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Conceptual design of eVTOL A Nonlinear Dynamic Model of an eVTOL on Simulink-MATLAB

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Abstract

eVTOL (electric vertical take-off and landing) for urban mobility is currently evolving and many concepts of configurations with which vertical take-off and landing could be made possible are discussed like a multi-copter, lift and cruise, and tilt-wing. All these concepts have different behavior from the flight dynamics perspective. The one which is predominantly discussed here is the proposed model Cityhawk by Urban Aeronautics with a ducted fan vane control system. Urban Aeronautics has very high levels of aerospace experience on its team (including experts from Boeing and military development) and has completed flights of Cormorant drones which prove the concept for the passenger CityHawk. This project aims to conceptually design and building a nonlinear 6 DOF dynamic model of an eVTOL with a proposed configuration on a MATLAB Simulink.

Keywords: eVTOL, Urban Air Mobility, Simulink, MATLAB, Urban Aeronautics.

INTRODUCTION

Urban air mobility with eVTOL is currently the most prominent field which is being researched around the globe. Certainly, the idea of availing this kind of technology for Air taxing in midair is going to facilitate our lifestyle but we still have a long way to go and there are many factors which are needed to be taken into consideration. An enormous amount of research has been done on this particular topic but since our main focus was to develop a conceptual model based on first principles and assess the final model from an aerodynamics and flight dynamics perspective, it was mandatory to get through with the previous concepts of VTOLs that is why we decided to study the Wheel of misfortune prepared by Mike Hirschberg. Various other types of VTOL aircraft came up where the hovering vehicle's weight is taken directly by rotors or propellers, with the axis of rotation perpendicular to the ground. One of the popular vehicles of this type is the conventional helicopter with a large rotor mounted above the vehicle fuselage [1–4].

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In terms of stability and control, the VTOLs are usually more stimulating than fixed-wing aircraft. The real struggle rises from the fact that contradictory to fixed-wing aircraft which accelerate on the ground until enough airspeed is attained on their flight surfaces, VTOL vehicles hover with sometimes zero forward airspeeds. For these vehicles, the control depends on employing the rotors or propellers themselves, or the flow of air that they produce to generate the control forces and moments and forces around the center of gravity (CG) of the vehicles. The usually used method is to mechanically change, by sending commands from the pilot the pitch of the rotating rotor blades both collectively and cyclically, and to improve the major thrust in addition to moments and/or inclination of the rotor's thrust line that the propeller or rotor applies on the vehicle. The drawback of using collective controls, and especially cyclic controls, lies in their added complexity, weight, and cost. Therefore, a simple thrust unit that is also able to generate moments and side forces, while still holding on to a simple rotor not requiring the cyclic blade pitch angle changes, has superiority over the more complex solution [5, 6].

SIMPLIFIED ARRANGEMENT FOR SIDE FORCES AND ROTATIONAL MOMENT

As illustrated in the Figure 1 (a) to provide directional control the duct 10 is provided with multiple parallel vanes 15 pivotally mounted across the inlet end 13 of the duct. Vanes are supported by suitable arrangement and are parallel to the longitudinal axis of the vehicle frame to produce desired horizontal control force in addition to the lift force applied to the vehicle by the movement of air produced by propeller 11.

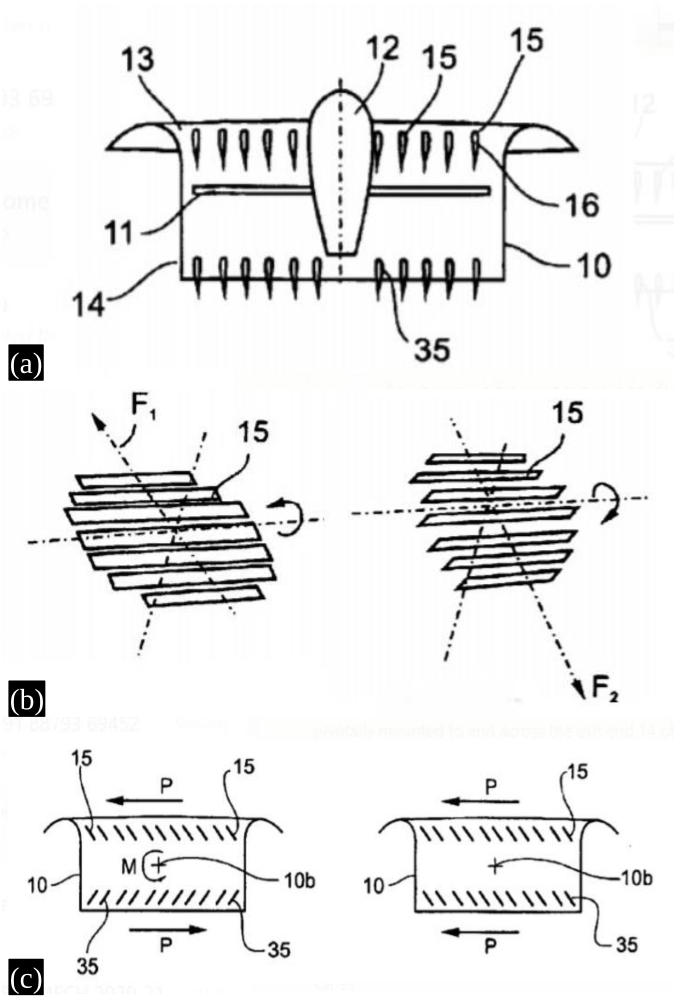

Figure 1. (a) to (c) Ducted Fan.

As illustrated in the Figure 1 (b) as soon as vanes 15 get pivoted about their axes, they produce the desired control force in the direction of the arrow F1 and if they are pivoted in the opposite direction, they produce the desired control force in the direction of the arrow F2. As shown in the vanes, 15 shape of the airfoil is symmetric and are spaced from each other at distance equivalent to its chord length [7].

Figure 1 (c) illustrates a further embodiment that may be included wherein duct 10 also has a second plurality or cascade of parallel, spaced Vanes, but in this case, the second plurality is pivotally mounted to and across the exit end 14 of duct 10. Duct 10 includes the first plurality or cascade of blades 15 mounted to and across the inlet end 13 of the duct, and a second plurality or cascade of blades 35 mounted to and across the exit end 14 of the duct 10, also perpendicular to the longitudinal axis of the duct and Substantially parallel to the longitudinal axis of the vehicle frame. Each assembly or cascade 15, 35 of the vanes may be pivoted independently of the other to produce selected Side forces or rotary moments about the duct transverse axis 10b for pitch or roll control of the vehicle [8].

DESIGN FROM FIRST PRINCIPLES

A. Momentum Theory

Momentum theory is used in the case of Helicopters (as they are VTOLs configuration aircraft) to find the induced power for Hovering and cruising, Induced power for the eVTOL model is calculated using momentum theory and all other important calculations are discussed in Figure 2:

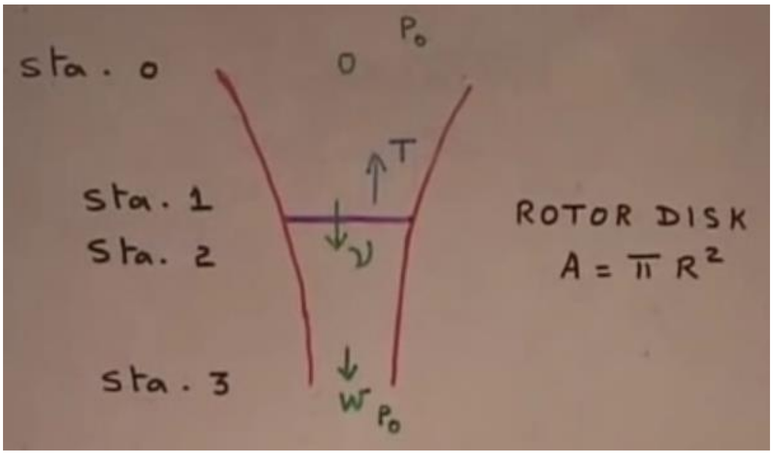

Figure 2. An actuator disk accelerating a fluid flow from top to bottom.

Using Momentum theory,

1) Mass flow rate,

$$\dot{m} = \rho \cdot A \cdot v \quad (1)$$

2) Momentum Conservation,

$$T = \dot{m} \cdot \omega \quad (2)$$

3) Energy Conservation,

$$T \cdot \gamma = \frac{1}{2} \rho \cdot A \cdot v \cdot \omega^2 \quad (3)$$

4) Induced Power,

$$P = T \sqrt{\frac{T}{2 \cdot \rho \cdot A}} \quad (4)$$

B. Weight Estimation

Weight estimation (shown in Table 1) for the eVTOL model is explained below:

Table 1. Weight Estimation of eVTOL.

S.N.	Group	Weight (in kg)
1	Payload Capacity (Passengers & Baggages)	500
2	Battery Weight	500
3	Operating Empty Weight	1450
4	Maximum Take-Off Weight	2500

1) *Thrust:* According to newton's law thrust required for eVTOL would be nothing but the weight of the eVTOL itself.

Thrust (T) = (MTOW) * 9.81
= 2500 * 9.81
= 24525 N

2) *Rotor diameter and Area of Rotor:* Maximum width of the vehicle as recommended by IRC is 2.44m thus to design it from an urban mobility point we have considered the rotor diameter for VTOL should be 2.3m

$A = 2 \text{ x } \frac{\pi}{4} \text{ x } D^2$

$A = 2 \text{ x } \frac{\pi}{4} \text{ x } 2.3^2$

$A = 8.309 m^2$

3) *Induced Inflow Velocity:*

$V=\sqrt{\frac{T}{2 \cdot \rho \cdot A}}$

$V = \sqrt{\frac{24525}{2x1.225x8.309}}$

V = 34.709 m/s

4) *Mass flow rate*:

$\dot{m} = \rho \cdot A \cdot v$

$\dot{m}$ = 1.225 x 8.309 x 34.709

$\dot{m}$ =353.286 kg/s

5) *Tip speed and Angular Velocity:*

- As the rotor radius increases, the power required decreases.
- As the angular velocity increases, the tip speed increases which in turn increases the drag force. And thus the power required increases [9].

Therefore, it is not possible to achieve tip speed higher than 200m/s.
Tip speed = 200m/s
Also,
Tip speed = R x Ω
where,
R = radius of rotor
Ω = angular velocity

$200 = \frac{2.3}{2}\ x\ \Omega$
Ω = 173.913 rad/sec
Also,
$\Omega = \frac{2\pi N}{60} = 173.913$
$\therefore$ N = 1660.746 rpm
For safety,
Power factor =1.5

N = 1660.746 x 1.5
N = 2491.119 rpm

Thus, maximum rpm allowed for the rotor would be N=2500 rpm.

6) *Power required to produce thrust:* To evaluate the power required to produce the required thrust, we will use, the standard Disk actuator theory or Momentum Theory:

$$P = T\sqrt{\frac{T}{2 \cdot \rho \cdot A}}$$

where,
T = Thrust (in N)
ρ = density of air (1.225 kg/m^3)
A = area of rotor disc (in m^2)

$$P = 24525\sqrt{\frac{24525}{2x1.225x8.309}}$$

P = 851.248 x 10^3 W

Induced power for eVTOL for Hovering comes out to be 852 kW

7) *Selection of Motor:*
As per the values obtained above, the Siemens P260D motor fulfills our requirement. Thus selecting, SIEMENS P260D motor [10].

A NON-LINEAR DYNAMIC MODEL OF EVTOL

This eVTOL Figure 3 (a-b). has two rotor systems installed longitudinally at either end of the fuselage. Due to two rotors, it resembles the tandem rotor helicopters. The only difference between tandem rotor helicopters and single main rotor helicopters is that there is no net yaw moment on the helicopter because the torque of the rotors is equal and opposing. The tandem helicopter behaves as if it had a single main rotor with truly decoupled longitudinal and lateral dynamics. Similarly in the case of eVTOL due to the tandem position of rotors, no net yaw moment on aircraft is present. The rotors are incorporated in ducts in which vanes are mounted to and across both inlet and outlet ends of ducts. Vanes are supported in such a way that can be pivoted about the longitudinal axis of the vehicle frame. As vanes are pivoted to an angle with the longitudinal axis of the vehicle frame side force is produced with a combination of the rotational moment which is favorable for normal control.

Directional control of eVTOL can be achieved as tabulated in Table 2.

Table 2. Directional control of eVTOL.

Hover & Low-Speed Manoeuvre (LSM)	Forward cruise flight
Produces sideward motion by deflecting all vanes in direction desired movement	Produces rolling motion by deflecting all lower rows of vanes in the direction opposite to upper rows of vanes
Produces Forward-Aft translation motion movement motion by varying pitch angle of blades on both rears mounted pusher propellers	Produces angular pitching motion by varying differentially pitch angle of blades on fore V.S. aft main lift rotors
Produces vehicle altitude change by varying collectively pitch angle of blades on fore and, aft main lift rotors	Produces vehicle altitude change by varying collectively pitch angle of blades on fore and, aft main lift rotors
Establishes trimmed Forward. Aft Fore-Aft speed by setting pitch angle of blades on both aft-mounted pusher propellers	Establishes trimmed Forward.-Aft speed by setting pitch angle of blades on both aft pusher propellers
Produces angular yawing motion by deflecting differentially forward V.S. aft Control vanes, as well as pitch on blades of right V.S. left pusher propellers	Produces angular yawing by deflecting differentially forward V.S. aft Control vanes, as well as pitch on blades of right V.S. left pusher propellers

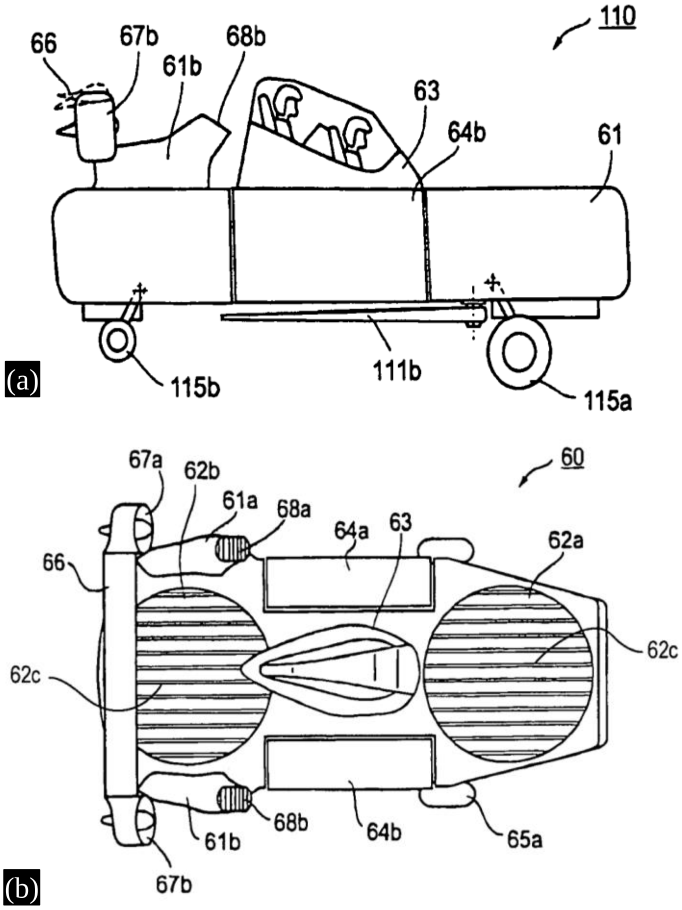

Figure 3. (a-b) eVTOL – CityHawk proposed model.

The model is proposed using the Newton-Euler method with the following assumptions.:

- The front rotor blades are assumed to rotate in an anti-clockwise direction when viewed from above and the rear rotor blades rotate in a clockwise direction.
- The collective pitches of the front rotor and rear rotor are equal and the rotation velocity of the rotors holds the same. So the thrusts of the two rotors are identical.
- The aerodynamic interference created by the operation of the rear rotor in the wake of the the front is ignored.

A. Pilot control limit saturation:

$$\bar{u} = \begin{bmatrix} u1 \\ u2 \\ u3 \\ u4 \\ u5 \end{bmatrix}$$

B. State Variables:

$$\bar{x} = \begin{bmatrix} u \\ v \\ w \\ p \\ q \\ r \\ \phi \\ \theta \\ \psi \end{bmatrix} = \begin{bmatrix} x1 \\ x2 \\ x3 \\ x4 \\ x5 \\ x6 \\ x7 \\ x8 \\ x9 \end{bmatrix} = \begin{bmatrix} \text{velocity in body x} - \text{axis} \\ \text{velocity in body y} - \text{axis} \\ \text{velocity in body z} - \text{axis} \\ \text{angular rate about body x} - \text{axis} \\ \text{angular rate about body y} - \text{axis} \\ \text{angular rate about body z} - \text{axis} \\ \text{bank Euler angle} \\ \text{pitch Euler angle} \\ \text{yaw Eulerangle} \end{bmatrix}$$

C. Non-dimensional aerodynamic coefficients in Fs:
Using Prandtl's theory and Kutta-Joukowski;

1) Total Coefficient of Lift,
$$C_L(\theta) = \frac{|aF(\theta)|}{V2\ (\rho V^2 \infty(\theta)|dl|)} = \frac{2Vx(\theta)\Gamma(\theta)}{V^2 \infty c(\theta)}$$

2) Induced angle of attack by its self-downwash affect:
$$\xi\ (\theta) = V \arctan\left(\frac{Viz(\theta)}{V\infty}\right) \cong \frac{Viz(\theta)}{V\infty}$$
(Since, from Biot Savort law $Viz(\theta) = V\infty \sum_{n=1}^{\infty} \frac{nAn \sin (n\theta1)}{\sin(\theta)}$)

3) Total coefficient of Drag:
$$C_D = \frac{2}{V^2 \infty\ (\theta)} \int_0^a r1\ (\theta)\alpha i(\theta)\ Vx(\theta)[\frac{b}{2} \sin(\theta)\ d\theta$$

4) Total side force coefficient:
$$C_y = -1.6\ \beta + 2.4\ u3$$

D) Explicit First Order form
$$\begin{bmatrix} \dot{x}1 \\ \dot{x}2 \\ \dot{x}3 \end{bmatrix} = \begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{w} \end{bmatrix} = \frac{1}{m} F^b - \omega_{\underline{b}\,e}{}^b \times V^b$$

Where, $F^b = F_g{}^b + F_e{}^b + F_a{}^b$

$$\begin{bmatrix} \dot{x}4 \\ \dot{x}5 \\ \dot{x}6 \end{bmatrix} = \begin{bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} = I_b{}^{-1}(M_{cg}{}^b - \omega_{\underline{b}\,e}{}^b \times I_b \times \omega_{\underline{b}\,e}{}^b)$$

Where, $M_{cg}{}^b = M_{Ecg}{}^b + M_{Acg}{}^b$

$$\begin{bmatrix} \dot{x}7 \\ \dot{x}8 \\ \dot{x}9 \end{bmatrix} = \begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} 1 & \sin\emptyset\tan\theta & \cos\emptyset\tan\theta \\ 0 & \cos\emptyset & -\sin\emptyset \\ 0 & \sin\emptyset/\cos\theta & \cos\emptyset/\cos\theta \end{bmatrix} x \begin{bmatrix} p \\ q \\ r \end{bmatrix}^b$$

After applying the above mathematical to eVTOL using Matlab Simulink:-

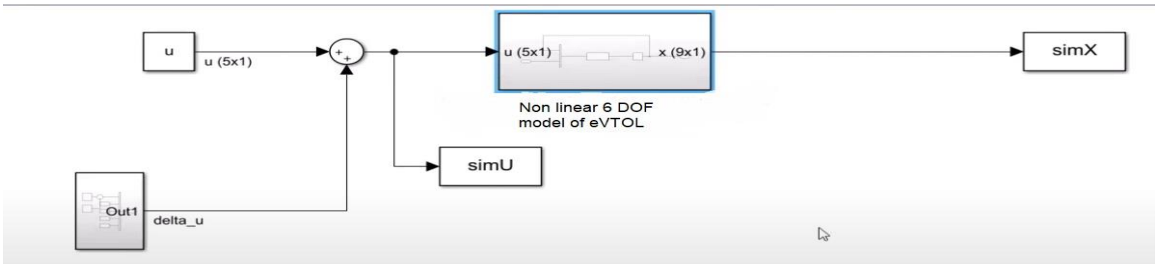

Figure 4. Nonlinear 6 DOF Simulink model.

SIMULATION RESULTS

In this section, we present the behavior of eVTOL using a Non-linear 6 DOF dynamic model on MATLAB Simulink shown in Figure 4. The experiment does not consider the case of stabilization of eVTOL dynamics.

Initialize constants for the eVTOL simulation:

$$x0=\begin{bmatrix}85\\0\\0\\0\\0\\0\\0\\0.1\\0\end{bmatrix} \text{ and } u0=\begin{bmatrix}0\\-0.1\\0\\0.08\\0.08\end{bmatrix}$$

*m=2500 kg TF=60 (*Final simulation time)

Figure 5 shows the initialized pilot inputs & Figure 6 shows the behavior of the eVTOL after initialized pilot inputs.

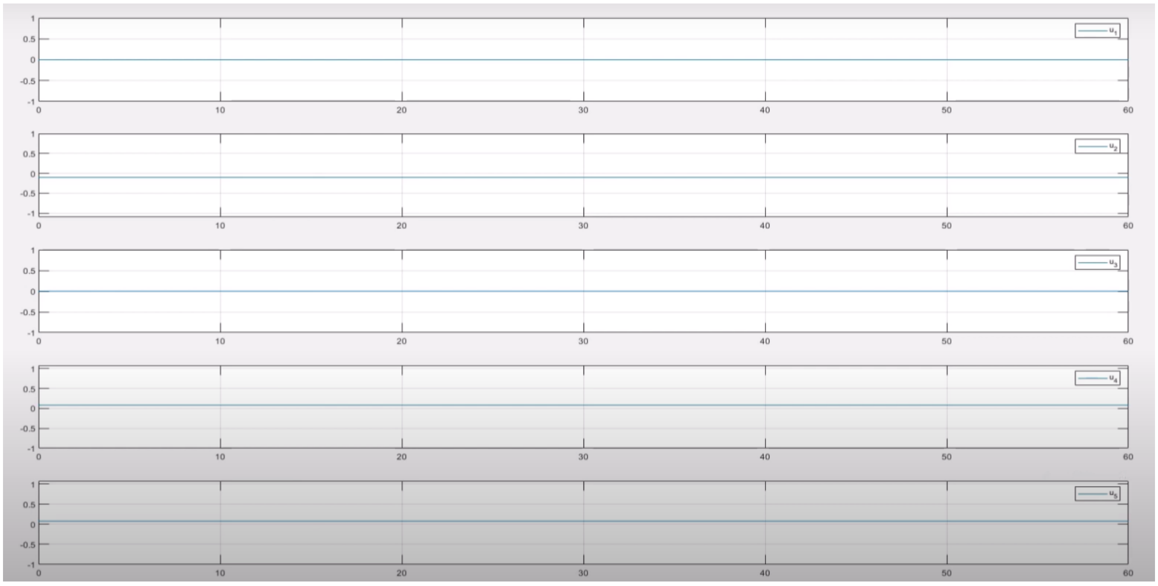

Figure 5. Initialized pilot inputs.

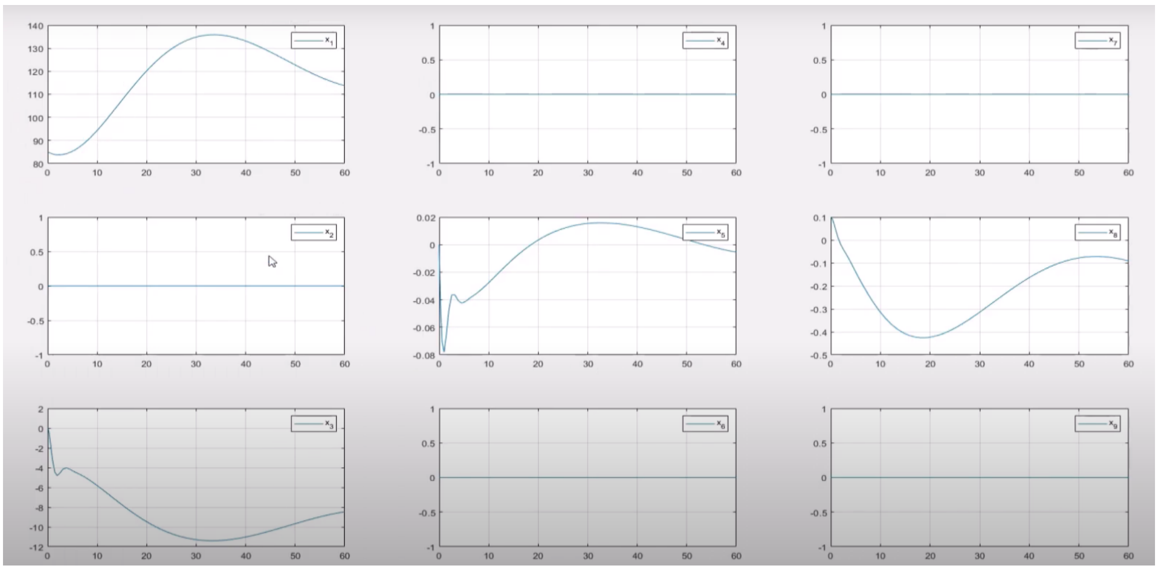

Figure 6. Behavior of the eVTOL after initialized pilot inputs.

CONCLUSIONS

In this paper using simple flight dynamics principles, we have derived a mathematical model which can be applied to anticipate the behavior of eVTOL with initialized pilot inputs. This article outlined a design process for the conceptual design of a "air taxi," which is defined as an electric VTOL (Vertical Take-Off and Landing) aircraft designed for Urban Air Mobility.

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