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Effect of Winglets on Performance and Handling Qualities of General Aviation Aircraft

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Recent flight and wind-tunnel evaluations of winglets mounted on general aviation airplanes have shown improvements in cruise fuel efficiency and climbing and turning performance. Some of these analyses have also uncovered various effects of winglets on airplane handling qualities. Retrofitting an airplane with winglets can result in reduced crosswind takeoff and landing capabilities. Also, winglets can have a detrimental effect on the lateral directional response characteristics of aircraft which have a moderate to high level of adverse yaw due to aileron. Introduction of an aileron-rudder interconnect, and reduction of the effective dihedral by canting-in of the winglets, or addition of a lower winglet can eliminate these flying quality problems.

Nomenclature

A = wing aspect ratio, b^2/S
b = wing span, m (ft)
C_D = drag coefficient
C_L = lift coefficient
C_{L_m} = lift coefficient for maximum lift-to-drag ratio
C_ℓ = rolling moment coefficient
C_{ℓ_β} = coefficient of rolling moment due to sideslip, $\partial C_\ell/\partial\beta$, deg^{-1}
C_n = yawing moment coefficient
C_{n_β} = coefficient of yawing moment due to sideslip, $\partial C_n/\partial\beta$, deg^{-1}
$C_{n_{\delta_A}}$ = coefficient of yawing moment due to aileron deflection, $\partial C_n/\partial\delta_A$, deg^{-1}
C_y = sideforce coefficient
C_{y_β} = coefficient of sideforce due to sideslip, $\partial C_y/\partial\beta$, deg^{-1}
e = Oswald's (airplane) efficiency factor, $1/[\pi A(\partial C_D/\partial C_L{}^2)]$
j = $\sqrt{-1}$
$K_{\phi\delta_A}$ = gain constant in ϕ/δ_A transfer function, deg/deg
$(L/D)_{\max}$ = maximum lift-to-drag ratio
M_r = wing-root bending moment, N-m (ft-lb)
S = reference wing area, m^2 (ft^2)
s = Laplace transform operator, $\sigma + j\omega$
T_R = roll mode time constant, s
T_S = spiral mode time constant, s
V = true airspeed, knots
V_m = true airspeed for maximum lift-to-drag ratio, knots
W = aircraft gross weight, N (lb)
W_w = wing structural weight, N(lb)
β = sideslip angle, deg
δ_A = aileron deflection, $(\delta_{A_R}+\delta_{A_L})/2$, deg
ζ_d = Dutch roll mode damping ratio
ζ_ϕ = damping ratio of numerator of ϕ/δ_A transfer function
η_p = propulsive efficiency
σ = real part of Laplace operator
ϕ = bank angle, deg
ω = imaginary part of Laplace operator
ω_d = Dutch roll undamped natural frequency, rad/s
ω_ϕ = undamped natural frequency of numerator of ϕ/δ_A transfer function, rad/s

Subscripts

b = basic (without winglets)
L = left
R = right
w = with winglets

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Introduction

IN an era of fuel shortages and soaring fuel prices, there is a growing interest in reducing fuel consumption of existing and future aircraft. Methods for improving aircraft efficiency are continually being investigated and innovative aerodynamic drag reduction technologies are constantly being sought. The winglet concept appears to offer significant increases in aerodynamic/structural efficiency by reducing aircraft lift-induced drag without overly penalizing wing weight.[1]

The majority of winglet development efforts have been oriented toward modification of existing aircraft in order to enhance their performance and capabilities.[2-7] The effectiveness of a wing tip modification is controlled by the existing aerodynamic and structural characteristics of the configuration. The winglet-induced drag reduction potential is directly influenced by the magnitude of wing tip loading, while structural design of a wing may significantly influence the choice and size of the wing tip device.

Recent tests have examined the effect of winglets on the performance and handling qualities of a light, single-engine general aviation airplane (Fig. 1).[8] Although this plane has a

Fig. 1 Six-passenger general aviation airplane with winglets.

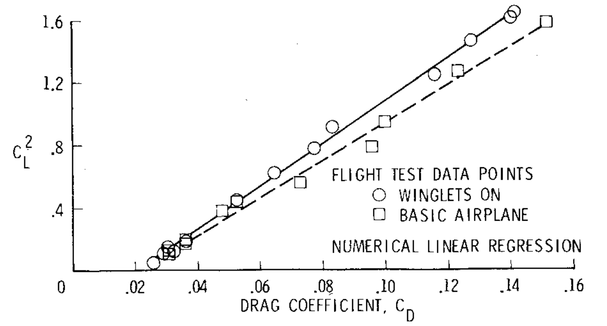

Fig. 2 Influence of winglets on airplane drag for single-engine airplane of Fig. 1.

relatively low wing loading, installation of winglets improves the cruise efficiency and climb and turn performance. The handling qualities of the airplane do not change significantly. However, wind-tunnel and simulator research on an agricultural airplane with and without winglets indicates that a reduced or a reversed aileron roll response may result from winglets due, in part, to the increase in effective dihedral.[9,10]

The stall characteristics of the light single-engine airplane of Ref. 8 appear improved due to winglets. However, the spinning characteristics of aircraft with winglets have not been determined in flight. Rotary balance data obtained with a 0.10-scale model of the agricultural airplane indicate that the spinning characteristics may be unaffected by the relatively large winglets installed on that airplane.[11] Research on the effect of winglets on stalling and spinning characteristics of general aviation aircraft is continuing.

The wing-winglet lifting system design studies which appear in the literature (e.g., Ref. 12) clearly illustrate that the benefits of winglets can be realized only by careful attention to aerodynamic and structural design details. In the end, the justification for use of winglets on an airplane design may hinge on considerations other than reduction of induced drag at the cruise design point.

Agricultural airplanes, for example, may benefit from the effect which winglets can have on the interaction between the airplane wake and the materials dispensed in the wake. Scale-model tests in the NASA Langley Vortex Facility have demonstrated the potential for reduced off-target drift of agricultural chemicals and improved pesticide spray pattern uniformity.[13] On the basis of mission economics and environmental safety, these benefits can justify the incorporation of winglets regardless of any cruise performance benefits. In addition, winglets offer a reduction in the time required to turn around at the end of a swath run. This reduced turn time has a significant effect on the economics of aerial application missions in which as much as 50% of the total flight time may be spent in turns.

A second example of an alternative justification for winglets could be their use for directional stability on a canard configuration.[14] In addition to induced drag benefits, directional stability and control are provided by the winglets. Thus a performance benefit accrues indirectly from the winglet due to the reduction in total airplane wetted area resulting from elimination of a conventional vertical stabilizer surface.

A third example of an alternative justification for winglets might be their use on aircraft which are constrained in gross weight due to the Federal Aviation Regulation Airworthiness Standards for minimum climb performance (FAR 23.65, 23.67, and 23.77). FAR 23.65 discusses the minimum climb performance of aircraft with all engines operating; FAR 23.67 indicates the minimum rate of climb of multiengine aircraft with one engine inoperative; and FAR 23.77 presents the minimum climb performance for balked landings. These climb requirements can constrain the gross weight of single-engine and multi-engine general aviation aircraft. Wind-tunnel tests predict and flight tests have confirmed significant improvements in climb performance due to the decreased induced drag with winglets installed. As a result, winglets may offer sufficient improvement in climb performance to obviate the need for a gross weight reduction to meet the airworthiness requirements mentioned above.

As noted above, winglets can offer the airframe designer an additional tool for meeting certain airplane performance or mission objectives. Careful attention must be directed, however, to the effects which winglets might have on airplane stability, controllability, and stall/spin characteristics. Winglets also affect aircraft structural weight. All of these effects must be accounted for in the winglet design.

Performance

When a wing is retrofitted with wing tip-mounted winglets, the following performance changes will occur:

1) The primary effect of winglets is to reduce the lift-induced drag.

2) The profile drag of the winglets will negate some of the induced drag reduction.

3) The required airplane lift coefficient will be reached at a lower angle of attack than for the wing without winglets (the lift curve slope increased due to an increase in effective wing aspect ratio). The reduced angle of attack will result in a changed configuration profile drag.

4) The interference effect on drag at the wing-winglet juncture may offset some of the induced drag reduction.

5) In the case of a swept wing, the aerodynamic center will shift aft, as would be expected with the more highly loaded wing tips. An increase in trim drag may be the result.

At low lift coefficients, the increase in zero-lift drag due to winglets can offset the decrease in lift-induced drag resulting in a slightly higher drag. The drag polar of a light, single-engine, general aviation airplane (Fig. 1) with and without winglets is plotted in Fig. 2. The crossover, as shown in Fig. 2, occurs at a very low lift coefficient. This is an indication that the wing-winglet juncture is well designed. An improvement in Oswald's efficiency factor of 13% due to winglets is measured.

As a result of the changes in zero-lift drag and Oswald's efficiency factor, the maximum lift-to-drag ratio $(L/D)_{max}$ and the lift coefficient for maximum lift-to-drag ratio C_{L_m} are affected. Based on the parabolic drag polar, $(L/D)_{max}$ increases by 11% with the addition of winglets. However, C_{L_m} changes from 0.51 for the basic airplane to 0.55 for the airplane with winglets. The increase in C_{L_m} produces a decrease in airplane velocity for maximum lift-to-drag ratio V_m from 116 to 111 knots at 1524 m (5000 ft) altitude. Alternatively, increased C_{L_m} requires a higher altitude for maximum fuel economy at a given speed. This latter effect is reflected in Fig. 3 where, at an airspeed of 120 knots, the altitude of peak fuel efficiency increases from 2200 m (7240

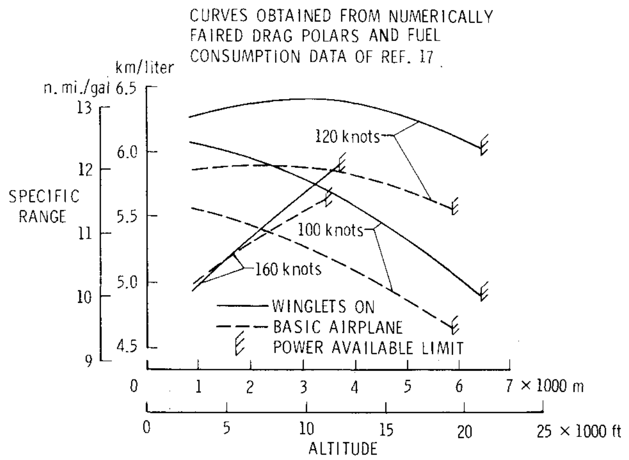

Fig. 3 Effect of winglets on specific range for airplane of Fig. 1 [W = 16,013 N (3600 lb)].

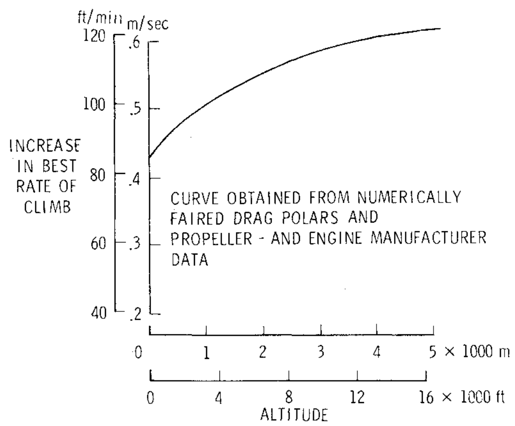

Fig. 4 Predicted increase in best rate of climb due to winglets for airplane of Fig. 1 (W = 16,013 N, $\eta_p = 0.85$).

ft) without winglets to 3050 m (10,035 ft) with winglets. In spite of the slightly lower speed for cruise at maximum lift-to-drag ratio or the higher altitude required for maximum fuel economy at a given speed for the configuration with winglets, the absolute benefit of winglets on fuel economy is significant, as shown in Fig. 3, for all conditions except high speed (160 knots) at low altitudes.

Best rate of climb is obtained while flying at lift coefficient for maximum excess thrust power. Presented in Fig. 4 is a plot which demonstrates the improvement in best rate of climb due to winglets as a function of altitude. This plot is obtained by using the drag polars of Fig. 2 and propeller and engine manufacturer data to compute the increment in climb performance due to winglets. At sea level the increase in best rate of climb is approximately 0.43 m/s (84 ft/min) while at 5000 m altitude the increase is 0.61 m/s (120 ft/min). The increment in best rate of climb results in an increase in service ceiling of approximately 610 m (2000 ft).

A reduction in time to turn 180 deg is generally not important for general aviation aircraft. However, it is highly important for agricultural aircraft. Agricultural aircraft can spend as much as 50% of their flight time in turning at high angles of attack. As means of relative comparison, the calculated minimum time to turn 360 deg is plotted as function of airspeed and power setting in Fig. 5. The curves are based on the drag polars of Fig. 2 and propeller and engine manufacturer data. At sea level and maximum takeoff weight, the reduction in minimum turning time due to winglets will be approximately 8%. In Ref. 15, the important effect of turn time reduction on the productivity of agricultural aircraft is demonstrated.

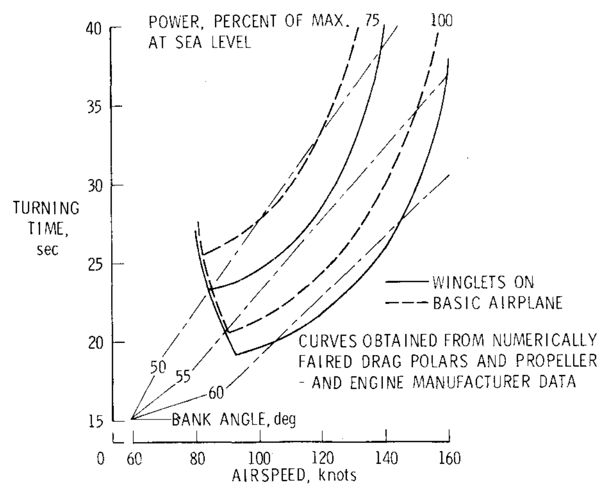

Fig. 5 Steady level turn time at sea level for airplane of Fig. 1 (W = 16,013 N).

Structural Weight

Winglets will increase the wing-root bending moment when added to a wing. References 3 and 16 indicate that structural weight changes are approximately proportional to changes in the wing-root bending moment:

$$(W_w)_w/(W_w)_b \approx (M_r)_w/(M_r)_b$$

Therefore, the wing weight will increase due to winglets for a constant load factor. However, the reduction in mission fuel requirements will partly or completely offset the increase in aircraft empty weight for carefully designed winglets. A comparison of the change in induced drag and the change in wing-root bending moment between tip extensions and winglets is discussed in several publications.[2,3,16] It is shown that, at an identical level of root bending moment, a winglet provides a greater induced drag efficiency increment than does a tip extension. Alternatively, at an identical level of induced drag efficiency, a tip extension generates a greater wing-root bending moment increment than a winglet.

Stability and Control

The influence of winglets on the static and dynamic handling qualities of an airplane can be very significant, as is demonstrated in Refs. 7, 9, and 10. However, for other aircraft, the changes in handling qualities are much less pronounced.[8,18,19] It is important to note that the effect of winglets added to an airplane depends in part on the baseline configuration stability and control characteristics.

Longitudinal

Winglets on an approximately unswept wing should not significantly affect the longitudinal stability and control characteristics of the airplane. The phugoid stability and short-period response will change only slightly.

Lateral-Directional

Major changes may occur in the lateral-directional stability and control characteristics of an airplane due to installation of winglets. Primarily the roll due to sideslip derivative C_{ℓ_β} and the sideforce due to sideslip derivative C_{y_β} will be affected. Both dihedral effect and C_{y_β} will become more stable due to winglets. For winglets on unswept wings, the directional stability C_{n_β} will be virtually unaffected. However, in some cases, winglets reduce the value of C_{n_β}.[7,9] The reduction is probably caused by the forward tilt of the winglet resultant force vector which for a straight wing lies forward of the airplane center of gravity.

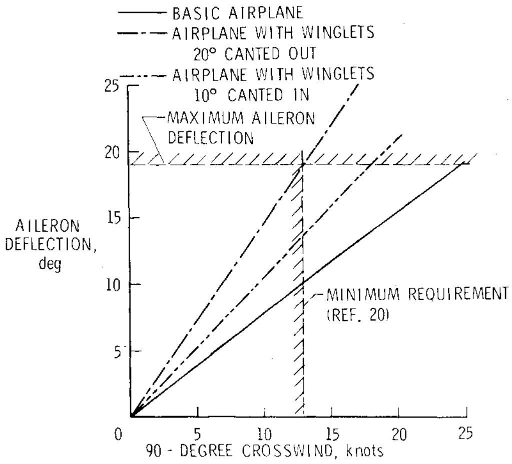

Fig. 6 Aileron required for steady sideslip during final approach for agricultural airplane of Ref. 9.

The increase in effective dihedral will have a significant effect on the lateral-directional control in crosswinds. The effect of winglets on the crosswind capabilities of the agricultural airplane[9] during final approach for landing is indicated in Fig. 6, which shows the aileron required for steady sideslip during final approach with various crosswinds. The large amount of dihedral generated by the 20 deg canted-out winglets greatly reduces the crosswind landing capabilities of the airplane. The airplane in this configuration does not meet the requirements of Ref. 20 which, while not applicable for certification of this airplane, do represent a desirable quality. In Ref. 9, canting-in of the winglets is suggested in order to reduce the effective dihedral. The effects of this modification on the performance of the airplane are minor; however, the crosswind landing performance is improved. The effective dihedral can also be reduced by adding a lower winglet.[7]

Installation of winglets will influence the lateral-directional mode characteristics. In many cases the Dutch roll undamped natural frequency increases slightly while a small reduction of the Dutch roll damping will occur. Both changes are mainly caused by the increase in C_{ℓ_β}. The spiral mode becomes more stable due to the increase in C_{ℓ_β} while the roll mode will be approximately unchanged.

Winglets can critically affect the lateral directional dynamic response characteristics of an airplane. The dynamic response characteristics are stated in terms of response to atmospheric disturbances and in terms of allowable roll rate and bank angle oscillations, sideslip excursions, and control forces that occur during rolling and turning maneuvers. In Refs. 21-23, excellent discussions are presented concerning these problems and criteria are listed. The problem of Dutch roll excitation as it affects roll control is usually studied in terms of the transfer function relating bank angle and aileron deflection:

$$\frac{\phi(s)}{\delta_A(s)} = \frac{K_{\phi_{\delta_A}}\,(s^2+2\zeta_\phi\omega_\phi s+\omega_\phi{}^2)}{(s+1/T_S)\,(s+1/T_R)\,(s^2+2\zeta_d\omega_d s+\omega_d{}^2)}$$

Installation of winglets causes relatively small changes in the angular distance between the Dutch roll pole and the zero. However, the ratio of the radial distances from the origin to the zero and the origin to the Dutch roll pole ω_ϕ/ω_d may change by a large amount representing a deteriorated pilot rating. This is especially true in the case of aircraft with a moderate to high level of adverse yaw due to aileron deflection. In Fig. 7, the locations of the Dutch roll pole and zero are plotted as function of airplane configuration for the agricultural airplane of Ref. 9. For the airplane with winglets canted-out 20 deg the value of ω_ϕ/ω_d is greatly reduced from the winglets-off configuration. As shown in Fig. 7, canting-in

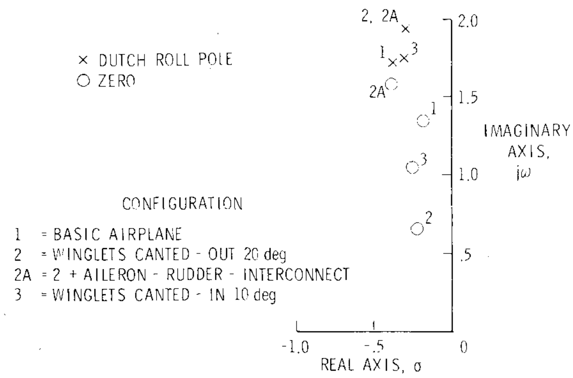

Fig. 7 Predicted location of zero and Dutch roll pole of the ϕ/δ_A transfer function for agricultural airplane.

the winglets will improve the airplane handling qualities. Another solution is reducing the adverse yaw by means of an aileron-rudder interconnect. The location of the zero is shown for the winglets canted-out 20 deg configuration plus aileron-rudder interconnect ($C_{n_{\delta_A}}=0$). It can be seen that the pole and zero move closer together, indicating improved pilot rating.

In Ref. 8, the pilots reported improved flying qualities due to winglets on the single-engine airplane of Fig. 1 (this airplane utilizes an aileron-rudder interconnect). Stalling the forward winglet at high sideslip angles did not change the balance of forces and moments noticeably. The stalled winglet did not induce a separated flow region on the wing upper surface as occurred with the winglet-equipped airplane of Ref. 7.

Stalling Characteristics

Frequently, winglets cause an increase in maximum lift coefficient.[7,9] The stall characteristics of the winglet-equipped airplane of Ref. 8 were slightly improved when compared with the basic airplane. In the case of no sideslip stalls, the basic airplane displayed a tendency to roll off or drop a wing. The winglets appeared to prevent the wing tip from stalling early, thus reducing the tendency to roll off. This resistance to roll off was also exhibited in stalls with moderate amounts of sideslip.

Conclusion

Recent preliminary flight and wind-tunnel evaluations of winglets mounted on general aviation aircraft have shown improvements in airplane performance and indicated both good and bad effects of winglets on airplane handling qualities.

Except when cruising fast at low altitude, winglets will improve airplane fuel efficiency. Airplane climb performance is improved considerably due to winglets and, as a result, the service ceiling of the airplane with winglets will be higher. The maneuverability of the airplane in terms of minimum time to turn 360 deg is upgraded significantly.

Adding winglets to an airplane can result in reduced crosswind takeoff and landing capabilities. Also, winglets have a detrimental effect on the lateral-directional response characteristics of aircraft which have moderate to high levels of adverse yaw due to aileron. Introduction of an aileron-rudder interconnect and reduction of the effective dihedral by canting-in of the winglets or addition of a lower winglet can eliminate these flying quality problems. The effect of winglets on the longitudinal stability and control characteristics will be minor.

Research on the effect of winglets on stalling and spinning characteristics of general aviation aircraft is continuing. Also full-scale spraying tests will be performed to substantiate the predicted beneficial effect of winglets on the spraying pattern of agricultural aircraft.

References

[1] Whitcomb, R.T., "A Design Approach and Selected Wind-Tunnel Results at High Subsonic Speeds for Wing-Tip Mounted Winglets," NASA TN D-8260, July 1976.

[2] Loptien, G.W., "The Effect of Winglets on the KC-135A Aircraft," AFFDL-TR-78-124, Nov. 1978.

[3] Flechner, S.G. and Jacobs, P.F., "Experimental Results of Winglets on First, Second, and Third Generation Jet Transports," NASA TM-72674, May 1978.

[4] Gilkey, R.D., "Design and Wind Tunnel Results of Winglets on a DC-10 Wing," NASA CR-3119, April 1979.

[5] Ewald, B., "Winglets, a Contribution to Aircraft Performance Improvement," DGLR Paper 77-031, Sept. 1977 (in German).

[6] Reynolds, P.T., "The Learjet Longhorn Series—The First Jets with Winglets," SAE Paper 79-0581, April 1979.

[7] Eliraz, Y. and Ilan, D., "Performance of the ARAVA Aircraft with Wing-Tip Winglets," *Israel Journal of Technology*, Vol. 15, 1977, pp. 35-43.

[8] Holmes, B.J., van Dam, C.P., Brown, P.W., and Deal, P.L., "Flight Evaluation of the Effect of Winglets on Performance and Handling Qualities on a Single Engine General Aviation Airplane," NASA TM-81892, Dec. 1980.

[9] Johnson, J.L. Jr., McLemore, H.C., White, R., and Jordan, F.L. Jr., "Full Scale Wind-Tunnel Investigation of an Ayres S2R-800 Thrush Agricultural Airplane," SAE Paper 79-0618, April 1979.

[10] Ogburn, M.E. and Brown, P.W., "Exploratory Piloted Simulator Study of the Effects of Winglets on Handling Qualities of a Representative Agricultural Airplane," NASA TM-81817, April 1980.

[11] Mulcay, W. and Chu, J., "Rotary Balance Data for a Single-Engine Agricultural Airplane Configuration for an Angle-of-Attack Range of 8° to 90°," NASA CR-3311, Dec. 1980.

[12] Shollenberger, C.A., "Application of an Optimized Wing-Winglet Configuration to an Advanced Commercial Transport," NASA CR-159156, Nov. 1979.

[13] Jordan, F.L. Jr., "Development of Test Methods for Scale Model Simulation of Aerial Applications in NASA Langley Vortex Facility," NASA TM-81805, April 1980.

[14] Rutan, B., "Development of a Small High-Aspect-Ratio Canard Aircraft," *Society of Experimental Test Pilots, Technical Review*, Vol. 13, No. 2, Sept. 1976, pp. 93-101.

[15] Hinely, J.T. Jr. and Boyles, R.Q. Jr., "Advanced System Design Requirements for Large and Small Fixed Wing Aerial Application Systems for Agriculture," NASA CR-158939, Jan. 1979.

[16] Heyson, H.H., Riebe, G.D., and Fulton, C.L., "Theoretical Parametric Study of the Relative Advances of Winglets and Wing-Tip Extensions," NASA TP-1020, Sept. 1977.

[17] Anon., "Pilot's Operating Handbook and FAA Approved Airplane Flight Manual for the Beechcraft Bonanza A36 (E-927 and after)," Beech Aircraft Corp., Wichita, Kan., Oct. 1976.

[18] Conley, N.E., "Winglet Toe Out Angle Optimization for the Gates Learjet Longhorn Wing," *Journal of Aircraft*, Vol. 17, Dec. 1980, pp. 851-855.

[19] Crenshaw, K.R., "Stability and Control Characteristics of the Winglet Configured KC-135A," Master's Thesis, Air Force Institute of Technology, Dec. 1976 (Rept. AD-A034940).

[20] Anon., "Military Specification-Flying Qualities of Piloted Airplanes," MIL-F-8785B(ASG), Aug. 1969.

[21] Chalk, C.R., Neal, T.P., Harris, T.M., Pritchard, F.E., and Woodcock, R.J., "Background Information and User Guide for MIL-F-8785B(ASG), Military Specification-Flying Qualities of Piloted Airplanes," AFFDL-TR-69-72, Aug. 1969.

[22] Ellis, D.R., "Flying Qualities of Small General Aviation Airplanes, Part 4," FAA-RD-71-118, Dec. 1971.

[23] Ellis, D.R., "Flying Qualities of Small General Aviation Airplanes, Part 2," FAA-RD-70-65, April 1970.