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Aerodynamic Design and Analysis of Autonomous Medical Drone to Carry 5 KG Payload

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Abstract: *This paper presents the design, analysis and simulation of fixed-wing vertical take-off landing (VTOL) medical drone to carry the supply of 5 kg payload. For the easy manufacturing, symmetric airfoil NACA 0012 is selected and analyzed in Xflr5 where the coefficient of lift is 1.1 and the coefficient of drag is 0.065 at low Reynolds number. To uplift the maximum take-off weight (MTOW) of 18 kg considering airframe weight as variable weight, the thrust-to-weight ratio is taken as 1.2 from where the thrust required for each motor is 5.4 kg. The flow analysis of wings and V-tail in Xflr5 has showed coefficient if lift/coefficient of drag as 21.905 at a 5.5 angle of attack (AOA). The range and endurance depend upon battery capacity of 22000 mAh is obtained as 64.5 km for 78.8 minutes. The conceptual design is done in OpenVSP with the area criteria the parasite drag coefficient shows wing contribution is 19% higher than the fuselage section of unmanned aerial vehicle (UAV). The control system is used to control the drone autonomously from the ground station by mapping its waypoints in the mission planner. For the control system, the trial-and -error method is chosen as a conventional method to determine the tuning value of proportional-integral-derivative (PID) using the transfer function of the motor, the rising time is decreased to less than 0.0002 seconds compared to the initial value.*

Keywords: *UAV, fixed-wing VTOL, Xflr5, Thrust, PID, AOA, OpenVSP, Power.*

1. INTRODUCTION:

In recent years, the development of unmanned aerial vehicle (UAV) has seen remarkable advancements, particularly in field of medical applications. Among these UAVs, fixed-wing vertical take-off landing (VTOL) drone have garnered significant attention. In a geographical challenge area like Nepal where VTOL drones supplying medical supply is the effective way of safe transportation. This drone combines the efficiency and endurance of fixed-wing aircraft with flexibility and precision of vertical take-off and landing, making them ideal for delivering medical supplies, conducting aerial surveys for medical purposes, and supporting emergency medical services. This introduction sets the stage for exploring the design, and flow analyses with functionality of medical fixed-wings VTOL drones, highlighting their potential performance calculation.

2. MISSION REQUIREMENTS AND PARAMETER ESTIMATION:

For VTOL FW drones the control system goes to five phases for a complete mission. The first one is vertical take-off where it uses motor to create the required thrust. Second one is transition to forward flight helped by push-back propeller for this drone. Third one is loitered to the fixed point. Once flight mission concludes, it transitions to vertical landing using multi-rotor.

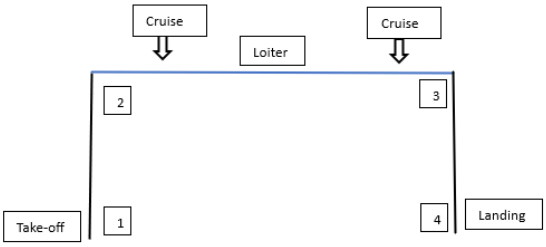


Fig. 1. Mission profile of fixed-wing VTOL drone

Mission requirement is drone should be fixed-wing of wing span of 1.6 m, it should carry payload of 5 kg and long rang vehicle and high endurance.

2.1 Weight estimation:

Initial weight estimation and weight build-up is given below: [3]

$$W_0 = W_{struct} + W_{avi} + W_{prop} + W_{fuel} + W_{misc} + W_{pl} \quad (1)$$

W_{struct} = Airframe Structures

W_{avi} = ESCs + Servos + Sensors

W_{prop} = DC Motors

W_{fuel} = Fuel Cells and/or Batteries

W_{misc} = Miscellaneous Weights (as in connecting wires, fasteners)

W_{pl} = Payload

From the above equation 1 the initial weight is calculated 12 kg without the payload. Airframe structure weight is variable weight as it depends upon the density of the chosen material. The motor, battery and other miscellaneous weight are taken from the online product source.

The maximum take-off weight (MTOW) is 18 kg. The thrust-to-weight ratio should be more than 1 for vertical lift of the drone so, it is considered to be 1.2. The thrust required for each motor for vertical lift of the drone is obtain as,

Thrust = (18*1.2) /4

Here the 18 is MTOW and 4 is the quadcopter motor. So, the required thrust will be 5.4 kg for each motor.

2.2 Performance calculation:

The performance calculation consists of power required, range, endurance, rate of climb (ROC), and battery efficiency.

2.2.1 Power required

It's important to calculate the power consumption to determine the total power required for the whole system (take-off, cruise, climb and landing). [2]

$$P_{take-off} = \frac{T_{to}V_{to}}{2}[1 + \frac{2T_{to}}{\rho_\infty V_{to}{}^2 A_{prop}}]$$

$$P_{climb} = [W \sin\theta + C_d q_\infty S_w]\ 1.2\sqrt{(\frac{2W}{S_w \rho_{sl} C_{l,max}})}$$

$$P_{cruise} = VT_{cruise}$$

$$P_{landing} = 1.2W_{to}(V_i - V_d)$$

The total power is: P_{total} = 373.66 + 62.11 + 100 + 163.4 = 372 W

2.2.2 Battery Efficiency:

This parameter refers to how efficiently a battery can convert a stored energy into usable energy. It can be calculated as:

Battery efficiency $= \frac{\text{Usefull energy output}}{\text{Total energy input}} \times 100$

The efficiency of battery taken average as 0.8.

2.2.3 Endurance:

It can be calculated as:

Endurance = (battery capacity) / (power consummation)

The endurance is 78.8 minutes.

2.2.4 Range:

The range is calculated as;

Range = Endurance * ground speed

The range is 94.5 km.

2.2.5 Rate of climb (ROC)

The rate of climb is calculated as;

$$\text{ROC} = \frac{\text{power required} - \text{power available}}{\text{weight}}$$

Power available from a battery is multiplication of battery efficiency, voltage and Amp hour. It is estimated as 390.72 W. Therefore, ROC of the drone will be 1.04 m/s.

From the ecalc, easy-propeller-calculator the selected material (motor, propeller, and battery cell) is given to the system. The output shows the thrust produced by the propeller. The input is given as lithium polymer battery of 22000 mAh -30/45C with six cells and maximum discharge as 85%, controller type as X-110-opto-Pro, motor as ROXXY C63-62-08 (320) and two blade propellers as APC electric E with diameter 22 inch and pitch of 10. The result shows that static thrust by single motor is 7222 g which is sufficient than the required of 5.4 kg.

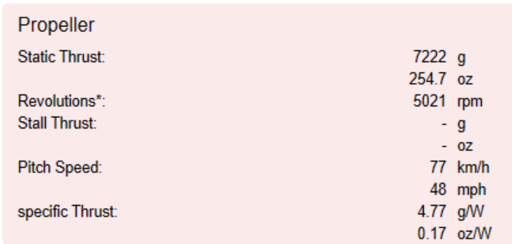


Fig. 2. Propeller static thrust by ecalc [9]

3. DESIGN AND ANALYSIS:

The mythology is selection of airfoil followed by wing design and tail configuration with payload and battery carrying fuselage and their analysis.

3.1 Airfoil selection:

The mission requirement is symmetric airfoil so, the few symmetric airfoil is selected based on their camber.

Table 1. Airfoil data from airfoil tools [10]

Airfoil	Cl/Cd_{max}	$a_{max(°)}$
FX76120	67.9	6.25
NACA 0012	61.7	6.5

NACA 0015	66.4	7.5
NACA 0018	65.8	9.25
NACA0021	60.6	10.25

Above table compare the maximum Cl/Cd at angle of attack. It shows airfoil has high lift coefficient and lower drag. At lower angle of attack NACA 0012 has maximum Cl/Cd.

In the Xflr5 [13] with the low Reynolds number of 300,000 and cruse speed of 22 m/s, the airfoil in table 1 are analyzed.

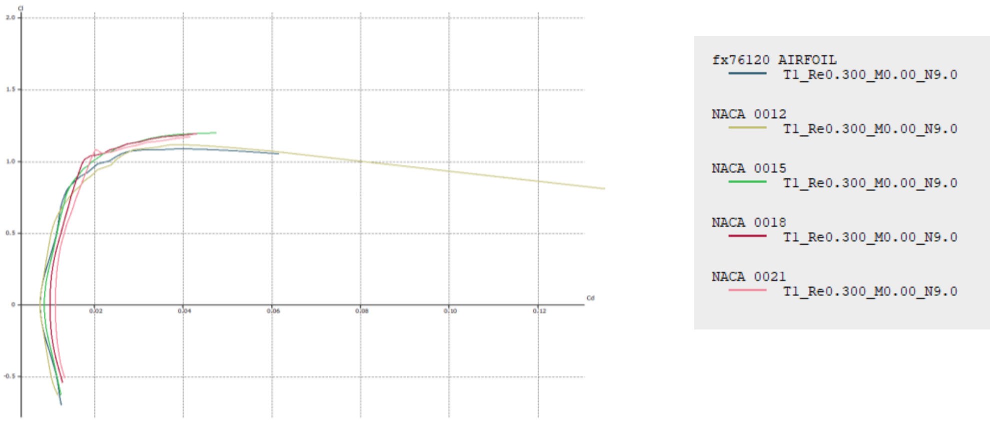


Fig.3. Airfoil analysis in the Xflr5 with Cl vs Cd [13]

From the figure 3, NACA 0012 profile obtain higher coefficient of lift at low drag coefficient and it decreases too. For UAVs airfoil has high range Cl/Cd, easy take-off (Clmax), and high stall characteristic. With the coefficient of lift as 1.1 and area of wing is 0.34 m^2 the stall speed is calculated as 8.86 m/s. The selected airfoil is NACA 0012 which is shown in the figure 4.

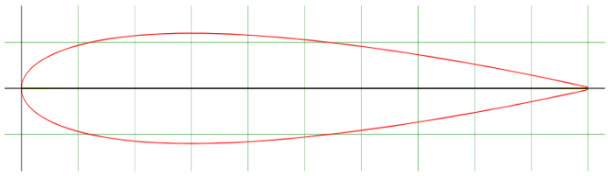
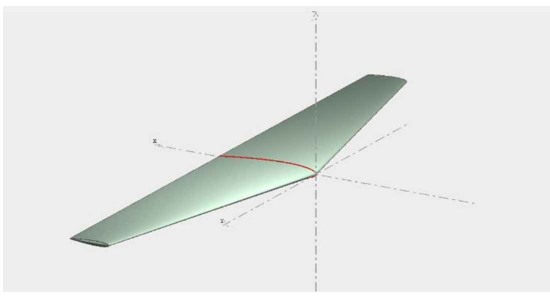


Fig.4. Selected airfoil NACA 0012 in Xflr5

3.2 Wing design:

The design requirement is wing span of 1.6 m. Using Xflr5 the wing of root chord 0.3m and tip chord of 0.12m where mean aerodynamic chord is 0.22m. The tapper ratio is 0.40 and root chord 0.3m and tip chord of 0.12m where mean aerodynamic chord is 0.22m. The tapper ratio is 0.40 and root to tip sweep is 9.58 degree. The area of wing is 0.3m^2.



The design is drawn in the figure 5 by the help of Xflr5 open-source software.

Fig. 5. Wing design in Xflr5

3.3 Wing analysis:

The wing is analyzed in Xflr5 with the inlet velocity of 20 m/s.

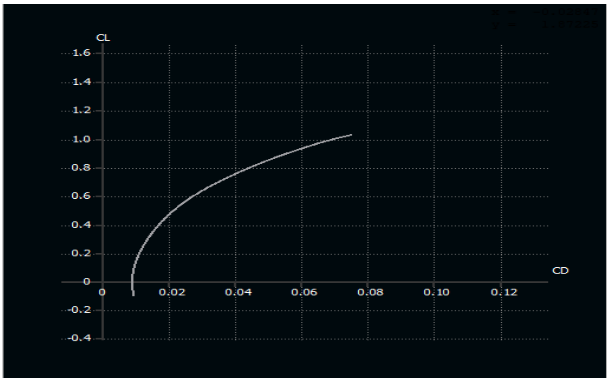


Fig. 6. Cl vs Cd graph

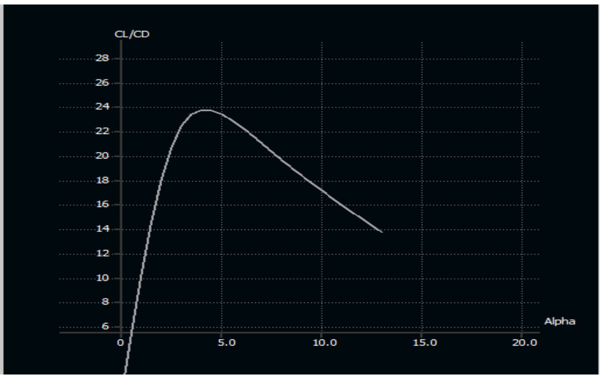


Fig. 7. Cl/ Cd Vs angle of attack.

The coefficient of lift maximum seen is 1.1 whereas the coefficient of drag is 0.065. The wing is lift generating wing at lower angle of attack as Cl/Cd is maximum at 4.5 degree.

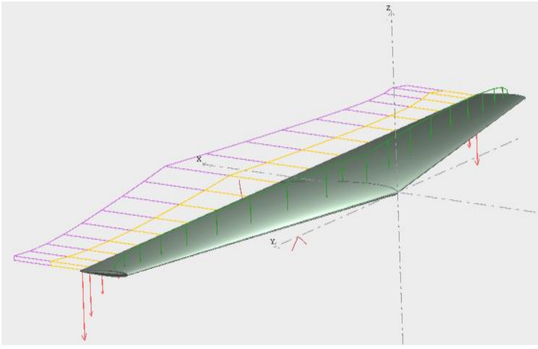


Fig. 8. Flow analysis of wing in Xflr5

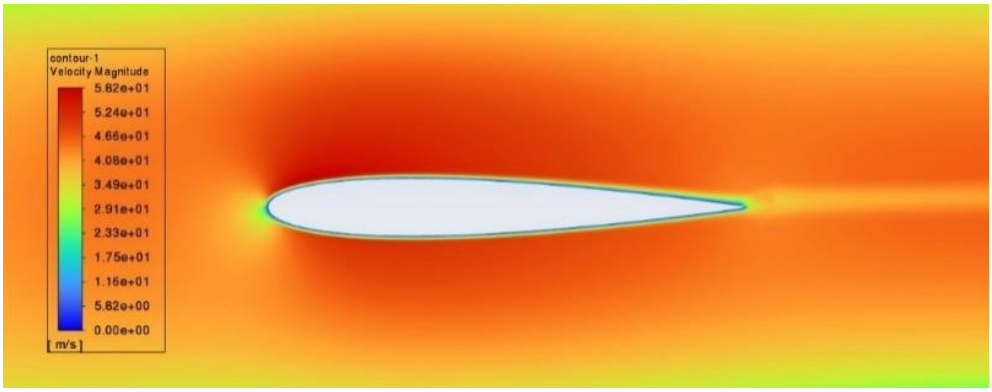


Fig. 9. Velocity contour of 2D NACA 0012 airfoil

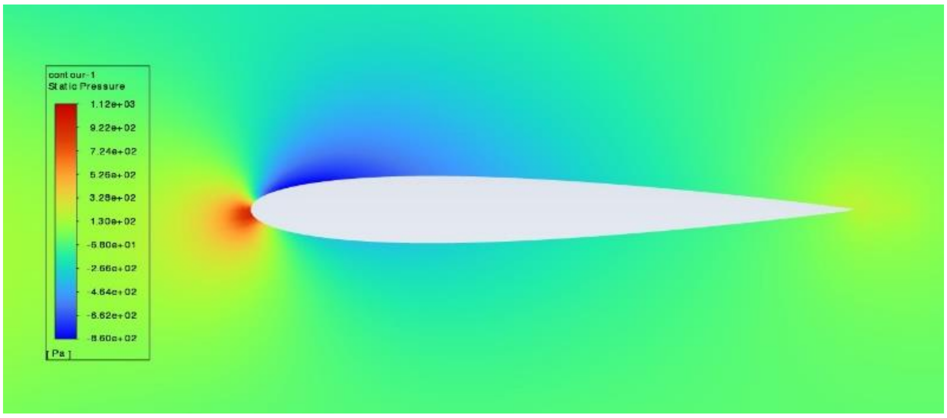


Fig. 10. Pressure contour of 2D NACA 0012 airfoil

The pressure contour shows the pressure difference on the upper surface and lower surface. The upper surface has lower pressure and lower surface has higher pressure by which the airfoil can produce the minimum lift at zero angle of attack. From the velocity contour the inlet velocity was 18 m/s and output velocity are achieved as 58 m/s.

3.4 Wing with V-tail:

The wing of design in figure 5 further V-tail section is added in the wing and following aerodynamic characteristic result is obtained.

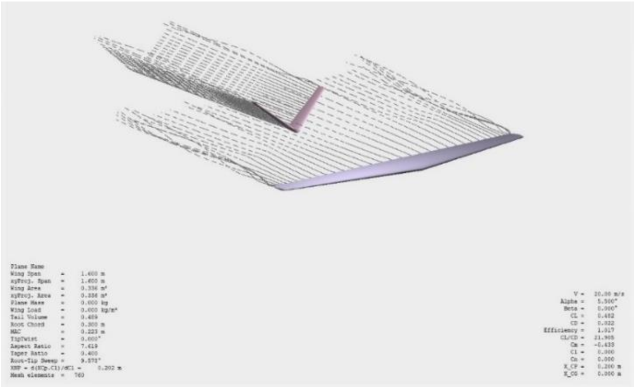


Fig. 11. Wing with V-tail flow analysis at 5.5 AOA using Xflr5

At 5.5 angle of attack the wing and tail section generate maximum Cl/Cd as 21.905. The Cl is 0.482 and Cd is 0.022. the flow was given as 20 m/s.

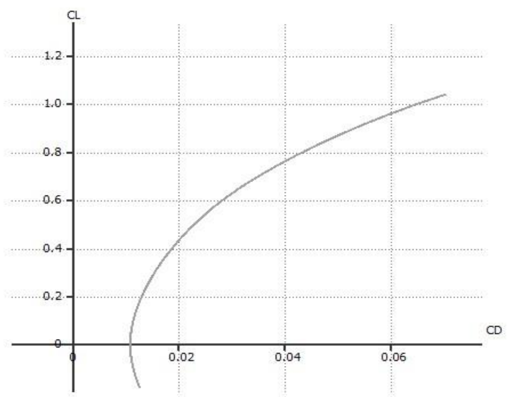


Fig. 12. Drag polar graph in Xflr5

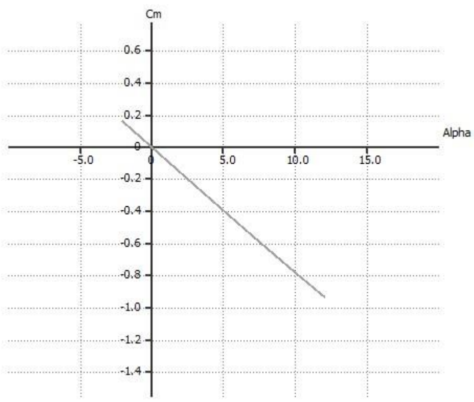


Fig. 13. Pitching moment Vs alpha graph in Xflr5

The drag polar shows the induced drag and zero lift drag. Where the zero-lift drag is 0.01 and induced drag is 0.05. The line passes through the origin which indicates the aircraft is stable. Pitching moment (Cm) = 0 = balance = plane operating point.

3.5 Conceptual design analysis:

The conceptual design is drawn in the OpenVSP open-source software [11] with the four motors as VTOL and one push-back propeller for forward flight. A high fixed-wing is attached to the fuselage section.

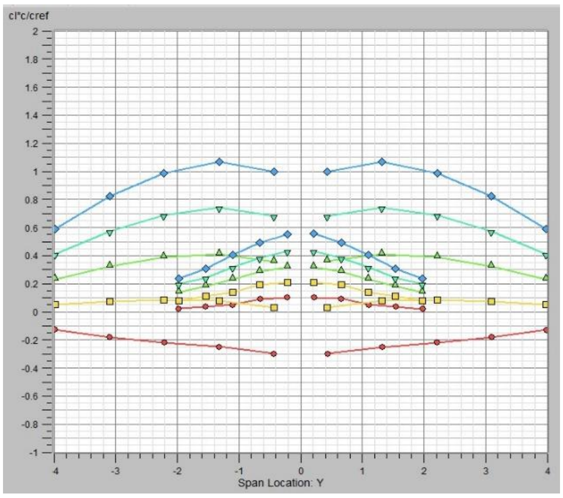


Fig. 14. Lift distribution over the span of UAV

The lift is distrusted equally on the both side of the UAV. Both the wings and v tail section lift distribution is shown with big scale and small scale respectively.

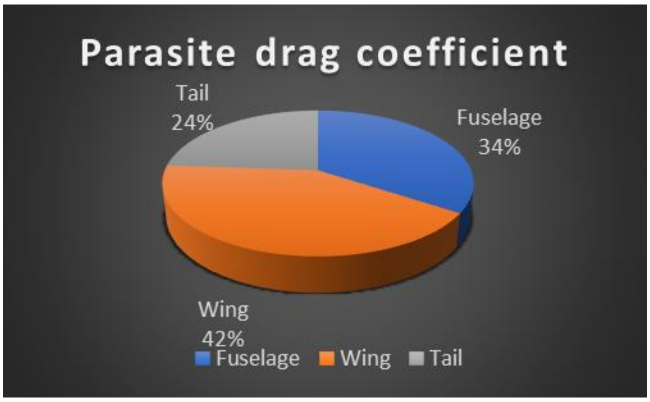


Fig. 15. Parasite drag coefficient contribution

The parasite drag coefficient for whole UAV is 0.007393 as it always refers to the area where the area is not optimal to the actual design. It shows the wing section contribute more to the parasite drag coefficient than other parts of body.

3.6 Design of UAV:

In the SolidWorks the actual design of drone is drawn. The different views are shown below.

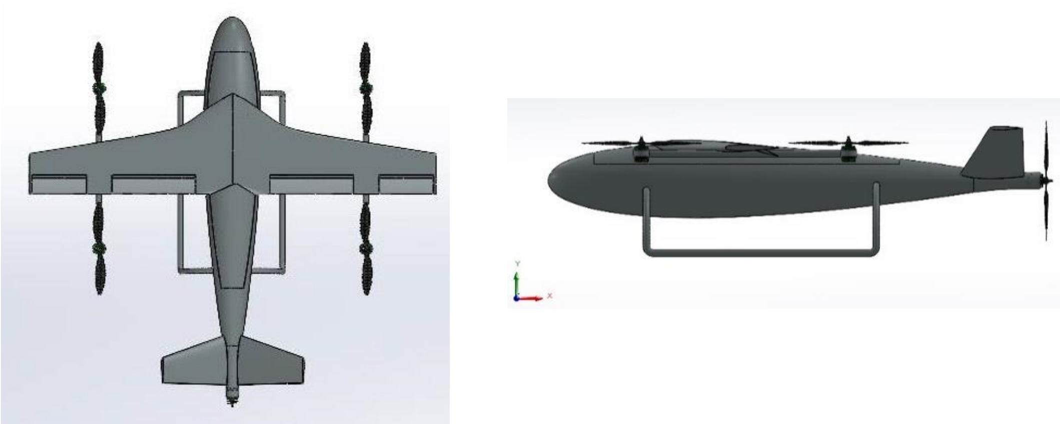


Fig. 16. Top view and side view of drone in SolidWorks

3.7 Payload section:

The middle section of the fuselage is for payload. The compartment volume is v = length * breath * height = 25 * 12 * 15 = 4500 cm^3. As the medical supplies include many medicines and vaccine. Considering the density of blood as 1050 kg/m^3. Payload capacity is 5 kg. Volume to store the 5 kg blood is 4761.905 cm^3. So, it can carry the blood of 4 kg and remining volume for tablets and other medicine.

3.8 PID controller:

The control system model is simulated in MATLAB/Simulink where only motor is formulated in transfer function.

Table 2 Motor parameter [8]

Inductance (mH)	L	0.436
Thermal resistance (Ω)	R	8.72
Torque Constant (mNm/A)	K_t	3.14
Rotor Inertia (gcm^2)	J	0.00703
Number of phases		3

The motor can be represented in the transfer function and gain transfer function can be calculated by [6], [7].

$$G(s) = \frac{\frac{1}{K_e}}{\tau_m \cdot \tau_e \cdot s^2 + \tau_m \cdot s + 1}$$

Fig. 18. Gain transfer function [6], [7]

Where Ke = Electrical torque constant = Kt * 0.0605

τe = Electric Constant = L/0.004R

τm = Mechanical Time constant (ms) = 3RJ/ Ke Kt

Based on the formulas and the given values from the parameters of the motor, the gain function of the selected motor can be represented in Simulink as [12]:

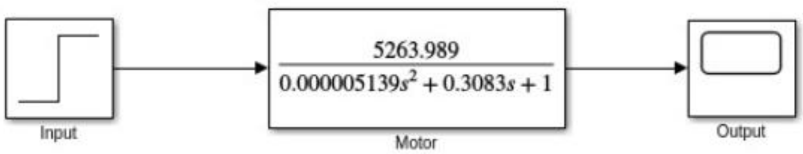


Fig. 19. Gain function value with input and output in Simulink [12]

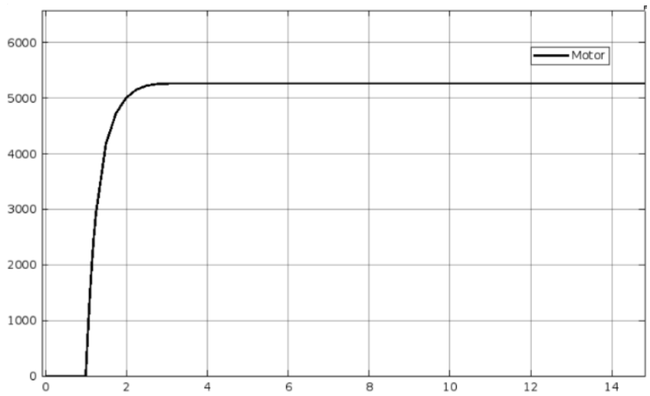


Fig. 20. Open loop step response

After adding the Proportional-Integral-Derivative (PID) ahead of gain transfer function. The following results are obtained [12].

Fig. 21. The PID with gain function in Simulink

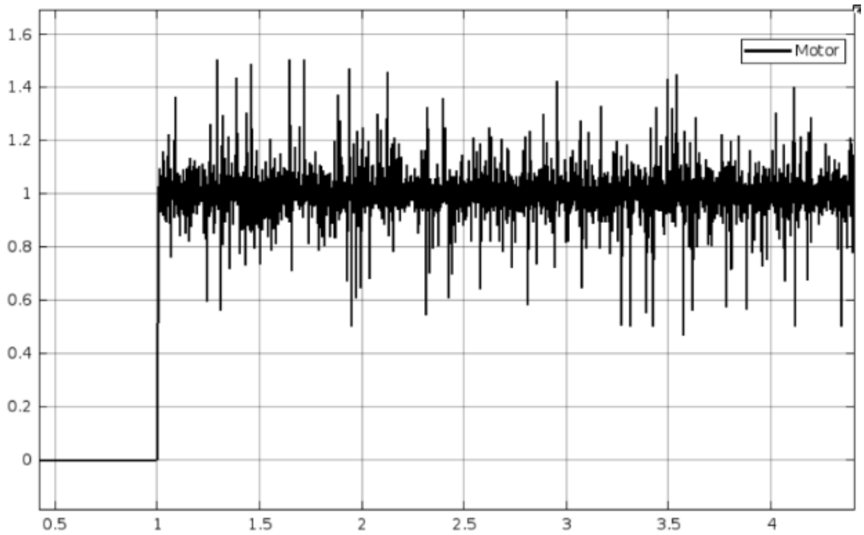


Fig. 22. Proportional controller gain effect

The proportional controller gain effect made the overshoot to decrease to reasonable value but the steady-state error is still high. Therefore, additional iterations are performed to bring the graph onto a steady state. This is done by changing the integral and derivative value to unit value and then step by step increasing them to higher number till steady state graph is obtained. The graphs for each iteration are presented.

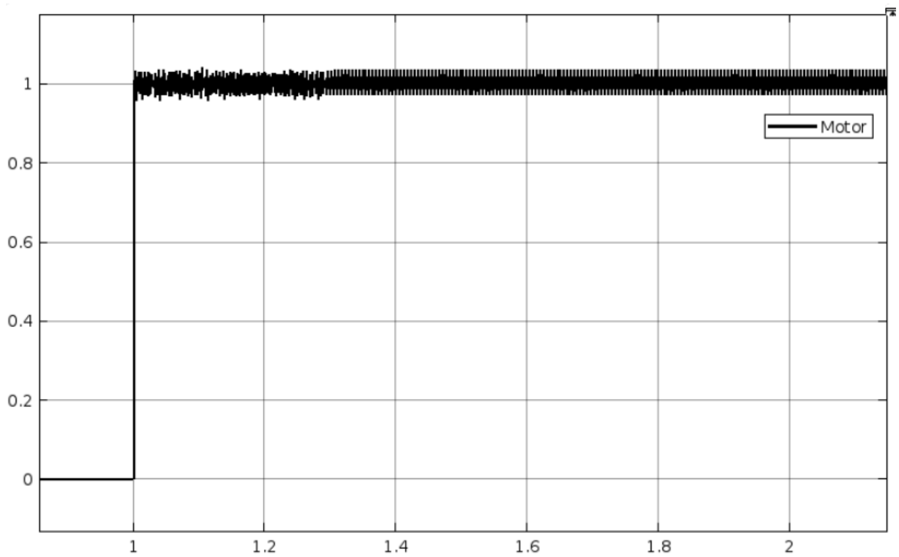


Fig. 23. PID controller gain effect

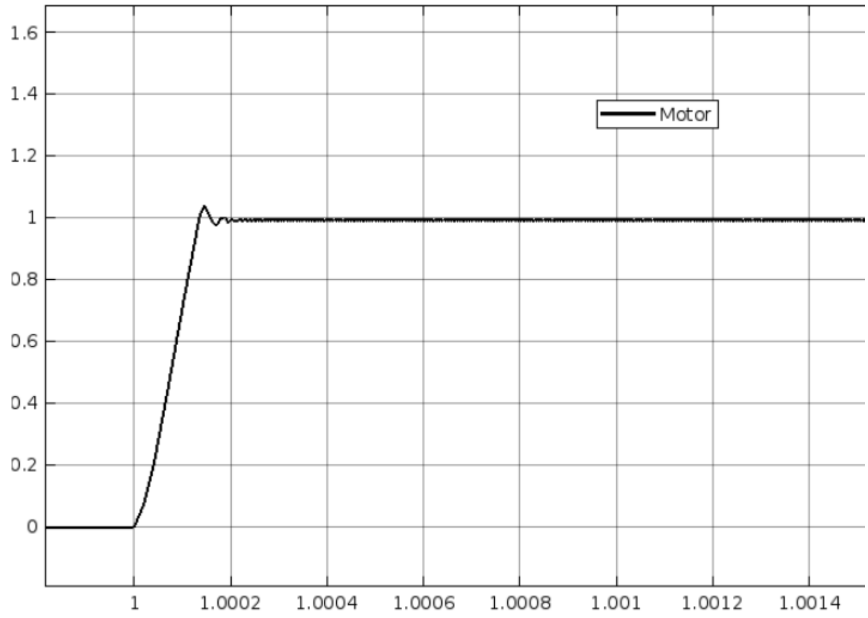


Fig. 24. PID Controller (with higher values) gain effect

As it is shown on the figure 25 the rising time is decreased to less than 0.0002 second compared to the initial value obtained from figure 23. Also, the steady state error has almost decreased to zero as it is shown on the graph.

4. CONCLUSION:

The high fixed-wing multi-rotor medical drone is design and analyzed in Xflr5 and the actual design is drawn in SolidWorks. Ansys flow analysis of 2D airfoil provided the lift generating NACA 0012 airfoil. The conceptual design is analyzed in OpenVSP where the parasite drag coefficient is calculated based on area of drone. Further most, the motor parameter is configured into transfer function and gain function where PID is added to reduce the rising time.

5. ACKNOWLEDGMENT:

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