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Winglet Toe-Out Angle Optimization for the Gates Learjet Longhorn Wing

Norm Conley*
Gates Learjet Corporation, Wichita, Kansas

The Gates Learjet Model 28 Longhorn was the first turbojet to be certified with winglets. It has now been joined by the stand-up cabin Model 55 in applying NASA advanced technology to American business jet aircraft. This paper describes the effect of tailoring toe-out (incidence) angle for best winglet performance. A winglet with little or no twist must be toed out to reduce separation at the root on the upper surface because of the large inflow angles near the upper surface of the wing at the tip. The need for toe out disappears rapidly with radial distance from the chord of the wing tip due to the reduction in local flow angles to freestream flow angles. Results of wind tunnel testing and flight testing will be presented and their relative merits weighed. Some criteria for useful winglet design will be suggested.

Nomenclature

AR	= aspect ratio, b^2/S
b	= span
C_L	= lift coefficient
C_D	= drag coefficient
C_{N_z}	= winglet normal force coefficient
C_l	= rolling moment coefficient
C_n	= yawing moment coefficient
C_y	= side force coefficient
C_t	= tip chord
C_r	= root chord
D	= drag, lb
L	= lift, lb
M	= Mach number
S	= wing reference areas, ft^2
i_z	= winglet toe-out angle (incidence), deg (negative is leading edge out)
α	= angle of attack, deg
δ_A	= aileron deflection, deg
Δ	= increment
Λ_{LE}	= leading edge sweep angle, deg
λ	= taper ratio, c_t/c_r

Background

WINGLET has become the generic term for the special purpose aerodynamic devices that are small, nearly vertical, wing-like surfaces mounted at the tips of a wing. They are intended to provide reductions in drag greater than those achieved by a simple wing tip extension with the same structural weight penalty. Since winglets reduce lift-induced drag, benefits from their use increase rapidly with increasing lift coefficient at subsonic Mach numbers (Fig. 1).

The winglet that works produces a thrust component of lift like the sail on a boat. This results in a forward chord force on the wing tip for higher lift coefficients. Figure 2 illustrates the physics of this process.

Winglets are useful for existing airplanes to increase wing efficiency when complete wing redesign is undesirable or when ground handling is a serious problem which limits wing span. As a general rule, winglets work on highly loaded wings operating at high lift coefficients.

For a given winglet size, parametric studies[1] indicate that the chordwise location of the winglet does not affect significantly lift, induced drag, pitching moment, nor root bending moment; but when set aft, the increased velocities over the inner surface of the winglet are not superimposed on the high velocities over the forward region of the wing upper surface. To reduce interference, the root of the winglet should not be ahead of the upper surface crest of the wing-tip section. Moving the winglet far aft can cause structural problems.

Winglet cant angle (dihedral) is the angle the winglet plane makes with an X-Z plane. Positive cant angle is away from aircraft centerline at the tip of the winglet. Increasing cant angle increases pitching moment and longitudinal stability, reduces wing/winglet interference drag, and increases wing root bending moment.

As winglet area is reduced, the lift coefficient at which the winglet must operate to produce the same benefit limits its minimum size. As winglet area increases, airplane C_{L_α} increases slightly. Pitching moment becomes more negative due to a rotation of the pitching moment curve in the direction of increased stability.

This paper discusses our winglet and a program conducted at Gates Learjet directed toward tailoring winglet toe-out angle for best airplane performance on the Longhorn wing.

Configuration

The airfoil section for the Longhorn winglet was that designed and tested by NASA.[2] The section is a thinned LS(1)0413 [8% t/c opposed to 13% t/c for LS(1)0413]. Whitcomb[2] reported the section provides superior low-speed high-lift characteristics and satisfactory supercritical characteristics. The low shockloss type of airfoil is used on the winglet to improve its efficiency.

The winglet sweep was chosen for esthetic purposes and high Mach number characteristics. The 40 deg leading edge sweep matches the Gates Learjet vertical tail sweep. The winglet sweep improved the airplane static directional stability.

The 6 ft^2 reference area of the winglets placed on the Gates Learjet was chosen from structural considerations. The planform was laid out to give a pleasing shape with a taper ratio low enough to offer weight savings. The trailing edge is of constant thickness to simplify construction. The winglet airfoil twists the leading edge out one degree about its trailing edge during the lower 40% of its span to reduce local flow angle of attack at the root.

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*Group Engineer, Basic Aerodynamics. Associate Fellow AIAA.

Figure 3 illustrates the planform of the Gates Learjet configuration. Flow surveys over wing tips have indicated that local flow angle decreases dramatically with radial distance from the chord of the wing tip.[3] In order to delay winglet root separation to as large an airplane angle of attack as possible a large winglet root nose down camber and/or twist is desirable. This allows the flow at the wing tip to be turned back into the freestream direction over the chord of the winglet. Large twist angles will cause under winglet separation at low airplane angles of attack. Spillman[3] has used a cascade of "tip sails" to reduce this angle effect. A single winglet can be toed out or twisted to accomplish this to a degree. Gates Learjet used both twist (1 deg) and toe out (−2 deg). The initial winglets tested in the low speed wind tunnel had a straight tapered planform. The strake was added to the Gates Learjet design to reduce the amount of twist required at the winglet root and to facilitate the blending of the winglet into the wing through a smooth transition region.

Fig. 1 Model 55.

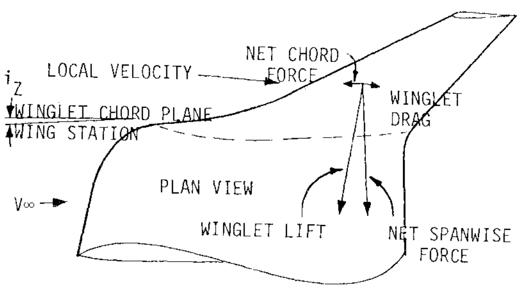

Fig. 2 Winglet forces.

Analysis Method

The effect of toe-out angle on the Longhorn winglet has been tested in the wind tunnel and in flight on an instrumented aircraft. The initial check on the effect of toe out was a test at the Wichita State University low speed wind tunnel.[4] The data from that test provided positive results that led to a decision to start the Longhorn program. High speed wind tunnel tests that measured the effect of toe out, and provided the data in this paper were conducted at the Boeing Transonic Wind Tunnel[5] and at Calspan[6] (Fig. 4). A low speed wind tunnel test that showed the effect of toe-out angle on the Model 28 and 55 was also conducted at the Wichita State University low speed wind tunnel.[7]

Flight tests have been conducted for winglet toe out angles of −2 and −5 deg using the prototype Model 35 with a Longhorn wing.

Range Factor

Last year we reported on the Gates Learjet Model 28/29, the first "Longhorn" Learjet.[8] The range factor improvement on the Model 28 was compared to the tip tank Model 25. Figure 5 was from that report. The increment due to winglets was taken from Fig. 5 and plotted to compare the incremental effect of winglet toe-out angle with the total effect of the winglets. Figure 6 shows the increase in $M(L/D)_{max}$ for the winglets at toe-out angles of −2 and −5 deg. These results, from the wind tunnel, show a reduction in

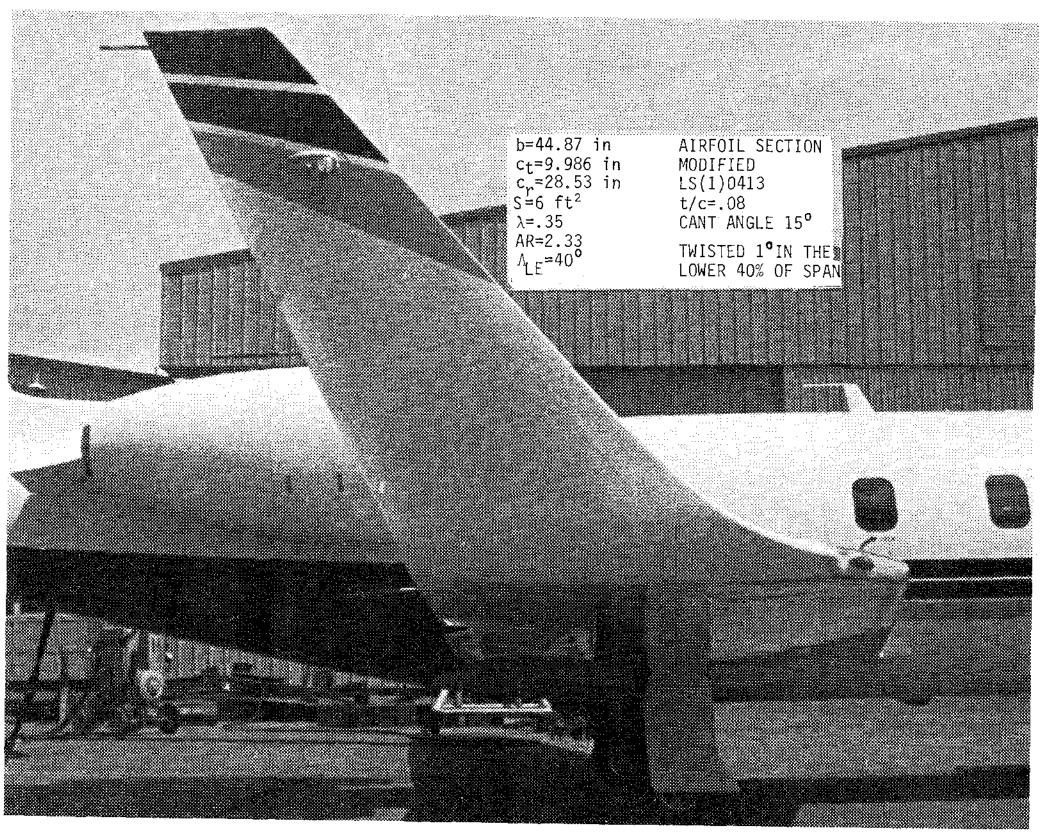

Fig. 3 The "Longhorn" winglet.

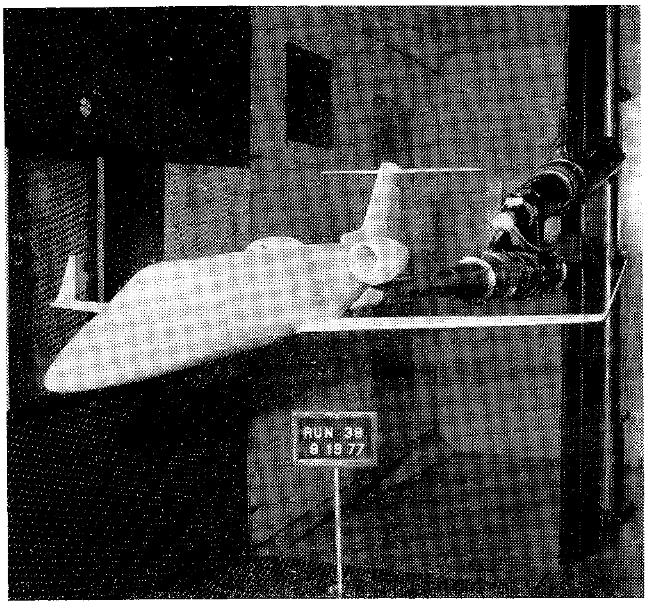

Fig. 4 Model 55 at CALSPAN.

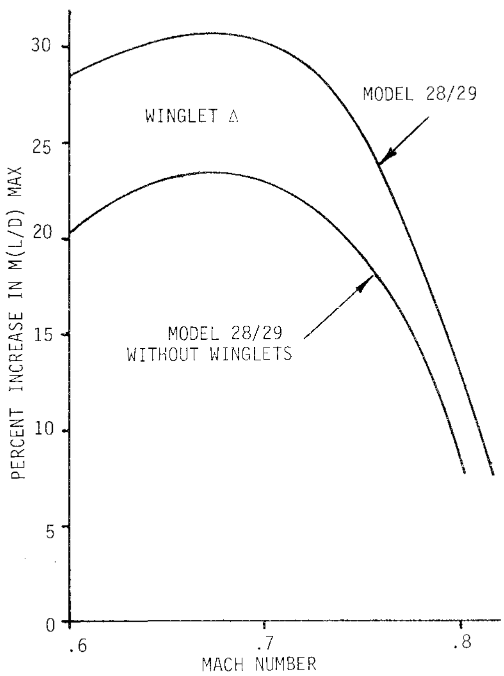

Fig. 5 Range factor improvement over the model 25.

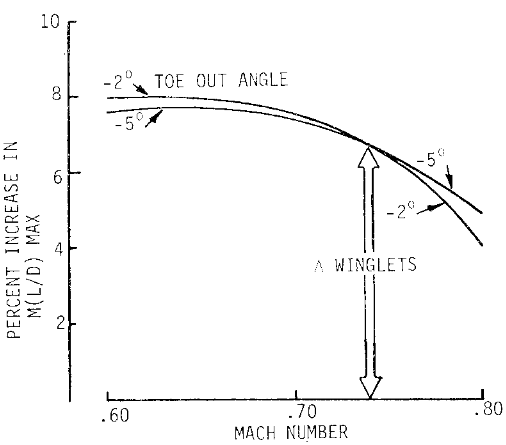

Fig. 6 The effect of winglets and winglet toe-out angle on the range factor of a model 25.

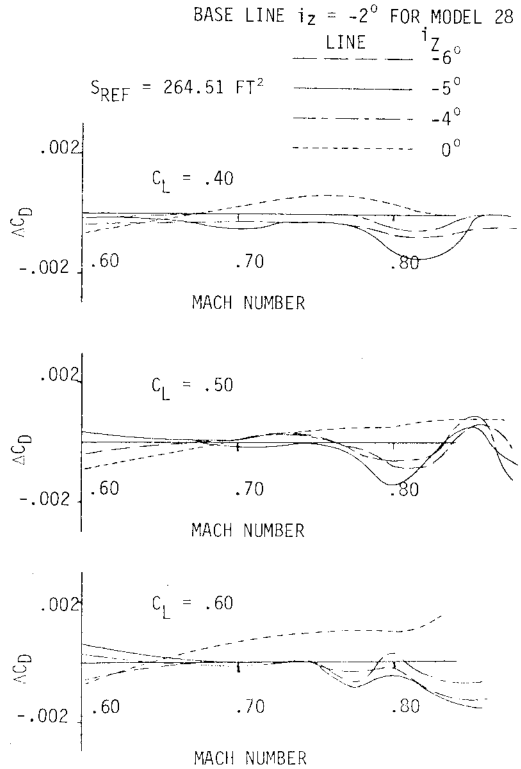

Fig. 7 The effect of toe-out angle on model 28 drag.

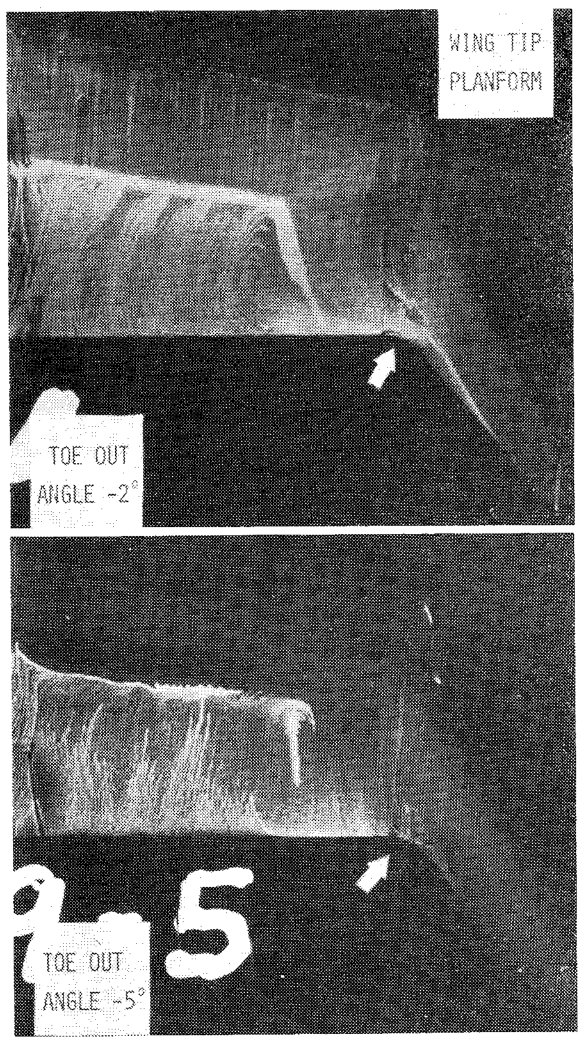

Fig. 8 Oil flow results showing winglet root flow separation at Mach 0.825 and $C_L = 0.4$

Fig. 9 Prototype model 35 with a Longhorn wing.

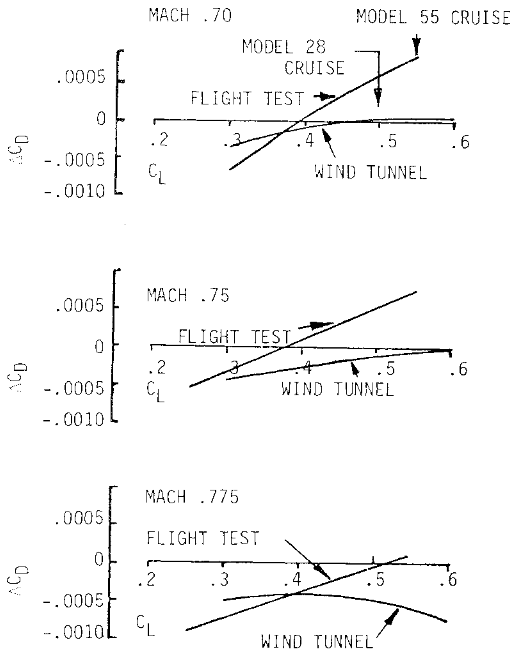

Fig. 10 Incremental drag due to winglet toe out from −2 to −5 deg comparing flight test and wind tunnel test.

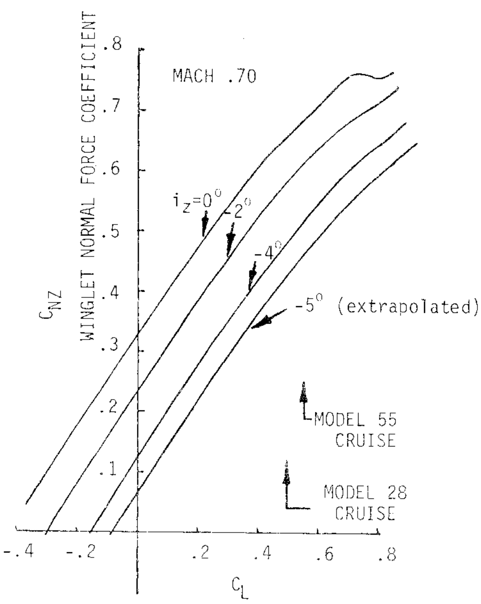

Fig. 11 The effect of toe out on winglet normal force coefficient.

$M(L/D)_{max}$ for a change in toe-out angle from −2 to −5 deg at Mach 0.70 and an improvement in $M(L/D)_{max}$ at Mach 0.80.

Drag from the Wind Tunnel

The effect of winglet toe-out angle on drag of the production Longhorn winglet ($i_z = -2$ deg) is compared to the drag at toe-out angles of 0, −4, −5 and −6 deg and the results are shown in Fig. 7. The data are for constant lift coefficients of 0.40, 0.50 and 0.60 and Mach numbers from 0.60 to 0.875. The drag increments include data scatter, but the data indicate that a small improvement in drag at 0.80 Mach is possible for a change in toe-out angle to −5 deg. This change will cost a small penalty in drag at cruise. The data show the drag penalty for reducing toe-out angle to zero deg. Optimum toe-out angle is a function of both the desired cruise Mach number and the wing loading limits within which the airplane will most often fly.

High speed oil flow data which were taken during the high speed wind tunnel tests show a small amount of separation in the root of the winglet on the upper surface at the wing tip. This area of separation is reduced by toeing out the winglet as shown in Fig. 8. There is no separation in the root of the winglet at cruise Mach number. Video recordings of tufted wings in high speed flight later confirmed these oil flow results.

Flight Test of Toe Out

The effect of winglet toe out was checked in flight on the Gates Learjet prototype Model 35 with a Longhorn wing (Fig. 9). A comparison of incremental drag between flight and wind tunnel test is shown in Fig. 10. A comment made on the flight test data reduction was that a single drag polar could have been extracted from the combined data showing no difference between −2 and −5 deg configurations and still maintain a reasonable data scatter, but −2 deg winglets showed slightly favorable results at cruise when the data was evaluated for the two configurations independently. The trend toward an improvement in performance indicated for higher Mach numbers is like that found in the wind tunnel.

Winglet Load

Toe-out angle unloads the winglet as is illustrated in Fig. 11. These data from the high speed wind tunnel show the

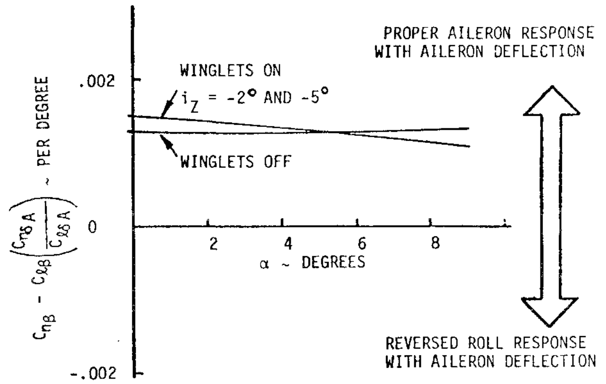

Fig. 12 Effect of winglets on the lateral-directional control parameter of the Longhorn.

reduction in winglet normal force coefficient for various airplane lift coefficients at a Mach number of 0.70. The weight reduction possible from designing for lower winglet loads may offset the cruise drag penalty. These data also show the winglet stalls well before the wing.

No attempt was made to analyze the weight savings that might be achieved by designing for lower winglet loads. The winglet was added to the Learjet at the same time the tip tank was removed and replaced with a six ft tip extension. The structural penalty in the wing for the addition of the winglet was not broken out. Each winglet assembly weighs 22.2 lb. 2.5 lb of that weight is a mass balance near the winglet tip to change structural frequency modes found in the winglet during flight test.

Lateral Directional Control

The winglets on the Longhorn wing increase C_{l_β}/C_{n_β} by about 60% which causes a reduction in dutch roll damping ratio. Toe out has a negligible effect on the magnitude of this factor. The yaw damper does a good job of controlling this motion through the use of the rudder. The pilot can easily control the dutch roll if the yaw damper is turned off.

An indication of potential lateral-directional control problems can be determined from the lateral-directional control parameter for the aircraft with and without winglets. Some winglet configurations exhibit lateral-directional control problems.[9]

The lateral-directional control parameter

$$C_{n_\beta} - C_{l_\beta}\left(C_{n_{\delta_A}}/C_{l_{\delta_A}}\right)$$

is used as an indicator of lateral response to ailerons. If the parameter attains low or negative values, the airplane will roll in a direction opposite to that intended. The Longhorn shows a positive value of this lateral-directional control parameter and the plot in Fig. 12 shows the change in lateral-directional control parameter due to the winglets on the Longhorn wing. We see that for typical cruise angles of attack, the winglets on the Longhorn wing improve the lateral response to ailerons. Winglet toe-out angle had no effect.

Conclusion

Optimum winglet toe-out angle is a compromise between airplane performance, design loads, and stability and control considerations. The results of these toe-out studies lead us to believe that nominal −2 deg toe-out angle on the Longhorn winglet is optimum for maximum airplane performance benefit on the existing wing at the cost of higher winglet loads. A toe-out angle of −5 deg would reduce these loads at a small penalty to maximum range and no change in stability. The −5 deg toe-out angle also reduces the flow separation in the winglet root at high Mach number.

Flight tests are not very useful for parametric toe-out studies due to inherent scatter in thrust calculation. We have found no good substitute for parametric wind tunnel testing of winglet toe-out angle.

References

[1] "Design and Analysis of Winglets for Military Aircraft," Boeing Commercial Airplane Co., AFFDL-TR-76-6, Feb. 1976.

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

[3] Spillman, J.J. and Allen, J.E., "The Use of Wing Tip Sails to Reduce Vortex Drag," A.R.C. 37190 Perf. 3550.

[4] Conley, N.E., ".15 Scale, Wind Tunnel Investigation of Winglets on the Aerodynamic Characteristics of the Gates Learjet Model Airplane in the Wichita State University 7×10 Foot Low Speed Wind Tunnel—Test WSU IX, October, 1976," Nov. 1976.

[5] Conley, N.E., "Wind Tunnel Investigation for High Speed Aerodynamic Characteristics of the Gates Learjet .09 Scale Model 28 in the Boeing Transonic Wind Tunnel, Boeing Test 1570, May 1977," Aug. 1977.

[6] Struzynski, N.A., "Transonic Wind Tunnel Tests of the .09 Scale Gates Learjet Models 28, 35/36 and 55," Aug. 1978.

[7] Conley, N.E., ".15 Scale, Wind Tunnel Investigation of the Aerodynamic Characteristics of the Gates Learjet Airplane in the Wichita State University 7×10 Foot Low Speed Wind Tunnel—Test WSU X," Feb. 1978.

[8] Reynolds, P.T., Gertsen, W.M., and Voorhees, C.G., "Gates Learjet Model 28/29, the First "Longhorn" Learjet," AIAA Paper 78-1445, Los Angeles, Calif., Aug. 1978.

[9] Johnson, J.L., McLemore, H.C., White, R., and Jordan, F.L., "Full Scale Wind Tunnel Investigation of an Ayres S2R-800 Thrush Agricultural Airplane," SAE 790618, presented at SAE Business Aircraft Meeting, Wichita, Kan., April 1979.