CHAPTER 3

DEVELOPMENT OF NON-LINEAR SIX-DEGREES-OF-FREEDOM AIRCRAFT MODEL

3.1 INTRODUCTION

The objective of this chapter is to develop a non-linear 6-DOF model for an experimental UAV which is capable of taking large payloads. The open-loop response of the UAV is generated using the Aerosim blockset tool. Aerosim(2005) is a product from Unmanned Dynamics, LLC, Hood River, USA. It has been designed by flight control engineers for UAV flight control applications. Though Aerosim discusses about Aerosonde UAV weight about 10kg. In this work the tools has been used for the experimental UAV. It is open-source software which comes as a big advantage for academic users.

3.2 BUILDING AN AIRCRAFT CONFIGURATION SCRIPT

The aircraft model used for the UAV is the 6-DOF Aircraft Model (with Body-frame EOM) from the AeroSim blockset. The aircraft configuration script is developed in this section. The internal structure of entire non-linear model with its various blocks are discussed. To build any aircraft model parameters such as it's aerodynamics, propulsion, inertia etc. are required. These parameter models are considered which computes the airframe loads (forces and moments) as functions of control inputs and environment model which takes into account atmosphere and earth effects.
The resulting accelerations are then integrated by the Equations of Motion to obtain the aircraft states namely position, velocity, attitude and angular velocities.

3.2.1 Conventions

Figure 3.1 shows the various reference points used throughout the aircraft configuration script. The locations of these points are specified with respect to the arbitrarily chosen origin of the body-frame. These reference points included the CG locations for zero-fuel, full-tank. The orientation of the body axes are chosen as shown in Figure 3.1.

Figure 3.1 Airframe Reference Points

X-axis is positive forward, through nose of aircraft, Y-axis is positive to right of X Axis, perpendicular to X-axis and Z-axis is positive downwards, perpendicular to X-Y plane. All parameters are given in metric (SI) units.
3.2.1.1 Aerodynamics section

The following sections describe the aerodynamic parameters of the aircraft:

Reference point: This specifies the location, w.r.t to the body-frame origin, of the aerodynamic forces application point. This is a 1x 3 row vector with the x, y and z coordinates. All the aerodynamic coefficients (force and moment coefficients) are given referenced to this point.

Aerodynamic parameter bounds: To limit the outputs of the aerodynamic model within the linear region, bounds are specified on the airspeed, sideslip and angle-of-attack, which is given as 1x 2 vector of min and max values. The aerodynamic model would provide acceptable results only in the linear aerodynamics conditions (small angles).

Aerodynamic reference parameters: These include the reference wing chord, the wingspan and the reference wing area.

Lift coefficient terms: The lift coefficient is computed using the expression:
\[ C_L = C_{L0} + C_L \alpha + C_{Lf} \delta_f + C_{Le} \delta_e + (c/2V_a) (C_{L_{\alpha \dot{\alpha}}} \dot{\alpha} + C_{Lq} q) + C_{LM} M \]
(3.1)

Drag coefficient terms: The drag coefficient is computed using the expression:
\[ C_D = C_{D0} + (C_L - C_{L0})^2/ (\pi eAR) + C_{Df} \delta_f + C_{De} \delta_e + C_{D\alpha} \delta_\alpha + C_{Dr} \delta_r + C_{DM} M \]
(3.2)

Side-force coefficient terms: The side force coefficient is computed using the expression:
\[ C_Y = C_{Y^\beta} \beta + C_{Ya} \delta_a + C_{Yr} \delta_r + (b/2V_a) (C_{Yp} p + C_{Yr} r) \]
(3.3)
Pitch moment coefficient terms: The pitch moment coefficient is computed using the expression:

\[ C_{m} = C_{m0} + C_{m} \alpha + C_{m} \delta f + C_{m} \delta e + (c/2V_{a}) (C_{m} \alpha \dot{\alpha} + \alpha \dot{\delta} + C_{m} q) + C_{m} M \]  

(3.4)

Roll moment coefficient terms: The roll moment coefficient is computed using the expression:

\[ C_{l} = C_{l} \beta + C_{l} \delta a + C_{l} \delta r + (b/2V_{a}) (C_{l} \dot{p} + C_{l} r) \]  

(3.5)

Yaw moment coefficient terms: The yaw moment coefficient is computed using the expression:

\[ C_{n} = C_{n} \beta + C_{n} \delta a + C_{n} \delta r + (b/2V_{a}) (C_{n} \dot{p} + C_{n} r) \]  

(3.6)

3.2.1.2 Propeller section

In this section of the aircraft configuration script, the geometry and aerodynamic performance of the propeller are specified.

Propeller hub location: Its specifies the position of the propulsion force and moment application point. The location is specified as a 1x3 row vector of x, y and z coordinates.

Advance ratio: The aerodynamic performance of the propeller is given as a look-up table of propeller coefficients \( C_{p} \) and \( C_{T} \) as functions of the propeller advance ratio.

Coefficient of thrust: The vector of coefficients of thrust for the given advance ratio.

Coefficient of power: The vector of coefficients of power for the advance ratio.
**Propeller radius**: The radius of the propeller, which is used by the propulsion model to compute the force and torque from the normalized coefficients. These loads are computed as follows:

\[ F_P = \left(\frac{4}{\pi^2}\right) \rho R^4 \Omega^2 C_T \]  

(3.7)

\[ M_P = -\left(\frac{4}{3\pi^3}\right) \rho R^5 \Omega^2 C_P \]  

(3.8)

Propeller inertia specifies the propeller moment of inertia, which is used by the propulsion equation of motion (dynamics) to solve for the current rotation speed.

### 3.2.1.3 Engine section

In this section of the aircraft configuration script, engine characteristics are specified. All engine data were given at sea-level. The engine model would correct the data for altitude effects.

**Revolutions Per Minute (RPM)**: The vector of engine speeds for which the engine data is given in rotations-per-minute. All engine parameters are specified as 2-D look-up tables.

**Manipulated Air Pressure (MAP)**: The vector of manifold pressures for which the engine data are given in kilo-Pascal.

**Fuel Flow**: The sea-level fuel flow as a function of RPM and MAP.

**Power**: The engine power at sea level is a function of RPM and MAP.
Engine Shaft Inertia: The moment of inertia of the rotating parts of the engine. This is added to the propeller inertia and used in the propulsion equation of motion to compute the current engine speed.

3.2.1.4 Inertia section

In this section of the aircraft configuration script the inertia parameters of the aircraft are defined.

Empty aircraft mass: The mass of the aircraft without fuel.

Gross aircraft mass: The mass of the aircraft with the fuel tank full.

CG empty: The position of the center of gravity for the aircraft without fuel.

CG gross: The position of the center of gravity for the aircraft with full fuel tank.

Empty moments of inertia: The moments of inertia of the aircraft without fuel.

Gross moments of inertia: The moments of inertia of the aircraft with full fuel tank. These are provided as a 1x6 vector of moment of inertia about body axes: $J_x, J_y, J_z, J_{xz}, J_{xy}$ and $J_{yz}$.

3.2.1.5 Other parameters

In this section of the aircraft configuration script, the other parameters are also specified, such as calendar date used by the World Magnetic Model to compute the magnetic field at aircraft location.
3.3 DESCRIPTION OF COMPLETE AIRCRAFT MODEL BLOCK

The block implementation of 6-DOF nonlinear aircraft model is done using AeroSim blockset. Velocities are computed in body frame i.e., the equations of motion are implemented in body frame as described in Section 3.2.1. The aircraft configuration file is saved and executed in MATLAB workspace. The open-loop response generated in Simulink environment. The initial conditions such as initial velocity, initial position, initial fuel mass and initial engine speed are set in the block parameter window of the blockset and the open-loop response of the UAV is observed.

3.3.1 Block Characteristics

The block characteristics are parameters, inputs and outputs. They are described below:

3.3.1.1 Parameters

Aircraft configuration file: The path and name of the aircraft parameter mat-file is provided as a string.

Initial velocities: The 3x1 vector of initial aircraft velocities in body axes (ground speed in body axes) \([u \, v \, w]\).

Initial angular rates: The 3x1 vector of initial angular rates (in body axes) \([p \, q \, r]\).

Initial attitude: The 4x1 vector of initial quaternion \([e_0 \, e_x \, e_y \, e_z] \).
Initial position: The 3x1 vector of initial aircraft location [Lat Lon Alt] in [rad rad m].

Initial fuel mass: The initial mass of the quantity of fuel on-board the aircraft in kg.

Initial engine speed: The initial engine shaft rotation speed in rad/s.

Ground altitude: The altitude of the terrain relative to mean-sea-level, at aircraft location, in meters.

World Magnetic Model (WMM) coefficient file: The complete path to the magnetic model coefficient file, as a string.

Simulation date: The date to be used for the magnetic model [day month year]

Sample time: It is the model sample time at which the aircraft model would run.

3.3.1.2 Inputs

Controls: The 7x1 vector of aircraft controls [flap elevator aileron rudder throttle mixture ignition]. Aerodynamic controls are measured in radians, throttle varies from 0 to 1, mixture is a fraction of air/fuel flow, ignition is 0 (engine OFF) or 1 (engine ON).

Winds: The 3x1 vector of background wind speed components in navigation frame [North East Down] in m/s.
Reset Time (RST): The integrator reset flag (took values 0 or 1, all integrators on rising edge)

3.3.1.3 Outputs

States: The 15x1 aircraft state vector [Velocities, Angular rates, Quaternions, Position, Fuel mass and Engine speed] i.e., [u v w p q r e_0 e_y e_z Lat Lon Alt mfuel \Omega_{eng}]

Sensors: The 18x1 vector of sensor outputs [GPS Position, GPS Groundspeed, Accelerometers, Gyros, Air data and Magnetometer] i.e., [Lat Lon Alt V_N V_E V_D ax ay az p q r pstat pdyn OAT Hx Hy Hz]

VelW: The 3x1 vector of aircraft velocity in wind axes [Airspeed, sideslip and angle of attack] i.e., [V_a \alpha \beta] in [m/s rad rad].

Mach: The current aircraft Mach number.

Ang Acc: The 3x1 vector of body angular accelerations [p \dot{q} \dot{r}]

Euler: The 3x1 vector of attitude of the aircraft given in Euler angles (roll, pitch and yaw) [\phi \theta \psi] in radians.

AeroCoeff: The 6x1 vector of aerodynamic coefficients [C_D C_Y C_L C_I C_m C_n] in rad^{-1}

PropCoeff: The 3x1 vector of propeller coefficients [J C_T C_P]

EngCoeff: The 5x1 vector of engine coefficients [MAP Airflow Fuelflow BSFC Power] given in [kPa kg/s kg/s g/(W*hr) W].
Mass: The current aircraft mass in kg.

ECEF: 3x1 vector of position of the aircraft in the Earth-centered and Earth-fixed frame [X Y Z].

MSL: The aircraft altitude above mean-sea-level in m.

AGL: The aircraft altitude above terrain.

REarth: The Earth equivalent radius at current aircraft location in m.

AConGnd: The aircraft-on-the-ground flag (0 if aircraft above ground, 1 if aircraft on the ground).

3.4 INTERNAL STRUCTURE OF AIRCRAFT MODEL BLOCK

The internal structure of aircraft model has an aerodynamic model with linear aerodynamics, propulsion model with piston-engine propulsion, inertia model which has weight variation due to fuel consumption, atmosphere model with standard atmosphere, wind gusts and Von Karman wind turbulence blocks, Earth model (which provided Earth radius, gravity and magnetic field components at current aircraft location) and equations of motion subsystem with non-linear equations of motion. The control inputs are given to the aerodynamics, propulsion and the inertia models. The wind inputs were given to the atmosphere model.
The integrator reset flag input is given to the equations of motion subsystem. The sensor outputs from the equations of motion subsystem are fed back as inputs to both atmosphere and earth models. The outputs of atmosphere and earth models are fed to aerodynamic, propulsion and inertia models. The outputs of the aerodynamic, propulsion and inertia models are fed as inputs to the equations of motion subsystem.

The internal structure of the aircraft model has four subsystems. The aerodynamics model, the atmosphere model, the earth model and the equations of motion block are implemented in subsystems. The propulsion model and the inertia models also part of the UAV dynamics.
There are another two blocks, which are masked. They are total moment block and total acceleration block. Thus, totally eight blocks are available inside the aircraft model. There are three input ports and 15 output ports.

3.4.1 Aerodynamic Model

In the aerodynamic model, the aerodynamic force and moment coefficients are computed using linear combinations of aerodynamic derivatives. The wind-axes velocities block computes the wind-axes parameters including airspeed, angle-of-attack, sideslip as well as the wind angle’s time derivatives and Mach number. The dynamic pressure block computes the current dynamic pressure. All the aerodynamic coefficients namely lift coefficient, drag coefficient, side-force coefficient, pitch moment coefficient, roll moment coefficient and yaw moment coefficient are computed as a linear combination of individual contributions of various flight parameters. The aerodynamic moment block computes the aerodynamic moment that acted on the airframe, based on current aerodynamic moments and dynamic pressure. The aerodynamic force block computes the aerodynamic force based on the current aerodynamic force coefficients and dynamic pressure.

3.4.2 Propulsion Model

The propulsion model was implemented using the General-Aviation propulsion block available in the Aerosim library. The General-Aviation propulsion system has a fixed-pitch propeller, a piston engine and the differential equation, which is solved for the engine shaft rotation speed. The differential equation describes the dynamics of the propulsion system is given by:
\( \left( I_{\text{eng}} + I_{\text{prop}} \right) \dot{\Omega} = M_{\text{eng}} + M_{\text{prop}} \)  

This equation was integrated forward in time to compute the engine speed \( \dot{\Omega} \) at the next time step. The block parameters are: Initial engine speed in rad/s, the engine speed interpolation vector (in rpm), the manifold air pressure interpolation vector, in kPa, the 2-D look-up table for fuel flow, as function of MAP and RPM (in g/hr), the 2-D look-up table for power, as function of MAP and RPM (in W), engine moment of inertia, advance ratio, coefficient of thrust, coefficient of power, the propeller radius, propeller moment of inertia and the ambient temperature for which the above engine look-up tables are given. The block inputs are: The 3x1 engine control vector [Throttle Mixture Ignition], out-of-fuel flag (0 or 1), static pressure at current altitude (in Pa), the air temperature at current altitude (in K), the air density at current altitude, in kg/m\(^3\), the 3x1 vector of body velocities in wind axes [Airspeed Sideslip Angle-of-attack] in [m/s rad rad] and the integrator reset flag. The block outputs are the 3x1 vector of propulsion system forces applied to the airframe (at the propeller hub location), the 3x1 vector of propulsion system moments applied to the airframe, the engine shaft rotation speed, in rad/s, the mass fuel flow, in kg/s, the 5x1 engine coefficient vector [MAP Airflow Fuelflow BSFC Power] in [kPa kg/s kg/s g/(W*hr) W] and the 3x1 propeller coefficient vector \([J, C_T, C_P] \).

3.4.2.1 Piston engine block

The Piston Engine block provided a simple internal combustion engine model based on look-up tables of engine parameters. The throttle input to this Piston Engine block represented the fraction between the manifold pressure and atmospheric pressure. For normally-aspirated engines, the manifold pressure would always be less than or equal to the atmospheric pressure at current altitude, therefore the pressure fraction took only values
from 0 to 1. The engine power is computed as function of RPM and MAP. The MAP was computed based on the throttle setting, current atmospheric pressure and the minimum MAP specified in the MAP vector.

The aircraft configuration file, which was developed first, did not give correct throttle control. The aircraft was found to climb even for zero throttle. The reason is that the engine characteristics are available from 2000 rpm to 2700 rpm. The MAP and power corresponds to those RPM. Thus the minimum MAP corresponds to high power output even at zero throttle command. Later, the problem is understood and extrapolation of power characteristics was done manually on paper. The fuel flow extrapolation is done using look-up table technique.

The replacement of 1-D look-up table for power gives satisfactory results and thus has been adopted in the experimental UAV 6 DOF model. For ‘0’ throttle the MAP corresponded to minimum MAP. The power corresponding to minimum MAP of say 59 KPa is considerable that it made the UAV to climb even at zero throttle. To fill the look-up table correctly, there is a need to have relationship between throttle to MAP then MAP to engine power.

The relationship between throttle to MAP is not available, therefore the following modification was done in the piston engine block. The 2-D look-up table from the piston engine block was deleted. A 1-D look-up table having a linear relationship between throttle and engine power was included in the place of 2-D look-up Table.

The block performed linear 1-D interpolations using \( <J, \text{CT} > \) and \( <J, \text{CP} > \) look-up tables. The current advance ratio was computed as:

\[
J = \left( \frac{\Pi V_a}{\Omega R} \right)
\]  

(3.10)
Where $R$ represents the propeller radius.

Knowing the thrust ($C_T$) and power ($C_P$) coefficients, the thrust force and propeller moment were computed respectively as:

\[
F_p = (4/\pi^2) \rho R^4 \Omega^2 C_T \tag{3.11}
\]
\[
M_p = (-4/\pi^3) \rho R^5 \Omega^2 C_P \tag{3.12}
\]

The block airspeed inputs are from Wind-axes Velocities in Aerodynamics and the air density from Standard Atmosphere in the Atmosphere model and the rotation speed from the Piston Engine model in Propulsion. Propulsion Force and Propulsion Dynamics blocks in Propulsion used the block outputs. The Fixed-pitch Propeller block was used in the General Aviation Propulsion System block.

3.4.3 Aircraft Inertia Block

The block integrated the fuel flow rate and updated the inertia parameters of the airplane knowing the current fuel quantity. The parameters used by the block are: Initial fuel mass, Mass of empty aircraft, Gross mass of the aircraft, the 3x1 position vector from origin to the empty aircraft CG location, the 3x1 position vector from origin to the gross aircraft CG location, the 4x1 vector of moments of inertia for the empty aircraft and the 4x1 vector of moments of inertia for the gross aircraft. The inputs used by the block are: Fuel flow and Reset flag for resetting the fuel integrator back to the initial value. The outputs of the block are: Current aircraft mass, current aircraft CG location, current aircraft moments of inertia and the flag that got set to 1 if the aircraft was out of fuel.
3.4.4 Atmosphere Model

The following blocks are available in the atmosphere model. They are standard atmosphere, background wind, turbulence and wind shear. The standard atmosphere block provided the air parameters at the current altitude. The standard atmosphere block is using interpolation through look-up tables, which provided air data for an altitude range of 0 to 86000 meters. The input to the block is the current altitude above Mean-Sea Level, in [m]. The outputs from the block are: \( p \) = static pressure, in [Pa], \( T \) = Outside-Air Temperature, in [K], \( \rho \) = air density, in [kg/m\(^3\)] and \( a \) = speed of sound, in [m/s].

The background wind block is applying a frame transformation from inertial (geographic) to body frame, using the rotation matrix provided. The numerical time derivative of the resulting velocity vector is then computed. This captured the effect of time-varying background wind which was encountered in some weather conditions (wind shear, thermals and cyclones). The block inputs are: Winds NED = The \([3 \times 1]\) background wind velocity components in inertial frame (North-East-Down) and DCM = The \([3 \times 3]\) direction cosine matrix for inertial to- body transformation. The block outputs are: WindVel = The \([3 \times 1]\) wind velocity components in body axes and WindAcc = The \([3 \times 1]\) wind acceleration components in body axes.

The turbulence block provided a Von Karman turbulence model. The block is applying Von Karman turbulence shaping filters for longitudinal, lateral, and vertical components to 3 white-noise sources. The filter parameters depended on background wind magnitude and current aircraft altitude. The block parameter is Sample time = The sample time for the white-noise sources. The block inputs are: VelW = The \([3 \times 1]\) vector of wind-axes velocities \([V_{a \alpha \beta}]\) (airspeed is in [m/s]), AGLAlt = The current altitude.
Above Ground Level, in [m] and WindVel = The 3x1 vector of background wind velocity in body axes, in [m/s]. The block outputs are: TurbVel = The 3x1 vector of turbulence velocities, in body axes, in [m/s] and TurbAcc = The 3x1 vector of turbulence accelerations, in body axes, in [m/s²].

The wind shear block computed the angular rate effects caused by the variation in time/space of the background wind and turbulence velocities. The inputs to the block are: WindAcc = The 3x1 vector of background wind accelerations, TurbAcc = The 3x1 vector of turbulence accelerations, Velocities = the 3x1 vector of aircraft velocities in body axes. The outputs from the block are WindAngRates = The 3x1 vector of body angular rates caused by wind components, WindAngAcc = The 3x1 vector of body angular accelerations caused by the wind components.

3.4.5 Earth Model

The Earth model had the following blocks, namely, WGS-84, EGM-96, WMM-2000, ECEF position and ground detection.

The WGS-84 block computed the local Earth radius and gravity at current aircraft location using the WGS-84 Earth model coefficients.

The EGM-96 block computed the sea-level altitude with respect to the WGS-84 ellipsoid, using the EGM-96 geodetic model.

The Ground Detection block computed the aircraft altitude Above Ground Level and sets a flag if it was zero.

The WMM-2000 block computed the Earth magnetic field components at current location using the Department of Defense World Magnetic Model 2000.
3.4.6 Total Acceleration

This block added all accelerations applied to the airframe due to aerodynamics and propulsion, and returned the sum as body-axes components. The block inputs are: \( F_{\text{aero}} = \) the 3×1 vector of aerodynamic forces in body axes \([F_{x\text{aero}} F_{y\text{aero}} F_{z\text{aero}}]^T\), \( F_{\text{prop}} = \) the 3×1 vector of propulsion forces in body axes \([F_{x\text{prop}} F_{y\text{prop}} F_{z\text{prop}}]^T\) and \( \text{Mass} = \) the current aircraft mass. The block output has \( \text{Acc} = \) the 3×1 vector of total acceleration in body axes \([a_x a_y a_z]^T\).

3.4.7 Total Moment Block

This block computed the total moment applied to the airframe by the aerodynamics and propulsion. The moment was computed about the current aircraft CG location. The block parameters are: Aerodynamic force application point = the coordinates of the point at which the aerodynamic forces and moments were given, in body axes \( r_{\text{aero}} = [X_{\text{aero}} Y_{\text{aero}} Z_{\text{aero}}]^T\) and Propulsion force application point = the coordinates of the point at which the propulsion forces and moments were given, in body axes \( r_{\text{prop}} = [X_{\text{prop}} Y_{\text{prop}} Z_{\text{prop}}]^T\) The block inputs were \( F_{\text{aero}} = \) the 3×1 vector of aerodynamic forces in body axes \( F_{\text{aero}} = [F_{x\text{aero}} F_{y\text{aero}} F_{z\text{aero}}]^T\), \( M_{\text{aero}} = \) the 3×1 vector of aerodynamic moments in body axes \( M_{\text{aero}} = [M_{x\text{aero}} M_{y\text{aero}} M_{z\text{aero}}]^T\), \( F_{\text{prop}} = \) the 3×1 vector of propulsion forces in body axes \( F_{\text{prop}} = [F_{x\text{prop}} F_{y\text{prop}} F_{z\text{prop}}]^T\), \( M_{\text{prop}} = \) the 3×1 vector of propulsion moments in body axes \( M_{\text{prop}} = [M_{x\text{prop}} M_{y\text{prop}} M_{z\text{prop}}]^T\) and \( \text{CG}_{\text{pos}} = \) the 3×1 vector of current CG position in body axes \( r_{\text{CG}} = [X_{\text{CG}} Y_{\text{CG}} Z_{\text{CG}}]^T\). The block output was \( M_{\text{cg}} = \) the 3×1 vector of total moment about the Centre of gravity \( M_{\text{CG}}=[M_x M_y M_z]^T\).
3.4.8 Body Frame EOM Block

The equations of motion have the following blocks. They are forces, moments, kinematics (quaternions), navigation, euler angles from quaternions and body-inertial DCM from quaternions. The force block implemented the rigid-body 6 degrees-of-freedom force equations that described the time variation of the aircraft velocities. The block parameters were Initial velocities = the 3×1 vector of initial body velocities \( [u_0 \ v_0 \ w_0]^T \).

The block inputs were Rates = the 3×1 vector of body angular rates \([p \ q \ r]^T\), Acc = the 3×1 vector of body accelerations \([a_x \ a_y \ a_z]^T\), Gravity = the gravitational acceleration as a scalar, DCM = the 3×3 frame transformation matrix (from navigation (geodetic) to platform (body) frame and RST = the integrator reset flag, which could be 0 or 1. The block output was Velocities = the 3×1 vector of body velocities \([u \ v \ w]^T\).

The moments block integrated the rigid-body 6 degree-of-freedom moment equations to obtain the instantaneous body angular rates. The block parameters were Initial angular rates = the 3×1 vector of initial body angular rates \([p_0 \ q_0 \ r_0]^T\). The block inputs were Inertia = the 4×1 vector of current moments of inertia \([J_x \ J_y \ J_z \ J_{xz} ]^T\), Moments = the 3×1 vector of airframe moments with respect to the CG \([L \ M \ N]^T\), RST = the integrator reset flag, which could be 0 or 1, Angular Rates = the 3×1 vector of body angular rates \([p \ q \ r]^T\), Angular Acc = the 3×1 vector of body angular accelerations \([pdot \ qdot \ rdot]^T\).

The Kinematics (Quaternions) block integrated the angular rates to obtain the aircraft attitude as quaternion representation. The block parameters were: Initial quaternions = the 4×1 vector of initial values for the quaternions \([e_0 \ e_0 \ e_0 \ e_0]^T\). The block inputs are Rates = the 3×1 vector of body
angular rates \([p \ q \ r]^T\), given in rad/s and \(RST\) = the integrator reset flag, which could be 0 or 1. The block outputs are: Quaternions = the 4×1 vector of quaternions \([e_0 \ ex \ ey \ ez]^T\).

The Kinematics (Euler Angles) block integrated the angular rates to obtain the aircraft attitude as Euler angle representation. The block parameters were: Initial Euler angles = the 3×1 vector of initial values for the Euler angles \([\phi \ \theta \ \psi]^T\). The block inputs are: Rates = the 3×1 vector of body angular rates \([p \ q \ r]^T\), given in rad/s and \(RST\) = the integrator reset flag, which can be 0 or 1. The block outputs are Euler = the 3×1 vector of Euler angles \([\phi \ \theta \ \psi]^T\).

The Navigation block integrated the navigation equations to obtain the current aircraft position. The block parameters were: Initial position = the 3×1 vector of initial geographic position \([\text{Lat}_0 \ \text{Lon}_0 \ \text{Alt}_0]^T\), where latitude and longitude were given in radians. The block inputs were: Velocities = the 3×1 vector of body-axes velocities \([u \ v \ w]^T\), DCM = the 3×3 direction cosine matrix for inertial to-body transformation, \(R_{\text{meridian}}\) = the meridian radius, in meters, \(R_{\text{normal}}\) = the normal radius, in meters, \(A_{\text{ConGnd}}\) = the “Aircraft on the Ground” flag (0 or 1) and \(RST\) = the integrator reset flag, which can be 0 or 1. The block outputs were Position = the 3×1 position vector \([\text{Lat} \ \text{Lon} \ \text{Alt}]^T\), Latitude and longitude were provided in radians and \(Gnd_{\text{spd}}\) = the 3×1 ground speed vector components in geographic frame \([V_{\text{North}} \ V_{\text{East}} \ V_{\text{Down}}]^T\).
3.5 OPEN LOOP ANALYSIS OF THE DEVELOPED EXPERIMENTAL UAV MODEL

The aircraft configuration script developed for the experimental UAV is saved as M-file. When this MATLAB script is run at the command prompt the data available in the M-file is stored as the mat-file. The name for the MATLAB data file (mat file) is assigned as a string. The 6-DOF non-linear model developed for the experimental UAV is taken for open loop analysis. In the open loop analysis, all the controls are kept to ‘0’ (except throttle and engine in the first case). In the following sections, the results obtained by the simulation of the open loop model are discussed.

3.5.1 Setting up and Running the Open Loop Model

The block parameters for the experimental UAV model are as given below: The aircraft configuration file is saved. The initial velocities were [35 0 0], the initial angular rates were [0 0 0]. The initial attitude was [1 0 0 0] in quaternion representation. The initial altitude of the flight is given as 1000 m. The initial engine speed was 800rpm, the ground altitude was 0m (but the model is taking a default ground altitude as 15.43m, the path for the magnetic file (set to default path), the simulation sample time as 0.005 and the simulation date. The aerodynamic controls to the block namely flap, elevator, aileron and rudder are all set to ‘0’ radians. The throttle is given a value of 0.7. The air to fuel mixture ratio is kept at optimum 13. The ignition flag, which control the engine ON or OFF position, is set at 1 (indicating that the engine was ON). The winds in the North, East and Down directions were set as [0 0 0]. The integrator reset flag is set at ‘0’. The 6 DOF model has 3 inputs namely the 7×1 control vector, the 3×1 wind velocities and the integrator reset flag. In the output block, there are 15 outputs available. The 15×1 states, the 18×1 sensors (from which altitude plot was taken), the 3×1 wind velocity
vector which gives the airspeed, sideslip and the AoA responses, the $3 \times 1$ vector of Euler angles (output in radians is converted to degrees by using R2D block from Aerosim library), the aircraft on the ground flag, which is connected to the stop simulation block.

In the configuration parameters, the solver type is set to fixed-step. The integration scheme is set to Ode 4 or Ode 5 (Runge-Kutta). The fixed step size is set to match the aircraft model sample time, which is 0.005. The open-loop response is generated by running the Simulink model for 20 seconds. The various open loop plots given below are airspeed response, bank angle response, pitch angle response, heading response, AOA response and the altitude response.

![open loop airspeed response](image)

**Figure 3.3 Open Loop Airspeed Response**

Figure 3.3 shows the open loop airspeed response w.r.t time scale, it is seen from the above Figure that airspeed smoothly increases from 35 m/s to 80 m/s and then it becomes constant at about 13 sec. There is no change in the speed after reaching 80 m/s with increase in time, it become independent of time.
Figure 3.4 shows open loop response for bank angle and limit to the maximum bank angle is provided which can be seen from the graph. The bank angle increases up to 23 degree approximately at around 11 sec and then it start decreasing, thereby providing good bank angle control in the event of out of operating range bank angle command.

![Figure 3.4 Open Loop Bank Angle Response](image)

Figure 3.5 shows open loop response of the pitch angle w.r.t time scale, it is seen that initially there is a large change in the pitch angle with time, but finally it settled down after 16 sec and reached the desired altitude.

![Figure 3.5 Open Loop Pitch Angle Response](image)
Figure 3.6 provides open loop response of heading w.r.t to time, it can be seen that there is a pulsive response at the start of simulation and then it reaches to zero for about 2.5 sec and again suddenly it increases to initial level after that it decreases slowly.

![Figure 3.6 Open Loop Heading Response](image1)

Figure 3.6  Open Loop Heading Response

Figure 3.7 shows open loop response for angle of attack, which is the angle between the aircraft longitudinal axis and relative wind direction, it increases suddenly initially with little disturbance in the vertical direction and then settles down to small negative value.

![Figure 3.7 Open Loop AoA Response](image2)

Figure 3.7  Open Loop AoA Response
The airspeed of the UAV increased steadily and reached the maximum limit of 80m/s. The altitude dropped in nearly linear manner confirming the steady increase in airspeed. The pitch response dropped to around -58 degrees. The bank angle dropped to around -21 degrees. The bank response suggested that the spiral mode is unstable. The unbalanced roll moment was caused by the propulsion system. This was verified by making the developed aircraft model to run with controls unconnected. This implied that the model is run with engine off and controls at their neutral position. The other option is that the ignition switch is kept at the OFF position ('0') and then the model is run.

The open loop responses with controls unconnected are given below. The bank angle and heading responses were ‘0’ degrees, indicating that the spiral mode instability was due to engine torque. The pitch response, the altitude response, the AoA response, the airspeed response were all similar to the open loop response with controls connected.
Figure 3.9  Open Loop Bank Angle Response with Unconnected Controls

Figure 3.9 shows the open loop bank angle response with unconnected control inputs. It can be seen that bank angle is constant throughout the entire time scale, and it remains zero without any change in value which gives a robust control to the banking control law.

Figure 3.10  Open Loop Pitch Response with Unconnected Controls
Figure 3.11 Open Loop Altitude Response with Unconnected Controls

Figure 3.11 shows the open loop altitude response with unconnected control inputs. It can be seen that variation in altitude is smooth and the rate at which it is changing is almost constant. The altitude reaches to zero around 22 sec.

Figure 3.12 Open Loop AoA Response with Unconnected Controls
Figure 3.13 shows the open loop airspeed response with unconnected control inputs. It can be seen that it decreases slightly initially and then increases smoothly up to 20 sec.

3.6 CONCLUSION

This chapter deals with the design of non-linear six-degree-of-freedom aircraft model for an experimental UAV using Aeronautical Simulation Toolbox. Before validating the model, a routine to determine trim settings for specified flight conditions were also written. The script developed to drive the linearization process was also presented. This results in longitudinal and lateral state space representation matrices. The required transfer functions are generated from these matrices are shown in Appendix-1. Once the model was trimmed, it was validated to check whether it actually behaved like an aircraft. The tests were performed to determine whether the model reacted correctly to control inputs.