The Effect of Winglet Twist and Toe Angle on the Drag of a High Aspect Ratio Wing

1986

Thomas T. Moore
University of Central Florida

Find similar works at: https://stars.library.ucf.edu/rtd

University of Central Florida Libraries http://library.ucf.edu

Part of the Engineering Commons

STARS Citation

https://stars.library.ucf.edu/rtd/4983

This Masters Thesis (Open Access) is brought to you for free and open access by STARS. It has been accepted for inclusion in Retrospective Theses and Dissertations by an authorized administrator of STARS. For more information, please contact lee.dotson@ucf.edu.
THE EFFECT OF WINGLET TWIST AND TOE ANGLE ON THE DRAG OF A HIGH ASPECT RATIO WING

BY
THOMAS THORPE MOORE
B.S.A.E., University of Alabama, 1976

RESEARCH REPORT
Submitted in partial fulfillment of the requirements for the Master of Science in Engineering in the Graduate Studies Program of the College of Engineering University of Central Florida Orlando, Florida

Fall Term
1986
ABSTRACT

Winglets have been shown to significantly reduce the lift induced drag. Different parametric studies have identified important winglet characteristics, but none have examined effects on drag from varying winglet twist and toe angle. The purpose of this research report is to examine the drag reducing effect of winglet twist and toe angle on a transport type high aspect ratio wing.

By using a cost-effective three dimensional vortex-lattice program which included two dimensional profile drag, the effect of winglet twist was found to have a moderate drag reduction against an untwisted winglet for the same toe angle. For the wing-winglet configuration studied, a minimum total drag was obtained when the winglet has 2.8 degrees toe out and 2.5 degrees wash-in twist.

A more sophisticated computer program was used to find areas of boundary layer separation, which were evident from the output results. If the winglet has a large enough toe out to prevent interference drag caused by separated flow at the wing-winglet juncture, winglet twist can be varied to reduce the total drag compared to an untwisted winglet.
TABLE OF CONTENTS

LIST OF FIGURES ........................................ iv
SYMBOLS ..................................................... v
CHAPTER
  I.  INTRODUCTION ....................................... 1
  II. WINGLET STUDIES FOR DRAG REDUCTION .............. 3
  III. APPROACH ........................................... 11
  IV. DISCUSSION OF RESULTS .............................. 18
  V.  CONCLUSIONS ......................................... 31
LIST OF REFERENCES ...................................... 32
LIST OF FIGURES

1. Elliptic Lift Distribution .......................... 4
2. Winglet .............................................. 5
3. Vortex-Lattice Simulation of Swept Wing .......... 12
4. Drawing of Winglets and Semi-span Wing-Winglet Model ............................................. 16
5. Range of Twist and Toe Angles Studied .......... 19
6. Effect of winglet Twist and Toe Angle on Total $C_D$ .................................................. 21
7. Minimum Total $C_D$ for Untwisted and Optimally Twisted Winglets at Various Toe Angles .... 22
8. Effect of Winglet Twist at Optimum Toe Angle on Minimum Total $C_D$ ................................ 24
9. Effect of Optimum Twisted and Untwisted Winglets on Span Loading (Winglet Data in Wing Plane) .................................................. 26
SYMBOLS

Force data has been reduced to coefficient form on the basis of the planform area of the wing, except for the normal force coefficient. All dimensions are in feet, pounds, or seconds.

b  wing span  
c  local chord, feet  
c_{av}  average chord of wing  
C_{D}  drag coefficient, \( \text{Drag} / (q*S) \)  
C_{Df}  skin friction drag coefficient  
C_{Di}  lift induced drag coefficient  
C_{Do}  profile drag coefficient, \( C_{Df} + \text{pressure drag} \)  
C_{Dt}  total drag coefficient, \( C_{Di} + C_{Do} \)  
C_{l}  section lift coefficient, normal to surface, of section normal to surface quarter chord line  
C_{L}  lift coefficient, \( \text{Lift} / (q*S) \)  
C_{n}  section force coefficient, normal to surface, of section parallel to free-stream flow  
MN  Mach number  
q  free-stream dynamic pressure, pounds/feet\(^2\)  
Re  Reynolds number  
S  wing area, feet\(^2\)  
x  distance along chord line, measured from leading edge, feet  
y  distance along wing semi-span, measured from centerline, feet  
*  multiplication
CHAPTER I

INTRODUCTION

Since the oil embargo of the early 1970s, the aerospace industry has emphasized increasing the fuel-efficiency of existing and future transport aircraft. One way to accomplish this is to reduce the drag of the aircraft while maintaining the same weight-carrying capabilities. Whitcomb (1) found that by attaching small wings, or winglets, to the wing tips and orienting the winglets nearly vertical, the lift induced drag of transport type wings could be reduced up to 20 percent.

Subsequent theoretical and experimental studies (2-18) have fine-tuned winglet designs for existing and future transports with varying degrees of success. Researchers have found that a wing which has more of the lift distribution near the tip (tip loaded) has a higher potential for drag reduction from winglets. Computer analysis and design programs, wind tunnel experiments and flight tests were used in these studies to develop the winglet with the greatest drag reduction by varying winglet sweep, taper ratio, size, toe angle and cant angle parameters. Since computer time is so much cheaper than wind tunnel experiments or flight tests, most of the
parametric studies have been done computationally. The design programs (2,3,5,7) were used to twist the winglet for minimum drag due to lift, or induced drag, for each parameter change, and the analysis programs (3,5,16,18) were used for induced drag computations where winglet twist was not examined along with the other parameters.

The purpose of this research report is to examine on a high aspect ratio wing-winglet configuration the drag reduction effect of winglet twist and toe angle. Since there is a wealth of data about the Boeing KC-135 aircraft fitted with winglets and because of the proven benefits of winglets on this tip loaded wing, a wing-winglet configuration similar to the KC-135 was chosen as the base line for this study.
CHAPTER II

WINGLET STUDIES FOR DRAG REDUCTION

Whitcomb (1) found that to be fully effective, winglets must efficiently produce significant side forces, unlike end plates which reduce lift induced drag, but have high viscous and interference drag. To efficiently produce the side force, the winglet itself must produce a high "lift" to drag ratio \( \frac{L}{D} \), considering both winglet-induced drag and profile drag. An elliptical lift distribution, shown in Figure 1, gives the least induced drag (19). To obtain a lift distribution close to elliptic, wings are usually tapered and twisted along the span.

Whitcomb (1) used winglets, shown in Figure 2, with large winglet root to tip chord length ratio, or taper ratio, without winglet twist. By adjusting the winglet incidence angle, or toe angle, with respect to the local flow induced by the wing tip vortex, Whitcomb was able to determine the optimum side load for minimum drag. No aerodynamic theories were available which included the drag caused by the viscous boundary layer, termed profile drag \( C_{D_0} \), as well as induced drag, so these experiments were accomplished by wind tunnel experiments. With positive toe angle being defined as the leading edge of the winglet root.
Figure 1. Elliptic Lift Distribution.
Figure 2. Winglet.
chord closer to the wing center line than the winglet root trailing edge, Whitcomb found that the greatest reduction in drag occurred at a negative 4 degrees toe angle, or 4 degrees toe out.

Whitcomb (1) also maintained that although substantial winglet twist would be required to obtain the desired winglet span load in undistorted flow (no wing tip induced flow), the wing tip vortex would provide local flow at the winglet which would effectively give the winglet the correct aerodynamic twist. Thus, no geometric twist would be required. The present research report examines the validity of this hypothesis.

Cary (2) used a non-planar lifting surface theory to parametrically study winglet effects. The trends for drag reduction agreed reasonably well with Whitcomb's work, verifying the validity of the theory. But the actual values of drag did not match wind tunnel experiments because the theory did not include profile drag. One area of disagreement in the parametric study versus wind tunnel experiment was the optimum toe angle. Because Cary's study took into account only induced drag and neglected profile drag, the optimum toe angle was positive 3 degrees, whereas Whitcomb found the optimum was negative 4 degrees.

As a lifting surface increases in angle of attack, the lift increases almost linearly near lift coefficients of transport aircraft at cruise conditions. The induced drag
increases proportionally to the square of the lift, but the profile drag of a wing also increases because of changes in the boundary layer transition point (from laminar to turbulent flow). This effect on drag is neglected in many cases because at cruise lift coefficients, induced drag changes more than profile drag for a small variation of lift (21). By ignoring profile drag, a theory which computes only the lift induced drag will result in a winglet optimum toe angle more positive than a real flow experiment optimum toe angle. This is why any study which neglects profile drag would not completely predict the total drag reduction capabilities or optimum design parameters for a winglet.

Boeing (3) thoroughly studied winglets with computer codes which performed different functions in the design process. The initial parametric studies were accomplished using a mean camber line vortex-lattice simulation which changed the winglet twist to obtain minimum induced drag during a computer run. This resulted in the minimum induced drag for a set of winglet parameters. After the winglet was optimized for all parameters and a winglet design was chosen, a three-dimensional potential flow analysis of the wing-winglet surfaces was made on the final design to compute detailed pressure data. This pressure data was used in a two dimensional viscous flow computer code to obtain the profile drag on the winglet, whereas the wing profile drag was estimated from wind tunnel test data.
Boeing's method compared favorably to wind tunnel data, but like Cary's study, profile drag was not included in the design process. Although the wing-winglet angle of attack was less than the wing alone for the same lift, resulting in slightly less wing drag, the increase in wing tip profile drag due to increased wing tip lift coefficients caused by the winglet were not considered. Instead a drag increment was used from wind tunnel data for a wing alone, which was loaded differently than the wing on the wing-winglet combination. Additionally, as the winglet twist is changed the winglet profile drag will change due to changing loads on the winglet. Therefore, though profile drag was examined in this study, and the study correctly predicted the drag of a specific design, the design of the winglet utilized only induced drag optimization, with profile drag being used only in a final analysis of this wing-winglet combination.

Conley (4) did extensive studies of winglet toe angles for a transonic business jet. He found through wind tunnel and flight tests that a winglet with 2 degrees toe out resulted in the greatest drag reduction at cruise conditions. But, through flow visualization techniques with wind tunnel oil flow and flight test tuft studies, Conley showed that an area of flow separation at the wing-winglet root existed, which was a factor in deciding to increase the winglet toe out angle to 5 degrees. These tests confirmed
Whitcomb's theory that toe out of a few degrees reduced total drag more than toe in or zero toe angle. But the winglet was twisted only 1 degree, without a study of the combined effects of toe angle and twist.

Later studies of the KC-135 (6,10-15) and the McDonnell Douglas DC-10 (7-9,14) winglets were of winglets of varying toe angles, but no twist. This lack of winglet twist was probably due to Whitcomb's hypothesis that winglet twist has a negligible effect on drag reduction.

Until recently studies of the incident effects (toe angle and twist) of winglets have been accomplished by testing designs in wind tunnels, in flight tests or by computational methods which only modeled lift induced drag. But by including profile drag in a winglet study, Asai (22) was able to computationally make deductions more like real flow tests results than previous computational efforts. He compared winglets to wing tip extensions on an unswept rectangular wing using an induced drag comparison and an induced plus profile drag comparison. Asai chose to make the wings and winglets simple to isolate the parametric studies, so the results cannot be used for decisions about swept transonic winglet versus wing tip extensions. But the study did show that when profile drag was added to induced drag computed by vortex-lattice theory the optimized winglet parameters could be quite different than winglets designed with just minimizing induced drag as done
in previous studies. The research conclusively showed that considering profile drag as well as lift induced drag is necessary when using computational methods to design winglets.
CHAPTER III

APPROACH

For reasons of economy and simplicity, a cost-effective three dimensional wing aerodynamics program by Kuhlman (23,24) was chosen as the main tool for this study. This program (24), called OWDCVIE for "optimum wing design code, viscous included, extended," uses a three dimensional vortex-lattice simulation of a lifting surface mean camber line. Potential flow theory and the Biot-Savart law are used to solve the linear Laplace's equation subject to flow tangency boundary conditions in the wing and winglet planes. A vortex-lattice simulation, shown for a wing in Figure 3, divides each lifting surface into a number of panels. Each panel is modeled by a discrete "horseshoe" vortex, consisting of a finite bound vortex and two semi-infinite trailing vortices. Flow tangency to the lifting surface is satisfied at control points located on each panel. The vortex strengths are solved simultaneously by the flow tangency boundary condition at the control points. Lift and induced drag are obtained from integrating vortex strengths along the span. Using a vortex-lattice code initially developed by Luckring (25), Kuhlman modified the code to allow discontinuous changes in chord (as might occur
Figure 3. Vortex-Lattice Simulation of Swept Wing.
at a wing-winglet juncture) and allow correct induced drag calculations for planforms which do not extend to the configuration centerline (winglets).

Kuhlman obtained the total drag ($C_{Dt}$) for a configuration by the addition of the induced drag computed by the vortex-lattice model and the profile drag. OWDCVIE used an iterative optimization subroutine which changes the lifting surface twist to obtain minimum $C_{Dt}$ for design purposes, but for this analysis, the subroutine was removed to analyze the effects of specific winglet toe and twist angles.

Since three dimensional viscous boundary layer effects are difficult to model (20) without using a code which is costly to operate, Kuhlman chose to use the method of Nash and Tseng (26). Using this method, OWDCVIE computes a wing boundary layer wake momentum thickness pressure drag normal to a surface leading edge by subtracting skin friction drag ($C_{Df}$) (20) normal to the surface leading edge from experimental two dimensional airfoil profile drag data. This experimental data is input by the user at a given Mach number (MN), various effective Reynolds numbers (Re) (24) and lift coefficients ($C_1$). Experimental data usually has a wide enough range of $C_1$ to cover all the expected wing span-station section $C_1$ for a transport wing-winglet configuration at cruise conditions. But the wide range of effective Re affecting transport type configurations
(1 x 10^6 to 30 x 10^6 for the KC-135 wing-winglet configuration in Whitcomb's tests) is difficult to duplicate experimentally. If a reliable two dimensional airfoil analysis code were available, profile drag data could be obtained at a wide enough range of Re to use in OWDCVIE.

Once the normal boundary layer momentum thickness pressure drag is computed, the free-stream component of the pressure drag is added to the skin friction drag in the freestream direction, resulting in the profile drag of a wing span-station section. Integrating this profile drag over the entire span of the configuration gives the configuration profile drag. Interference drag is neglected in this code because three dimensional boundary layer separation effects cannot be modeled. Since no supersonic shock waves are modeled by this method, the free-stream MN for this research was maintained at 0.73. According to wing sweep theory (26), this would result in a MN of 0.6 normal to a configuration constant quarter chord sweep of 35 degrees. This swept MN is small enough that no shock induced boundary layer separation occurred on the airfoil (27) used in this research.

The experimental two dimensional data used in this research (27) was obtained at a MN of 0.6 with Re ranging from 3 x 10^6 to 25.6 x 10^6. This Re range limited the wing root to winglet tip ratio to less than 4.25. A ratio of 3.51 was chosen to assure staying within the allowable Re
range. Boeing research (3) found that a winglet span to wing semi-span ratio of 0.15 resulted in a good trade-off between drag reduction and aircraft weight increase due to wing structure strengthening from an increased wing root bending moment. Whitcomb (1) recommended a large winglet taper ratio, but the recommended taper ratio was not obtained due to the Re limitation.

The wing-winglet configuration used is shown in Figure 4. This transport type wing has a high aspect ratio (7.66) and medium sweep angle, with no twist along the span. The winglet sweep at the constant quarter chord line is the same as the wing, and the winglet is varied in toe angle and twist for each test case.

To obtain detailed results at the wing tip, where the winglet has the most effect on the local flow, the spanwise variation of trailing vortices in the vortex-lattice model is varied according to

\[
y/(b/2) = \sqrt{X/15 + 0.1} - \sqrt{0.1} \over \sqrt{1.1} - \sqrt{0.1}
\]

where \(0 \leq X \leq 15\) and \(X\) changes in increments of one. This created a vortex-lattice where the trailing vortices were closer at the wing tip than at the wing root. Winglet modeling was accomplished with seven equally spaced trailing vortices. Ten bound (chordwise) vortices were used along the chords of both the wing and the winglet. It was
Figure 4. Drawing of Winglets and Semi-Span Wing-Winglet Model.
determined that increasing the density of bound vortices to 15, as recommended by Lamar (28), increased the computer code run time without much change in wing-winglet drag characteristics.

Following the parametric study of winglet toe angle and twist, Rosen's (29) fully transonic, three dimensional winglet analysis program was used to examine local flow for regions of supersonic flow and boundary layer separation not computed by OWDCVIE. Rosen's program solves a modified transonic small-disturbance potential flow equation where the actual surface, not the mean camber line, is modeled in a Cartesian grid for the wing and a cylindrical grid for the winglet. Because terms are retained from the full potential equation for transonic modeling and to allow for cross flows in the x-y plane, the flow equation is not a linear Laplace's equation like OWDCVIE, but a nonlinear equation. Pressures from this potential flow solution are then used in a two dimensional turbulent boundary layer analysis to predict boundary layer separation as well as $C_{Dt}$. Since this code uses 1.5 hours of IBM 4381 computer processing time versus two minutes for the OWDCVIE code, its use was limited to analysis of the wing without a winglet and the wing-winglet configurations which were computed to have the least total drag from OWDCVIE results.
CHAPTER IV

DISCUSSION OF RESULTS

This discussion is limited to small twist and toe angles, as shown in Figure 5. Extreme values of toe and twist angles were not examined since the purpose of this research was for finding the effects of these parameters on minimum drag. Extreme values would cause large regions of local flow separation, which OWDCVIE cannot simulate.

Toe angles were measured from the free-stream flow direction to the winglet root chord line. Positive angles corresponded to a positive angle of attack, or, the winglet root chord leading edge closer to the configuration centerline than the trailing edge. Twist angles were measured from the winglet root chord line to the winglet tip chord line. Positive angles corresponded to wash-in, or, the leading edge of the winglet tip chord closer to the configuration centerline than the root leading edge. Linear lofting is used by OWDCVIE along the winglet span, which is more representative of wing manufacturing techniques.

All research was done at a free-stream MN = 0.73 and configuration lift coefficient $C_L = 0.5$, parameters which are similar to values used in other transport wing-winglet configuration studies (1-18). For the effective section Re
Figure 5. Range of Twist and Toe Angles Studied.
to be within the limits of experimental two dimensional airfoil data (27), the free-stream Reynolds number was set at \(1.25 \times 10^6\) per foot. This set the winglet tip effective Re at \(3.4 \times 10^6\) and the wing root effective Re at \(24.6 \times 10^6\), as computed by OWDCFIE.

For this research, toe angle was held constant for a specific range of twist (Figure 5) to obtain values of \(C_{Dt}\) versus twist, as shown in Figure 6. Initially, twist was changed using increments of two degrees. Once the general curve shape was established, the increment was reduced to 0.2 degrees for the region within two degrees of the estimated minimum \(C_{Dt}\). From this finer increment, the minimum \(C_{Dt}\) could be determined. The constant toe angle value is under the corresponding plotted curve. Each of the curves display similar parabolic characteristics. For each constant toe angle, as the winglet is twisted at varying increments, \(C_{Dt}\) steeply decreases to a minimum value. For a specific toe angle, winglet twist can have an effect on reducing the drag of a configuration.

The locus of the minimum \(C_{Dt}\) for the range of toe angles examined is depicted in Figure 7. Values for an untwisted winglet with varying toe angle is shown for comparison. For the twisted winglet the minimum drag varies with toe angle. From the locus plot it can be seen that there is one toe angle with lesser \(C_{Dt}\) than any other. The degree of \(C_{Dt}\) variance with toe angle for an optimally
Figure 6. Effect of Winglet Twist and Toe Angle on Total $C_D$. 

[Graph showing the effect of twist and toe angle on $C_D$.]
Figure 7. Minimum Total $C_D$ for Untwisted and Optimally Twisted Winglets at Various Toe Angles.
twisted winglet is less than Figure 6 because each toe angle case in Figure 7 has already been twisted to the minimum $C_{Dt}$. The untwisted winglet curve shows that if a winglet twist is held constant, $C_{Dt}$ can vary with toe angle to a large extent. From Figure 7, it can be determined that for an optimally twisted winglet for this wing-winglet configuration, a toe angle of -2.8 degrees results in the minimum total drag. The untwisted winglet needs a toe angle of -1.7 degrees to reach a minimum total drag.

To find the exact value of twist for minimum drag with the winglet toe angle of -2.8 degrees, the winglet was again examined using OWDCVIE. Figure 8 shows the results. The twist angle with the least $C_{Dt}$ was 2.5 degrees wash-in, which is opposite conventional wing design practices (30).

Because of vortex flow around the front part of the wing tip not covered by the winglet root, the winglet root will be at a higher local angle of attack than if this vortex flow did not exist, as would be the case at the root of a wing tip extension. From the Biot-Savart vortex law (30), where the velocity induced on a point is proportional to the inverse of its distance from a vortex filament, the wing tip vortex flow has less influence on the local angle of attack of a span section near the winglet tip than the winglet root. Whitcomb (1) states this when he says that "the decrease in inflow with increase in winglet height above the wing approximately provides the desired
Figure 8. Effect of Winglet Twist at Optimum Toe Angle on Minimum Total $C_D$. 

$C_D$ vs. Twist (Degrees)

-2.8° Toe Angle
aerodynamic twist." If a winglet has a negative toe angle to prevent high local angles of attack at the winglet root sections, the influence of the wing tip vortex flow does cause an effective "aerodynamic twist" to a winglet. But this "twist" may not be the optimum for a specific toe angle to obtain the minimum $C_{Dt}$, as seen in figures 6 and 8. For this configuration, comparison of the untwisted winglet minimum $C_{Dt}$ in Figure 7 and the optimum design determined from Figure 8 shows very little difference in drag values, since interference drag is neglected.

Figure 9 shows the span loading, or lift distribution, along the span of the configuration. The loading along the winglet span is depicted on the end of the wing span by rotating the winglet spanwise axis down to the wing spanwise axis. By adding winglets, the lift along approximately the first 80 percent of the wing span is reduced and is increased from 80 percent of the wing span to the wing tip. The untwisted winglet (-1.7 degrees toe angle) has more of the winglet lift distribution inboard towards the root than the twisted winglet (-2.8 degrees toe angle, +2.5 degrees twist), resulting in a slightly higher $C_{Di}$ and $C_{Dt}$, as shown in Table 1.

These two optimum winglets were examined in Rosen's program (29) for boundary layer flow separation regions that cannot be simulated in OWDCVIE. Figure 10 shows the point on the local chord where flow separation occurs along the
Figure 9. Effect of Optimum Twisted and Untwisted Winglets on Span Loading (Winglet Data in Wing Plane).
<table>
<thead>
<tr>
<th>TOE ANGLE</th>
<th>TWIST ANGLE</th>
<th>$C_{D_i}$</th>
<th>$C_{D_t}$</th>
<th>REDUCTION IN DRAG (COMPAARED TO WING WITHOUT WINGLET $C_{D_t}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wing without Winglet</td>
<td>.01070</td>
<td>.01876</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>-1.7°</td>
<td>0°</td>
<td>.00886</td>
<td>.01778</td>
<td>5.22 %</td>
</tr>
<tr>
<td>-2.8°</td>
<td>2.5°</td>
<td>.00885</td>
<td>.01776</td>
<td>5.33 %</td>
</tr>
<tr>
<td>-2.8°</td>
<td>0°</td>
<td>.00893</td>
<td>.01782</td>
<td>5.01 %</td>
</tr>
<tr>
<td>-4°</td>
<td>4°</td>
<td>.00888</td>
<td>.01778</td>
<td>5.22 %</td>
</tr>
<tr>
<td>-4°</td>
<td>0°</td>
<td>.00906</td>
<td>.01793</td>
<td>4.42 %</td>
</tr>
<tr>
<td>-6°</td>
<td>8°</td>
<td>.00891</td>
<td>.01781</td>
<td>5.06 %</td>
</tr>
<tr>
<td>-6°</td>
<td>0°</td>
<td>.00940</td>
<td>.01826</td>
<td>2.67 %</td>
</tr>
</tbody>
</table>
Figure 10. Effect of Optimum Twisted and Untwisted Winglet on Boundary Layer Separated Flow Region (Winglet Data in Wing Plane).
span of the configuration, with the winglet span being depicted the same as in Figure 9. This program poorly predicts drag values when there exist large regions of separated flow, but it can still be used to predict where separation occurs. Without a winglet, the flow separates on the wing at around 93 percent of the local chord along the span. Local vortex flow at the wing tips reduces the separated flow region on the outer portion of the wing. With the untwisted winglet, the flow separation region is quite large on the wing tip and winglet root areas, or, the wing-winglet juncture. This would cause a larger increase in the drag than predicted by OWDCVIE (21).

Comparing the twisted winglet to the untwisted winglet in Figure 10, the separated flow region is reduced in the wing-winglet juncture because of the decreased section lift at the winglet root for the twisted winglet, as shown in Figure 9. Winglet twist can be seen to have very little effect on separated flow.

A sophisticated program, like Rosen's, can be used by a designer to find a toe angle which results in acceptably small regions of separated flow. For this case, a toe angle of between $-4$ degrees and $-6$ degrees would probably reduce the separated flow region to an acceptable amount. This would agree with the toe angle comparative results of Conley (4) and for the KC-135 (13), which found reduced separated flow regions at these toe angles. If these
increased toe out angles decrease the separated flow regions, then winglet twist would have an even greater effect on reducing the total drag over an untwisted winglet, as can be seen in Table 1.
A computational investigation of the effect of winglet twist and toe angle on an aircraft transport type wing has been conducted. Minimum drag considerations have utilized the total drag of a wing-winglet configuration, including viscous boundary layer drag as well as lift induced drag.

A twisted winglet can accomplish a greater drag reduction for a wing than an untwisted winglet at the same toe angle. Whitcomb's suggestion (1) to use an untwisted winglet does not allow for the amount of "aerodynamic twist" imparted on the winglet by local vortex flow. This research shows that to gain the greatest drag reduction from winglets, twist angle should be included in the design process.

Toe angle has a large effect on total drag because of the corresponding local angle of attack of the winglet root. To prevent excessive interference drag from large regions of boundary layer separated flow at a wing-winglet juncture, a sophisticated computer code should be used to examine wing-winglet juncture flow. A less sophisticated, less costly code can then be used to optimize the winglet twist.
LIST OF REFERENCES


