

Aerodynamic Characteristics of Biplanes with Winglets

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This paper examines, both theoretically and experimentally, the possibility of improving the aerodynamic characteristics of a biplane configuration by adding winglets. Theoretical calculations show good agreement with experiment in predicting inviscid drag due to lift. Theoretical and experimental results indicate that the addition of winglets to an optimized biplane configuration can increase the ideal efficiency factor by up to 13%, as well as increasing the lift-curve slope and maximum lift coefficient. A theoretical analysis comparing the biplane with an optimized winglet to an equivalent monoplane indicates that the biplane has the potential for a 6.4% increase in L/D_{\max} and a 13% increase in $C_L^{3/2}/C_D$, the classical endurance parameter.

Nomenclature

b	= wing span
c	= wing chord
C_D	= total drag coefficient
C_{Di}	= induced drag coefficient
ΔC_{DP}	= incremental profile drag coefficient
$C_{D\min}$	= minimum drag coefficient
C_L	= lift coefficient
$C_L^{3/2}/C_D$	= endurance parameter
Dec	= incidence angle between upper and lower wings, positive when upper wing is at higher angle of attack than the lower wing
EMAR	= equivalent monoplane aspect ratio, $= S/[2c^2(1+\delta)]$
e	= efficiency factor
Ga	= vertical distance between the two wings, non-dimensionalized by chord
L/D	= lift-drag ratio
St	= longitudinal distance between the 50% mean chord points of the two wings, non-dimensionalized by chord
α	= angle of attack
δ	= Prandtl's biplane interference factor

Introduction

THE high cost of aviation fuel, coupled with increasing manufacturing and operating costs, is forcing aircraft manufacturers to build faster, more efficient aircraft. Considerable research has been conducted in government, industry, and universities in the areas of advanced aerodynamics. One such is the study of winglets and wing-tip extensions. Research by NASA has determined that properly designed winglets can significantly reduce induced drag at cruise-lift coefficients without imposing severe additional structural loads.^{1,2} The presence of the winglet causes a

physical constraint to the flowfield at the location of the winglet, which is usually at or near the wing tip. This constraint weakens the strength of the trailing vorticity shed near the outboard section of the wing, resulting in a corresponding reduction in the induced downwash. By reducing the induced downwash, the effective angle of attack of the outboard section of the wing is increased. This results in a more even downwash distribution across the entire wing span, resulting in greater induced span efficiency.

Since the early days of biplane theory, it has been shown by Prandtl,³ Munk,⁴ and others that, for a given span, the biplane produces less induced drag than a monoplane of equal span and area. Many studies, both theoretical and experimental, have been made of the efficiency of biplanes having various combinations of gap, stagger, and decalage.⁵⁻⁸ Nenadovitch⁹ and Olson¹⁰ discovered certain combinations that appeared to be nearly optimum in L/D ratio for rectangular untwisted biplane wings. Numerical two-dimensional analysis by Rokhsaz¹¹ confirmed that the combinations of gap, stagger, and decalage determined by Nenadovitch do approach optimum arrangements.

The purpose of the present study is to examine, both theoretically and experimentally, the possibility of further increasing the aerodynamic efficiency of a biplane configuration by adding winglets. The first step in the study was to produce experimental and theoretical data for a biplane configuration. The experimental data were obtained from wind-tunnel tests performed in the Pennsylvania State University subsonic wind tunnel at a Reynolds number of 510,000. The theoretical calculations were carried out using two vortex-lattice-type potential flow codes. Then, the computed results were verified by comparison with the experimental data. Finally, the computer codes were used to develop an improved winglet for the biplane.

Theoretical Analysis

Theoretical predictions for the biplane configurations, both with and without winglets, were primarily carried out using a vortex-lattice-type potential flow code developed by the author specifically for multiwing winglet configurations.¹² The code utilizes a vortex-lattice representation of the aircraft lifting surfaces, coupled with classic equations and theorems for computing such aerodynamic characteristics as lift, induced drag, spanwise and chordwise load distributions, and wing efficiency factors. Both sidewash and downwash components of the induced flow are taken into account at each control point in order to accommodate the winglet effects. The code assumes steady, irrotational, inviscid, incompress-

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ible attached flow. Therefore, numerical results can only be assumed valid at subsonic speed when the wing is operating at a less than critical angle of attack. Induced drag calculations are performed by applying Munk's theorems I and II to the wing-induced flowfield located an infinite distance downstream from the lifting surfaces in the Trefftz plane. Munk's first theorem states that the induced drag of a multiplane lifting system is unaltered if any of the lifting elements are moved in the direction of the motion, provided that the attitude of the elements is adjusted to maintain the same distribution of lift among them. Munk's second theorem states that when calculating the induced drag of a lifting system, one may, instead of using the actual values of the velocity normal to the lifting elements at the original point of application of the forces, use one-half of the limiting value of the normal velocity for the corresponding values at the original points. This theorem allows the drag computations to be done for the Trefftz plane.

The second vortex-lattice code, which was used to verify the results of the first code, was a unified vortex-lattice code (NARUVL) developed by North American Rockwell.¹³ In both codes, the lifting surfaces were modeled with zero thickness airfoils.

Experimental Procedure

Experimental results were obtained by testing a half-span wind-tunnel model of the biplane-winglet configuration in the Pennsylvania State University subsonic wind tunnel at a Reynolds number of 510,000.

The model consisted of two identical wings, each having a chord of 8 in. and a semispan of 20 in., yielding a full-span aspect ratio per wing of five. Figure 1 is an isometric view of the model. The airfoil used was a symmetrical NACA 0012 section. It is recognized that symmetrical airfoils are less efficient than cambered airfoils in L/D ratio at typical flight angles of attack. This fact is particularly true of biplane wings, because of the induced camber, or local curvature of the flow caused by one airfoil acting on the other, which reduces the effective camber. This effect is pointed out by Addoms and Spaid.¹⁴ However, it was considered a more general approach to use a symmetrical airfoil for relative performance with and without winglets, rather than to identify the study with a specific camber configuration. Spanning the tips of the wings was a constant chord, 3% thick symmetrical airfoil winglet. The configuration with winglets may be thought of as a "box" wing. The model was constructed to have a fixed gap and stagger, both equal to one chord length, and a decalage angle that could be varied between 0 and -6 deg.

The model was tested throughout the operating angle-of-attack range at decalage angles of 0 and -5 deg. All configurations were tested with and without winglets.

Through calibration tests conducted on the balance, the following experimental accuracies were determined: $C_D \pm 0.0005$, $C_L \pm 0.02$, and $\alpha \pm 1$ deg.

Results and Discussion

Theoretical and Experimental Results

The purpose of obtaining the experimental data was to study the relative differences in induced drag for the various configurations and then to compare these results to theory.

The results are presented for both 0 and -5 deg decalage configurations. Figures 2 and 3 present C_L as a function of α for the 0 and -5 deg decalage configuration. For the 0 deg decalage configuration, loss of lift begins to occur at an angle of attack of approximately 13 deg. This is probably due to the stall onset of the upper wing. The vortex-lattice code predicts that at $\alpha = 12$ deg, the upper wing is at a C_L of 0.870, while the lower wing is at a C_L of only 0.614. This occurs since the lower wing is immersed in the induced downwash of the upper wing; hence, the lower wing operates at a less effective angle of attack. For the -5 deg decalage configuration, the lower wing is only slightly more highly loaded while approaching the stall,

resulting in only a slight increase in $C_{L_{max}}$ over the 0 deg decalage configuration.

The additions of winglets to both configurations resulted in approximately a 5% increase in lift-curve slope and a 4% increase in maximum lift coefficient. The maximum lift coefficient for the 0 deg decalage configuration was 0.850 without winglets and 0.881 with winglets.

The magnitudes of the experimental data cannot be taken to be characteristic of full-scale designs, or of designs using new

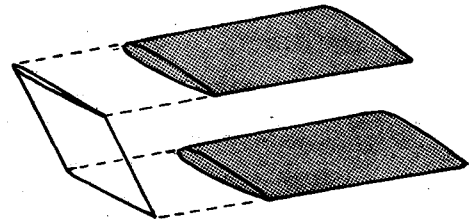


Fig. 1 Isometric view of model.

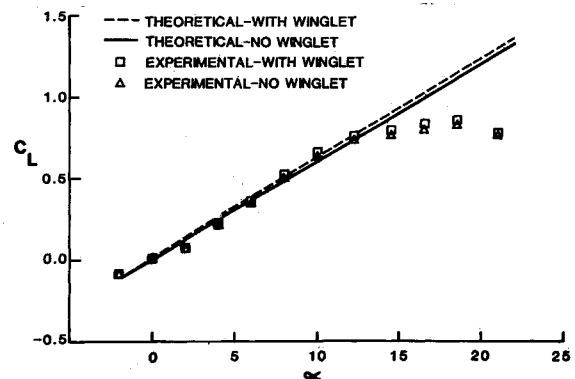


Fig. 2 Lift coefficient as a function of angle of attack: $Ga=1.0$, $St=1.0$, $Dec=0$ deg.

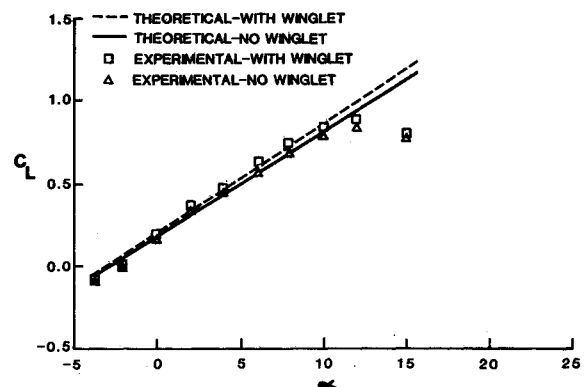


Fig. 3 Lift coefficient as function of angle of attack: $Ga=1.0$, $ST=1.0$, $Dec=-5$ deg.

Table 1 Theoretical and experimental efficiency factors

	Theoretical		Experimental	
	e winglet	e no winglet	e winglet	e no winglet
Monoplane	—	0.975	—	—
Biplane I	1.091	0.974	0.991	0.870
$Ga=1.0$				
$St=1.0$				
$Dec=0$ deg				
Biplane II	1.166	1.083	0.981	0.831
$Ga=1.0$				
$St=1.0$				
$Dec=-5$ deg				

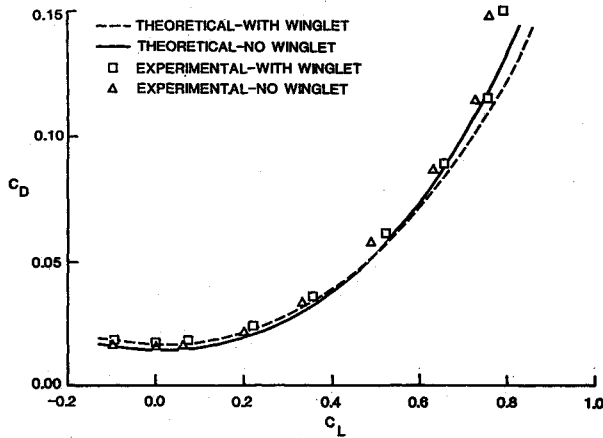


Fig. 4 Biplane drag polars: $Ga=1.0$, $St=1.0$, $Dec=0$ deg.

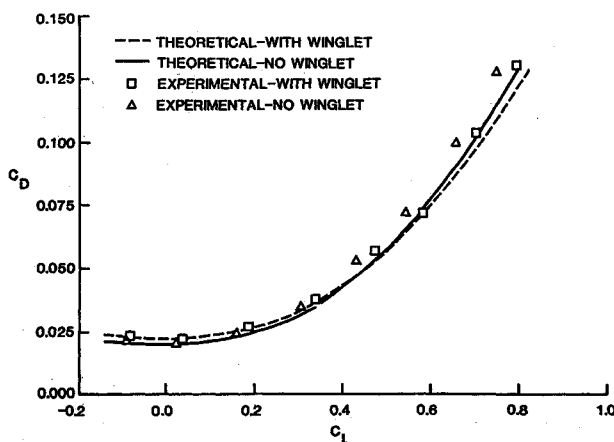


Fig. 5 Biplane drag polars: $Ga=1.0$, $St=1.0$, $Dec=-5$ deg.

high-lift, low-drag airfoils. A much higher maximum lift coefficient could be expected at full-scale Reynolds numbers. For example, a NACA 0012 two-dimensional airfoil tested at a Reynolds number of 500,000 has $C_{L_{max}}=0.9$,¹⁵ whereas the same airfoil tested at a typical full-scale Reynolds number of 6,000,000 has $C_{L_{max}}=1.6$.

At low Reynolds numbers, profile-drag coefficients can vary quite considerably with Reynolds number¹⁵; therefore, it is important to know the effect of Reynolds number on profile drag when analyzing the drag data. The profile-drag coefficient, which consists of skin-friction drag, pressure (form) drag, and interference drag, can be expressed as

$$C_{D_p} = C_{D_{min}} + \Delta C_{D_p}$$

where ΔC_{D_p} is the incremental change in profile drag due to lift. In a two-dimensional airfoil test, where there can be no induced drag, ΔC_{D_p} represents all the drag due to lift. For the biplane-winglet configuration tested, it was necessary to determine the relationship between the incremental profile drag and the lift coefficient at the test Reynolds number of 510,000. This was done by studying the experimental results of Ref. 9, which were obtained from tests on a two-dimensional biplane configuration utilizing symmetrical airfoils.

Drag polars for the model were considered next. Figures 4 and 5 show experimental and theoretical drag polars for both configurations. The symbols represent experimental data. The theoretical curves, which include viscous and inviscid drag, were computed from

$$C_D = C_{D_{min}} + \Delta C_{D_p} + C_{D_i}$$

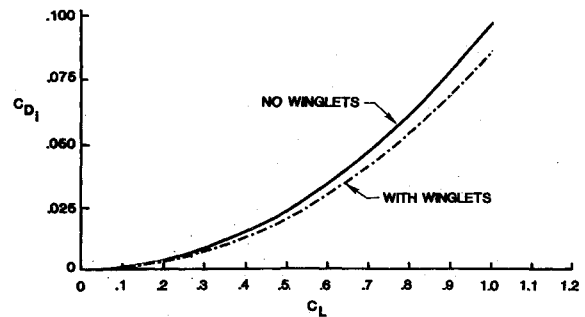


Fig. 6 Theoretically predicted induced drag: $Ga=1.0$, $St=1.0$, $Dec=0$ deg.

Values of $C_{D_{min}}$ were obtained from the experimental data. $C_{D_{min}}$ for the 0 deg decalage no-winglet configuration was experimentally found to be 0.0150; at a full-scale Reynolds number of 6,000,000, $C_{D_{min}}$ would be only 0.007.¹⁶ The experimental data also showed that the presence of the winglets increased $C_{D_{min}}$ by 15–20 counts. Values for ΔC_{D_p} were obtained from Ref. 9. The induced drag coefficient C_{D_i} was predicted theoretically using the vortex-lattice codes.

The relative advantages of the winglets cannot be realized at zero lift, since the configuration with winglets produces additional profile drag. However, as lift increases, the reduction in induced drag caused by the winglets begins to take effect. At lift coefficients beyond 0.4, the configuration with winglets produces less total drag.

Table 1 presents the experimental and theoretical efficiency factors for the various biplane configurations. Theoretical values were calculated using the vortex-lattice codes. Experimental values were determined by first subtracting the incremental profile-drag coefficients of Ref. 9 from the measured drag and then plotting them in the form of C_L^2 vs C_D . The data from Ref. 9 were for symmetrical Joukowski airfoils of 14% thickness at a decalage angle of -6 deg. However, for lack of any better information, this was considered adequate to approximate the correction for the airfoils tested. Some error may be introduced by this method at the higher angles of attack and, in particular, the maximum lift coefficients. The efficiency factors were calculated from the slopes of the C_L^2 vs C_D graphs.

It is common in biplane theory to calculate efficiency factors based on the plane equivalent monoplane aspect ratio (EMAR), which is 3.38 for the configuration tested. The EMAR is a theoretical aspect ratio calculated for the biplane using Ref. 17. This calculation, which takes into account Prandtl's biplane interference factor, assumes equal and optimal load distributions on both biplane wings. Because of the assumptions used in deriving EMAR,¹⁷ it is only a crude measure of relative span efficiency; however, it is used here since no alternate monoplane data were obtained.

For 0 deg decalage, the theoretical efficiency factors were 1.091 and 0.974, with and without winglets, respectively. Thus, the addition of winglets caused an increase in the theoretical span efficiency factor of 12.0%. The experimental efficiency factors were determined using algebraic linear regression. They were 0.991 and 0.870; thus, a 13.9% increase was obtained experimentally.

For the -5 deg decalage case, the theoretical efficiency factors were found to be 1.083 and 1.166, an increase due to the winglet of 7.7%. Experimentally, the values were 0.831 and 0.981, a difference of 12.8%. Therefore, based on experimental results, the addition of winglets increased the span efficiency by approximately 13%. It should be noted that the theory predicts higher span efficiency for the -5 deg decalage configuration, whereas the experimental results show the 0 deg configuration to be larger. These results could be attributed to the approximation for the ΔC_{D_p} correction from Ref. 9 in the theoretical calculations. The important result, however, is the

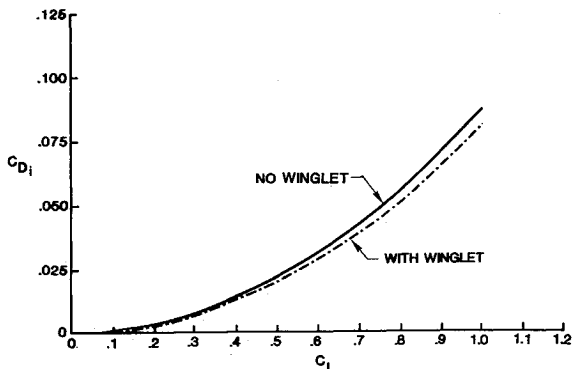


Fig. 7 Theoretically predicted induced drag: $Ga = 1.0$, $St = 1.0$, $Dec = -5$ deg.

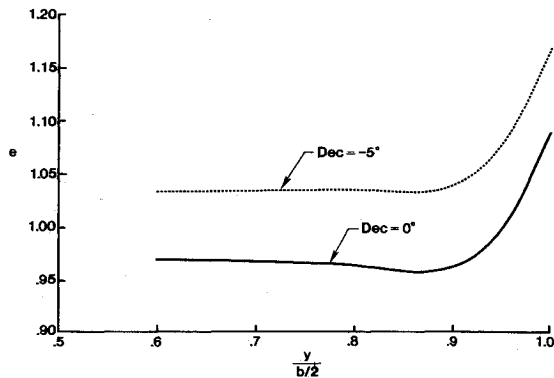


Fig. 8 Biplane efficiency as a function of winglet spanwise position.

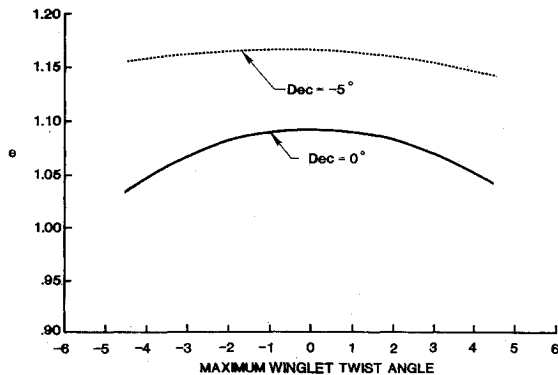


Fig. 9 Biplane efficiency as a function of winglet twist.

increase in span efficiency factor with the addition of winglets in all cases.

The predicted induced drag is shown in Figs. 6 and 7. It is of interest to note that the winglet effect is more pronounced for the 0 deg decalage case than for the -5 deg decalage case.

Parametric Study

Additional theoretical studies were made to study the effect of various winglet geometries on the biplane lifting efficiency and performance. Figure 8 shows the effect of winglet spanwise location on lifting efficiency. The winglet appears to have little effect unless it is located very close to the wing tip. Relative differences in efficiency between the 0 and -5 deg decalage cases appear negligible. No reason for the slight decrease around 0.85 span could be given.

Figure 9 shows the effect of winglet twist. The winglet is toed in (at the maximum twist angle) at the upper wing-winglet intersection and toed out (in the same manner) at the lower

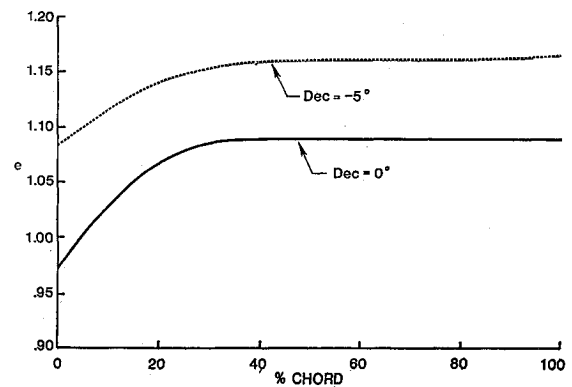


Fig. 10 Biplane efficiency as a function of winglet chord.

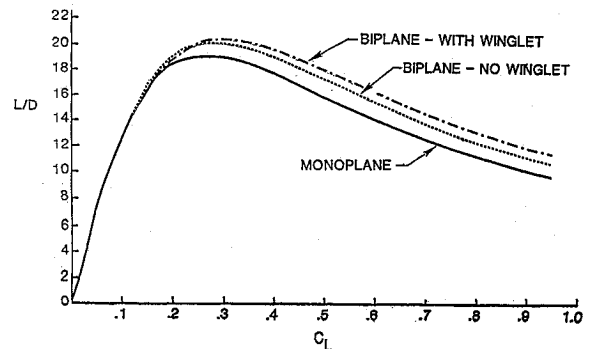


Fig. 11 Biplane and monoplane lift-drag ratios: $Ga = 1.0$, $St = 1.0$, $Dec = -5$ deg.

wing-winglet intersection, with a linear variation of twist occurring in between. For both decalage cases, the optimum twist appears to be zero.

Figure 10 shows the effect of decreasing the winglet planform area with a constant optimum twist angle. Planform area was decreased by stripping away constant chord sections of area at the leading edge of the winglet. The winglet maintains its effectiveness quite well until approximately 70% of its original area is removed. Therefore, in order to minimize skin-friction drag, the winglet should be resized to approximately 30% of its original chord.

Figures 11 and 12 show a theoretical comparison of the aerodynamic performance characteristics of the monoplane and biplane configurations. The biplane utilizes the resized winglet, which has been reduced to 30% of its original size in order to obtain good lifting efficiency while minimizing skin-friction drag. All configurations were analyzed on the grounds of equal planform area and EMAR as previously described. Viscous drag was predicted using the equivalent parasite area method of Ref. 16. This method is not valid with very closely coupled airfoils due to the interactive boundary-layer effects; however, it was considered to be applicable in this case where the gap was equal to one chord length. Inviscid drag was computed using the previously discussed potential flow codes.

Overall, the results indicate improved performance for the biplane. The no-winglet biplane showed a 5.4% increase in L/D_{max} , whereas the biplane with winglets showed a 6.4% increase. The most significant performance improvement, however, was in the classical endurance parameter $C_L^{3/2}/C_D$. The no-winglet biplane showed an 8.1% increase in $C_L^{3/2}/C_D$ over the monoplane, whereas the biplane with winglets showed a significant 12.9% increase. Since the biplane wing configuration was considered to be most applicable to propeller-driven aircraft, no attempt was made to study $C_L^{1/2}/C_D$, the jet range parameter.

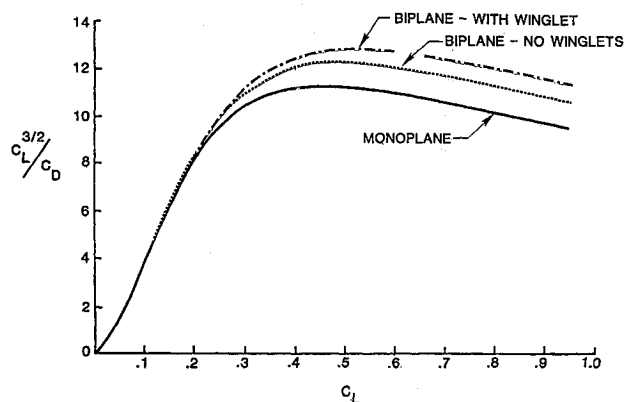


Fig. 12 Biplane and monoplane endurance parameter: $Ga = 1.0$, $St = 1.0$, $Dec = -5$ deg.

It should be understood that no attempt was made to project the results to a complete airplane, or to a full-scale, configuration. The biplane wing was also not optimized from a structural detail standpoint to provide the best overall aerodynamic-strength-weight configuration. The wing model tested had no external struts or bracing wires. The overall minimum drag considering various combinations of these components and the effects of such things as trim drag are topics for possible further study.

Conclusions

This study of the effects of winglets applied to biplanes shows the following:

1) Theoretical computations are in good agreement with experiment in predicting inviscid drag due to lift.

2) Theoretical and experimental results indicate that the addition of winglets to an optimized biplane configuration can increase the ideal efficiency factor by up to 13%, as well as increasing the lift-curve slope and maximum lift coefficient.

3) A theoretical analysis comparing the biplane with an optimized winglet to an equivalent monoplane indicates that the biplane has the potential for a 6.4% increase in L/D_{\max} and a 13% increase in $C_L^{3/2}/C_D$, the classical endurance parameter.

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