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Experimental Analysis of Double Box Wing UAV

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Abstract-- **In an attempt to reduce the induced drag on a wing, Prandtl found that induced drag reduced significantly by highly increasing the number of vertically offset wings. The same result could be obtained by joining the wingtips of two vertically offset wings. This helped increase payload capacity and also reduced fuel consumption and emissions. Such a wing configuration came to be known as Prandtl's box wing. In this work, the design and analysis of a box wing aircraft model has been carried out. The preliminary analysis is performed using XFLR5, and the computational analysis is done with the help of ANSYS 18.2. The values of experiments are computed with the help of MATLab R2017. The box wing model has shown a nearly 53.74% reduction in drag as compared with conventional wing models. The computational results of drag have been compared and validated with the results of analytical and the experimental results from the wind tunnel and found to be within 10% of the computational result. Since the drag of the box wing is significantly lesser than the conventional wings the box wing is a feasible configuration which can be used to design various aircrafts including Unmanned Aerial Vehicles and Commercial Planes.**

Keywords-Prandtl wing; wind tunnel test; induced drag; Ansys

1 INTRODUCTION

Man has always been fascinated with nature and has taken inspiration from all species, be it for running on ground, swimming in water like a fish, or flying in air like a bird. Like running or swimming, till this date, man cannot fly all by himself but the advancements in research and technology has enabled man to fly with the help of machines. Since the development of the first aircraft, researchers have been trying to improve flights by trying out different structural aspects to minimise drag and fuel consumption.

One such wing configuration is of the Prandtl's box wing which was proposed by Ludwig Prandtl for the reduction of drag. With his work, Prandtl found that by highly increasing the number of wings which were vertically offset the induced drag reduced significantly and almost approached zero [1]. The same result could be achieved by joining the wing tips of two vertically offset wings which came to be known as Prandtl's box wing [1]. This configuration helped in distributing the uplift requirement between two wings rather than just applying it all on one lifting surface, which helped in increasing the payload [2].

This paper presents a theoretical introduction and experiment-based research on Prandtl's box wing for Unmanned Air Vehicles (UAV) applications. The box wing design helps drag reduction of the plane to quite an extent, thus reducing fuel consumption of the aircraft significantly [3]–[6]. The aircraft emissions will be reduced if the fuel consumption is reduced [2], [7], [8]. Few studies were performed to understand the flow behaviour to reduce the drag on the bio inspired corrugated wings and found that the drag is significantly reduce by using corrugated wings found in natural low Reynolds number flight [9], [10].

For the air to develop lift we take into consideration the generation of lift by circulation. When a stream of jet fluid flowing in contact with a curved surface follows the curved path rather than flowing away in a straight line, the effect is called the 'Coanda effect'. This effect can be seen on an airfoil moving in air. The air flows from higher pressure to lower pressure region and since the bottom surface has higher pressure compared with the pressure on top surface of the wing, at the wing tips the air flows from the bottom surface to the top surface from around the wing tips along with the airflow from the leading edge to the trailing edge at the tips. The air flows from root to tip at the bottom surface of the wing and from tip to root at the top surface of the wing. We can thus say that the flow is non-linear from leading edge to trailing edge along the upper and lower surfaces of the wing along with a span wise component of airflow. The air flows in opposite directions on each wing span wise.

A flow is generated due to the combination of the free stream flow and the rotating flow around the wing tips which is termed as the 'wing tip vortices'.

The span wise flow will be a function of the generated lift which will result in a greater pressure difference due to more lift, in turn forming larger vortices. The wing tip vortices from the trailing edge of the wing tips induces a flow circulation along the chord. This produces a vertical component of the flow which is 'upwash' ahead of the wing and aft of the wing is 'downwash' because of which the wing is in a relative flow inclined downwards. Due to the downwash effect a larger angle of attack is required for providing additional lift in order to make up.

The lift is produced only due to a vertical component of the lift vector as the lift vector is inclined at an angle because of induced flow. The horizontal component of the lift vector is in the direction opposite to the thrust vector which is a drag component called induced drag. Lift generated from a finite wing induces this drag. An angle of attack is induced, which is called the induced angle of attack, it is the angle between the effective airflow (or the velocity of the airstream relative to the wing) and the horizontal.

A conventional wake rake having 28 Pitot probes and 2 Pitot static probes was used for the test. The pressure data spanning the entire wake can be collected using the conventional wake rake, where individual pressures can be accurately measured with the help of a multi-tube manometer. The conventional wake rake can accurately calculate drag and clearly establish the shape and height of the wake. But this method requires a large amount of equipment and separate tubing for each pressure probe. [5]

2 METHODOLOGY

The Equation for total drag of a multi-plane as given by Prandtl [1]is

$$D = \frac{L^2}{\pi q {b_m}^2} \frac{1-\sigma^2}{r(r+\frac{1}{r}-2\sigma)} \qquad (1)$$

Which can be re-iterated as

$$CD = \frac{cL^2 A}{\pi {b_m}^2} \frac{1-\sigma^2}{r(r+\frac{1}{r}-2\sigma)} \qquad (2)$$

Where,

D= total drag, L= total lift, q= dynamic pressure head, i.e. $\frac{1}{2}\rho v^2$

σ= Coefficient of additional drag induced due to biplane configuration

Which is equal to

G= vertical distance between two wings, b_1= wing span of primary wing

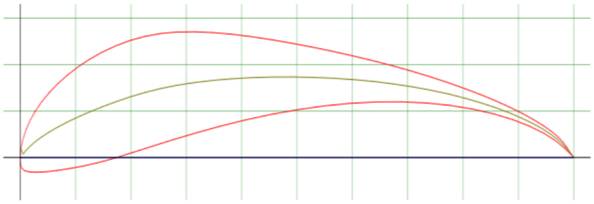
$$\sigma = \frac{1-0.66\frac{G}{b_1}}{1.05+3.7\frac{G}{b_1}} \qquad (3)$$

As the coefficient of lift was assumed to be same for both the wings by Prandtl in his equation the result we will get through the experimental analysis and CFD will be different from the theoretical value we got through Prandtl equation.

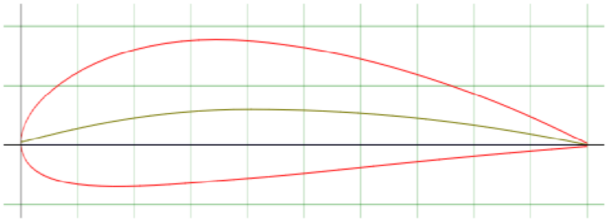
2.1 AIRFOIL SELECTION

The airfoil profiles have been taken from UIUC database and interpolated in XFLR5.

A modified S1223 airfoil has been used for the main wings while NACA 3412 has been used for the rear wings. NACA 0010 has been used for winglets and the vertical and horizontal stabilizers (Fig.1). The preliminary analysis was carried out in XFLR5 at Re=10,000 corresponds to 10 m/s of the free stream velocity and results are shown in figure 2 with XFLR results of CL, CD with angle of attack.



S1223



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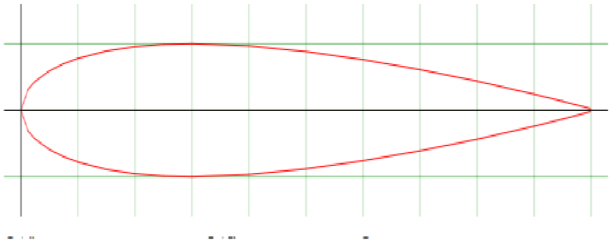

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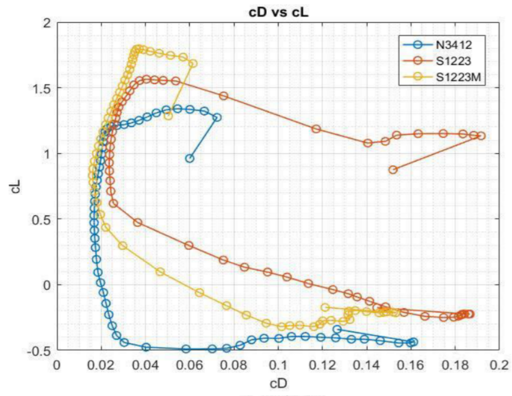
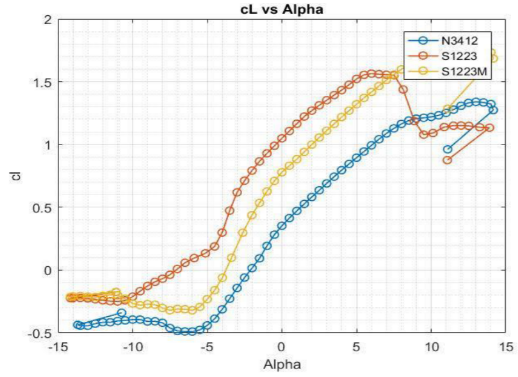
Fig. 1 Airfoil profiles for different parts





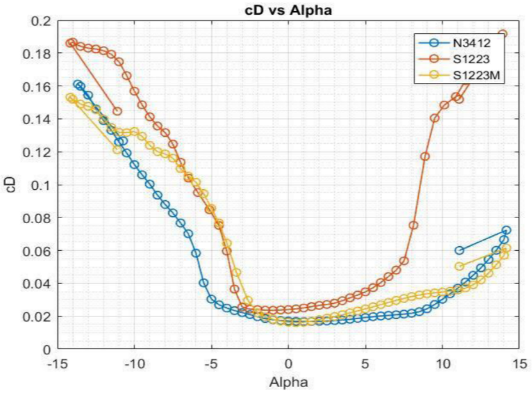


Fig. 2 Graphs from XFLR5- C_D vs C_L, C_L vs alpha, C_D vs alpha

3 COMPUTATIONAL ANALYSIS

The model has been designed in accordance to [4][6] using CATIA V5 R20. The main wing is made of modified S1223 airfoil, while NACA 3412 is used for rear wing and NACA 0010 has been used for winglets. The detail CAD model of box wing aircraft model is shown in figure 3.

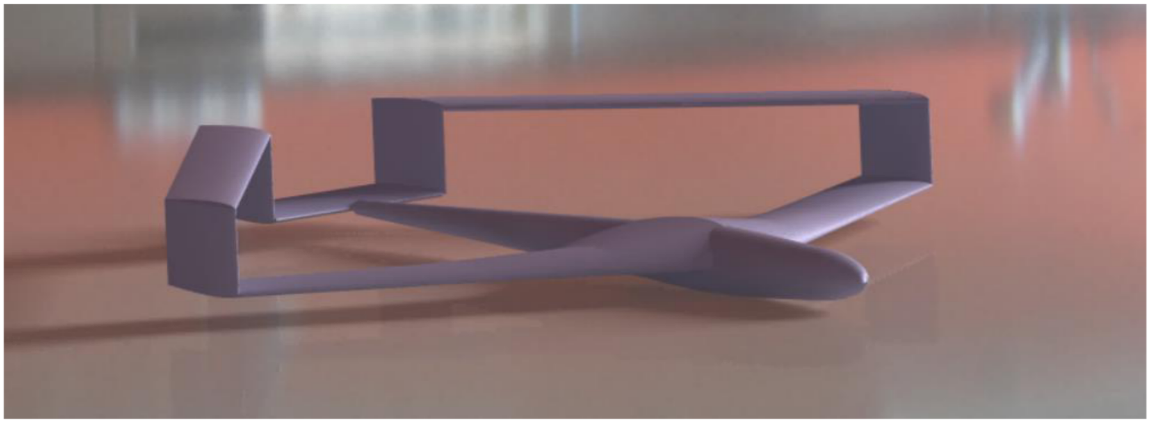


Fig. 3 Box Wing Model CATIA Design

3.1 Meshing

The meshing was done using unstructured tetrahedral elements since it allows clustering of cells in selected regions, and so can be created with fewer cells than quadrilateral or hexahedral cells [3]. Face meshing was done using elements of size 2 mm. The boundary conditions applied were as follows;

At inlet- velocity (v_i)= 10 m/s ; pressure (p_i)= 1 atm

At outlet- pressure (p_o)= 1 atm ; walls at slip condition

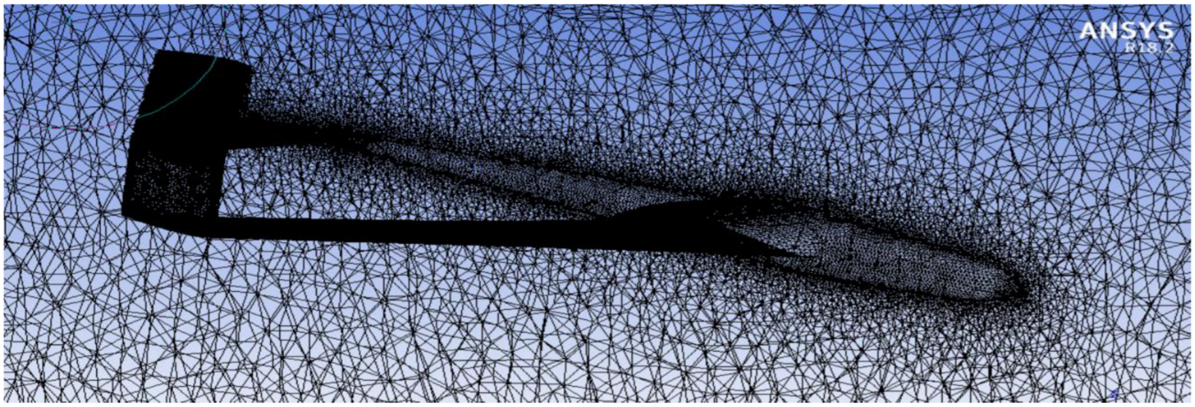


Fig. 4 Meshing in ANSYS

4 EXPERIMENTAL SETUP

4.1 Drag Estimation using wake rake

The wind tunnel was used to measure the drag by using wake rakes as shown in figure 5. The drag from the wake rake analysis [5] was computed using MATLab R2017 with equation 4.

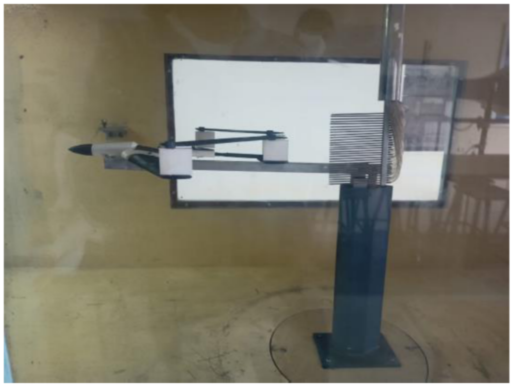
$$C_D = \int_{-\infty}^{\infty}\left(\sqrt{\frac{\Delta P_i}{\Delta P_\infty}} - \frac{\Delta P_i}{\Delta P_\infty}\right)\frac{dy}{d} \qquad (4)$$

where,

ΔP_i is the pressure at probe, ΔP_∞ is the pressure at free stream conditions

dy is the distance between probes, d is the longitudinal length of the model

(a)



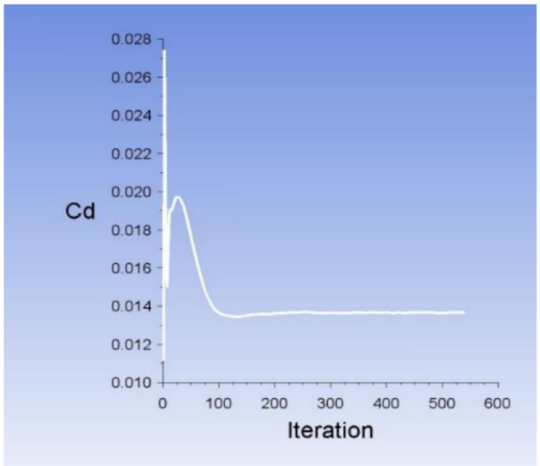
(b)

Fig. 5 (a)Wind Tunnel and (b)Model Setup in Wind Tunnel

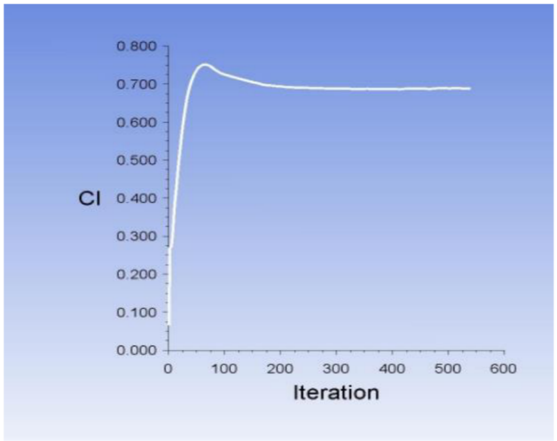
5 RESULTS AND DISCUSSION

All the results were extracted from ANSYS 18.2 from which the value of cL is 0.688 and cD is 0.0136. The cL/cD value is 50.58. According to Eq 2 the value of C_D is 0.023 for the design, it can be inferred that the drag value has decreased in computational analysis as a different Airfoil is used for the rear wing.

The Calculated drag value of the box wing plane is 0.0136 which is close to the value 0.0181 obtained from wind tunnel testing, thus, it can be inferred that the computational analysis has been validated and the plane has an effective L/D ratio of approximately 50.

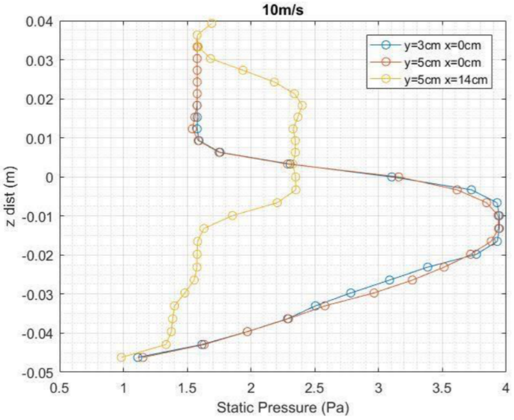


(a)



(b)

Fig. 6 ANSYS results for coefficient of lift and drag



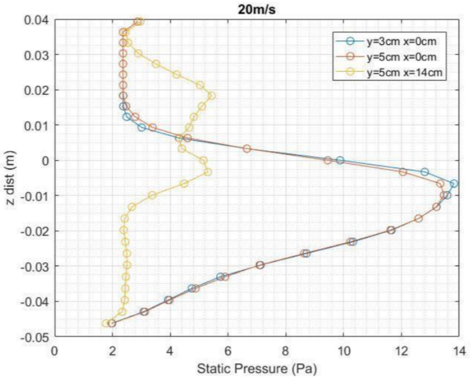


Fig. 7 Graphs from MATLab

In the graphs above, y is distance from trailing edge to the wake rake and x is the spanwise length x=0 at the root and x = 14cm at the tip. It can be observed that the effects of wing tip vortices are less.

$$\frac{c_{d\ conventional}-c_{d\ box\ wing}}{c_{d\ conventional}}\ x\ 100 = 53.74\% \quad (5)$$

5.1 VALIDATION

The results of drag coefficient theoretical, experimental and numerical are given in table 1. These results are very near to each other hence the numerical results obtained by this research is validated.

Table1. Validation of results

Method	*Drag Coefficient*
Theoretical	0.023
Experimental	0.0181
Numerical	0.0136

6 CONCLUSION

Box wing is an effective design where its efficiency outweighs its disadvantages which include adverse yaw, difficulty in manufacturing and structural issues all of which can be reduced by implementing new advancements in the field of unmanned aerial vehicles. The box wing configuration showed 53.7% decrease in drag coefficient in comparison to conventional wing drag coefficient. Further analysis at different geometric conditions can be carried out for this configuration. Due to the reduction in drag, it can be inferred that the box wing configuration is a viable configuration which can be implemented in designing of various UAVs and commercial airplanes. Due to its high aerodynamic efficiency the cost of the operation would be reduced significantly when compared to other conventional configurations.

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