IJRAME

INTERNATIONAL JOURNAL OF RESEARCH IN AERONAUTICAL AND MECHANICAL ENGINEERING
WWW.IJRAME.COM
ISSN (ONLINE): 2321-3051

Vol.11 Issue 5,
May 2023
Pg:- 01- 10

An Overview of Numerical Methods for Analyzing Wingtip Devices to Enhance Aircraft Performance

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Abstract- One of the biggest challenges for the aviation industry in today's scenario is keeping jet fuel consumption as low as possible to maintain business profitability and meet low carbon emission requirements. This makes a revolution in aircraft design imperative. With the development of advanced computational techniques, researchers in this field are increasingly interested in exploring reliable numerical approaches to study the design changes necessary to achieve stated goals. Wingtip devices, commonly referred to as winglets, have shown to reduce approximately 40% of the total drag experienced by an aircraft by reducing wingtip vortices. This article mainly focuses on numerical investigation techniques used and explored by different researchers to validate the method by comparing experimental results of previous investigations in wind tunnel testing. Achieving error-free and reliable results with minimal computation time remains a challenge. There are many open-source and prepackaged software packages available that can be used to perform the simulations necessary for optimized and rapid results. Numerically proven methods help reduce experimental testing, reducing setup costs and time.

Keywords: Winglets, Wingtip vortices, Induced Drag, aircraft performance, Numerical Analysis

1. Introduction

The rising cost of aviation fuel and increasing carbon emission due to big airliners has always been an upfront challenge for aircraft design engineers and manufacturers. Solution to these challenges is to reduced aviation fuel consumption by the transport as well as passenger aircrafts. Though the reduced fuel consumption can be achieved by improved and advanced aviation engines but reducing the overall drag on aircraft has proven history of reducing fuel consumption and improving aircraft performance and efficiency. Particularly lift-induced drag as shown in Figure 1. contributes almost 35-40% of the total drag experienced by the aircraft during cruise segment of the flight [1]. It is therefore has become a primary choice of researchers / aerodynamicist to bring down induced drag as low as possible, as it can result upto 7% of saving of aviation fuel and less carbon emission. It also leads to extended range of the aircraft. These all benfits can be achieved by diminishing the vortex generation at the wing-tip with the help of wingtip device popularly known as *Winglets*.

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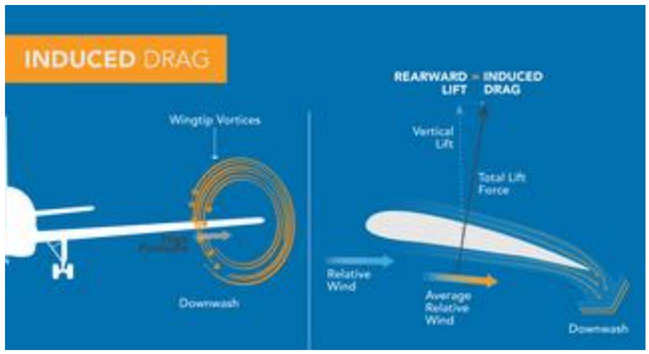

Figure 1. Vortex formation at wingtip and concept of Induced Drag (AeroGuard Flight Training Centre: Timeline Photos, 2020)

The term winglet was first introduced by Richard T. Whitcomb who referred the theoretical research of Frederic Lanchester. Lanchester a British Aerodynamicist patented his study on reducing the vortex formation at end of a wing like structure by placing a vertical plate at end of the wing and called them as *endplates*. This drove Whitcomb to explore further practically and he carried out wind tunnel tests at NASAs laboratory and was successful in establishing that if wingtips are provided with vertical extensions than these vertical extensions (which he named as winglets) were capable of reducing the induced drag by destroying the large primary vortices generated due to the rolling up of air at the wingtip from the high pressure zone at the bottom to low pressure zone on the top of the wing [2, 3] as shown in Fig 2.

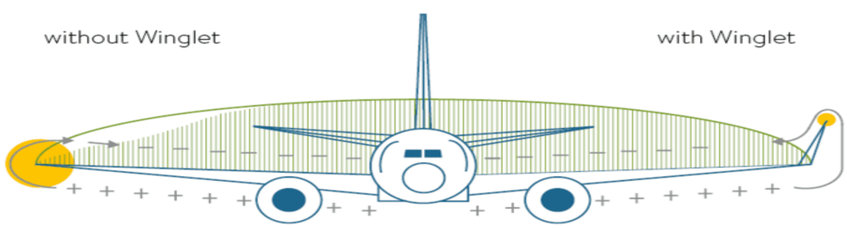

Figure 2. Vortex at wingtip (yellow) with and without winglets (www.facc.com)

In the last three decades the winglets has proven to improve aircraft efficiency and performance [1,2,3]. It is well known that an experimental investigations in any aerodynamic or aero-structural study demands huge funds and ample amount of time. With the advent of computers and evolving computational techniques it has become possible to simulate the various flow regimes in virtual wind-tunnel test sections through available CFD packages like ANSYS, Autodesk CFD, SimScale etc. By the application of various numerical methods the emerging interest of aerospace scientists or engineers is to bring down the computational cost associated with numerical investigation.

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2. Types of Wingtip Devices

Since the winglets were first introduced and successfully retrofitted on KC-135 in 1977 with joint efforts of US Airforce and Boeing, various types of wingtip device have been developed [4], are shown in Fig 4.

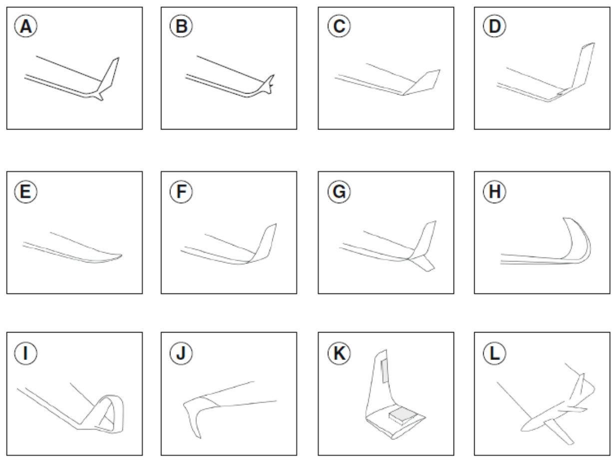

Figure 3. Types of Wingtip devices
a) Whitcomb winglets. b) Tip fences. c) Canted winglets. d) Vortex diffusers. e) Raked winglets. f) Blended winglets. g) Blended split type winglets. h) Sharklets. I) Spiroid winglets. j) Drooped winglets. k) Active winglet. l) Slotted winglets. [4]

3. Investigation Approaches

3.1 Experimental Approach

There is no replacement to experimental investigation, but as far as aerodynamics or aero- structural investigation is concern the experimental procedures are very costly and time consuming Fig 4. depicts the NASA's wind tunnel testing of scaled model of an aircraft and scaled model of a wing.

(a) (b)

Figure 4. (a) NASA wind tunnels to test new airplane designs (b) Gulfstream V model winglet flutter tests at NASA Langley transonic wind tunnel

This approach helps in accurate prediction of a prototype under desired conditions. In [5] Catalano et al used a hot-wire anemometry to map the wake formation and determine aerodynamic characteristics of adaptive winglets. They found accelerated increase in aerodynamic efficiency of the wing along with increase in wing Aspect Ratio. In [6] the experimental investigation showed rapid decomposition of downwash and almost 25% of improved performance. Panagiotou et al [7] used smoke generators to observe vortices and 3D Doppler anemometry for flow visualization.

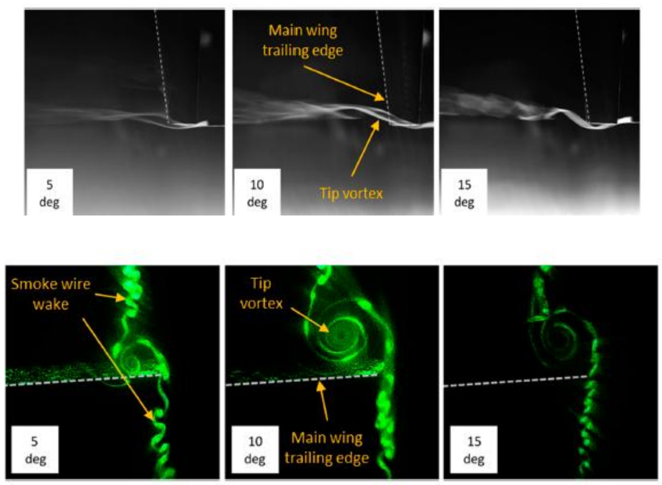

Figure 5. Smoke-probe and laser sheet visualization studies at the wingtip [7]

In [8] Birch, D. et al observed that by creating artificial turbulence to force transition flow before separation improves winglet performance. Arora, Prithvi Raj, A. et al [9] found in their experiment that the lift curve slope increases more with addition of the elliptical winglet and at the same time the drag decreases more for the aircraft model with elliptical shaped winglet giving an edge over the aircraft model without winglet as far as L/D for the elliptical winglet is considered. All the experimental setup used to investigate the above mentioned conditions required a costly setup and arrangement for data acquisition and visualization.

Figure 6. Aircraft model with elliptical winglet [9]

3.2 Numerical Approach

Aerospace researchers are using CFD analysis because of advent of computational techniques and high cost of experimental procedures to provide reliable solutions for modeling aerodynamic forces, moments and viscosities. 3D models of wings and winglets are created with the given configuration by using solid modeling packages like SolidWorks, CATIA, Solid Edge etc and then for advanced aircraft analysis along with numerical optimization the model is analyzed in software packages like ANSYS Fluent, StarCCM+, Optistrut & Acusolve There are four important steps to be done for successful execution of computational analysis: Step 1) Part modeling, Step 2)Pre-processing of 3D geometry and meshing, Step 3) CFD simulation using FVM(finite volume method) Solver, and Step 4) Post-processing aerodynamic characteristics of wings with winglets [10].

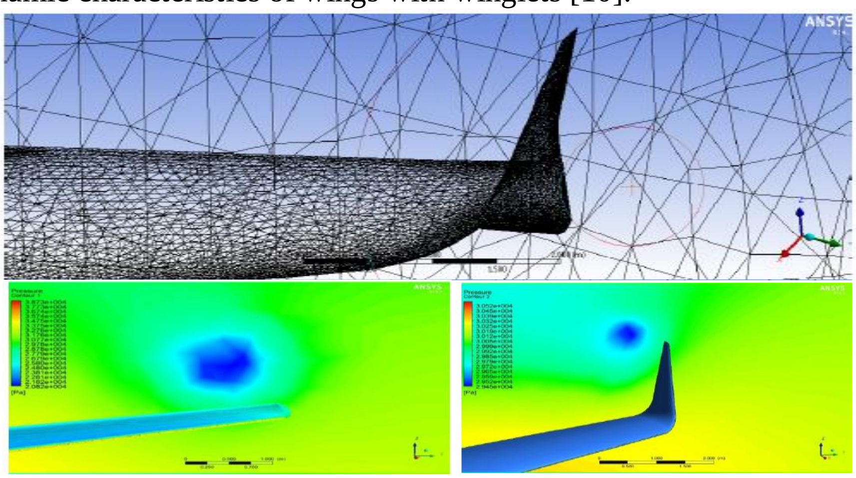

Figure 7. Computational Grid and pressure fields behind the wing without and with winglets [10]

Many researchers have used MATLAB to analyze the aerodynamics of winglets to design aircraft using the FPM (full-panel method), VLM (Vortex Lattice Method), and relaxed wake modeling [11].

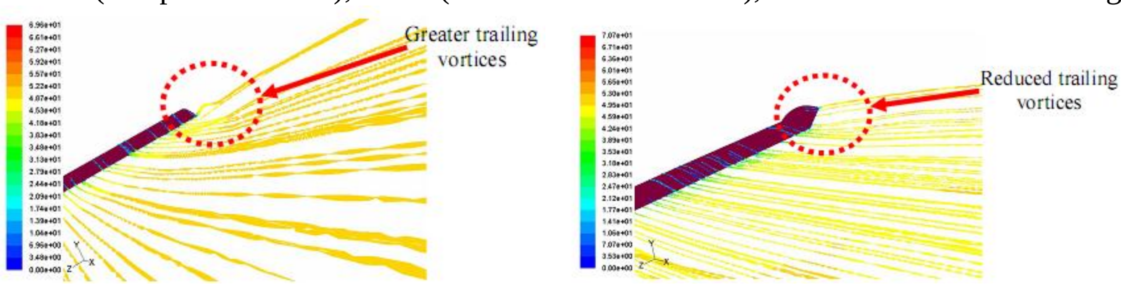

Figure 8. Pathlines showing reduced Trailing Vortices due to winglets [11]

Induced drag, a crucial parameter, was calculated using the higher-order panel method in conjunction with Trefftz plane and Munk's theorem. [12, 13]. To overcome the challenge caused due dihedral wing

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the span-wise lift distribution of the wing was calculated using Lifting line theory.
The numerical analysis was conducted through the control volume method, in which K-omega model and 7 equations Reynolds stress model were utilized to predict aerodynamics of the wing and winglets. [14]. The Upwind scheme method was employed by the researchers to reduce numerical solution error. The flow around the models was simulated using the RANS equation together with a range of turbulence models in order to foresee the turbulence and external flow with substantial pressure gradient for the emergence of boundary layers. This simulation demonstrates the strong relationship between the tip vortex's size and shape and the aerodynamic parameters. [15]

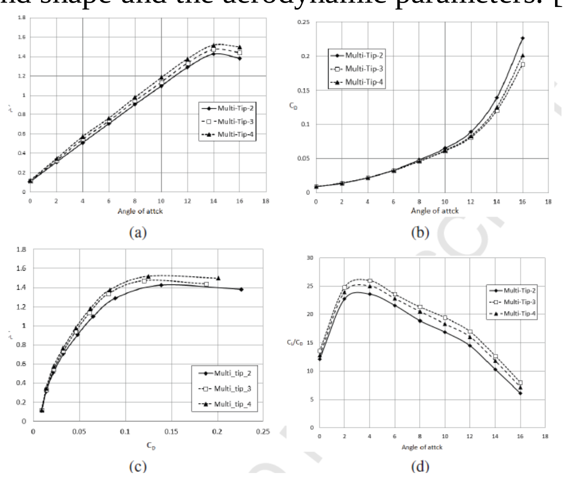

Figure 9. Comparison of aerodynamic parameters: (a) Lift coefficient, (b) Drag Coefficient, (c) Drag polar and (d) Lift to drag ratio [15]

In order to achieve high fidelity analysis, methods such as the automated CFD mesh generation MDM (midfield decomposition method), MOGA (Muliti-Objectve Genetic Algo) and Surrogated models were used [16]. Numerous studies have shown improved simulation accuracy that the Devenport test case based on grid-free simulation, with variable grids and curvature corrections on Low-Reynolds models that analyze tip vortices. [17].

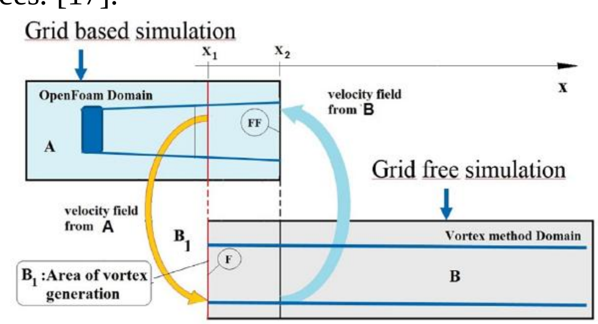

Figure 10. Domain-decomposition method for the tip vortex problem [17]

Aero-structural analysis was also important as the addition of winglet causes deformations in wing, these were analyzed using fluid-structure coupling. Winglets of large size or strongly loaded causes large wing deformations. These deformations alter the performance and structural loading.

The numerical approach in aero-structural analysis has following components: RANS equation and multiblock Newton-Krylov-Schur flow solver For structural analysis and optimization, use of structural solver, using a MM (mesh moment) technique to move the aerodynamic grid based on the linear elasticity equation, the S-A turbulence model coupled with an implicit solver to determine the flow around the models, the spline parameterization method for geometry control coupled with the linear elastic moment technique of the mesh, and the surface-based free-form deformation technique to move the structured mesh [18].

It was found that for un-swept wings mounted with drooped winglets the L/D ratio performs well.

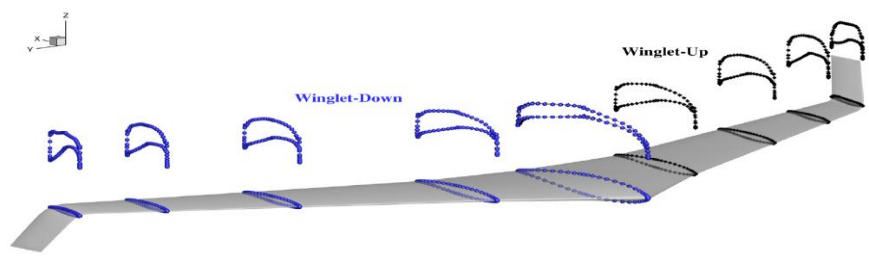

Figure 11. Plots of pressure coefficient in cruise condition for the optimized winglet-up and winglet-down configurations. [18]

Several studies have shown that at a higher AOA, the downwash angle at the horizontal part of the wing and at the winglets is lower because flow separation occurs at a high AOA, which increases the drag coefficient (C_D) and decreases the lift coefficient C_L [19].

In addition, the suction flow originates from the leading edge and reaches a sharp suction tip in the winglets with high AOA. [20]

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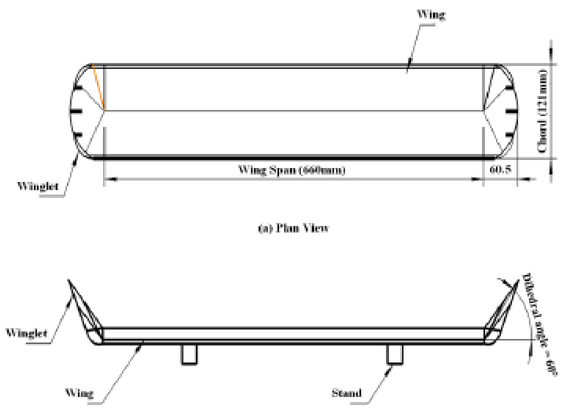

Figure 12. Wing model for wind tunnel. [21]

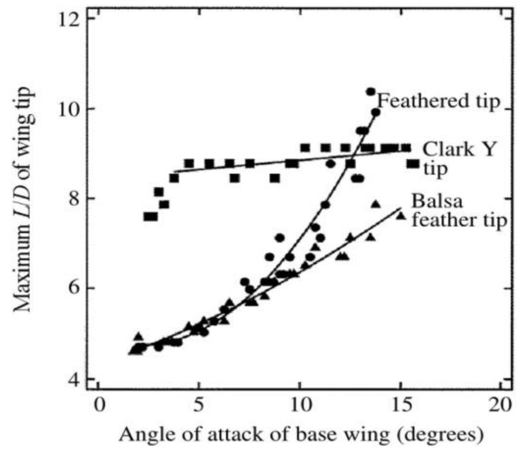

Figure 13. The effect of the angle of attack of the base wing on the maximum lift-to-drag ratios of three tips

In [21] it was observed that the majority of scholars conducted their research experimentally for slotted wingtip and gained lift improvement, drag reduction, and yaw stabilization. As far as numerical simulation of the discussed setup is concerned the researchers are advised implement LES(Large Eddy Simulation) and DNS (Direct Numerical Simulation) for more accurate results

4. Conclusion

The concluding remarks for this short review is that, though the experimental approach has no replacement as it fetches highly reliable data but the huge cost associated with experimental approach is a big constraint for making fast revisions or modifications in the existing design.

The well established and experimentally validated research done by many researchers as discussed above has shown that computationally investigated designs can be directly implemented for prototype building or retrofitting of winglets to successfully achieve about 6-7% of fuel saving with less carbon emission and extended range of the aircraft. This approach is comparatively less expensive and time saving as far as growth in aviation sector is concerned.

This review also exhibits that the researchers working in this area of interest are exploring new computational methods so that the cost of numerical investigation can be cut down without compromising more reliable and error free results.

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