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Science Article

Experimental Investigation of The Geometric Properties of Different Rotor Blades for Controlling the Wingtip Vortex

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This study focuses on using rotor blade turbine winglets for the purpose of controlling the wingtip vortex in airplanes. The aim of the study is to investigate the effective geometric properties of the rotor blades that are used as winglets, as well as experimental evaluation of their effects on drag, lift coefficient and the aerodynamic efficiency ratio of the airplane. Seven different types of rotor blades were chosen in regard of their span length, number of blades, and the shape of the blades and experimented in a wind tunnel. The drag and lift force were directly measured via a 3-axis external balance. The position and place of installment of the rotor blades were selected through the studies mentioned in the literature and their geometric properties were further investigated. A finite wing with a NACA64$_1$412 cross-sectional airfoil, two similar rotor blades with different span length, two similar rotor blades with different blade count, and three rotor blades with different aerodynamic shapes in terms of installation and twist angle were used as models in this study. All the experiments were conducted at a Reynolds Number of 100,000 and angles of attack ranging from negative 4 to positive 20. The results showed the existence of turbine winglets has increased the lift coefficient and results in a reduction in the drag coefficient. Rotor blades with larger span lengths have increased the aerodynamic efficiency, although they have increased the drag coefficient as well. The number of the blades has had different effect in different angles of attack. The results indicate that rotor blades with acceptable aerodynamic properties can increase the value of aerodynamic efficiency almost twice its base value and delay the wing stall up to the attack angles above 20 degrees.

Keywords: *Wind tunnel testing; Winglet; Force Measurement; Tip Vortices; Induced Drag*

Introduction

Due to the increasing costs and environmental challenges that lie ahead of increasing the planes; efficiencies, plane manufacturers have been under a lot of pressure. One of the main factors that contributes to this problem is the high price of fuel, the need for lower pollutants and the demand for creating environmental-friendly airplanes that help to lower the effects of global warming [1].in the field of aerospace engineering, drag reduction poses a great and challenge for engineers, so it

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could still be improved and novel ideas and creative works could still change the fate of this field [2]. The flow over the wing of an airplane is a three-dimensional; that is, a factor of the flow is aligned with the wingspan. the difference in pressure distribution results into the creation of lift force. In addition, this pressure differential between upside and downside of the wings, transfers the high-pressured flow which is below the wings to the above-surface of the upper wing, creating a vortex on both wing-edges of the airplane [3]. In aviation and aerospace, the existence of such vortices is dangerous and causes air traffic for the airports. These vortices are so strong that it takes at least 2 minutes for them to weaken and shed. This two-minute time is actually the time gap between two landings and takeoffs in an airplane [4]. These vortices finally lead to the induced drag force, which its reduction is one of the primary goals. reducing the drag can be beneficial and reduce fuel-consumption and increase the flight range. In fact, these environmental challenges and functional costs have impelled the aviation industry into finding new ways to increase the efficiency and frugality of commercial air transportation, which in turn have resulted into emergence of some novel and innovative ways for reducing induced drag [5].
Distribution of elliptic force, increasing the aspect ratio/ wingspan, and a lower lift coefficient or the weight are some of the preliminary methods of reducing the drag force of wingtip vortices. However, there is a limit to how much the wingspan or the aspect ratio can be increased since it would pose structural penalties; hence, they are neither efficient or possible. It's also worth noting that lower lift coefficients require longer wings which in turn would add more weight, resulting into an increase of the drag force that is caused by viscosity. Ultimately, using winglet configurations is also another way for reducing the induced drag which depend on the design and the exerted force on the winglets can reduce the drag force from 5 to 15 %. Increasing the wingspan results into an increase in the bending moment of wing root which then would need a heavier structure for tolerating more stress. [6] This is one of the main reasons behind the application of the winglet. Since winglets do not cause a considerable change in the weight of the wings and the exerted force on the structure, they can increase the effective aspect ratio and reduce the vortex force of the wingtip, in turn by reducing the induced drag force of wingtip vortex, the efficiency of the airplane (lift-to-drag ratio, L/D) efficiency of fuel consumption, maximum flight range would increase. All these developments save millions of dollars for airlines in case of fuel consumption and as a result they have been widely used in modern day airplanes. [4] Sohn and Chang [7] in 2012 managed to visualize the wingtip vortices through the smoke wire technique and proved that using Whitcomb winglet configuration can be effective in reducing the strength of wingtip vortices. The results of their study were also confirmed through Particle Image Velocimetry (PIV) measurement and aerodynamic load measurement of the model.
The notion of winglet was first introduced and developed in the late 18^{th} century by British aerodynamicist, Frederick Lanchester. He believed the existence of a vertical surface in the wingtip can control the strength and size of wingtip vortices and reduce the drag force. However, the extent of increase in drag caused by flow separation from the wing surface and surface drag didn't meet his expectations. Long after Lanchester, the engineers at Langley research center read an article about birds that use winglets for flight control, and decided to continue Lanchester's unfinished research about reducing the induced drag and increasing efficiency. Thanks to them, a new applicable and precise definition of winglet was introduced in the late 20t century. [8] To add to the airplane efficiency, various winglet configurations have been developed, of course their usage depends on flight conditions and the airplane they are being used on. Since Economic airliners spend most of their professional flight time in cruise phase, all winglet configurations shall be tested in this experiment for the ultimate goal and angle to be found. [9] many numerical and experimental studies have been conducted on the appliance of winglets in airplanes. [10] Halpert et al. (2010) evaluated the different parameters involved in designing and using winglets with raked wingtips on a KC-135R in the wind tunnel. The results of the study showed a 6-12 % increases in the endurance and range of KR-135R, the wingtips also helped to reduce the fuel consumption up to 8%. [11] Gavrilovick et al. (2015) conducted a numerical study on the effects of using different wingtips on airplanes which included a variation of no winglets, maxi, spiroid, and blended winglets. Their results obtained that in the most efficient way of using winglets the lift-

to-drag ratio increases up to 15 %. Narayan & John (2016) conducted a similar numerical study on the effectiveness of three different winglet designs in reducing lift induced drag and concluded that the multi-tip-3 showed the highest performance in light of aerodynamic efficiency [12]. Azlin et al. (2011) conducted a numerical study on the effects of two shape configurations of winglet, semicircular and elliptical, on the aerodynamic factors or the NACA65$_3$218 cross sectional airfoil. According to their results, the elliptical winglet showed the best results with an 8 % increase in lift curve slope and the best Lift-to-drag ratio [13]. Apart from the studies that were conducted on conventional winglet shapes, another winglet shape has been also the center of attentions among researchers which is the wingtip vortex turbine, first introduced by Patterson (1990) [14].

It is worth noting that in all the previous studies, all the investigations that sought to control the wingtip vortex were only limited to using traditional winglets, while no study could be found that has focused on the efficiency of using turbine wingtips. The turbine wingtips can be beneficial not only in that they help reducing three-dimensional effects of the wings but also in that their rotation can help generate energy. In this experimental study, the effects of using turbine vortex winglets on a finite wing are investigated. A number of rotor blades with different shapes were used in this investigation in order to find the effects of the blade spans, the number of the blades, and the aerodynamic shape of the blades in light of their installation angle and twist. The primary aim of the study was to investigate the effects of applying wingtip vortex turbine on a finite wing as well as evaluating the effects of different geometric properties of the turbine blades.

Methodology

Seven types of rotor blades along with a finite wing were selected for this study. Due to the importance of using winglets in takeoff and landing phase, and regarding the point that planes that fly at transonic flight regime usually use airfoils that have unoptimized performance in low-speed; a rectangular finite wing with a 30 cm span length and a 15cm chord length was used in the study that has an aspect ratio of 1.5. this rectangular wing has been developed by using a fixed NACA64$_1$412 which falls under the category of transonic wings. The seven chosen rotor blades can be seen in Fig.1 . Rotor blades (1) and (2) have similar geometric properties including similar airfoil, installation angle, twist angle, and the taper ratio with the blade span being the only point of difference between the two. The blade span of rotor blade (1) is 25% larger than the blade span of rotor blade (2); rotor blade (1) has a 5 cm span and rotor blade (2) has a 7.5 cm span.

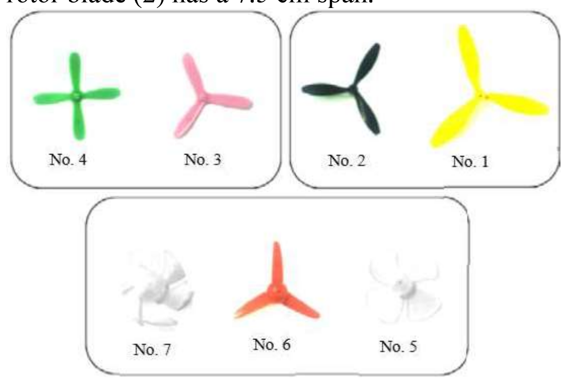

Fig. 1 – The chosen rotor blades used in the study as sample

Rotor Blades (3) and (4) which were selected to analyze the effects of the number of blades are again geometrically similar. In light of the importance of the three-dimensional flows that are formed on each blade, it was assured that the simplest blades in terms of change in their installation and twist angle were chosen. Rotor blade (3) is three-bladed and rotor blade (4) is four-bladed. Rotor blades (5),(6), and (7) are aerodynamically different regardless of their geometric properties. In other words, the numbers of blades, the twist angle and the taper ratio is different in the three rotor blades. The results would show how each of these rotor blades effects the behavior and performance of the wing.

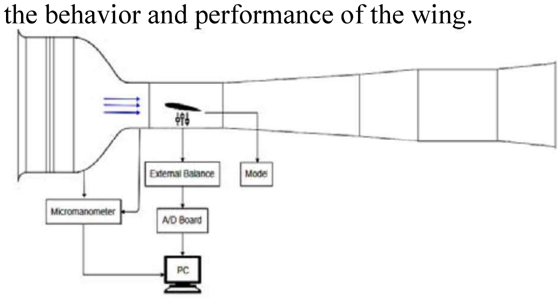

Fig. 2 – Schematic presentation of the wind tunnel and the experiment setup

Fig. 3 – Installed wing and the external balancer in the wind tunnel

All the experiments of this study were conducted at the open-circuit wind tunnel located in faculty of Aerospace engineering of Amir Kabir University of Technology. This is suction type open-circuit wind tunnel with a rectangular 1.8×1×1 m^3 test section which supports the velocity range of 2.5 up to 60 m/s. using a nozzle with compression ratio of 9 to 1, a honeycomb layer, and 3 lace layers, the turbulence in the wind tunnel in the test section is lower than 0.1 %. To control the velocity of the flow in the wind tunnel, a MP120 digital micromanometer model by KIMO is used which can measure the velocity with an accuracy of 0.1 m/s. a 3-axis external balance by Plint which a Loadcell made by Interface was used which allows to measure the drag force, lift force, and the pitching moment. Fig. 2 shows the schematic presentation of the wind tunnel and equipment that were used. The installed wing on the external balance in the wind tunnel can be seen in the Fig. 3. By putting the accuracy ranges of each sensor in the equation {1} which measures the drag coefficient, the measurement error for the drag coefficient is 0.138% at its peak. However, it should be noted that when the experiments were repeated a 0.1 difference was in the repeatability of the drag coefficient and since this value is higher than the measurement error percentage, the repeatability value will be used as measurement error value. Hence, all numerical results concerning the drag coefficient have a ±0.1 measurement error, therefore no existing change in this range is acceptable.

$$C_D = \frac{F_X}{\frac{1}{2}\rho V^2 S} = \frac{F_X}{(P_{SC}-P_{TS})S} \quad (1)$$

Results

The results of the direct measurement of drag and lift force as well as drag and lift coefficient of the wing in different attack angles ranging from -4 to +20 degree are shown in this section. The charts for drag coefficient, lift coefficient, and aerodynamic efficiency in different attack angles regarding each case are also presented here to be compared regarding the previously mentioned points and factors.

Clean Wing

Fig.4 shows the results of measuring the drag coefficient for the clean wing in the different attack angles. The drag coefficient increases additively with the changes of the attack angle. In the 10 degrees attack angle, the steep rise in the drag increases until it reaches to an almost constant state in 14 degrees. As it can be seen in the lift coefficient chart in Fig. 5, the lift coefficient has remained constant between 10-to-16-degree attack angle and then suddenly drops. It is expected that there is subtle stall in this wing that starts at 10-degree angle of attack. The aerodynamic efficiency chart of the clean wing can also be seen in Fig. 6. The aerodynamic efficiency reaches its peak at a 10-degree angle and at angle of attack of 3 degrees, the lift coefficient and the aerodynamic efficiency almost reach 0.

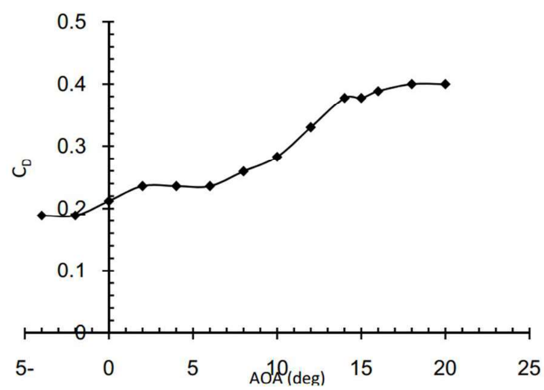

Fig. 4- Drag coefficients of the clean wing in different attack angles

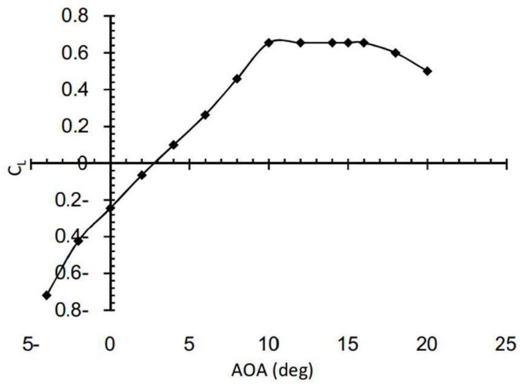

Fig. 5 - Lift coefficients of the clean wing in different attack angles

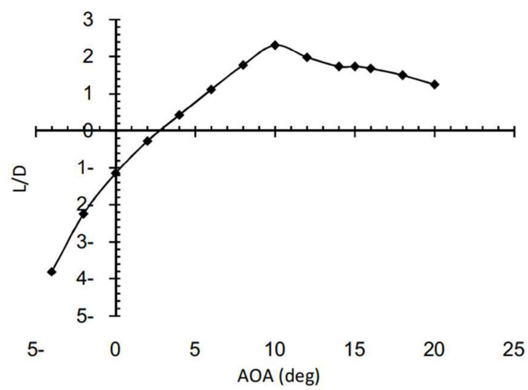

Fig. 6 – Aerodynamic efficiency of the clean wing in different attack angles

Effects of Changing the Blade Span

Fig. 7 shows the drag coefficients for rotor blades (1) and (2) in different angles of attack compared to the same results taken from the clean wing. As it can be certainly seen in the chart, different wings show similar behavior, however the value of drag coefficient for the rotor blade (1) is higher than the other two patterns. Rotor blade (1) has a larger span length and consequently has a larger cross-sectional area against the flow. All of these result in a higher drag force valve when this kind of winglet is used. The lift coefficient chart for rotor blades (!) and (2) in different angles of attack compared to the same results taken from the clean wing are shown in Fig. 8. Unlike the lift coefficients of the clean wing, the lift coefficients for the wings that are equipped with turbine wingtips do not show a linear behavior around the stall point. The rotor blade (1) with attack angles of less than 4 degrees has resulted in an increased lift coefficient. However, rotor blade (2) has deduced the value of lift coefficient in all of the attack angles. Generally, the rotor blade (1) which has a larger span length shows more desirable behavior in terms of lift coefficient. In Fig. 9 which shows the aerodynamic efficiency of rotor blades (1) and (2), only the rotor blade (1) in the angles of 0 and 2 degrees and negative degrees can have a better efficiency dependent. This shows that using rotor blades that have larger span length can be more efficient. Moreover from the angles in which the efficiency has improved indicate that using rotor blade (1) can be useful in the landing phase.

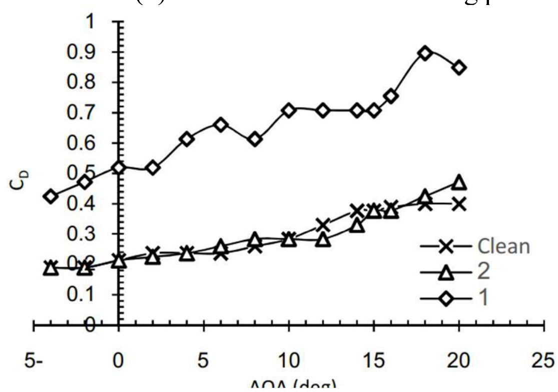

Fig. 7- Drag coefficients for rotor blade No. (1) & (2) in different attack angles in comparison to the clean wing (investigation of the blade span effects)

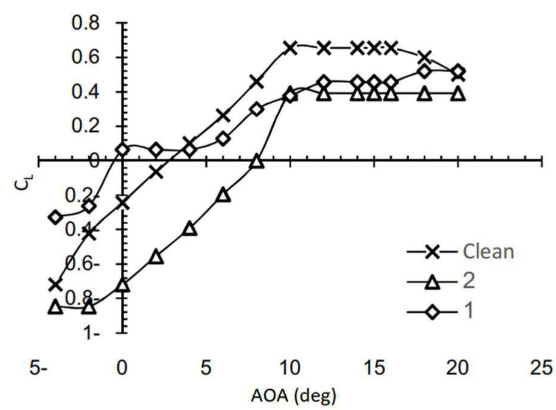

Fig. 8- Lift coefficients for rotor blade No. (1) & (2) in different attack angles in comparison to the clean wing (investigation of the blade span effects)

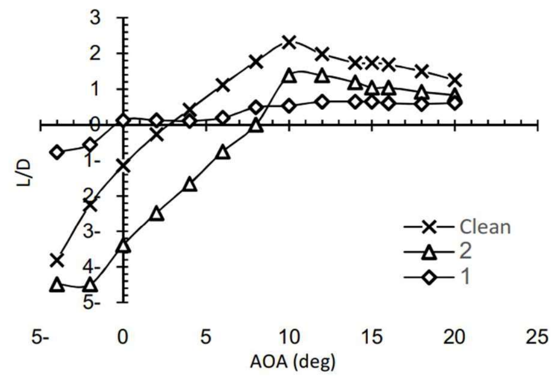

Fig. 9- Aerodynamic efficiency ratio for rotor blade No. (1) & (2) in different attack angles in comparison to the clean wing (investigation of the blade span effects)

The Effect of Number of The Blades

Two rotor blades with similar geometric properties were selected for the purpose of investigating the effect of the number of blades involved. In light of the importance of the three-dimensional flows that are formed on each blade, it was assured that the simplest blades in terms of change in their installation and twist angle were chosen. The drag coefficient values in different attack angles in comparison to the results of the clean wing are shown in Fig. 10. The rotor blade (3) shows a different behavior compared to the behavior of clean wing at 2 degrees and rotor blade (4). The values of this rotor blade in attack angles out of the range of 5 to 10 degrees are higher than the drag coefficient values of the clean wing. yet the rotor blade (4) has only higher drag values than the clean wing in instances with an attack angle lower than 5 degrees. When the wing is equipped with the rotor blade (4), and the angle of attack is higher than 10 degrees, the rotor blade (4) has managed to reduce the drag coefficient value to an acceptable extent, as much as that it has managed to reduce the drag coefficient by 20% in 12 degrees attack. The chart in Fig. 11 also shows that the rotor blade (3) at 10 degrees attack angle does not suffer from any wing stall and shows a constant lift coefficient. The same increase in the lift coefficient could still be seen after 18 degrees. The results of the experiments on this set show that up until the range of attack angles in this study which does not exceed 20 degrees, the rotor blade (3) does not suffer any wing stall. The rotor blade (4) shows similar results and behavior however it suffers severe wing stall at attack angle of 16 degree. Of course, it is notable that in negative degrees, the wing with rotor blade (3) shows more desirable results than the wing equipped with rotor blade (4). Fig. 12 presents the aerodynamic efficiency values of the rotor blade No. (3) & (4) in different attack angles in comparison to the clean wing. the rotor blades have improved the aerodynamic efficiency almost in all of the attack angles. The wing with rotor blade (3) in attack angles from 5 to 10 degree has had the best efficiency while in other angles the wing with rotor blade (4) has shown better results. In general, it can be concluded that the effect of the blade counts is not monotonous and direct like the effect of the span length and the effects vary in different angles. This event could be caused by the difference in the strength of the vortices that are formed in different attack angles which consequently result in different effects of applying turbine winglets.

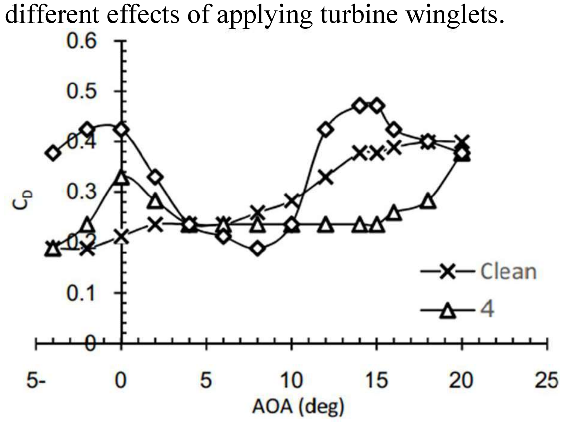

Fig. 10 – drag coefficients for rotor blade No. (3) & (4) in different attack angles in comparison to the clean wing (investigation of the number of blades)

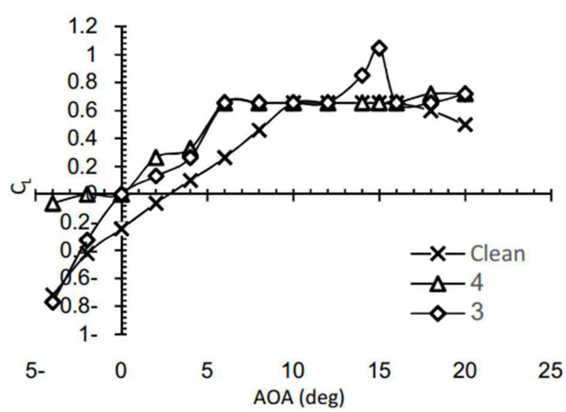

Fig. 11 – Lift coefficients for rotor blade No. (3) & (4) in different attack angles in comparison to the clean wing (investigation of the number of blades)

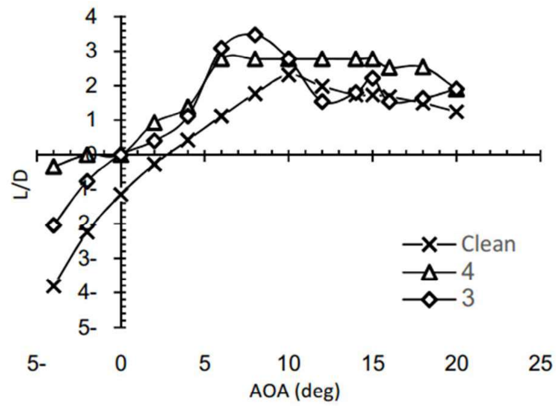

Fig. 12 - Aerodynamic efficiency ratio for rotor blade No. (3) & (4) in different attack angles in comparison to the clean wing (investigation of the number of blades)

The Aerodynamic Shape of The Rotor Blades

In Fig. 13 the drag coefficient values of rotor blades (5), (6), and (7) in different angles of attack in comparison to the results of the clean wing have been presented. Due to the effect of the blades that have aerodynamic shape, the behavior of diagram of the drag coefficients no longer follows the normal behavior of the wings that are close to the parabolic diagram. Rotor blade (5) which has four blades with a low twist angle, shows the worst performance in terms of drag coefficient values and has the highest value of drag coefficient in almost all of the attack angles. the drag coefficient values in attack angles of lower than 4 degrees have been increased in rotor blade (6) almost twice the size. However, in attack angles higher than 6 degrees, the value of drag coefficient has decreased with and to a desirable rate almost to the extent that drag coefficient has reduced 25 % in angle of attack of 10 degree. The same behavior is seen in rotor blade (7) with a slight difference in that until the attack angle of 10 degree the drag coefficients of rotor blade (7) are higher than the clean wing but they get lower than the values of clean wing in angles higher than 10 degree. Overall, it can be said that in terms of the drag coefficient, the rotor blade (7) which is consisted of 5 blades and has a twist angle and taper ratio of larger than 1, shows better results compared to the other wings.in Fig. 14 presents the lift coefficients of rotor blades (5), (6), and (7) in different angles of attack in comparison to the results of the clean wing. rotor blade (6) has a higher lift coefficient than the other wing states and has manages to increase the lift force almost in all of the attack angles. As it can be seen in the respecting chart in Fig. 14, the wing with rotor blade (6) does not suffer any wing stall stage and the value of lift coefficient suddenly increases even in the attack angles that are higher than 15 degrees. The same pattern of behavior and no trace of wing stall can also be seen in rotor blade (7) in spite of the fact that the lift coefficient values for rotor blade (7) are lower than the other wings. It is expected that in the wings the wing goes through a separation process from the leading edge and the vortices shed in a way that the rotation of these rotor blades would increase. These rotations then would result in formation of vortex flows in the wake region of the wing and hence would result in an improve in terms of energy in the regions where flow separation takes place. The respecting diagram of rotor blade (5) shows that compared to the clean wing, the wing stall in wing with rotor blade (5) has occurred in a higher angle of attack despite its sudden occurrence. The behavior of rotor blade (5) can indicate that the existence of this rotor blade helps the wing in flow separation process but this take place in angles where the rotor blade itself is in the stall state; therefore, it would result in a sudden decrease in lift coefficient. In general, the behavior and performance of the rotor blade (6) in terms of optimizing the lift coefficient is highly acceptable. Fig. 15 shows the he aerodynamic efficiency chart of rotor blades (5), (6), and (7) in different angles of attack in comparison to the results of the clean wing. with a desirable value in all different angles of attack, the wing with rotor blade (6) is the most aerodynamically efficient one. It was previously observed that this wing suffers from no stall state until the angle of attack of 20 degree, however the efficiency of this wing lowers in larger angles and its most efficient performance is observed in angles of attacks ranging form 5 to 10 degree. Then the wing with rotor blade (7) has the best efficiency in angles lower than 5 degree although its efficiency is only better than the clean wing in angles of attack higher than 15 degree.

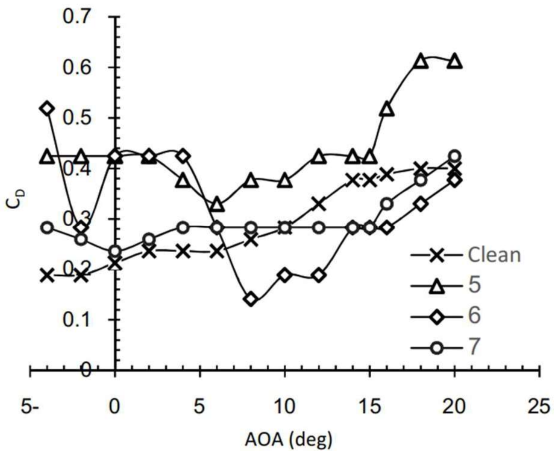

Fig. 13 – The drag coefficients of rotor blades (5), (6), and (7) in different angles of attack in comparison to the results of the clean wing (investigation of the aerodynamic effect of rotor blades)

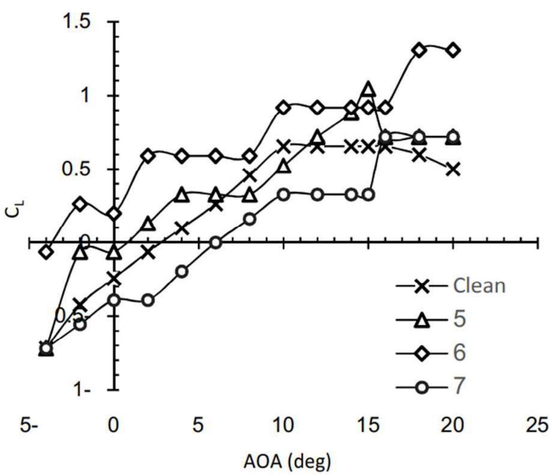

Fig. 14 – The lift coefficients of rotor blades (5), (6), and (7) in different angles of attack in comparison to the results of the clean wing (investigation of the aerodynamic effect of rotor blades)

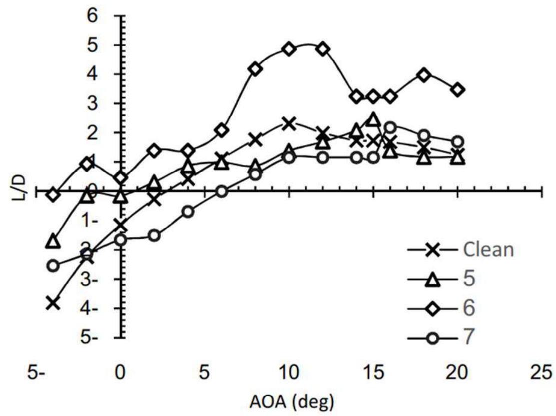

Fig. 15 – The aerodynamic efficiency values of rotor blades (5), (6), and (7) in different angles of attack in comparison to the results of the clean wing (investigation of the aerodynamic effect of rotor blades)

Conclusion

The primary focus of this study was to apply winglet turbines in order to control the wingtip vortex in airplanes. The main aim of the study was also to investigate effective geometric properties of rotor blade shapes used as winglets as well as their experimental investigation of their effects on drag & lift coefficient, and the aerodynamic efficiency. 7 different types of rotor blades were chosen in regard of their span length, number of blades, and the shape of the blades and experimented on in a wind tunnel. The drag and lift force were directly measured via a 3-axis external balancer. The position and place of installment of the rotor blades were selected through the studies mentioned in the literature and their geometric properties were further investigated. A finite wing with a NACA64$_1$412 cross-sectional airfoil, two similar rotor blades with different span length, two similar rotor blades with different blade count, and three rotor blades with different aerodynamic shapes in terms of installation and twist angle were used as samples in this study. All the experiments were conducted at a Reynolds Number of 100,000 and angles of attack ranging from negative 4 to positive 20. The following results were extracted from comparing the charts of drag coefficients, lift coefficients, and aerodynamic efficiency in different angles of attack for seven different rotor blades with the results of the clean wing;

1- According to the results, controlling the wingtip vortex via turbine winglets has proven to reduce the drag coefficient and increase the lift coefficient in a finite wing with low aspect ratio and transonic airfoil to a desirable extent which would indicate that lower fuel consumption, and shorter take off and landing length for the flying body. Since the rotor blades help in flow control with their rotations, the rotations can also be useful in generating energy.

2- Rotor blade (1) which has a larger span length than rotor blade (2) yet gematrically similar with it, has a higher drag coefficient which could be caused by its larger cross-sectional area against the flow. Nonetheless the rotor blade (1) has increased the value of lift coefficient in angles of attack lower than 4 degree angle, and the rotor blade (2) has reduced the lift coefficient in all of angles of attack. Rotor blade (1) has better aerodynamic efficiency in attack angles lower than 2 degree and in negative angles which highlights that blades with longer span length are, in this sense, more efficient despite that it increases the drag coefficient. Moreover, the angles which have a higher efficiency show that rotor blade (2) winglet can be useful in landing phase. In general, it can be said that using rotor blades with longer span length adds to the aerodynamic efficiency while simultaneously increasing the drag force.

3- Rotor blade (3) and rotor blade (4) which are respectfully triple and quadruple bladed were comparatively experimented on. in angles of attack outside the range of 5 to 10 degree, the drag coefficient for wings equipped with these rotor blades were more than drag coefficient of the clear wing. Although in attack angles lower than 5 degree, the rotor blade (4) had a higher drag coefficient than the clear wing, the wing equipped with rotor blade (4) in attack angles higher than 10 degrees has reduced the drag coefficient to a desirable extent. The results of these set of experiments showed that wing with rotor blade (3) does not suffer from any stall state in any of the experimented angles up to 20 degrees. The equipped wing with rotor blade (4) shows similar behavior with an slight difference in that it suffers a severe wing stall in angle of attack of 16 degree. It is also notable that in negative attack angles the rotor blade (3) wing performs better than the rotor blade (4) wing. the rotor blades have almost optimized efficiency in all of the attack angles. Rotor blade (3) wing in angle range of 5 to 10 degree has comparatively shown to be the most efficient one while rotor blade (4) wing shows better results in the lower and upper remaining attack angles. Generally, it can be inferred that the effect of the of the blade counts is not monotonous and direct like the effect of the span length and the effects vary in different angles.

4- The effect of rotor blades that have an aerodynamic shape has resulted the behavior of drag coefficient chart to change from the normal behavior of the wings. The rotor blade (5) which is consisted of four blades with small twist angle, shows the worst results in terms of drag coefficient. The rotor blade (6) has increased the drag coefficient in angles lower than 4 degree but it has managed to decrease the drag coefficient to a desirable and acceptable extent in attack angles above 6 degree. The rotor blade (7) shows higher drag coefficients compared to the clear wing up to the 10 degree angle point while its drag coefficient is lesser than the clear wing's in attack angles above 10 degree. In the end it can be inferred that in terms of drag coefficient, rotor blade (7) wing which has 5 blades and a twist angle and taper ratio above 1, shows the best performance in this set. The rotor blade (6) has a higher lift coefficient compared to the rest of wings in this set and has almost managed to increase the lift coefficient in all angles of attack. Rotor blade (6) wing does not suffer from any wing stall state and its lift coefficient continues to increase suddenly even in angles above 15 degree. However, in rotor blade (5) the angle in which the wing stall happens is higher in comparison to the stall angle of the clear wing, and it occurs suddenly. In general, the performance of the rotor blade (6) in terms of lift coefficient optimization is highly desirable. This rotor blade also shows an acceptable value of aerodynamic efficiency in all the angles of attack.

5- The concluding point of this study is that the performance and efficiency of winglet turbines are acceptable. The investigated parameters of aerodynamic properties that effected the turbine winglets could be useful in investigating the amount of energy that would be generated by the rotation of the turbines, designing certain mechanisms for attaching and installing these turbines on the wings, and designing highly efficient turbines for the purpose of optimized control of wingtip vortex.

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