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Simulation of tilt-rotor UAV flight dynamics in horizontal flight

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Abstract. Tilt-rotor unmanned aerial vehicles (UAV) have gained significant importance in the aeronautical industry due to their ability to transition between vertical and horizontal flight. One of the important steps in the development of such UAVs is to assess their performance and stability characteristics. Simulation of flight dynamics is an essential tool that enables the designers to test and optimize the flight characteristics of these UAVs. This paper presents a complete procedure for developing a 6-degree-of-freedom flight dynamics model of a tilt-rotor UAV in fixed-wing mode using a physics-based modeling approach. All necessary sub-models are developed and integrated into the Simulink simulation environment to allow for predicting the UAV's dynamic response. The developed model is verified for correct operation by simulating horizontal steady-level flight and exciting its natural longitudinal modes.

1. Introduction

Combining the advantage of fixed-wing aircraft (e.g., high range, endurance, speed) and rotor-craft (e.g., vertical take-off and landing, hovering) in one system is an important goal that engineers have been dreaming of it for decades. Recently, diverse systems have been investigated, where the most popular are tilt-rotor, tilt-wing and tail-sitter. A tilt-rotor is an aircraft that uses one or more powered rotors (also known as prop-rotors) installed on rotating shafts or nacelles, often at the ends of a fixed-wing, to produce lift and thrust. The rotors are oriented for vertical flight so that the plane of rotation is horizontal, providing lift in the same way as a typical helicopter rotor does. As the aircraft acquires speed, the rotors gradually tilt forward, until the plane of rotation becomes vertical. In this mode, the rotors act as a propeller, while the airfoil of the fixed wings provides lift via the forward motion of the entire aircraft. Also, tilt-rotor concept is considered as the most promising combination in either manned or unmanned applications. It is essential for many current and future civilian/military applications (e.g., air taxi, package delivery, troop transportation, mapping and survey, traffic tracking, search and rescue). However, the effective development of tilt-rotor aircraft is still in its infancy and immature in terms of many aspects like design philosophy, flight dynamics modeling, control, guidance, navigation [1]. This work aims to tackle one of these important aspects, which is the flight dynamics modeling of tilt-rotor unmanned aerial vehicles (UAV).

Modeling of tilt-rotor UAV flight dynamics is crucial for analyzing UAV performance/stability characteristics, verifying their design, test any suggested design modification for existing aircraft, and determining/validating the flight-control parameters. Typically, there are two approaches used for the modeling process. The first is the physics-based modeling approach and the second is the system identification approach. Many assumptions about the characteristics of the aircraft are implemented in physics-based simulation. The model is typically built using the individual aircraft components that have been characterized in terms of their aerodynamic, inertial, and physical properties, such as the wing, tail, fuselage, and rotor. This approach is laborious, and requires the prediction or measurement of the aerodynamic, inertial, and structural properties of the many aircraft elements. It is undeniably advantageous that this method is used to determine the aircraft's dynamic behavior, which results from given control inputs, before the aircraft is constructed.

The accuracy of the physics-based simulation model depends not only on the mathematical formulation but also on the accuracy of airplane parameters contained inside these models. Such parameters can be obtained by theoretical, computational, semi-empirical or experimental methods. Generally, airplane flight dynamics simulation of tilt-rotor UAV in horizontal flight should include six main underlying models. These models are the dynamic, geometric, aerodynamic, propulsion, atmospheric, and actuator as shown in figure 1.

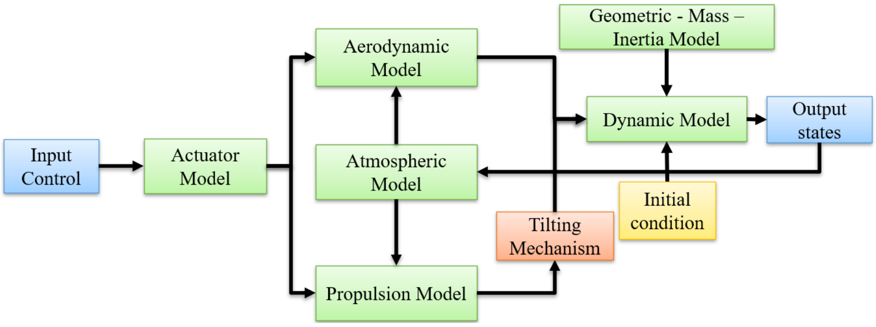


Figure 1. Typical block diagram for tilt-rotors flight dynamics simulation model.

In 2015, Gryte [2] developed a software-in-the-loop (SITL) for the Skywalker X8 fixed wing UAV. The geometric data were gathered using 3D scanning. XFLR5 software was used to estimate the aerodynamic parameters and study the stability of the UAV. The inertia tensor was obtained experimentally using compound pendulum method. MATLAB/Simulink was used to solve the nonlinear equations of motion with Flight Gear as a simulator. Unfortunately, the propulsion modeling was not introduced.

In 2016, B. Yuksek, [3] developed a complete non-linear six degrees-of-freedom mathematical model for a tilt-rotor UAV named TURAC. The propulsion model including the effect of the propeller with the free stream velocity was calculated by the momentum theory. Computational Fluid Dynamics (CFD) was used to obtained the aerodynamic characteristics of the UAV and embedded into nonlinear model as a look-up table. Inertia moments were calculated using bifilar (two wire) pendulum tests. Although, the aerodynamic parameters were obtained at various Reynolds numbers, the effects of control surfaces were not implemented and the actuator dynamics were not modeled.

In the same year, Kamal [4] presented a complete process to build a low cost, high fidelity simulation model, starting by modeling, simulation, and followed by flight-testing to assess the accuracy of the developed model and parameter estimation for model tuning. The quaternion attitude representation was used for modeling the six DoF nonlinear differential equation of motion. Physical measurements with the help of a set of orthogonal photos for the airplane and its parts and a CAD software are used to fully acquire the airplane geometric model. The mass, the position of center of gravity along all three axes, and the moments of inertia of the airplane are obtained experimentally. The propulsion model (a reciprocating piston engine with a 11X6 propeller) was modeled experimentally inside a low-speed subsonic wind tunnel. Airplane aerodynamic characteristics are modeled via a developed user-friendly Graphical User Interface (GUI) that facilitate the use of the UASF Digital Datcom (DDatcom). A model of the actuator is identified by measuring the input and output signals.

In 2017, Willian [5] presented a methodology for mathematical modeling, simulation and control design for the longitudinal dynamics of a fixed-wing Unmanned Aerial Vehicle (UAV). SolidWorks is used to calculate the assembly moments of inertia, based on the weight and distribution of each part. The UAV used in this study is the University of Toronto explorer (UT-X). The stability and control derivatives for the UAV were obtained using USAF DATCOM. The UT-X has pusher propeller/engine configuration with an electric motor, the propulsive force was modeled using empirical formula and assuming the propeller efficiency is 70%. A comparison between the analytical simulation (DATCOM-MATLAB/Simulink) and X-plane model showed that both techniques resulted in similar responses for the UT-X UAV. Although, the result showed that this analysis methodology is interesting for simulating conceptual and real airplanes, the comparison data should be compared with real test flight data to validate both analytical and X-Plane models.

In 2020, Dantsker Or [6] presented a flight and ground testing methodology for fixed-wing UAV that can be used for the modeling process. For the aerodynamic model, XFLR5 and AVL were used as a low-fidelity tools and the CFD Ansys Fluent was used as a high-fidelity and the outputs were compared with the flight test results [7] . The Geometric data needed for calculating the aerodynamic characteristics were gathered by a 3D scanner (ZScanner 800 self-positioning handheld) and the final CAD model was developed using Solidworks software. The measurements of moment of inertia (MOI) was done using high-fidelity experimentally [8] The test rig measures the moment of inertia with minimum allowable error using Al Volo FDAQ 100 Hz data acquisition system and a 3 axis gyroscope. The propeller static and dynamic performance characteristics was obtained for Aero-Naut CAM through wind tunnel testing [9].

The objective of this work is to apply a scientific procedure to develop a flight dynamics model for tilt-rotor UAV in horizontal flight mode using physics-based modeling approach. This includes building all required sub-models of the tilt-rotor UAV.

2. Description of the case-study tilt-rotor UAV

The case study tilt-rotor UAV is the Nimbus 1800 (shown in figure (2)) developed and manufactured by Foxtech company [10]. It is constructed with light weight foam and carbon fiber, it consists of a fixed-wing aircraft equipped with three electric motor, two of them are tiltable and hanged on the wing by 28 kg servo to convert between hover and fixed-wing modes while the third on is fixed on the tail boom and work to balance the other two in hover mode only. The Nimbus UAV came with CUAV V5+ Autopilot manufactured by CUAV [11]. Table 1 presents the tilt-rotor UAV specifications as described in the user manual [12].

Figure 2. Nimbus 1800 Tilt-rotor UAV.

Table 1. Nimbus Specifications

Property	Value
Max Take-off Weight	6 [kg]
Max Payload	800 [g]
Ceiling	3.5 [km]
Max Speed	35 [m/s]
Length	1.3 [m]
ESC	50[A]
Tilt-Motors	2* 3520 KV520
Tail Motor	1*X5008 KV330
Tiltabel Propeller	13*8 Wooden pair
Tail Propeller	17*55 MARKII Matte CW

3. Flight Dynamics Modeling for the tilt-rotor UAV (Fixed-wing Mode)

3.1. Dynamics Model

To describe the airplane motion, the nonlinear differential equations [13] represent the force, moment, attitude, and trajectory equations in vector form are given as per [Equations (1 - 5)]. To avoid the problem of singularity, the attitude equation is presented in quaternion instead of Euler representation.

$$\dot{\overrightarrow{V_B}} = -\overrightarrow{\omega_B} \times \overrightarrow{V_B} + \mathbf{B}\overrightarrow{g_o} + \frac{1}{m}\overrightarrow{F_B} \quad (1)$$
$$\dot{\overrightarrow{\omega_B}} = \mathbf{I_B}^{-1}[-\overrightarrow{\omega_B} \times \mathbf{I_B}\overrightarrow{\omega_B} + \overrightarrow{M_B}] \quad (2)$$
$$\dot{\overrightarrow{\mathbf{q}}} = -\frac{1}{2}\Omega\overrightarrow{\mathbf{q}} + k\lambda\overrightarrow{\mathbf{q}} \quad (3)$$
$$\dot{\overrightarrow{r_E}} = \mathbf{B}^T\overrightarrow{V_B} \quad (4)$$
$$\overrightarrow{\dot{\mathbf{\Phi}}}_B = f(q_0, q_1, q_2, q_3) \quad (5)$$

The above equations are the hub of the flight dynamics model. By solving these equations, a state vector $\mathbf{X}$ that completely describe the airplane velocity, orientation, and position at each instant of time can be obtained. This state vector is defined as $\mathbf{X} = [u, v, w, p, q, r, \phi, \theta, \psi, x, y, z]^T$

It should be noted that $\overrightarrow{F_B}$ and $\overrightarrow{M_B}$ are the resultant vectors of all forces (excluding gravity) and moments affecting the airplane in body axes. These loads are conveniently classified into aerodynamic and propulsion loads as given by Eqs. (6) and (7).

$$\overrightarrow{F_B} = \overrightarrow{F_A} + \overrightarrow{F_P} \quad (6)$$
$$\overrightarrow{M_B} = \overrightarrow{M_A} + \overrightarrow{M_P} \quad (7)$$

3.2. Atmospheric Model

In order to calculate the change of air properties with altitude, the international standard atmosphere [ISA] model is used to calculate the pressure, temperature, density, and dynamic viscosity at each altitude.

3.3. Mass/Moment of Inertia Model

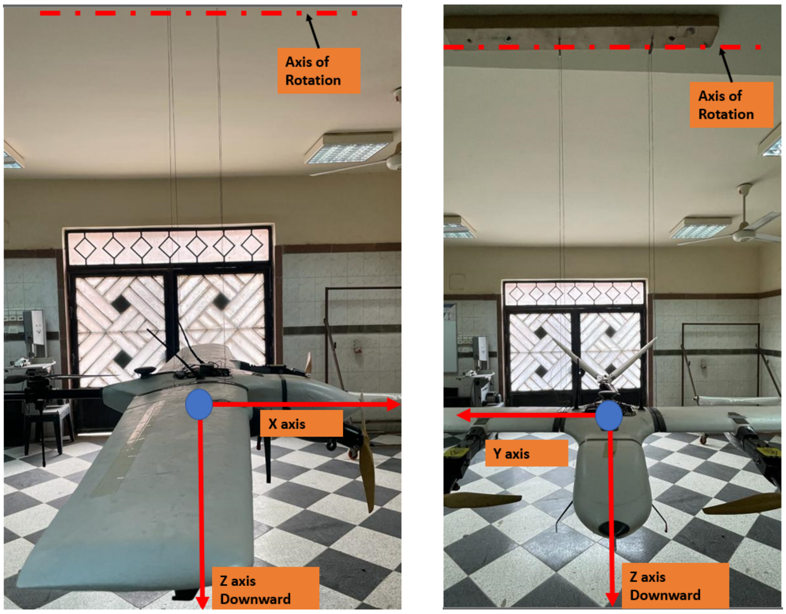
The UAV moments of inertia (MoI) are essential for both dynamic stability & control analysis and the development of flight dynamics model. Many techniques were used to obtain the MoI of the UAV, such as physical pendulum, bifilar pendulum, compound pendulum, torsional pendulum, and torque [14–18].

In this work, the compound pendulum method is implemented to measure the case study UAV MoI experimentally in horizontal flight (as shown in figure 3). In this method, the oscillation period need to be measured. Thus, the UAV is oscillated about each axis with the assumption of small amplitude, the oscillation data are gathered using a gyroscope mounted at the center of gravity of the UAV. Then, the data are smoothed using Robust quadratic regression to get the peaks of the oscillation. Finally, the average period can be obtained by averaging the time between each two peak (as shown in Figure 4.) After measuring the average time period of each oscillation and also measuring the distance from the axis of rotation to the center of gravity of th UAV, the moment of inertia is calculated using Eq. (8).

$$I = \frac{T^2WL}{2\pi^2} - \frac{WL^2}{g} \quad (8)$$

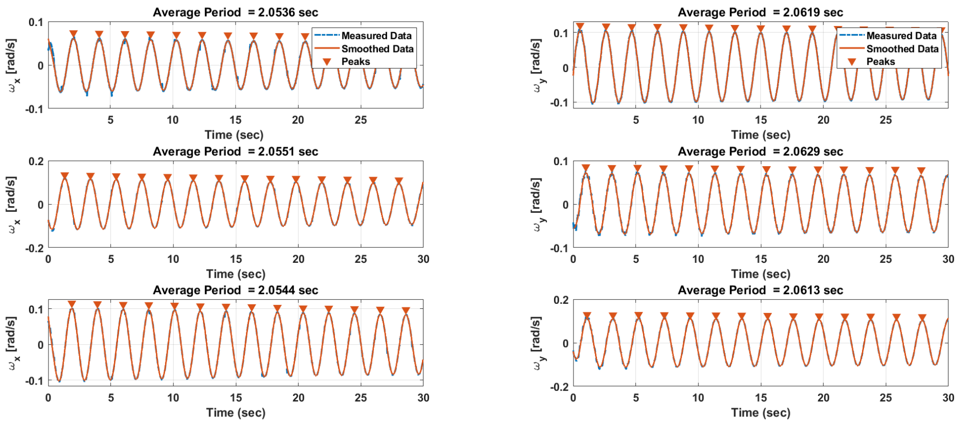
Where: T is the average time period, L is the distance from the axis of oscillation to the center of gravity of the UAV, and W is the weight of the UAV.

On the other hand, a computer-aided design (CAD) software (INVENTOR) is used to draw the UAV and by defining the material properties of each component the MoI of the UAV can be obtained. The results from the CAD software are compared with the experimental results in order to assess their validity in modeling mass-inertia if the real airplane has not been built.



(a) I_x measurement (b) I_y measurement

Figure 3. MoI Measurement using Compound Pendulum method.



(a) Average Period oscillation about x-axis for 3 trial (b) Average Period oscillation about y-axis for 3 trial

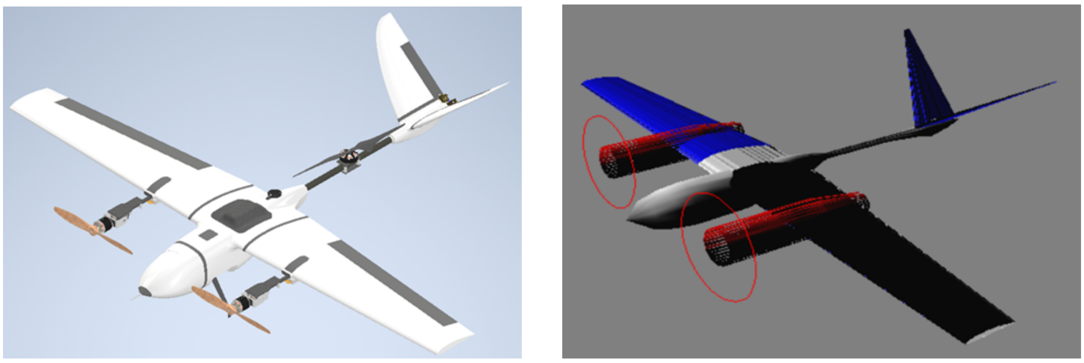
Figure 4. Moment of inertia experimental data results.

Table 2. Moment of inertia results

Property	Experimental	Inventor
I_{xx} [kg.m^2]	0.0594	0.179
I_{yy} [kg.m^2]	0.0931	0.273
I_{zz} [kg.m^2]	-	0.446

3.4. Aerodynamic Model

The Nimbus UAV aerodynamic properties mainly depend on its configuration (i.e. type of wings, horizontal tail, and vertical tail) and their airfoils. Therefore, all geometric and aerodynamics characteristics of the airfoils for the case-study UAV are identified as the first step in developing the aerodynamic model. Then, using a semi-empirical approach, the aerodynamics data of the UAV are estimated. Finally, Matlab/Simulink is used to implement the UAV aerodynamic model.



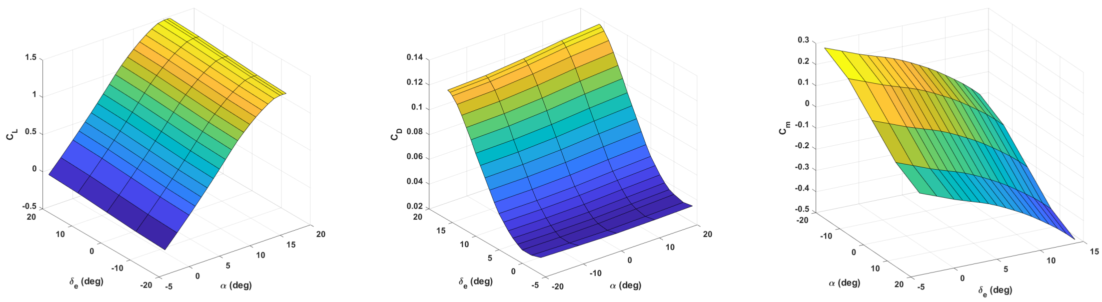
(a) CAD model for Nimbus 1800 (b) USAF Digital Datcom 3D model

Figure 5. Developed CAD and DDATCOM Models for Nimbus tilt-rotor UAV

The identification process is performed done using Profili software and the results reveal that Clark-Y airfoil present the highest similarity for the wing cross-section, while NACA0011 for the V-tail cross-section.

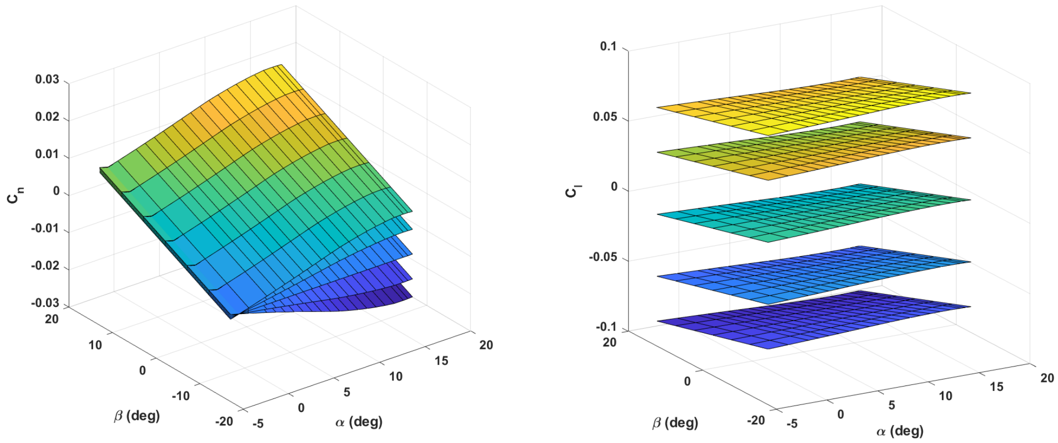
As the computational and experimental approaches are time and cost consuming, a semi-empirical approach (USAF Datcom) is used to estimate the aerodynamic coefficients and derivatives. The input file of the case study UAV is defined at flight condition (**FLTCON**) of H = 1000 m and V= 20 m/s. After that, the reference geometric parameter (**OPTINS**) was defined as obtained from the geometric model. Then, the synthesis parameters (**SYNTHS**) which include the center of gravity, (wing/tail) location, and (wing/tail) incidence. To fully define the case-study wing, the wing section (**WGSCHR**) and wing plan-form (**WGPLNF**) are required. The wing plan-from is defined including the wing geometric parameters of the case study UAV. The wing section (Clark-Y) is defined by providing the upper and lower ordinates with respect to the non-dimensional chord. The UAV body (**BODY**) is defined by providing the upper coordinates, lower coordinates, width of the fuselage, area, perimeter and equivalent radius at 20 section divided longitudinally. Additionally, the propeller (**PROPWR**) effect on the longitudinal stability is estimated. Finally, the control surfaces are defined as elevator and aileron with $\pm$ 15 deg.

Unfortunately, the USAF DDATCOM only define the conventional tail. So, to define the V-Tail, the horizontal tail is defined in the (**HTPLNF**) with a dihedral angle. This will only affect the longitudinal stability characteristics. Figure 6 presents the longitudinal aerodynamic characteristics for the case study UAV. To get the effect of V-tail for the lateral stability, a virtual vertical tail were defined in the (**VTPLNF**) by projection the V-tail on the symmetric plane of the UAV. Figure 7 presents the lateral aerodynamic characteristics for the Nimbus UAV.



(a) Lift curve (b) Drag curve (c) Pitch moment curve

Figure 6. Basic longitudinal aerodynamic characteristic for the case study UAV.



(a) Yawing moment curve (b) Rolling moment curve

Figure 7. Basic lateral aerodynamic characteristic for the case study UAV.

3.5. Propulsion model (Propeller Characteristics)

The propulsion model used in fixed-wing mode of the case study UAV, as described in table 1, consists of two motors of 520 KV. The propeller used are 13X8, its characteristics are obtained form the data available [19]. Figure 9 shows the thrust and power coefficients of the propeller function of rpm and advance ratio. Equations 9 to 22 are used in the developed propulsion model to calculate the thrust and moment developed by the two rotor, where T_1, T_2, M_2, and M_1 represent the thrust and moment produced by the right and left motors respectively as shown in figure 8. R_{E_1}, R_{E_2} represent the moment arms from the center of gravity to the right and the left motors respectively.

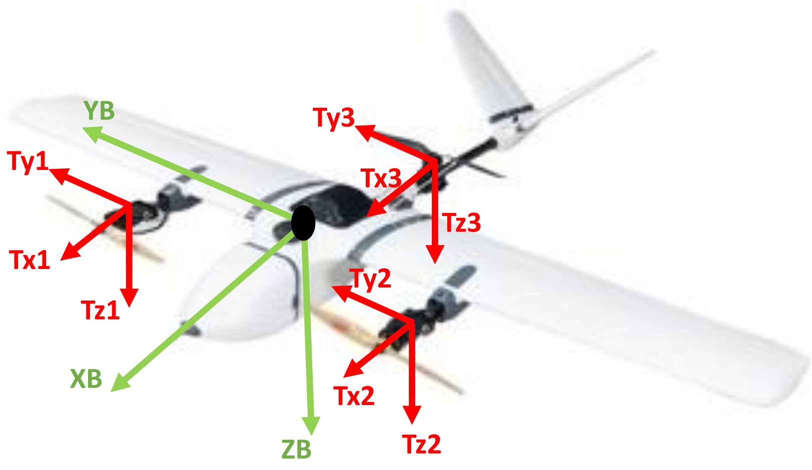


Figure 8. Body and motors axes system of the Nimbus UAV.

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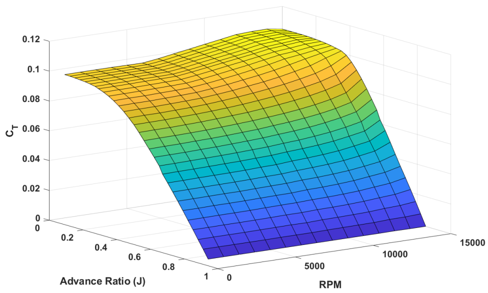
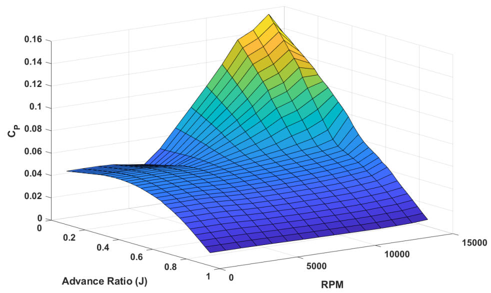
$$\overrightarrow{F_P} = \overrightarrow{T_1} + \overrightarrow{T_2} \tag{9}$$
$$T_{x1} = C_t \rho n^2 D^4 \tag{10}$$
$$T_{y1} = 0 \tag{11}$$
$$T_{z1} = 0 \tag{12}$$
$$\overrightarrow{T_1} = T_{x1}\hat{i} + T_{y1}\hat{j} + T_{z1}\hat{k} \tag{13}$$
$$Q = C_q \rho n^2 D^5 \tag{14}$$
$$\overrightarrow{M_P} = \overrightarrow{M_1} + \overrightarrow{M_2} \tag{15}$$
$$\overrightarrow{M_{o_1}} = Q\hat{i} + 0\hat{j} + 0\hat{k} \tag{16}$$
$$\overrightarrow{M_{o_2}} = -Q\hat{i} + 0\hat{j} + 0\hat{k} \tag{17}$$
$$\overrightarrow{R_{E_1}} = (X_{E1} - X_{cg})\hat{i} + (Y_{E1} - Y_{cg})\hat{j} + (Z_{E1} - Z_{cg})\hat{k} \tag{18}$$
$$\overrightarrow{R_{E_2}} = (X_{E2} - X_{cg})\hat{i} + (Y_{E2} - Y_{cg})\hat{j} + (Z_{E2} - Z_{cg})\hat{k} \tag{19}$$
$$\overrightarrow{M_1} = \overrightarrow{M_{o_1}} + \overrightarrow{R_{E_1}} \times \overrightarrow{T_1} \tag{20}$$
$$\overrightarrow{M_2} = \overrightarrow{M_{o_2}} + \overrightarrow{R_{E_2}} \times \overrightarrow{T_2} \tag{21}$$
$$\tag{22}$$



(a) Thrust Coefficient



(b) Power Coefficient

Figure 9. 13X8 Propeller data.

4. Verification of the fixed-wing simulation model

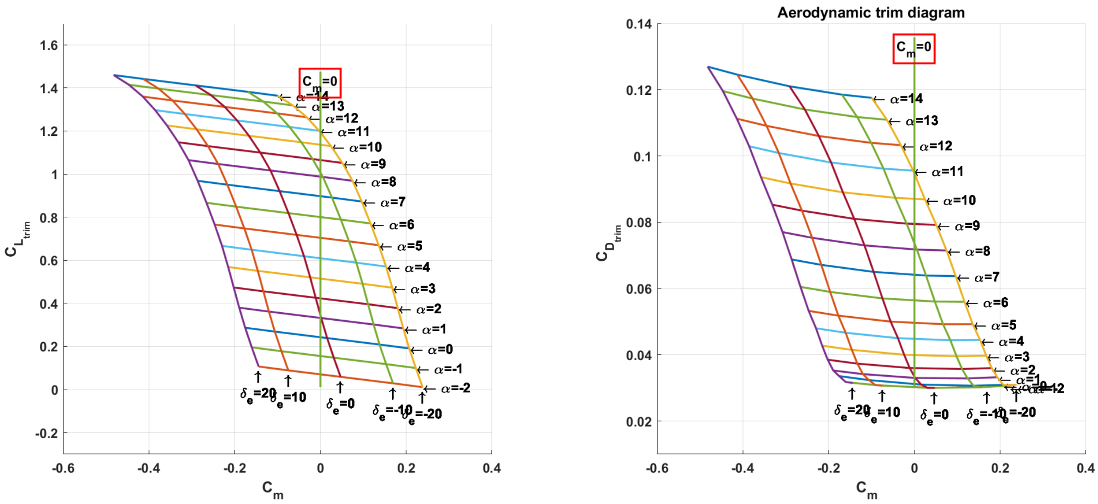
In order to verify the developed simulation model, the following horizontal flight maneuvers are simulated: 1) Steady-level flight; 2) Typical longitudinal flight maneuvers (e.g., elevator pulse, doublet, and 3-2-1-1).

4.1. Steady-level flight

In steady-level horizontal, the trim data presented in table 3 are obtained using the graphical trim diagram [20] that presented in figure 10 where the initial state vector and control inputs at the reference steady state are summarized Table 4 .

Table 3. Nimbus UAV Trim Data

Parameter	$C_{L_{trim}}$	α_{trim}	$\delta_{e_{trim}}$	$\delta_{th_{trim}}$	$\delta_{a_{trim}}$	$C_{D_{trim}}$
Value	0.5753	2.35 [deg]	-2.0 [deg]	71.2 %	0 [deg]	0.048



(a) Lift-Pitch moment (b) Drag-Pitch moment

Figure 10. Aerodynamic trim diagram.

Table 4. Initial state vector and control inputs at the selected trim conditions

State			Control Inputs
X			U
u = 19.993 [m/s]	v = 0 [m/s]	w = 0.47 [m/s]	$\delta_{e_{trim}}$ = -2.0 [deg]
p = 0 [rad/sec]	q = 0 [rad/sec]	r = 0 [rad/sec]	$\delta_{a_{trim}}$ = 0 [deg]
ϕ = 0 [deg]	θ = 2.3517 [deg]	ψ = 0 [deg]	$\delta_{r_{trim}}$ = 0 [deg]
x = 0 [m]	y = 0 [m]	z = -500 [m]	$\delta_{th_{trim}}$ = 71.2 (%)

Figure 11 presents a 50 seconds time history for the trim control inputs and the UAV response as well as the 3D trajectory of the UAV. It is shown that the altitude, velocity, pitch rate, and pitch angle are constant during the simulation, which are the characteristics of steady-horizontal flight.

4.2. Typical Longitudinal maneuvers

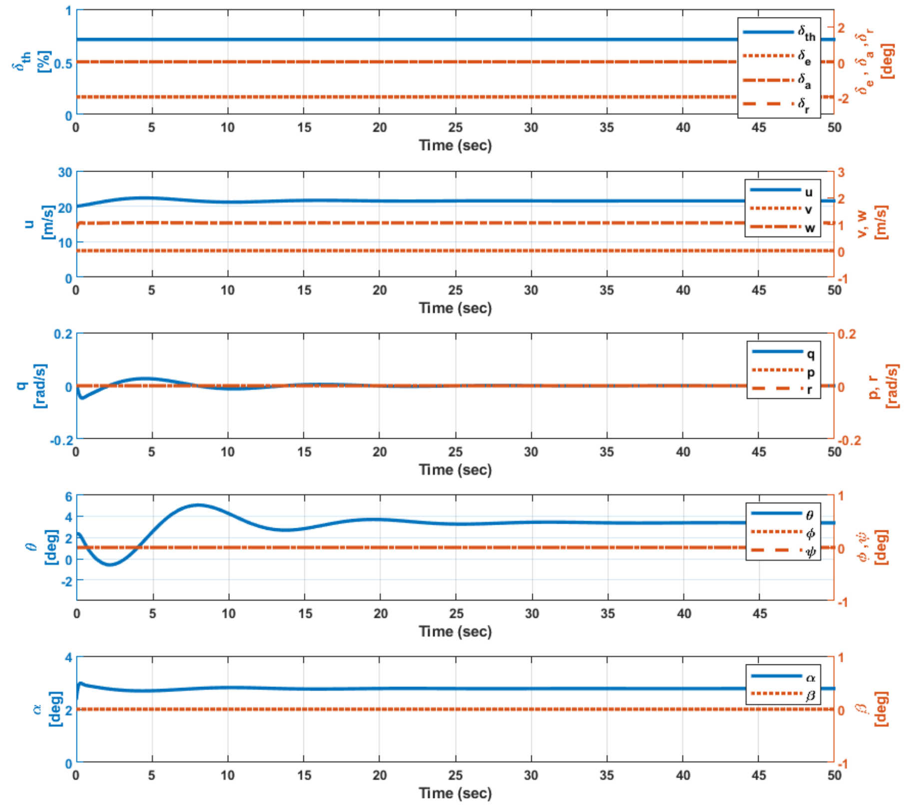
The longitudinal response of the case-study UAV is simulated in different maneuvers that excited with typical elevator control inputs.

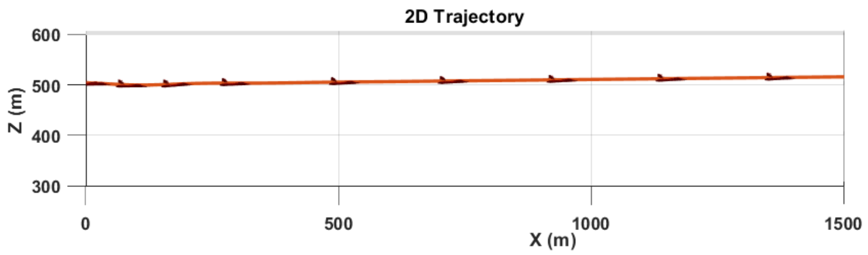
The first longitudinal maneuver is the pulse input. A two deg elevator up is applied to the trimmed UAV (for 1 sec from t= 50 to t = 51) and the response is obtained for 70 sec as shown in Figure 12. The UAV enter an oscillation mode and reaches its equilibrium condition after 12.24 seconds. The second longitudinal maneuver is doublet (symmetrical pulse of equal magnitude and opposite sign) [according to reference [21]]. A five degree elevator up and down are applied to the trimmed UAV (for 2 sec from t = 50 to t = 52) and the response is obtained for 35 sec as shown in Figure 13. The response shows that the UAV enters a stable and heavily damped oscillatory mode with a period of 4.63. The last longitudinal maneuver is 3-2-1-1. This input applied to the trimmed airplane with two degree up, down, up, and down (for 2.5 sec from t= 50 to t=52.5) and the response is obtained for 50 sec as in Figure 14. The UAV enters a heavily damped oscillatory mode with period of 4.98 [sec].

Future work will involve validation of the developed model by flight testing using Pixhawk 4 as a flight data recorder [22]. Also, reading of the flight data will be done using the a graphical user interface (GUI) developed in Ref. [23].

5. Conclusion

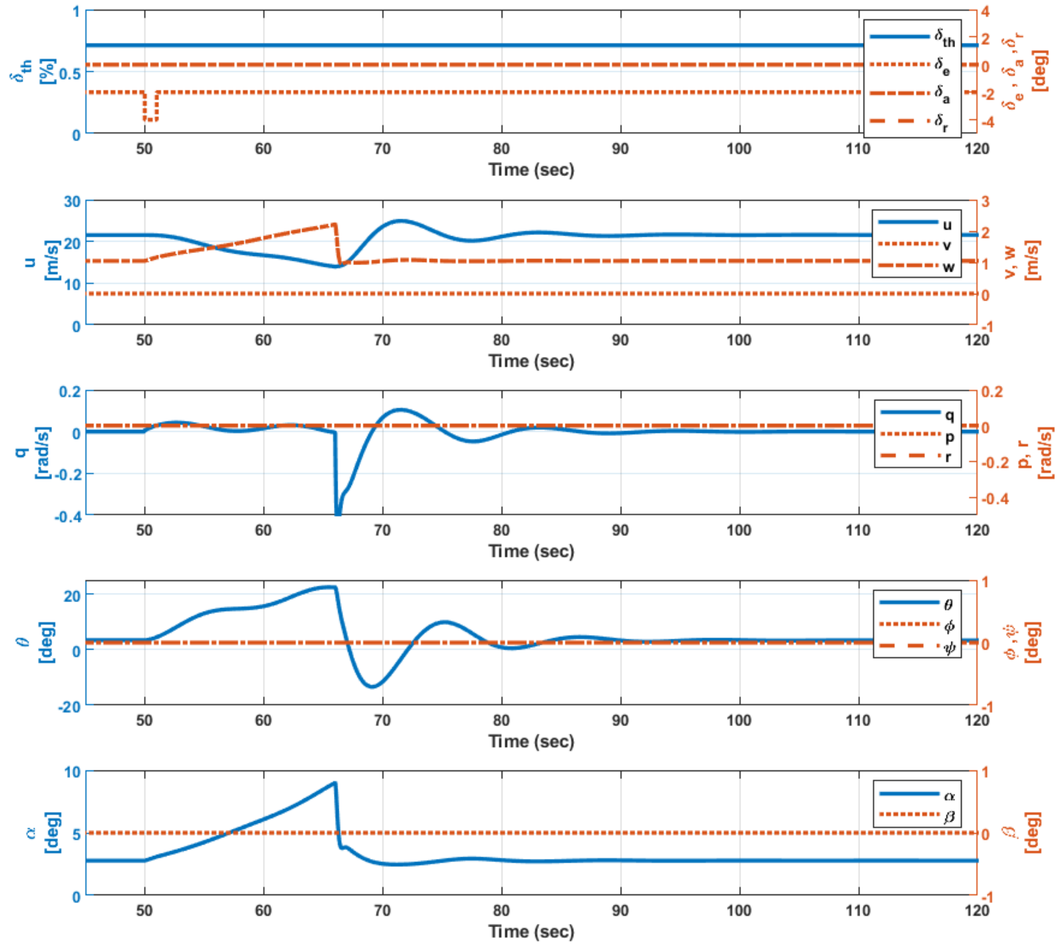
This paper present a procedure for building a nonlinear 6 DoF flight simulation model for a tilt-rotor UAV in horizontal flight. A CAD software and experimental method were used to obtain the moments of inertia of the case-study UAV. The propeller characteristics were obtained from the available published data. An empirical method (USAF Digital Datcom) was used to obtain aerodynamic coefficients and derivatives. Then, MATLAB/Simulink was used to integrate all the sub-model together. A graphical trim diagram was developed and the trim data were implemented in the developed model. Diverse typical longitudinal maneuvers were excited to verify the developed model. The results showed that the model appears to be coherent and predicts the behavior of the tilt-rotor UAV in forward flight. Future work will conclude comparing the simulation results with the analytical solution, then validation of the developed model through flight testing.



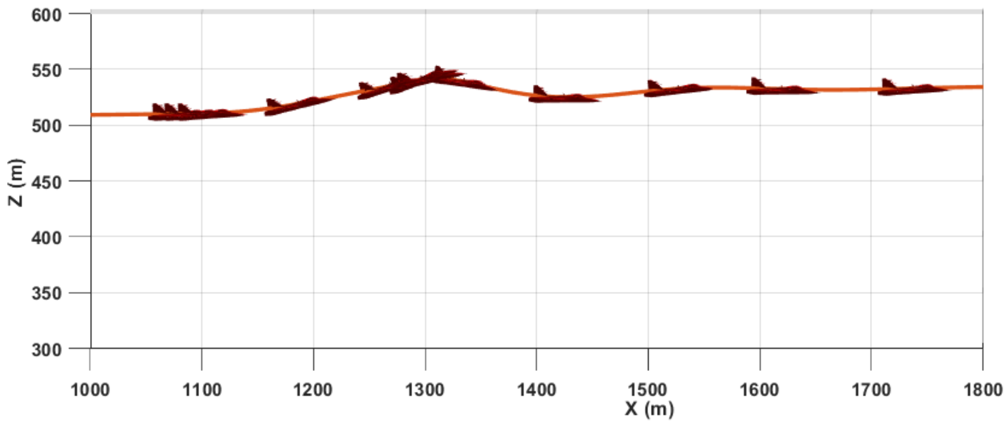


(b) 2D trajectory

Figure 11. Inputs and Outputs of the case-study simulation model at trim.

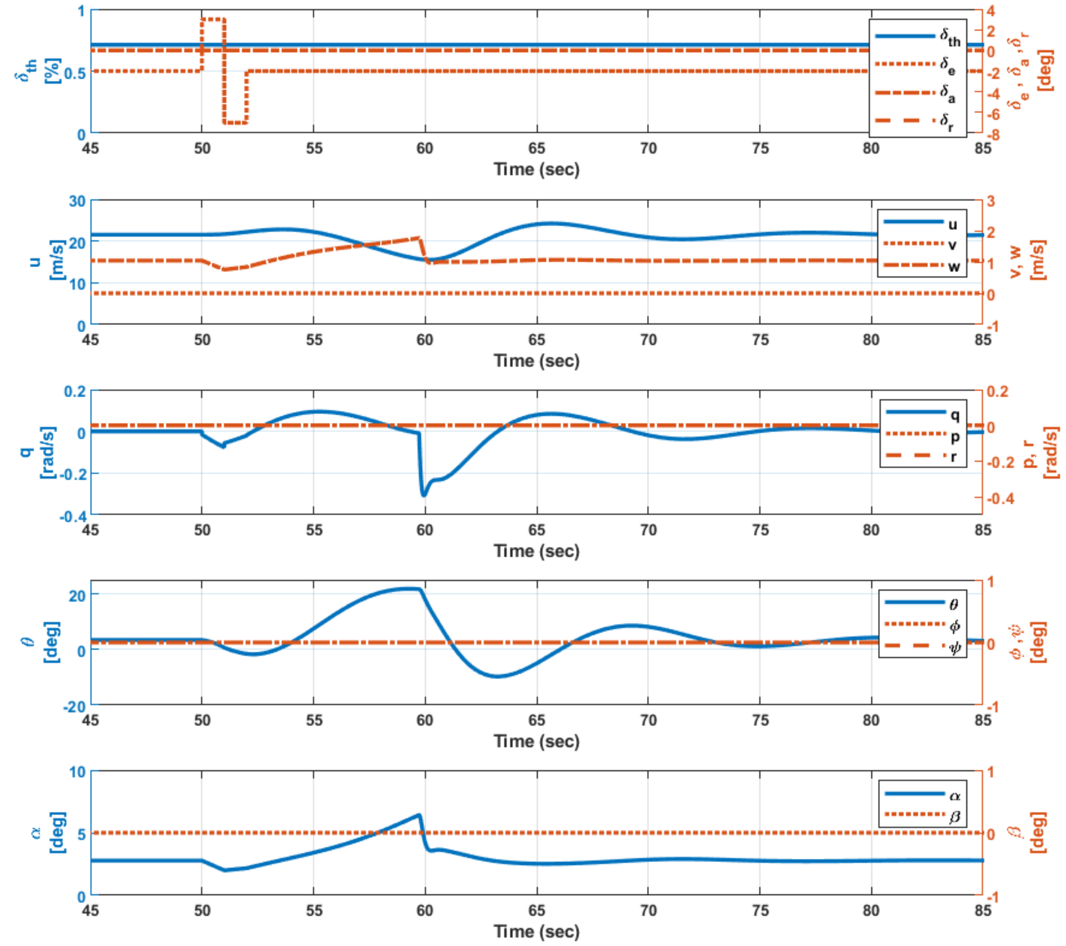


(a) Time-series for inputs and outputs stats

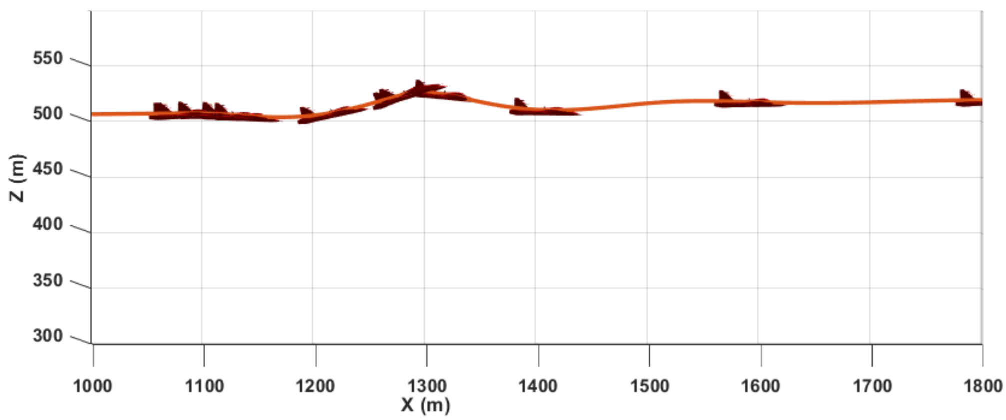


(b) 2-D trajectory

Figure 12. Case-study simulation response to pulse elevator input

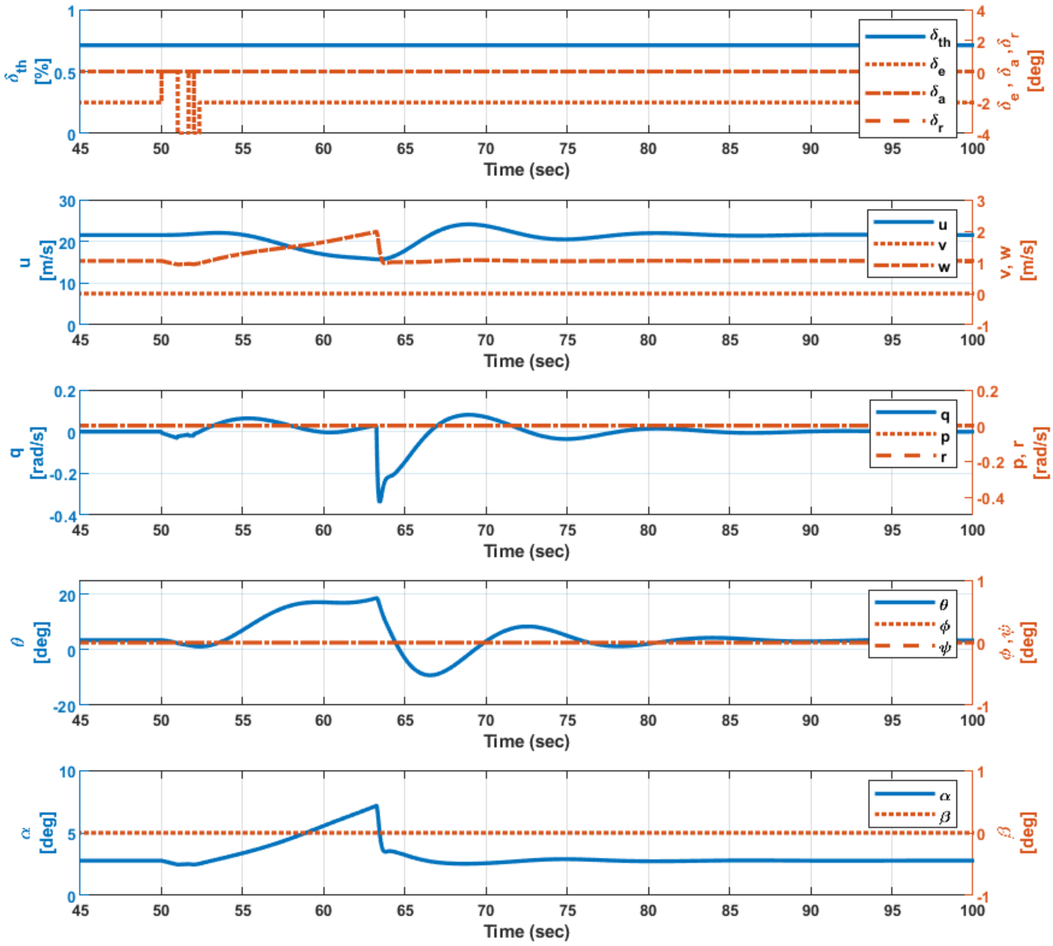


(a) Time-series for inputs and outputs stats

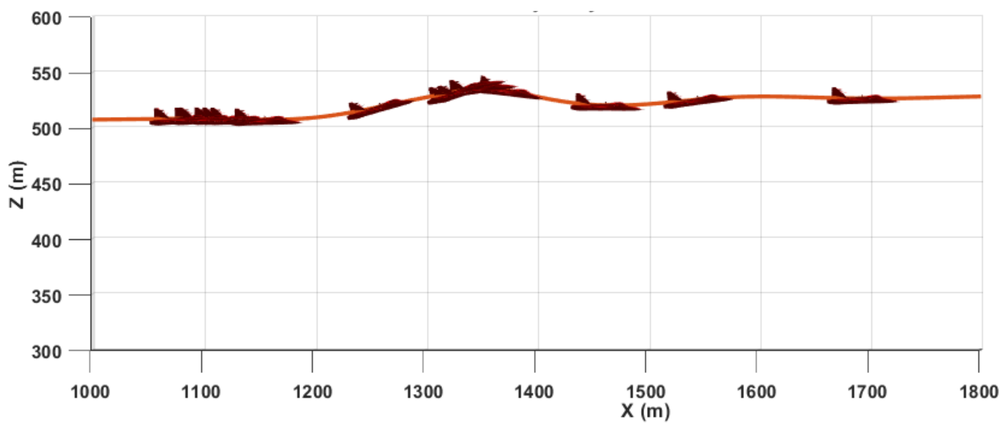


(b) 2-D trajectory

Figure 13. Case-study simulation response to doublet elevator input.



(a) Time-series for inputs and outputs stats



(b) 2-D trajectory

Figure 14. Case study simulation response to 3-2-1-1 elevator input.

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