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DESIGN AND DEVELOPMENT OF DUCTED VTOL UAV

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Abstract*- Unmanned aerial vehicle has triumphed over manned aircraft because of its numerous advantages such as remote accessibility, autonomous mission completion for both military and civil work. This paper describes a comprehensive method for designing, construction and control of a ducted VTOL UAV. A systematic design procedure is obtained by the aerodynamics of ducted fan and duct geometry. Control system for flight stability and innocuous takeoff and landing is also presented. Various ground and flight tests have been performed to investigate the aerodynamic characteristics as well as the stability of the UAV.*

Keywords: Unmanned aerial vehicle, duct, VTOL, aerodynamics, control.

1. INTRODUCTION

Ducted fan UAV (Unmanned Arial Vehicle) are introduced in modern UAV platform due to its several engrossing features. There are some distinct advantages of this vehicle which are perfectly suited for certain purposes .Ducted fan UAV are inherently VTOL(Vertical takeoff and landing) and can hover, tilt into the wind in case of high speed flight in any desired direction. a duct. Duct reduces thrust losses due to the tip leakage flow. It also controls the flow velocity and pressure at the rotor section. The converging diverging duct develops an additional thrust by accelerating the flow which accomplishes low speed application like VTOL. In this kind of aircraft the propulsion system is surrounded by Hovering.

Moreover combining with a fixed-wing it is possible to establish level flight like airplane [1]. There exist some remarkable advantages of Ducted UAV over other aircraft like Airplane or Helicopter. Ducted fan produces more thrust than a free propeller of same diameter and of equivalent power. As compared to Helicopter the primary advantage is Hovering capability and efficiency. There are losses at helicopter rotor tips due to vortices but adding a duct these losses can be eliminated [2] .Lets have a short look over the propeller momentum theory [3]:

$$P_{open}=\frac{T^{3/2}}{\sqrt{2A_{disk}\rho}}$$

$$P_{ducted}=\frac{T^{3/2}}{\sqrt{4A_{disk}\rho\sigma_d}}$$

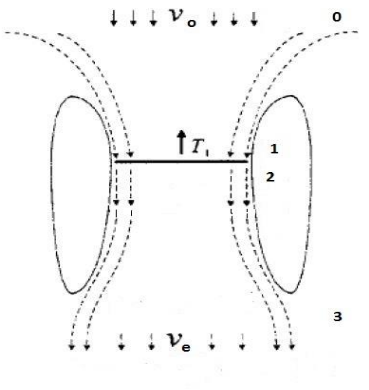
$$\frac{P_{open}}{P_{ducted}}=\sqrt{2\sigma_d}$$

Here P is the power required , T is the thrust ,ρ is the air density, A_{disc} is the disk area of the propeller , σ_d is the duct expansion ratio(ratio to exit area to disk area).Here without any expansion (σ_d=1) shows that ducted propeller will require only 71% of power required by an open propeller . Most of the fixed-wing UAV offer a great complexity for launching but in case of ducted fan VTOL this problem can be eliminated. Duct acts as a barrier which protects the surroundings from propeller blade and also functions as a sound barrier. The ducted fan UAV's are very unstable due to its very complicated aerodynamics. The flow through the duct is also very complex. If the distance between the tip of the blade and the duct remains very large then the duct will act like a drug source [4]. So it is very challenging to obtain stable flight to complete desired mission successfully.

2. MODELING

2.1 Ducted Fan Theory

For analysis of flow through duct it must be considered that the converging diverging phenomena maintains the Bernoulli's equation of momentum conservation [1]. Flow through the propeller can be analyzed by following figure:



Considering incompressible flow let's apply Bernoulli's equation between the section 1 to 2 and 2 to 3

$$P_0 + \frac{1}{2}\rho v_0 = P_1 + \frac{1}{2}\rho v_1$$

$$P_2 + \frac{1}{2}\rho v_2 = P_3 + \frac{1}{2}\rho v_3$$

Mass flow rate for section 1 and 2 is given by

$$\dot{m}_1 = \rho v_1 A_1$$

$$\dot{m}_2 = \rho v_2 A_2$$

here $A_1 = A_2$ and $\dot{m}_1 = \dot{m}_2$

So it can be written that $v_1 = v_2$

Now $v_1 = v_2 = v_0 + v_i$; Here v_i is the induced velocity of the propeller

Consequently exit velocity can be expressed as $v_3 = v_0 + v_e$; Here v_e is the slipstream velocity

Thrust generated T= $(P_2 - P_1)\, A_d$

Now solving these equations we get the final form as below

$$v_e = -v_0 + \sqrt{v_0^2 + \frac{2T}{\rho A_d}}$$

This formula can be applied for optimization of ducted propeller.

2.2 Duct and Control Surfaces

Selection of duct is accomplished by means of Integral of some equations as sated below [5]:

The radial flow velocity around the duct and the flow velocity along the z-component is given as:

$$V_r(\theta) = V_{xy} \cdot e_r = -v_x\, cos\theta - v_x\, sin\theta \text{ ; Here } e_r = \hat{\imath} cos\theta + \hat{\jmath} sin\theta \text{ and } V_{xy} = -v_x\hat{\imath} - v_y\hat{\jmath}$$

$$V_z(\theta) = v_i - v_z$$

Dynamic pressure and angle of attack are written as:

$$q_d(\theta) = \frac{1}{2}\rho_\propto (V_r^2 + V_z^2)$$

$$\alpha_d(\theta) = \tan^{-1}\left(\frac{V_r}{V_z}\right)$$

Now lift and drag per unit span around the duct is given as:

$$l(\theta) = C_{l,d}(\alpha) q_d c_d$$

Here $C_{l,d}(\alpha)$ is duct airfoil lift curve

$$d(\theta) = C_{d,d}(\alpha)\, q_d c_d$$

Here $c_{d,d}(\alpha)$ is duct airfoil drag curve

Now the components of lift and drag are written as:

$$l_x(\theta) = l\cos\alpha\cos\theta \quad l_y(\theta) = l\cos\alpha\sin\theta \quad l_z(\theta) = -l\sin\alpha$$

$$d_x(\theta) = l\sin\alpha\cos\theta \quad d_y(\theta) = l\sin\alpha\sin\theta \quad d_z(\theta) = -l\cos\alpha$$

Integrating these quantities we get

$$L_x = r\int_0^{2\pi} l_x(\theta) d\theta;$$

the values of $C_{l,d}(\alpha)$ and $C_{d,d}(\alpha)$ are expressed as below:

$$C_{l,d}(\alpha) = \min\left(C_{l,max}, \max\left(\frac{1}{2}C_{l_\alpha}\sin(2\alpha), C_{l,min}\right)\right)$$

$$C_{d,d}(\alpha) = C_{d,offset} - C_{d,gain}\cos(2\alpha)$$

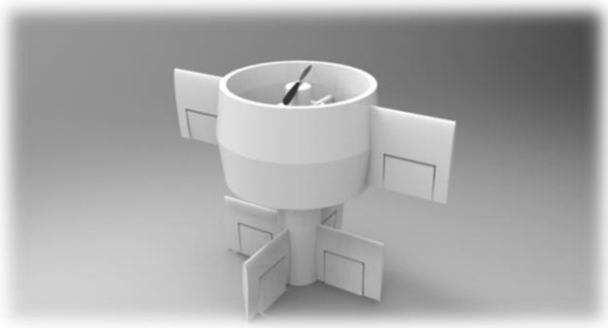


Figure: Designed UAV

Total lift of this UAV can be expressed by the following equation:

$$L = L_{wing} + L_{duct} + L_{control\ surface}$$

$$L_{wing} = \frac{1}{2}\rho v^2 S_w C_{l_w} \alpha$$

$$L_{duct} = \frac{1}{2}\rho v^2 S_d C_{l,d}(\alpha)\alpha$$

$$L_{control\ surface} = \frac{1}{2}\rho {v_e}^2 S_{cs} C_{l_{cs}} \alpha_{slip\ stream}$$

In the same way the drag is equal to

$$D = D_{wing} + D_{duct} + D_{contral\ surface}$$

$$D_{wing} = \frac{1}{2}\rho v^2 S_w C_{d_{wing}} \alpha$$

$$D_{duct} = \frac{1}{2}\rho v^2 S_d C_{d,d}(\alpha)\alpha$$

$$D_{control\ surface} = \frac{1}{2}\rho v^2 S_{cs} C_{d_{cs}}(\alpha_{slip\ stream} + \delta_e)$$

All those equations based on fundamental Aerodynamics were used to design the UAV.

3. CONSTRUCTION AND CONTROL

The main objective was to develop an UAV system combining a structure with an embedded control system. This has brought an accomplishment named DUCTED UAV. This UAV comprised of framework (the fuselage, wing, Rudder, Elevator and Duct), propulsion system and control mechanism. After an effortful analysis of several hardware platform combined with software such as KKmulticopter, ArduPilot, MultiWii, it was decided to choose MultiWii as a possible solution for controlling due to its easy operating techniques and cost effectivity. Moreover this is a well-recognized open source unmanned Arial control system. This control board is equipped with several important sensors such as Gyro, Accelerometer, Barometer and Magnetometer. An external GPS navigation system and onboard camera can also be connected to this system. According to the non-linear dynamics equation of force and moments like as roll, pitch, yaw moment for flight stability are given through the coded instruction to the microcontroller Atmega 32_u4. As this is an open source framework some basic coded instructions were taken from official page of Multiwii. Once the data from the sensors are taken through the I/O pins of MCU then by the aid of coded instruction these values are converted to physical command by means of servos to accomplish the roll, pitch and yaw control of the UAV. For cancellation of any error in calculating the exact desired angular value of servo or throttle value of motor at any altitude and flight condition the PID (Proportional Integral Derivatives) values were adjusted. For ground control system a 2.4 MHz transmitter and receiver was used. An wireless Bluetooth data communication system was installed to inspect the flight condition from ground station

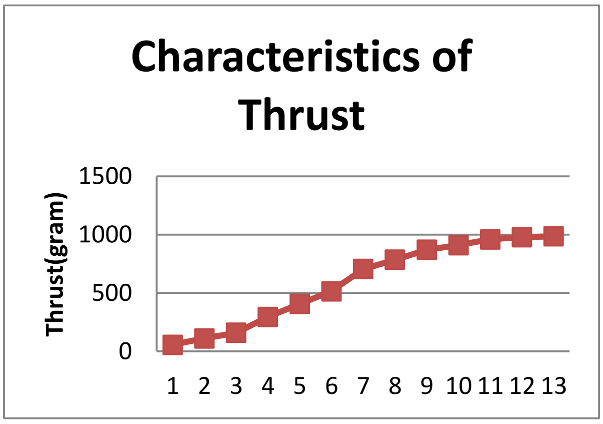
Material- Duct is made from Styrofoam. The control surfaces are made of commercial foam core.

Wing and control surface airfoil- NACA 0012

Motor and propeller- Brushless DC 1190 Kv and propeller 10×4.7

4. FIGURES

Thrust Vs Voltage graph-



The flight test of Ducted UAV started with a successful vertical takeoff then it begun hovering and maneuvered around a small area of hovering. After some successful horizontal translation it landed safely. The VTOL(vertical takeoff and landing) characteristics of this UAV was observed evidently. The flight test was performed at Aerodynamics & Arial Robotics Lab. at Khulna University of Engineering & Technology, Bangladesh.

5. CONCLUSIONS

Ducted VTOL UAV has several advantages as compared to other UAV platform. There is a less thrust required and optimization of the risk of collision between the propeller and the surroundings. This UAV has a remarkable hovering capability and has the ability to increase the payload while decreasing the vehicle size. It is significantly stable in both static and dynamic condition. It is observed that an effective duct size increase hovering in a crosswind. It is recommended that the model of this UAV can be modified by an effortful analysis of the duct aerodynamics, basic governing equation of flight dynamics, stability and control for ducted fan UAV. Flight simulation is an appreciable solution for this improvement.

6. ACKOWLEDGEMENT

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