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Computational Flow Analysis over an Aircraft Wing by Incorporating Turbulent Flow Generators

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Abstract - *In Modern Aviation, drag reduction plays a remarkable role in the betterment of fuel consumption as well as the aerodynamic performance of an aircraft. By optimizing the aerodynamic shape, better results in lift to drag ratio can be attained. Creating turbulence under the subsonic conditions over the wing surface, the boundary layer separation can be prolonged up to a certain distance in the chord. The additional components could be implemented on the upper surface of the wing to increase the lift to drag ratio. Fish scales, Inward dimples, and Vortex generators are some of the components which can increase the lift-drag ratio of the wing. These three components are designed and incorporated on the upper surface of the NACA 4412 wing and analyzed. They were analyzed at three different angles of attack using a simulation software.*

Key Words: Drag, Fish scales, Inward dimples, Vortex generators, Flow separation, L/D ratio.

1. INTRODUCTION

In fluid mechanics, Drag is a resisting force acting opposite to the relative motion of any object moving with respect to a surrounding fluid. Drag force is proportional to the velocity for a laminar flow and the squared velocity for a turbulent flow. When the aircraft travels through the air it encounters with many types of drag. Each drag has a source for it. The types of drag are generally divided into the following categories: i) Parasite drag which consists of form drag, and skin friction drag, ii) lift-induced drag, and iii) wave drag. Drag depends on the properties of the fluid and on the size, shape, and speed of the object. One way to express this is by means of the drag equation:

$$F_d = C_d \, ½ \, \rho \, V^2 A$$

The major factor influencing the generation of drag on aircraft wing is, boundary layer separation. Boundary layer separation is caused by the viscous forces adjacent to the wing surface. The flow over the top surface of the wing is generally laminar flow under subsonic conditions. When the angle of attack increases the flow attached to the upper surface of the wing tends to detach from it. This is known as the boundary layer separation. The flow aft of the boundary layer separation region has vortices that create drag on the aircraft. Researchers have found out that the conversion of laminar boundary layer to the turbulent boundary layer delays the boundary layer separation. The turbulent boundary layer has more momentum than the laminar boundary layer that allows the flow to reattach to the surface with increased momentum. Turbulent kinetic energy is the mean kinetic energy per unit mass associated with the eddies in a turbulent flow. In Automobiles, vortex generators and other additional drag reducing components such as dimples, spoilers, guide vanes are used to improve the performance of vehicles. These additional components can also be used in aircrafts to reduce the drag generated on the wing. In this analysis, the comparison on the effect of dimples, vortex generators and fish scales in the generation of turbulent boundary layer to reduce the drag is made. All the components work on the same principle, that is generating turbulent boundary layer to delay the boundary layer separation.

1.1 FISH SCALES

In this analysis, we discussed about skin friction drag which is generated when a solid moving object interacts with a fluid. It is generated by the viscous drag in the boundary layer around the solid object. Due to the skin friction, a solid object moving through a fluid experiences a drag force that restrict the forward motion of that object. By reducing the skin friction, we can improve the performance of an object moving along the fluid flow. In nature, the aquatic organisms like fishes have special adaption like scales (fig 1.1.1) on their skin that allow then to swim faster through the sea water by experiencing lesser drag force.

In general, an object with a smooth surface have less skin friction (fig 1.1.2) than an object with rough surface. But in aerodynamic aspect of an aircraft wing, the smooth surface cause the formation of laminar boundary layer which detaches quickly from the surface of the wing at higher angle of attack and causes creation of excessive drag. From researches, it is found that the conversion of laminar boundary layer to turbulent boundary layer can delay the boundary layer separation. To generate the turbulent boundary layer, researchers are using various methods. It is found that the fish scale can also help to create the turbulent boundary layer. The scale is a small rigid plate that grow out of the skin of the fishes. There are different types in the scales of the fishes that are *Placoid* (sharks and rays), *Cosmoid* (lungfishes and some fossil fishes), *Ganoid* (bichirs, Bowfin, paddlefishes, gars, turgeons), *Cycloid* and *Ctenoid* (bony fishes). Scientist and Researchers have been using new concepts that are inspired from the nature for the development in various fields of engineering. In this analysis we have used *Cycloid* type fish scale. The scales are generated over the surface of the aircraft wing to reduce the drag force and to delay the boundary layer separation.

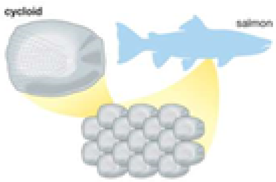


fig 1.1.1. Cycloid scales of Salmon fish

fig.1.1.2. Skin friction drag over an airfoil

1.2 DIMPLES

In aerodynamic field, the most important thing to solve is nothing but reducing drag. In an aircraft, the drag can be reduced by many techniques. One of those techniques is dimples. Dimples are nothing but simply vortex generators in a sphere shape. It is inspired from the golf ball which has dimples all over the surface. With the analysis of smooth surfaced golf ball(fig.1.2.1) and dimpled golf ball(fig.1.2.2), it was found that the dimpled ball has less drag and travels longer when compared to the smooth ball.

It is because, the dimples delay the flow separation. Flow separation is the major reason for increasing the drag by creating the wake region in rear part of the ball. In an airfoil, dimples are mostly placed on the upper surface at the flow separation point. It prevents the boundary layer separation for longer time which in turn helps in reducing the pressure drag. Dimples not only reducing drag but also increases lift. It creates turbulent boundary layer by creating the vortices. Because, turbulent boundary layer reduces the wake region than the laminar boundary layer. At zero angle of attack, the dimples do not reduce the drag. But when the angle of attack increases, the flow separation also increases where the dimples came into work. There are two types of dimples are used in airfoil.

One is inward dimple(fig.1.2.3) and another one is outward dimple(fig.1.2.4). In a recent study, it is found that inward dimple has greater lift to drag ratio when compared to outward dimple.

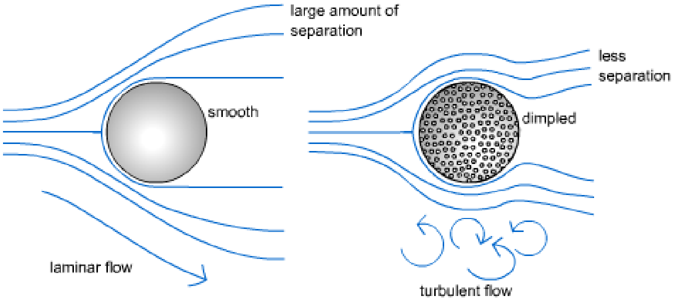


fig.1.2.1. Smooth surfaced **fig.1.2.2.** Dimpled golf ball
golf ball

fig.1.2.3. Airfoil with inward dimple

fig.1.2.4. Airfoil with outward dimple

1.3 VORTEX GENERATORS

Vortex Generators are the small plates, placed on the surface of the wings that changes the flow of air along the surface of wing. The main application of the vortex generator is to generate small vortices that keeps the flow of air closer to the surface, thus delaying the flow separation. This increase lift and reduces drag. Mostly the vortex generator plays key role at low flight speeds, climb, and high angles of attack. Vortex generators can increase the performance and stability of the aircraft. By placing vortex generators, the wing can now operate at higher angle of attack before the airflow separation causes a stall. In Short Take Off and Landing aircrafts the vortex generators will be along the leading edge of wing. In airliners, it is in front of the flaps, where large adverse pressure gradients are developed.

Vortex generators are positioned slantwise so that they have an angle of attack with respect to the local airflow. Since vortex generators can reduce the stalling speed of the aircraft, they can reduce the required one-engine-inoperative climb performance. The reduced requirement for climb performance allows an increase in maximum take-off weight, at least up to the maximum weight allowed by structural requirements. An increase in maximum weight allowed by structural requirements can usually be achieved by specifying a maximum zero fuel weight or, if a maximum zero fuel weight is already specified as one of the airplane's limitations, by specifying a new higher maximum zero fuel weight. For these reasons, vortex generator kits for many light twin-engine airplanes are accompanied by a reduction in maximum zero fuel weight and an increase in maximum take-off weight.

Vortex generators can also be used to reduce the noise of the aircraft, for example, Lufthansa claims a noise reduction of up to 2 dB achieved by using vortex generators.

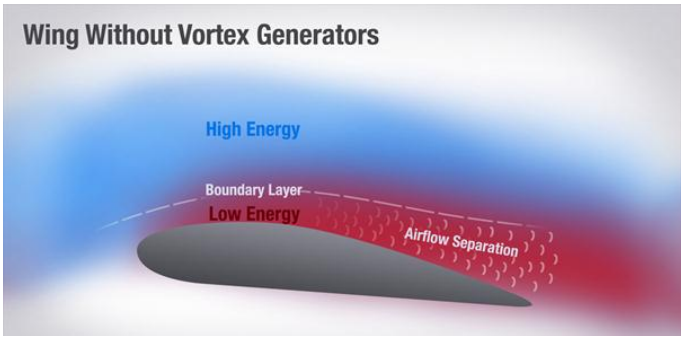


fig.1.3.1. Wing without vortex generators

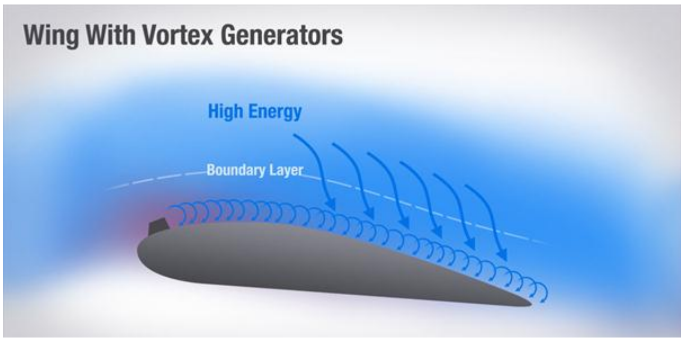


fig.1.3.2. Wing with vortex generators

2. LITERATURE SURVEY

- In 'Streak formation in flow over Biomimetic Fish Scale Arrays', Muthukumar Muthuramalingam, Leo S. Villemin and Christoph Bruecker did Numerical flow simulations and experiments with a physical model of the surface pattern in a flow channel by mimicking the flow over the fish surface with a laminar boundary layer. The scale samples of European bass fishes are analyzed with a digital microscope using 3D mapping feature. Later the scale surface is replicated using CAD design. The 3D printed scale model is placed in a flow channel and the flow over the scale surface with laminar boundary layer is visualized. The velocity variation along the arrangement of scales is analyzed and is found that the velocity at the center of each scale is low and the velocity at the scale overlapping region is high. The ratio between the boundary layer thickness and the scale high is varied and the skin friction drag and total drag are calculated. The results show that when the ratio between boundary layer thickness and scale height is about 15, the total drag on the surface with scale is reduced 3.83% compared to the flat surface.

- In this study of 'Water-trapping and drag-reduction effects of fish Ctenopharyngodon idellus scales and their simulations' by Wu LiYan, Jiao ZhiBin SongYuQiu, Ren WenTao, Niu ShiChao & Han ZhiWu, the surface microstructures of the scales of the fish Ctenopharyngodon idellus were observed and analyzed. A numerical simulation analysis was conducted through computational fluid dynamics. The entire structure of the fish scales of fish Ctenopharyngodon idellus is composed of a basal, laterals, scale focus and apical. The apical area is the only exposed part during swimming, which suffers friction from water. The "crescent" microstructures arranged in an orderly manner play a vital role in reducing the drag. With the increase in flow speed, more kinetic energy was required to maintain the vortex formation and existence, thus gradually increasing both the viscous resistance and pressure force, in turn increasing the total resistance in the near-wall area. However, compared to the flat plate, the flow rate in the non-smooth was approximately 0.66 m/s, and the maximum drag reduction rate was 3.014%. Thus, the bionic surface showed remarkable drag-reduction effect.

- In 'Analysis of Dimpled Wing of an Aircraft' research paper by Vishal Kaushik, Manoj Mahore, and Sandeep Patil, they designed and analyzed three types of wing: without dimples, with inward dimples, and with outward dimples. Their computational study proves that the wing with inward dimples produces more lift at low-speed than the other two configurations.

- In 'Effects of Dimples on Aircraft wing' research paper by Prasath. M. S and Irish Angelin. S carried out an experimental analysis on a symmetrical wing which will reduce the drag ad and delay the flow separation point over the upper surface wing by using the dimple effect. Dimples delay the flow separation point by creating a turbulent boundary layer by reenergizing potential energy into kinetic energy. They had taken symmetrical airfoil to construct the wing fabricated along with the probe holes to measure the pressure at the dimple. They conduct an experiment in a subsonic wind tunnel as well as numerical methods for computing integrals, the trapezoidal rule. From the experiments, it has concluded that the presence of dimples on Aircraft wings will reduce the drag as well as increases the stall angle and cannot be applied to all airfoil profiles.

- In 'Experimental Study of Airfoil performance with Vortex Generators,' a research paper by M.B.Bragg and G.M.Gregorek form Ohio State University, Columbus, Ohio., an experimental canard wing airfoil was constructed based on the Voyager aircraft. It was found that due to the roughness in the wings surface and some atmospheric conditions the separation of the boundary layer was too quick in the canard wing of the Voyager.

So, an experimental setup was made to analyze the effects of placing different types of vortex generators on the model of a wing. The types of vortex generators included: small, large, and delta. It was concluded that the delta vortex generators placed on the wings reduced more drag than the other types by slowing down the flow separation.

- In the research paper, 'On the Aerodynamics and Performance of active Vortex generators' by Ron Barrett and Saeed Farokhi, from University of Kansas, Lawrence. An experiment was conducted to find out the effect of vortex generators on NACA 4415 wing section in a Low speed wind tunnel at 1.6 ft/s and Reynolds number of 3400.The experiment was done with both Wedge (Singlet and doublet) and ramp vortex generators. From the result, it was found that ribbed ramp has greatest distance of flow separation than both singlet and doublet wedge Vortex generators and doublet wedge vortex generator has greatest Cl max among them. It was also found that pneumatically activated VGs increase the Cl max than the normal VG.

3. METHODOLOGY

3D CAD models are created with the help of CATIA V5 software. CATIA (Computer-Aided Three-dimensional Interactive Application) is a multi-platform software suite for computer-aided design, computer-aided manufacturing, computer-aided engineering, developed by the French company Dassault Systèmes. After modelling, the 3D models are analyzed using ANSYS software. ANSYS is a mechanical finite element analysis software is used to simulate computer models of structures, electronics, or machine components for analyzing strength, toughness, elasticity, temperature distribution, electromagnetism, fluid flow, and other attributes.

4. GEOMETRY MODELLING

4.1 PROPERTIES OF THE AIRFOIL

The NACA 4412 airfoil is chosen for modelling. The drag reducing components are created on the upper surface of the wing. The chord length of the airfoil is scaled up by 2 times and the wingspan is 2 times the scaled-up chord length.

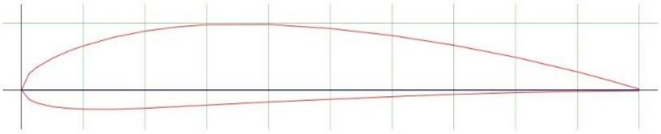


fig.4.1.1. NACA 4412 airfoil

Airfoil type	NACA 4412
Chord length	20 cm
Wing span	40 cm
Transition point	40% from leading edge
Max thickness	12% at 30% chord
Max camber	4% at 40% chord

Table – 1: Properties of the airfoil

4.2 FISH SCALES

In Catia V5, the fish scales are created on the surface of the wing as shown in the fig.4.2.1. The number of frontier scales are 19 and there are 20 scales in the second row. The Scales on the two rows overlap with each other. Each scale has the maximum thickness of 3mm and the distance between the cycloid scale from center to center, row wise is 20mm x 20mm. The distance between the cycloid scales from center to center, column wise is 10mm*10mm.

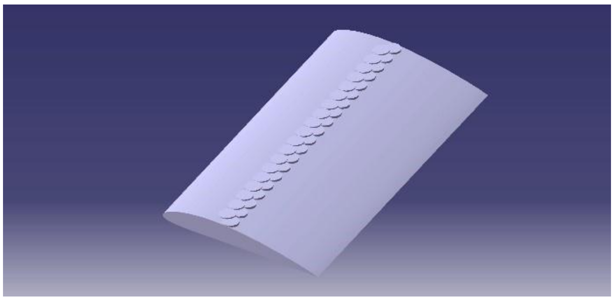


fig. 4.2.1. Wing with fish scales

4.3 INWARD DIMPLES

In Catia V5, the inward dimples are created on the surface of the wing as shown in the fig.4.3.1. The diameter of the inward dimple is 80 mm. There are 21 inward dimples. each of spacing 18mm from center to another center of the dimple.

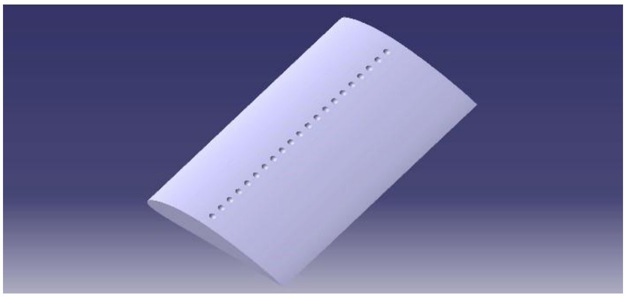


fig. 4.3.1. Wing with inward dimples

4.4 VORTEX GENERATORS

In Catia V5, the vortex generators are created on the surface of the wing as shown in fig.4.4.1. The dimensions of vortex generators are 16mm * 0.5mm * 3mm, respectively. The distance from the top end of one VG to another is 24.30 mm and distance between the bottom end of one VG to another is 36.95mm.

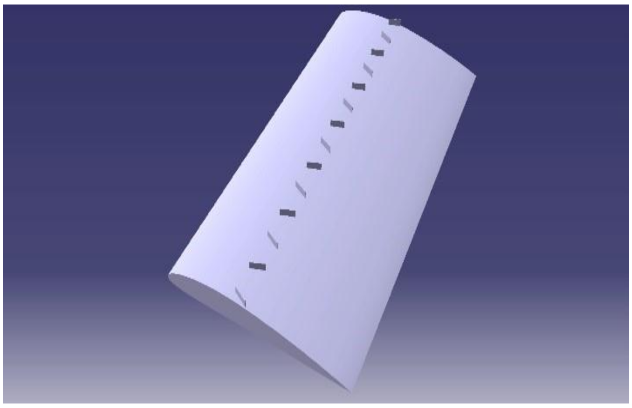


fig.4.4.1. Wing with vortex generators

5. ANALYSIS

5.1 MESHING

Meshing is an integral part of the engineering simulation process where complex geometries are divided into simple elements that can be used as discrete local approximations of the larger domain. The mesh influences the accuracy, convergence, and speed of the simulation. In this, C-type flow domain mesh is created and refined.

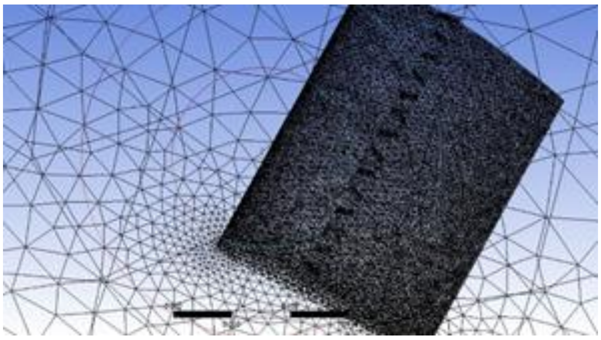


fig.5.1.1. Generated Mesh of the wing

5.2 FLUENT (CFD)

ANSYS 20 R1 - Fluent is used for simulation purpose. Fluent is the industry-leading fluid simulation software used to predict fluid flow, heat and mass transfer, chemical reactions and other related phenomena. Known for delivering the most accurate solutions in the industry without compromise, Fluent's advanced physics modeling capabilities include cutting-edge turbulence models, multiphase flows, heat transfer, combustion, shape optimization, Multiphysics etc.

The SST k-omega turbulence model is used for the calculations. It is a two-equation eddy-viscosity model that is used for many aerodynamic applications. The boundary conditions and inputs of the analysis are briefly mentioned in the table -2.

Boundary conditions	**Input**
Model	Viscous SST k-omega
Method	Coupled – Least cell square based
Time	Transient
Velocity	18 m/s

Table – 2: Boundary conditions

6. RESULTS

All the three modified wings are analyzed at three different angles of attack (9°, 12° and 15°) and the magnitude of velocity is given as 18m/s. After the initial hybridization is done, the calculations are run. The plain wing without any drag reducing components is first analyzed at 15° angle of attack and its C_L and C_D are obtained. The default colourmap as shown in fig.6.01. is used to visualize all the contours. Blue represents the minimum value, green the middle, and red the maximum value.

fig.6.01. Colourmap

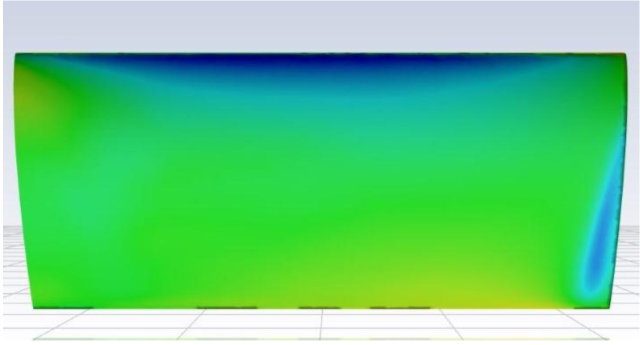


fig.6.02. [Top view] Contours of pressure

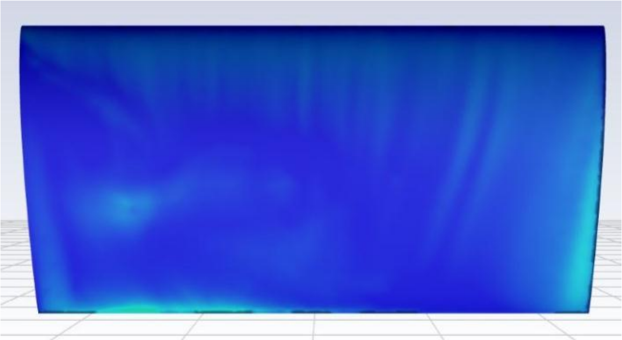


fig.6.03. [Top view] Contours of turbulent kinetic energy

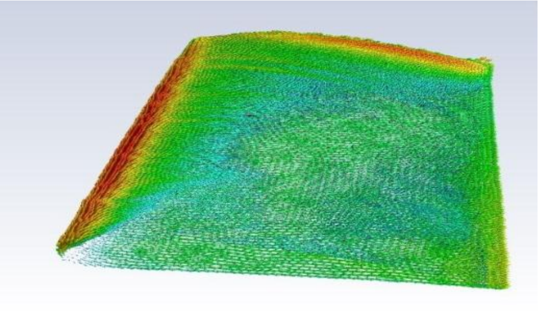


fig.6.04. Vectors of velocity

6.1 FISH SCALES

a) At the angle of attack-9°

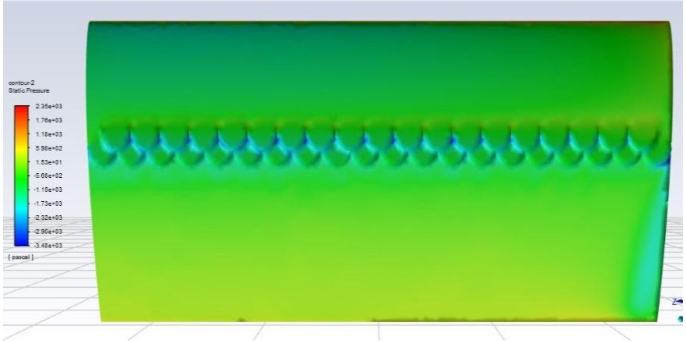


fig.6.1.11. Pressure contours

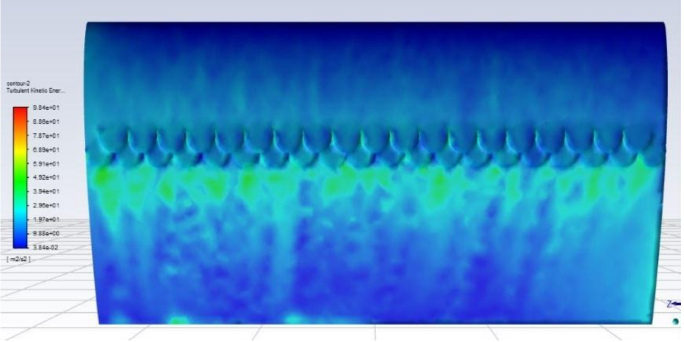


fig.6.1.12. Turbulent kinetic energy

b) At the angle of attack-12°

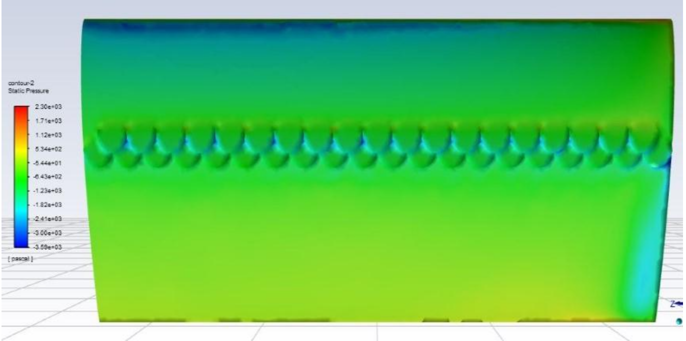


fig.6.1.21. Pressure contours

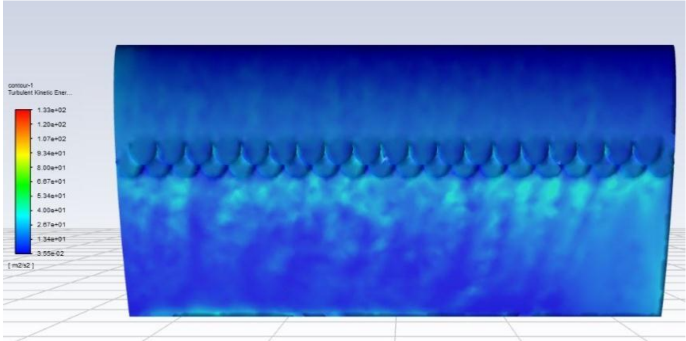


fig.6.1.22. Turbulent kinetic energy

c) At the angle of attack-15°

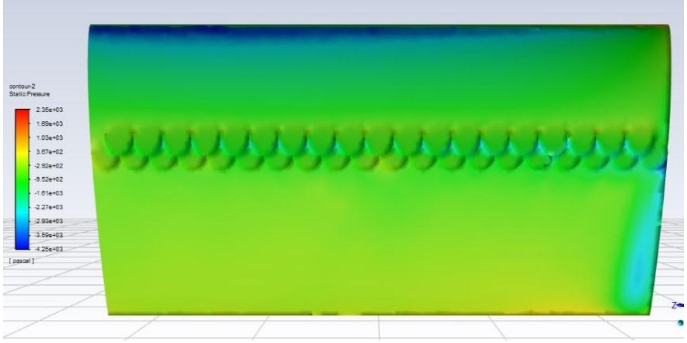


fig.6.1.31. Pressure contours

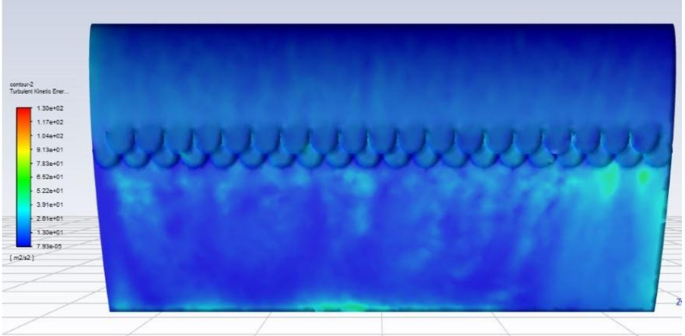


fig.6.1.32. Turbulent kinetic energy

6.2 INWARD DIMPLES

a) At the angle of attack-9°

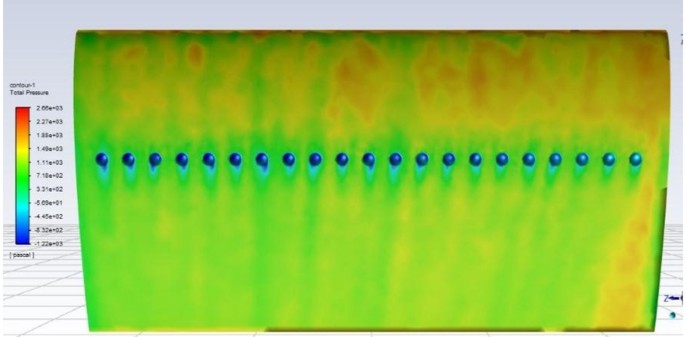


fig.6.2.11. Pressure contours

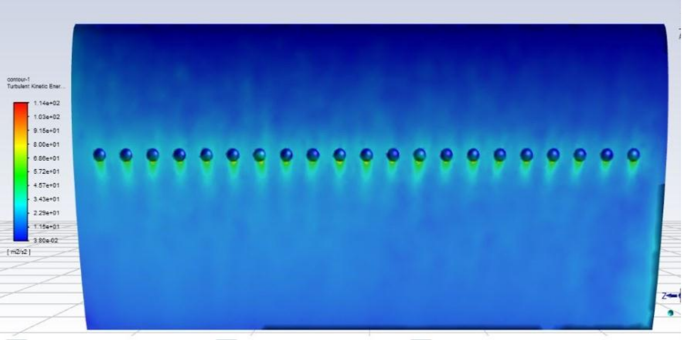


fig.6.2.12. Turbulent kinetic energy

b) At the angle of attack-12°

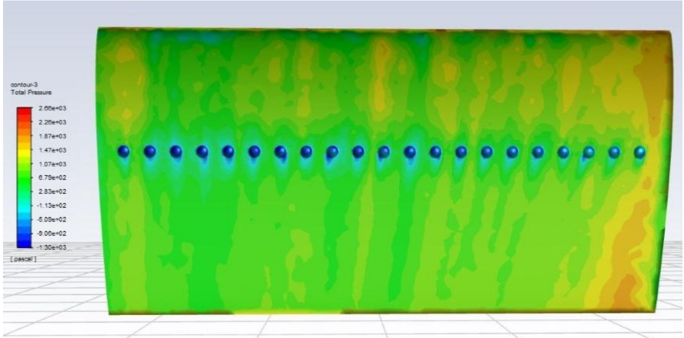


fig.6.2.21. Pressure contours

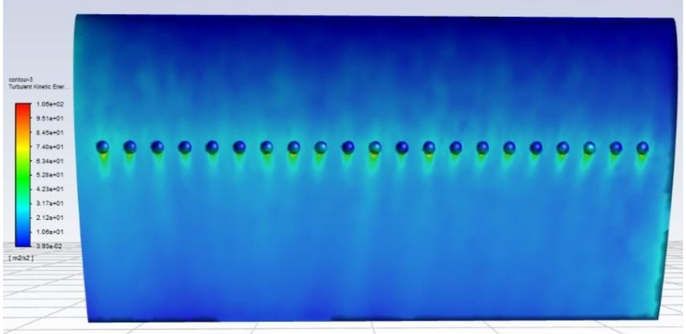


fig.6.2.22. Turbulent kinetic energy

c) At the angle of attack-15°

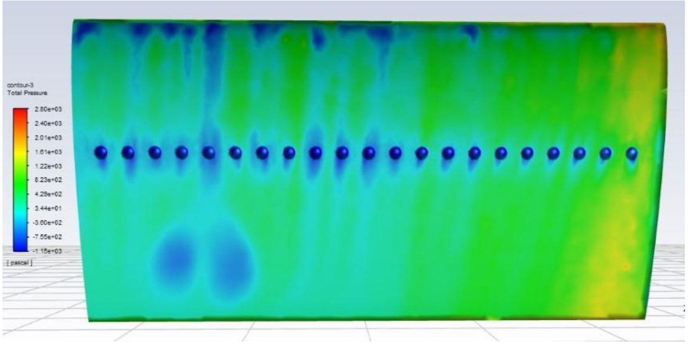


fig.6.2.31. Pressure contours

fig.6.2.32. Turbulent kinetic energy

6.3 VORTEX GENERATORS

a) At the angle of attack-9°

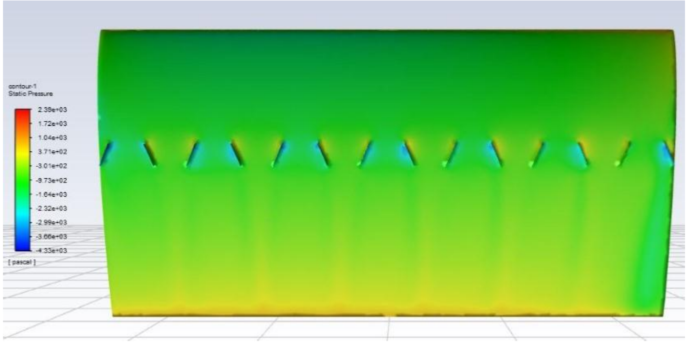


fig.6.3.11. Pressure contours

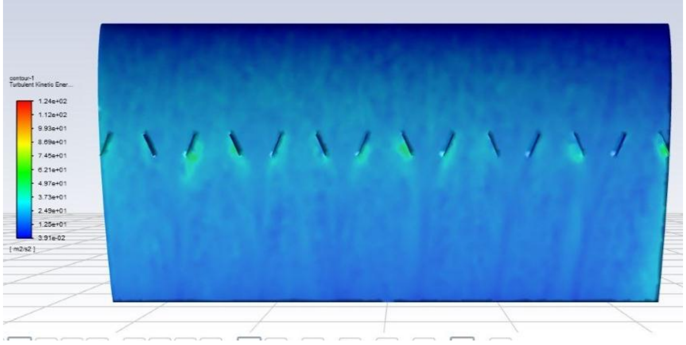


fig.6.3.12. Turbulent kinetic energy

b) At the angle of attack-12°

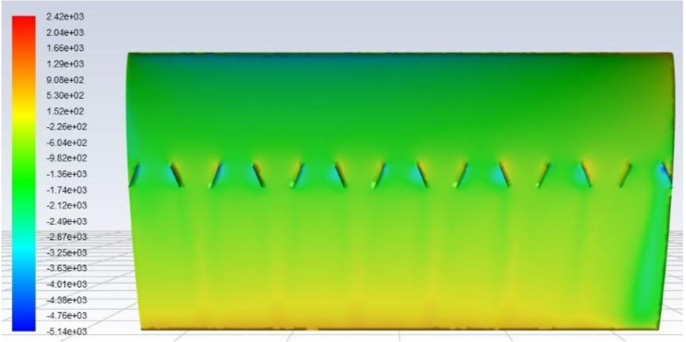


fig.6.3.21. Pressure contours

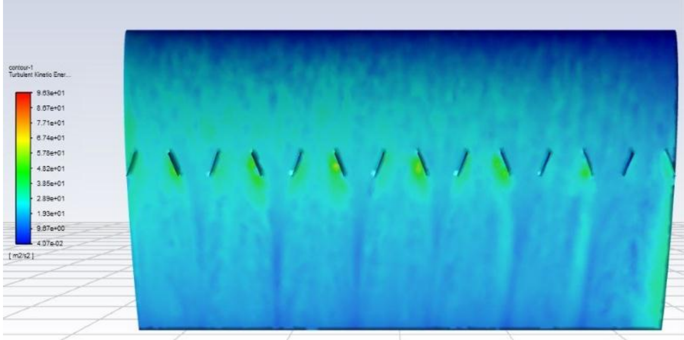


fig.6.3.22. Turbulent kinetic energy

c) At the angle of attack-15°

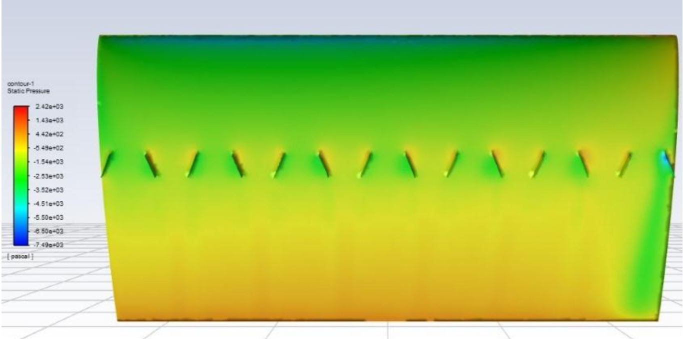


fig.6.3.31. Pressure contours

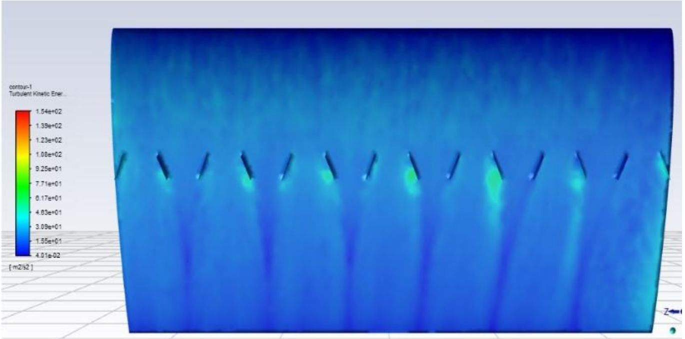
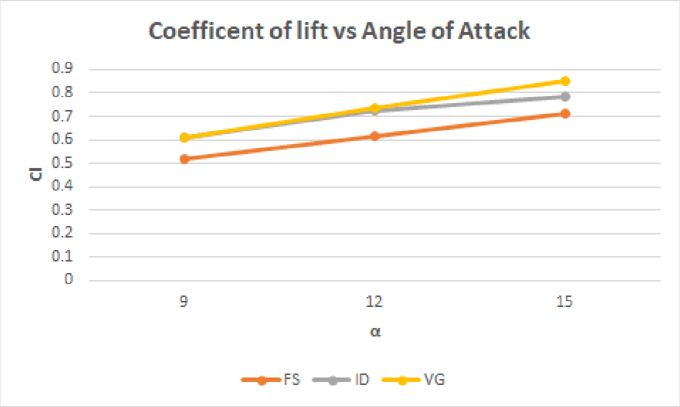
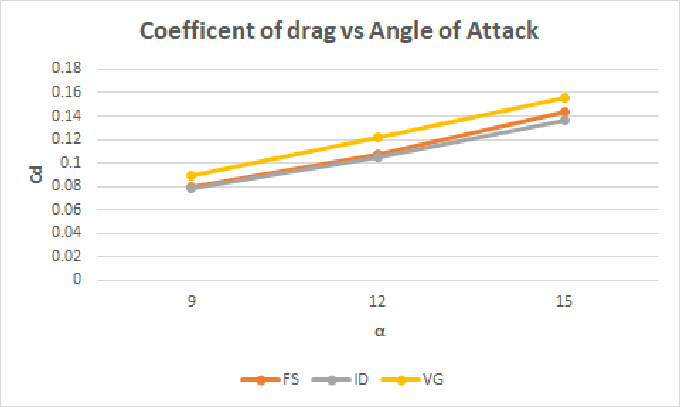


fig.6.3.32. Turbulent kinetic energy

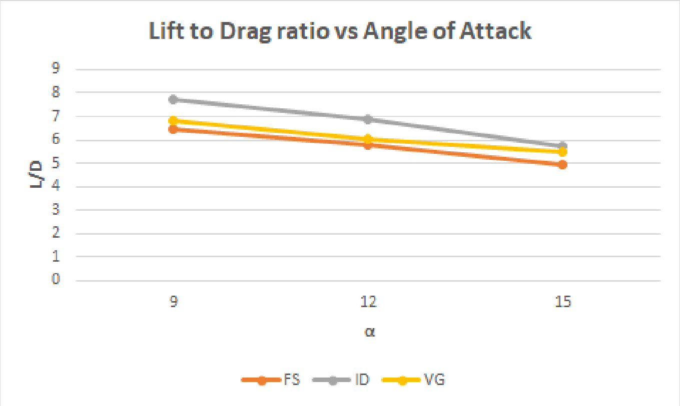
7. COMPARISON - GRAPHS



Graph – 1: C_L vs α



Graph – 2: C_D vs α



Graph – 3: C_L /C_D vs α

FS – Fish scales, ID – Inward dimples, VG – Vortex generators

8. COMPARISON – TABLE

8.1 COEFFICIENT OF LIFT (C_L)

ANGLE OF ATTACK	FISH SCALES	INWARD DIMPLES	VORTEX GENERATORS
9°	0.51813332	0.60868076	0.60895898
12°	0.61706762	0.72318932	0.73575341
15°	0.70970283	0.78371795	0.85421434

Table – 3: Values of C_L

8.2 COEFFICIENT OF DRAG (C_D)

ANGLE OF ATTACK	FISH SCALES	INWARD DIMPLES	VORTEX GENERATORS
9°	0.07996112	0.07854953	0.08965995
12°	0.10704083	0.10539106	0.12132659
15°	0.14335013	0.13690259	0.15634461

Table – 4: Values of C_D

8.3 LIFT – DRAG RATIO ($C_{L/}$ C_D)

ANGLE OF ATTACK	FISH SCALES	INWARD DIMPLES	VORTEX GENERATORS
9°	6.47981569	7.74900575	6.791872848
12°	5.76478732	6.86196078	6.064238763
15°	4.95083492	5.72463932	5.463663506

Table – 5: Values of $C_{L/}$ C_D

9. CONCLUSION

On analyzing the wings at different angle of attacks, it has been obviously observed that lift to drag ratio drastically increases (under subsonic condition) when it is added up with certain aerodynamic components (fish scales, inward dimples, and vortex generators). These three components have the ability to generate vortices and the boundary layer flow changes from laminar to turbulent. It results in delayed boundary layer flow separation and reduces the drag. The inward dimples give better results compared to vortex generators and fish scales. From the results it is evident that when inward dimples are added on the upper surface of the aircraft wing it gives higher aerodynamic efficiency (L/D ratio increases), increases the stall angle, and gives better aircraft fuel economy. However, experimental studies might be needed to be performed. It is also necessary to determine the feasibility of generation of dimples on aircraft wings. This concept cannot be applied to all airfoil profiles.

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