Experimental Study - Flow Characteristics of Dimpled Wing

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***Abstract*— In the present work the flow characteristics of dimpled wing have been investigated experimentally and compared with a smooth wing. Flow visualization was carried out in a water flow channel at constant flow of 0.22 m/s with Reynolds number 3.2934×10^4 and Experiments tests were carried out in the low speed open-typed wind tunnel at constant air speed 21.75m/s and Reynolds number 1.92×10^5 based on chord of the wing. The objective of this project is to determine how the dimples varies the flow characteristics of the wing section. This can be achieved by wing section of NACA 2412 were fabricated by wood with eight pressure port to measure the pressure distribution over the wing surface. First smooth wing section is flow visualized on water flow channel by pouring wood power over the surface of water current to find the transition point. After that round dimple with 2.5mm radius is added near the transition point to create premature turbulence which re-energizes the impeded flow and hence delays the flow separation and reduces the pressure drag. And the wing section is analysis by low speed wind tunnel with smooth and dimpled wing. And coefficient of lift and drag are calculated for both wings. Then results are verified by comparing both dimpled and smooth wing. Which ensures the Dimpled wing produce more lift to drag ratio than smooth wing by delaying the boundary layer separation hence increasing aerodynamic efficiency.**

Keywords—airfoil; flow visualization; wind tunnel; dimpled wing; lift to drag ratio; aerodynamic efficiency.

I. INTRODUCTION

All solid objects traveling through a fluid acquire a boundary layer of fluid around them, which may be a laminar or turbulent that can be say by Reynolds number of the local flow condition. **Flow separation** is the detachment of flow from the surface, which occurs when the boundary layer travels far enough against an adverse pressure gradient. At present, there are different kinds of surface modifications are being studied to delay the flow separation inorder to improve the aerodynamic efficiency of the aircraft. In which Micro riblets and vortex generators are current techniques used to modify the surface of an aircraft wings. A vortex generator is an aerodynamic surface, consisting of a small vane that creates a vortex. The effect of vortices produce turbulence which delays the boundary layer separation resulting in decrease of pressure drag and also increase in lift at high angle of attack. They are typically rectangular or triangular, about 80% as tall as the boundary layer, and run in spanwise lines near the thickest part of the wing. Riblets are another type of modification that is being considered these days. The surface modifications which are being considered in the given study are dimples. Till now these have been ignored because dimples help in reduction of pressure drag. In case of aerodynamic bodies pressure drag is very little compared to bluff bodies. An airfoil is an aerodynamic body so dimples do not affect to its drag much at zero angle of attack, but as soon as airfoil attains some angle of attack, wake formation starts due to boundary layer separation. Application dimples on aircraft wing model works in same manner as vortex generators. Various forms of recessed vortex generators exist, including simple grooves of various profiles, dimples, and porous cavities designed to take advantage of adverse pressure gradients and create circulation around separation points. One of the earliest investigations of the flow features near surfaces with spherical dimples was made by Bearman and Harvey. This study assessed the effects of dimples on the flow around a cylinder and a golf ball as they underwent transition from subcritical to post-critical flow. The results of this study demonstrated the effectiveness of dimples as a technique for causing early boundary layer transition without the drag penalties associated with surface roughness. In addition, they found that the reduction in drag is related to the **vortex shedding frequency**. The shedding vortices are thought to be the feature generated by dimples that help to keep the flow from separating.

II. EXPERIMENTAL STUDY

Flow channel Visualization

This project is start from flow visualization test with wooden wing section of NACA2412 fabricated with eight pressure ports as shown in fig 2.1.

Fig 2.1 Top view and cross-section of wing section NACA 2412

Flow visualization primarily undertaken to recognize the points of flow separation on as a function of varied angle of attacks of the wing section. Saw dust was used for the flow visualization technique. The point at which the saw dust withdraws from the surface of the airfoil is taken to be the point of flow separation of the flow. The water in the flow channel is circulated by motor driven paddle. The paddle and the driving motor are coupled by means of conveyor belt. The flow velocity 0.22m/s and the Reynolds' number 3.2934×10^{4}.

$$\text{Reynolds number Re} = \frac{\rho v c}{\mu} \qquad (2.1)$$

Below figures shows the flow separation of smooth and dimpled wing at different angle of attacks.in which smooth creates separation at α = 10 itself at 30% of the chord, but in case of dimpled which shows attached flow even at α = 15.

Fig: 2.1a Smooth wing at α = 0

Fig: 2.1b Dimpled wing at α = 0

Fig: 2.2a Smooth wing at α = 5

Fig: 2.2b Dimpled wing at α = 5

Fig: 2.3a Smooth wing at α = 10

Fig: 2.3b Dimpled wing at α = 10

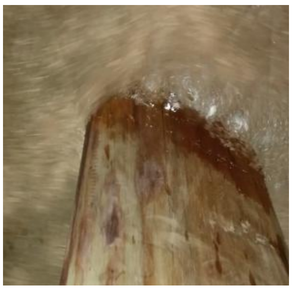

Fig: 2.4a Smooth wing at α = 15

Fig: 2.4b Dimpled wing at α = 15

Wind tunnel tests

The wooden prototype of NACA 2412 was fabricated with pressure ports to measure static pressure. There are a total of 8 ports, with 3 ports on each side, one on the leading edge and one on the trailing edge of the airfoil. The wind tunnel in the laboratory is of suction type with its test section measuring is 60cm x 60 cm. The maximum velocity of flow which can be achieved in the wind tunnel is 40m/s. The velocity of flow is calculated using an inclined manometer. The inclination of the manometer is 30^{O} and it measures the difference between stagnation pressure and static pressure. The 8 pressure ports are connected to vertical manometers as shown fig2.5, indicating the local static pressure at the corresponding ports.

Fig 2.5 Wing section before install into the windtunnel

The manometer gives you the difference of pressure between the pressure you are trying to measure and the ambient or atmospheric pressure, from this we find the values of stagnation pressure P_0, static pressure P_s and indicating surface pressure P_i that are tabulated in table 2.1. from this C_p values are calculated by the equation (2.2)

$$C_p = \frac{Pi - Ps}{Po - Ps} \qquad (2.2)$$

PRESSURE DISTRIBUTION OF NACA 2412 ORDINARY WING															
	Re=1.92×10^{5}			velocity=21.75 m/s					Ps = 3	Po = 0.2					
			α = 0		α = 5		α = 10		α = 15		α = -5		α = -10		
Port	x	x/c	Pi	Cp	Pi	Cp	Pi	Cp	Pi	Cp	Pi	Cp	Pi	Cp	
1	0	0	0	1.071	6.7	-1.321	16	-4.643	18.5	-5.535	0.8	0.786	2	0.357	
2	6	0.4	6	-1.071	6.6	-1.286	7.4	-1.571	7	-1.429	5	-0.714	4.4	-0.5	
3	9	0.6	5.8	-1	6	-1.071	6.2	-1.143	5.5	-0.892	5.2	-0.786	4.8	-0.643	
4	12	0.8	5.5	-0.892	5.4	-0.857	5	-0.714	5	-0.714	5	-0.714	5	-0.714	
5	15	1	4.4	-0.5	4	-0.357	4.5	-0.536	5	-0.714	4.9	-0.679	4.8	-0.643	
6	12	0.8	4.5	-0.536	4	-0.357	4.2	-0.429	4.4	-0.5	5.2	-0.786	5.4	-0.857	
7	9	0.6	4.5	-0.536	3.8	-0.286	3.7	-0.25	3.5	-0.179	5.4	-0.857	6.2	-1.143	
8	6	0.4	4.6	-0.571	3.7	-0.25	3.3	-0.107	3	0	5.8	-1	7.9	-1.75	
1	0	0	0	1.071	6.7	-1.321	16	-4.643	18.5	-5.535	0.8	0.786	2	0.357	

Table 2.1. Smooth wing pressure distribution.

From the tabulation pressure distribution graphs are plotted for C_p verses x/c, In which orange color curves shows pressure distribution at upper C_{pu} and blue lines shows pressure distribution at lower $C_{pl.}$

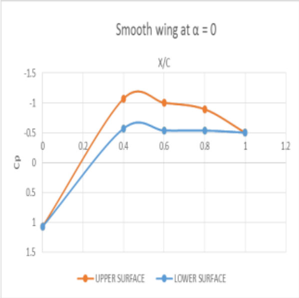

Fig: 2.6a Smooth wing at α = 0

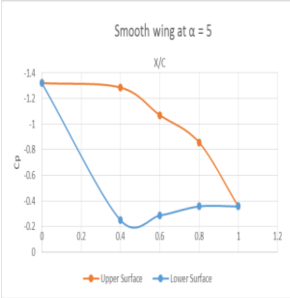

Fig: 2.6b a Smooth wing at α =5

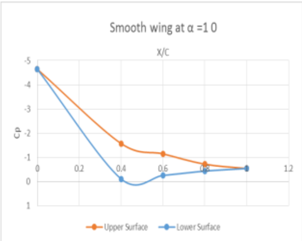

Fig: 2.6c a Smooth wing at α = 10

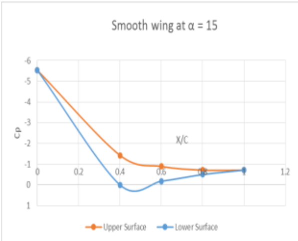

Fig: 2.6d a Smooth wing at α =15

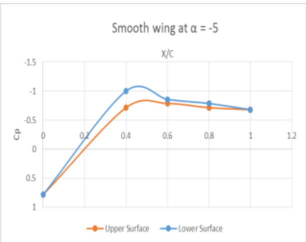

Fig: 2.6e Smooth wing at α = -5

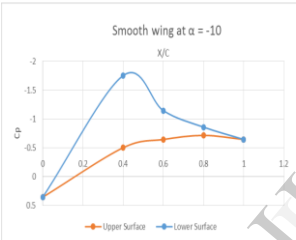

Fig: 2.6f Smooth wing at α = -10

The experiment with surface modification in the form of dimple made by wood in a hemispherical shape as shown fig.2.7 Size of the dimple is 2.5 mm radius and its location at 20% of chord. The dimpled is attached on the surface with Anabond glue.

Fig 2.7 Attachment of dimple on the surface of wing section

After the attachment dimple the wing section is test by same setup through the wind tunnel. The readings obtain from the manometer are table in table 2.2.

PRESSURE DISTRIBUTION OF NACA 2412 DIMPLED WING														
	Re=1.92x10[5]		velocity=21.75m/s				Ps=2		Po=0.2					
			α=0		α=5		α=10		α=15		α=-5		α=-10	
Port	x	x/c	Pi	Cp	Pi	Cp	Pi	Cp	Pi	Cp	Pi	Cp	Pi	Cp
1	0	0	0.4	0.888	8.2	-3.44	13	-6.111	18.5	-9.166	0	1.111	2.5	-0.277
2	6	0.4	5.3	-1.833	6.2	-2.333	7	-2.778	6.5	-2.5	4.7	-1.5	4	-1.111
3	9	0.6	6	-2.222	6.4	-2.444	6.5	-2.5	5	-1.667	5	-1.667	4.5	-1.389
4	12	0.8	5.7	-2.055	5.7	-2.055	5.5	-1.944	5.3	-1.833	4.9	-1.611	4.7	-1.5
5	15	1	4.5	-1.388	4.4	-1.333	4.5	-1.388	5.3	-1.833	4.5	-1.388	4.7	-1.5
6	12	0.8	4.8	-1.555	4.3	-1.277	4.3	-1.278	4.5	-1.389	4.9	-1.611	5	-1.667
7	9	0.6	4.8	-1.555	4.1	-1.167	3.9	-1.056	3.8	-1	5.2	-1.778	5.6	-2
8	6	0.4	5	-1.666	4	-1.111	3.6	-0.889	3.2	-0.667	5.6	-2	7.2	-2.888
1	0	0	0.4	0.888	8.2	-3.44	13	-6.111	18.5	-9.166	0	1.111	2	-0.277

Table 2. Dimpled wing pressure distribution.

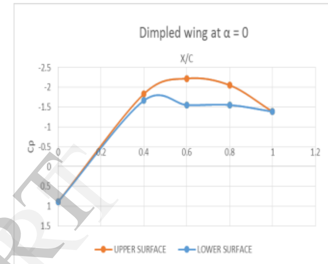

Fig: 2.8a Dimpled wing at α =0

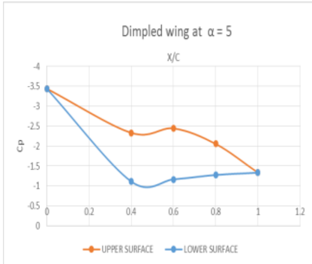

Fig: 2.8b Dimpled wing at α =5

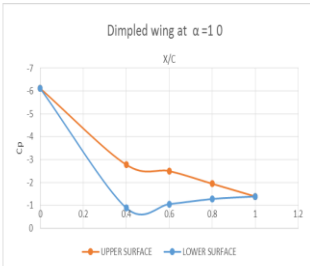

Fig: 2.8c Dimpled wing at α =10

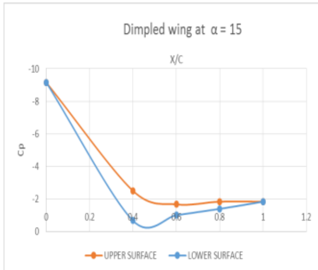

Fig: 2.8d Dimpled wing at α =15

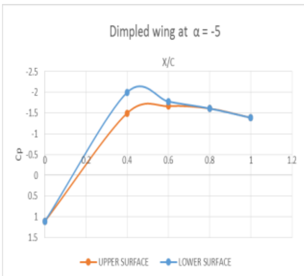

Fig: 2.9e Dimpled wing at α = -5

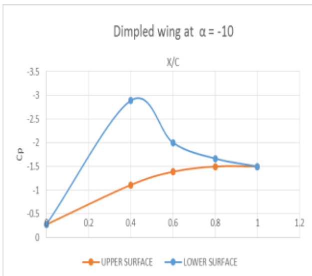

Fig: 2.9f Dimpled wing at α = -10

III. RESULT AND DISCUSSION

The study starts with Flow visualization analysis of NACA2412 wing section with smooth and dimpled surface. After finding the transition point on the surface, dimple is placed at 20% of chord which delays the flow separation in satisfaction manner. Then the model is tested in wind tunnel, the pressure distribution of both wing sections are find out, from that the pressure distribution graphs are drawn. The coefficient of lift C_L and coefficient of drag C_D are calculated and tabulated by using equation (3.3) & (3.4). Since the C_p values are determined experimentally, we can use one of the simplest numerical methods for computing integrals, the trapezoidal rule. The coefficient of lift (C_L) is calculated for both of these configurations. The study shows dimple produces lesser drag at positive angle of attacks with increase of lift.

$$C_L = \frac{1}{c}\int_{LE}^{TE} C_{pl}\,dx - \frac{1}{c}\int_{LE}^{TE} C_{pu}\,dx \qquad (3.1)$$

$$C_L = \frac{1}{c}\int_{LE}^{TE} (C_{pl} - C_{pu})\,dx \qquad (3.2)$$

$$C_L = \int_{0}^{1} (C_{pl} - C_{pu})\,d(x/c) \qquad (3.3)$$

$$C_D = \int_{0}^{1} (C_{pu} - C_{pu})\,d(y/c) \qquad (3.4)$$

In words, equation (3.3) says the sectional lift coefficient is equal to the difference between pressure coefficients. Evaluated on the lower surface and upper surface, integrated along the chord line in terms of the fractional distance measured from the leading edge to the trailing edge.

α	C_{pu}	C_{pl}	C_L
-10	-0.4143	-0.9179	-0.5036
-5	-0.4249	-0.5393	-0.1144
0	-0.5355	-0.2215	0.314
5	-1.0713	-0.5035	0.5678
10	-1.8249	-1.1501	0.6748
15	-1.9283	-1.3142	0.6141

Table 3. C_L values of smooth wing from C_p values

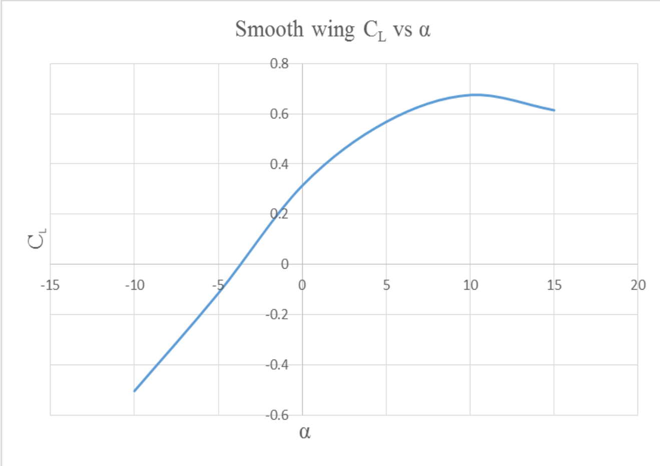

Fig: 3.1 Cl vs α for smooth wing.

α	Cp	Cpl	Cl
-10	-1.11648	-1.8052	-0.68872
-5	-1.0222	-1.1944	-0.1722
0	-1.3665	-1.083	0.2835
5	-2.421	-1.64334	0.77766
10	-3.08314	-2.09436	0.98878
15	-3.4665	-2.69429	0.77221

Table 4. Cl values of dimpled wing from Cp values

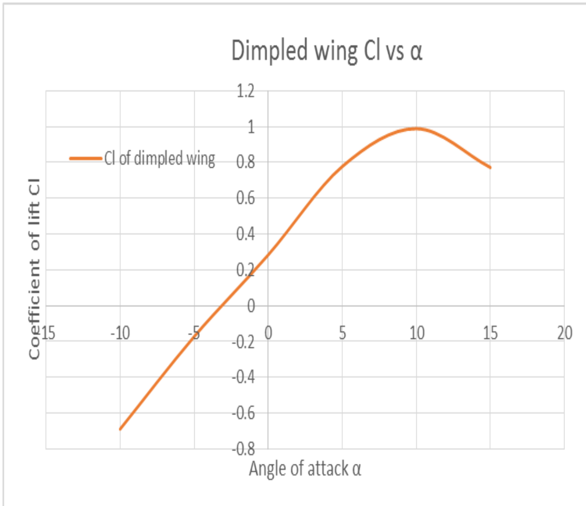

Fig: 3.2. C_L vs α for dimpled wing.

α	Smooth wing C_L	Dimpled wing C_L
-10	-0.5036	-0.68872
-5	-0.1144	-0.1722
0	0.314	0.2835
5	0.5678	0.77766
10	0.6748	0.98878
15	0.6141	0.77221

Table 5. Comparison of C_L values of smooth and dimpled wing

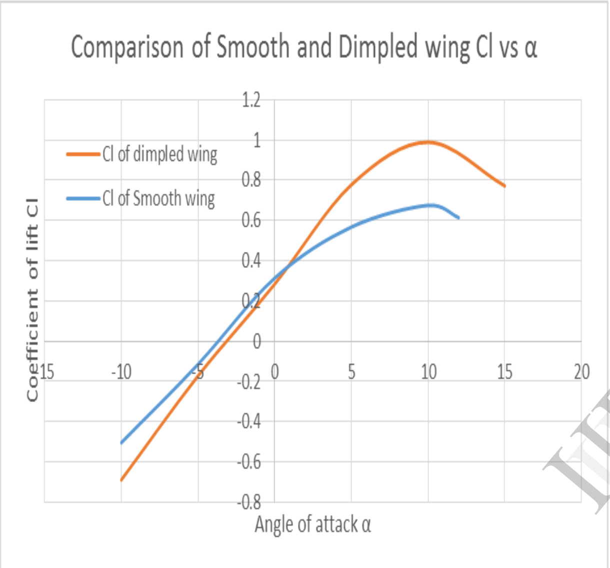

Fig: 3.3 Comparison of Cl vs α for smooth and dimpled wing.

IV. CONCLUTION

The presence of 2.5 mm radius hemispherical dimple at 20% of chord has greatly altered the flow characteristics over the surface of an airfoil. The aerodynamic efficiency increases for different angle of attacks listed in table, which shows dimpled wing section produce more lift than smooth wing. There is also marked improvement of coefficient of lift and coefficient of drag with surface modification. Flow separation has been delayed locally. This creates room for a safe assumption that there shall be an increase in stalling angle value for the airfoil. This, if incorporated would be extremely beneficial in making an aircraft more maneuverable and increase the aircraft's fuel economy.

Addition of dimples has proven to be effective in altering various aspects of the flow structure. With such significant flow structure the resultant lift and drag forces are also altered. Based on these results a new Smart dimple matrix is suggested over airfoils which will sense boundary layer separation and arrange dimple in the least drag and high lift configuration.

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