Design and Analysis of Coaxial Ducted Propulsion Systems of Unmanned Aerial Vehicles

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Abstract. Drone Technology is one of the major areas of research in numerous aspects and purposes. Less flight time and more power consumption has become the major problem in flying drones and UAVs. This project aims in analysing the thrust and other parameters of Coaxial propellers by ducting them uniquely and comparing them with conventionally ducted propellers. Ducting increases the thrust and in this, two propellers were individually ducted. Increase in the efficiency will allow the drones to fly effectively with adequate power consumption. The experiment results were tabulated and compared with each different case such as hover and forward flight configurations. In this Coaxial system one propeller rotates in Clockwise whereas the other in Counter-clockwise direction.

Keywords: Coaxial propellers, Drone, Duct, Efficiency, Thrust, UAV.

1. Introduction:

Coaxial ducted propellers can increase the efficiency and decreases power consumption of Unmanned Aerial Vehicles (UAVs). Ducts increases additional weight but also increases the efficiency of the UAV. Less flight time, thrust and more power consumption have become the major problems in drone technology. The stack of coaxial propellers provides more thrust without increasing UAV’s power consumption [1]. Coaxial propellers do not operate on motor’s maximum power [2]. In hover flight case, pusher configuration increases 2 to 4% efficiency. Using multi-blade propellers such as tri-blade decreases the noise and because of lower RPM it also reduces the risk [3]. The swirl generated by the puller motor (front motor) let the aft rotor to benefit from additional tangential velocity [4]. Also, propellers which are ducted have a better efficiency than non-ducted one. This is because to generate maximum thrust with minimum disturbance, the resulting airflow trajectory moves downward [5]. Increase in battery and payload problems occurs when UAV is developed [6]. This problem can be addressed by ducting propellers which can increase thrust by 94% [7]. Among square and circular ducts, circular ducted system was found to be 4.5% more efficient than the square one [8]. This is why circular ducts were opted for these experiments. Lift of the propeller increases with increase in the propeller blade pitch [9]. Thus, ducting propellers which are coaxial increases thrust and efficiency. The application of ducted propellers will be an advantage only in the case of low speed and high loading [10].

Based on the literature survey, to achieve more thrust and more flight time with less power consumption, ducting is necessary. In this research, coaxial propellers with Separate ducts, Common duct and no duct were tested and compared its result with each other. The experiments were done in two configurations, which are, forward and Hover flight configurations. Both the propellers rotate in the opposite directions. All the experiments were done in static air conditions.
2. Conceptual design:

Based on the literature survey [1][2][3][5][8][9], the following conceptual designs were made. Designing of a Thrust measuring stand was made as shown in the Fig 1. This stand was used to measure the thrust using a weighing machine by connecting the duct setup on the top end of it. The stand pole is 90 degrees to the other pole which will be rested on weighing machine as shown in Fig 1.

![Thrust measuring stand](image)

**Fig 1. Thrust measuring stand**

To conduct the experiment on Co-axial propeller system with no duct, a CAD model was designed as shown in Fig 2. This model was made according to the dimensions of the BLDC motors and the propellers. For the experiment on Co-axial propeller system with a common duct, a duct was designed as shown in Fig 3. In this setup, both BLDC motors were ducted using one duct and its dimensions are shown in Fig 3. Propeller of motor 1 (M1) (puller) is 26.9mm from the top of the duct and propeller of M2 (pusher) is 10 mm distance from the bottom of the duct. A CAD model was designed also for the experiment on Co-axial propellers using two separate ducts as shown in Fig 4, 5. As shown, each duct in this setup has 72.81mm height and 167.26mm, 139mm of inlet and outlet diameter whereas the distance between propellers maintained constant in all the experiments.

![Design for Co-axial propellers with no ducts](image)

**Fig 2. Design for Co-axial propellers with no ducts**

![Common duct design](image)

**Fig 3. Common duct design**

![Separate ducts design (side view)](image)

**Fig 4. Separate ducts design (side view)**

![Separate ducts design](image)

**Fig 5. Separate ducts design**
3. Development of prototype:

Cylindrical duct geometry was properly designed based on the adequate parameters and needs. All the designs were 3D printed using PLA filament and these ducts are durable, light weight and made as shown in Fig 6,7,8. Usage of ducts changes the flight characteristics depending on whether it is a forward flight or hover flight. Two tri-blade propellers which are 5 inches and have 4.5 inches fixed pitch, 2 BLDC motors of 2300KV along with 30A speed controller and 4 cell LiPo battery of 1000mAh, 30C/60C were used. For a propeller if the pitch angle increases, power loading ratios increases [11]. To control the speed of the BLDC motors, digital multi servo tester was used. Anemometer, Tachometer and Multimeter were using to check wind speed, RPM of the propellers and power.

Two propellers were fixed properly to the two BLDC motors and both the motors were connected to an ESC. M1 acts as puller/tractor and M2 acts as pusher motor. ESC was connected to the motors M1, M2 and a servo controller which was used to control the BLDC motors speed and also connected to a lithium polymer battery (LiPo). Entire unit was mounted to the stand as shown in the Fig 9.
4. Experimental studies:

Two polycarbonate propellers rotate in opposite direction are 5 inches whereas the top rotor turning CCW (puller/tractor) and the bottom is CW (pusher) and the clearance between propellers and duct inner wall is 3mm. Duct upper radius is 167.26mm and the height of the duct is 125.94mm. This duct includes two propellers and the distance between two propellers is 90mm whereas duct wall thickness is 3mm. Diameter (D) of propeller is 127mm and height (H) between two propellers is 90mm. It is proven that by comparing upper and lower rotor in torque balance setup, lower rotor operates at lower efficiency compared to the upper rotor. [12] H/D value of this setup is 0.7, whereas large manned aircraft use a 0.1 H/D ratio [13]. The weight of the duct used in common duct experiment is 130 grams and can be reduced, whereas the weight of duct used in separate duct experiment is 125 grams. Weight of the motor along with propeller is 36 grams. In this, both propellers rotate in opposite directions whereas it is proven that coaxial propeller system has the same efficiency whether the propellers rotate in same or opposite direction [14]. Drones are very vital for mankind and even in military. Drones have vital role in military, by helping in detection of buried bombs and bombers [15]. Testing of coaxial propellers with no duct, common duct and separate ducts were done. Several experiments were carried out on various cases and had tested in both forward and hover flight conditions. The following experiments were done in the static air condition.

4.1. Experiment without a duct:

In this, BLDC motors were aligned coaxially with 90mm distance between each other. Both rotate in the opposite direction. BLDC motors were operated using a controller and had tested at various power inputs and noted the thrust generated by this setup.

4.1.1. Results:

Result shows that at 107.2 watt, thrust generated was 500g and is represented in the graph shown in Fig 10. There was a uniform increase in the thrust by increase in the current. 50g of thrust generated at 10 watt of power supply.
4.2. *Experiment with Common Duct:*

In this, BLDC motors were aligned coaxially and both the propellers were ducted using one common duct. This duct is mounted to the thrust measuring stand which measures thrust using a weighing machine.

4.2.1. *Forward Flight:*

Entire duct setup was aligned in forward flight configuration and tested. In order to measure current, rpm and wind speed; multimeter, tachometer and anemometer were used. In forward flight experiment, the coaxial rotor needs less power compared to the equivalent solidity single rotor upto moderate advance ratios [16]. Same tri-blade propellers, motors, battery, ESC, servo tester were used like before in this and the following experiments and tested. Only duct varies between experiments.

4.2.2. *Results:*

At 7.6 watt of power input, 65g of thrust was generated and at 66.43 watt power input, 500g of thrust was generated. Results shows that the thrust is increased compared with the results of no duct experiment. Power vs Thrust graph in Fig 11 shows the detailed results of this experiment.

4.3. *Hover Flight:*

Experiment was carried out in hover flight configuration with the same setup. In hover flight configuration, duct will have tendency to move up by forcing the wind down. Thrust was measured by using two scales and tested properly.
4.3.1 Results:
At 42.9 watt of power, this flight configuration has generated 300g of thrust and it varied with respect to power as shown in the graph which is in Fig 12. Whereas in forward flight condition gravitational force is at 90 degrees to the force of thrust. Where as in forward flight configuration, to generate 300g of thrust, 32 watt power was consumed. Increase in power consumption is because of the gravitational force acting opposite to the direction of flight.

![Power Vs Thrust Graph](image)

**Fig 12.** Power vs Thrust Graph

4.4 Experiment with Separate ducts:
In this, BLDC motors were aligned coaxially and both BLDC motors were ducted separately using two ducts. Propeller of M1 is 26.9mm from the top of its duct and propeller of M2 26.9mm distance from the top of its duct. This duct weighs 125 grams and can be reduced using lightweight materials.

4.4.1 Forward flight:
Entire duct setup was aligned in forward flight configuration and tested. In order to measure current, rpm and wind speed; Multimeter, tachometer and anemometer were used. Same components from previous experiments were used except a new duct design.

4.4.2 Result
From the obtained results, at 9.71 watt power input, 55g of thrust was generated and at 72.85 watt power input, 500g of thrust was generated. Thrust is more than the thrust generated by no duct setup and less than common duct setup. Detailed data of the experiment is graphically represented in Fig 13.

![Power Vs Thrust Graph](image)

**Fig 13.** Power vs Thrust Graph
4.5 Hover flight
Entire setup was mounted as shown in Fig 14 to measure hover flight characteristics of the setup. Used another weighing scale from the top of the duct to measure its thrust accurately.

![Hover flight setup](image)

**Fig 14. Hover flight setup**

4.5.1 Result
Result shows that at 15.4 watt power input, 100g of thrust was generated and at 57 watt of power input, 300g of thrust was generated. Thrust is less compared to the thrust generated by common duct setup. It was tested at different power inputs and results are shown in Fig 15.

![Power vs Thrust Graph](image)

**Fig 15. Power vs Thrust Graph**

5. Comparative study:
Comparing power and thrust from the results of No duct, Common duct and Separate duct shows that Common duct has less power consumption compared to the setup with no duct. Whereas a Separate duct setup result shows that the thrust is slightly less compared to the Common duct setup. As shown in Fig 16, P v T graph, common duct can generate more thrust with less power consumption than both the other cases.
From No duct experiment forward flight configuration, obtained results are tabulated in Table 1.

**Table 1. No duct forward flight results**

| Thrust (g) | Voltage (V) | Current (A) | M1 RPM | M2 RPM | Wind speed (Mt/sec) | Power (Watt) |
|------------|-------------|-------------|--------|--------|---------------------|--------------|
| 63         | 16.2        | 0.55        | 4130   | 410    | 4.5                 | 8.91         |
| 100        | 16.1        | 0.86        | 5040   | 5050   | 5.4                 | 13.8         |
| 150        | 15.9        | 1.34        | 6210   | 6220   | 7                   | 21.3         |
| 200        | 15.3        | 2.03        | 7262   | 7289   | 8.2                 | 31.8         |
| 400        | 15.3        | 5           | 9940   | 9950   | 10.2                | 76.5         |
| 500        | 14.9        | 7.2         | 10967  | 10936  | 12.8                | 107.2        |

From Common duct experiment forward flight configuration, obtained results are tabulated in Table 2.

**Table 2. Common duct forward flight results**

| Thrust (g) | Voltage (V) | Current (A) | M1 RPM | M2 RPM | Wind speed (Mt/sec) | Power (Watt) |
|------------|-------------|-------------|--------|--------|---------------------|--------------|
| 65         | 15.2        | 0.5         | 4158   | 4146   | 4.2                 | 7.6          |
| 100        | 15.1        | 0.68        | 4760   | 4735   | 5                   | 10.2         |
| 150        | 15.1        | 1.03        | 5822   | 5797   | 6.3                 | 15.5         |
| 200        | 15          | 1.3         | 6496   | 6480   | 7                   | 19.5         |
| 400        | 14.8        | 3.1         | 9020   | 9000   | 9.3                 | 45.8         |
| 500        | 14.6        | 4.55        | 10260  | 10264  | 12                  | 66.43        |

**Fig 16.** Power vs Thrust comparison graph
From Separate duct experiment forward flight configuration, obtained results are tabulated in Table 3.

| Thrust (g) | Voltage (V) | Current (A) | M1 RPM | M2 RPM | Wind speed (Mt/sec) | Power (Watt) |
|-----------|-------------|-------------|--------|--------|---------------------|--------------|
| 55        | 16.6        | 0.59        | 4452   | 4450   | 4.6                 | 9.79         |
| 100       | 16.5        | 0.89        | 5441   | 5451   | 5.9                 | 14.6         |
| 150       | 16.4        | 1.2         | 6347   | 6362   | 6.7                 | 19.68        |
| 200       | 16.3        | 1.6         | 7035   | 7043   | 7.8                 | 26           |
| 400       | 15.9        | 3.5         | 9550   | 9570   | 8                   | 55.6         |
| 500       | 15.5        | 4.7         | 11350  | 11390  | 10.1                | 72.85        |

Where, g= grams; V=Voltage; A= Ampere; Mt/sec= Meter/Second; RPM= Rotations per minute.

6. Conclusions:
Ducted coaxial propellers increases thrust and decreases power consumption. Common duct for two motors is very effective compared to the motors with no duct and separate ducts. Motors with no ducts generated 500g of thrust at 107.2watt power input and separate ducts generated 500g of thrust at 72.85watt, which means 32% of power consumption in common duct experiment is reduced compared to the no duct experiment. Whereas in the case of common duct, two motors generated 500g of thrust at 66.43watt of power input, which means 38% of power consumption was reduced compared to the motors with no duct. Using ducts effectively increases thrust and reduces power consumption but adds weight to the UAV. If the extra thrust generated at same power consumption by using ducts is more than the weight of the ducts, then UAV efficiency will be increased. Coaxial ducted propellers make Vertical take-off easy which is Hover flight.

Future works based on this project can be, Reduction in the weight of duct can be done by using other lightweight materials like balsa wood. H/D value is 0.7, whereas it can be varied and tested by doing iterations. Number of blades of the propellers can be changed along with pitch angle, length of the propellers can be varied and tested. Clearance value between propeller and duct inner wall can be reduced and tested. Separately ducted coaxial propellers might enable UAV to move during hover flight without using any rudders. This might be possible by making lower duct tiltable and can be used as an alternate method where rudders cannot be used. But the power consumption will be 4% less than common duct ones. Other configurations like downward and backward flight configurations can be tested by making suitable changes.

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