 8. | Flight path inclination angle command |

## Output Variables Requirements

According to the EFCS model, the FCP model receives the sensor measurements from the FCC. To accommodate the FCP function of receiving the sensor measurements, the PFD design shall display output variables as written in TABLE 3.

**TABLE 3.** Output requirements.

| No. | Variable | Symbol | Unit |
|---|---|---|---|
| 1. | Airspeed | $V$ | km/h |
| 2. | Altitude | $h$ | m |
| 3. | Attitude (roll, pitch, and yaw angle) | $\Phi, \Theta, \Psi$ | deg |
| 4. | Vertical speed | $\dot{h}$ | m/s |
| 5. | Surface deflection (aileron, elevator, and rudder) | $\xi, \eta$, and $\zeta$ | deg |
| 6. | Throttle position | $\eta_F$ | % |
| 7. | Aerodynamics angle (Angle of attack and Angle of sideslip) | $\alpha$ and $\beta$ | deg |
| 8. | Flight path inclination and flight path azimuth angle | $\gamma$ and $\chi$ | deg |
| 9. | Wind inclination and wind azimuth angle | $\gamma_W$ and $\chi_W$ | deg |
| 10. | Geodetic position (x, y, and z distance) | $x, y, z$ | km |
| 11. | Angular rate (roll, pitch, and yaw rate) | $p, q, r$ | deg/s |

## Input-Output Indicator Type Requirements

The PFD design shall adopt some indicators type to display input-output variables. The indicators type selected to accommodate the FCP model function shall follow the requirements as written in TABLE 4.

**TABLE 4.** Indicator type requirements.

| No. | Variable | Indicator | Type |
|---|---|---|---|
| 1. | Flight mode | Numerical input | Input |
| 2. | Flight command | Numerical input and virtual knob | Input |

| No. | Variable | Indicator | Type |
|---|---|---|---|
| 3. | Airspeed | Airspeed indicator | Output |
| 4. | Attitude | Artificial horizon indicator | Output |
| 5. | Altitude | Altitude indicator | Output |
| 6. | Vertical speed | Vertical speed indicator | Output |
| 7. | Heading | Heading indicator | Output |
| 8. | Other flight variables | Display indicator | Output |

## Layout Requirement

To arrange the variables and parameters indicators, the PFD design layout is essential to construct. It shall fulfill some requirements as written in TABLE 5.

**TABLE 5.** Layout requirement.

| No. | Requirement |
|---|---|
| 1. | T configuration is placed in the middle design, consists of the airspeed indicator, attitude indicator, altitude indicator, and heading indicator |
| 2. | The airspeed indicator is placed on the left side of the T configuration |
| 3. | Artificial horizon indicator is placed in the center of T configuration |
| 4. | Altitude indicator is placed on the right side of T configuration |
| 5. | The heading indicator is placed on the bottom side of the T configuration |
| 6. | Vertical speed indicator shall be located near the altitude indicator, it is placed beside the altitude |
| 7. | Throttle and primary control surfaces are placed in the middle of the T configuration |
| 8. | Input variables are placed in the top design, above the artificial horizon indicator |
| 9. | Output variables are placed below the artificial horizon indicator and parallel with the heading indicator |

## FCP Functionality Requirements

FCP model is divided into two blocks which are FCP command and FCP display. These blocks are mandatorily required to verify their functionality. The PFD design shall be used to verify the functionality whose requirements are listed in TABLE 6.

**TABLE 6.** FCP functionality requirements.

| No. | Requirement |
|---|---|
| 1. | Provide speed command |
| 2. | Provide heading command |
| 3. | Provide altitude command |
| 4. | Provide vertical speed command |
| 5. | Provide flight path inclination angle command |
| 6. | Provide vertical mode command |
| 7. | Display the other flight variables with respect to given commands |

## PFD DESIGN

Completing requirements definitions, the PFD design is conducted firstly by defining the arrangement of flight variables and parameters to be displayed. To comply with layout, input-output variables which are mentioned in TABLE 5,TABLE **2**, and TABLE **3** respectively, the PFD design architecture is arranged as depicted in FIGURE 7.

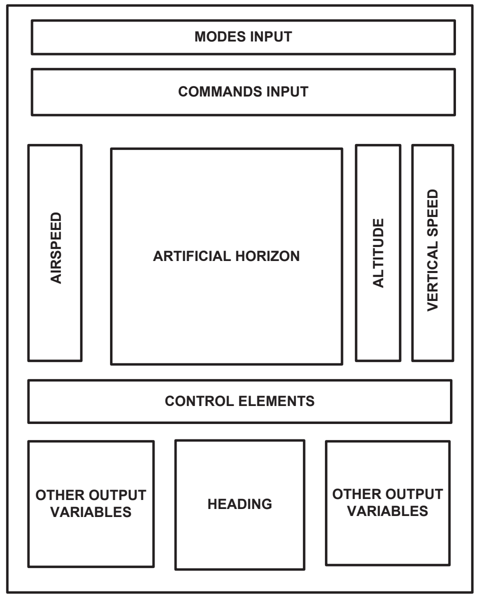



**FIGURE 7.** PFD design architecture.

Subsequently, the HMI is built based on the PFD design architecture and input-output indicator type requirements which are given in FIGURE 7 and TABLE 4 respectively. The PFD design result is depicted in FIGURE 8.

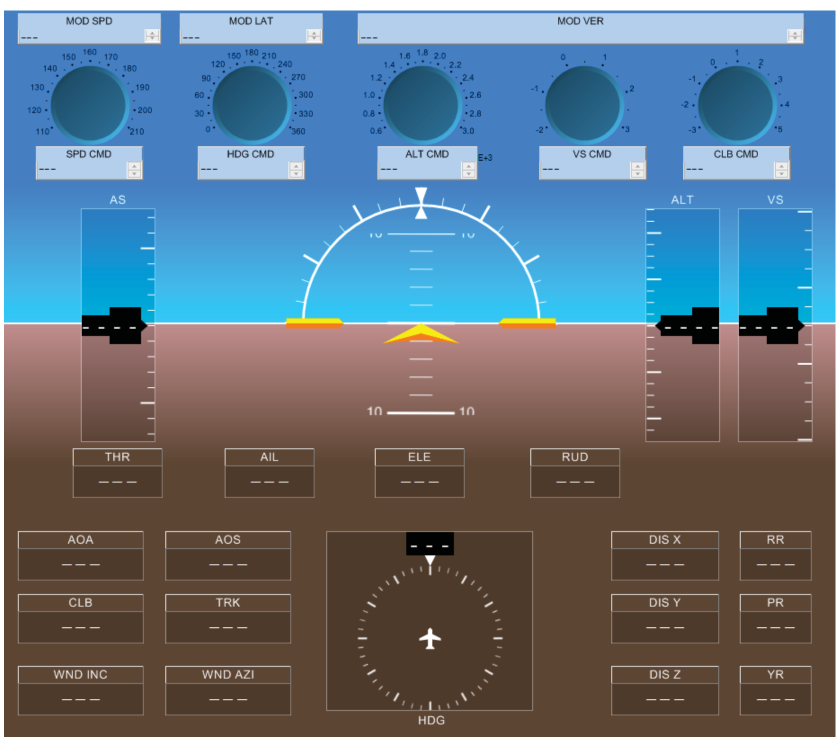



**FIGURE 8.** PFD design for FCP model verification. Design is realized by employing ControlDesk software.

Detail of flight variables and parameters which are displayed in PFD design as shown in FIGURE 8 are written in TABLE 7.

**TABLE 7.** List of flight variables and parameters displayed in PFD design.

| No. | Abbreviation | Variable | No. | Abbreviation | Variable |
|---|---|---|---|---|---|
| 1. | MOD SPD | Speed mode | 15. | RUD | Rudder deflection |
| 2. | MOD LAT | Lateral mode | 16. | AOA | Angle of attack |
| 3. | MOD VER | Vertical mode | 17. | AOS | Angle of sideslip |
| 4. | SPD CMD | Speed command | 18. | CLB | Flight path inclination (climb) angle |
| 5. | HDG CMD | Heading command | 19. | TRK | Flight path azimuth (track) angle |
| 6. | ALT CMD | Altitude command | 20. | WIND INC | Wind inclination angle |
| 7. | VS CMD | Vertical speed command | 21. | WIND AZI | Wind azimuth angle |
| 8. | CLB CMD | Flight path inclination angle (climb) command | 22. | HDG | Heading (yaw) angle |
| 9. | AS | Airspeed | 23. | DIS X | Distance (position) in x-axis |
| 10. | ALT | Altitude | 24. | DIS Y | Distance (position) in y-axis |
| 11. | VS | Vertical speed | 25. | DIS Z | Distance (position) in z-axis |
| 12. | THR | Throttle position | 26. | RR | Roll rate |
| 13. | AIL | Aileron deflection | 27. | PR | Pitch rate |
| 14. | ELE | Elevator deflection | 28. | YR | Yaw rate |

## PFD SIMULATION FOR FCP MODEL VERIFICATION

The constructed PFD design as depicted in FIGURE 8 shows that the entire requirements have been successfully complied with except for FCP functionality requirements as mentioned in TABLE 6. To comply with the FCP functionality requirements, the developed PFD design must be tested through simulation in a full EFCS model as displayed in FIGURE 2. Therefore, the integration of flight variables and parameters from the EFCS model to PFD design shall be performed in the beginning. The integration process needs a connection between real-time computer and development PC (host PC) as displayed in FIGURE 9. The integration process must be initiated by firstly building the EFCS and aircraft models to PFD development PC. Later, the EFCS and aircraft models are uploaded to a real-time computer. The PFD then is set up by connecting input-output indicators on PFD design to specifically addressed flight variables in the EFCS model. PFD design is performed based on a written test definition to verify airspeed, heading, altitude, vertical speed, flight path inclination angle, and vertical mode commands. Subsequently, verification via EFCS simulation is conducted through all trim points which can be seen in TABLE 8. Finally, simulation analysis is carried for FCP model verification.

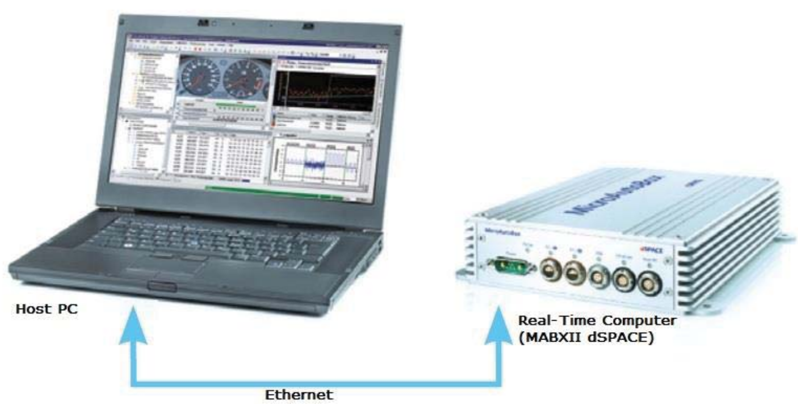



**FIGURE 9.** Integration of real-time computer and host PC.[17]

**TABLE 8.** Trim point for aircraft model.

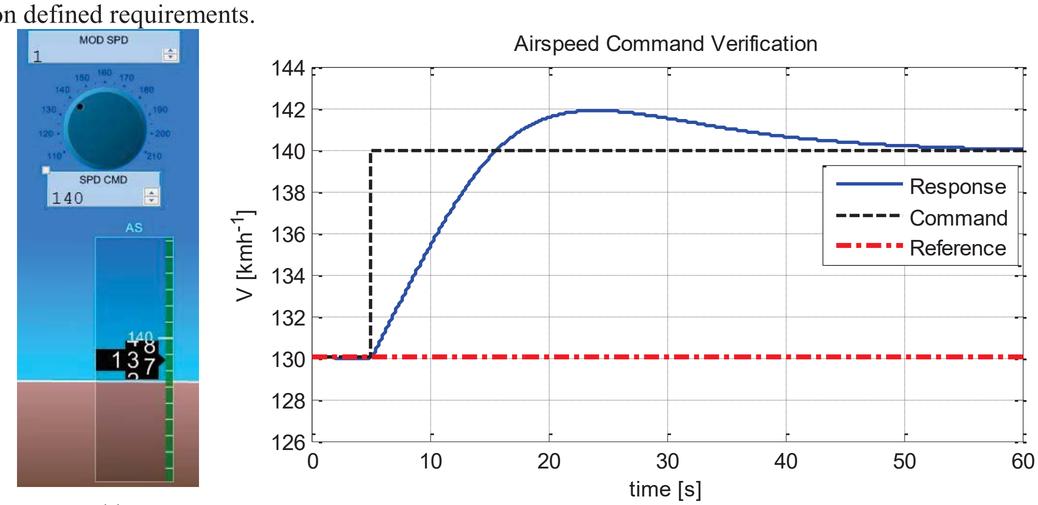
| Trim Point | h (m) | m (kg) | $x_{CG}$ (m) | $V_K$ (km/h) |
|---|---|---|---|---|
| 1 | 1000 | 1000 | -2.71 | 130 |
| 2 | 1000 | 1000 | -2.71 | 160 |
| 3 | 1000 | 1000 | -2.71 | 190 |
| 4 | 1000 | 1000 | -2.62 | 130 |
| 5 | 1000 | 1000 | -2.62 | 160 |
| 6 | 1000 | 1000 | -2.62 | 190 |

| Trim Point | h (m) | m (kg) | $x_{CG}$ (m) | $V_K$ (km/h) |
|---|---|---|---|---|
| 7 | 1000 | 1000 | -2.51 | 130 |
| 8 | 1000 | 1000 | -2.51 | 160 |
| 9 | 1000 | 1000 | -2.51 | 190 |

## Airspeed Command Verification

The first simulation is conducted to verify the airspeed command in the developed PFD design. The scenario in the first simulation is as follows. Firstly, the EFCS model is run based on the given references shown in TABLE 8. From the selected airspeed reference after five seconds, the test pilot changes the airspeed command. The simulation is conducted for 60 seconds. An example of airspeed command verification is displayed in FIGURE 10.

The simulation shown in FIGURE 10 verifies the airspeed response follows the given airspeed command all time from 0 to 60 seconds. Therefore, the airspeed command which is part of the FCP model has complied its functionality based on defined requirements.



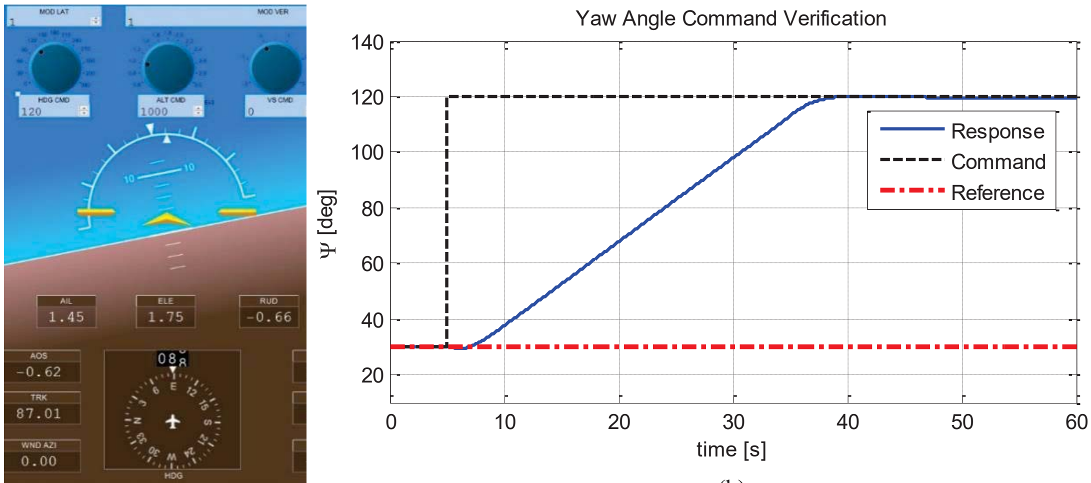

(a) (b)

**FIGURE 10.** An example of airspeed command verification for trim point 1 with $V_{c,kmh}$ $(t_0)$ = 130 and $V_{c,kmh}$ $(t_5)$ = 140, (a) airspeed command and response in PFD design, (b) plot of airspeed command and response.

## Heading Command Verification

The second simulation is conducted to verify the heading command in the developed PFD design. The scenario in the second simulation is as follows. Firstly, the EFCS model is run based on the given references shown in TABLE 8. From the selected heading reference after five seconds, the test pilot changes the heading command. The simulation is conducted for 60 seconds. An example of heading command verification is displayed in FIGURE 11.

The simulation depicted in FIGURE 11 verifies the heading response follows the given heading command all time from 0 to 60 seconds. Therefore, the heading command which is part of the FCP model has complied its functionality based on defined requirements.



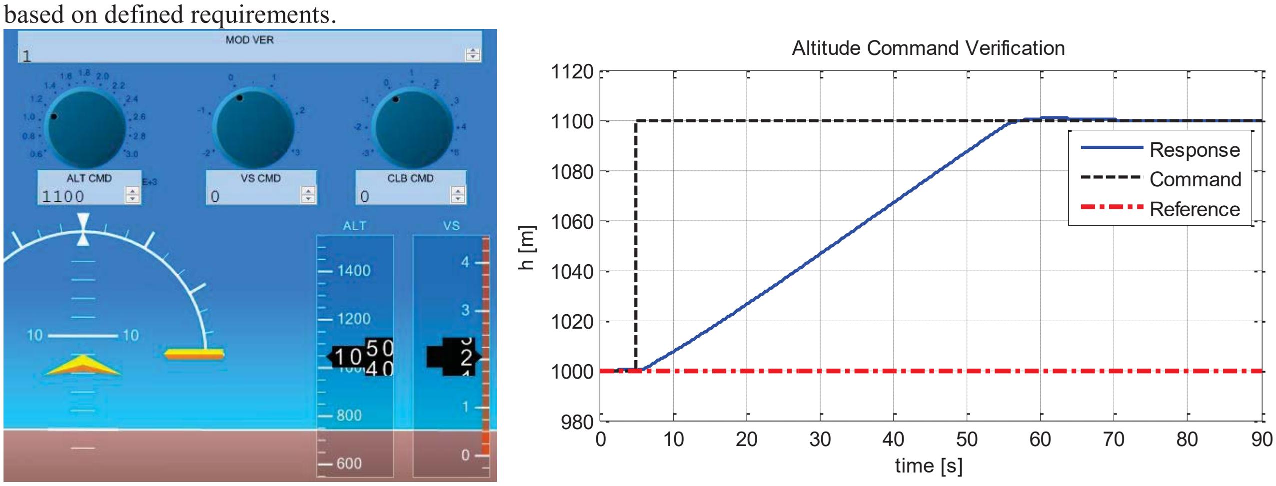
(a) (b)

**FIGURE 11**. An example of heading command verification for trim point 1 with $\Psi_{c,deg}\,(t_0) = 30$ and $\Psi_{c,deg}\,(t_5) = 120$, (a) heading command and response in PFD design, (b) plot of heading command and response.

## Altitude Command Verification

The third simulation is conducted to verify the altitude command in the developed PFD design. The scenario in the third simulation is as follows. Firstly, the EFCS model is run based on given references shown in TABLE 8 and the vertical mode is set at 1 to activate altitude control. From the selected altitude reference after five seconds, the test pilot changes altitude command. The simulation is conducted for 90 seconds. An example of heading command verification is displayed in FIGURE 12.

The simulation shown in FIGURE 12 verifies the altitude response follows the given altitude command all time from 0 to 90 seconds. Therefore, the altitude command which is part of the FCP model has complied its functionality based on defined requirements.



(a) (b)

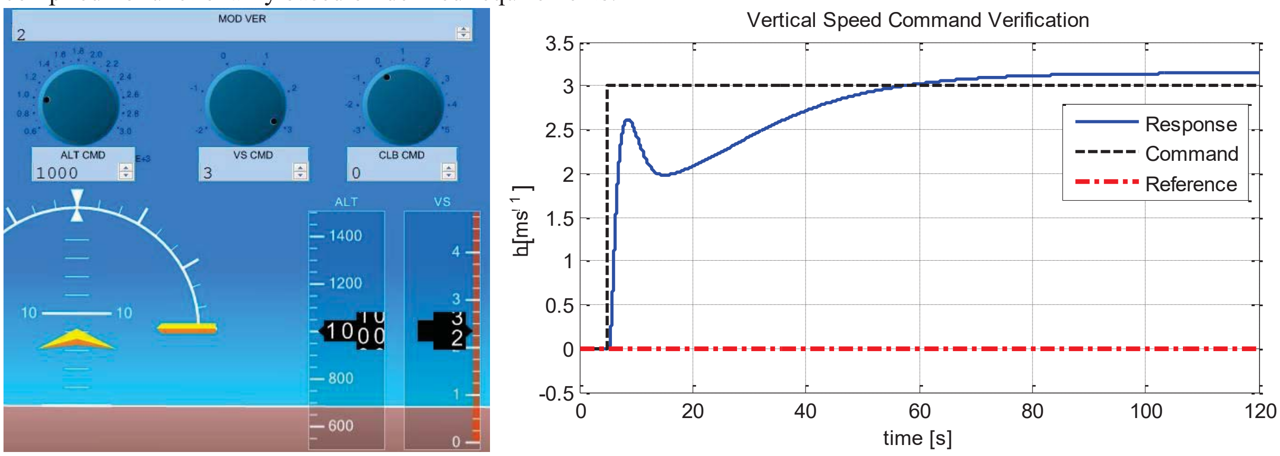
**FIGURE 12.** An example of altitude command verification for trim point 1 with $h_{c,m}\,(t_0) = 1000$ and $h_{c,m}\,(t_5) = 1100$, (a) altitude command and response in PFD design, (b) plot of altitude command and response.

## Vertical Speed Command Verification

The fourth simulation is conducted to verify the vertical speed command in the developed PFD design. The scenario in the fourth simulation is as follows. Firstly, the EFCS model is run based on given references shown in

TABLE 8 and the vertical mode is set at 2 to activate vertical speed control. From the selected vertical speed reference after five seconds, the test pilot changes the vertical speed command. The simulation is conducted for 120 seconds. An example of vertical speed command verification is shown in FIGURE 13.

The simulation depicted in FIGURE 13 verifies the vertical speed response follows the given vertical speed command all time from 0 to 120 seconds. Therefore, the vertical speed command which is part of the FCP model has complied its functionality based on defined requirements.




(a) (b)

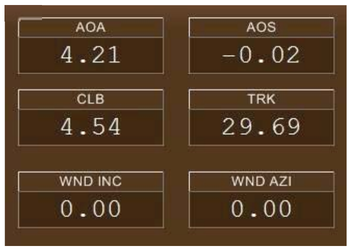
**FIGURE 13.** An example of vertical speed command verification for trim point 1 with $\dot{h}_{c,ms}(t_0) = 0$ and $\dot{h}_{c,ms}(t_5) = 3$, (a) vertical speed command and response in PFD design, (b) plot of vertical speed command and response.

## Flight Path Inclination Angle Command Verification

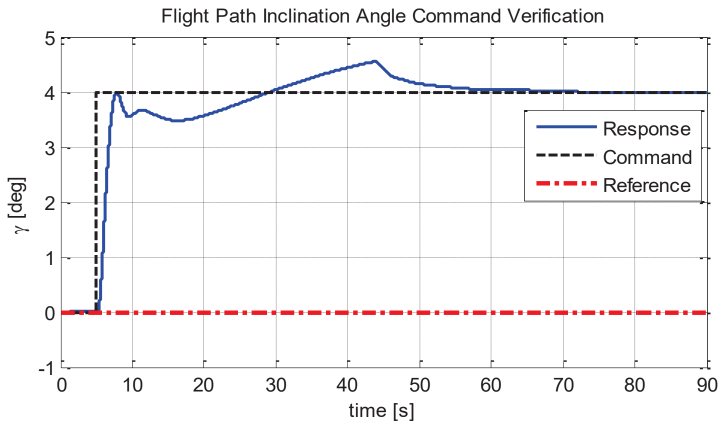
The fifth simulation is conducted to verify the flight path inclination angle command in the developed PFD design. The scenario in the fifth simulation is as follows. Firstly, the EFCS model is run based on given references shown in TABLE 8 and the vertical mode is set at 3 to activate the flight path inclination angle control. From the selected flight path inclination angle reference after five seconds, the test pilot changes the flight path inclination angle command. The simulation is conducted for 90 seconds. An example of flight path inclination angle command verification is displayed in FIGURE 14.

The simulation shown in FIGURE 14 verifies the flight path inclination angle response follows the given flight path inclination angle command all time from 0 to 90 seconds. Therefore, the flight path inclination angle command which is part of the FCP model has complied its functionality based on defined requirements.


(a)




(b)



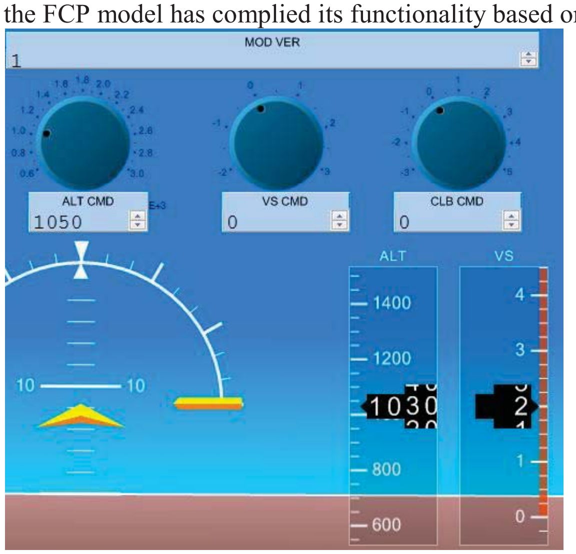

(c)

**FIGURE 14.** An example of flight path inclination FPI angle command verification for trim point 1 with $\gamma_{c,deg}$ ($t_0$) = 0 and $\gamma_{c,deg}$ ($t_5$) = 4, (a) flight path inclination angle command and response in PFD design, (b) plot of flight path inclination angle command and response.

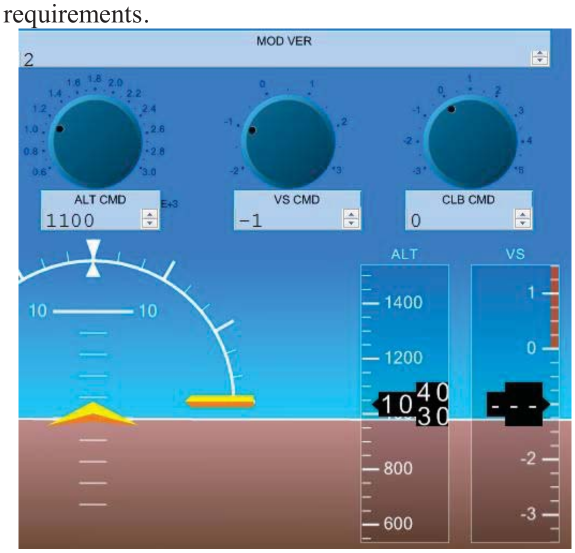
## Vertical Mode Verification

The sixth simulation is conducted to verify the functionality of vertical mode input. The scenario in the sixth simulation is as follows. Firstly, the EFCS model is run based on the given references shown in TABLE 8. After five seconds, the test pilot changes the altitude command. Then, the test pilot changes the vertical mode after forty seconds. Later, the test pilot changes the altitude and vertical speed commands simultaneously after fifty seconds. The simulation is conducted for 90 seconds. An example of vertical mode verification is displayed in FIGURE 15 and FIGURE 16.

The simulation depicted in FIGURE 15 and FIGURE **16** verify the altitude and vertical speed response follow the given vertical mode command all time from 0 to 90 seconds. Therefore, the vertical mode command which is part of the FCP model has complied its functionality based on defined requirements.

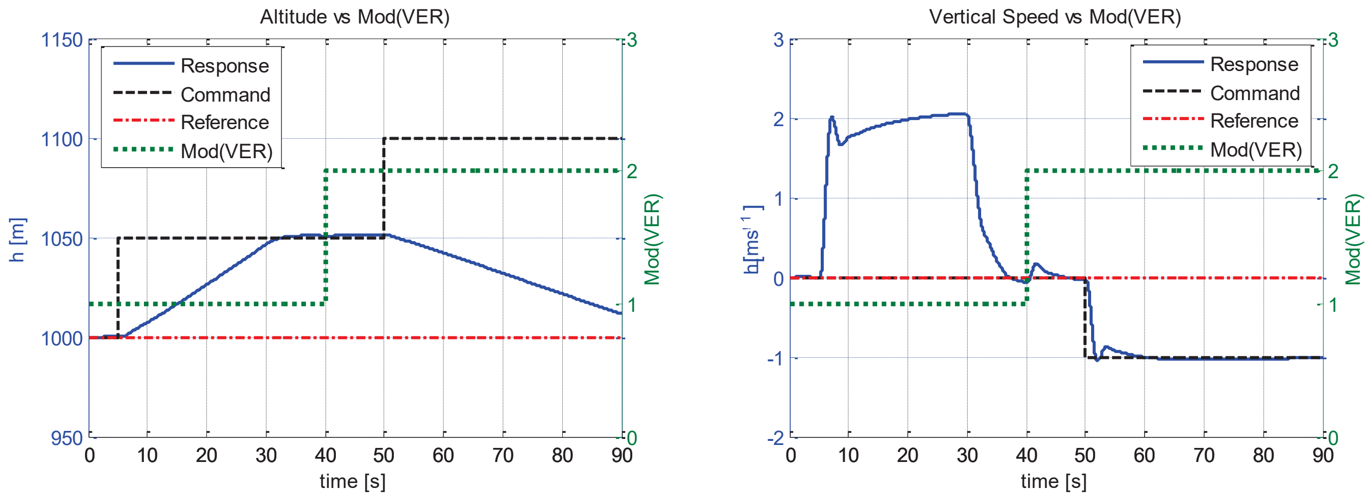



(a)




(b)

**FIGURE 15**. An example of vertical mode command and response in PFD design (a) vertical mode is set at 1 for altitude control, (b) vertical mode is set at 2 for vertical speed control.




(a) (b)

**FIGURE 16.** An example of vertical mode verification, (a) plot of altitude command and response, (b) plot of vertical speed command and response.

## CONCLUSIONS

PFD design requirements as an initial part of PFD design development have been defined. Later, the PFD design has been constructed by following the defined requirements. The developed PFD design is equipped with virtual knobs and numerical input instrument to provide airspeed, heading, altitude, vertical speed, and flight path inclination angle commands. The PFD design adopts a basic T configuration with an additional vertical speed indicator. The PFD design additionally displays information for aircraft control elements such as throttle, aileron, elevator, and rudder. Other flight variables are supplemented in the bottom area of the PFD design.

The developed PFD design has been tested using simulation in a full EFCS model which is implemented in a real-time computer while the PFD is operated in a host PC. Tests definition has been firstly formulated then the PFD simulation for FCP model verification is executed. The simulation result indicates that the PFD design has successfully verified the FCP model functionality.

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