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Experimental Aerodynamic Investigation of an UAV Wing with Wing Mounted Propellers

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Abstract*: *The present study aims at evaluating the aerodynamic coefficients of wing with and without propellers for various configurations at different locations. Also to ascertain the effect of clearance over the wing, wake survey analysis is performed for different clearances. It is observed that aerodynamic coefficients such as lift increased by 12 to 13% with a considerable reduction in drag of the order 2 to 3%, followed by increase in stall angle by 3° - 4°. The result is suitably bolstered by flow visualization technique, which indicated attached flow over the wing even at higher degrees of angle of attack. It is followed by an increase in dynamic pressure, being the obvious denouement to follow, therefore enhancing aerodynamic characteristics with an improved performance of UAVs

***Index Terms*: *Propeller – based propulsion system, aerodynamic coefficients, angle of attack, UAV, propeller configuration, coefficient of lift, coefficient of drag, stall*.**

I. INTRODUCTION

Since the advent of aircraft by Wright Brothers in 1903, the propulsion methodologies have evolved significantly with considerable changes in the conventional methods for aerial vehicles. Though the evolution of propulsion systems began during early 90s, the contributions by several researchers to improve the efficiencies and performance of the propeller-based propulsion systems is still extant. On the other hand, the arena of non-propeller-propulsion methodologies also has remained touched in the mid of 19th century which has led to the evolution of turbo-jet and turbo-fan engines. Whereas, some of the researchers have identified that low speed regime of operation of propeller-based propulsion systems has better efficiency in comparison with other propulsion systems operating in the same regime. This has led to extensive research on propeller-based propulsion systems with an aim to improve their performances.

Considerable effort has been invested on the studies of propeller based propulsion system, some of the commendable efforts noteworthy are the propeller wing interaction with steady state cases for Reynolds numbers greater than 350,000 [1][2][3].

Wind tunnel measurements were carried out on rectangular flat-plate wings of aspect ratios 2, 3 and 4 under different propeller-induced flow conditions and Reynolds numbers ranging between 60,000 to 90,000 [1].

Some of salient outcomes of this study were identified to be increase in lift-curve slope followed by significant delay in stall and increase in maximum lift due to propeller induced flow. Though the study [1] was carried out for a fixed position and inclination of the propeller, it formed the basis for the study on influence of inclination and position of propeller [2]. Some of interesting facts revealed are increase in lift-to- drag ratio for propeller inboard upward rotation at constant power settings and increase in lift coefficient for high positioned propeller configuration.

Since the influence of position and inclination of propeller on the performance was understood without considering the influence of dynamics of flow over the propeller. The merits and demerits of propeller wash were identified through a study [3], which was carried out for tractor and pusher configurations propeller. Though both the configurations revealed the same behavior with increased lift coefficient, due to propeller induced flow over the wing, but pusher configuration had upper hand as the effect of propeller induced flow was more intense. Also, its performance was influenced by propeller position along the wing. Further the study of pusher configuration of propeller had immense effect on the rear end of the wing.

The study of interaction between low aspect ratio wing and propeller for the range of incidence in transition between horizontal and vertical flight [5] revealed that the pusher configuration gives best results by enhancing the flow characteristics. Closer the propeller, the better is the result due to reattachment of the flow to the wing surface. With the aspect ratio taken to consideration, propeller flow effects over flexible wing were studied [6]. It was established that the flexible wings can provide higher Lift-to-Drag ratios at any of attacks.

Though the previous efforts were made with single propeller, an attempt was made to understand the performance of wings with Multi-propellers at the leading edge. This was proclaimed as LEAP technology (Leading Edge Asynchronous Propeller). The results suggested that the performance at the design conditions are much better and will exceed the desired design (Cl)max to 4.3.

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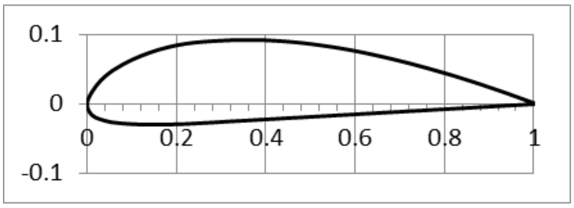
Based on the above discussion, it can be observed that the studies are carried out with single propellers. Therefore, convincing data related to effect of more than one propeller has to be generated.

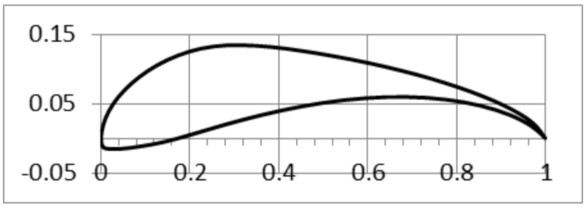
II. EXPERIMENTAL METHODOLOGY

A. Selection of Airfoil Geometry

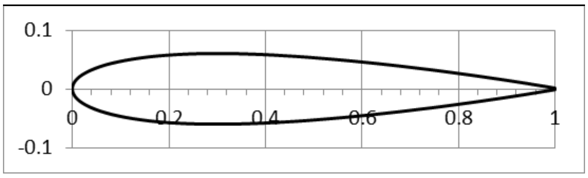
There are innumerable airfoils available, which forms considerably huge database for the researchers to select the airfoil ensuring the congruence for the application addressed by the research work. In order to ascertain the apt airfoil, analysis has been carried out on three airfoils viz. Clark Y (Fig.1 (a)), Selig S1223 (Fig.1 (b)) and NACA0012 (Fig.1 (c)). The three airfoils considered are used in the UAVs such as Yak-18T, Atomics MQ-9 and Catapult –dee29 [10]. The result of the analysis is indicated in Table-1, from which it can be observed that Clark-Y and Selig1223 airfoils outperform NACA0012. Among the Clark-Y and S1223 airfoils, the prior airfoil has better maneuverability, controllability due to its flat bottom, which justifies the usage of the airfoil section for the current study.



(a)



(b)



(c)

Fig.1 (a) Clark Y Airfoil geometry; (b) Selig1223 Airfoil geometry; (c) NACA0012 Airfoil geometry

Paramete r	Clark-Y	Selig122 3	NACA0012
C_{lmax}	1.35	1.76	0.83
$(L/D)_{max}$	76 at $\alpha=13°$	63 at $\alpha=13°$	38 at $\alpha=13°$
α_{stall}	14	14	13

Table 1: Comparison of airfoils

B. Fabrication and Experimental Set-Up

As indicated in the previous section, Clark-Y airfoil was selected for present study, which was fabricated using wood with monokote coating to avoid surface irregularities. Clamp is accommodated at suitable place to facilitate mounting of wing on force balance. While for propeller mounting, an exclusive mechanism was designed and fabricated as illustrated in Fig.2. Current research was executed with the aid of an Open-Circuit Low-Speed Subsonic Wind-Tunnel of specification indicated in Table-3

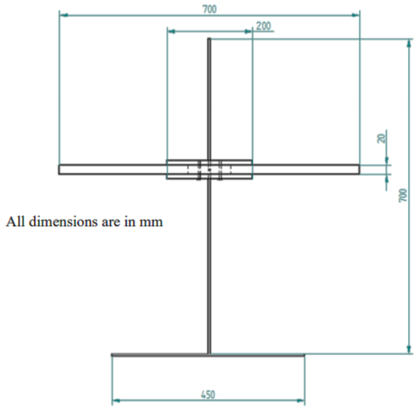


Fig-2: Mounting mechanism for Propellers

Fig-3: DYS D2826-10 BLDC Motor for propeller

Fig-4: EMP Propeller 7x3

C. Propeller Motor selection

Table 2: Specifications of Wing used for the study

Description	Dimension
Wing Section	Clark-Y
Material	Wood
Span	480mm
Chord	190mm
Thickness	0.118c
Camber	0.42c

The motor used to run the propeller is selected based on the cruise condition evaluated for wing-only configuration, from which the minimum power required to propel is obtained. The thrust required for 9.3m/s is obtained to be 0.643N and assuming a loss of 15%, the actual thrust required is therefore calculated as 0.739N. Based on the actual thrust required, DYS D2826-10 BLDC Motor is selected as indicated in Fig-3. The propeller (Fig.4) is designed to suit the requirement and maximum thrust generated by the motor.

Table 3: Specifications of Wind Tunnel

Description	Dimension
Test Section	600mm x 600mm
Length of Test Section	2000mm
Maximum Speed	50m/s
Maximum Fan Speed	1500rpm
Contraction Ratio	9:1
Contraction Length	1.8m

D. Force Balance Measurement

The primary aerodynamic data *viz.* Lift coefficient and Drag coefficient of the wing model for a given Reynolds numbers and angles-of-attack conditions is recorded using a thoroughly calibrated six-component strain gauge force-balance, WBAL-00106 (Fig.5). The balance system is a floor type balance specially customized for the wind tunnel up to 50m/s free-stream velocity. The load cell equipped in the balance can measure lift forces up to +/- 100N, drag forces up to +/-30N and pitching moment to the tune of 50N.m. The force balance system is very rugged and can be conveniently attached to the floor of the test section. Significant functional components of the force balance equipment are the balance mechanisms, strain gauge instrumentation amplifiers and microcontroller based measurement system. The balance mechanism consists of a vertical stem of length 355mm protruding into the test section. A mounting mechanism is facilitated at the tip of the vertical bar to which the model can be hinged anywhere between -100 to +200 angles of attack. The vertical stem is fixed to a metric plate which appropriately transfers all the loads generated on the model to the six strain elements through suitable link system. Strain elements are similar to cantilever links used to sense/respond to the transverse loads generated on the model. The strain gauges fixed at the root of the cantilever forms a full bridge and the bridge output is proportional to the load that comes on the cantilever. For the balance, there are six straining elements and six full bridges formed capable of measuring three vertical and three horizontal reaction forces. From these six reaction forces, lift, drag, side force, pitching moment, yawing moment and rolling moment can be established. Further, the output from the strain gauge mounted on the strain elements are amplified by signal conditioned amplifiers with low drift and high stability dispensing a large gain up to 3100. Finally, the outputs form these amplifiers are measured using a microcontroller based measuring system. Through an RS 232 link, the measured voltages/loads are transferred to the PC for further analysis. Extreme care was taken during the handling of the force balance, so, as to avoid any undue errors creeping into the equipment due to mishandling of the equipment. From the recorded values, the Lift coefficient and Drag coefficient are subsequently recorded & compared graphically for both the infinite wing models with and without sinusoidal leading edge tubercles for various Reynolds number operated at different angles of attack. Later, wall effects as well as the solid and wake-blockage effects are accounted for the tunnel. [4].

Fig. 5: Force balance equipment

E. Uncertainty Analysis

The probable uncertainties propagated during the experimental investigation have been accounted by adopting Kline McClintock uncertainty analysis presented by Kline and McClintock [8]. The uncertainty in the measurement technique is given by the result R, which is a function of the independent variables x_1, x_2, x_3…… x_n. Thus,

$R=R(x_1, x_2, x_3, x_n)$...................................(1)

By following the above method, the uncertainties in the lift and drag coefficients were calculated to be +/-0.0132. The estimated uncertainty for the angle of attack was 0.25

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deg. With all the errors, the total percentage in error was found to be around 3.14%.

III. RESULTS AND DISCUSSIONS

Based on the location of the propeller with respect to the wing (Fig.6 and Table-3), behavior of Coefficient of Lift and Drag are obtained and plotted against the Angle of Attack (α) for three different conditions viz. wing with propeller ON, propeller OFF and wing without propeller (Fig.7 to Fig.12). Also, plots associated with Cl/Cd against α is plotted (Fig.13 to Fig.18). It is observed that for location of propeller above the wing has dire consequences on the lift as the flow is accelerated along on the upper surface, leading to reduction in lift. As observed in Fig.7 (a), the performance of wing without propeller is better than the wing with propeller for configuration-1with highest lift and increased drag. Whereas the variation of Cl/Cd ratio is found to be considerably small for higher degrees of angle of attack (Fig.13).

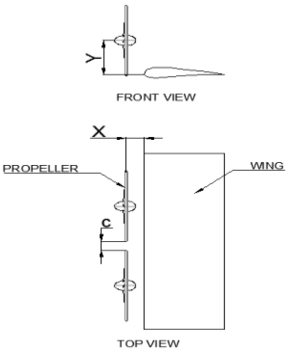

Fig-6: Position of Propellers with respect to wing

It can therefore be noted that providing the propeller above the wing axis though seems to negate the merits of the propeller at the leading edge, whereas the ratio of C_l/C_d remains the same as decrease in the lift is compensated with corresponding decrease in drag. On the other hand, configuration-2 has better performance when compared to configuration-1, as the propeller is slightly below the axis which also accelerates the flow over the wing leading to an additional lift at higher angles of attack. There is also an increase in stall, with better lift at maximum angle of attack as observed in Fig 8(a). There is also an augmentation of drag but overall C_l/C_d is found to be better than wing without propeller (Fig.19). The overall comparison of the C_l/C_d curves across all configurations reveals that configuration-1 induces better performance than any other configuration (Fig. 20).

Table 3: Specifications of different configurations of wing with propeller

Config. No.	X (in mm)	Y (in mm)	Clearance (in mm)	Propeller Dimension
1	50	3	10	7X3
2	50	-3	10	7X3
3	50	0	10	7X3
5	50	0	480 (Tip)	7X3
6	90	0	5	7X3
7	120	0	10	7X3

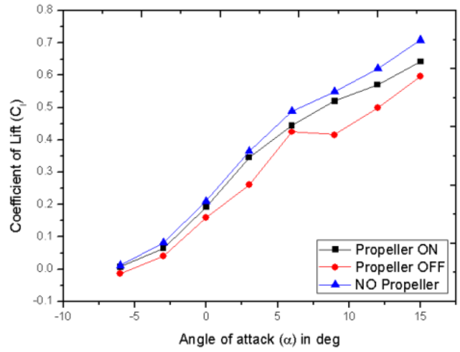

Fig-7(a): C_l Vs α for Configuration – 1

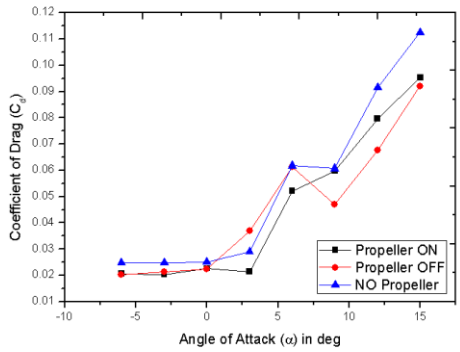

Fig-7(b): C_d Vs α for Configuration – 1

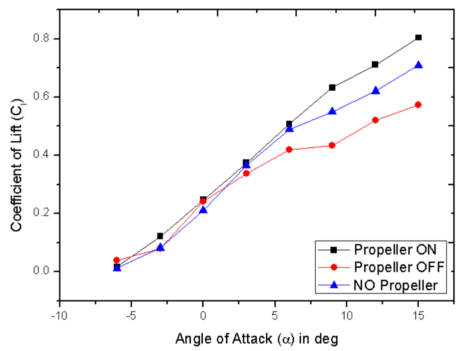

Fig-8(a): C_l Vs α for Configuration – 2

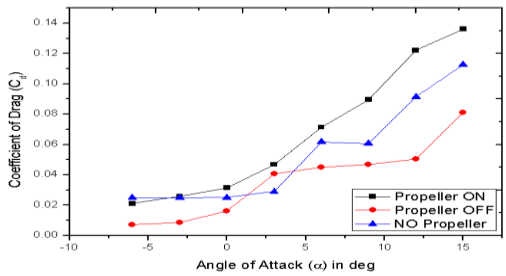

Fig-8(b): C_d Vs α for Configuration – 2

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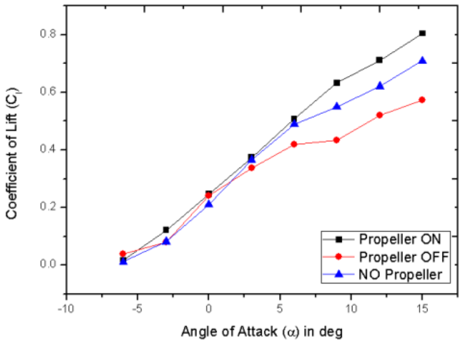

Fig-9(a): C_l Vs α for Configuration – 3

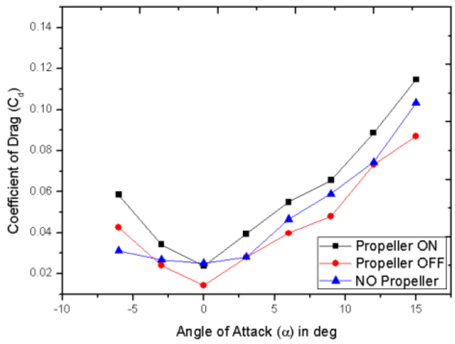

Fig-9(b): C_d Vs α for Configuration – 3

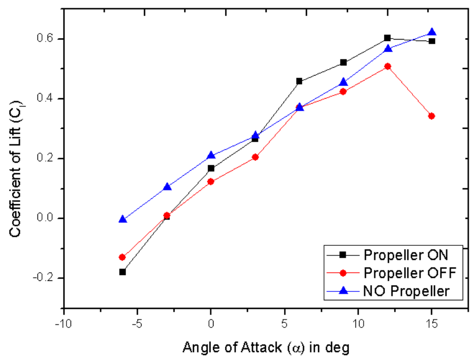

Fig-10(a): C_l Vs α for Configuration – 4

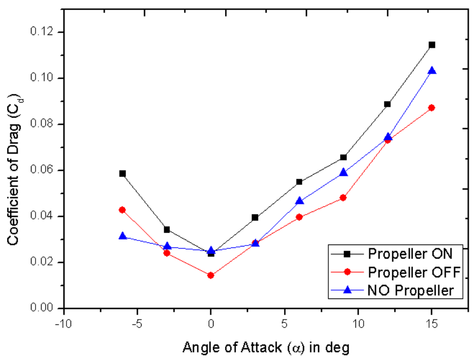

Fig-10(b): C_d Vs α for Configuration – 4

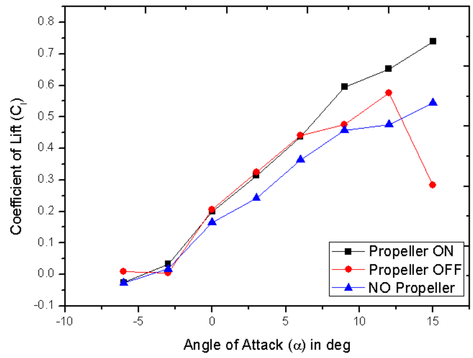

Fig-11(a): C_l Vs α for Configuration – 5

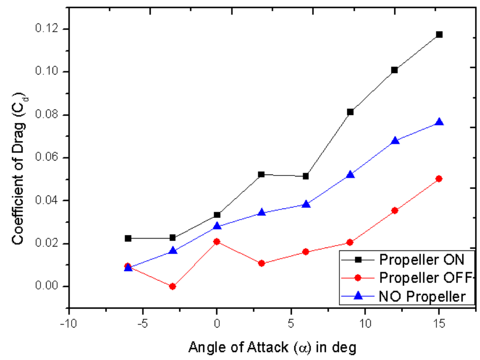

Fig-11(b): C_d Vs α for Configuration – 5

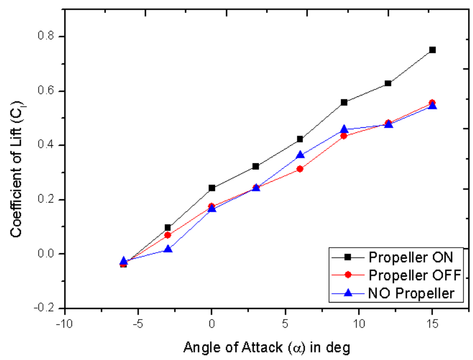

Fig-12(a): C_l Vs α for Configuration – 6

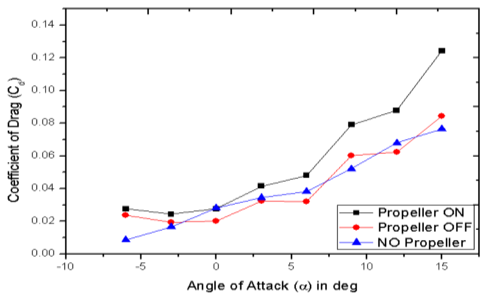

Fig-12(b): C_d Vs α for Configuration – 6

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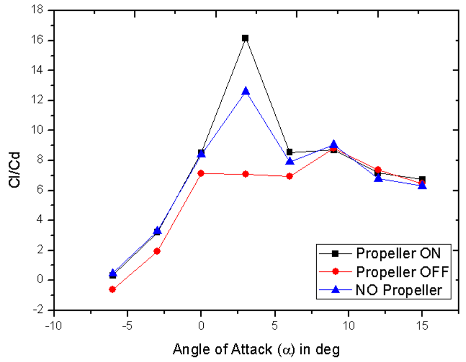

Fig-13: C_l/C_d Vs α for Configuration – 1

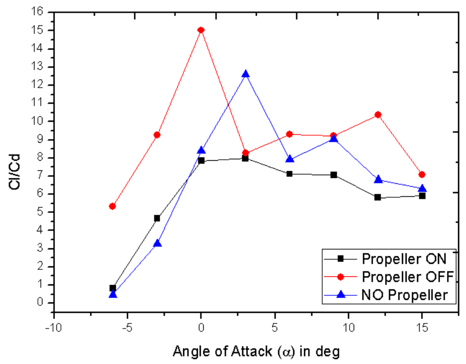

Fig-14: C_l/C_d Vs α for Configuration – 2

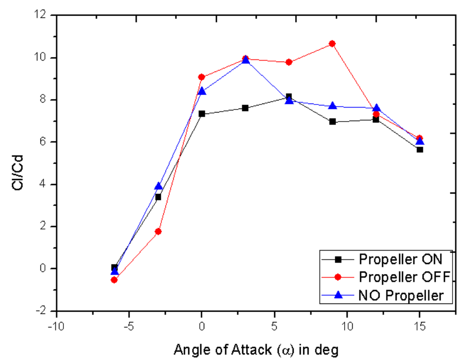

Fig-15: C_l/C_d Vs α for Configuration – 3

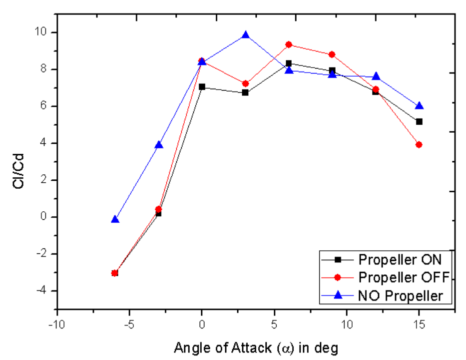

Fig-16: C_l/C_d Vs α for Configuration – 4

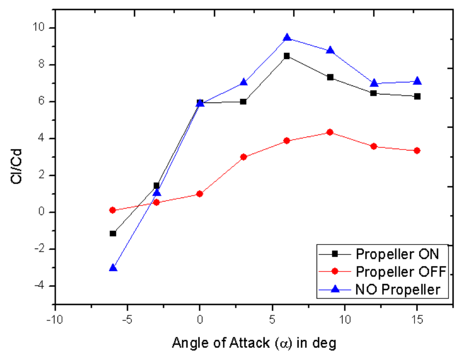

Fig-17: C_l/C_d Vs α for Configuration – 5

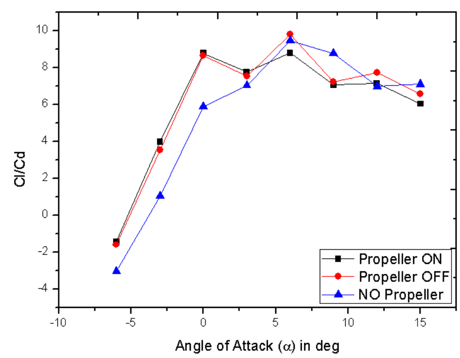

Fig-18: C_l/C_d Vs α for Configuration – 6

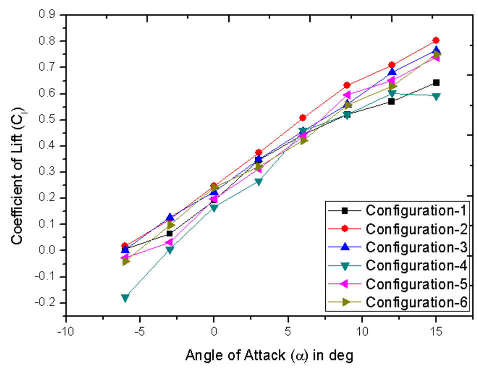

Fig-19: C_l Vs α for all configurations

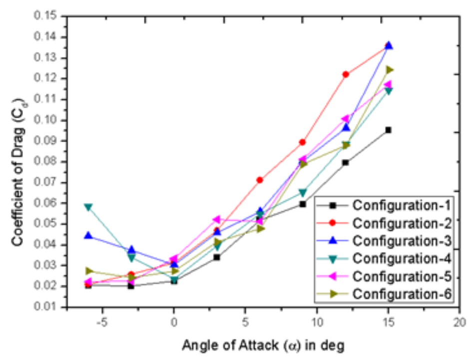

Fig-20: C_d Vs α for all configurations

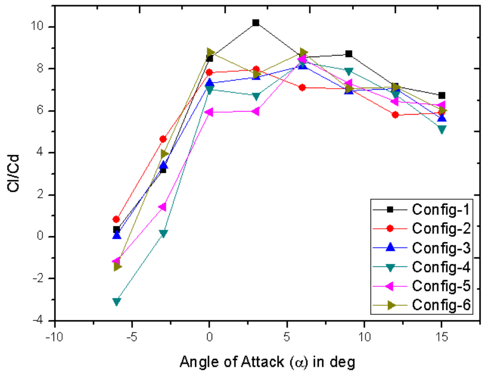

Fig-21: C_l/C_d Vs α for all configurations

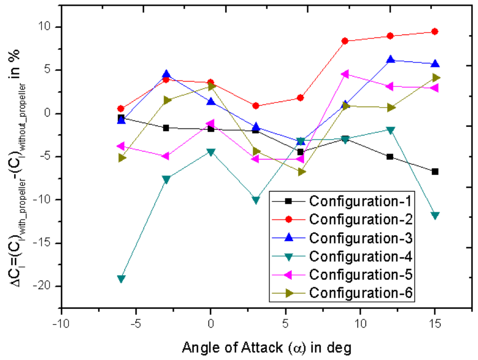

Fig-22: Percentage change in C_l Vs α for all configurations

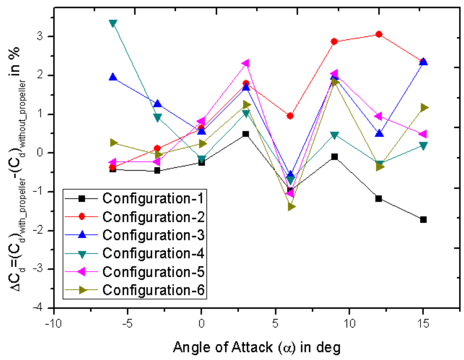

Fig-23: Percentage change in C_d Vs α for all configurations

Table-4: Comparison of C_d values for wing with and without propeller

Angle of Attack	Without Propeller		$\Delta C_d = (C_d)with-prop - (C_d)without-prop$					
(α in deg)	C_d	C_l	Config-1	Config-2	Config-3	Config-4	Config-5	Config-6
-6	0.02484	0.01176	-0.42%	-0.37%	1.95%	3.37%	-0.23%	0.27%
-3	0.02483	0.08168	-0.46%	0.11%	1.27%	0.94%	-0.22%	-0.04%
0	0.02508	0.21057	-0.24%	0.64%	0.55%	-0.14%	0.83%	0.25%
3	0.029	0.36562	0.49%	1.79%	1.70%	1.05%	2.33%	1.25%
6	0.0618	0.48932	-0.97%	0.96%	-0.57%	-0.68%	-1.03%	-1.38%
9	0.06071	0.54926	-0.10%	2.88%	1.97%	0.49%	2.06%	1.84%
12	0.09146	0.62083	-1.18%	3.07%	0.50%	-0.27%	0.95%	-0.35%
15	0.11251	0.70915	-1.72%	2.35%	2.34%	0.22%	0.50%	1.18%

Table-5: Comparison of C_l values for wing with and without propeller

Angle of Attack	Without Propeller		$\Delta C_l = (C_l)with-prop - (C_l)without-prop$					
(α in deg)	C_d	C_l	Config-1	Config-2	Config-3	Config-4	Config-5	Config-6
-6	0.02484	0.01176	-0.48%	0.58%	-0.88%	-18.99%	-3.78%	-5.09%
-3	0.02483	0.08168	-1.67%	3.95%	4.55%	-7.51%	-4.88%	1.56%
0	0.02508	0.21057	-1.79%	3.59%	1.36%	-4.34%	-1.15%	3.17%
3	0.029	0.36562	-1.98%	0.87%	-1.56%	-9.91%	-5.22%	-4.33%
6	0.0618	0.48932	-4.42%	1.83%	-3.27%	-3.09%	-5.22%	-6.72%
9	0.06071	0.54926	-2.89%	8.35%	1.03%	-2.90%	4.59%	0.89%
12	0.09146	0.62083	-4.99%	8.99%	6.20%	-1.81%	3.18%	0.73%
15	0.11251	0.70915	-6.70%	9.50%	5.74%	-11.69%	3.02%	4.20%

From the above tables (Table 4 and 5), it can be summarized that the percentage increase in Cl increased by 9.5% for Configuration-2 with a corresponding increase in Cd by around 2.5% at higher angle of attack when compared to wing without propeller, which is indicative of increase in stall angle for wings with propeller.

IV. CONCLUSION

Estimation of aerodynamic coefficients on Clark-Y wing was conducted without propeller and with propeller for various configuration and result showed improvement in aerodynamic characteristic for all configurations, but for certain configurations such as propeller positioned below the wing and ahead of the wing shows even better performance. Smaller propellers were more effective in distributive manner along wings leading edge wind milling condition was more predominant in larger size propellers. Wake survey analysis was carried on different propeller clearances to know the multiple propeller flow interactions and its effect on wing, wherein small clearances paved way for greater distribution of propellers along wing with an increased efficiency.

UAV technology will always improve further in future where in different and complex propeller configuration may be considered such as given below. Aerodynamics of coaxial propeller flow effect over wing (coaxial propellers have a beneficial effect of less turbulent smooth flow and also reduced gyro effects and vibration). Studying this type of flow helps in development of futuristic tilt rotor aircraft. Rigid wings are generally used in present UAV technology but Aerodynamics of flexible wing mounted propeller flow interaction can show many advantages than compared to rigid wing. Also other than flow interaction benefits it has an added advantage of less fluttering due to damping effects.

Usually higher cruise speed aircraft have swept wing than straight wing. So, Aerodynamics of forward and backward swept wing mounted propeller flow interaction has to be studied to help the designing of swept wing UAVs with electric propulsion

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AUTHORS PROFILE

Srinivasan S personal profile which contains their education details, their publications, research work, membership, achievements, with photo that will be maximum 200-400 words.

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