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Drag Analysis of an Aircraft Wing Model with and without Bird Feather like Winglet

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***Abstract*—**This work describes the aerodynamic characteristic for aircraft wing model with and without bird feather like winglet. The aerofoil used to construct the whole structure is NACA 65_3-218 Rectangular wing and this aerofoil has been used to compare the result with previous research using winglet. The model of the rectangular wing with bird feather like winglet has been fabricated using polystyrene before design using CATIA P3 V5R13 software and finally fabricated in wood. The experimental analysis for the aerodynamic characteristic for rectangular wing without winglet, wing with horizontal winglet and wing with 60 degree inclination winglet for Reynolds number 1.66×10^5, 2.08×10^5 and 2.50×10^5 have been carried out in open loop low speed wind tunnel at the Aerodynamics laboratory in Universiti Putra Malaysia. The experimental result shows 25-30 % reduction in drag coefficient and 10-20 % increase in lift coefficient by using bird feather like winglet for angle of attack of 8 degree.

***Keywords*—**Aerofoil, Wind tunnel, Winglet, Drag Coefficient.

I. Introduction

ONE of the primary obstacles limiting the performance of aircraft is the drag that the aircraft produces. This drag stems out from the vortices shed by an aircraft's wings, which causes the local relative wind downward (an effect known as downward) and generated a component of the local lift force in the direction of the free stream called induced drag. The strength of this induced drag is proportional to the spacing and radii of these vortices. By designing wings which force the vortices farther apart and at the same time create vortices with large core radii, one may significantly reduce the amount of the drag the aircraft induces [1]. Airplanes which experience less drag require less power and therefore less fuel to fly an arbitrary distance, thus making flight, commercial and otherwise, more efficient and less costly. Vortices at the wing tip can cause crash in aircraft. This is when a big aircraft goes in front of a small aircraft; this big aircraft which has larger vortices can cause the small aircraft to loose control and crash. In airport to minimize the separation rule, an aircraft of a lower wake vortex category must not be allowed to take off less than two minutes behind an aircraft of a higher wake vortex category. If the following aircraft does not start its take off roll from the same point as the preceding aircraft, this is increased to three minutes. One promising drag reduction device is winglet. For a number of years many investigations have been carried out to prove the possible benefits of modifying wing tip flow. Tip devices have become a popular technique to increase the aerodynamic performances of lifting wings. The present demand on fuel consumption has emphasized to improve aerodynamic efficiency of an aircraft through a wingtip device which diffuses the strong vortices produced at the tip and thereby optimise the span wise lift distribution, while maintaining the additional moments on the wing within certain limits.

The current study in winglets has been started for the last 25 years. Small and nearly vertical fins were installed on a KC-135A and flight was tested in 1979 and 1980 [2-3]. Whitcomb showed that winglets could increase an aircraft's range by as much as 7% at cruise speeds. A NASA contract [4] in the 1980s assessed winglets and other drag reduction devices, and they found that wingtip devices (winglet, feathers, sails, etc.) could improve drag due to lift efficiency by 10 to 15% if they are designed as an integral part of the wing. The advantages of single winglets for small transports were investigated by Robert Jones [5], on which they can provide 10% reduction in induced drag compared with elliptical wings. Winglets are being incorporated into most new transports, including the Gulfstream III and IV business jets [6], the Boeing 747-400 and McDonnell Douglas MD-11 airliners, and the McDonnell Douglas C-17 military transport.

The first industry application of the winglet concept was in sailplane. The Pennsylvania State University (PSU) 94-097 airfoil had been designed for use on winglets of high-performance sailplanes [7]. To validate the design tools, as well as the design itself, the airfoil was tested in the Penn State Low-Speed, Low-Turbulence Wind Tunnel. Performance predictions from two well-known computer codes were compared to the data obtained experimentally, and both were found in good agreement with the wind tunnel measurements. Another investigation was carried out on wing tip airfoils by J. J. Spillman at the Cranfield Institute of technology in England [8]. He investigated the use of one to four sails on the wingtip fuel tank of a Paris MS 760 Trainer Aircraft. Experiments on flight test confirmed the wind tunnel tests and demonstrated shorter takeoff rolls and reduced fuel consumption [9]. Spillman later investigated wingtip vortex reduction due to

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wing tip sails, and found lower vortex energy 400-700 m behind the aircraft, although the rate of decay beyond that was somewhat lower [10]. A biologist with an aerodynamic background has done extensive investigation of the split wingtips of soaring birds and he demonstrated that the tip slots of soaring birds reduce induced drag and increase the span factor of the wings [11]. He found remarkable improvements of slotted wingtips compared with conventional wing with a Clark Y airfoil by reducing the drag of 6%.

The multi-winglet [12] design was evaluated to demonstrate to improve the advanced performance potential over the baseline wing and an equivalent single winglet. The results of their wind tunnel testing show that certain multi-winglet configurations reduced the wing induced drag and improved L/D by 15-30% compared with the baseline 0012 wing. In Europe, an extension to the wing tip airfoils has been developed called Wing-Grid [13]. Wing-Grid is a set of multiple wing extensions added to the wing. These small wings are added at various angles so that their tip vortices do not interact to form a strong vortex. Winglets show greater efficiency when there is high loading near the tips of the wing and it is more efficient than a wing tip extension producing the same bending moment at the root [14]. It enables to increase the aircraft efficiency. A group of biologists at the Technical University of Berlin has worked and demonstrated the effectiveness of multiple slotted wings or wing grid. They have shown how these features could have evolved naturally in birds through gradual increases in wing effectiveness. This theory has been emulated in an aircraft optimization algorithm developed by the researchers [15]. But this concept is limited, since it is not able to change configuration in flight to optimise drag reduction. Two bird feathers like winglets have been used with the aircraft model wing to do the experiment with the wind tunnel in Aerodynamics Laboratory of Aerospace Engineering Department, Universiti Putra Malaysia. The longitudinal aerodynamic characteristics of aircraft wing with two-winglet configurations have been the subject of this research work. The study on the enhanced performance of the aircraft models is also given by incorporating elliptical and circular winglets and aerodynamic characteristics for the aircraft model with and without winglet having NACA wing No. 65-3-218 has been explained [16]. An interaction matrix method has also been presented to revalidate the calibration matrix data provided by the manufacturer of the six-component external balance. The calibration of free stream velocity and flow quality in the test section has been established and documented in the earlier published paper [17-18].

II. Methodology

A. Wind tunnel, Model details and Instrumentation

The aircraft model's wing with two sets of bird feather like winglet has been designed and fabricated using wood for aerodynamic characteristic analysis in subsonic wind tunnel at Aerodynamic Laboratory, University Putra Malaysia. The NACA 65_3-218 airfoil has been used for the structure of wing, winglet and adapter. The winglet design is shown in Fig. 1. The aircraft wing model has a span of 0.66 m and a chord of 0.121 m as shown in Fig. 2.

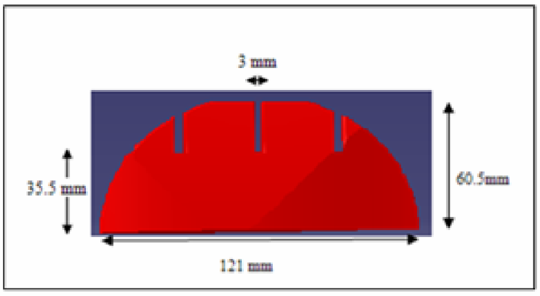

Fig.1. Geometry of Bird Feather like Winglet from Top View

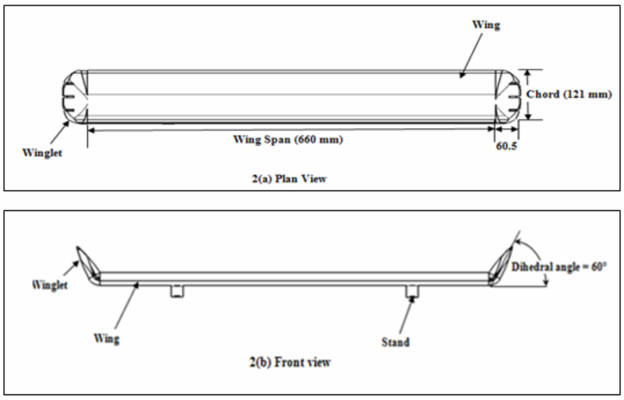

Fig.2. Rectangular Wing with Winglet using Adapter

B. Theoretical Models

Lift Coefficient and drag coefficient are defined as [19-20],

$$C_L = \frac{L}{\frac{1}{2}\rho_\infty V_\infty{}^2 S} \quad (1)$$

$$C_D = \frac{D}{\frac{1}{2}\rho_\infty V_\infty{}^2 S} \quad (2)$$

where L is the lift force in N, D is the drag force in N, ρ_∞ is the air density in kg/m^3, V_∞ is the free stream velocity in m/s, c is the chord length in m, and S is reference area in m^2.

Using equations of state for perfect gas the air density, ρ_∞ in kg/m^3 is defined as

$$\rho_\infty = \frac{p}{RT} \quad (3)$$

Where, p is the absolute pressure in N/m^2, T is the temperature in K, and R is the gas constant of air in Nm/(kg) (K).

Reynolds number based on the chord length is defined

$$\mathrm{Re} = \frac{\rho_\infty v_\infty c}{\mu_\infty} \quad (4)$$

Where, v_∞ is the free stream velocity in m/s; μ_∞ is the dynamic viscosity in kg/(m)(s) and c is the chord length in m.

The air viscosity, μ_∞ is determined using the Sutherland's equation [19] described below

$$\mu_\infty = 1.458 \times 10^{-6} \frac{T^{1.5}}{T + 110.4} \quad (5)$$

Where, T is the temperature in K.

C. Experimental Procedure

Experiments were conducted in the Aerodynamics Laboratory Faculty of Engineering (University Putra Malaysia) with subsonic wind tunnel of 1 m ×1 m rectangular test section and 2.5 m long. The wind tunnel could be operated at a maximum air speed of 50 m/s and the turntable had a capacity for setting an angle of attack of 14 degree. The ambient pressure, temperature and humidity were recorded using barometer, thermometer, and hygrometer respectively for the evaluation of air density in the laboratory environment. Fig. 3 shows a photograph of the aircraft wing model with winglet, which is mounted horizontally in the test section of the wind tunnel.

Fig.3. Schematic diagram of the wing with winglet

The tests were carried out with free-stream velocity of 21.36 m/s, 26.76 m/s, and 32.15 m/s respectively with and without winglet of different configurations. The coefficient of lift (Table I) and coefficient of drag (Table II) were obtained from the experimental results as per the procedure explained in [16-17]. The simulations on the parameters were conducted at Reynolds numbers 1.7×10^5, 2.1×10^5, and 2.5×10^5 respectively by using the MATLAB.

D. Calibration of External Balance

Calibration of the six-component balance has been done to check the calibration matrix data provided by the manufacturer. Fig. 4 shows a photograph of the calibration rig used for the validation of calibration matrix, which is mounted on the upper platform of the balance in place of model. The relationship between signal readings, L_i and the loads, F_i applied on the calibration rig are given by the following matrix equation, the detailed procedure of calibration using Matlab software is explained elsewhere [17-18].

$$\{L_i\} = \lfloor K_{ij} \rfloor \{F_i\} \quad (6)$$

Where, $[K_{ij}]$ is the coefficient matrix, $\{L_i\}$ is the signal matrix, and $\{F_i\}$ is the load matrix.

TABLE I
LIFT COEFFICIENTS DATA

Winglet Configuration	Reynolds number 10^5	Lift coefficient, C_L		
		Initial angle of attack 0^0	Stall angle of attack 8^0	Final angle of attack 14^0
Without Winglet	1.7	0.228	0.804	0.666
	2.1	0.256	0.787	0.589
	2.5	0.308	0.880	0.735
Configuration 1 (0^0 angle)	1.7	0.405	0.850	0.572
	2.1	0.433	0.915	0.722
	2.5	0.414	0.972	0.759
Configuration 2 (60^0 angle)	1.7	0.442	0.993	0.780
	2.1	0.456	0.956	0.750
	2.5	0.481	0.990	0.828

TABLE II
DRAG COEFFICIENTS DATA

Winglet Configuration	Reynolds number 10^5	Drag coefficient, C_D		
		Initial angle of attack 0^0	Stall angle of attack 8^0	Final angle of attack 14^0
Without Winglet	1.7	0.088	0.156	0.258
	2.1	0.085	0.152	0.289
	2.5	0.067	0.136	0.218
Configuration 1 (0^0 angle)	1.7	0.062	0.103	0.193
	2.1	0.055	0.094	0.164
	2.5	0.053	0.085	0.131
Configuration 2 (60^0 angle)	1.7	0.076	0.118	0.193
	2.1	0.064	0.104	0.171
	2.5	0.052	0.139	0.159

Fig.4. Calibration rig mounted on the wind tunnel test section

The calibration matrix is obtained by finding the inverse of K_{ij}, coefficient matrix and it compares well with the calibration matrix data supplied by the manufacturer with six component external balance.

E. Speed Calibration

The airflow velocity was controlled by the RPM controller of the wind tunnel. For the different Hz settings at the RPM controller the flow velocities in wind tunnel test section were recorded using six-component external balance software. The validity of the digital manometer was confirmed by comparing the dynamic pressure measured through the digital manometer and through the tube manometer used along with the pitot tube mounted in the test section. The experimental error using the external balance was nearly 6% [16, 21]. The flow velocity readings of the external balance are corrected through the following calibration equation obtained through the data shown in Fig.5,

$$y = 1.0796x - 0.2336 \qquad (7)$$

Where x denotes external balance software velocity (m/s) and y denotes digital manometer velocity (m/s).

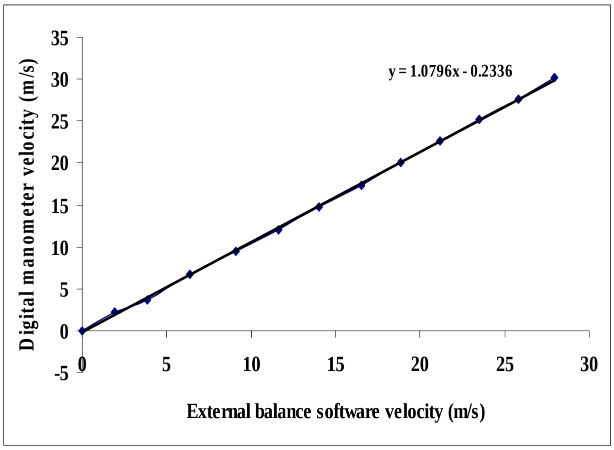

Fig.5. Flow velocity calibration for external balance

Using the equation (7), the actual value of free stream air velocity would be 21.36 m/s for corresponding 20 m/s of air velocity from six-component external balance software.

F. Flow Uniformity

The dynamic pressure was measured using digital manometer at different locations in the test section in YZ-plane by means of a pitot tube for a RPM controller setting of 15 Hz. For different locations of the measurement grid the experiments were repeated three times and the experimental data was given in [16]. The average (mean) dynamic pressure was obtained from the measured dynamic pressure data. The dynamic pressure variations from the mean were calculated in percentage at different locations of YZ-plane. Using these data dynamic pressure variations from the mean (%) versus distance from wind tunnel floor (cm) were plotted as shown in Fig.6. It was observed that the variation of dynamic pressure in the test section was within ± 0.5% which indicated that the there was very good uniformity of flow in the test section of the wind tunnel during the experimental set up for the aircraft wing model with and without winglet.

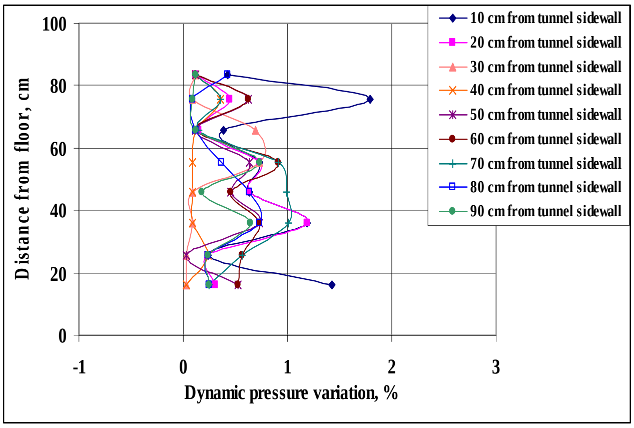

Fig.6. Dynamic pressure variation in the test section

III. Results And Discussions

A. Test Conditions

The aircraft model tests with different configuration of winglets and without winglet were carried out at Reynolds numbers 1.7×10^5, 2.1×10^5, and 2.5×10^5. The measured values for the lift force, and drag force for the various configurations were given in Ref. [16-17] and coefficient of lift and coefficient of drag were calculated as per the procedures explained.

B. Coefficient of Lift

The coefficient of lift versus angle of attack for the aircraft wing model with and without winglet studied in the present investigation are shown in Fig. 7 for the maximum Reynolds number of 2.5×10^5. From the figure it is observed that the lift increases with increase in angle of attack to a maximum value and thereby decreases with further increase in angle of attack.

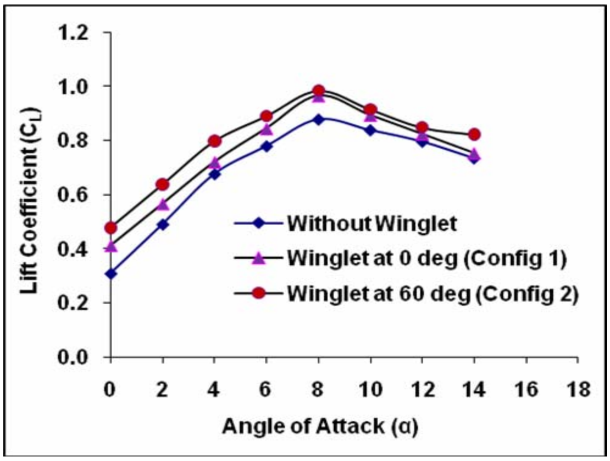

Fig.7. Lift Coefficients for the Aircraft Wing Model

The initial values of lift coefficient occur at zero angle of attack and the maximum values of the lift coefficient occur at an angle of attack of 8 degrees. Above this angle of attack lift curve begins to decrease with further increase in angle of attack. The reason for a drop in lift coefficient beyond 8 degree angle of attack is probably due to the flow separation, which occurs over the wing surface instead of having a streamlined laminar flow there. The stalling angle happens to be approximately 8^0 for all the Reynolds numbers under the present study. In case of the winglet for both configurations 1 and 2 a similar pattern is observed. For the maximum Reynolds number of $2.5x10^5$ the lift coefficients for different configurations are found as 0.88, 0.972 and 0.99 respectively corresponding to an angle of attack of 8^0 which is stall angle of attack also. From the graph, it can be concluded that lift coefficient for using winglet is higher than without winglet.

C. *Coefficient of Drag*

The drag coefficients of the aircraft wing model under test for all Reynolds numbers are shown in Fig. 8. From the graph, it is observed that the drag coefficient for the aircraft wing model measured under all the configurations under this study shows an increasing trend with angle of attack for a Reynolds number $0.25x10^6$. The drag increases slowly with increase in angle of attack to a certain value and then it increases rapidly with further increase in angle of attack. The rapid increase in drag coefficient, which occurs at higher values of angle of attack, is probably due to the increasing region of separated flow over the wing surface, which creates a large pressure drag. From the figure it is observed that the values of the minimum drag coefficients are 0.067, 0.053, and 0.052 respectively for different configurations for the maximum Reynolds number of $2.5x10^5$ which occur at zero angle of attack. In particular the measured drag values against the angle of attack are minimum for the winglet of configuration 1 and 2 over the values of the range of angle of attack considered under this study. To establish the superiority of the winglet at 0 degree over the winglet at 60 degree more detailed experiments are required.

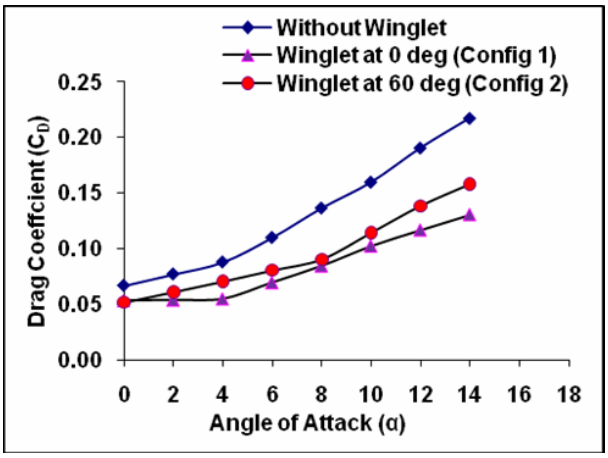

Fig.8. Drag Coefficients for the Aircraft Wing model.

D. *Lift/Drag ratio Characteristics*

The lift/drag ratio is the outcome of the observations made in the two preceding sections. It is observed from the Fig. 9 that the lift/drag ratio for all the configurations considered increases with an angle of attack to its maximum value and

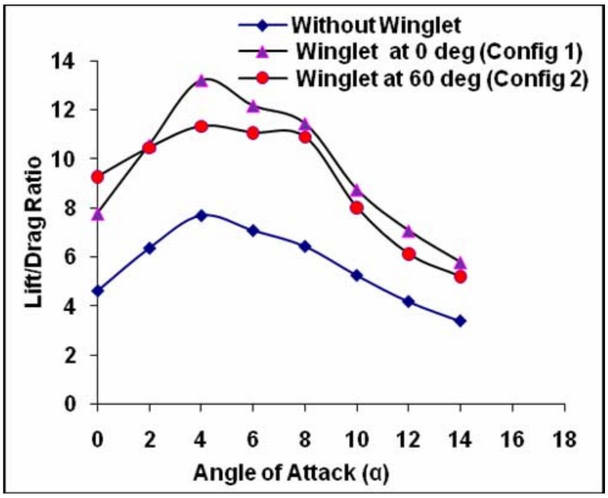

Fig.9. Lift/Drag ratio for the Aircraft Wing model

thereby it decreases with further increase in angle of attack for a Reynolds number $2.5x10^5$. In particular it is observed that the maximum lift/drag ratio for all the configurations considered in the study falls in the range of 4 to 6 degrees of angle of attack. The aircraft wing model without winglet gives a measured lift/drag ratio of 7.71 whereas the respective values of the lift/drag ratio for the different configurations are 13.09, and 11.31 respectively at an angle of attack of 4^0. The lift/drag ratio values for the angle of attack of 6^0 are 7.1, 12.2, and 11.1 respectively for the different configurations. Practically it is observed that the lift/drag ratio versus angle of attack curve gives similar results for 4 to 8 degrees, for the winglet of configuration 1, and for winglet of configuration 2.

From this investigation it is observed that at the maximum Reynolds number of $2.5x10^5$ winglet of configuration 1 and 2 provides the largest increase of lift force, ranging from 10% to 20% increases and at the same time drag decreases more for these two configurations ranging from 25% to 30% decrease, giving an edge over other configurations as far as $L/_D$ for the winglet of configuration 1 and 2 are considered. Decisively it can be said that the wing with winglet of configuration 1 (Winglets inclination at 0^0) has the better performance as compared to other configurations and it is giving the better lift/drag ratio (13.1).

IV. Conclusion

Following are the conclusions drawn from this investigation

i) From the drag coefficient and lift coefficient graph it is clearly shown that using bird feather like winglet will increase lift force and reduce drag force.

ii) This winglet design is capable to reduce induced drag force and convert wing tip vortices to additional thrust which will save cost by reducing the usage of fuel, noise level reduction and increase the efficiency of the aircraft engine.

iii) The experiment result shows 25-30 % reduction in drag coefficient and 10-20 % increase in lift coefficient by using winglet for angle of attack of 8 degree.

iv) The developed model can be used as a reference for the prototype.

v) This investigation provides a better understanding for the winglet concept and its inclusion to the wing of aircraft wing model**.**

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