ISSN: 2634-9221
European Journal of Applied Sciences; Vol. 14 No. 01 (2026) (267-272)
https://doi.org/10.14738/aivp.1401.19870

Improved Performance of Airfoils Through Vortex Generators Flow Control

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Abstract: Commercial airliners are an irreplaceable aspect of modern society with 4.1 billion passengers per year on 37 million flights. Commercial flights are integral to not only passenger transportation but also to transportation of freight.[4] According to the Air Transport Action Group using air transportation significantly impacts the environment. In 2019, the global aviation industry accounted for 2.1% of all human carbon dioxide emissions and 12% of all transportation carbon dioxide emissions [5]. To increase the efficiency of commercial flights, optimizations can be made in subsonic or transonic regimes via flow control. In this work “Smart” Vortex generators, which only are active at low altitudes, were explored for subsonic flow using CFD. It is found that climbing performance is increased. In addition, while the plane's lift is triple, flow separations is reduced at a free stream velocity of 150 mph and at an angle of attack of 8. The overall result suggests the effectiveness of vortex generators as a flow control mechanism especially at a subsonic flow regime. It is however recommended that a combination of flow control strategies over a range of flow regimes will be of great advantage taking into consideration the gains from individual control mechanism.

Keywords: Airfoil, Vortex generators, Flow control.

NOMENCLATURE

CL	Coefficient of Lift
CD	Coefficient of Drag
CL/CD	Ratio of lift and drag used for efficiency
CP	Coefficient of pressure
CP,crit	Critical coefficient of pressure
γ	Ratio of specific heat
Mcr	Critical Mach number
M_∞	Free stream Mach number
P	Pressure
P_∞	Freestream pressure
q_∞	Dynamic freestream pressure
Re_∞	Free stream Reynolds number
α	Angle of attack

V_∞	Free stream velocity
S	Surface area of wing
Pc	Corrected pressure
(L/D)c	Corrected ratio of lift to drag
VG	Vortex generator
CAD	Computer aided design
CFD	Computational fluid dynamics
CFJ	Co-flow jets

INTRODUCTION

At the start of aviation, the design of airfoil geometries was unrefined and guesswork. The first airfoils implemented on the planes flown by the Wright brothers in 1903 and by Santos-Dumont in 1906 were effectively thin flat planes while the Bleriot XI flown over the English Channel by Louis Bleriot in 1909 had an overly large degree of camber [1]. It was not until the early 1940's that an airfoil with camber and thickness was recognized as beneficial for aerodynamic performance [1]. This development was due to input from two major contributors. The first contributor was Ludwig Prandtl in 1917 who discovered that thick airfoils are beneficial due to allowing higher angles of attack and producing less drag. The second contributor was NACA, an organization who in the 1930's developed and tested the NACA series of airfoils giving parameters like pitching moment and lift at zero angle of attack for each airfoil [1]. With the introduction of the turbojet engine during WWII, flight speeds were approaching the speed of sound and entering the transonic flight regime. This sudden advance in flight speeds forced the development of supercritical airfoils, airfoils designed to delay the onset of shockwaves and therefore wave drag [1]. The early designs of supercritical airfoils performed well at transonic speeds, but this came at the cost of low-speed performance. Significant efforts were made in the experimental and theoretical fields to remedy this effect. The perfection of the supercritical airfoil, which had excellent low and high-speed performance, in the late 1960's marked what scientists believed to be the end of airfoil performance improvements through geometric means. This induced an industry shift to focus on flow control for further aerodynamic improvements [2]. The University of Illinois defines flow control as "forced changes to flow structures, mixing behavior, or momentum injection in the flow field to produce more desirable performance characteristics from an aerodynamic geometry." [3]. Flow control in low-speed flight is used to achieve reduced flow separation, increased lift, reduced drag, and delay the transition from laminar to turbulent flow. Flow control in transonic flight is used much in the same way that it is during low-speed flight with the added objective of delaying the onset of shockwaves at increasing Mach numbers. Flow control can be broken into two general categories, passive and active. Passive flow control is always a part of the wing and can't be turned on and off. Some examples of passive flow control are winglets, vortex generators, and dimpled surfaces. Active flow control, on the other hand, can be turned on and off. An example of active flow control is pneumatic systems that increase or decrease pressure along sections of the airfoil.

PROBLEM DEFINITION AND OBJECTIVES

With 37 million flights and 4.1 billion passengers per year commercial flights are integral to not only passenger transportation but also to transportation of freight [4]. However, this reliance on air travel comes at a cost. According to the Air Transport Action Group [5], in 2019, the global aviation industry accounted for 2.1% of all human carbon dioxide emissions and 12% of all transportation carbon dioxide emissions. The commercial aviation industry is projected to grow at 4.3% per year over the next 20 years [4] which would further exacerbate this issue. Modern commercial aircraft are capable of flying long distances without stopping to refuel, thus a well-optimized wing and fuselage profile can have drastic effects on things such as fuel efficiency, travel time, and range. Modern commercial aircraft aerodynamic efficiency can be divided into two major sections. First is the performance of the airfoil at low speeds. Low speed performance affects things like takeoff distance and max angle of attack during takeoff. If low speed performance could be improved commercial airliners could take off from shorter runways and reach cruising altitude faster resulting in more efficient flight. Second is the performance of the airfoil at high speeds. Most commercial airliners cruise at around 30,000 feet, which is an altitude at which the shear stress caused by the viscous effect of the airflow around the wing is negligible. However, the issues of flow separation and downwash are still significant sources of drag even at these higher altitudes, thus it is vital to develop efficient airfoils that keep the flow over their surface laminar for as long as possible to mitigate the effects of pressure and induced drag. Commercial aircraft typically limit their speed to the range of Mach 0.75 to 0.85 [6]. This limitation in speed is to avoid wave drag which typically forms at Mach 0.8 [7]. Wave drag occurs when an airfoil hits its critical Mach number and starts producing normal shock waves. The production of normal shockwaves causes boundary layer turbulence and flow separation which correlates to a loss of lift and increase in drag. An increase in high-speed performance would allow commercial aircraft to cruise at higher speeds with less drag allowing faster trips and less fuel consumption. The goal of this study is to modify the wing of a Boeing 737-200 ADV via the method of flow control. This means the profile of the airfoil will not be changed, but instead devices will be added to the wing to further enhance the performance characteristics. A Boeing 737 was chosen due to its high market share. The 737 is the 2nd most popular plane in the 21st century only behind the airbus A320 and is also the most delivered commercial aircraft ever [8]. Methods of flow control will be explored at both low speed and high speed to try to improve the performance of a 737 cruise and takeoff/landing. However, it is unlikely that one method of flow control will work for improving performance at both speeds. This is due to the principle that in aerodynamic design improving something always comes at the cost of something else. So instead of trying to find one method of flow control that works at both speeds, this paper will seek to find methods of flow control that work at each extreme and what their effect would be in the opposite flow that they are designed for.

PROPOSED APPROACH

Flow separation causes increased drag and reduced lift for the wings, and laminar flow is more prone to flow separation compared to turbulent flow. This leads to many considerations for improvement to involve causing turbulent flow across the wing. A simple method to augment turbulent flow on an airfoil would be the addition of vortex generators

(VG). VG's work by causing a tip vortex that pulls faster moving air down into the slower moving boundary layer, causing an increase in momentum. This vortex is generated by placing the VG's obliquely, with an angle of attack with respect to the airflow across them to pull in the air. They are generally placed along the leading edge causing the flow to be turbulent across the whole wing. In order to assess the effect of the vortex generators for flow control on the 737-200 wing, a full-scale CAD model of the 737-200 wing was created using publicly available data. Airfoil sections were found at Airfoiltools.com [9]. Wing geometry was found at the 737-information site [10].

To fully examine the effect of the vortex generator two models were made. One model without the vortex generators was made, and another model was created with a set of extremely crude vortex generators as shown in Figures 1 and 2 . In order to decrease the computational time of the calculations the models were made with the wings only extending to half their full length.

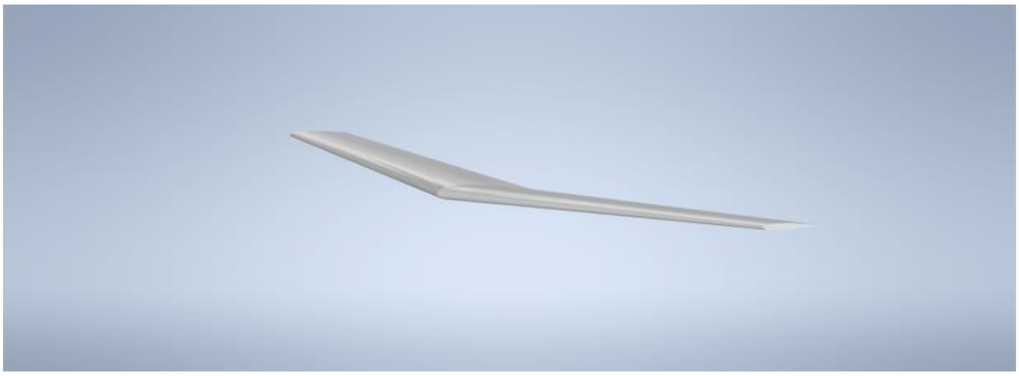

Figure 1: Wing Modelled Without Vortex Generators

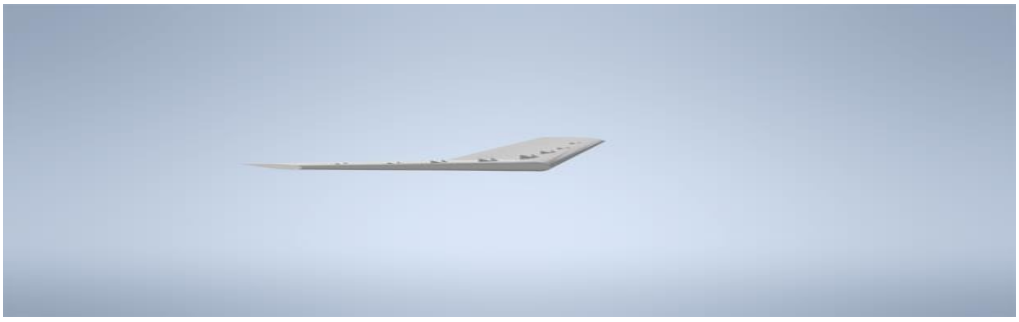

Figure 2: Wing Modelled with Vortex Generators

RESULTS AND DISCUSSION

Once modeled, each wing was simulated using Autodesk CFD to find the lift on the wings. They were simulated at an approximate speed of 150 mph which is in the approximate takeoff speed of the 737. The wings were simulated then at an angle of attack of 8 degrees which causes flow separation on the wing with no flow control. The simulated wing with no flow control yielded flow results as in Figure 3. This gave a total lift of approximately 60000 lbf. The simulated wing with the vortex generators gave a flow field in Figure 4. This gave an approximate lift of 200000 lbf. This is over three times the lift of the wing without vortex generators. Additionally, it had a delayed onset of the separated flow region shown by the decreased size and delayed onset of the green region in Figure 4 compared with Figure 3. It is however suggested that by employing another flow control in combination with this present method can offer a great advantage over a range of flow regimes. Moreover, by using both vortex generators and co-flow jets for flow control in both subsonic and transonic regions of flight, the performance of the airfoil for Boeing 737-200 ADV wings can be greatly improved. This combination will allow for better fuel efficiency during takeoff and landing, as well as during cruising flights.

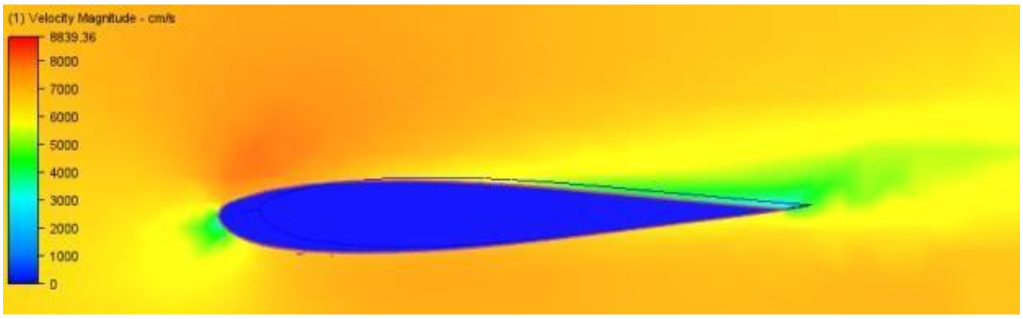

Figure 3: CFD Results of Wing Without Vortex Generators

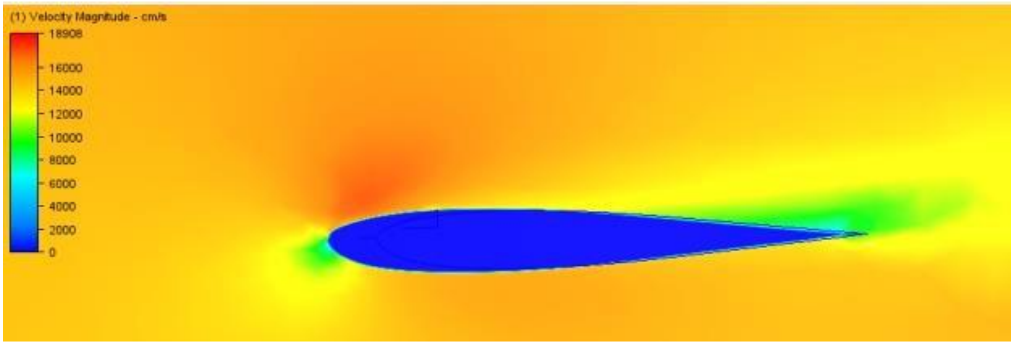

Figure 4: CFD Results of Wing with Vortex Generators

CONCLUSION

Analyzing the wing of a Boeing 737-200 ADV, modified with flow control devices showed improvement of the performance of the airfoil, both increasing lift and decreasing drag. It was found that by employing flow control methods in the form of vortex generators at the subsonic regimes an improvement in performance can be gained. Utilizing vortex generators tripled the lift under the takeoff conditions of the Boeing 737 and greatly decreased the flow separation on the wing. The vortex generators became detrimental under cruising conditions. It is suggested that using smart vortex generators that are temperature sensitive can removes this detriment. Moreover, by using both vortex generators and co-flow jets for flow control in both subsonic and transonic regions of flight, the performance of the airfoil for Boeing 737-200 ADV wings can be greatly improved. This combination allows for better fuel efficiency during takeoff and landing, as well as during cruising flights. Additionally, the reduction in flow separation will aid in mitigating wake turbulence behind larger aircraft, thus allowing for faster traffic flow around larger airports, especially those catering to a wide range of different aircraft. The extent of the decrease in wake effects will need to be further investigated to determine the extent of this benefit.

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