Tubercles Effect on Wing Performance for NACA 0015 and 4415

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Abstract- P Watts and F E Fish researched tubercles to create their turbine blades. On the leading edge of their flippers, humpback whales have a morphological feature that allows for significant maneuverability. Wind turbines, maritime propellers, and other wing-like constructions have all adopted the tubercle design, which was inspired by nature. The purpose of this study is to investigate the effect of leading-edge tubercles on theaerodynamics performance of NACA 0015 and 4415 airfoil by using Ansys Fluent and investigate how the change in amplitude of tubercles affects the performance. The tubercles model results are compared with those of straight wing. The analysis is carried out at a constant velocity of 95 m/s, on three different amplitudes of an airfoilby keeping wavelength constant and for angle of attacks ranging from 0-30° with a step of 3° and the results are compared.

I. INTRODUCTION

Recent research has highlighted the crucial role of wing structures in enhancing the efficiency and effectiveness of mechanisms. Among these structures, wing tubercles have emerged as significant contributors to the aerodynamic performance of wings. Inspired by the maneuverability of humpback whales, these small, curved, and sharp structures found on the leading edge of wings have attracted attention across various applications, such as airplane wings, compressors, fans, and turbines. This paper aims to investigate the impact of wing tubercles on aerodynamic performance, comparing it to a baseline wing without tubercles. Wing tubercles, resembling those found on humpback whales, owls, and bats, have been extensively studied and are believed to serve multiple functions. Amplitude (A) and wavelength (λ) are two essential parameters that can be used to describe them. When positioned on the leading edge of a wing, tubercles promote a more gradual stall and delay its occurrence.

One of the primary functions of wing tubercles is drag reduction during flight. By disrupting the airflow over the wing, these structures create small vortices that help maintain attached airflow, resulting in reduced drag and increased flight efficiency. Additionally, wing tubercles play a vital role in increasing lift by delaying the separation of airflow from the wing surface. When airflow separates from the wing, lift decreases. However, the presence of wing tubercles delays this separation, leading to longer and more efficient lift generation.

In summary, recent research has focused on the influential role of wing tubercles in improving aerodynamic performance. These structures, inspired by the humpback whale's maneuverability, offer benefits such as reduced drag and increased lift by promoting attached airflow and delaying separation. By comparing their effects to a baseline wing, this study aims to shed further light on the advantages of utilizing wing tubercles in various applications.

II. LITERATURE SURVEY

Ongoing research explores the use of tubercles wing technology on various NACA airfoil profiles, considering different Reynolds numbers and angles of attack. The goal is to assess its effectiveness in improving aerodynamic performance.

In their analysis, Gracio Joyal Lobo and Amrutha K investigated the flow characteristics of the NACA 634-421 airfoil with and without tubercles at a Reynolds number of 200,000. The study emphasized the significance of amplitude and wavelength as crucial parameters for optimizing performance. Additionally, the researchers observed that both the □58A16 and

 116A16 models exhibited higher lift-to-drag ratios at lower angles of attack. Specifically, the 116A16 model demonstrated greater lift coefficient (CL) at lower angles of attack, which decreased as the angle of attack increased.

An analysis was conducted by Paremeshwar Paul and Anjali A. Vyas at a speed of 95 m/s, corresponding to a Reynolds number of 5.005*105. The study focused on examining the effects of varying angle of attack ranging from 0 to 300 on the performance of the airfoil with tubercles. The results demonstrated that the tubercled airfoil exhibited a higher lift coefficient in the post-stall region, effectively delaying stall by a minimum of 40.

A wind tunnel experiment was conducted by D.S. Miklosovic and M.M. Murray to investigate the behavior of a humpback whale fin model at a high Reynolds number. The results indicated that as the angle of attack increased from 12.10 to 18.50, there was a gradual stall phenomenon observed. This stall led to a decrease in lift generated by the fin.

In a study conducted by K.L. Hansen and R.M. Kelso, the performance of the NACA 0021 airfoil was compared to airfoil with tubercles of different amplitudes and wavelengths. The findings revealed that the tubercle airfoil effectively delayed stall, although the overall improvement in performance was not substantial.

This study aims to investigate the influence of tubercles on the aerodynamic characteristics of NACA 0015 airfoil shapes, both rectangular and tapered, as well as 4415 airfoil shapes, also in rectangular and tapered forms. The experiments are conducted at a Reynolds number of 5*105 to examine the performance changes resulting from varying the amplitude while keeping the wavelength constant. The objective is to gain a deeper understanding of the impact of tubercles on the aerodynamic behavior of these airfoil shapes.

III. METHODOLOGY

NACA 0015 Baseline and Tubercle Configurations was designed using the software – Solid Works. Calculations based on scale factor were done prior to design. Tubercle Design was done by creating planes at a certain distance that fit the span of the airfoil. Alternating 2D airfoil designs were created in each successive plane till the length of the span. The final model was obtained by "skinning" or by Lofting the alternating sketches. The same was done for NACA 4415 Baseline and with Tubercle Configurations. This model was then saved in the .iges format from Solid works and then imported in Ansys Workbench in the geometry tab of the Fluent Program. A popular 3D C- Section Domain is then constructed around the airfoil and respective named sections were given to the domain - INLET, OUTLET, AIRFOIL. Now this section is then meshed and updated to the default mesh settings on ANSYS. Then the Solution tab is opened in which the fluent flow simulation launcher opens. Basic boundary conditions are given like Flow model, inlet velocity, outlet pressure etc. Then the solution is initialized using hybrid initialization. Report definitions like Lift Coefficient and Drag Coefficient are then given. Number of iterations for the solution is entered. The solution provides accurate values of lift coefficient and drag coefficient and a respective iterations vs lift, drag coefficient plot is obtained. The obtained lift and drag coefficient values are tabulated; this is done for varying angle of attacks at the same flow speed. The range of angle of attack is from 0° to 30° for symmetric airfoils and negative angle of attack when lift coefficient is 0, to 30°.Respective lift to drag ratio(L/D) is also calculated. The tabulated results of every wing - the parameters are then compared - the baseline values and the values of different configurations of tubercles. This comparison is done for different angle of attacks and to check which is the most optimum configuration that give more coefficient of lift and a higher L/D Ratio.

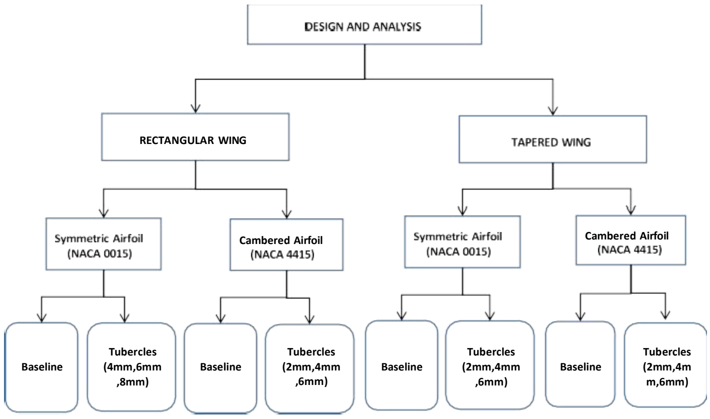

Fig 1. Flow chart of methodology

IV. DESIGN OF WINGS

The design typically involves determining the optimal tubercle size, spacing, and angle of attack. Here are some general steps involved in the calculation process:

1. Determine the required lift coefficient (Cl) and angle of attack (AoA) for your aircraft. These values are typically based on the desired flight characteristics, weight distribution, and other design considerations.
2. Calculate the baseline wing geometry and performance without tubercles. This includes determining the wing area, aspect ratio, and airfoil selection based on the aircraft's mission and performance goals.
3. Estimate the optimal tubercle size and spacing. The tubercle size is typically expressed as a percentage of the local chord length. For example, a tubercle size of 10% means the height of the tubercle is 10% of the local chord length. The spacing between tubercles is typically expressed as a multiple of the chord length.
4. Conduct computational fluid dynamics (CFD) simulations or wind tunnel testing to evaluate the aerodynamic performance of the wing with tubercles. These simulations help assess lift, drag, and stability characteristics under various operating conditions.

The amplitude and wavelength of the tubercles is taken from the literature paper as reference for Symmetrical airfoil (NACA 0015) and Cambered airfoil (NACA 4415) and have designed the wings for different amplitude of tubercles for rectangular wing and tapered wing. The formula to calculate the amplitude of the tubercles for rectangular and tapered wing is as follows:

No. of planes: $\frac{\quad}{\frac{Wavelength}{2}}$

Scaling factor: $1 - \frac{amplitude}{chord\ length}$

Taper ratio: $\frac{chord\ length\ at\ the\ tip}{chord\ length\ at\ the\ root}$

For Rectangular wing, the scaling factor for different amplitude of tubercles is as follows:

No. of planes: $\frac{240}{\frac{30}{2}} = 16$

Scaling Factor:

i. For 2 mm amplitude of tubercles: $1 - \frac{2}{74} = 0.9729$

ii. For 4 mm amplitude of tubercles: $1 - \frac{4}{74} = 0.9459$

iii. For 4 mm amplitude of tubercles: $1 - \frac{6}{74} = 0.9189$

Table 1. Calculation for tubercle design for tapered wing (NACA 0015 and NACA 4415)

No. of planes	Chord length (mm)	Scaling factor for 2 mm amplitude tubercles	Scaling factor for 4 mm amplitude tubercles	Scaling factor f 6 mm amplitu tubercles
1	74	0.9729	0.9459	0.9189
2	71.516	0.9720	0.9440	0.9161
3	69.03	0.9710	0.9420	0.9130
4	66.547	0.9699	0.9398	0.9098
5	64.064	0.968	0.9375	0.9063
6	61.581	0.967	0.9350	0.9025
7	59.098	0.966	0.9323	0.8993
8	56.615	0.9646	0.9293	0.8940
9	54.132	0.9630	0.9261	0.8891
10	51.649	0.9612	0.9225	0.8838
11	49.166	0.9593	0.9186	0.8779
12	46.683	0.9571	0.9143	0.8714
13	44.2	0.9547	0.9095	0.8642
14	41.717	0.9520	0.9041	0.8561
15	39.234	0.949	0.8980	0.8470
16	36.751	0.9455	0.8911	0.8367

To design a rectangular wing using SolidWorks, the steps are as follows:

1. Create a new part file in SolidWorks by selecting "New Part" from the startup screen.
2. Set the units and dimensions according to your preference. You can choose inches or millimeters depending on your project requirements.
3. Sketch the airfoil profile:
   a. Select the "Front Plane" from the feature manager tree.
   b. Click on the "Sketch" icon from the command manager.
   c. Use the sketch tools (lines, arcs, splines, etc.) to create the NACA 0015 airfoil profile.
   d. Make sure to fully define the sketch by adding dimensions and constraints.
4. Extrude the airfoil profile to create the wing:
   a. Click on the "Extruded Boss/Base" icon from the command manager.
   b. In the "PropertyManager" window, select the sketch you just created as the profile.
   c. Specify the desired thickness or depth for the wing section.
   d. Click "OK" to extrude the sketch and create the wing.

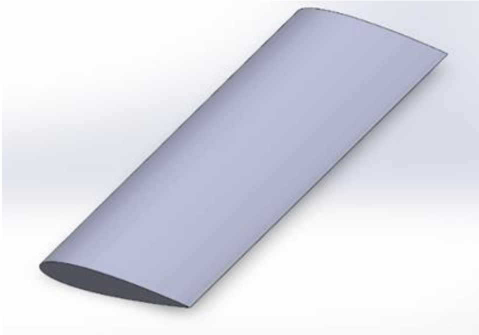

Fig 2. NACA 0015 Rectangular Baseline wing

To design a rectangular wing with tubercles of different amplitudes using SolidWorks, repeat the steps 1-4 from previous section and then continue with the following steps:

1. Sketch the tubercles with different amplitudes:
   a. Create a new sketch on the front plane or any other appropriate plane.
   b. Use the sketch tools to draw the shape of the tubercles. You can use arcs, lines, splines, or other sketching tools.
   c. Add dimensions and constraints to define the tubercles and their amplitudes. You can create different tubercles with varying amplitudes by adjusting the dimensions of each tubercle individually.
2. Extrude the tubercles:
   a. Click on the "Extruded Boss/Base" icon from the command manager.
   b. In the "PropertyManager" window, select the tubercle sketch as the profile.
   c. Specify the desired height or depth for the tubercles.
   d. Click "OK" to extrude the sketch and create the tubercles.
3. Blend the tubercles with the wing:
   a. Select the "Fillets" icon from the command manager.
   b. Choose the edges where the tubercles meet the wing.
   c. Set the desired fillet radius to smoothly blend the tubercles with the wing surface.
   d. Click "OK" to create the fillets.

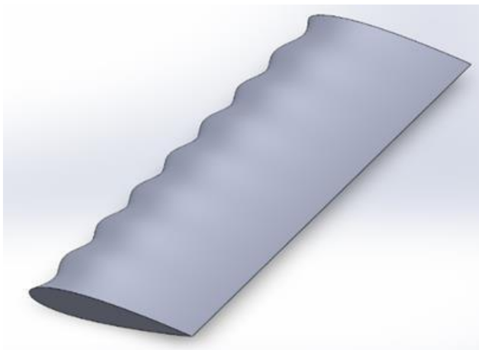

Fig 3. NACA 0015 Rectangular wing with 4 mm amplitude of tubercles

To design a tapered wing using SolidWorks, the steps are as follows:

1. Create a new part file in SolidWorks by selecting "New Part" from the startup screen.
2. Set the units and dimensions according to your

preference. You can choose inches or millimeters depending on your project requirements.

3. Sketch the root airfoil profile:
   a. Select the "Front Plane" from the feature manager tree.
   b. Click on the "Sketch" icon from the command manager.
   c. Use the sketch tools (lines, arcs, splines, etc.) to create the airfoil profile at the root section of the wing. You can refer to airfoil coordinates for the specific points required for the airfoil profile.
   d. Make sure to fully define the sketch by adding dimensions and constraints.
4. Extrude the root airfoil profile to create the root section of the wing:
   a. Click on the "Extruded Boss/Base" icon from the command manager.
   b. In the "PropertyManager" window, select the root airfoil sketch as the profile.
   c. Specify the desired thickness or depth for the root section of the wing.
   d. Click "OK" to extrude the sketch and create the root section.
5. Sketch the tip airfoil profile:
   a. Create a new sketch on a plane parallel to the front plane, representing the tip section of the wing.
   b. Use the sketch tools to create the airfoil profile at the tip section, ensuring it is appropriately tapered.
   c. Fully define the sketch by adding dimensions and constraints.
6. Extrude the tip airfoil profile to create the tip section of the wing:
   a. Click on the "Extruded Boss/Base" icon from the command manager.
   b. In the "PropertyManager" window, select the tip airfoil sketch as the profile.
   c. Specify the desired thickness or depth for the tip section of the wing.
   d. Click "OK" to extrude the sketch and create the tip section.
7. Create a Loft feature to blend the root and tip sections:
   a. Click on the "Lofted Boss/Base" icon from the command manager.
   b. In the "PropertyManager" window, select the root section and the tip section as the profiles.
   c. Specify any additional guide curves or sections as needed to control the lofting shape.
   d. Click "OK" to create the lofted wing.
8. Modify the wing section as needed:
   a. Adjust the dimensions, such as span, taper ratio, or sweep, to meet your design requirements.
   b. Use additional SolidWorks tools like fillets, chamfers, etc., to add desired details or refine the wing shape.

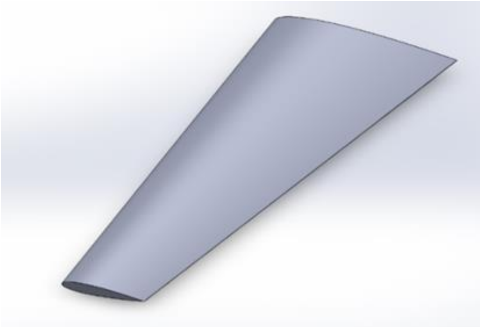

Fig 4. NACA 0015 Tapered Baseline Wing

V. ANALYSIS & RESULTS

The CFD analysis of the wings is done using ANSYS Fluent. The analysis is done for NACA 0015 and NACA 4415 wings. Both wings are modified for analysis of rectangular and tapered wing. The wings are designed for different dimensions of tubercles by changing the amplitude of the tubercles. The rectangular and tapered wing for NACA 0015 and NACA 4415 is analysed for baseline and different amplitude of tubercles.

Coefficient of lift (Cl) and coefficient of drag (Cd) plots are to be obtained for all modifications of NACA 0015 and NACA 4415 rectangular and tapered wings and Lift to drag ratio (L/D) is calculated for the respective wings. These values are then compared between baseline and wings with tubercles for different modifications and prove that wings with tubercles are aerodynamically better than baseline model. Also, we figure out the stalling angles for each modification of wings.

Analysing the aerodynamic characteristics of a NACA 0015 and NACA 4415 wing for rectangular and tapered modification using ANSYS Fluent involves several steps. Here's a general outline of the process:

1. Geometry Creation: Create a 3D model of wing geometry using CAD software or ANSYS DesignModeler.
2. Mesh Generation: Import the wing geometry into ANSYS Fluent and generate a mesh. Use a suitable meshing technique, such as structured or unstructured meshing, depending on your requirements. Ensure that the mesh is refined enough near the wing surface to capture the boundary layer accurately.
3. Physics Setup: Set up the fluid domain and define the fluid properties, such as density, viscosity, and inlet conditions. Specify the boundary conditions for the wing, including the wing surface as a wall boundary, inlet velocity, and outlet pressure.
4. Solver Settings: Configure the solver settings in ANSYS Fluent. Select appropriate turbulence models, such as the k-epsilon or SST model, depending on the flow regime and turbulence characteristics. Set convergence criteria and time step size.
5. Solution Initialization: Initialize the flow field by specifying initial conditions, such as velocity and pressure, based on the desired flow conditions.
6. Solution Run: Run the simulation in ANSYS Fluent to solve the governing equations for fluid flow. Monitor the convergence of the solution and adjust the solver settings if necessary.
7. Post-processing: Once the simulation is complete,

analyze the results using the post-processing capabilities of ANSYS Fluent. Generate plots and visualize quantities of interest, such as lift and drag coefficients, pressure distribution, velocity contours, and streamlines.

For all the modifications of wings, 1 baseline wing and 3 wings with different amplitude of tubercles are analysed at the step of 3º from 0 º to 30 º AOA. The above steps are repeated for every different AOA. The performance of the wings with tubercles are compared to the baseline model and the most efficient wing is found.
The results of the analysis obtained for all modifications of wings are as follows:

1. NACA 0015 TAPERED WING

In aerodynamic testing on airfoil with varying amplitudes at 0mm amplitude, the stall occurred at 18° AOA, with Cl = 248.41574 (15° AoA), Cd = 96.090369 (15° AoA), and l/d = 7.549382. At 2mm amplitude, the stall occurred at 15° AoA, with Cl = 314.87885 (12° AoA), Cd = 88.997032 (12° AoA), and l/d = 9.466303 (0° AoA). At 4mm amplitude, the stall occurred at 18° AoA, with Cl = 372.24547 (15° AoA), Cd = 79.06426 (15° AoA), and l/d = 8.400538 (15° AoA). At 6mm amplitude, the stall occurred at 24° AoA, with Cl = 332.418 (21° AoA), Cd = 104.805 (21° AoA), and l/d = 9.24191 (9° AoA).

2. NACA 4415 TAPERED WING

The aerodynamic testing of an airfoil at different amplitudes revealed that at the baseline amplitude of 0mm, the stall occurred at 30° AoA, with maximum Cl, Cd, and l/d values of 879.7777 (27° AoA), 216.7068 (27° AoA), and 8.22407 (6° AoA) respectively. Increasing the amplitude to 2mm resulted in a stall at 21° AoA, with maximum Cl, Cd, and l/d values of 599.9089 (18° AoA), 168.8933 (18° AoA), and 8.22407 (6° AoA) respectively. At 4mm amplitude, the stall occurred at 15° AoA, with maximum Cl, Cd, and l/d values of 492.3787 (12° AoA), 62.43892 (12° AoA), and 11.87493 (3° AoA) respectively. Lastly, at 6mm amplitude, the stall occurred at 27° AOA, with maximum Cl, Cd, and l/d values of 430.573 (24° AoA), 144.4625 (24° AoA), and 9.155528 (12° AoA) respectively.

3. NACA 0015 RECTANGULAR WING

In aerodynamic testing, varying amplitudes were applied to an airfoil design. At a baseline amplitude of 0mm, the stall occurred at 18° AoA, with Cl = 885.90 (15° AoA), Cd = 105.238 (15° AOA), and l/d = 9.332 (9° AoA). At 4mm amplitude, the stall still occurred at 18° AoA, with Cl = 679.30 (15° AoA), Cd = 102.579 (15° AoA), and l/d = 8.379 (0° AoA). At 6mm amplitude, the stall occurred at 21° AoA, with Cl = 711.95002 (18° AoA), Cd = 132.88 (18° AoA), and l/d = 8.547 (9° AoA). At 8mm amplitude, no stall occurred, with Cl = 701.7229 (30° AoA), Cd = 343.1264 (30° AoA), and l/d = 8.237 (9° AoA).

4. NACA 4415 RECTANGULAR WING

A comprehensive aerodynamic testing was conducted on an airfoil with varying amplitudes. At the baseline amplitude of 0mm, no stall was observed. The airfoil exhibited a maximum lift coefficient (Cl) of 1382.697 (30° AoA), a maximum drag coefficient (Cd) of 400.849 (30° AoA), and a maximum lift-to-drag ratio (l/d) of 7.153414244 (9° AoA). Increasing the amplitude to 2mm resulted in a stall occurring at 21° AoA. The airfoil achieved a maximum Cl of 987.024 (18° AoA), a maximum Cd of 391.078 (30° AoA), and a maximum l/d of 8.2686 (6° AoA). Further increasing the amplitude to 4mm caused the stall to occur at 24° AOA. The airfoil demonstrated a maximum Cl of 516.526 (21° AoA), a maximum Cd of 168.719 (21° AoA), and a maximum l/d of 12.074 (6° AoA). At 6mm amplitude, the stall occurred at 18° AoA. The airfoil achieved a maximum Cl of 484.658 (15° AoA), a maximum Cd of 130.009 (15° AoA), and a maximum l/d of 13.089 (0° AoA).

VI. VALIDATION

The results of NACA 0015 (Tapered and Rectangular) and NACA 4415 (Tapered and Rectangular) wings are considered with respect to its maximum coefficient of lift, maximum coefficient of drag and maximum lift to drag ratio within the pre stall region. The Tapered NACA 0015 baseline wing stalls at 18° AOA whereas the wing with tubercles of amplitudes 2mm, 4mm and 6mm stalls at 15° AOA, 18° AOA and 24° AOA respectively. Accordingly, the Tapered NACA 4415 baseline wing stalls at 30° AOA whereas the wing with tubercles of amplitudes 2mm, 4mm and 6mm stalls at 21° AOA, 15° AOA and 27° AOA respectively. And the Rectangular NACA 0015 baseline wing stalls at 18° AOA whereas the wing with tubercles of amplitudes 4mm, 6mm and 8mm stalls at 18° AOA and 21° AOA respectively and the stall doesn't occur in 8mm amplitude. Accordingly in the analysis of Rectangular NACA 4415 baseline wing, the wing doesn't stall but the wing with tubercles of amplitudes 2mm, 4mm and 6mm stalls at 21° AOA, 24° AOA and 18° AOA respectively.
Considering the stalling angle, the maximum C_l, C_d, and l/d values were considered.

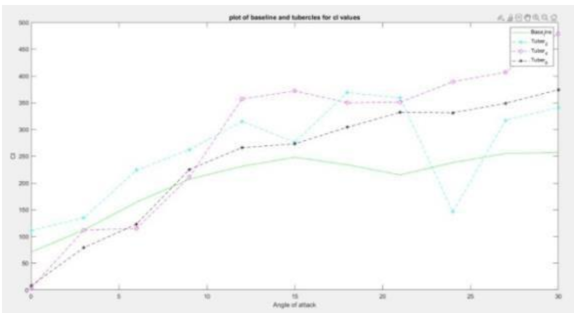

Fig 5. C_l Curve for Tapered 0015

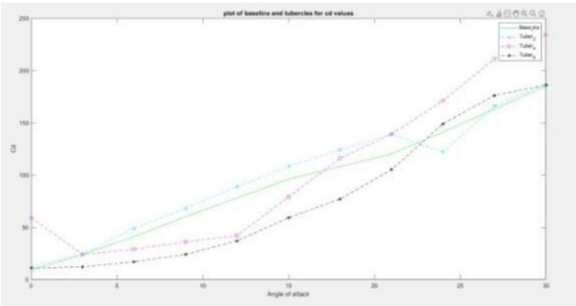

Fig 6. C_d curve for Tapered 0015

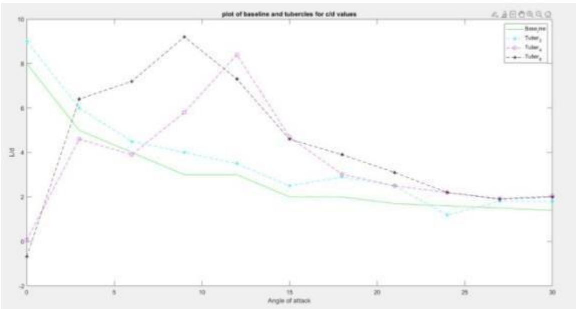

Fig 7. l/d curve for Tapered 0015

To know the variations in the values of Coefficient of lift, coefficient of drag and maximum lift to drag the graph is plotted with respect to Angle of Attack using simulation as the example graphs for Tapered 0015 aerofoil are shown in the above figures.

VII. CONCLUSION

The analysis of NACA 0015 Tapered and rectangular and NACA 4415 Tapered and rectangular is done using ANSYS FLUENT.

All the four airfoil NACA series analysis is done using different amplitudes. Comparing all the four-airfoil series i.e., NACA 0015 and NACA 4415 modified for rectangular wing and tapered wing, the airfoil without tubercles of NACA 0015 stalls around 18º and airfoil with tubercles provides better lift performance by delaying stall. NACA 4415 Tapered and Rectangular wing without tubercles stalls around 30º and 9º respectively and the better lift performance is provided by the airfoil with tubercles. The tubercles help in delaying the stall and the coefficient of lift increases as tubercles amplitude is decreased.

Overall, the performance of the wing with tubercles is better than the wing without tubercles by delaying stall.

VIII. REFERENCES

[1] Tubercles and Their Applications by Micheal. D. Bolzon; Richard M. Kelso and Maziar Arjomandi in 2015.

[2] Tubercles Effect on a Wing Performance for NACA 634-421 Airfoil by Gracio Joyal Lobo and Amrutha K in 2020.

[3] Effect of Tubercles on Aerodynamic Performance of NACA 0015 by Hardeep Singh Lall and Jaitra Khanna in 2019.

[4] How Bumps on Whale Flippers Delay Stall: An Aerodynamic Model by Ernst A. van Nierop, Silas Alben, and Michael P. Brenner in 2008.

[5] Leading-edge tubercles delay stall on humpback whale flippers by D. S. Miklosovic, M. M. Murray, L. E. Howle, F. E. Fish in 2004.

[6] The influence of passive, leading edge tubercles on wing performance by P. Watts and F. E. Fish.

[7] Carija, E. Marusic. Numerical Analysis of Aerodynamic Characteristics of a Bumped Leading Edge Turbine Blade. Engineering Review Vol 34, Issue 2. 2014.

[8] An Investigation of Three-Dimensional Effects on the Performance of Tubercles at Low Reynolds Numbers by Kristy Hansen, Bassam Dally, and Richard M. Kelso in 2010.

[9] http://airfoiltools.com/