

## Experimental Investigation of Aerodynamic Characteristics of Dimpled 3D Aircraft Wing

D. Harish<sup>1</sup>, V.L. Jagannatha Guptha<sup>2\*</sup>, Ramesh S. Sharma<sup>2</sup>

### Abstract

*There is a strong demand for innovative designs, optimization of the aircraft components for their parts with respect to design, etc. One such innovation is by introduction of dimples in the wing of the aircraft. To study the effect of geometry modification of the wing, the present work compares the aerodynamic efficiency, ratio of lift to drag coefficients, along with different aerodynamic characteristics of an Inward and outward circular dimpled aircraft wing with an un-dimpled wing by using 3D structures for NACA 2412 airfoil. A diameter of 300mm for dimples, with 8 and 16 numbers of circular dimples, both inward and outward type, at 0° to 16° angle of attack with range of 4° interval was considered. 3D aircraft wing models were simulated in CATIA V5 software tool and fabricated by 3D Printing method. The wind tunnel test results show that the Inward circular dimpled aircraft wing model with 16 numbers of dimples has the highest aircraft efficiency of 10.69. Thus 16 dimples were selected and analyzed for various angles of attack from 0° to 16°. Lift force is maximum for an inward 16 circular dimpled aircraft wing of 5.74 N followed by 4.57 N for un-dimpled aircraft wing and 4.38 N for outward 16 circular dimpled aircraft wing, at 16° Angle of attack. The lower drag force of 0.73 N is for an outward 16 circular dimpled aircraft wing compared to both un-dimpled and inward 16 circular dimpled aircraft wings, at 16° angle of attack.*

**Keywords:** Aircraft wing, Dimpled wing, Aerodynamic efficiency, 3D printing, CATIA V5

### INTRODUCTION

With the increasing research and development trend from major aircraft wing players to meet the growing demand for lightweight and evolutionary aircraft [1]. The demand for innovative design and design optimization to improve aircraft efficiency is projected to support the growth of the commercial aircraft wing market. Original equipment manufacturers are exploiting new innovations and planning techniques to improve streamlined execution and reduce part heaviness throughout the aircraft wing structure, improving environmental friendliness [2-6]. Various NACA airfoils have been selected, such

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as NACA 0018, 4418, 0011. The addition of dimples in the aircraft wing has been found to be effective in modifying various aspects of the flow structure as well as aerodynamic characteristics. It is also shown that the dimple plays an important role in reducing resistance [7-9]. The implementation of dimples in NACA 0018 has been found to be more effective in modifying various aspects of the flow structure with different lift and drag forces [10-18]. The dimples modification creates turbulence to delay the separation of the flows, which increases the stall angle at which the aircraft is no longer controllable when the air is not flowing correctly over the wing [19-25]. Experimental studies were carried out in the wind tunnel of honeycomb

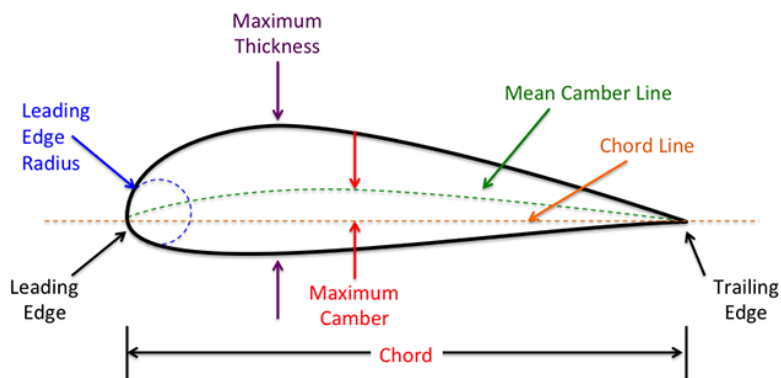
airplane wings to validate the results of the CFD analysis carried out by numerous researchers [26- 29]. The defined airfoil CAD model was designed to analyze the flow characteristics of the modified surface by placing cells of different shapes. For a range of  $-5^\circ$  to  $+20^\circ$  were studied on NACA 2412, NACA 2414 and NACA 2415 wing segments considering maximum value coefficient of the lift / resistance ratio as  $4^\circ$  and  $5^\circ$  respectively. Researches were carried out on modified airfoil surface giving internal and external semicircular dimples on the lower surface with coefficients ranging from 0 to 12 [30-32]. Also, 3D aircraft wing examination was done using CFD Fluent using ANSYS 15 FLUENT. Similar such profile showed that the lift coefficient, the lift force, lift and lift segments, the lift coefficient was found to be higher at a point of  $25^\circ$ , there was a reduction in fuel consumption [33, 34]. Study on improved lift and reduced drag was completed for the NACA 2412 airfoil featuring dimples on the airfoil surface [35].

It is observed from the literature that shape of the airfoil in 2D has been extensively explored, with only a few have focused on the impact of the 3D dimpled aircraft wing. Many researchers have also conducted research on the effect of the dimple on the section of the airfoil in 2D and 3D models. However, very few have researched the wing of a 3D aircraft inward and outward dimples on the aircraft wing. The present work focuses on the experimental investigation of the effect of surface modification for the 3D aircraft wing of NACA 2412 airfoil section, prepared by 3D Printing method, by providing circular dimples of inward and outward configuration, on the aerodynamic characteristics lift force, drag force and aerodynamic efficiency to select the aircraft wing model for the highest aerodynamic efficiency and hence, to suggest the best Angle of Approach (AoA). Various angles of approach from  $4^\circ$  to  $16^\circ$  with a range of  $4^\circ$  are considered.

## A Brief Theory

### Airfoil Nomenclature and Terminologies

Various nomenclature of the airfoil is shown in the Figure 1.



**Figure 1.** Terminologies of airfoil section.

### Effect of Dimples

Aerodynamics has constantly been the core of aeronautics, including both subsonic and supersonic flights. The design of a few airplane parts are strongly overwhelmed by streamlined features. Dimples on golf balls have been inspiring researchers in the field of vehicle aerodynamics and optimal design thinking about its impact in diminishing the drag and enhancement of lift a golf ball with a dimpled surface can travel higher and farther than a smooth-surface golf ball when exposed to indistinguishable power. Dimples in golf balls cause turbulence at the lowest Reynolds number, giving additional strength or vitality to the boundary layer and causing a delay in stream separation. This wonder causes smaller wake areas, or regions of swirling currents behind the bullet, along those lines, reducing absolute drag. Until now, these have been overlooked in light of the fact that dimples help decrease resistance to pressure. If an occurrence of contoured bodies occurs, the drag pressure is not compared to the bluff bodies. An airfoil is a streamlined body, so dimples don't influence your drag much on approach zero, however when the airfoil reaches a certain approach, wake layout begins due to boundary layer

partitioning. The application dimples on the model airplane wing work the same as vortex generators. Numerous studies have shown that dimples in an airfoil generate additional turbulence to delay boundary layer separation. Including a dimple in a smoothed body can help delay flow splitting and reduce wake size, but it can also increase frictional drag as a tradeoff. Therefore, it is important to advance the position and measurements of the dimple in relation to the size of the whole body.

### GEOMETRIC MODELING OF THE 3D AIRCRAFT WING

The 3D aircraft wing model of airfoil NACA 2412 was prepared in CATIA V5 software.

#### NACA 2412 Airfoil Details and Aircraft Wing Dimensions

The first number indicates the maximum camber percentage of the chord, which is 2%. The second number indicates the maximum camber distance from the leading edge of the airfoil in tenths of the chord. Therefore, a maximum camber of 2% is located in 40% of the chords. The last two digits indicate the maximum airfoil thickness as a percentage of the chord, which is 12% of the chord. The dimensions of the wings of the aircraft selected to model the aircraft are shown in Table 1.

**Table 1.** Cessna M-2 aircraft wing dimensions.

Aircraft wing	Dimensions
Aircraft wing Span	16764 mm
Aircraft wing Area	24.60 m <sup>2</sup>
Aspect Ratio	6.782
Taper Ratio	3.206
Dihedral	2.3°
Sweep Angle (Leading Edge)	15.85°
Sweep Angle (25% Chord)	10.54°
Sweep Angle (Trailing Edge)	1.03°

The coordinates of the root section of the aircraft wing, the mean aerodynamic chord of Aircraft wing and tip section in X, Y, Z directions are as shown in Tables 2–4. These were obtained from airfoiltools.com, imported into the Microsoft Excel macro file according to the original dimensions of the aircraft wing and macros file was then run to obtain the required coordinates in three parallel planes.

**Table 2** Coordinates of the aircraft wing at Root Section.

X (mm)	Y (mm)	Z (mm)
3795.505810	0	-112.420890
3605.884290	0	-68.2187290
.	.	.
0	0	0
.	.	.
3605.639230	0	-129.7056050
3795.466480	0	-122.2891540

**Table 3** Coordinates of the Aircraft Wing at Mean Aerodynamic Chord.

X (mm)	Y (mm)	Z (mm)
3884.300880	-3975.02380	157.8090640
3748.435080	-3975.02380	187.9680540
.	.	.
1165.6060	-3975.02380	208.280
.	.	.
3748.32520	-3975.02380	143.925340
3884.283240	-3975.02380	150.740480

Coordinates were traced to obtain three airfoil shaped curves parallel XZ planes and surface model and Solid Model of the aircraft wing with a pad of 1303.61 x 4676.19 mm cross section was generated using CATIA V5 software and are as shown in Figure 2. It is NACA 2412 based un-dimpled model with the aircraft wing of span 16764 mm, area of 24.6 m<sup>2</sup> and an aspect ratio of 6.78.

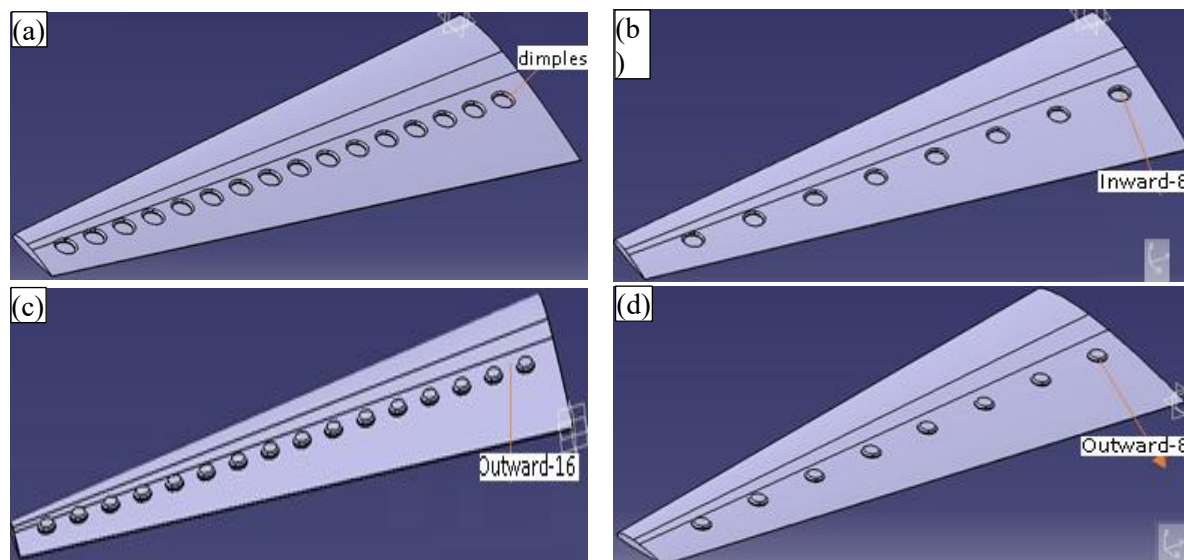
**Table 4** Coordinates of the Aircraft wing at the Tip Section.

X (mm)	Y (mm)	Z (mm)
4009.152130	-9634.7280	532.4434910
3949.927740	-9634.7280	543.1021310
.	.	.
2825.2420	-9634.7280	504.92660
.	.	.
3949.973780	-9634.7280	523.9227270
4009.159520	-9634.7280	529.3653150

Similarly, models for two configurations of circular dimples, inward and outward dimples, for two cases of 8 and 16 number of dimples was considered on top of the aircraft wing surface with dimensions  $\phi 300 \times 50$  mm with a fillet radius of 10mm at 60% chord line from the leading edge were generated. A spacing of 1038.45 mm and 569.23 mm was considered for 8 and 16 dimpled models respectively.

### Scaling of Models

To achieve the dimensions of prototype which is allowable to fit in experimental setup (wind tunnel), the scaling has been done. After the scaling the length of the wing is 192.694mm, chord length is 75.91mm and the thickness is 10mm. The inward and outward dimples diameter reduced to 6mm and the depth is 1mm.

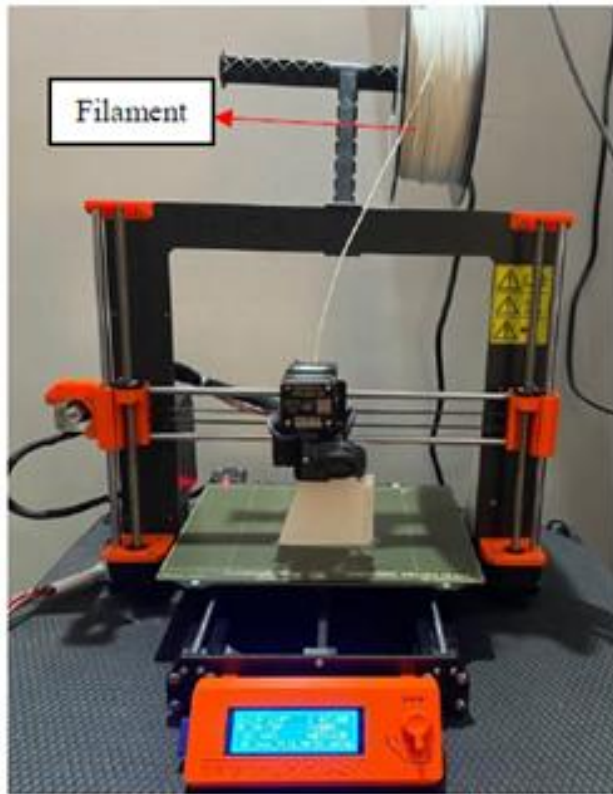


**Figure 2.** Surface and 3D models, (a) and (b) 16, 8 inward circular dimpled, and (c) and (d) 16, 8 outward circular dimpled.

## FABRICATION AND EXPERIMENTATION

### Fabrication of Wing Models

Fabrication of wing models was done by Fused Filament deposition method, a 3D printing process that uses a continuous filament of a thermoplastic material. The 3D Printer used for the fabrication is as shown in Figure 3.



**Figure 3.** 3D Printing machine

**Fabrication Process Parameters by 3D Printing Method**

The 3D aircraft wing model selected for testing was fabricated by 3D Printing method employing Filament deposition technique. PRUSA MK3S 3D printer with PRUSA Slicer was used. It has an ability to provide a layer height of 0.2 mm with monotonic Top Infill, Bottom Infill and Rectilinear Infill Pattern with 100% Infill percentage. 5 numbers of solid layers for Top and 4 numbers for Bottom layer, a minimum of 4 perimeters were considered. A Perimeter speed 60 mm/s, a temperature of 215°C for Extruder, and 60°C for Bed were adopted. Supports were provided for the case of dimpled configuration. Total printing time take was 7 Hours 43 Minutes, 7 Hours 50 Minutes, 5 Hours 30 Minutes for inward dimpled, outward dimpled and un-dimpled wings respectively. PLA White material was used to fabricate all the three 3D wing configurations (Un-dimpled, Dimpled - Circular Inward, Circular Outward). Other parameters for 3D Printing are as shown in 6 5.

**Table 5.** Process parameters for fabrication of aircraft wings.

Parameters	Un-dimpled, Inward dimpled and Outward dimpled,
Skirt	Loops – 1, Distance from Object – 2 mm Height – 3 Layers
Small Perimeter	25 mm/s
External Perimeters	35 mm/s
Infill	200 mm/s
Solid Infill	200 mm/s
Top Solid Infill	50 mm/s
Support Material	50 mm/s
Support Material Interface – 80% Bridges	30 mm/s
Gap Fill - 40 mm/s Ironing	15 mm/s

The NACA2412 airfoil was selected for the construction of the 3D wind model. Three configurations – un-dimpled, inward dimpled and outward dimpled models were prepared. They are as shown in Figures 4–6.



**Figure 4** Fabricated model of Un-dimpled 3D aircraft wing



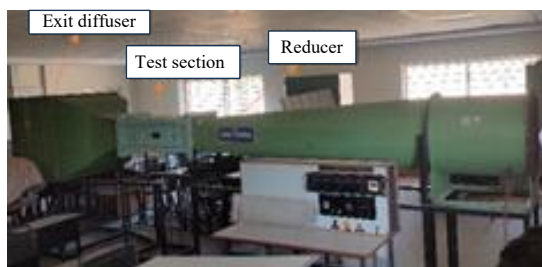
**Figure 5** Fabricated model of Inward 16 Circular dimpled 3D aircraft wing



**Figure 6** Fabricated model of Outward 16 Circular dimpled 3D aircraft wing

### Experimental Setup

The experiments were carried out with a subsonic wind tunnel with a rectangular test section (0.8x0.5x0.5) m. The blower could operate at different speeds by changing the speeds of the motors. And in the test section it is possible to change the angle of attack of the wing model up to 45 degrees.



**Figure 7.** Experimental setup - wind tunnel

Figure 7 shows wind tunnel Experimental setup. A small model is suitable for examining the aerodynamic characteristics of the experiments. The model was placed in the middle of the test section supported by a load cell. And the load cell is used to measure the lift and drag forces acting on the wing models. When the engine is started, the fluid flows from the diffuser to the mesh section where the dust particles present in the fluid are removed. Then the fluid passes through the reducer where the speed of the fluid can be increased with the presence of a convergent section then the fluid will pass through the test section where the wing model can be placed. Using the anemometer, one can measure the speed of the fluid flow in the test section. Also, the speed of the fluid can be changed with the speed control unit. Table 6 shows the specifications of wind tunnel setup.

**Table 6.** Specifications of wind tunnel.

Wind Tunnel	Dimension
Length of test section in X-direction	0.8m
Length of test section in Y-direction	0.5m
Length of test section in Z-direction	0.5m
Maximum velocity of fluid	30m/s
Minimum velocity of fluid	10m/s
Maximum angle of attack	45 degrees

### RESULTS AND DISCUSSION

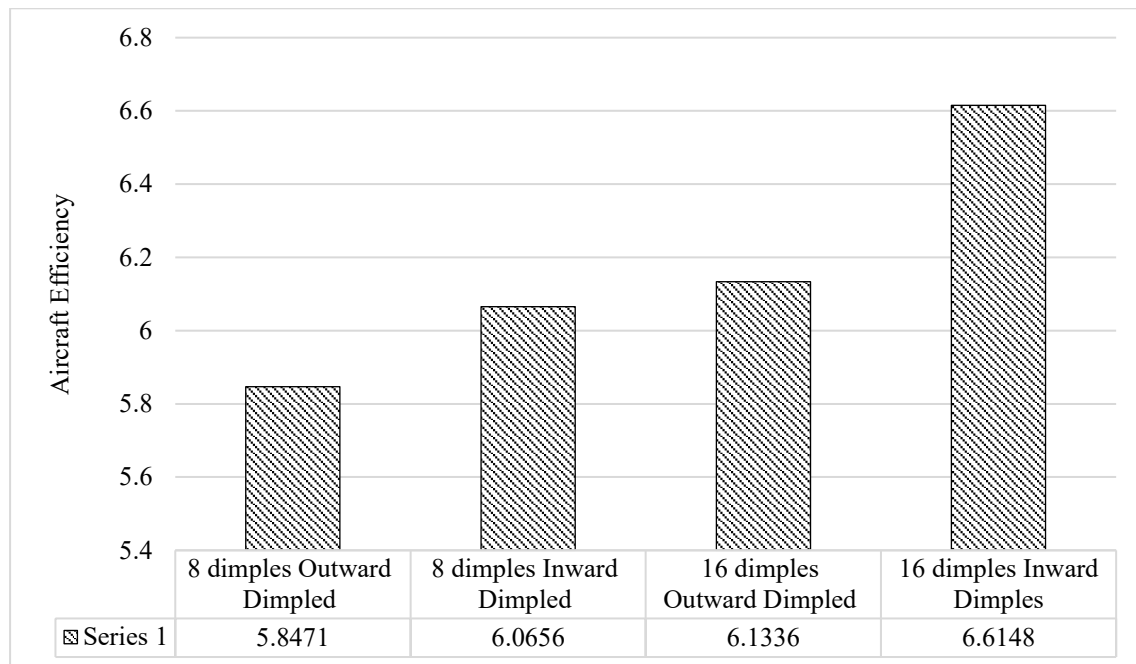
The study of several aerodynamic properties such as lift, drag, coefficients of lift and drag, aerodynamic efficiency for various angle of attack (AoA) was carried out and the results obtained were tabulated and plots for all the models were prepared. Optimized number of the dimples to be selected for the analysis of various aerodynamic characteristics is determined by analyzing the aircraft efficiency.

### Aerodynamic Efficiency of the Un-dimpled, Inward Dimpled and Outward Dimpled Aircraft Models.

The results obtained for 0° angle of approach are as shown in the Table 7.

**Table 7.** Aerodynamic efficiency of the models at 0° approach (AoA).

3D wing Type/Configuration	No. of dimples	Coefficient of Lift (CL)	Coefficient of Drag (CD)	Aerodynamic Efficiency (CL/CD)
Outward Dimpled	8 dimples	0.1534	0.0262	5.8471
Inward Dimpled	8 dimples	0.1609	0.0265	6.0656
Outward Dimpled	16 dimples	0.1589	0.0259	6.1336
Inward Dimpled	16 dimples	0.1684	0.0255	6.6148



**Figure 8.** Plot of Aerodynamic Efficiency Vs. 3D Aircraft Wing Configuration for 0° AoA.

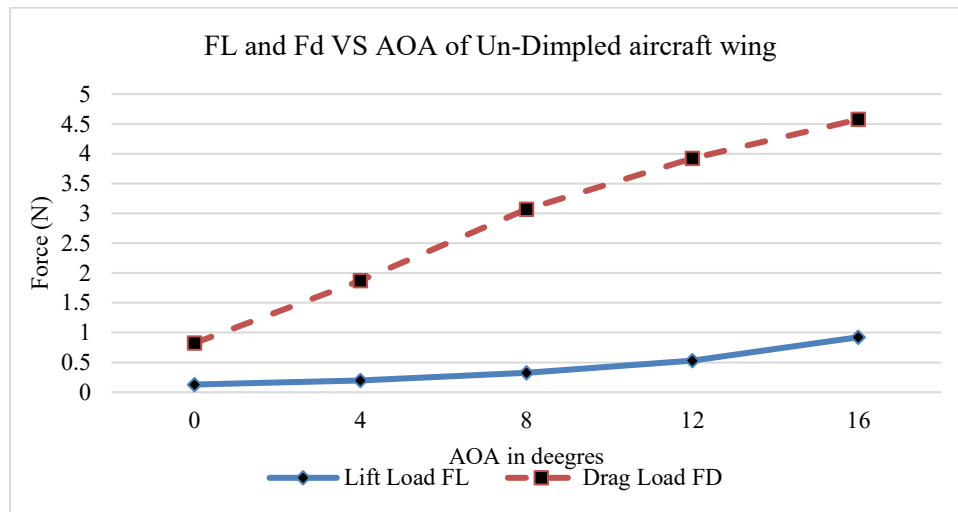
Figure 8 shows the plot of Aerodynamic Efficiency Vs. 3D Aircraft Wing Configuration for 0° AoA for different type viz. Un-dimpled, Inward and Outward dimpled air craft wing with 8 and 16 numbers of dimples. It is observed from the results that aerodynamic efficiency of inward 16 dimpled aircraft wing model is higher than that of inward 8 dimpled aircraft wing model by 10.87 %. And the aerodynamic efficiency for outward 16 dimpled aircraft wing model is higher than that of the outward 8 dimpled aircraft wing model by 5.12 %. Hence, to carry out further investigations and studies, Inward and Outward 16 dimpled 3D aircraft wings were suggested and selected.

### Lift and Drag force Components of Un-dimpled Aircraft Wing

The lift and Drag Components of Un-dimpled aircraft wing of NACA 2412 for various angles of attack (AoA) are as shown in Table 8.

**Table 8** Lift and Drag force Components of Un-dimpled Aircraft wing

Angle of attack (AoA) in degrees	Lift Load FL (N)	Drag Load FD (N)	Ratio FL /FD
0	0.8232	0.1296	6.3527
4	1.8717	0.1988	9.4120
8	3.0681	0.3257	9.4203
12	3.9253	0.5275	7.4412
16	4.5753	0.9221	4.9621



**Figure 9.** FL and FD vs AoA plot of un-dimpled wing.

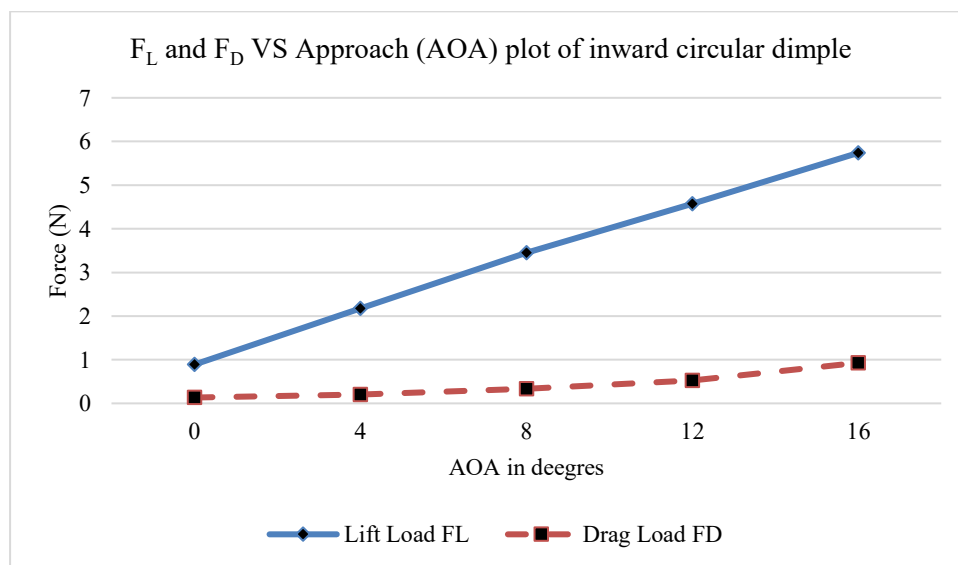
From the FL and FD vs Angle of Approach (AoA) plot as shown in Figure 9, it is observed that at 8° angle of attack (AoA), there is highest ratio of Lift force to Drag force. And for the angle of attack other than the 8° (AoA), there is a decrease in the ratio by 48.21%, 26.59%, and 89.84% for the 0°, 12° and 16° respectively. This is because of adverse pressure gradient condition.

**Lift and Drag Force Components of Inward 16 Circular Dimpled Aircraft Wing**

The lift and Drag Components of a inward circular dimpled aircraft wing of  $\phi 300\text{mm}$  is shown in Table 9 at various angle of attack.

**Table 9** Lift and Drag force Components of Inward 16 Circular Dimpled Aircraft Wing

Angle of attack (AoA) in degrees	Lift Load FL (N)	Drag Load FD (N)	Ratio FL /FD
0	0.8900	0.1345	6.6151
4	2.1735	0.2033	10.6905
8	3.4531	0.3342	10.3331
12	4.5726	0.5223	8.7533
16	5.7381	0.9292	6.1767



**Figure 10.** FL and FD vs AoA plot of Inward circular dimpled wing.

From the FL and FD vs AoA plot as shown in Figure 10, it can be shown that at 4° angle of attack (AoA), there is highest ratio of Lift force to Drag force. When the angle of attack is greater than the 4° (AoA) there is a decrease in the ratio by 61.6%, 3.458%, 22%, and 73% for the 0°, 8°, 12° and 16° respectively. This is because of adverse pressure gradient condition.

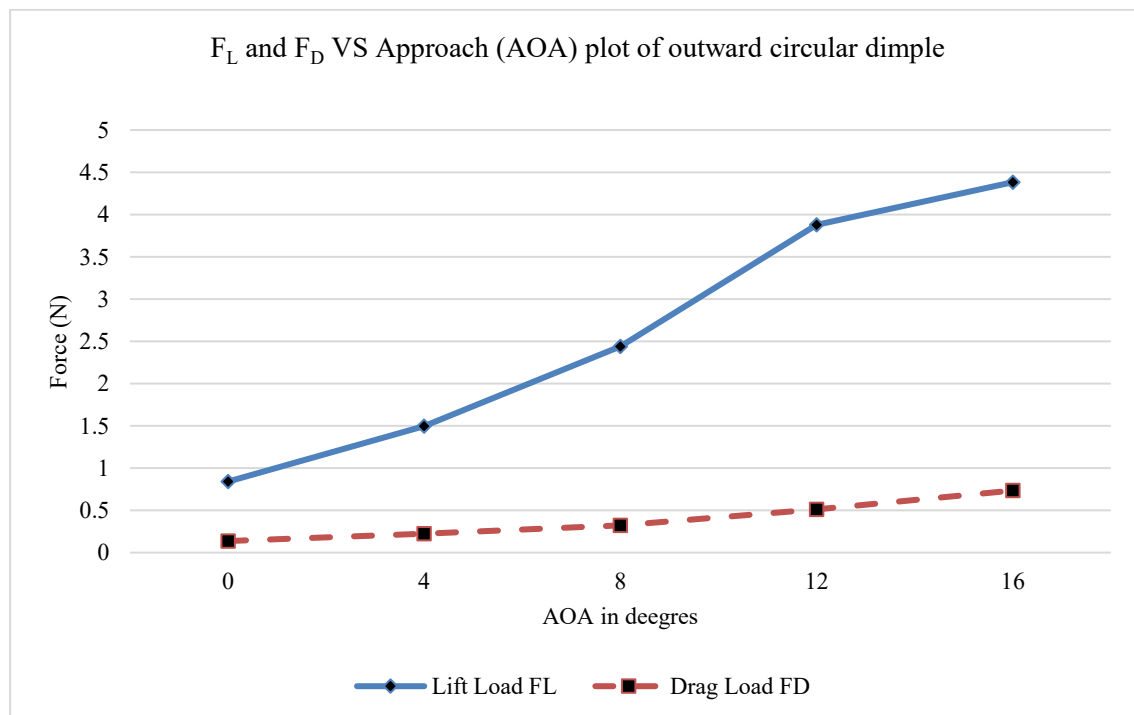
### Lift and Drag force Components of 16 Outward Circular Dimpled Aircraft Wing

The lift and Drag Components of Outward circular dimpled aircraft wing of  $\phi 300\text{mm}$  is shown in Table 9 at various angles of attack.

**Table 9.** Lift and Drag force Components of Outward 16 Circular Dimpled Aircraft wing.

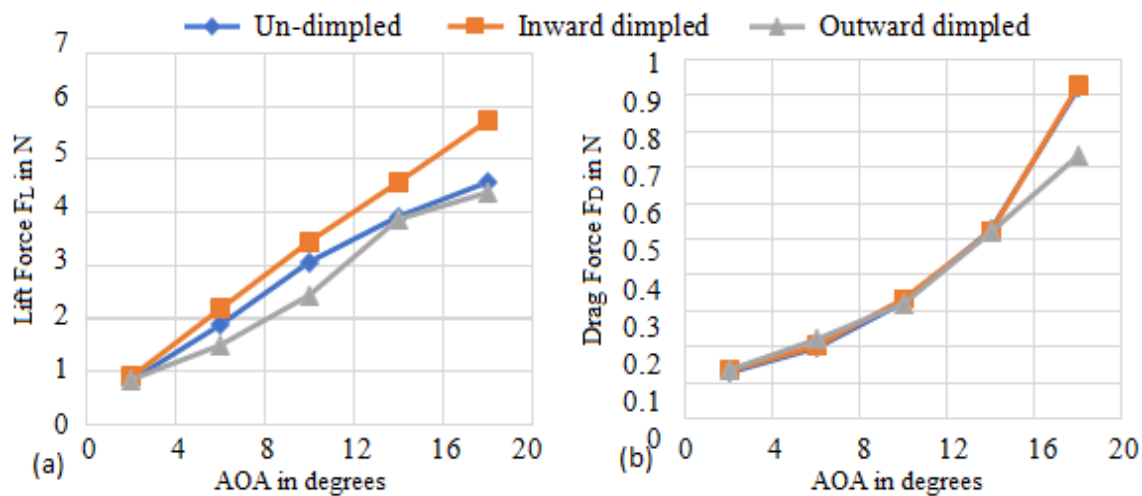
Angle of attack (AoA) in degrees	Lift Load FL (N)	Drag Load FD (N)	Ratio FL /FD
0	0.8405	0.1371	6.1336
4	1.4953	0.2223	6.7267
8	2.4375	0.3227	7.5530
12	3.8795	0.5210	7.4461
16	4.3820	0.7339	5.9706

From the FL and FD vs Approach (AoA) plot as shown in Figure 11, it can be shown that at 8° angle of attack (AoA), there is highest ratio of Lift force to Drag force. When the angle of attack is 8° (AoA) there is a reduction in the ratio by 23%, 12.3%, 1.4%, and 26.5% for the 0°, 4°, 12° and 16° respectively. This is because of adverse pressure gradient condition.



**Figure 11.** FL and FD vs AoA plot of Outward 16 circular dimpled wing.

The Lift and Drag forces for various angles of attack (AoA) for Un-dimpled, Inward dimpled and outward dimpled 3D aircraft wing models are as shown in Figure 12 (a and b). It can be inferred from the plots that the maximum value of Lift force is 5.748 N for an Inward circular dimpled aircraft wing, 4.57 N for Un-dimpled aircraft wing and 4.38N for Outward circular dimpled aircraft wing at 16° Angle of Attack and the lower drag force of 0.73 N is for an Outward dimpled aircraft wing compared to both Un-dimpled and Inward dimpled aircraft wings, at 16° angle of attack.



**Figure 12.** (a) Plot of Lift Force Vs AoA, (b) Plot of Drag Force Vs AoA for Un- dimpled, Inward 16 circular dimpled & Outward 16 circular dimpled 3D aircraft wing

## CONCLUSIONS AND FUTURE SCOPE OF WORK

### Conclusions

The following conclusions were made from the present work.

- The Geometric modeling of the NACA2412 airfoil based aircraft wing models of un-dimpled, inward dimpled, and outward dimpled with 8 and 16 number of circular dimples, was done and 3D aircraft wing models were fabricated by 3D Printing manufacturing method using PLA material.
- The prepared 3D aircraft wing models were preliminarily studied by experimental method for aerodynamic efficiency at  $0^\circ$  angle of attack to identify the suitable wing configuration.
- By comparing, aerodynamic efficiency (CL/CD) of inward 16 dimpled aircraft wing model is higher by 10.87% than that for inward 8 dimpled aircraft wing model for  $0^\circ$  AoA.
- The aerodynamic efficiency of outward 16 dimpled aircraft wing model is higher by 5.12 % as compared to the aerodynamic efficiency of outward 8 dimpled aircraft wing model.
- Similarly, due to the recirculation of flow, aerodynamic efficiency in the 16 dimpled aircraft wing model is high compared with the 8-dimpled airfoil model. Hence, 16 dimpled aircraft model, both inward and outward dimple configuration, was suggested for further studies.
- The maximum lift force is 5.74 N for an inward 16 circular dimpled aircraft wing followed by 4.57 N for un-dimpled aircraft wing and 4.38N for outward 16 circular dimpled aircraft wing, at  $16^\circ$  Angle of attack.
- The lower drag force of 0.7339 N is for an outward 16 circular dimpled aircraft wing compared to both un-dimpled and inward 16 circular dimpled aircraft wings, at  $16^\circ$  angle of attack.

### Scope for Further Work

The study was concentrated on comparing the various aerodynamic characteristics on (circular) Inward and outward dimpled wings with the un-dimpled aircraft wing according to NACA 2412 airfoil standards. However, the study may be extended to:

- Perform CFD Analysis and carry out experiments on various profiles of dimples such as complex shapes, and combinations of different shapes dimples.
- Design Optimization based on the position of the dimples and study the effect on aerodynamic characteristic on the aircraft wing.

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