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Experimental and CFD Analysis of Surface Modifiers on Aircraft Wing: A Review

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ABSTRACT

This paper elucidates the comparative experimental and CFD analysis study of various roughness (surface modifiers) on the aircraft wing, which thereby shows how the aerodynamic characteristics differ. This roughness generates turbulences and vortices around the cavity. As the vortex's strength increases, they improve the energy impact of the flow near the wing surface and thus keep the boundary layer attached with decreased wake; this could be achieved by absolute positioning and dimension. These boundary layer separation results in pressure drag reduction, due to decreased wake expansion along with enhancement in lift and stall angle of attack. Improving the stalling characteristics generally improves the aircraft stability and landing efficiency. Study has shown that the airfoil with surface roughness has least drag formation than the baseline beyond certain angle of attack. In this survey, various type of modifiers is discussed, which mainly improves the stalling characteristics and thereby delays the boundary layer separation on the suction side of the aircraft. Each and every modifier has own wake divergence factor according to their roughness parameters. The growth of these wake regions restricts the aircraft to elevate beyond the stall angle.

1. Introduction

There are huge variant of issues hinders the aerospace industry; one among them is the stall factor. Many passive modifiers are embossed on the wing surface which disturbs the boundary layer flow that results in attached flow, incorporation with stream wise vortices. This is a nutshell study on wing surface modifiers to increase the angle of stall and decrease pressure drag by delaying the boundary layer separation. At stall condition, the lift drops and drag heaps (i.e.) at higher angle of attack (AOA) region. Further, the percentages drop of lift increases at critical AOA, where they undergo dominant flow separation. These flow separation lags the lift generated by the wing [1]. This improved aerodynamic efficiency enhances the commercial and military use of air vehicles.

Scientist were inspired on the dimple effect of the golf ball due to its long range and trajectory, and also for the huge resistance for the flow of air around the dimpled surface compared to the smooth surface. Engineers employed these ideas on flying vehicles and hence variant of surface protrusions

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and depressions were designed [2,3]. Vortex generators play out the next vital role in controlling the flow separation at the range of subsonic condition. Vortex generators are active or passive vanes over the wing surface, which alters the angle of stall by providing extra momentum (or) energy to the boundary layer and there by delays the flow separation [4,5]. The performance of the vortex generators are predominant at higher AOA, when it is placed aft of dominant flow separation point, hence modifies the flow to a large range leaving the flow attached to airfoil surface [6]. Both the dimple effect and vortex generators work similar, creating swirling flow around the modified area. These swirl flow shifts the flow from laminar to turbulence, thereby reducing the wake expansion and pressure drag [7]. The studies proved that the turbulence boundary layer transition helps to long last the flow to be attached.

The main objective of the study is to determine the variant type of suitable symmetrical and un-symmetrical airfoil/wing surface modifiers, with all its physical parameters to categorize each individual model benefits towards different AOA. This study is carried to replace the smooth airfoil section with a rough airfoil in-order to neglect early boundary layer separation and stall.

2. Roughness Parameters

To improve the aerodynamic efficiency, numerous attempts were carried out in modifying the wing surface leading edge, trailing edge and wing tip. These modifiers disturb the flow in random motion, hence leads to turbulence. Random motion at the wing tip diverts into circular motion called vortex and this phenomenon is called vorticity [1,8]. The strength and magnitude of these vortices are dependent on the Reynolds number (R_e) and AOA of the flow and is independent on the boundary and inlet condition over the airfoil surface. By creating roughness on the wing surface, it converts the phase of laminar to turbulence by adding momentum to the flow, thereby improves the attached flow capabilities due to irregular movement of fluid flow around the protuberance region. These complete concepts are being observed from the golf ball, which creates a very narrow wake at the aft section [2,8] as shown in Figure 1.

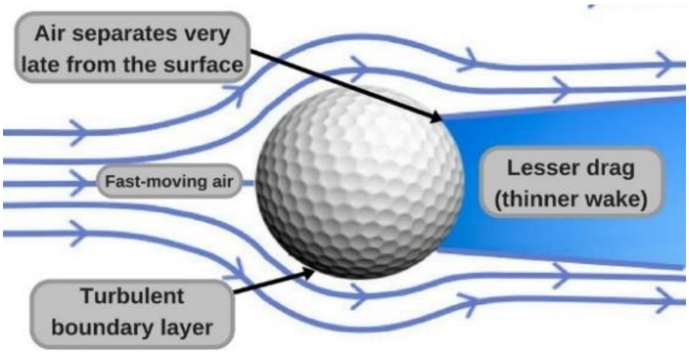

Fig. 1. Flow separation behind dimples golf ball [9]

Figure 2 illustrate how the fast-moving air delays flow separation and expand into thinner wake. Optimum positioning of the modifiers plays out the vital role in differing the flow attachment at variable AOA as shown in Figure 3 [10]. Based on this survey, upstream placement of modifiers gives maximum performance. The two main varying parameters for the modifiers are AOA and positioning. As because these two effects shift in the pressure distribution over the surface [11]. Then the sub parameters like size, shape, length, height and thickness also have contribution to pressure variation.

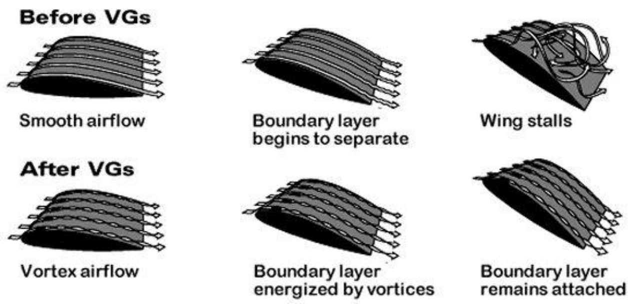

Fig. 2. Flow separation behind vortex generators [12]

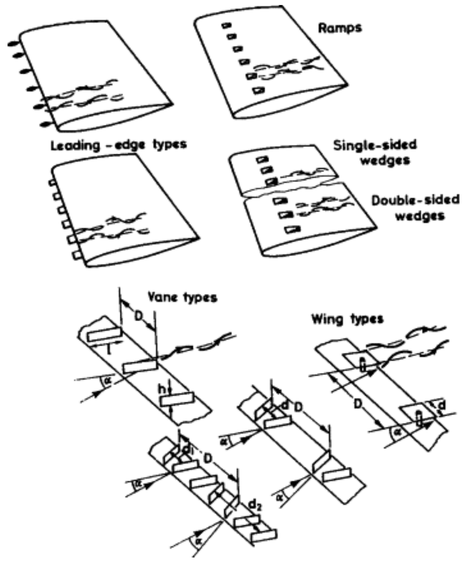

Fig. 3. Flow behavior for variable positioning of vortex generators [13]

2.1 Effect of Roughness on Wing Surface

Every design parameters of protrusion (or) depression on wing surface has its own cores of benefits towards compressible and in-compressible flow (as shown in Figure 4). These modifiers are typically round, square (or) triangular, which are higher than boundary layers, runs through the wing surface along spanwise direction [14]. Performance of wing is very sensitive to wing surface. The general existing surface modifiers are classified in Figure 5. Coefficient of drag (C_D) has its highest impact on dimension of the surface modifiers. According to Harun Chowdhury [15], each dimension of the modifiers could change the transition region and C_D at trans-critical regime to lower *Re*.

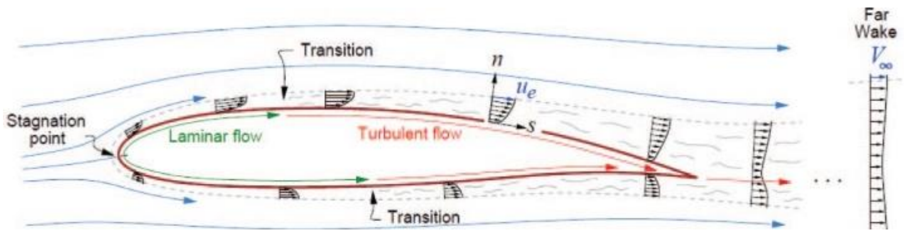

Fig. 4. Schematic view of flow transition [14]

During higher AOA, the vortex generators acts as a vane on suction side of the wing, which fosters the momentum transfer and keep the flow re-attached due to co-rotated flow; these reattachments occurs at the downstream of the modifier. The main concept behind is that, the trailing vortices are generated streamwise along the fluid flow, which thereby increase the transfer of momentum. Vortex generators are found out to be the boundary layer energizer by mixing high energy free stream fluid [5,6,11]. The complex flow vortex formation due to the re-attached flow is shown in Figure 6. The constant streamwise flow approach incorporated with the relationship between the velocity (v) and circulation (Γ) are studied [16].

Roughness height, spacing and skewness are the important parameters considered in sand grain roughness modifier. Analysis results shows that, the turbulence intensity visualize to be larger behind the trailing edge, which could be altered with uniform or random sand grain distribution [17]. Inward and outward dimples have variable performance for same flow condition and AOA. Majority of the research work says that the inward dimple performs better compared to outward dimple in delaying the stalling characteristics. Separation bubbles are formed at the cavities, which vitalize flow transition and prolongs boundary layer separation. Varying aspect ratio dimples were used in investigating the efficiency of skin-friction drag and lift [18].

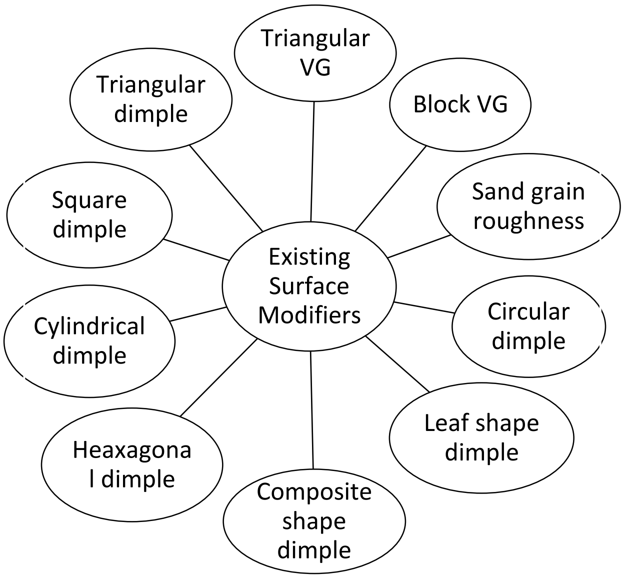

Fig. 5. Wing surface modifiers

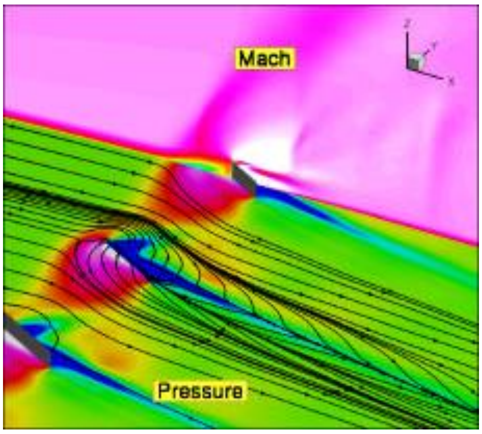

Fig. 6. Friction line around VG's due to re-circulations [6]

2.2 Roughness Application

The complete effectiveness study is based on depth, shape, size, orientation of the modifier and importance should also be given to the corners of the modifiers. These parameters change the turbulence effect of the flow [19]. Results shows that high impact (height) of roughness over the wing surface drastically decrease the (L/D) ratio [17]. Random location of cavity may result better only for certain airfoil, hence positioning roughness helps in determining boundary separation angle and velocity [14]. Dimples on sinusoidal leading edge improves the aerodynamic efficiency to a great extent compared to a baseline wing [8]. Huge variant of modifiers is designed and analyzed both numerically and experimentally by the researches as illustrated in Figure 5, which have different flow separation properties according to the stabilization.

3. Modified Wing Surface Aerodynamics

The performance of an aerodynamic object can be observed by monitoring the flow behavior around the object. The main aim of this study is to identify the ways to delay the boundary layer separation, which is achieved through flow separation control techniques. At initial discoveries, water tunnel flow visualization was preferred in-order to visualize the aft flow pattern. But recent technological hype has made it easier through wind tunnel as experimental analysis and CFD as numerical analysis.

3.1 Numerical Study

CFD simulation technique is an economical tool to investigate the performance of a model, which is utilized by most of the researchers as a first step to determine the model efficiency. Generally, sand grain roughness on the surface of wing showed improved lift and degradation in drag. Roughness height plays a very vital role and has a drastic extreme behavior with 15 % vast variation between modulated flows [17]. The influence of introducing protuberance on the sinusoidal leading edge of wing surface, keeps the flow attached due to stream-wise vortices distribution.

Simulation carried out, showed efficient results at Mach number 0.266 (90 m/s) at various AOA (0°-20°) [8]. The aerodynamic efficiency was compared to show the best result by estimating the effect of inward and outward dimples, designed with tapered streamlined shape [14]. The inward dimple impression has improved (L/D) by 21.6% [20]. An illustration of an inward dimple cad modeling is shown in Figure 7. Numerically analyzing, each dimple parameters (Figure 8) have two different vortex structures: 1)Horse shoe vortex: by increasing R of dimple, the horse shoe vortex moves farther downstream and terms as the dominant vortex in the dimple flow structure. 2) Hairpin vortices: it's a sub layer of horseshoe vortex. Where these both vortex energize the boundary layer flow behavior by mixing up the flow stream [21].

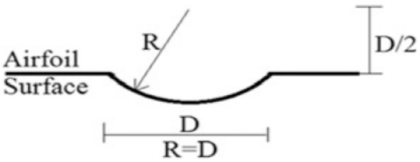

Fig. 7. Inward dimple dimension for CFD [2]

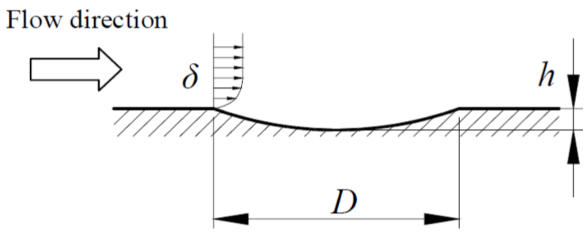

Fig. 8. Dimple flow parameter [21]

Computational simulation over a streamline body with passive flow control devices is carried out. Two different AOA 0°, 20° under the flow R_e 1.3x10^5, with corresponding velocity 10 m/s was simulated and examined to show that, surface modifiers decreases the performance of the airfoil at lower AOA, while in higher AOA the drag formation is very less compared to the smooth airfoil [22]. Investigation of vortex generators showed effective result by replacing the vortex generator position on the NACA (National Advisory Committee for Aeronautics) 4412 wing surface. Simulations were carried under RANS coupled with Spalart - Allmaras model under governed condition at *Re* 10^5. The vortex generator performance differs for every position and every AOA (i.e.) 10° AOA – 0.25C positioning, 15° AOA – 0.15C positioning, 17° AOA – 0.1C positioning, these are all measured from leading edge [11]. Theoretical approach shows that, wakes are generated along with the trailing vortex and moves downwards the velocity of general flow [16]. At higher AOA, the boundary layer separation take place with clockwise circulation of weak vortices, which enhances induced velocity, hence disengage the boundary layer farther upstream the airfoil. Vortex perturbed near the T.E of airfoil gets trapped and moves in clockwise direction as shown in Figure 9.

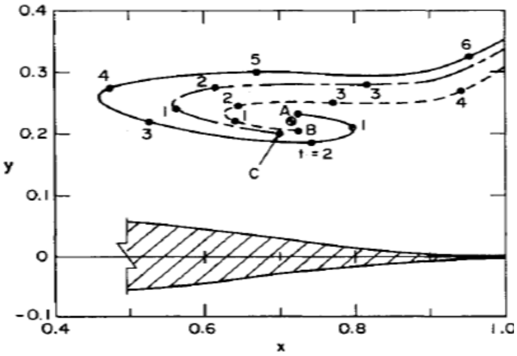

Fig. 9. Trajectories of displaced vortices [23]

An CFD study on hemi-spherical [24] wing with indentation for mini-aerial vehicle was carried out with AOA ranging -4^o to 24^o. The study resulted that at higher AOA, the surface pressure of the conventional airfoil is about 1/3rd the length of the airfoil. The indentation on the airfoil re-circulates the flow creating a turbulence layer at the aft section of the dimple, which encourages the flow re-attachment. Releasing or generating of free stream vortices, traps in the re-circulation flow on the upstream of the airfoil, thereby increases the strength of the streamwise re-attachment flow [23]. In-order to determine the streamwise dimple location, dimple of various thickness to depth ratio (R) – 0.378, 0.994, 1.453 are studied [21]. The spanwise arrangement of dimple creates 3D spanwise deformation at the separation point along with counter rotating vortices [25], where R =$\frac{\delta}{h}$, δ – boundary layer thickness and h –dimple depth.

Proper locating of the vortices improves lift and even generates more drag due to the finite displacement of equilibrium position. Numerical analysis has been carried out on a flat narrow-plate [26] with elongated spherical dimple, in-order to determine the transformation of turbulence flow and its separation, spot depth is kept constant and differing the dimple Aspect Ratio. The depth and length of the dimple is maintained at 0.13 and3, where the width ranges from 0.17 to 0.5. Upon analysis it was observed that helical vortices are generated when the transverse flow velocity go beyond 80% to that of the mass flow velocity.

3.2 Experimental Study

Even the numerical investigation has examined and produced an efficient model, accurate real time results could be predicted only through physical experimental analysis. Inward and out-ward passive dimples as shown in Figure 10 [20,27] were experimentally analyzed at flow speed of 43 m/s and at 45^o AOA. Analysis on various type of dimples have experimentally proven that dimple surface wing keeps flow attached even at higher AOA compared to baseline wing. Active dimple actuators were experimentally investigated to study the flow separation at turbulence layer and laminar layer at various AOA [25]. A dimple of diameter 7.5 mm and depth of 13D were chosen and experimented under the flow velocity of 40 m/s and R_e- 2.2 x 10^5 to 3.72 x 10^5 with 1% turbulence.

(a) Inward dimple [20] (b) Outward dimple [27]

Fig. 10. Dimpled wing model

An aerodynamic effect of dimples on golf ball in concern with the depth and width were studied [15]. The dimple of width 3.5 mm and height ranging 0.5 mm to 1.5 mm were experimentally analyzed for variable R_e of 2 x 10^4 to 4 x 10^4 with a speed regime of 5.5 to 33.3 m/s. From the examined relationship between different dimple impressions, the findings indicated that the shallow dimple can perform better than the deeper dimples at higher AOA and velocities. An experimental study over an NACA 0015 airfoil has been executed with various L.E surface modifiers. The study clearly proved that modifying the smooth airfoil surface near the L.E up to 20 % of chord length, will never improve the stalling characteristics [28], it also shows that placing dimples over the symmetrical airfoil will not show efficient result, instead decreases the performance.

Series of wind-tunnel test Figure 11 were conducted for different positioned triangular vortex generators (shown in Figure 12) of 0.2 mm thickness and 2 mm wide with different AOA (0^o-14^o) [4]. This study experimentally proved that, the positioning and AOA plays a vital role accompanied with R_e. The flow visualization clearly showcase that static vortex generators perform better than active vortex generators, by splitting the air bubbles rather than eliminating it [5]. Similar case can be observed in Jumahadi *et al.,* [4]'s research, using hybrid vortex generators which showed better performance at sub-sonic condition with delayed stall by 4 %.

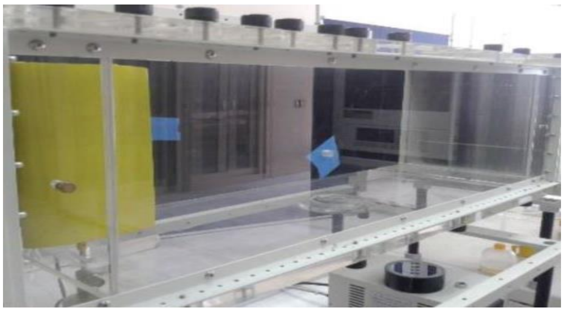

Fig. 11. Wind tunnel set-up [4]

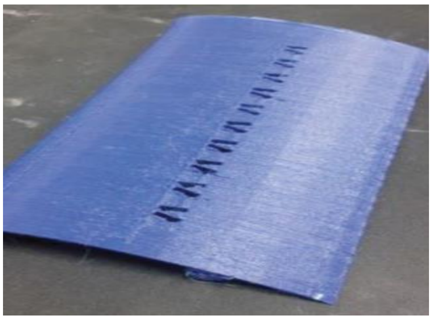

Fig. 12. Triangular vortex generators [4]

4. Result and Discussion

The main objective of this review paper is to bring out the research contribution towards stalling characteristics. Enormous explorations are available, which provides solution for improving the aerodynamic efficiency. Some of the findings are tabulated below in Table 1, in-order to give the gist of different type of modifiers. Due to the presence of dimples and vortex generator's the stall angle has upgraded to 18^o [17,19].

The main goal of these surface modifiers is to create turbulence, without improving the C_D by delaying the onset flow separation. Many research works are carried out to determine the best modification and still it's on leap. Depth, dimension and modifiers distribution on wing surface alters each and every aft flow distribution. Presence of this roughness on the wing surface distributes the pressure along the trailing edge and thereby creates low pressure over the modified region. From the researcher's work it's clear that the flow over the cavity is split into two, one which circulates inside the cavity and the other passes over.

Similar observation is brought for the protruded surface, where one flow run past the surface and the another recirculates behind the protrusion. These flow patterns energize the flow over the wing surface and keeps the flow attached, thereby improves the aft stagnation point by resisting the adverse pressure gradient and improving the velocity gradient. These re-circulation leads to vorticity as the vortex strength increases, they improve the energy impact of the flow near the wing surface and thus keeps the boundary layer attached with decreased wake. This could be achieved by modifiers position and dimension. The strength of vortex interaction is more for deeper groves, which are closely packed. Hence concern has to be taken for the distribution of these protrusion (or) depression. The aerodynamic performance is mainly deteriorated by the formation of induced drag, which is created by trailing edge vortex due to the circulation effect of the lift, the lift is generally generated by the variable velocity of air stream [16].

Positioning of the modifier is mainly concerned on the boundary layer separation point. From the survey, the following positioning of the modifier showed better performance (with respect to chord length) as 0.12C, 0.25C, 0.4C, 0.5C, 0.6C and 0.68C, with a fillet radius of R/10 around the modifiers in-order to prevent sudden shock waves [4, 5, 14]. Table 1 elucidate modifiers dimension, shape and spacing showed the best result in the case of symmetrical and unsymmetrical airfoil, where each having their own random movement of flow around their medium. The following medium has the deeper consideration as NACA 0012, NACA 4412, NACA 4415, round shaped dimple, triangular VG, and aspect ratio of 0.8. The impact of modifiers up to 8 % of airfoil chord with a velocity of 30 m/s and R_e ranging from 1.6 x 10^5 to 2.5 x 10^5 proved to show higher benefits for both symmetrical and unsymmetrical airfoil [1, 2, 4, 5, 11, 14, 19, 20].

From the complete survey it's clear that each type of surface modifiers exposed its own performance and has clearly distinguished the modifier type to be used for symmetrical and un-symmetrical airfoil. The protuberance with different width to depth can be modeled up on the flow requirement as shown in Table 2. The performance of individual modifier is only studied by most of the researchers, use of two are more different type of modifier on to the wing surface is not studied or shown elaborately.

Table 1

Types of surface modifiers with performance categorization

No	Author	Type of modifiers	Airfoil	Method	Flow behavior	Model	Performance
1.	Srivastav *et al.,* [1].	Outward dimples	NACA 0018	Numerical		Airfoil	A steady state simulation was carried out under velocity 20 m/s, around an airfoil of span 0.8 cm at various AOA. Round shaped dimple performed better in minimizing the wake size, hence suitable for aerodynamic efficiency and stability.
2.	Hossain *et al.,* [20].	Inward / outward dimples	NACA 4415	Experimental	√	Wing	Series of wind tunnel tests were carried out and inward dimple showed the best performance by improving lift by 16.43% and degrades drag by 46.6%, at velocity 43 m/s.
3.	Ali *et al.,* [17].	Sand grain	NACA 2412	Numerical	√	Wing	Steady state CFD simulation was carried out at two different velocities and has proven the wing performance has sensitivity nature to roughness and also differs for compressible and incompressible flow.
4.	Masud *et al.,* [8].	Outward dimple	NACA 2412	Numerical		Wing	The sinusoidal wave leading edge with outward dimples shows better performance at stalling angle by increasing lift 18% and decreases drag by 20% compared to baseline wing.
5.	Agarwal *et al.,* [11].	Vortex generators	NACA 4412	Numerical	√	Wing	Vortex generators has high effect on aerodynamic efficiency at higher AOA and has negative effect at low AOA, all these are

							controlled by the optimum positioning of VG on the wing surface.
6.	Seshagiri *et al.,* [5].	Vortex generators		Experimental	√	Wing	Static vortex generators have shown 25% improvement in lift curve at 45 m/s and has shown diminished pressure drag with greater performance enhancement.
7.	Jumahadi *et al.,* [4].	Vortex generators	NACA 4415	Experimental		Wing	Active hybrid vortex generators have potential better performance at sub-sonic condition with 11.3% improvement in lift and 16.5% increase in drag but decreases at high AOA.
8.	Ramprasadh *et al.,* [24].	Dimple	Selig 4083	Numerical	√	Wing	Hexagonal indents are distributed along the curvature of the wing leading edge, in 10 rows with 8mm apart from each other, resulted negative inclination of vortices strength due to the local rotation flow along the leading edge to wing tip.
9.	Binci *et al.,* [29].	Inward dimple	NACA 64-014A	Both	√	Wing	A dimple wing of 1.4m span is investigated under 40 m/s and with 0.3% turbulence intensity, resulted that about 2.81% CD decreases and 2.93% for different turbulence model.
10.	Seong-Ho Seo *et al.,* [30].	Groove	NACA 0015	Numerical	√	Turbine blade	Grooved wing showed effective flow separation control, by recovering the flow velocity losses around the airfoil at 7o AOA, with 15.3% improvement in aerodynamic characteristics.

Table 2
The best cases of symmetrical and unsymmetrical airfoil details

Airfoil Type	Parameters	Description
Symmetrical airfoil	Dimple width (mm)	2, 4, 6, 100
	Dimple depth (mm)	3, 4, 5, 60
	VG width (mm)	2
	VG height (mm)	3
	Adjacent spacing (mm)	25, 100
	VG thickness (mm)	0.2, 1
Unsymmetrical airfoil	Dimple width (mm)	20, 40, 60
	Dimple depth (mm)	1.5, 10
	VG width (mm)	2.4
	VG height (mm)	0.8, 2
	Adjacent spacing (mm)	25, 100
	VG inclination	30^o
	VG Yaw angle	0.5C

5. Conclusion

The result outcome shows that the primary source to delay the flow separation is to minimize the size of the wake behind the wing. Protuberance on the wing surface resulted out in increasing the boundary layer momentum (or) energy and there by delays the flow separation. By installing modifiers on the wing surface, a formidable increase in wing stall efficiency is achieved, which enhances the maneuverability of the aircraft. A parametric investigation to deduce the effect of modifiers position, size, and shape is being performed in this study. Optimizing the location and size of modifier will enhance the aerodynamic efficiency. Advancement in surface roughness technology without increasing the frictional drag will shift the aeronautical industry to next level.

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