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Research paper



Simulation and Analysis of Aircraft Dynamic Response in the Presence of System Failures

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Abstract

Flight simulator development has been started since 1910, named Sanders Trainer, which is an aircraft replica on the ground. As computing technology began to grow rapidly at that time, a numerical computing device started to take over aircraft replica-model simulator. Flight simulator has several classes based on its purpose and its qualification, those are Amateur Flight Simulation, Combat Flight Simulator, FAA Certified Simulator, and EASA Certified Simulator. One of the purposes of performing a flight simulation is to analyze aircraft stability in the various condition. Here, writers make a simulator platform which comprises aircraft observer, aircraft failure manipulator, and an aircraft model that accommodates failure model utilizing Matlab, Simulink, and X-Plane. The aircraft non-linear model accommodates failure scenario for engines and control surfaces whether it is inoperative or jammed. Both aircraft failure manipulator and observer GUI were made using Matlab. Aircraft motion then visualized on X-Plane using a python script. To analyze aircraft stability, the aircraft model, linearized with one or several components has failed at a certain operating point and given impulse input to obtain its state-space form. From linearization results, writers perform open-loop analysis to determine its stability, then the LQR method was used to make closed-loop feedback.

Keywords: *Matlab, Simulink; X-Plane; Flight Dynamics; Stability*

1. Introduction

First aircraft simulator was built around 1910 named The Sanders Trainer which comprised a cockpit that could move when exposed to a fairly strong wind corresponding to the input of the pilot. Similar devices were developed by Walters and Antoinette in the same year, where cockpit motion was controlled by instructors. Along with the development of analog computing technology in 1945-1965, modeling aircraft motion as sets of non-linear differential equations was easier. It also made a significant improvement in the fidelity of flight models and real-time simulation purpose as well. Unlike analog computing, digital computing development was quite slow at that time until late 1970 when the development of transistor initiated major advance in digital computation as well, in this era processors could achieve an update rate around 50-60 Hz and visual systems began to be developed as well. As the microelectronics revolution began in 1980, standard PC outperformed minicomputers of 1970. For flight simulation, attention focused on the development of visual systems and smooth motion system as well [1]

Flight simulator also has several classes based on its purpose and its qualification, those are Amateur Flight Simulation, Combat Flight Simulator, FAA certified simulator (Aviation Training Devices, Flight Training Devices, Full Flight Simulators), and EASA certified simulator (Flight Navigation and Procedures Trainer, Flight Training Devices, and Full Flight Simulators). Amateur flight simulation refers to the simulation of various aspects of flight or the flight environment for purposes other than flight training or aircraft development. Combat flight simulators are simulation video games used to simulate military aircraft and their operations. These are distinct from dedicated flight simulators used for professional pilot and military flight training which consist of realistic physical recreations of the actual aircraft cockpit [1]

In our laboratory, there are two types of simulator that we use based on aircraft motion modeling method. The first one is using X-Plane as the main software for calculating aircraft motion, and the second one is using Matlab and Simulink as the main software to model its motion where X-Plane used for visualization only. The second type of simulator is being developed. This paper is part of the development of the second type of simulator.

The aircraft that used in this paper is a Phantom F4 model [3]. Its modeled mathematically in Matlab and Simulink that also modeling failure on several components of the aircraft, those are the engine(s), left and right aileron, left and right elevator, and rudder. Failure model can be full inoperative mode or jammed at a certain value. In order to do that, common equations of motion will be modified to accommodate failure scenario.

After the non-linear aircraft model built, then it trimmed and linearized using built-in linear analysis tools in Matlab and Simulink to obtain its state-space model. Using the state-space model, its eigenvalue can be obtained to observe its stability. Then for each of failed component case, open-loop and closed-loop analysis will be performed.

This paper has the following writing layout. Chapter 1 consists of introduction. In chapter 2, the aircraft dynamics and failure scenario will be discussed. In chapter 3, the mathematical model of normal aircraft and abnormal aircraft will be presented. In chapter 4 the simulator platform and its components will be presented. In chapter 5 examples of this simulator operation will be presented. In chapter 6 stability analysis and stabilization of the aircraft mod-

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el will be presented. In chapter 7 conclusions and future works will be discussed.

2. Flight Condition

2.1 Flight Dynamics

Flight dynamics is the study of the performance, stability, and control of vehicles flying through the air or in outer space [4]. It is concerned with forces and moments acting on the vehicle influencing its speed and attitude over time. To be able to determine how forces and moments affect the aircraft, we need to specify what called reference frames.

2.1.1 Body-Fixed Reference Frame (Fb)

A body-fixed reference frame (G, X_b, Y_b, Z_b) is a right-handed orthogonal axis-system with the origin, in general, at the aircraft's center of mass and coincides with the center of gravity of the aircraft. The most common way to use this reference frame is X_b-axis pointed along aircraft's nose, Y_b-axis directed to the right perpendicular to symmetry plane, and Z_b-axis pointed downward and also lies in symmetry plane as shown in Fig. **1**.

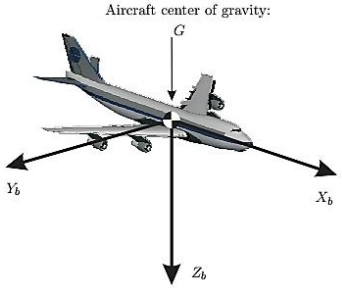

Fig. 1: Body-fixed reference frame [5]

Common and modified equations of motion presented in this paper will be used body-fixed reference frame (Fb).

2.1.2 Degree of Freedoms

The degree of freedom is described as number of parameters that determine the state of a physical system. An aircraft has six degrees of freedom because it is defined by three components of translation and three components of rotation, whether it is flying through space or doing the ground maneuver. It is common to describe aircraft's six motion in term of the body-fixed reference frame, those are described in the table and figure below,

Table 1: Aircraft Motion in Six Degrees of Freedom

Axes	Translation Motion	Rotation Motion
X_b	Surge (u)	Roll (p)
Y_b	Sway (v)	Pitch (q)
Z_b	Heave (w)	Yaw (r)

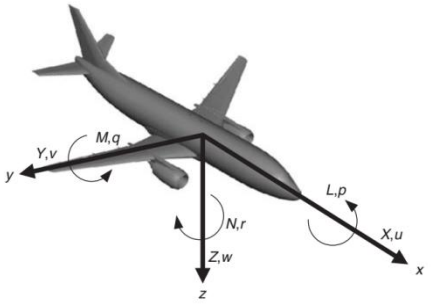

Fig 2: Illustration of 6 Degree of Freedom on Aircraft Body-Fixed Reference Frame [1].

2.2 Aircraft Condition

2.2.1 Normal/Fully Operative Condition

When aircraft flying through space, its motion highly depends on its control devices (control surface(s) and engine(s)). In conventional aircraft. On conventional aircraft, there are several control devices, aileron for manipulating rolling motion, rudder for manipulating yawing motion, elevator for manipulating pitching motion, and thrust lever for controlling the speed of the aircraft. Combination of those control devices can make the aircraft behave as desired and do certain task or mission that is designed for. For example, when aircraft want to change its heading, it will perform a roll motion by deflected its aileron. When one or more of the control device(s) is did not work/inoperative, aircraft motion will become abnormal and will be discussed in the next subchapter.

2.2.2 Abnormal/Inoperative Condition

- Engine Failure

Either left or right engine failure will affect in X_b-axis (surge) translational motion and add moment in Z_b-axis (yaw).

- Aileron Failure

Failure modes for aileron can be right or left only and both of them. If one of the ailerons failed/jammed, it will make aileron deflection bigger than operative condition, and rudder have to do more work to compensate rolling motion of the aircraft. If both of aileron failed, the rolling motion can be controlled only by the rudder.

- Elevator Failure

Failure modes for the elevator can be right or left only and both of them. If one of the elevators failed/jammed, it will produce an additional moment in X_b-axis (roll) and has to be compensated by aileron and rudder in order to make the aircraft stable.

- Rudder Failure

If rudder failed/jammed, moment in Z_b-axis (yaw) has to be compensated with the aileron.

Table 2: Control Surfaces and Engines Failure Effect on Aircraft Motion

Aircraft Motion and Aerodynamic Variables Affected	Device that Failure						
	δ_{e_L}	δ_{e_R}	δ_{a_L}	δ_{a_R}	δ_r	ENG_L	ENG_R
Surge-C_X	x	x				x	x
Sway-C_Y	x	x			x		
Heave-C_Z	x	x	x	x			
Roll-C_l	x	x	x	x	x		
Pitch-C_m	x	x	x	x		x	x
Yaw-C_n	x	x	x	x	x	x	x

3. Mathematical Model

3.1 Mathematical Model of Normal Aircraft

Non-linear mathematical model represents by equations of motion that described aircraft motion in the body-fixed reference frame, it consists of 12 equations that comprised translational and rotational motion, and aircraft position as well.

$$\dot{u} = -qw + vr + g\,sin\,\phi + \frac{F_{a_X} + F_{e_X}}{m} \quad (1)$$

$$\dot{v} = -ru + pw + g\cos\theta\sin\phi + \frac{F_{a_Y} + F_{e_Y}}{m} \quad (2)$$

$$\dot{w} = -pv + qu + g\cos\theta\sin\theta + \frac{F_{a_Z} + F_{e_Z}}{m} \quad (3)$$

$$\dot{p} = \frac{\left[qr\left(I_Y I_Z - {I_Z}^2 - {I_{ZX}}^2\right)\right]}{I_Z I_Z - {I_{ZX}}^2} + \frac{[pqI_{ZX}(I_Z + I_X - I_Y) + LI_Z + NI_{ZX}]}{I_Z I_Z - {I_{ZX}}^2} \quad (4)$$

$$\dot{q} = \frac{[rp(I_Z - I_X) + I_{ZX}(r^2 - p^2) + M]}{I_Y} \quad (5)$$

$$\dot{r} = \frac{[qrI_{ZX}(I_Y - I_Z - I_X) + pq(I_{ZX}{}^2 + I_X{}^2 - I_X I_Y)]}{I_Z I_X - I_{ZX}{}^2} + \frac{[LI_{ZX} + NI_X]}{I_Z I_X - I_{ZX}{}^2} \quad (6)$$

The rest of the equations (Euler angle rate and position) refer to [7].

Below are a complementary equations in terms of aerodynamic angles (alpha and beta) and definition of aerodynamic force and propulsion force that worked on the aircraft.

$$V_t = \sqrt{u^2 + v^2 + w^2} \quad (7)$$

$$\alpha = tan^{-1}\left(\frac{w + V_{wind_{long}} * \sin(\theta_{body} - \theta_{wind})}{u + V_{wind_{long}} * \cos(\theta_{body} - \theta_{wind})}\right) \quad (8)$$

$$\beta = tan^{-1}\left(\frac{v + V_{wind_{latdir}} * \sin(\psi_{body} - \psi_{wind})}{V_t + V_{wind_{latdir}} * \cos(\psi_{body} - \psi_{wind})}\right) \quad (9)$$

$$\rho = 1.4467 * e^{(-10^{-4} * h)} \quad (10)$$

$$\bar{q} = 0.5\rho V_t^2 \quad (11)$$

$$F_{a_i} = \bar{q} * S * C_i, i = x, y, z \quad (12)$$

$$F_{e_i} = thl * (T_L + T_R) * tf \quad (13)$$

The equation for density (16) obtained from simulation in X-Plane. The simulation took place in Halim Perdana Kusuma Airport (WIHH) area in clear and calm condition. Aircraft database and non-linear aerodynamic coefficients obtained from Ref [3] based on aircraft model F4 Phantom.

3.2 Mathematical Model of Abnormal Aircraft

3.2.1 Engine Failure

If one or both engines failed, the mathematical model of aircraft's motion become,

$$\dot{u} = -qw + vr + g\sin\phi + \frac{F_{a_X} + thl * (T_L * ff_L + T_R * ff_R) * tf}{m} \quad (14)$$

$$\dot{q} = \frac{[rp(I_Z - I_X) + I_{ZX}(r^2 - p^2) + M]}{I_Y} + * thl * (T_L * ff_L + T_R * ff_R) * tf * \frac{l_z}{I_Y} \quad (15)$$

$$\dot{r} = \frac{[qrI_{ZX}(I_Y - I_Z - I_X) + pq(I_{ZX}{}^2 + I_X{}^2 - I_X I_Y)]}{I_Z I_X - I_{ZX}{}^2} + \frac{[LI_{ZX} + NI_X]}{I_Z I_X - I_{ZX}{}^2} + thl * (T_L * ff_L - T_R * ff_R) * tf * l_y * \frac{I_X}{I_Z I_X - I_{ZX}{}^2} \quad (16)$$

3.2.2 Aileron Failure

First, aileron's variable in chapter 1.5 modified into

$d_a = 0.5 * (d_{a_L} + d_{a_R})$

For this mode of failure, all aerodynamic coefficient calculation using variable defined above.

3.2.3 Elevator Failure

First, elevator's variable in chapter 1.5 modified into

$d_e = 0.5 * (d_{e_L} + d_{e_R})$

For this mode of failure, all aerodynamic coefficient calculation using variable definition above and there is an additional rolling moment in the equations of motion

$$\dot{p} = \frac{[qr(I_Y I_Z - I_Z{}^2 - I_{ZX}{}^2)]}{I_Z I_Z - I_{ZX}{}^2} + \frac{[pqI_{ZX}(I_Z + I_X - I_Y) + LI_Z + NI_{ZX}]}{I_Z I_Z - I_{ZX}{}^2} + C_{Z_{de}} * (de_L - de_R) * q * S * \frac{I_Z}{I_Z I_Z - I_{ZX}{}^2}, * l_{de} \begin{cases} C_{Z_{de}} = -4.76 * 10^{-3}, \alpha < 15^o \\ C_{Z_{de}} = -6.27 * 10^{-3}, 15^o < \alpha \leq 30^o \\ C_{Z_{de}} = 6.2 * 10^{-3}, \alpha > 30^o \end{cases} \quad (17)$$

3.2.4 Rudder Failure

Rudder's variable d_r remain unchanged for the rest of the aerodynamic calculation

3.3 Linear Mathematical Model

Linear mathematical model of a dynamic system usually represented in a state-space which shown in equation 24.

$$\dot{\bar{x}} = A\bar{x} + B\bar{u}$$
$$\bar{y} = C\bar{x} + D\bar{u} \quad (18)$$

In this paper, $\bar{x} = [p\ q\ r\ u\ v\ w]$, and $\bar{u} = [\delta_{al}\ \delta_{ar}\ \delta_{el}\ \delta_{er}\ \delta_r]$. Procedure for obtaining the aircraft's state-space explained below. First, the aircraft has to be trimmed at certain flight condition, here the speed and altitude is set to be in steady-state at 150 m/s, 207 m/s, and 500 m, 2000m. The rest of translational speed and rotational speed are set to steady-state as well with a value close to zero. At certain trimmed condition, its state-space can be obtained by choosing one of the methods on linearize panel as well as its response (frequency response, time response, pole-zero map, etc). Fig 3 shows a pop-up window that tells the user whether the system successfully trimmed or not. Fig 4 shows the impulse response of the system at certain operation condition, here is the example where the aircraft in fully operative mode. Fig 5 shows the state-space representing its response in Fig 4

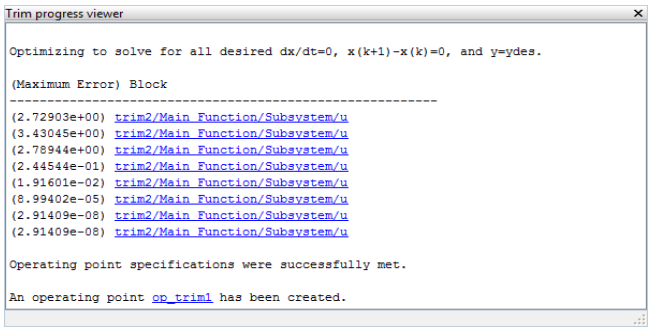

Fig 3: Trim Point Op_Trim1 Successfully Made

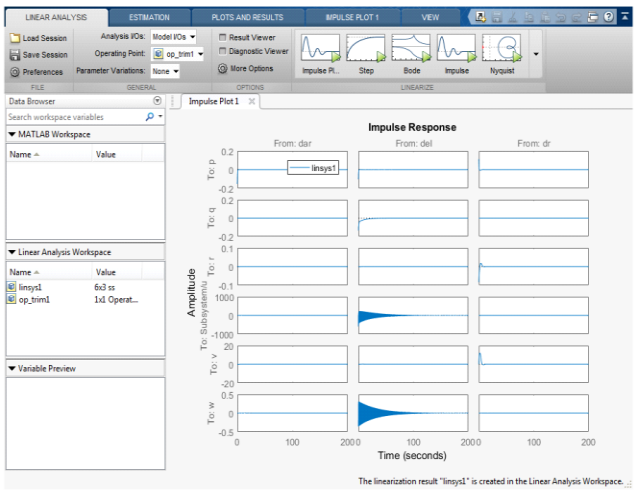

Fig 4: Impulse Response at Op_Trim1

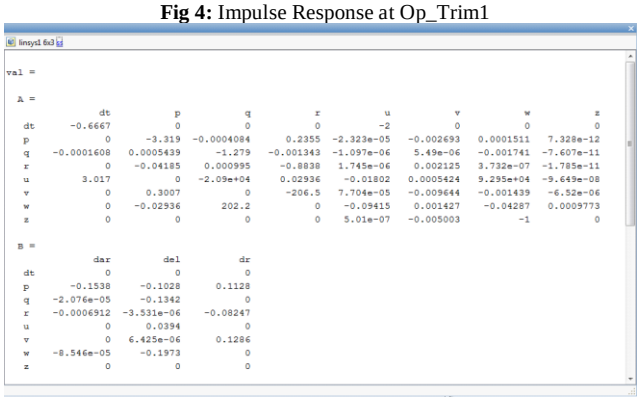

Fig 5: State-Space at Op_Trim1

4. Simulator Platform and Components

4.1 Simulator Architecture

In this chapter, simulator architecture will be discussed. First, the overview of this simulator will be presented in Fig 6, Fig 7, and Fig 8. In complete configuration, this setup need three computers in order to use in a correct way. The first computer is main computer that has aircraft model in Simulink in it, aircraft motion and position calculated in this computer. The first computer also has a function to visualize aircraft motion in X-Plane utilizing python interface and a python script. The second computer has a function to execute failure manipulator GUI, the user can manipulate aircraft failure scenario while pilot on the first computer flying the aircraft as well. Third computer has a function to do an observation aircraft attitude, position, and its control surfaces. The data received by utilizing UDP communication.

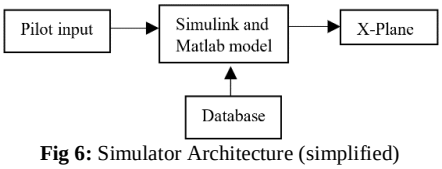

Fig 6: Simulator Architecture (simplified)

Fig 7 shows the complete architecture of this simulation platform. Red area describe this thesis researches scope, those are equations of motion that accommodate environment wind and failure model for engines and control surface, GUI for aircraft failure and environment wind manipulator, and GUI for observing aircraft attitude, position, and control devices value.

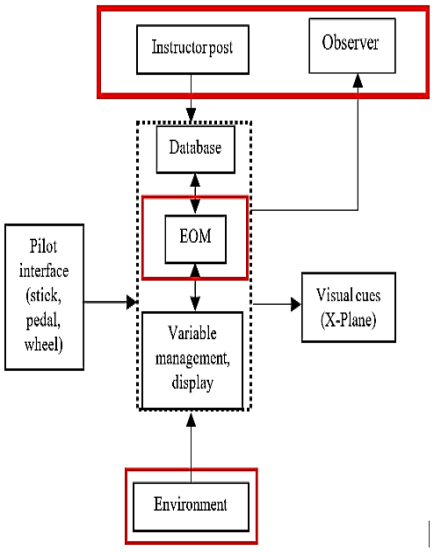

Fig 7: Simulator Architecture Components, Red circle describe thesis researches scope

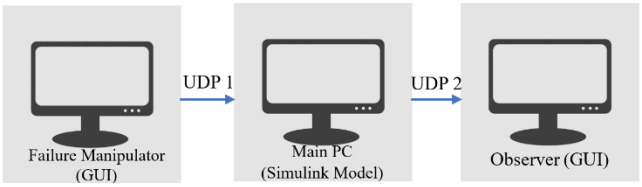

Fig 8: Data communication between computers

UDP 1 → 144-bit data occupied by 16 variables that will be sent to the main pc, each occupy 8 bit of data. Those 16 variables are operational status (operative/inoperative) of control surfaces and engine, its inoperative value, and wind speed and direction.
UDP 2 →104-bit data occupied by 13 variables that will be sent to Observer GUI. Those 13 variables are Euler angles, aircraft position in X_E, Y_E and altitude, also seven value of control surfaces and engines.

4.2 Numerical Simulation Model

This chapter will explain the Simulink model that has a function to execute mathematical model of aircraft that accommodate failure model for the engine and its control surfaces. This model has three main parts those are input (green square), main function (purple square), and output (red square). The building components of input, main function, and output described in the table below. Fig 9 shows Simulink blocks that used in this simulator platform and Table 3 shows its function

Table 3: Simulink Blocks Function

Part	Components
Input	Hardware input, aircraft database, initial condition, a command from GUI.
Main Function	Equations of motion, implementation of equation (1) until (17).
Output	Display time response, and sending aircraft data to X-Plane and observer GUI

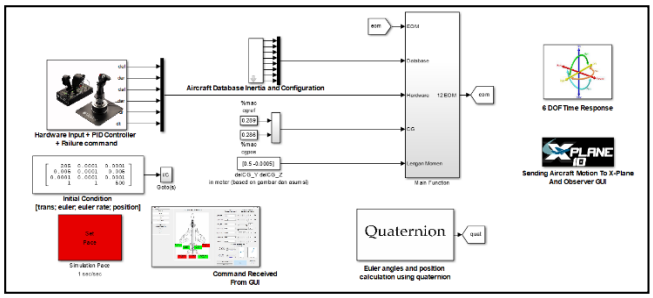

Fig 9: Overall View of Simulink Blocks

4.3 Graphical User Interface

4.3.1 Failure and Environment Manipulator

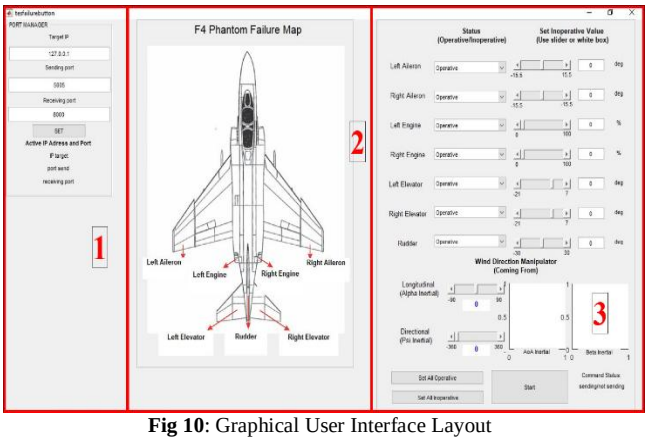

Fig 10: Graphical User Interface Layout

The picture above shows a graphical user interface made in Matlab with several main purposes, those are:

- To be able to set the communication address to another computer that runs the aircraft model in Simulink
- Choose individually or all aircraft components that will be failed
- Set the inoperative value of the engines (%) or control surfaces (degree)
- Set the environment wind angle (angle of attack and sideslip angle)

The GUI itself has 3 panels, those are,

1. Panel for insert destination PC's IP address and port, also port for receiving data from Simulink model as well.
2. "Failure Map" that describe what component(s) that have failed. Components selected will blink for a short time so it is easier to notice.
3. Panel for determining the aircraft component(s) is operative or inoperative as well as its level of damage for the engine and jammed value of the control device(s) There are also environment wind direction manipulator for the angle of attack and sideslip angle in local horizon reference frame and start/stop button.

Figures below show an example when this GUI is in operation. In the 1st panel (Fig 11), the target IP is 127.0.0.1, sending port is 5005, and receiving port is 8000 which means it will be sending commands to the computer that has IP 127.0.0.1 and port 5005, the receiving port is for the GUI receive the data from Simulink model or X-Plane. The 2nd (Fig 12) panel shows what components have failed on this aircraft, in this example are left the elevator, rudder, and right aileron. The 3rd panel (Fig 13) shows those components jammed value, -6.27 degree for the right aileron, -5.33 for the left elevator, and -13.57 degree for the rudder. For the environment wind, it shows an additional 11 degree of angle of attack and sideslip angle that came from 65 degree from the east.

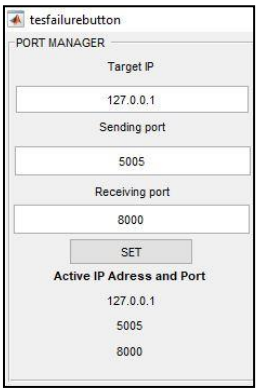

Fig 11: Port Manager

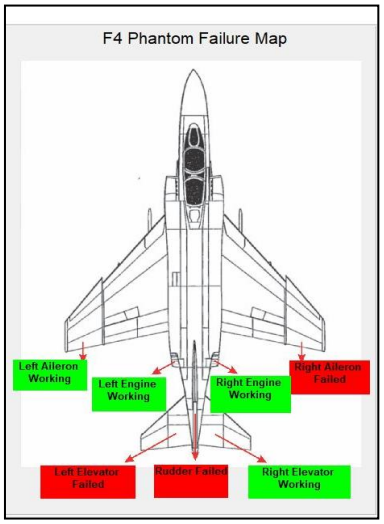

Fig 12: Aircraft Failure Map

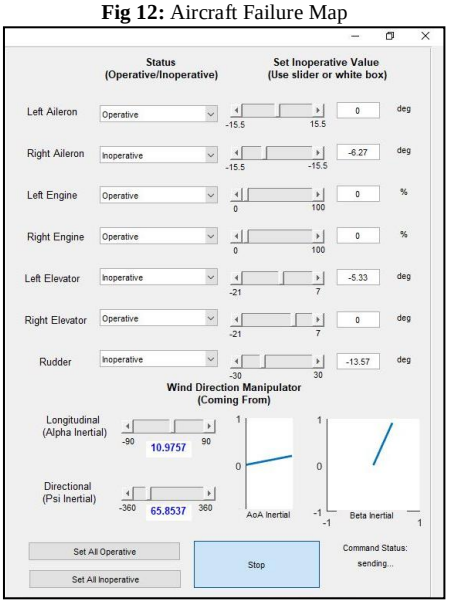

Fig 13: Aircraft Inoperative Value and Environment Wind Value

4.3.2 Observer

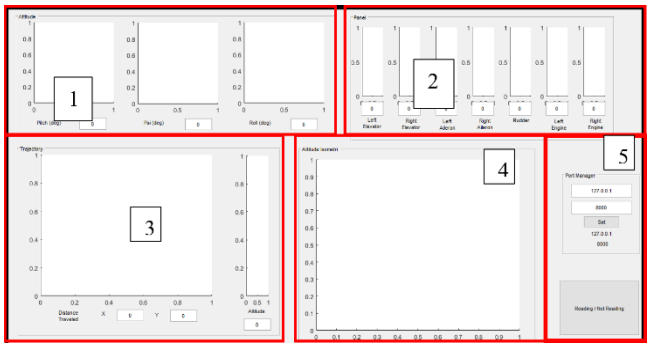

Fig 14: Observer GUI

Observer GUI consists of four panels, those are,
1. Aircraft projection in longitudinal, lateral, and directional axis represents Euler angles in degree.
2. Control surfaces deflection in degree and engines health in percentage.
3. Aircraft trajectory and its altitude in meter.
4. Aircraft attitude viewed from isometric projection, represented in the simple triangle.
5. Port manager to adjust sender IP address and local port value, and start button.

Figures below show an example when this GUI is in operation. In the first panel, it shows the aircraft attitude, for this example, the aircraft rolling, pitching, and yawing at the same time. The second panel shows control devices status, the elevator is asymmetric so it will produce additional rolling moment for the aircraft. The left engine also is not 100 percent operative, so it will produce additional yaw moment from this asymmetric condition. The third panel shows aircraft trajectory in two dimensions with altitude information on its right in meter. The fourth panel shows the aircraft attitude in isometric view. The fifth panel shows the IP and port for data communication.

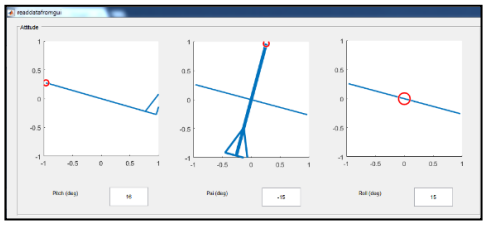

Fig 15: Attitude Projection of an Aircraft

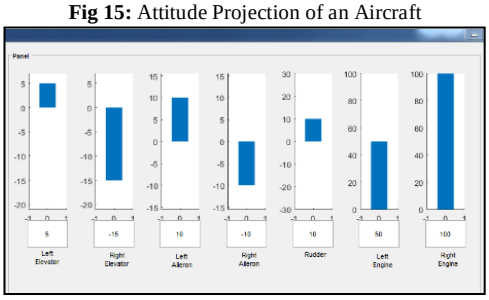

Fig 16: Control Surfaces Deflection Status

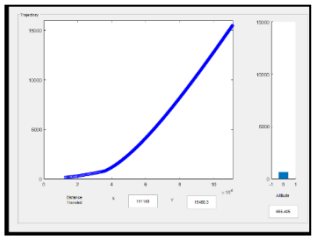

Fig 17: Aircraft Trajectory and Altitude Observer

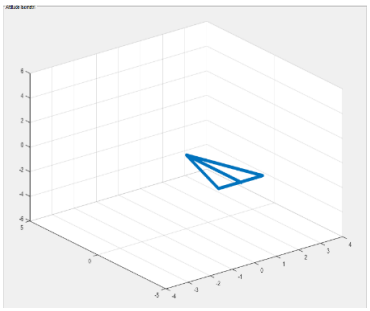

Fig 18: Aircraft Attitude in Isometric View

4.4 X-Plane

Here, X-Plane is used to visualize aircraft motion that was modeled before in Simulink or Matlab, X-Plane also has built-in basic world scenery and it still can be improved using another software. So X-Plane played a quite important role in order to give the right visual cue to both pilot and flight test engineer even though it is only a simulator. X-Plane itself has a built-in dynamic model for each aircraft, but we want to 'inject' our own dynamic data into X-Plane, so we use a python script named PI_DataInject.py that has a function to disable built-in X-Plane aircraft dynamics. Its pseudocode is shown in Fig 19.

```
/calling libraries/
...
/calling datarefs → planepath, simulation time, and control surface/
...
Loop:   /freeze → planepath, simulation time, and control surface/
        ...
        /activate port for UDP communication data/
        ...
        /sending or receiving UDP data to assign port/
```

Fig 19: Pseudo Code for Injecting Aircraft Motion from Simulink

5. Simulation Examples

In this chapter, a case of simulation will be performed. First, the aircraft stabilized/trimmed using PID at a certain speed and altitude. For this example, Euler angle response presented in Fig 20 and Fig 21. After the aircraft is stable, critical component(s) will be set to inoperative from aircraft manipulator GUI and visualize its motion and position on observer GUI and X-Plane.

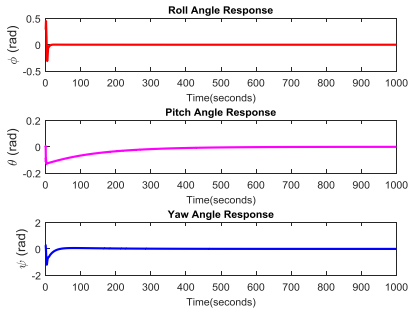

Fig 20: Trimmed Aircraft At Certain Speed And Altitude

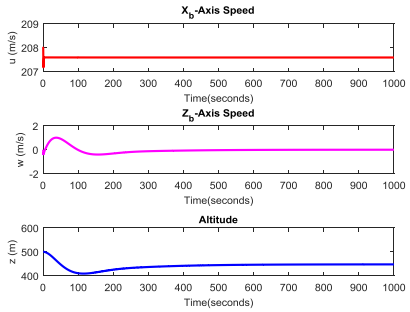

Fig 21: Trimmed Aircraft at Certain Speed and Altitude

5.1 Scenario

Here, an example of the simulation case is when the right engine, not operative (case 1). The right engine only produces thrust 0 percent from its maximum thrust available. The simulation started from the trimmed condition when the aircraft cruising at a certain altitude, and then aircraft failure manipulator change right engine status into inoperative with 0 percent maximum thrust available now. So the aircraft will produce yaw moment because unbalance thrust from the left and right engines. In order to maintain its attitude, the aircraft react with deflected its rudder more to counteract yaw moment produced by engines. While rudder deflected, it will produce rolling moment as well, so here the aileron will be more deflected as well.

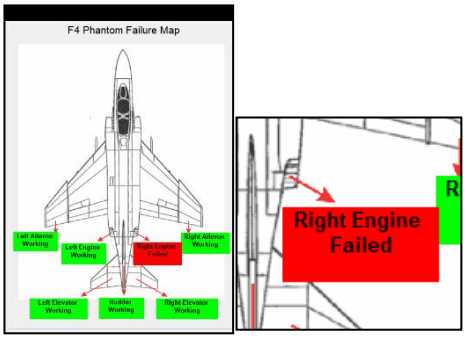

Fig. 22: Aircraft Manipulator Set the Right Engine Inoperative

5.2 Result

The simulation result presented in Fig 23 until Fig 27 show how this simulation platform works in operation. Fig 23 shows observer GUI when it comes to one engine inoperative case, in this example, the right engine shut off. Fig 24, Fig 25, and Fig 26 show the aircraft response when the right engine inoperative. The aircraft responded with yawing to the right because of asymmetric thrust produced by the left engine only. Then, there will be a rolling moment as well because of the position of the rudder that above of center of gravity. So that the rudder and aileron responded in such way to maintain aircraft attitude at the stable position as before. Fig 27 shows the moment where the aircraft lost the right engine until it comes back to its stable position.

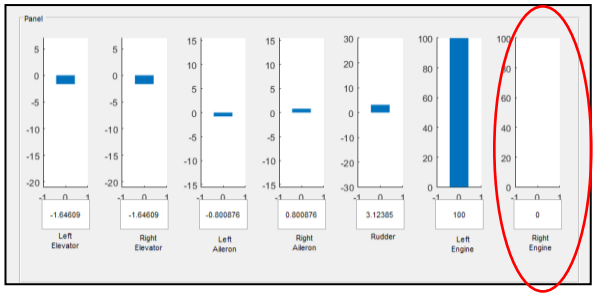

Fig 23: Control Devices Condition for Case 1, Red Circle Shows Right Engine Is In Inoperative Mode

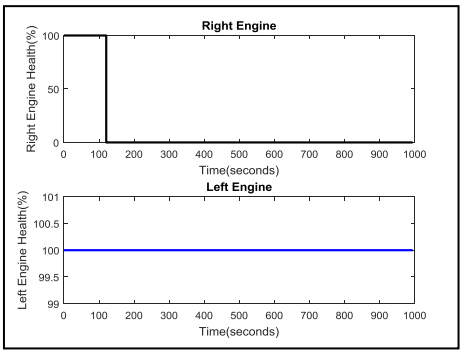

Fig 24: Engine Response in Case 1

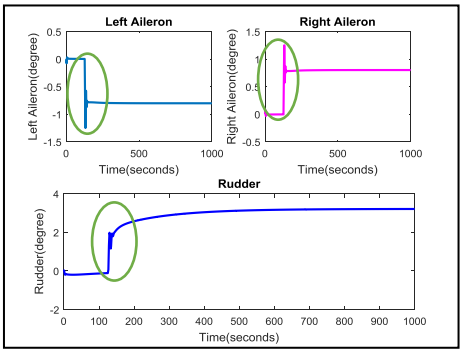

Fig 25: Aileron and Rudder Response for Case 1, Green Circle Indicates Moment Where the Right Engine Fail

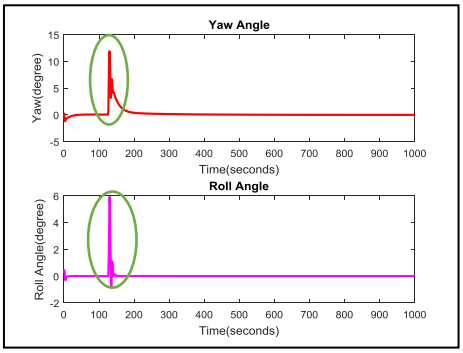

Fig 26: Aircraft Attitude Response Case 1, Green Circle Indicates Moment Where the Right Engine Fail

5.3 Visualization

Here, Simulink model outcome sent to X-Plane to visualize its motion. Control surfaces deflection do not represent the actual value of the Simulink model since the python script receive aircraft Euler angle and position only.

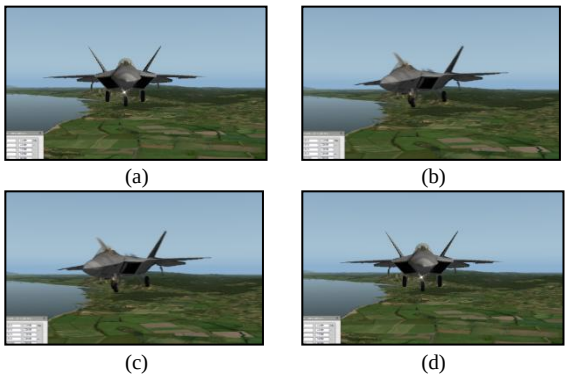

Fig 27: Visualization of Case 1 in X-Plane

5.4 X-Plane and Simulink Model Comparison

Here will be presented a simulation done in X-Plane with the right engine completely failed after the aircraft flies at the trimmed condition. This simulation is to verify Aircraft dynamic model in Simulink. The aircraft model used is F-22 with heading and altitude hold applied. The engine started to shut-off at around 190 seconds of simulation time as shown in Fig 30. At the moment where the engine shut-off, the aircraft responded by increasing heading angle and bank angle as shown in Fig 28 and Fig 29. It matches the simulation done using Simulink model which presented in Fig 26.

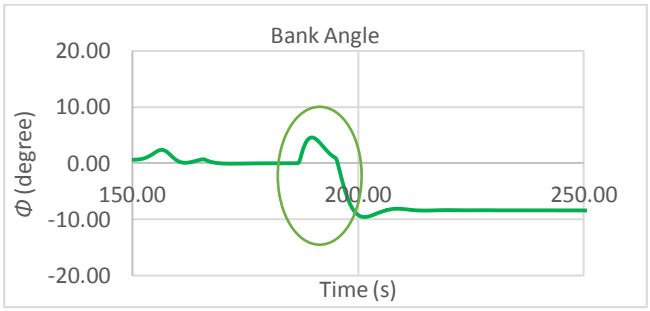

Fig 28: Bank Angle Response in X-Plane Simulation for Case 1, Green Circle Indicates Moment Where the Right Engine Fail

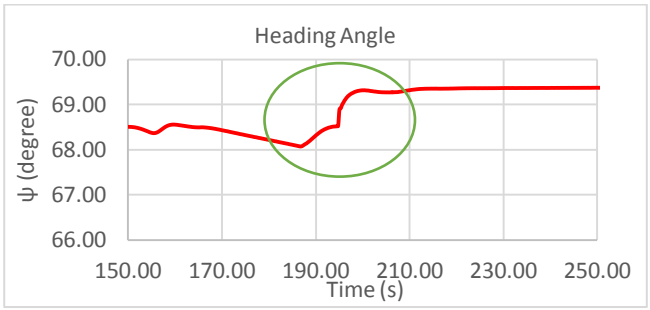

Fig 29: Heading Angle Response in X-Plane Simulation for Case 1, Green Circle Indicates Moment Where the Right Engine Fail

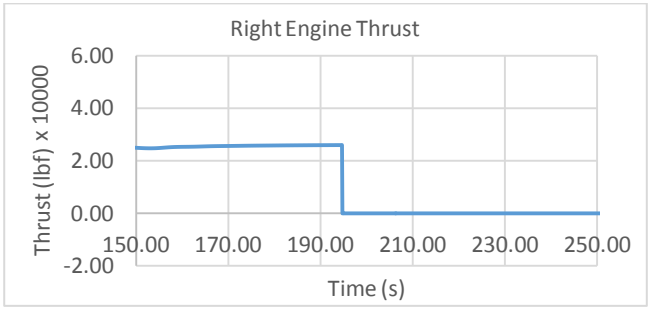

Fig 30: Right Engine Response in X-Plane Simulation for Case 1, Green Circle Indicates Moment Where the Right Engine Fail

5.5 Simulation Time

In this chapter, there will be presented simulation platform test regarding simulation time. The test runs in 10 various times starting from 5 seconds to 50 with 5 seconds interval to measure its error/delay which describes in equation 72. Here, t_{actual} means time that Matlthe ab needed to execute the simulation while t_{ideal} is target time for the simulation. The result presented in Fig. **31** and Fig. **32**. The average delay time is 2.08 seconds

$$\Delta_{time} = t_{actual} - t_{ideal} \quad (19)$$

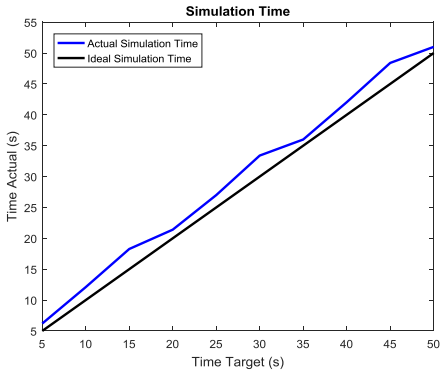

Fig. 31: Simulation Time vs. Target Time

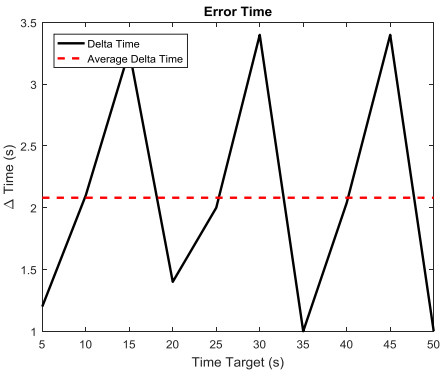

Fig. 32: Delay Time

6. Stability Analysis and Stabilization

6.1 Open Loop Analysis

In the linear simulation, the cases varied into four trimmed points and five aircraft condition as shown below.
Operation Point:
a. u=150 m/s at z=500 m (op 1)
b. u=150 m/s at z=2000 m (op 2)
c. u=207 m/s at z=500 m (op 3)
d. u=207 m/s at z=2000 m (op 4)
Aircraft Condition(Failure):
a. Fully Operative (fail 1)
b. One Engine Inoperative (fail 2)
c. Right Elevator Inoperative (fail 3)
d. Left Aileron Inoperative (fail 4)

e. Rudder Inoperative (fail 5) **Error! Reference source not found.** shows what failure that makes the aircraft unstable in certain operating condition.

Table 4: Stability of the Aircraft According to Operation Condition

	OP 1	OP 2	OP 3	OP 4
Full Operative	x	x	y	x
One Engine Failed	x	x	y	x
One Elevator Failed	x	x	x	x
One Aileron Failed	x	x	y	x
Rudder Failed	y	x	x	y
	x=unstable, y=stable			
	OP=Operation Point			

Figures below are poles location for each operation point with various aircraft condition.

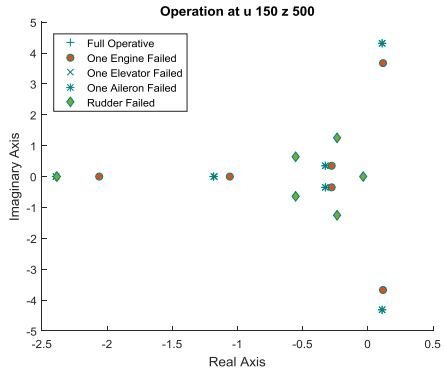

Fig. 33: Poles Location of Operation Condition 1

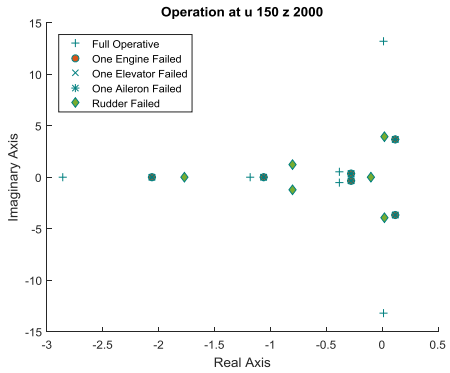

Fig. 34: Poles Location of Operation Condition 2

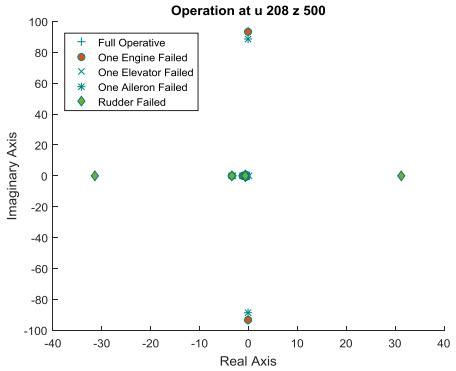

Fig. 35: Poles Location of Operation Condition 3

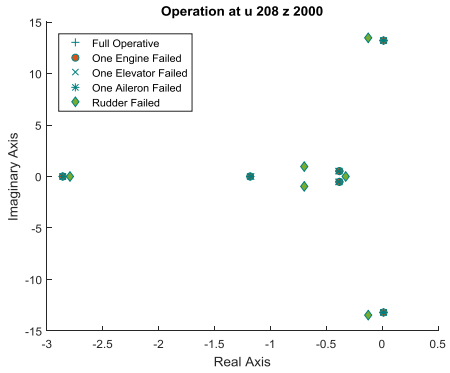

Fig. 36: Poles Location of Operation Condition 4

From the results presented in Fig. **33** until Fig. **36**, there is always one or several conditions that makes the aircraft unstable at a certain operation point. Next subchapters present linear closed-loop stabilization for each failure condition.

6.2 Closed-Loop Analysis

The first example is when the aircraft has one elevator only at operation condition at u 208 m/s and z 500 m. The trimmed condition is δ_{al}=-0.34461, δ_{el}=-0.7982, δ_{ar}=0.34461, δ_{r}=-0.0599 all in degree. The state-space matrix for this condition is presented below.

$$A = \begin{bmatrix} -3.3 & 0.0027 & 0.2293 & 0.0037 & -0.002597 & -0.0007177 \\ -0.003 & -1.279 & 0.2195 & 4.063e\text{-}05 & 3.828e\text{-}06 & -0.001742 \\ -0.045 & -0.162 & -0.883 & 8.914e\text{-}06 & 0.00212 & -2.226e\text{-}05 \\ 0 & 7.425 & 4.949 & -0.035 & -4.919e\text{-}05 & -0.3612 \\ 0.419 & 0 & -206.5 & -4.572e\text{-}05 & -0.009601 & 0.2335 \\ -4.949 & 202.2 & 0 & -0.088 & -0.2357 & -0.04293 \end{bmatrix}$$

$$B = \begin{bmatrix} -0.1539 & -0.1539 & -0.1028 & 0.1128 \\ -0.004315 & -0.004315 & -0.1343 & 0 \\ -0.0006913 & -0.0006913 & -5.188e\text{-}6 & -0.08251 \\ 0 & 0 & 0.03943 & 0 \\ 0 & 0 & 9.44e\text{-}6 & 0.1287 \\ 0.01776 & 0.01776 & -0.1974 & 0 \end{bmatrix} \quad (20)$$

$C = I(6x6), D = [0](6x4)$

$\bar{x} = [p\ q\ r\ u\ v\ w], \bar{u} = [\delta_{al}\ \delta_{ar}\ \delta_{el}\ \delta_{r}]$

First, the open-loop test must be conducted to check if the system stable, the system response presented in Fig. **37** and Fig. **38**.

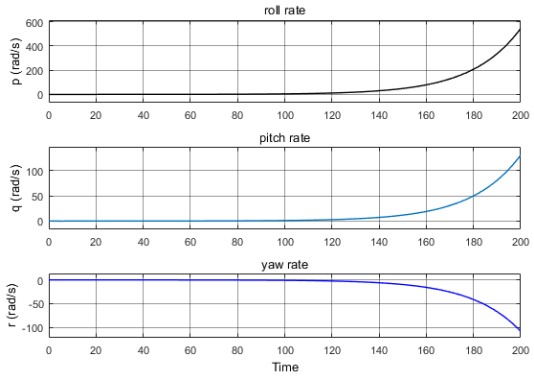

Fig. 37: Open-Loop Response of the System in Equation 25 (1)

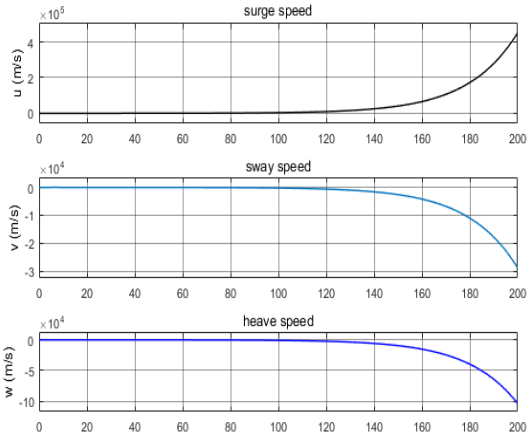

Fig. 38: Open-Loop Response of the System in Equation 25 (2)

According to Fig. **37** and Fig. **38** the open-loop system is not stable, so stabilization system must be made, here the pole placement method will be used. The damping ratio for open-loop and closed-loop system presented in Table 5. The gain values for this closed-loop system presented below.

$$\text{Gain(K)} = \begin{vmatrix} -0.082 & 2.626 & 0.315 & -0.074 & -0.003 & 0.067 \\ -0.082 & 2.626 & 0.315 & -0.074 & -0.003 & 0.067 \\ 0.907 & -46.43 & 1.542 & 0.917 & 0.0106 & -1.09 \\ 0.489 & -0.161 & -58.35 & 0.070 & 0.9741 & -0.01 \end{vmatrix} \quad (21)$$

Table 5: Damping Ratio Comparison for Case 1

Damp Open Loop	Damp Closed-Loop
1	1
-1	1
0.6109	0.7061
0.6109	0.7061
1	0.7106
1	0.7106

After gain for the closed-loop obtained, the closed-loop response can be calculated using Simulink and presented in Fig. **39**, Fig 40, and Fig 41. The results are quite good since control surface deflection is not exceeded the limit, and the state's response is not too high as well.

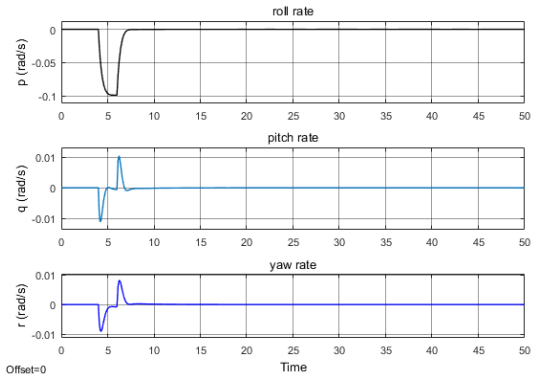

Fig. 39: Close-Loop Response of the System in Equation 25 (1)

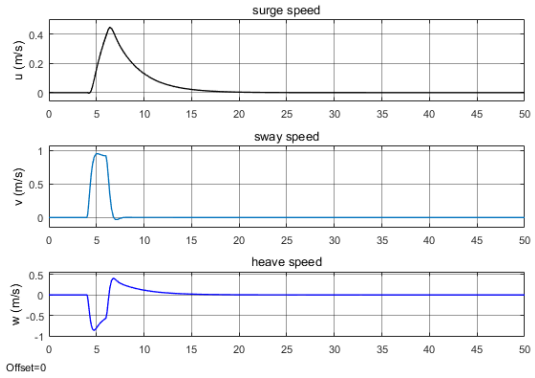

Fig 40: Close-Loop Response of the System in Equation 25 (2)

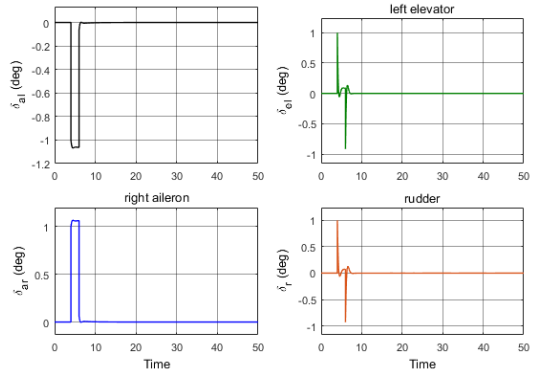

Fig 41: Control Surface Response for Closed-Loop System in Equation 25

7. Conclusion

In this research, the simulator platform works well as shown in section 5. The components are well integrated, and aircraft dynamics are consistent with the theory. The problem is, this simulator execute the model in pseudo-real-time by utilizing built-in Simulink block, and it is still delayed by average of 2.08 seconds. The modeled aircraft, Phantom F4, its stability was observed in a combination of four operation points (surge speed and altitude) and five aircraft failure cases, which result in 20 simulation cases. In each operation point, there is/are one or several conditions that make the aircraft unstable as mentioned in Table 4. Using that information, we try to stabilize the aircraft using pole-placement or LQR method to obtained gain values that are not too high because it will affect the control surfaces deflection when stabilizing the aircraft. Stabilization results are quite good since control surface deflection is not exceeding the limit, and the state's response is not too high as well, as presented in chapter 4. For the future works real-time simulation using obtained closed-loop gain must be performed in order to observe aircraft and its control system response so that we can determine whether the gain obtained is optimum or not. Moreover, the delay time between simulation time and real-time has to be researched further in order to optimize this platform.

Acknowledgment

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