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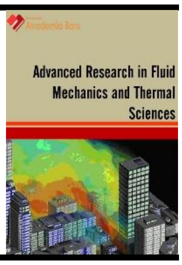

Review of Winglets on Tip Vortex, Drag and Airfoil Geometry

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ABSTRACT

This review is mainly based on the aerodynamic analysis and optimization of winglets, as well as the summarized induced drag (D_i) and vortex detection on different types of aircraft winglets. These winglets are optimal wing tip shape changers. Each optimized winglet model has its improvement toward uncertainty under various operating regimes. The phases of winglet design and development process are discussed. Special attention is provided to the performance of winglets with the change in design aspects. Experimental and theoretical investigations are exhibited under different operating conditions to access the performance. This review highlights previous research on different types of winglets, such as blended, spiroid, multi-tip, sharklets, raked wingtips, and wing fences. This survey determines that several drag reduction techniques use optimized winglets. The effect on the reduction of D_i will gradually increase the profile drag, which plays a challenge of balancing the two criteria.

1. Introduction

Recently, considerable effort has been exerted on the reduction of induced drag (Di) and the corresponding resultant vortex, which degrades the aerodynamic performance of an aircraft. The aerospace community is continuously generating exciting ideas for improving aircraft performance and aerodynamic efficiencies, especially for the passive devices at the wingtip. Generally, wingtip vortices influence turbulence in the wake behind the wing inboard, where these turbulences destroy the lift due to airflow delamination on the out-board wing section. The tip vortices often rotate in a counterclockwise direction and widens with its core strength as it dissipates the vortex.

The introduction of winglets induces secondary vortices, which acts as an energy dissipation device for destroying the primary vortices. Henceforth, a correlation exists between the vortex drag and intensity. The winglets re-shape and redistribute the vortices in the wake and wingtip, leading to the decomposition of swirl velocity components and peak velocity magnitude inside the vortex core region. Thus, the main concept of winglet design is to redirect the spanwise loading on the wing, thereby decreasing the overall drag.

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A planar wing has a linear structure, where the vortex spreads horizontally, whereas the non-planar wing has a non-linearized structure, with the wingtip bending upward or downward in the YZ plane. Hence, the vortices are spread horizontally and vertically, where the air circulation at the wake of the wingtip produces lift and drag upon leaving kinetic energy [1]. The frequency of vortex shedding has to be governed in-order to simulate the flow behavior of vortices around an object [2]. This can be easily measured during stabilized oscillatory flow condition.

The first fully framed-up patent of winglets, published in general research design approach, was presented by Whitcomb [3], who referenced the complete conceptual study of Lanchester [4]. Lanchester was a British aerodynamicist, who initially patented a vertical surface at the end of a wing in 1897, which led to an era of upgrades, by retrofitting and optimizing the existing design. The first implementation of winglet concept was on a sail plane. Whitcomb initially refined an airfoil, which reduced drag by interacting with the wingtip airflow circulation and vortex [3, 5].

Voevodin [6] divided the wake of vortex into three regions (i.e., near, intermediate, and far) to study the strength and behavior of vortices with and without winglets. The non-planar geometry has better elliptical lift distribution than the planar geometry [7]. The addition of winglets should not increase the stall characteristics, skin friction drags, disturbance to controls, and directional stability at high speed. Williams, Weaver [8] showed that the winglets improve flutter characteristics, lateral directional stability, damping ratio, and natural frequency for a short period.

The contributions of winglets to the aspect ratio (AR) of the wing, lift coefficient, L/D ratio with degradation in D_i, and strength of tip vortices should increase. The winglets actively limit the spanwise flow with the flow field on the main wing, creating a physical constraint near or at the wing tip, which weakens the strength of the outboard vortices, resulting in the reduction of D_i [8, 9]. Hence, the effective angle of attack (AOA) of the outboard section increases because of reduced downwash [7, 10].

The main motivation of this study is to showcase the contribution of the winglets in the case of aerodynamic improvement at various flow regime. The local relative wind which is produced downstream the wing engages induced drag, which has to be nullified with wing tip diversions. High order of aerodynamic efficiency has to be achieved with constrained wing span. The complexity of winglet design and its flow behavior has depreciated the wide variant usage in existence. In-depth understanding of the flow behavior around the wing tip can influence winglet aerodynamics to configurate wing efficiency. The vertical extension of the wingtip degrades the aircraft performance, if the trading-off shape and curvature of the tip offsets the wing aspect ratio. The prediction of optimal characteristic winglets based on its shape, size and angle with potential behavior, projects out to be suppressed in real-time scenario.

2. Winglet Designs

A vertical or looped wingtip device plays a vital role on decreasing the D_i and vortices. These devices must be carefully designed, as in the case of AOA, because when the AOA increases, the drag coefficient also increases with depreciation in lift coefficient, thereby pushes the primary vortex upstream and thereby strengthening the tip vortices. The successful design of winglets has balanced characteristics during climbing, cruising, and soaring conditions, which is completely dependent on its shape, angular deflection, and performance. For instance, during low-speed climbing, the airfoil should reasonably achieve CL_{max}, and vice versa at high-speed. Hence, the airfoil has to be specially designed because of its peculiar application in managing the laminar bubble separation at a low Reynolds number (Re) operation [11, 12].

The main idea behind the wingtip device is to modify the aircraft wake to increase the aerodynamic efficiency in a beneficial manner. These devices degrade the D_i by increasing the wings' effective AR with minimal added wing span [13]. Further investigation of planar and non-planar wings also concluded that the wing root bending moment and D_i barely improve the performance of winglets [14]. The adaptable angle winglets shows up better refinement in aerodynamic efficiency by degrading induced drag with biased tip vortex reduction [15].

2.1 Wingtip Designs

In general, winglets have been effective supplementary parts of an aircraft and lately have been applied in unmanned aerial vehicle (UAV) designs. A recent study on a rectangular wing with NACA 65_3-218 airfoil section, with three different Re, concluded that winglets have high performance with decreased drag coefficient up until stall AOA [16]. Another investigation on various winglet ARs showed that winglets produce a substantial amount of effective dihedral and has a high performance with noose droop airfoil [17]. Nevertheless, the numerous types of winglets are reviewed in this sub-section.

2.1.1 Blended winglets

Blended winglets are the simplest and most widely used, which were initially designed and still in operation. These winglets have a canted vertical extension on the wingtip that degrades Di by discontinuing the vortex between the wing and winglets. Performance and stability were investigated on the basis of the winglet dihedral angle, which deforms the magnitude of slope and pitching moment. Kubrynski [18] designed a blended winglet with approximately 0.6% increase in wing wetted area, resulting in 5% decrease in D_i and improved C_L.

Azlin, Taib [19] conducted a numerical investigation of winglets under low subsonic flow and found that blended winglets with a cant angle of 45° have the greatest vortex reduction compared with other models, with 8% improved performance on L/D ratio. Another investigation presented that winglets with variable cant angle show realistic performance on cruise and non-cruise conditions based on the flight path and obtain improved performance at 45° cant angle inclination [9, 18].

Roglin and Katz [20] investigated downward pointing blended winglets on an un-swept wing with an AR of 25. LN-1015 airfoil section was used for winglets, and twist varied in accordance with the spanwise positioning. Findings observed that attached flow was maintained due to drag reduction with the presence of winglets. Toor and Masud [21] performed a parametric analysis to determine winglet performance on UAV, at a Mach number of 0.1465 and R_e of 1.5×10^6 by using PSU-90-125WL winglet section. The analysis concluded that C_L and L/D increase by 3% and 6.5%, respectively, in a cruise condition at 6° AOA.

2.1.2 Spiroid winglets

Spiroid winglets are bio-inspired and believed to have the best structure for reducing D_i compared with other designs. However, this design is unfavorable in eliminating the trailing vortex wake due to its complex structure. Guerrero, Maestro [22] studied bio-mimetic (Fig. **1**) and numerically-simulated spiroid winglets at different AOA conditions on C_L and C_D characteristics. The drag increases rapidly at stall and C_L/C_D shows improved value till 4° AOA, where C_L presents a more rapid improvement than C_D for spiroid winglets. Nevertheless, the winglet exhibits a round performance at 5° AOA.

Mostafa, Bose [23] studied aft spiroid winglet optimization and found that the vortices exhaled by the spiroid winglets are relatively weaker than other conventional winglets.

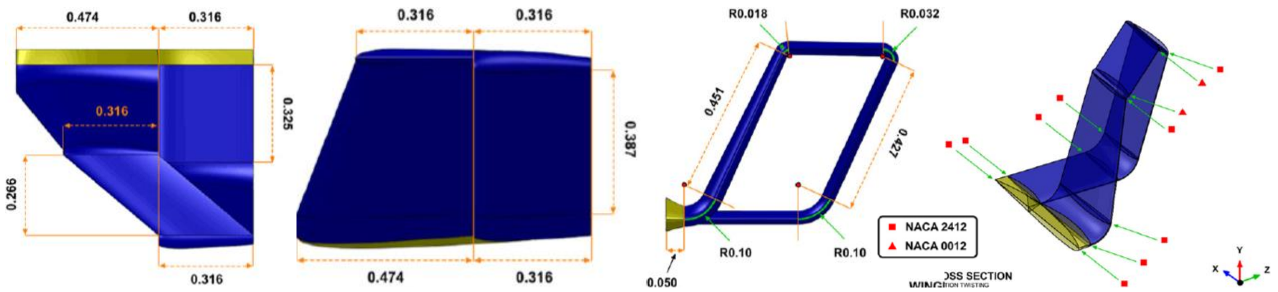

Fig. 1. Spiroid winglet geometry [22]

Ali Murtaza, Parvez [24] designed an optimized spiroid winglets by using NACA 2412 and NACA 0012 to determine the best aerodynamic performance. They found that the best winglet design specification has a 45° sweep angle, 0.2° dihedral angle, 0.78 taper ratio, and 4.5 AR. The numerical result showed a 16.9% increase in CL_{max} and 5.2% improvement at stall angle. Manikandan, Rajashree [25] implemented the same winglet design aspect and numerically examined the aerodynamic performance of winglets at various velocities and angular deflections, where C_L and C_D have improved performances at 4° AOA, with 6% L/D ratio improvement.

2.1.3 Multi-tip winglets

Multi-tip winglets modify the planar vortex sheet in the streamwise direction by preventing roll ups. A study of multiple winglets (Fig. **2**) involve three stages: 1) comparing the aerodynamic parameters of B-max, blended winglets with the baseline wing, 2) investigating the geometry and performance of multi-tipped winglets, and 3) analyzing the effectiveness of winglets on wing with different ARs [26]. The study concluded that three-tipped winglets have improved performance in (C_L/C_D) by 22.5% at 4° AOA.

An investigation was conducted on the use of adaptive multi-tipped winglets to reduce the D_i with variant cant angle by using NACA 653-018 section [27]. Findings showed that the three-tipped winglet (each tip with cant angles at 60°, 30°, and 0°) had improved C_L. Minimal C_D is observed in another three-tipped winglet (each tip with cant angles at 45°, 30°, and 15°) at 8° AOA. Flat plated multi-tip winglets were studied to reduce Di without increasing wing span in an untwisted rectangular wing with twisted winglets [28]. Theoretical and experimental analyses of such work concluded that the optimal dihedral spread and twisting of winglets enhance L/D.

Investigation on the influence of three multi-tipped winglet vortices and D_i at various AOAs on multiple winglets by using the Spalart–Allmaras turbulence model shows that C_L increases by 27% and C_D decreases by 9% [29]. Hence, optimizing the number of tips uplifts efficiency in terms of frictional drag due to wetted area. Reddy, Dulikravich [30] showed that the effectiveness of multi-tipped winglets through multi-objective optimization at different cant angles of each tip increases the lift by 12.8% and degradation drag by 4.5%. Similarly, Rabbi, Nandi [31] modeled optimized slotted winglets, which obtained 10%–20% lift increment at 30° cant angle and 8° AOA.

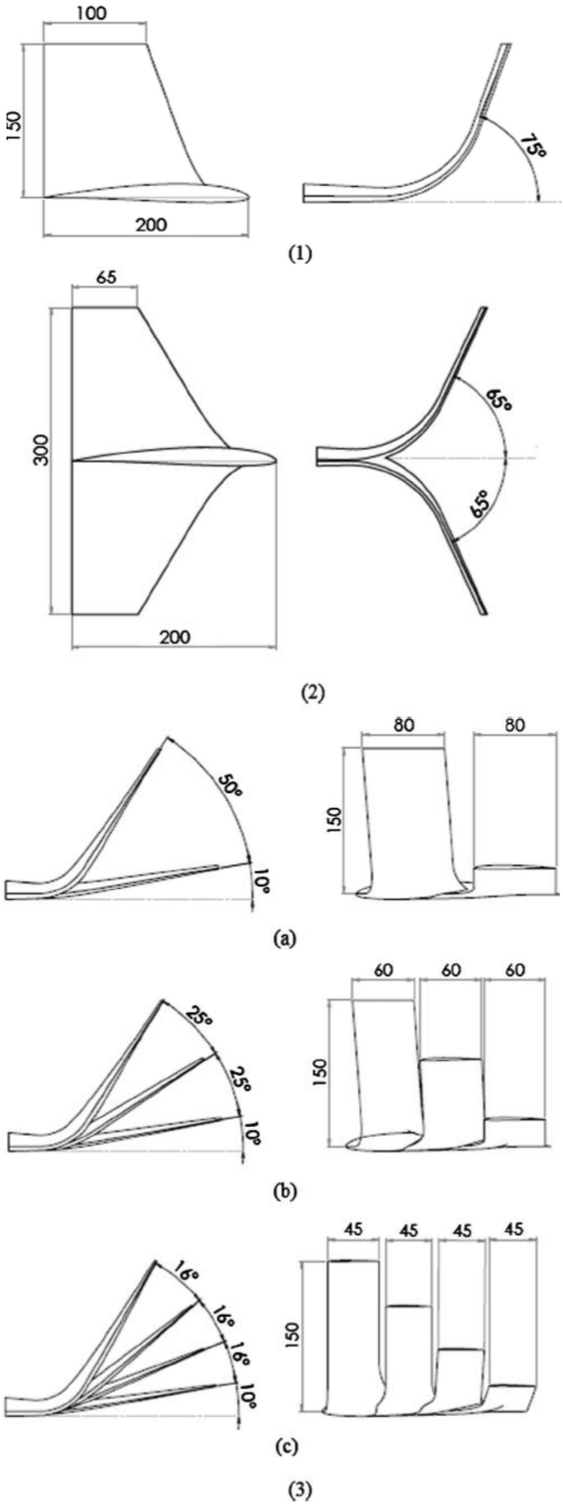

Fig. 2. Multi-tip winglet cant distribution [26]

2.1.4 Sharklets

Sharklets are the optimized concept of blended winglets [32] designed to split the flow at the wingtip. The adverse compressibility of winglets can be improved by designing the upper and lower winglets with careful spacing along the longitudinal and lateral axes. Montoya, Flechner [33] explored the aerodynamic characteristics of split-tip winglets at a Mach number of 0.78. The findings indicated that D_i depreciated by approximately 20% and L/D improved by 9%. Moreover, an investigation on trapezoidal planform sharklets with supercritical airfoil showed an increase in lateral and longitudinal stability [34].

A theoretical investigation was conducted on winglets by retrofitting secondary lower winglets to the blended wing, as shown in Fig. **3**, under a 0.25–0.3 Mach condition [35]. The secondary winglet is fitted with a 30° cant angle, 45° trailing edge sweep, and 35° leading sweep by using symmetrical PARSEC 11 airfoil, thereby increasing C_L by 6.54%, (C_L/C_D) by 14.48%, and C_D depreciation by 7.02% [35]. Whitcomb [3] experimentally investigated split-tip winglets and found that the lift improved by 0.44 by using upper winglets and 0.48 by using lower winglets. The findings also showed a 20% D_i reduction, which resulted in L/D ratio enhancement.

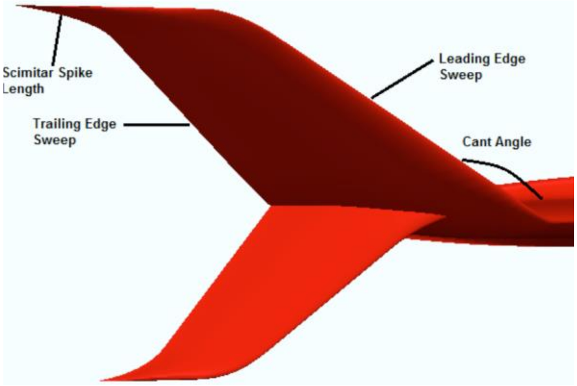

Fig. 3. Sharklet extension of Boeing 7E7 wing [35]

2.1.5 Other appendage types

Gold and Visser [36] experimentally studied raked wingtips (15° 20° 25° 30°
0°

Fig. 4) to examine the drag and vortex distribution due to dihedral wing-tip extension. Results indicated that the positive dihedral induces negative lift on the wake and positive lift on the wing; hence, a dihedral angle of 10° with a 55° sweep provides a 7% improvement in lift curve and 2% reduction in D_i. Gall and Smith [10] conducted numerical and theoretical aerodynamic analyses on biplane with winglets. Results showed a 13% improvement in lift curve and efficiency factor. Falcao, Gomes [37] focused on take-off performance and stall speed by designing an adaptive winglet, which showed a 20% improvement in overall performance.

15° 20° 25° 30° 0°

Fig. 4. Raked wingtips with different leading-edge sweeps [5]

Numerous studies have been conducted on C-type winglet in comparison with blended winglet Fig. **5** to understand the drag and flutter characteristics under limit cycle oscillation behavior through CFD analysis [38]. C-type winglets, which can be detected using double-lattice aerodynamic theory, affect the aeroelasticity. Findings showed 14.7% degradation in flutter speed, but only 0.1% improvement, compared with blended winglets.

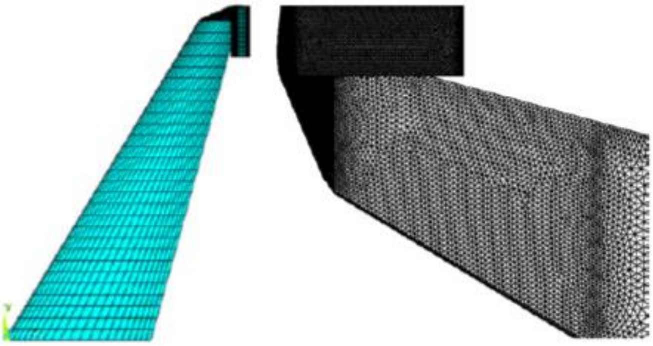

Fig. 5. C-wing with computational grid [38]

2.2 Design Parameters

The main optimizing parameters considered in winglets Fig. **6** [5] are as follows: 1) cant angle, 2) twist distribution, 3) sweep angle, 4) taper ratio, 5) root incident angle, 6) AR, and 7) toe angle. Winglet cant angle and span length are the dominating aspects for improving aerodynamic performance. Goals can be achieved with the change in cant and toe angles, indentation, twist, and airfoil to its corresponding winglets, with a constant iteration of sweep angle until the closest elliptical lift distribution is achieved [7, 39]. Winglets with small chord and high positive twist may improve lift coefficient with slight "off-design" factor, negative incidence, and twist [9, 18].

2.3 Optimization

The effect of winglet on performance differs in cruise and non-cruise conditions; thus, optimization must be performed to satisfy both conditions. Active optimization of the wingtips must be conducted to decrease D_i for degrading the vortex core strength through tip turbulence and the development of secondary vortices. Several optimization techniques include 1) high-fidelity computational fluid dynamic solution method, 2) multi-objective genetic algorithm, and 3) finite element-based winglet calculation [26].

Optimization on the airfoil changes with different AOAs at a wide range of Re was widely studied to investigate lift at various airfoil thickness values and its thickness location. Moreover, as the operating Re varies, the laminar separation bubbles and the associated profile drag also increases [11]; thus, the combination of low Re and low drag becomes difficult to achieve.

In addition, the wing and winglets have different operating conditions; hence, the airfoil used in the wing may not be improved with winglets [7]. Generally, the winglet airfoil must work under a large range of Mach number with a highly loaded flutter and low stall characteristics to prevent winglets from stalling before the wing. Hence, the design must withstand great challenges of aerodynamic effects. Therefore, the winglet airfoil should be selected to meet two main criteria: 1) C_L and Mach number condition should provide effective inward normal forces, and 2) boundary layer separation should be effective [3].

Nose droop airfoil is reasonable under stalling condition, which avoids unwanted drag, creep, and suction creep [17, 32]. However, twisting the wing from root to tip at certain degrees at opposite direction decreases D_i [40]. Thus, the same concept can be implemented in winglets to redirect and reduce the D_i flow with minimal increase in profile drag. Nevertheless, at typical flight AOA [10], the cambered airfoil performs better than the symmetrical airfoil in the case of L/D ratio.

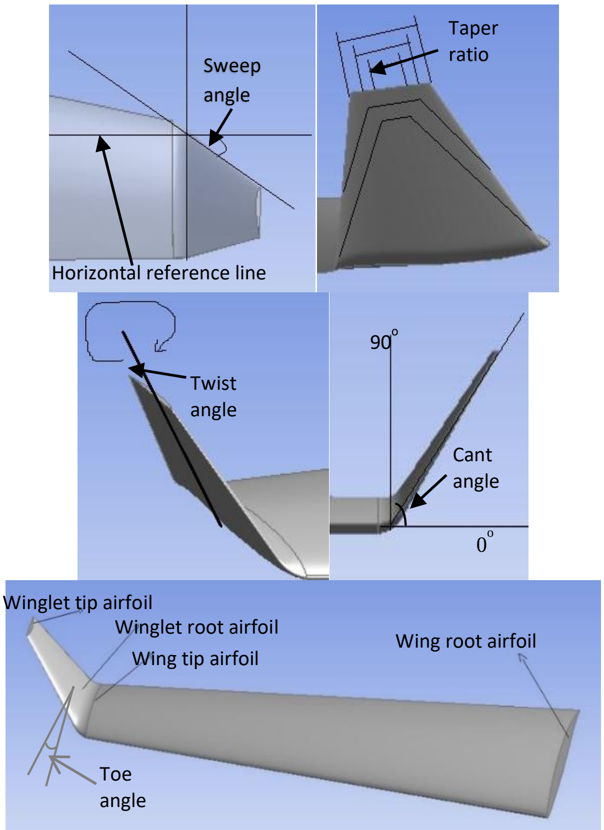

Fig. 6. Winglet design aspects

3. Survey of Winglet Aerodynamic Analysis

Numerical and experimental investigations are the main tools for analyzing the aerodynamic characteristics of a model. Thus, in this section, numerical and experimental investigations will be surveyed together with several theoretical works.

3.1 Numerical Investigation

Nowadays, CFD analysis is conducted by numerous researchers to provide a reliable solution for modeling performance (aerodynamic forces and moments) and viscous effect through efficient engineering design tool at less expenditure. Physical-based models of winglets were designed with straightforward configuration by using modeling software for advanced aircraft analysis and a multi-point numerical optimization with proper objective functions. The four main stages of computational efforts are 1) part modeling, 2)pre-processing 3D model geometry setup and grid generation, 3) CFD simulation with finite volume approach using FLUENT, and 4) post-processing aerodynamic characteristics of the winglets [41].

Generally, aerodynamic analysis of the wing winglet model can be investigated through MATLAB code (i.e., inviscid vortex lattice method with CFD analysis), whereas others used full-panel method, including relaxed wake modeling, for the design process [7]. D_i is determined through higher-order panel method coupled with transpiration techniques at the Trefftz plane and with Munk's theorem in the alternative approach, with path line representation [8, 18]. Lifting line theory was used to calculate the spanwise lift distribution of the wing, which is challenging with the dihedral wing.

Numerical study on a model with control volume method, through shear stress transport K-ω model and seven-equation Reynolds stress model can be investigated to predict the wing aerodynamics [42]. Upwind scheme method was conducted to decrease the numerical solution error. The computation of flow around the models was simulated with RANS equation coupled with various turbulence models to predict the turbulence and transitional external flow with strong pressure gradient for developing boundary layers. Such simulation illustrates the strong bondage between the aerodynamic parameters and tip vortex size and shape [26].

Several explorations were also made using high fidelity analysis on multi-disciplinary design with various techniques of CFD and optimization, through Midfield decomposition method, automatic CFD mesh generation, multi-objective genetic algorithm and Kriging surrogate model [43]. Several studies demonstrated that the Devenport test case based on grid-free simulation approach can improve simulation accuracy, with variable grid accompanied by curvature correction on SST Model that predict the evaluation of tip vortices [44].

Aero-structural optimizations were also prominent in numerical works and consist six main components: (i) Multiblock Newton–Krylov–Schur flow solver for Euler's and RANS equation, (ii) finite element structural solver for structural analysis and optimization, (iii) mesh moment technique based on linear elasticity equation for moving the aerodynamic grid, (iv) surface-based free-form deformation technique for moving the structured mesh, (v) spline parameterization method for geometry control coupled with linear elasticity mesh moment technique, and (vi) Spalart–Allmaras turbulence model coupled with an implicit solver for determining the flow around the models [45].

A numerical study found that the decrement of D_i and increment of lift are generally further associated at a low dihedral angle [22]. The L/D ratio performs well for downward pointing winglets for an un-swept wing. Several studies stated that the downwash angle on the horizontal part of the wing and winglets will be less when the AOA is small, because the flow separation takes place at high AOA, which increases C_D and decreases C_L [31]. Furthermore, a sharp suction peak occurs at the winglets with high AOA, and the suction flow develops from the leading edge [46].

3.2 Experimental Investigation

Experimental investigations were conducted to determine the accurate prediction of a model or prototype under the given working condition. Catalano and Ceron-Muñoz [27] performed an experimental analysis to determine the aerodynamic characteristics of adaptive multiple winglets and mapped the wake formation with hot-wire anemometry. As expected, experimental results show the rapid increase in aerodynamic wing efficiency with the increase in AR. Similarly, experimental investigation of slotted feathered wingtip with force transduced in wind tunnel [1] indicated that the L/D increases by 10% and the overall total drag decreases by 12%. The best L/D of multi-tipped winglets with Re ranging from 1.5 × 105 to 2.9 × 105 was investigated [28], where the winglets were equally segmented at 10°. The experimental outcome showed that the twisted winglets with sharp negative incidence present a 25% improved performance with a rapid decay of upwash beneath the wingtip.

The performance of the winglets can be improved by forcing the transition flow with artificial turbulence before the laminar separation occurs [47]. Numerous researchers [48] have performed flow visualization with 3D laser Doppler anemometry and smoke generators to investigate vortices. The wind flow pattern y attaching tufts on to the wing surface was recognized [49]. Near-field approach obtains the strength and shape of the wake vortex because the manipulation of the vortices begins on the wing surface, as illustrated in Fig. **7**. Fig. **8** show an example of a wind tunnel setup with the blended winglet prototype.

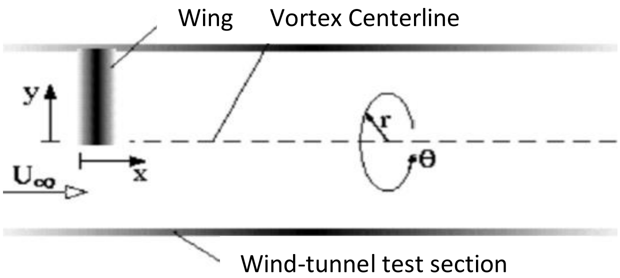

Fig. 7. Schematic of internal wind tunnel [44]

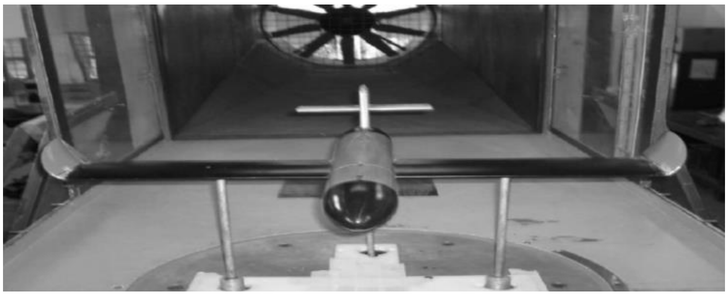

Fig. 8. Wind tunnel setup of blended elliptical winglet [50]

Force and moment data can be obtained by five-component strain gauge balance, and the flow field behind the winglets may be determined through a special string-mounted yaw head rake [33, 51]. Moreover, a two-component particle image velocimetry can determine the velocity vortex field behind the model through a towing tank with a towing rig and laser arrangement [52]. Here, the vortices distribution and core radius position determined by fitting the Lamb–Oseen vortex model to the wing enable the vortex core visibility in the mean of fine air bubbles following Neuwerth [52].

Various researchers [22, 26] have shown the strong circulation of loops in wake vortices, which increases the landing distance between successive aircrafts. These wakes are divided into two regions in accordance with axial velocities: 1) blunt body wake and 2) vortex wake [48], which affects the presence of vortex and shear layer separation. The vorticity has its peak value inside the vortex core of the base wing, which is three times that of the vortex in the winglet region [51].

However, D_i was initially predicted using a multiple lifting line method with the help of full panel method and relaxed wake modeling. Di can be minimized through an optimal load distribution with Munk's theorem with non-planar configuration on the Trefftz plane [18]. Nevertheless, Di depends on the elliptical lift distribution that may vary when the rigid wake is dihedral [37]. Moreover, advanced drag with flow field visualization may be predicted through mid-field decomposition method [43].

4. Summary of Winglet Performance

This review mainly discussed winglet aerodynamic characteristics focusing on C_L, C_D, L/D, path lines, vortex shape counters, different pressure contours, magnitude contours at different Mach numbers, and AOA. Table 1 (a)-(g) presents a summary of several winglet design categories on the basis of this comprehensive winglet feature survey. Each winglet projects out its own flow diversion tendency based on different angle of attack. The Table 1 (a)-(g) clearly presents the Theoretically- and experimentally-proven solutions show that the finlets have decayed the vortex formation to a maximum level with delay in stall condition [53]. A wide cant angle improves winglet performance, with thinning of airfoil and negative twist [10]. Furthermore, leading-edge flow and stalling are separated at the maximum AOA.

The following parameters showed favorable performance compared with others: 1) airfoil of NACA 0012, NACA 2412, NACA 653-218, 2) 8° AOA, 3) taper ratio between 0.2 and 0.5, 4) sweep angle between 30° and 50°, 5) twist angle of 0°–2°, 6) toe angle between −2° and 3°, 7) cant angle of 45°, and 8) inclination angle of 5°. At a typical flight AOA, the cambered airfoil performs better than the symmetrical airfoil in the case of L/D ratio, and the R_e has its influence only on the laminar boundary layer [10, 46]. The tip vortices observed during the analysis [51] varies with shape, strength, and center position, depending on the airfoil and cant angle of the winglets.

Nevertheless, the performance of different types of winglets greatly depends on various criteria and specification, such as operating condition, altitude, AOA, pressure differences, fuel level, and airspeed. These elements may provide the best favorable performance when optimized, especially for improving the overall design performance. Table 2 presents the finest winglet designs in each category to understand the aspects crucial in each design further. The findings show immense complications compared with the benefits of using winglets.

Each different type of winglet has features and advantages. All are aimed to improve lift generation, L/D ratio, take off/landing performance, directional stability, range and cruise, decay, total drag, air separation, and engine emission and decrease turbulence behind aircraft. Drawbacks generally include increases in parasite drag by increasing the wetted area, advance structural requirements, cost and complexity of construction, modified handling and stability characteristics, overloading of winglets, and increases in wing-root bending moment.

Table 1
(a) Performance analysis of winglets

Blended winglet								
Author	Design aspects	Vortex	D_i	Method	Optimize/ Retrofitted	Airfoil	Flow behavior	Output drawn
Eppler [13]			√	Mathematical model				D_i of the planar wing cannot be lower than the elliptical lift distribution but can be lower only when the rigid wake is dihedral.
Kuhlman and Liaw [54]	√		√	Theoretical		NACA 64A-006		Increasing the winglet toe out decreases the shockwave; hence, the drag decreases.
Mattos, Macedo [17]		√		Theoretical	√			Winglets with noose droop airfoil produce effective dihedral and provide high performance.
Maughmer [55]	√		√	Theoretical	√	PSU 94-097		For D_i, a winglet oriented downward has the same results as that oriented upwards.
Johansen and Sørensen [56]	√	√	√	Theoretical	√	NACA 64-018 64-518		Negative twist at the winglet tip decreases loading at a high AOA. −2° twist improves power by 1.3% and thrust by 1.6%.
Maughmer [7]	√	√		Theoretical		PSU 90-125		The generation of drag interpolates airfoil drag along with the moment data across operating C_L, R_e, and flap deflection range.
Lee and Gerontakos [57]	√	√	√	Theoretical		NACA 0015	√	D_i degradation can be achieved by negative dihedral winglets.
Johansen and Sørensen [58]		√	√	Theoretical				Winglets with 4% height radius and 12.5% curvature radius on a slender large AR projected increase in power and thrust.
Verstraeten and Slingerland [59]			√	Theoretical				The winglet wing has improved performance, with 5.4% decrease in C_D compared with C-wing tip extension.
Azlin, Taib [60]		√	√	Theoretical	√	NACA 65_3218		The elliptical winglet provides improved performance at a cant angle of 45° and AOA of −8°with 8% C_L increase.
A. Beechook [9]	√			Theoretical	√	NACA 65_3218		Variable cant angle in alternative phases of AOA improves aerodynamic efficiency and optimizes performance.
Mat Taib, Jaafar [61]	√			Theoretical		NACA 65_3218		The semi-circular winglets improve L/D and C_L at 45° cant angle and 2.73 AR with C_{Lmax} = 1.09.
Pooladsanj and Tadjfar [62]	√	√	√	Theoretical		NACA 0012 0002		Thinning of winglet airfoil improves the aerodynamic performance by 4%–5%, due to weakening of tip vortex magnitude.
Ashrafi and Sedghat [42]		√	√	Theoretical	√	NACA 65_3218		At 8° AOA, L/D ratio increases by 8.08%.
Sibi A Arul [63]	√	√		Theoretical	√	PSU90-125WL		PSU airfoil winglets have the flexibility over varied flow conditions and the best performance at 30° sweep angle.

Kaygan and Gatto [64]	√	√		Theoretical				Sharp, sweep edge, and positive twist in winglets have immense advantage of decreasing D_i up to 31% and C_D by 25%–30% and increasing C_L by 20%.
Narayan and John [26]	√	√	√	Theoretical	√	NACA 2412	√	Blended winglet improves efficiency by 3.5% compared with other models.
Toor and Masud [21]	√			Theoretical	√	PSU-90 125WL		Cant angle plays the major role by 6% decrease in C_D with high aerodynamic performance at 45°.
Helal, Khalil [65]	√		√	Theoretical	√	NACA 65_3-218		The winglets improve L/D ratio by increasing approximately 3%–15% with the optimization in winglet design aspects.
Hariyadi [66]		√	√	Theoretical		NACA 23018		High L/D ratio can be obtained when the chord line winglet (x/c) is 0.4, with maximum C_D reduction.
Golcuk and Kurtulus [67]	√	√		Theoretical	√			Elliptical winglets increase L/D by 8.3% and lift by 8% and decrease C_D by 3.51% at 45° cant angle.
Yuhara [68]			√	Theoretical	√		√	As the circular fillet radius decreases, the boundary layer separation occurs behind the shock waves due to the leading-edge pressure gradient reduction.
Holmes, VanDam [69]	√			Experimental		LS (1) 0413		Winglets increase the Oswald efficiency by 13% and AR by 6%.
Prithvi Raj Arora [50]				Experimental	√	NACA $65_3$218		L/D ratio has the maximum performance at maximum AOA with stages of R_e.
RUHLIN, RAUCH [70]	√			Both				Drag breaks near M = 0.85 with improvement in C_L of 0.474, but M = 0.82 is the safest limit for flutter characteristics with 7% reduction.
Roglin and Katz [20]			√	Both	√	NACA 0008 4612		The aft mounted winglet with the lowest dihedral angle was found to be highly effective. A downward winglet is suitable for un-swept and high AR wing.
Kauertz and Neuwerth [52]		√		Both	√	NACA 0014	√	Winglets are additionally equipped with triangular outboard flaps that have a capability to produce counter rotating vortex.
Nazarinia, Soltani [49]		√		Both	√		√	Winglets have large impact on low AR wing.
Hantrais-Gervois, Grenon [71]	√			Both	√ (retrofitted)			The downward pointing winglets orient the increase in neutral position relative to its wing root. Spiroid loop structure has 4.6% gains in L/D ratio.
Panagiotou, Kaparos [39]	√		√	Both		PSU 94-097	√	Winglet with cant angle 60° and taper ratio of 0.4 has C_{Lmax} of 1.75 and L/D of 22.39, which improve flight efficiency by 10%.

(b) Performance analysis of winglets

Multi-tip winglet

Author	Design aspects	Vortex	D_i	Method	Optimize/ Retrofitted	Airfoil	Flow behavior	Output drawn
La Roche and Palffy [72]		√	√	Numerical/ Mathematical	√			The winglet-grid device is proportional to the AR of the individual winglets.
Tucker [73]			√	Theoretical			√	The span factor can be kept constant by spreading the horizontal and vertical vortex at increased AOA.
Tucker [1]		√	√	Theoretical				Slotted winglets spread vorticity horizontally and vertically, thereby reducing the concentration of vortex core.
Shelton, Tomar [74]		√		Theoretical		NACA 0015/6		Multi-tip increase is 26%, and the active multiple winglets increase the L/D ratio to 10.0.
Zhang, Chen [29]		√	√	Theoretical		NACA 0015	√	At 15° AOA, the vorticity and C_D are decreased by 75% and 9%, respectively, where C_L increases by 27% to baseline wing.
Narayan and John [26]	√	√		Numerical	√	NACA 2412	√	Three-Multi-tip has improved performance by 22.5% in aerodynamic efficiency.
Nandi, Assad-Uz-Zaman [75]	√			Experimental		NACA 0012		Slotted winglets increase 10%–20% of C_L and decrease 20%–25% of C_D with C_{Lmax} of 1.542 at 10° AOA.
Smith, Komerath [28]	√	√	√	Both		NACA 0012	√	Negative incidence, dihedral spread, and twist improve L/D ratio and lift by re-orienting the winglet lift vector forward, with re-distribution of the tip vortex.
Catalano and Ceron-Muñoz [27]	√		√	Both		NACA 65_3-018	√	Three-winglet configurations have optimal result with an increase angle of 8° and cant angle among them.
Nazarinia, Soltani [49]		√		Both	√		√	Winglet grid does not show remarkable performance compared with spiroid and blended winglets, due to optimized drag reduction.
Hossain, Rahman [76]	√		√	Both	√	NACA 65_3-218		Bird feather-like winglet C_D deceases by 25%–30% and C_L increases by 10%–20% at 8° AOA.

(c) Performance analysis of winglets

Raked winglet

Author	Design aspects	Vortex	D_i	Method	Optimize/ Retrofitted	Airfoil	Flow behavior	Output drawn
W.Lishifelshyal [77]			√	Theoretical		NACA 65_3-218		Raked winglets work well in high AOA with low C_D and 15%–20% increase in C_L.
Halpert, Prescott [5]	√		√	Experimental	√			20° additional leading edge sweep off increases endurance by 8.32% and range by 4.69

(d) Performance analysis of winglets

Split-tip winglet

Author	Design aspects	Vortex	D_i	Method	Optimize/ Retrofitted	Airfoil	Flow behavior	Output drawn
Reddy, Sobieczky [35]	√		√	Theoretical	√	PARSE C-11		Split wingtip with scimitar tip spikes also increases wing tip vortex core radius with improved redirection flow, which in turn decreases D_i.
Narayan and John [26]	√	√		Numerical	√	NACA 2412	√	14% improvement was shown in aerodynamic efficiency with shrunken tip vortex core.
Whitcomb [78]	√	√		Experimental				The winglets improve L/D ratio more than wing tip extension with D_i drop of 0.23.
Montoya, Flechner [33]	√	√	√	Experimental				Winglets decrease cross flow velocity vector in vortex core area with a slight negative increment in pitching moment.
Gilkey [32]	√		√	Both	√ (retrofitted)		√	Aft pointing winglets provide superior performance with an incidence angle of −2°.

(e) Performance analysis of winglets

Spiroid winglet

Author	Design aspects	Vortex	D_i	Method	Optimize/ Retrofitted	Airfoil	Flow behavior	Output drawn
Guerrero, Maestro [22]			√	Theoretical		NACA 2412/0012		D_i reduction of 75% at $C_L = 0.95$, 35% at $C_L = 0.55$, and 28% at $C_L = 0.40$ at AOA 8°.
Mostafa, Bose [23]		√	√	Theoretical	√	NACA 0012		Two vortex cores are propagated due to the low-pressure region, which combine into a weak vortex.
Ali Murtaza, Parvez [24]			√	Theoretical	√	NACA 2412		Spiroid winglet increases C_{Lmax} by 16.9% at stalling 18° AOA.
Manikandan, Rajashree [79]			√	Theoretical	√	NACA 2412/0012	√	Spiroid winglet provides improved performance at 4° AOA, with C_D depreciation of −5% and increase in C_L of 1.5%.
Nazarinia, Soltani [49]		√		Both	√		√	Forward spiroid winglet performs well during cruise and Aft spiroid winglet during non-cruise condition.

(f) Performance analysis of winglets

C-wing

Author	Design aspects	Vortex	D_i	Method	Optimize/ Retrofitted	Airfoil	Flow behavior	Output drawn
Verstraeten and Slingerland [59]			√	Theoretical	√			Performance of the c-wing is lesser by 3.5% than blended winglet mainly due to the horizontal part of winglet tip.

Author	Design aspects	Vortex	D_i	Method	Optimize/ Retrofitted	Airfoil	Flow behavior	Output drawn
Cui and Han [38]			√	Both	√			The flutter characteristic is decreased by 19%. The horizontal wingtip contributes side forces, hence, weakened flutter with a minor impact on flutter frequency.
(g) Performance analysis of winglets								
Other Winglets								
Zhang, Zhou [51]		√		Experimental		NACA 0012	√	Near field vortex detection The wingtip vortices depend on circumferential velocity and stream wise velocity, in addition to the vorticity.
Giuni and Green [80]		√		Experimental		NACA 0012	√	Vortex formation on square and rounded tips. The intensity of the secondary vortex and the vortex shape influence the vorticity sheet of vortex system. High vorticity wakes are observed in the squared tips.
Vandam [46]			√	Both	√			Airfoil Winglet airfoil has better laminar flow than LS (1)-0413 airfoil with improved lateral directional handling qualities
Gall and Smith [10]	√		√	Both	√	NACA 0012		Bi-plane winglets Biplane wing with winglets improves C_L on the upper surface by 0.870 and the lower surface by 0.614, with 6.4% L/D_{max} increase.

Table 2
Best optimization drawn on various winglets

Winglet type	Winglets design aspects						Airfoil	Aspect ratio	Improvement factor		Depreciation factor			Optimization/retrofitting for improved result
	Cant angle	Toe angle	Twist angle	Sweep angle	AOA	Taper ratio			C_L	C_L/C_D	C_D	D_i	Vortex	
Blended winglet	45	−2° 3°	0	36.7°	6°	0.5	NACA 65_3-218	2.65	0.474	18%	0.045	15%	4.5×10^4	Increasing the winglets toe out will decrease the shock wave formation and alternatively decrease D_i.
Raked wingtip	15°	−4°	2°	50°	8°	N/A	NACA 0015	3.65	0.702	40%	0.017	13%	3.4×10^4	Single slot raked wingtip with slight twist provides improved results.
Split-tip winglets	75°/ 50°	2°/5°	0°/4°	38°/ 52°		0.40/ 0.32	LS (1)-0413	2.95	0.82	19%	0.013	29%	2.2×10^4	The upper winglet root chord is optimized to 77% of the wing-tip chord.
Spiroid winglet	50°	2.5°	0°	10°	11°	0.79	NACA 0012, 2412	4.47	0.55	30%	0.018	21%	2.5×10^4	Forward spiroid winglets with increased AR divide vortex core and improve efficiency.
Multi-tip winglet	60° (max)	3.5˚	1.5°	30°	8°	N/A	NACA 65_3-218	2.22	0.64	27%	0.032	13%	2.8×10^4	Three-multi-tip winglet has the best performance. Cant angle with constant interval improves performance.

Winglet Fence	0°	N/A	N/A	14°	12°	0.23	NACA 43018	2	0.36	17.5%	0.06	18%	2.3 $\times 10^4$	Rather than a vertical winglet, canted winglets show improved performance.

5. Conclusion

On the basis of numerous studies on various NACA standards, a complete survey on winglets, their performance characteristics, and optimization, as well as theoretical, numerical, and experimental analyses, has been conducted. Studies on D_i and vortex formation have been overviewed, which highlights that the strength has been cut short by the degradation of winglet structures. Increasing the AOA generally increases the streamwise and circulation velocity, resulting in large and strong tip vortices. A large improvement in visual flow characteristics and degradation of drag with small change in wing-winglet tailoring effect is observed. In addition, an aft winglet positioning yields superior results. On the basis of the far- and near-field approaches, when the circular fillet radius decreases, the profile drags maintain their pace of increment in the corner.

Nevertheless, the experimental outcomes of the NASA reports in the past centuries are completely relayed for present new optimal development. Studies have shown and proven that slight modification to existing winglet design aspects may meet the performance demands for the current era. Moreover, several new winglet studies are in progress, such as morphing winglets and adaptive winglets with retrofitting, which may beholden the requirement for future generation aircrafts.

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References

[1] Tucker, Vance A. "Drag reduction by wing tip slots in a gliding Harris' hawk, Parabuteo unicinctus." *Journal of experimental biology* 198, no. 3 (1995): 775-781.

[2] Mustaffa, Siti Hajar Adni, Fatimah Al Zahrah Mohd Saat, and Ernie Mattokit. "Turbulent Vortex Shedding across Internal Structure in Thermoacoustic Oscillatory Flow." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 46, no. 1 (2018): 175-184.

[3] Richard T. Whitcomb A Design Approach and Selected Wind Tunnel Results at High Subsonic Speeds for Wing-Tip Mounted Winglets in NASA Technical Note. Washington: Langley Research Center, Hampton Va, 1976.

[4] Lanchester, F.W. Aerodynamics, Constituting the First Volume of a Complete Work on Aerial Flight. London: Archibald Constable & Co. Ltd. Orange Street Leicester Square, 1907.

[5] Halpert, Joel, Daniel Prescott, Thomas Yechout, and Michael Arndt. "Aerodynamic optimization and evaluation of KC-135R winglets, raked wingtips, and a wingspan extension." In *48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition*, p. 57. 2010.

[6] Voevodin, A. V. "Numerical investigation of the effect of winglets on the evolution of an aircraft vortex wake." *Fluid Dynamics* 43, no. 5 (2008): 725-730.

[7] Maughmer, Mark. "The design of winglets for low-speed aircraft." *Technical Soaring* 30, no. 3 (2006): 6173.

[8] Williams, Chris, Joseph M. Weaver, Logan Fritz, and Aaron Blevins. "Effects of Winglets on Small Unmanned Aerial Systems." In *AIAA Modeling and Simulation Technologies Conference*, p. 1807. 2015.

[9] Beechook, Abhinivesh, and Jian Wang. "Aerodynamic analysis of variable cant angle winglets for improved aircraft performance." In *2013 19th International Conference on Automation and Computing*, pp. 1-6. IEEE, 2013.

[10] Gall, Peter D., and Hubert C. Smith. "Aerodynamic characteristics of biplanes with winglets." *Journal of Aircraft* 24, no. 8 (1987): 518-522.

[11] Maughmer, Mark D., Timothy S. Swan, and Steven M. Willits. "Design and testing of a winglet airfoil for low-speed aircraft." *Journal of Aircraft* 39, no. 4 (2002): 654-661.

[12] Tajuddin, Nurulhuda, Shabudin Mat, Mazuriah Said, and Shumaimi Mansor. "Flow characteristic of blunt-edged delta wing at high angle of attack." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 39, no. 1 (2017): 17-25.

[13] Eppler, R. "Induced drag and winglets." *Aerospace science and Technology* 1, no. 1 (1997): 3-15.

[14] Fujisono, Takashi, Hiroshi Yamashita, Atsushi Toyoda, Hiroki Nagai, Keisuke Asai, Takashi Matsuno, Hiromitsu Kawazoe, Shinkyu Jeong, and Shigeru Obayashi. "Supersonic Wind Tunnel Experiment on Aerodynamic Characteristics and Winglets Effects of the Tapered Supersonic Biplane." In *ASME-JSME-KSME 2011 Joint Fluids Engineering Conference*, pp. 3431-3440. American Society of Mechanical Engineers, 2011.

[15] Munshi, Adnan, Erwin Sulaeman, Norfazzila Omar, and Mohammad Yeakub Ali. "CFD Analysis on the Effect of Winglet Cant Angle on Aerodynamics of ONERA M6 Wing." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 45,no. 1 (2018): 44-54.

[16] Hossain, Altab, Ataur Rahman, A. K. M. P. Iqbal, M. Ariffin, and M. Mazian. "Drag analysis of an aircraft wing model with and without bird feather like winglet." *International Journal of Aerospace and Mechanical Engineering* 6, no. 1 (2012): 8-13.

[17] Mattos, Bento, Antonini Macedo, and Durval Silva Filho. "Considerations about winglet design." In *21st AIAA Applied Aerodynamics Conference*, p. 3502. 2003.

[18] Kubrynski, Krzysztof. "Wing-winglet design methodology for low speed applications." In *41st Aerospace Sciences Meeting and Exhibit*, p. 215. 2003.

[19] Azlin, M. An, CF Mat Taib, Salmiah Kasolang, and F. H. Muhammad. "CFD analysis of winglets at low subsonic flow." In *Proceedings of the World Congress on Engineering*, vol. 1, pp. 6-8. 2011.

[20] Roglin, Bernhard, and Joseph Katz. "Study of downward pointing winglets for unswept wings." In *39th Aerospace Sciences Meeting and Exhibit*, p. 268. 2001.

[21] Masud, Jehanzeb, Zakria Toor, Zaheer Abbas, and Umair Ahsun. "Part I: Uncertainty Analysis of Various Design Parameters on Winglet Performance." In *54th AIAA Aerospace Sciences Meeting*, p. 0556. 2016.

[22] Guerrero, Joel E., Dario Maestro, and Alessandro Bottaro. "Biomimetic spiroid winglets for lift and drag control." *Comptes Rendus Mecanique* 340, no. 1-2 (2012): 67-80.

[23] Mostafa, Suhail, Shyam Bose, Archana Nair, Mansoor Abdul Raheem, Thasneem Majeed, Atiqur Mohammed, and Young Kim. "A parametric investigation of non-circular spiroid winglets." In *EPJ Web of Conferences*, vol. 67, p. 02077. EDP Sciences, 2014.

[24] Ali Murtaza, Dr, Khalid Parvez, Hanzala Shahid, and Yasir Mehmood. "Design and Computational Fluid Dynamic Analysis of Spiroid Winglet to Study its Effects on Aircraft Performance." *International Research Journal of Engineering and Technology* 4, no. 12 (2017): 1298-1306.

[25] Manikandan, G., V. Rajashree, and S. Merryisha Sweety Gracia. "Design and Performance Analysis of Spiroid Winglet with Normal Wing." *Imperial Journal of Interdisciplinary Research* 3, no. 4 (2017): 773-778.

[26] Narayan, Gautham, and Bibin John. "Effect of winglets induced tip vortex structure on the performance of subsonic wings." *Aerospace Science and Technology* 58 (2016): 328-340.

[27] Catalano, Fernando, and Hernan Ceron-Muñoz. "Experimental analysis of aerodynamics characteristics of adaptive multi-winglets." In *43rd AIAA Aerospace Sciences Meeting and Exhibit*, p. 1231. 2005.

[28] Smith, M., N. Komerath, R. Ames, O. Wong, and J. Pearson. "Performance analysis of a wing with multiple winglets." In *19th AIAA Applied Aerodynamics Conference*, p. 2407. 2001.

[29] Zhang, Biao, Chang Chen, Te Zhu, Ruihai Fu, and Peiyi Xu. "The investigation of different wing-lets impact on Wing tip vortex." In *Proceedings of the 2018 International Conference on Service Robotics Technologies*, pp. 22-26. ACM, 2018.

[30] Reddy, Sohail R., George S. Dulikravich, Abas Abdoli, and Helmut Sobieczky. "Multi-winglets: Multi-objective optimization of aerodynamic shapes." In *53rd AIAA Aerospace Sciences Meeting*, p. 1489. 2015.

[31] Rabbi, Md Fazle, Rajesh Nandi, and Mohammad Mashud. "Induce Drag Reduction of an Airplane Wing." *American Journal of Engineering Research* 4, no. 6 (2015): 219-223.

[32] Gilkey, R.D. Design and Wind Tunnel Test of Winglets on DC-10 Wing in NASA Contractor Report 3119. Washington, D.C.: National Aeronautics and Space Administration, 1981.

[33] Montoya, L.C., S.G. Flechner, and P.F. Jacobs. Effect of Winglets on a First-Generation Jet Transport Wing. 2: Pressure and Spanwise Load Distributions for a Semispan Model at High Subsonic Speeds.[in the Langley 8 ft transonic tunnel], in NASA Technical Note. Washington, D.C.: National Aeronautics and Space Administration, 1977.

[34] Jacobs, P.F. and S.G. Flechner. The Effect of Winglets on the Static Aerodynamic Stability Characteristics of a Representative Second Generation Jet Transport Model in NASA Technical Note. Washington, D.C.: National Aeronautics and Space Administration, 1976.

[35] Reddy, Sohail R., H. E. L. M. U. T. Sobieczky, A. B. A. S. Abdoli, and GEORGE S. Dulikravich. "Winglets–Multiobjective Optimization of Aerodynamic Shapes." In *11th World Congress on Computational Mechanics*. 2014.

[36] Gold, N., and K. Visser. "Aerodynamic effects of local dihedral on a raked wingtip." In *40th AIAA Aerospace Sciences Meeting & Exhibit*, p. 831. 2002.

[37] Falcao, Luis, Alexandra Gomes, and Afzal Suleman. "Design and analysis of an adaptive wingtip." In *52nd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference 19th AIAA/ASME/AHS Adaptive Structures Conference 13t*, p. 2131. 2011.
[38] Cui, Peng, and Jinglong Han. "Prediction of flutter characteristics for a transport wing with wingtip devices." *Aerospace Science and Technology* 23, no. 1 (2012): 461-468.
[39] Panagiotou, P., P. Kaparos, and K. Yakinthos. "Winglet design and optimization for a MALE UAV using CFD." *Aerospace Science and Technology* 39 (2014): 190-205.
[40] Santhanakrishnan, R., S. Karthick Ram, S. Sam Vimal Kumar, SZ Syed Afsar, and S. Merrysha Sweety Gracia. "Numerical Simulation and Investigation on Performance Characteristics of NACA 0024 Twisted Wing." *International Journal of Applied Engineering Research* 10, no. 16 (2015): 37970-37973.
[41] Gavrilović, Nikola N., Boško P. Rašuo, George S. Dulikravich, and Vladimir B. Parezanović. "Commercial aircraft performance improvement using winglets." *FME Transactions* 43, no. 1 (2015): 1-8.
[42] ASHRAFI, Zabihollah NAJAFIAN, and Ahmad Sedaghat. "Improving the aerodynamic performance of a wing with winglet." *International Journal of Natural and Engineering Sciences (IJNES) E-ISSN: 2146-0086* 5, no. 3 (2014): 52-57.
[43] Takenaka, Keizo, Keita Hatanaka, Wataru Yamazaki, and Kazuhiro Nakahashi. "Multidisciplinary design exploration for a winglet." *Journal of Aircraft* 45, no. 5 (2008): 1601-1611.
[44] Feder, D-F., Mahesh Dhone, Nikolai Kornev, and M. Abdel-Maksoud. "Comparison of different approaches tracking a wing-tip vortex." *Ocean engineering* 147 (2018): 659-675.
[45] Khosravi, Shahriar, and David W. Zingg. "Aerostructural perspective on winglets." *Journal of Aircraft* 54, no. 3 (2017): 1121-1138.
[46] Vandam, C.P., Natural Laminar Flow Airfoil Design Considerations for Winglets on Low-Speed Airplanes, in NASA Contractor Report. Vigyan Research Associates, Inc, Hampton, VA, 1984.
[47] Birch, D., T. Lee, F. Mokhtarian, and F. Kafyeke. "Structure and induced drag of a tip vortex." *Journal of Aircraft* 41, no. 5 (2004): 1138-1145.
[48] Panagiotou, Pericles, George Ioannidis, Ioannis Tzivinikos, and Kyros Yakinthos. "Experimental Investigation of the Wake and the Wingtip Vortices of a UAV Model." *Aerospace* 4, no. 4 (2017): 53.
[49] Nazarinia, M., M. R. Soltani, and K. Ghorbanian. "Experimental study of vortex shapes behind a wing equipped with different winglets." (2006): 1-15.
[50] Arora, Prithvi Raj, A. Hossain, Prasetyo Edi, A. A. Jaafar, Thamir S. Younis, and M. Saleem. "Drag reduction in aircraft model using elliptical winglet." *Journal-The Institution of Engineers, Malaysia (IEM)* 66, no. 4 (2005): 1-8.
[51] Zhang, H. J., Y. Zhou, and J. H. Whitelaw. "Near-field wing-tip vortices and exponential vortex solution." *Journal of aircraft* 43, no. 2 (2006): 445-449.
[52] Kauertz, Sebastian, and Günther Neuwerth. "Excitation of instabilities in the wake of an airfoil by means of active winglets." *Aerospace science and technology* 10, no. 7 (2006): 551-562.
[53] Dwivedi, Y.D., P.M. Pratap, and D. Jagadish. "Design and Aerodynamic Analysis of Different Winglets." *International Journal of Innovations in Engineering and Technology* 7, no. 2 (2016): 401-410.
[54] Kuhlman, John M., and Paul Liaw. "Winglets on low-aspect-ratio wings." *Journal of Aircraft* 25, no. 10 (1988): 932-941.
[55] Maughmer, Mark D. "Design of winglets for high-performance sailplanes." *Journal of Aircraft* 40, no. 6 (2003): 1099-1106.
[56] Johansen, J. and N.N. Sørensen, Aerodynamic investigation of winglets on wind turbine blades using CFD, in Technical Report RISO. Technical University of Denmark, 2006.
[57] Lee, Tim, and Panayiote Gerontakos. "Effect of winglet dihedral on a tip vortex." *Journal of Aircraft* 43, no. 1 (2006): 117-124.
[58] Johansen, Jeppe, and Niels N. Sørensen. "Numerical analysis of winglets on wind turbine blades using CFD." In *European Wind Energy Congress*. Milano: EWEA, 2007.
[59] Verstraeten, Joram G., and Ronald Slingerland. "Drag characteristics for optimally span-loaded planar, winglетted, and C wings." *Journal of aircraft* 46, no. 3 (2009): 962-971.
[60] Azlin, M. An, CF Mat Taib, Salmiah Kasolang, and F. H. Muhammad. "CFD analysis of winglets at low subsonic flow." In *Proceedings of the World Congress on Engineering*, vol. 1, pp. 6-8. 2011.
[61] Mat Taib, C. F., Abdul Aziz Jaafar, and Salmiah Kasolang. "Numerical Study of Winglet Cant Angle Effect on Wing Performance at Low Reynolds Number." In *Applied Mechanics and Materials*, vol. 393, pp. 366-371. Trans Tech Publications, 2013.
[62] Pooladsanj, Sina, and Mehran Tadjfar. "Numerical Study of Winglet at Low Reynolds Numbers." In *ASME 2013 Fluids Engineering Division Summer Meeting*, pp. V01BT14A002-V01BT14A002. American Society of Mechanical Engineers, 2013.

[63] Sibi A Arul, D.V.M., Dinesh G. "Analysis of Winglet Designed from PSU Airfoils." *International Journal of Engineering Research & Technology* 3, no. 3 (2014).

[64] Kaygan, E., and A. Gatto. "Computational Analysis of Adaptable Winglets for Improved Morphing Aircraft Performance." *Int. J. Aerosp. Mech. Eng* 9, no. 7 (2015): 1127-1133. [65] Helal, H.S., et al., Aerodynamic Analyses of Aircraft-Blended Winglet Performance. IOSR Journal of Mechanical and Civil Engineering (IOSR–JMCE), 2016. **13**(3): p. 65-72.

[66] Hariyadi, Setyo. "An analysis on Aerodynamics Performance Simulation of NACA 23018 Airfoil Wings on Cant Angles." *JEMMME (Journal of Energy, Mechanical, Material and Manufacturing Engineering)* 2, no. 1 (2017): 31-40.

[67] GölcÃ¼k, Ali Ihsan, and Dilek Funda Kurtulus. "Winglet design and analysis for low-altitude solar-powered UAV." *International Journal of Sustainable Aviation* 3, no. 1 (2017): 64-86.

[68] Yuhara, Tatsunori, Kazuhiro Kubota, and Kenichi Rinoie. "Drag-Divergence Characteristics of Winglets." In *2018 AIAA Aerospace Sciences Meeting*, p. 0046. 2018.

[69] Holmes, Bruce J., Cornelis P. VanDam, Philip W. Brown, and Perry L. Deal. "Flight evaluation of the effect of winglets on performance and handling qualities of a single-engine general aviation airplane." (1980).

[70] RUHLIN, C., F. RAUCH, JR, and Catherine Waters. "Transonic flutter study of a wind-tunnel model of a supercritical wing with/without winglet." In *23rd Structures, Structural Dynamics and Materials Conference*, p. 721. 1982.

[71] Hantrais-Gervois, J-L., R. Grenon, A. Mann, and A. Büscher. "Downward pointing winglet design and assessment within the M-DAW research project." *The Aeronautical Journal* 113, no. 1142 (2009): 221-232.

[72] La Roche, Ulrich, and S. Palffy. "Wing-grid, a novel device for reduction of induced drag on wings." In *ICAS PROCEEDINGS*, vol. 20, pp. 2303-2309. 1996.

[73] Tucker, Vance A. "Gliding birds: reduction of induced drag by wing tip slots between the primary feathers." *Journal of experimental biology* 180, no. 1 (1993): 285-310.

[74] Shelton, Andrew, Agnivesh Tomar, J. V. R. Prasad, Marilyn Smith, and Narayanan Komerath. "Active multiple winglets for improved unmanned-aerial-vehicle performance." *Journal of aircraft* 43, no. 1 (2006): 110-116.

[75] Nandi, Rajesh, Md Assad-Uz-Zaman, Md Fazle Rabbi, and Mohammad Mashud. "Experimental Investigation of an Aircraft Wing Model Using Slotted Winglet.". *IEEE* (2014).

[76] Hossain, Altab, Ataur Rahman, A. K. M. P. Iqbal, M. Ariffin, and M. Mazian. "Drag analysis of an aircraft wing model with and without bird feather like winglet." *International Journal of Aerospace and Mechanical Engineering* 6, no. 1 (2012): 8-13.

[77] W.Lishifelshyal. "Analysis of Drag Over a Wing Model with & without Raked Wingtip." *EPRA International Journal of Research and Development* 1, no. 4 (2016): 65-70.

[78] Whitcomb, Richard T. A design approach and selected wind tunnel results at high subsonic speeds for wing-tip mounted winglets in Nasa Technological Note. Washington, D.C.: National Aeronautics and Space Administration, 1976.

[79] Manikandan, G., V. Rajashree, and S. Merryisha Sweety Gracia. "Design and Performance Analysis of Spiroid Winglet with Normal Wing." *Imperial Journal of Interdisciplinary Research* 3, no. 4 (2017): 773-778.

[80] Giuni, Michea, and Richard B. Green. "Vortex formation on squared and rounded tip." *Aerospace science and technology* 29, no. 1 (2013): 191-199.