(IJAER) 2019, Vol. No. 18, Issue No. VI, December **e-ISSN: 2231-5152, p-ISSN: 2454-1796**

ANALYSIS OF AERODYNAMIC PERFORMANCE OF AIRCRAFT WING ATTACHED WITH DIMPLE USING CFD

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ABSTRACT

Pressure drag is a mechanical force generated by a solid moving object in fluid. This work focuses on the reduction of pressure drag in aircraft. Pressure drag is an unavoidable force which forms as a reaction force to the motion of the aircraft and thereby decreasing its performance. So, the aircraft must put forth a huge extra force to pass through and needs more power to overcome the pressure drag which leads to more fuel consumption and decreasing the aircraft's efficiency. The complete aim of the work is to add Dimple shapes in wing to reduce the pressure drag and increase the performance and efficiency of the aircraft. The addition of Dimples will reduce the pressure on the wings surface and will decrease the pressure drag force that acts on the aircraft which thereby increases the aircraft's performance. This work holds the complete process of modeling aircraft in CATIA and analyzing the aircraft wings with dimple to clearly visualize the idea of using Dimple to reduce pressure drag. As computational fluid dynamics analysis using ANSYS FLUENT can easily compute results on applications that use airflow, it is used for analyzing the aircraft's wing to show the reduction of pressure drag.

Keywords—Pressure drag, Reduction of Pressure drag, Dimples, Computational Fluid Dynamics.

Abbreviations—Computational Fluid dynamics: CFD.

NOMENCLATURE

P_L = Pressure at leading edge

P_T = Pressure at trailing edge

P_R = Reduction in pressure at trailing edge

V_L = Velocity of air at leading edge

V_T = Velocity of air at trailing edge

V_I = Increase in velocity of air at trailing edge

F_{WD} = Force without Dimples

F_D = Force with Dimples

F_R = Reduction in pressure drag force

INTRODUCTION

An aircraft is a machine that is able to fly by gaining support from the air. It counters the force of gravity by using either static lift or by using the dynamic lift of an airfoil or in a few cases the downward thrust from jet engines [1]. Aim of the work is to decrease the pressure drag on the aircraft by modifying the object geometry with the help of pressure drag reducing agents to increase the efficiency of the aircraft. This work on reduction of pressure drag is done on the Boeing 737-600 aircraft because all the dimensional parameters are open source data. The pressure drag is more on the aircraft wings when compared to the fuselage and other parts of the aircraft [2, 3 and 4]. The fuselage pressure drag is neglected unless it is a supersonic or an aircraft with blended wings because the induced pressure drag is very less on the fuselage and it only has parasite pressure drag [5 and 6]. The pressure drag in this work on the wings is reduced using Dimples on the wing surface. The shape of the Dimple is a semi – spherical shape made on the surface of the wing to increase the performance of the aircraft and to reduce the pressure drag.

The literature survey for this work is from journals by Md. Fazle Rabbi, Rajesh Nandi, Mohammad Mashud et al. Induce Pressure drag Reduction of an Airplane Wing, describes some of the modeling aspects for the aircrafts [7]. Mohsen Jahanmiri et al. Aircraft pressure drag reduction an overview, states the various changes that have been done with respect to pressure drag reduction [8]. Staffan Hardie et al. Pressure drag force estimations on experimental aircraft, states the details and basics for meshing and analysis using Computational Fluid Dynamics [9]. Katsumi Aoki, Koji Muto, Hiroo Okanaga and Yasuki Nakayama et al. Aerodynamics Characteristic and flow pattern on Dimple structure of a sphere, describes the relation between the drag and the flow patterns of air on sphere [10]. Chang-Hsien Tai, Chih-Yeh Chao, Jik-Chang Leong and Qing-Shan Hong et al. Effects of Golf ball Dimple Configuration on Aerodynamics, Trajectory and Acoustics; portrays the effect of aerodynamics on a surface (on a golf ball) with Dimples [11]. C. K. Chear, S. S. Dol et al. Vehicle Aerodynamics: Drag reduction by surface dimples, describes the flow of air on a dimple and effects of simple in a surface [12].

The scope of this work is to improve the air transportation by increasing the performance and efficiency of the aircraft. Since the aircraft is very huge, high cost and time to experiment the change with a real aircraft. So, the aircraft is modeled and a CFD analysis is carried out to get the desired result of our work. The addition of Dimples in the aircraft will make the airflow to flow on the surface making rate of flow separation slow and reducing the pressure drag. The reduction in pressure drag is taken from the results of the CFD analysis.

The methodology of this work is studying of the aircraft, studying of pressure drag and factors affecting pressure drag, then the modification to reduce the pressure drag. After this the aircraft is modeled in CATIA, two models are made; one is the existing and the other with Dimples for easy comparison. Then the model is meshed in HYPERMESH software and analysis in Computational Fluid Dynamics by ANSYS Fluent software. Finally the results are inferred and the existing and new design are compared.

MODELING AND ANALYSING

A. *Dimples*

Dimple is a slight depression in the surface of an object. Dimples can make the air flow attached to the surface of the wing for a slight long period by making the flow separation on the surface occurring late. This continuous flow on the wing will be smooth without any whirls and will flow out of the surface without forming much wakes. This reduces the pressure drag created on the surface of the wing.

In this work Dimples are arranged from the leading edge towards the trailing edge spread across the surface of the wing, leaving space for lift generating components and other necessary components like flaps and ailerons. Dimples are also made with varying depth with equal radius along the wing surface to make sure that none of the dimple clashes on either side. The dimple is also not too shallow because shallow dimples can make way for quick flow separation which increases pressure drag [11, 12].

Figure 1 shows the front view of Dimple that is made on the aircraft wing surface. The dimensions taken are to make sure that Dimple on either side doesn't collide and also it is safe for the placement of flaps and ailerons to create lift. Dimples are placed on top and the bottom side of the wing to make the air flow through the wing surface evenly to reduce the pressure drag on the wing surface.

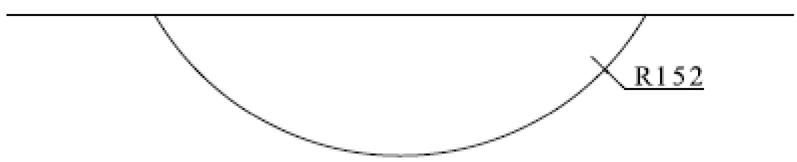

Fig. 1. Dimple's side view through a surface

(IJAER) 2019, Vol. No. 18, Issue No. VI, December **e-ISSN: 2231-5152, p-ISSN: 2454-1796**

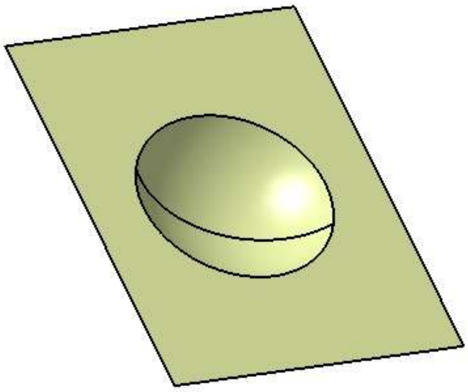

Fig. 2. Dimple on a surface

Figure 2 shows the Dimple on a surface. The dimple is a smooth arc type Dimple that can give a good air flow over the surface. Arc shape dimple is chosen because according to Katsumi Aoki, Koji Muto, Hiroo Okanaga and Yasuki Nakayama the smooth arc type dimple gives best results of smooth airflow compared to other shape dimples [10].

B. ***Existing and New design with and without Dimples***

Fig. 3. Existing model of Boeing 737-600's Wing without Dimples

Figure 3 shows the wing of Boeing 737-600 without Dimples or any other drag reducing agents. This is modeled and analyzed for comparing the new design of placing Dimples on the surface of the wing.

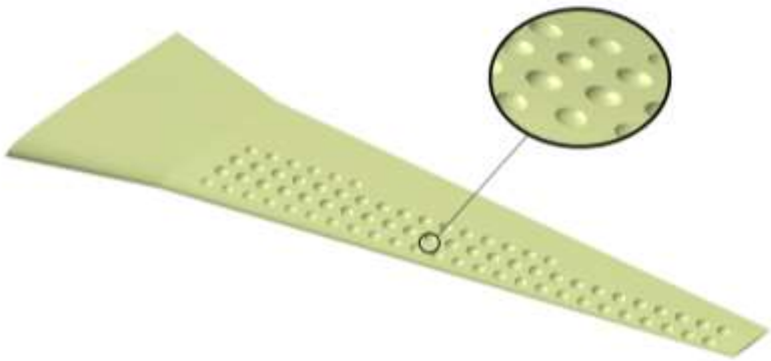

Fig. 4. New model of Boeing 737-600's Wing with Dimples on the surface

Figure 4 shows the model of Boeing 737-600's Wing with Dimples on the surface. This is modeled and analyzed and compared with the existing design.

C. *Analyzing using Computational Fluid Dynamics*

Ansys Fluent software is the most-powerful computational fluid dynamics tool available, empowering to go further and faster as optimizing the wing's performance. Fluent includes well-validated physical modeling capabilities to deliver fast, accurate results across the widest range of CFD and multi physics applications. So, we use Ansys Fluent as the software to do CFD analysis. The velocity of air used for analysis is $30 ms^{-1}$.

RESULTS AND DISCUSSION

A. *Meshing using HYPERMESH*

Fig. 5. Meshing of wing without Dimples

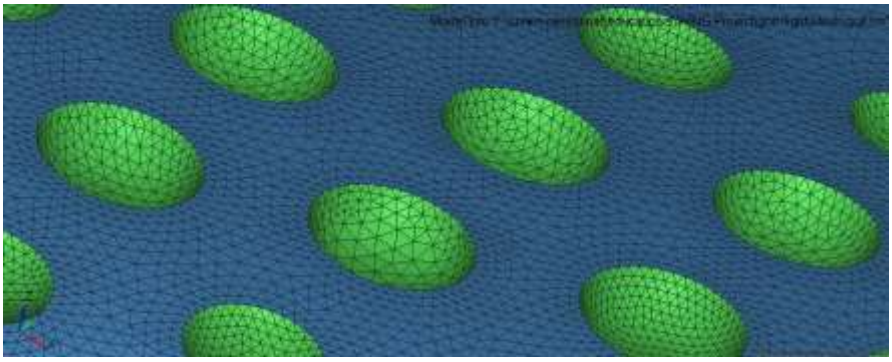

Fig. 6. Meshing of wing with dimples

Figure 5 and 6 shows the unstructured meshing done on the wing with and without Dimples. These meshed models are then exported to Ansys Fluent for CFD analysis.

B. *Analysis of Pressure*

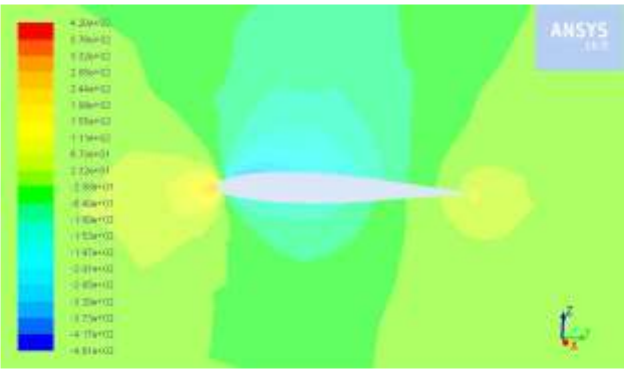

Fig. 7. Pressure without Dimples

Fig. 8. Pressure with Dimples

Figure 7 and 8 shows the pressure on the aircraft wing before and after placing Dimples. Pressure obtained are shown below and described in figure 9.

Leading edge pressure without Dimples, P_{1L} = 0.22Kpa

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Leading edge pressure with Dimples, P_{2L} = 0.22Kpa

Trailing edge pressure without Dimples, P_{1T} = 0.089Kpa

Trailing edge pressure with Dimples, P_{2T} = 0.037Kpa

Reduction in pressure on trailing edge, $P_R = P_{1T} - P_{2T}$

P_R = 0.089Kpa – 0.037Kpa, P_R = 0.052Kpa

Percentage of pressure reduced in trailing edge

$$=\left(\frac{\text{reduction in pressure on trailing edge}}{\text{actual pressure on trailing edge}}\right) \times 100 = \left(\frac{P_R}{P_{1T}}\right) \times 100$$

$$=\left(\frac{0.052}{0.089}\right) \times 100$$

= 58.42%

The amount of pressure reduced in trailing edge is 58.42% after placing Dimples.

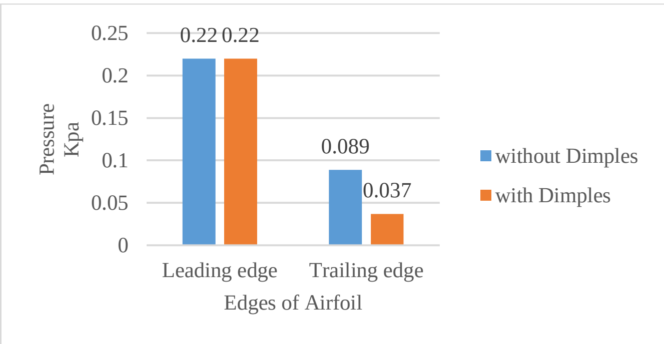


Fig. 9. Pressure on the wings

C. *Analysis of Velocity*

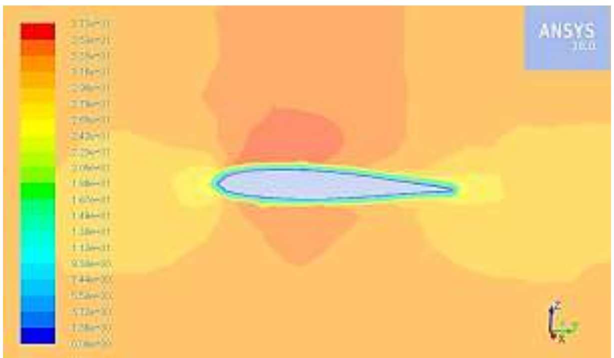


Fig. 10. Velocity without Dimples

Fig. 11. Velocity with Dimples

Figure 10 and 11 shows the velocity on the aircraft wing before and after placing Dimples. Velocity obtained are shown below and described in figure 12.

Leading edge velocity without Dimples, V_{1L} = 27m/s

Leading edge velocity with Dimples, V_{2L} = 27m/s

Trailing edge velocity without Dimples, V_{1T} = 28.8m/s

Trailing edge velocity with Dimples, V_{2T} = 30m/s

Increase in velocity on trailing edge $V_I = V_{2T} - V_{1T}$

V_I = 30m/s – 28.8m/s, V_I = 1.2m/s

Percentage of pressure reduced in trailing edge

$$= \left(\frac{\text{Increased velocity of air on trailing edge}}{\text{Actual velocity of air on trailing edge}}\right) \times 100 = \left(\frac{V_I}{V_{1T}}\right) \times 100$$

$$= \left(\frac{1.2}{28.8}\right) \times 100$$

= 4.16%

The amount of velocity of air increased on trailing edge is 4.16% after placing Dimples.

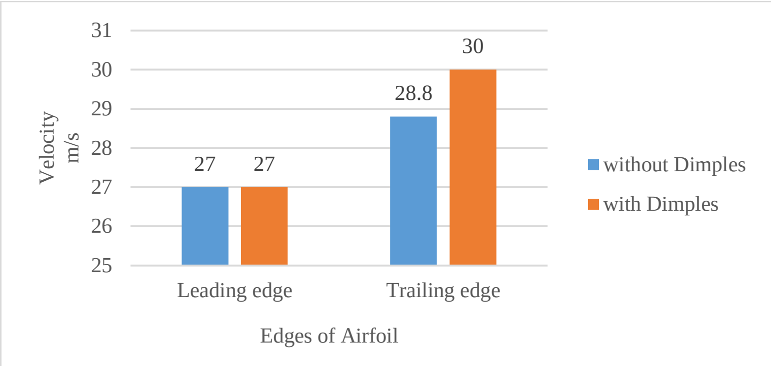


Fig. 12. Velocity of air on the wings

D. *Turbulence*

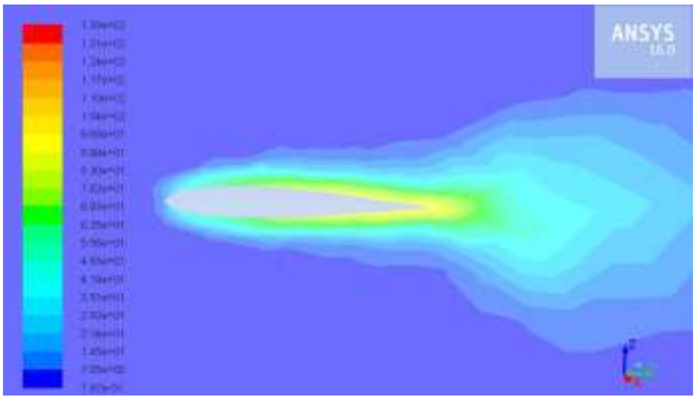


Fig. 13. Turbulence without Dimples

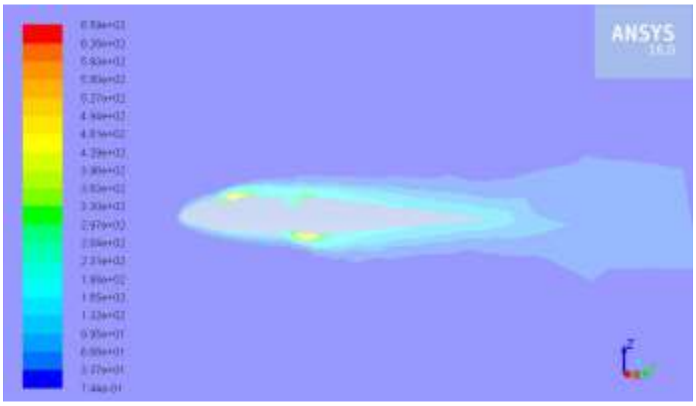


Fig. 14. Turbulence with Dimples

Figure 13 and 14 shows the turbulence on the aircraft wing before and after placing Dimples. Turbulence values obtained are shown below and described in figure 15.

Leading edge Turbulence without Dimples = 16%

Leading edge Turbulence with Dimples = 16%

Trailing edge Turbulence without Dimples = 88%

Trailing edge Turbulence with Dimples = 83%

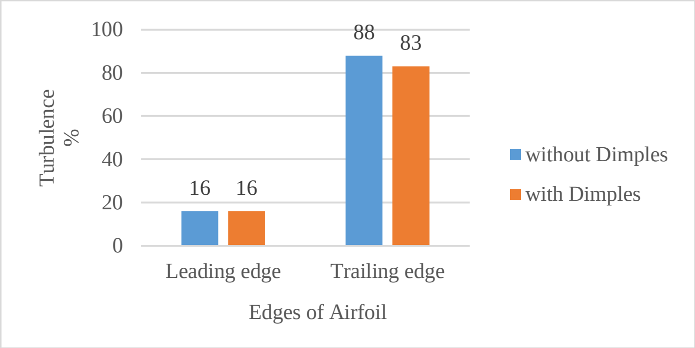
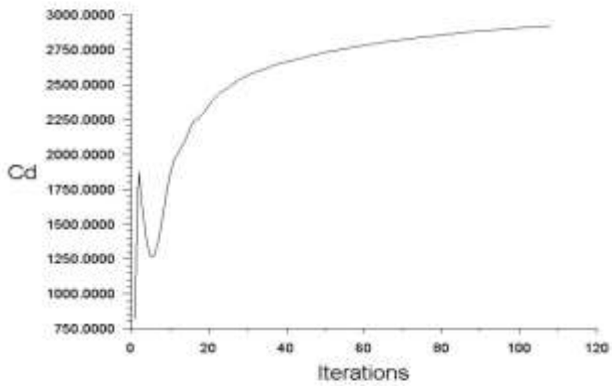


Fig. 15. Turbulence on wings

E. ***Convergence of Pressure drag, Lift and Equations***



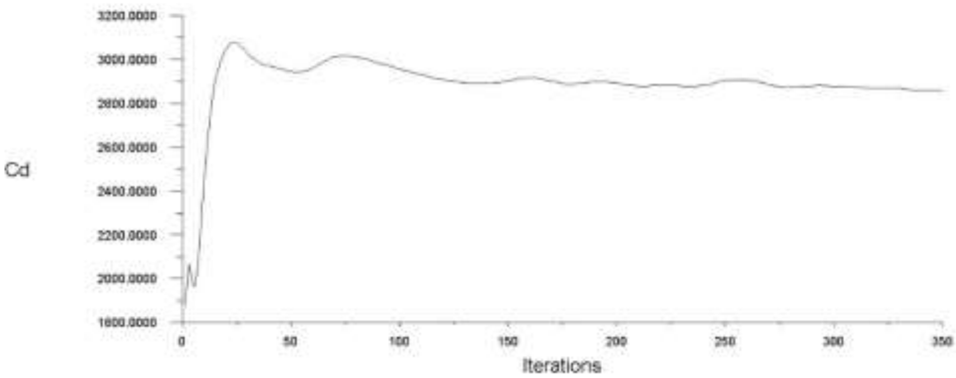


Fig. 16 and 17. Convergence of coefficient of pressure drag without and with Dimples respectively

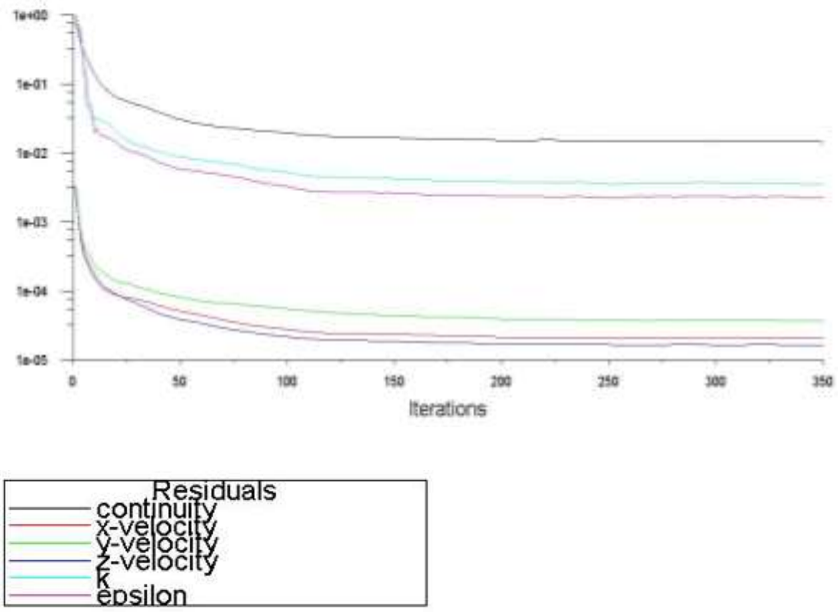


Fig. 18. General Convergence of equations

Convergence is a criteria where at a particular iteration, all the values will remain the same henceforth. The convergence criteria at which it should converge is fed in ANSYS Fluent. So, after convergence, the analysis is over; denoting that upcoming values have no change. Figure 16 and 17 shows the convergence of the coefficient of pressure drag. Figure 18 shows the general convergence of the equations. All the equations like continuity equation, momentum equation (x, y and z velocity), turbulent kinetic energy equation (k) and the turbulent dissipation equation (epsilon) are converged.

F. ***Force***

Table 1

Forces acting on wings in X, Y and Z direction without Dimples

ZONE	**PRESSURE DRAG FORCE (N)**		
	F_{X1}	**F_{Y1}**	**F_{Z1}**
WING MID, MEAN AND END CHORDS	-94.43	354.10	2865.73
NET FORCE	-94.43	354.10	2865.73

Table 2

Forces acting on wings in X, Y and Z direction with Dimples

ZONE	**PRESSURE DRAG FORCE (N)**		
	$\mathbf{F_{X2}}$	$\mathbf{F_{Y2}}$	$\mathbf{F_{Z2}}$
WING MID, MEAN AND END CHORDS	-98.83	336.40	2030.73
DIMPLES	17.97	251.89	531.99
NET FORCE	-80.86	588.30	2562.72

Table 1 and 2 shows the total forces acting in x, y and z direction that is inferred from ANSYS Fluent. The data in the table is for without and with Dimples respectively. The forces shown in the above table are for the wing's bottom, top, tail and head surfaces. The negative direction in the forces indicates the direction of the force. It can be inferred from the table that,

The total force on wing without Dimples

$F_{WD} = F_{x1} + F_{y1} + F_{z1}$

$F_{WD} = -94.43 + 354.10 + 2865.73$

$F_{WD} = 3125.4$ N = 3.12 KN

The total force on wing with Dimples

$F_D = F_{x2} + F_{y2} + F_{z2}$

$F_D = -80.86 + 588.30 + 2562.72$

$F_D = 3070.16$ N = 3.07 KN

Pressure drag force reduction in the wing

$F_R = F_{WD} - F_D$

$F_R = 3.12 – 3.07$

$F_R = 0.05$ KN

Percentage of overall pressure drag reduced in the wing is

$$= \left(\frac{\text{Overall Pressure drag reduction}}{\text{Pressure drag force on wing without Dimples}} \right) \times 100 = \left(\frac{F_R}{F_{WD}} \right) \times 100$$

$$= \left(\frac{0.05}{3.12} \right) \times 100$$

= 1.6 %

Pressure drag reduction considering total aircraft neglecting fuselage, is the average of pressure drag reduction percentage in each wing. Pressure drag reduction on wing on both sides are equal since both the wings are symmetrical.

Percentage of Overall pressure drag reduction

$$= \left(\frac{1.6 + 1.6}{2} \right) = \left(\frac{3.2}{2} \right) = 1.6\ \%$$

Overall pressure drag reduction in the total aircraft is 1.6 %.

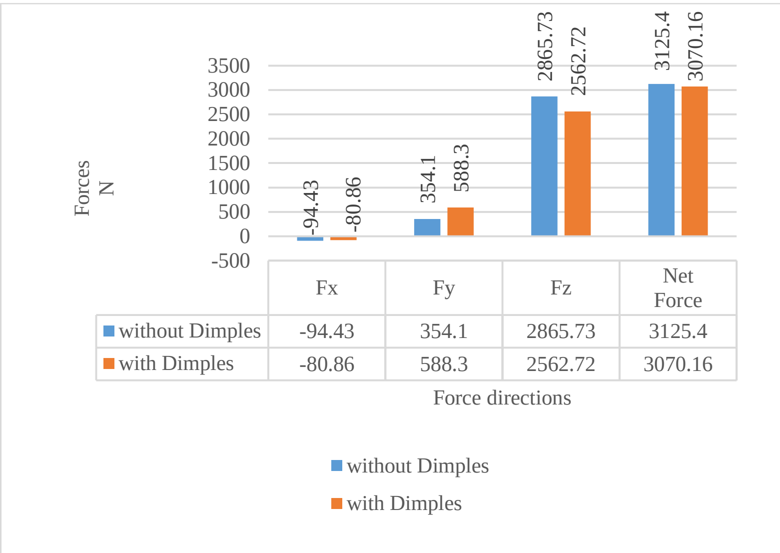


Fig. 19. Forces with and without Dimples

CONCLUSION

Table 3

Conclusion from the results

WITHOUT DIMPLES	WITH DIMPLES
1. Pressure in trailing edge is 0.089 Kpa.	1. Pressure in trailing edge is 0.037 Kpa.
2. Velocity in trailing edge is 28.8 m/s.	2. Velocity in trailing edge is 30 m/s.
3. Turbulence in trailing edge is 88%.	3. Turbulence in trailing edge is 83%.
4. Total pressure drag force on wing 3.12 KN.	4. Total pressure drag force on wing 3.07 KN.

Table 3 shows the conclusion of the work showing the analysis results for the existing design and the new design. From the results we can infer that

- Percentage of pressure reduced after placing Dimples is 58.42%. The Pressure should be reduced because more pressure leads to more Pressure drag.
- Percentage of velocity increased after placing Dimples is 4.16%. The Velocity should be increased because pressure and velocity are inversely proportional. If pressure decreases, the velocity will increase and vice versa. In other way, high velocity means less pressure drag.
- Turbulence decreased from 88% to 83%. The Turbulence should be decreased because increase in turbulence intensity leads to increase in Pressure drag.
- Percentage of overall pressure drag force reduced is 1.6%. The aim of the work is achieved.

From the CFD analysis results, it is clearly observed that the pressure drag force on the aircraft is reduced. It has been found that placing these Dimples can decrease pressure drag and increase the performance and efficiency of the aircraft. There are many works that can be done on aircraft wings in future like as to change shape of Dimples like changing its shape, placing other drag reducing elements with dimples to increase the aircraft’s performance. The reduction in aircraft pressure drag has many futuristic aspects as this particular field of research have got no end. Many aspects of an aircraft can be changed to reduce the pressure drag without altering the basics of flight.

(IJAER) 2019, Vol. No. 18, Issue No. VI, December **e-ISSN: 2231-5152, p-ISSN: 2454-1796**

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