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THE DESIGN INTEGRATION OF WINGTIP DEVICES FOR LIGHT GENERAL AVIATION AIRCRAFT

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Abstract

An investigation was conducted to determine the load carrying capabilities and structural design requirements for wingtip devices on general aviation aircraft. Winglets were designed and analyzed as part of a research program involving a typical agricultural aircraft. This effort involved analytical load prediction for the winglets, structural design for both the winglets and aircraft installation, structural load testing and flight test verification, and aeroelastic analysis.

Nomenclature

b	reference wing span, m (ft)
c	local chord, m (ft)
c_n	section normal force coefficient
C_L	airplane lift coefficient
l_{wlt}	winglet span, m (ft)
M	Mach number
p	pressure, N/m^2 (psi)
x	chordwise distance from leading edge, positive aft, m (ft)
y	distance along winglet span from wing-winglet juncture, m (ft)
β	angle of sideslip, deg
η_{wlt}	nondimensional winglet span station, y/l_{wlt}
KCAS	knots calibrated airspeed

Introduction

It has been recognized for many years that modifying the shape of the wingtip of an airplane may result in significant drag reduction at lifting conditions. Due to soaring fuel prices and fuel shortages in the early 1970's, the interest in nonplanar drag reduction devices has been revitalized. The increase in research has resulted in a number of concepts such as winglets, wingtip sails, and vortex diffusers[1-3]. These devices have been tested in wind tunnels and on airplanes ranging from high-speed heavy transport airplanes to low-speed light general aviation airplanes and sailplanes.[4-9]

The majority of wingtip development efforts have been oriented toward achieving airplane performance benefits, although alternative justifications have been made[10-13]. In the pursuit of these benefits, however, structural design and integration problems are encountered. These design problems may be of such significance as to effect the final decision to use wingtip devices. Aerodynamic loads resulting from the attachment of a highly efficient lifting airfoil section to a lightly loaded general aviation wing create a structural problem at the point of attachment on the wingtip. Structural weight required for load transmission in both the wingtip and wingtip device promotes the possibility of mass balance and aeroelastic effects detrimental to the behavior of the aircraft. Diminished airplane handling qualities and potential stability and control problems are also considerations.[14-16]

Various wingtip modifications are shown in Figures 1 through 4. Figure 1 shows a typical six passenger general aviation airplane with winglets designed to reduce induced drag and improve airplane fuel efficiency. Figure 2 shows a representative agricultural airplane fitted with winglets intended to diminish and reposition the wingtip vortices so as to improve the wing span effectiveness for spraying and dispersal operations. Figure 3 shows the same airplane with vortex diffuser vanes intended to accomplish the same purpose as the winglets by locating the device so as to intersect the wingtip vortex in the region of maximum vortex strength. A model of an airplane equipped with wingtip sails can be seen in Figure 4.

Figure 1. Six passenger general aviation airplane with winglets.

These wingtip devices all attempt to perform one or more of the following functions:
(1) diminish the wingtip vortex strength; (2) reposition the vortex; and (3) generate a thrust in the direction of flight. Research has indicated one factor common to all nonplanar wingtip devices in the significant sideforces that must be generated to maximize the effectiveness of the device.[1] This leads to the utilization of highly

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efficient airfoil sections which are capable of generating high lift coefficients at high angles of attack.

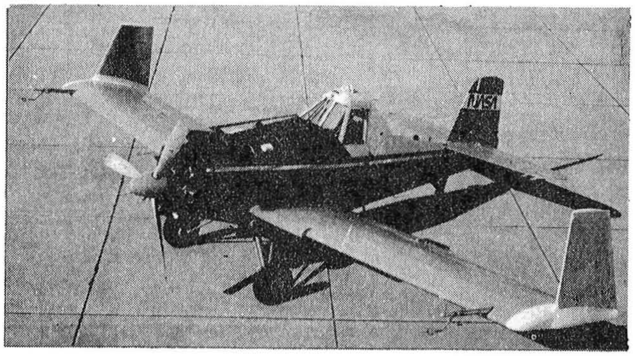

Figure 2. Agricultural airplane with winglets.

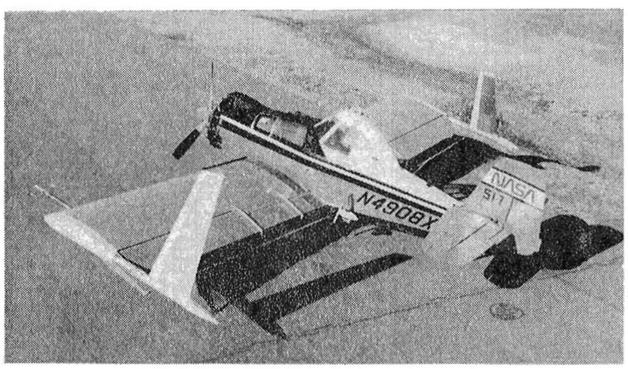

Figure 3. Agricultural airplane with vortex diffusers.

To identify and analyze the design problem areas, the aircraft shown in Figure 2 was used as a case study. It is a typical agricultural aircraft whose pertinent operational and physical characteristics are outlined in Table I.

Table I. Airplane Characteristics (With Winglets)

Gross weight, N(lb)	34,694 (7800)
Wing area, $m^2 (ft^2)$	28.62 (308.1)
Wing span, m(ft)	12.52 (41.08)
Engine power output, kw(hp)	596.5 (800)
Wing loading, N/m^2 (lb/ft^2)	1212 (25.3)
Power loading, N/kw (lb/hp)	58.2 (9.75)
Wing aspect ratio	5.5

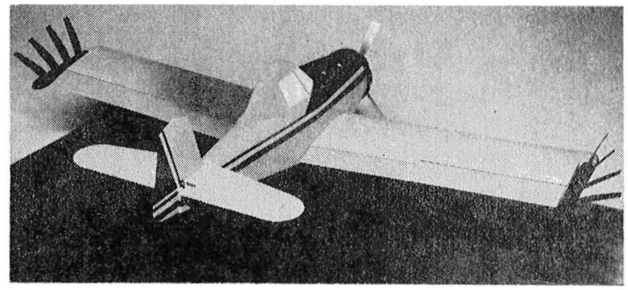

Figure 4. Agricultural airplane model with wingtip sails.

Structural Loads Analysis and Verification

A lack of wind tunnel data on the winglet configuration required the use of a vortex lattice analytical method to calculate the aerodynamic loading. The computer program used for this study was the North American Unified Vortex Lattice (NARUVL) method.[18] The NARUVL program satisfied the linearized boundary condition with the local airfoil slopes. Airfoil thickness and out-of-plane displacements due to camber are ignored. Displacements due to dihedral, however, are retained. Viscous effects are not included, although the effect of compressibility is taken into account through the Prandtl-Glauert transformation. In the analysis, the main wing was represented by 20 chordwise and 10 spanwise panels. The winglet was represented by 100 panels--20 chordwise and 5 spanwise.

The winglets tested were of a modified GA(W)-2 section and installed as in the configuration shown in figure 2. Each winglet has a root chord approximately equal to 65 percent of the aircraft wingtip chord, a span of 1.52 m (5 ft), a taper ratio of 0.56, and is unswept at the 50 percent chord. The winglets are canted inboard 13° from vertical, are mounted at 0° incidence angle, and are untwisted. Each winglet has an area of 1.81 m^2 (19.5 ft^2).

The "never exceed" speed for the research airplane is 138 KCAS, while the positive limit maneuvering load factor is 3.8 at a normal gross weight of 26,688 N (6000 lb) (2.92 at 34,695 N (7,800 lb)). This condition results in a design lift coefficient C_L = 1.15. Maximum winglet loading (onset of winglet stall) at the design condition was predicted to occur at a sideslip angle of approximately 17°. For that condition the upwind winglet was predicted to generate 9,790 N (2,200 lb) of normal force and winglet root bending moment of about 6,327 Nm (56,000 in. lb). Figures 5 and 6 show the design envelope in terms of normal force and root bending moment generated by the winglet. For airspeeds greater than 123 KCAS the maximum loading curve represents flight conditions at 2.92 g and maximum angle of sideslip (onset of winglet stall). For airspeeds less than 123 KCAS the maximum loading at maximum angle of sideslip is lift limited ($C_L = C_{L_{max}}$). For the flight tests the airspeed of the research airplane was limited to 125 KCAS in combination with a load factor of 2 and a sideslip angle of 10°. At this condition the winglet was predicted to generate 5,782 N (1,300 lbs) of normal force and a root bending moment of 3,615 Nm (32,000 in. lb).

In-flight winglet pressure measurements were obtained on the right winglet. Three rows of orifices, each consisting of 14 surface pressure ports (7 upper, 7 lower) were located at 25, 50, and 75 percent of the winglet span (Figure 7). The pressure orifices were connected to a scanivalve which was located in the wing leading edge close to the wingtip. The winglet pressures were referenced to the corrected freestream static pressure. The air data measurements were obtained from two instrument heads mounted on wingtip booms on both wingtips. Dynamic pressure, static pressure, angle-of-attack, and angle of sideslip were measured. The airspeed system was calibrated using the trailing anemometer technique.[17]

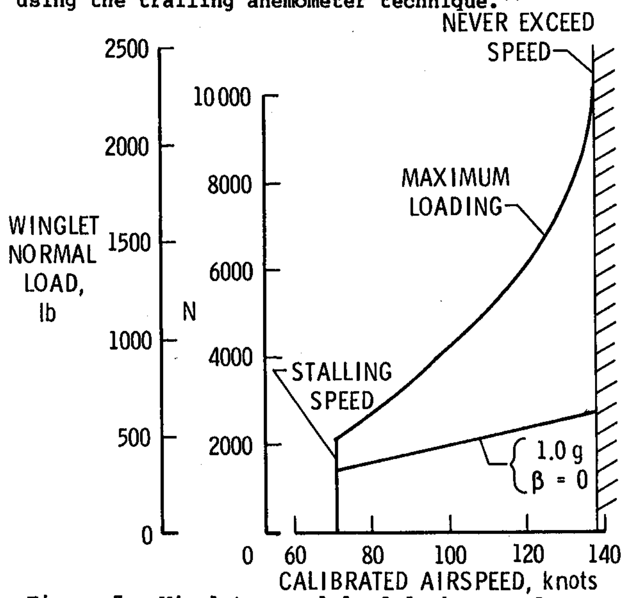

Figure 5. Winglet normal load design envelope for airplane at 34,694 N (7800 lb) gross weight.

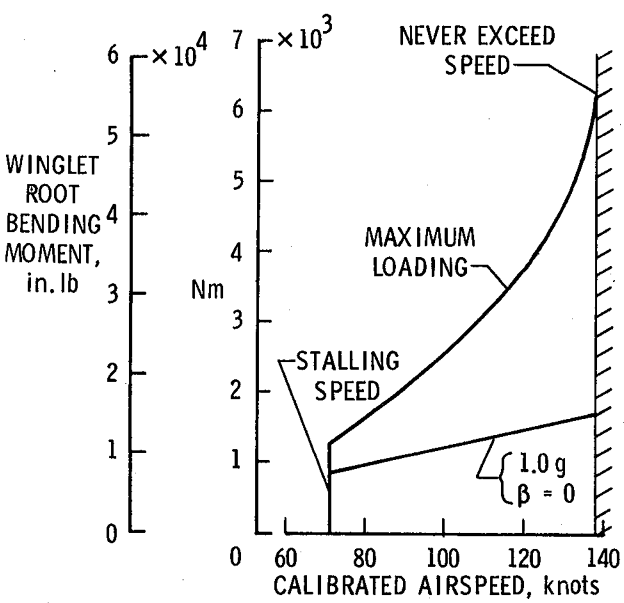

Figure 6. Winglet root bending moment design envelope for airplane at 34,694 N (7800 lb) gross weight.

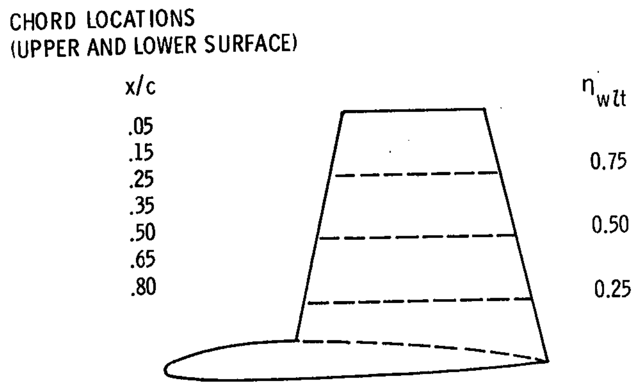

Figure 7. Winglet pressure orifice locations.

Comparisons of flight test measured and predicted pressure distributions are shown in Figure 8. As can be seen in this figure the winglet pressure comparisons at 25, 50, and 75 percent of the winglet span are in fair agreement. In Figure 9 the measured and predicted winglet spanload are shown for the same test condition. The results indicate that the analysis method, NARUVL, slightly under predicts the loading at the winglet root.

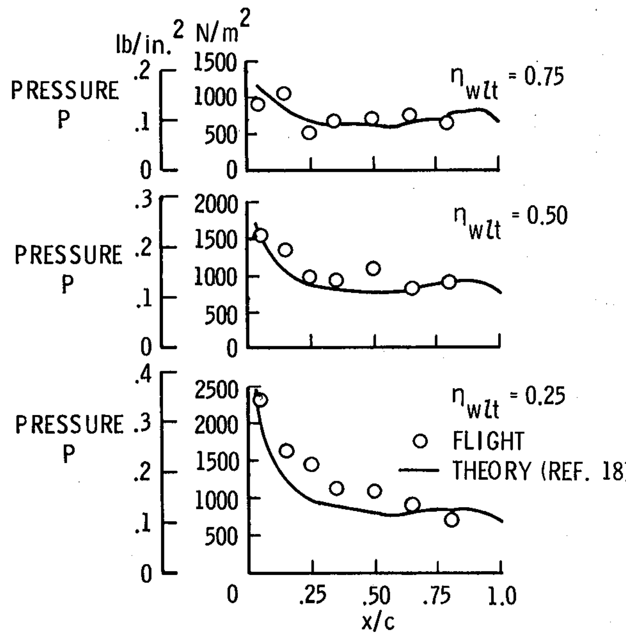

Figure 8. Chordwise pressure distributions for typical cruise condition (C_L = 0.714 at M = 0.15).

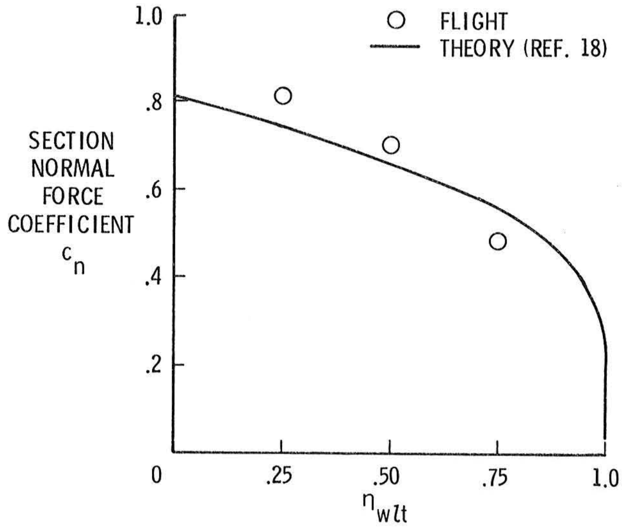

Figure 9. Winglet span load for typical cruise condition (C_L = 0.714 at M = 0.15).

The highest winglet loading condition at which pressure data were obtained was for an airspeed of 121 KCAS and a sideslip angle of 9.5°. For this condition the right winglet was found to generate a normal load of 3,870 N (870 lb) and a winglet root bending moment of 2,334 Nm (20,662 in. lb). For the same condition the theory predicted a 3,883 N (873 lb) normal force and a winglet root bending moment of 2,588 Nm (22,910 in. lb).

Structural & Aeroelastic Considerations

Originally the winglets were designed and constructed based on load predictions derived from classical airfoil theory. The aerodynamic loads analysis described in the preceding section revealed that these predictions were inadequate to describe the loading conditions that would be encountered during the flight test program. As a result, the winglets required modification to provide sufficient structural integrity in an orientation compatible with the aircraft wingtip structure. Figures 10 and 11 show the details of the winglet construction and the modifications to the aircraft wingtip are shown in Figures 12 and 13.

Figure 10 reveals the internal structure of the left winglet as viewed from the inboard side. The arrangement is a two cell beam design with full span spars at 15 percent and 50 percent chord stations and ribs at each 25 percent span location. The spars were stiffened with aluminum doublers and high strength steel spar caps on both upper and lower surfaces. These caps were riveted and bonded to both the spars and skin for the entirety of their length. The winglet to wingtip attachment fittings were machined from aluminum and were bolted to the two main spars. The trailing edge was also machined from aluminum and integrated into the structure to provide effective bending resistance. Figure 11 shows these details.

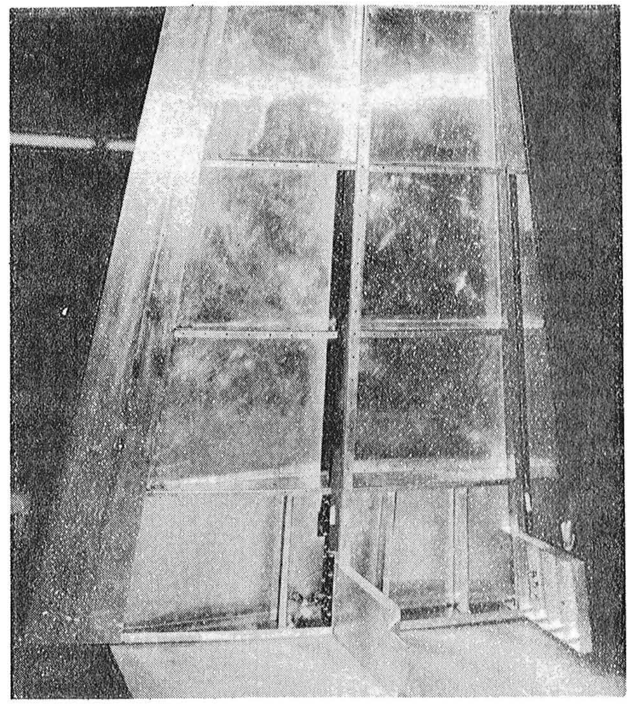

Figure 10. Winglet construction.

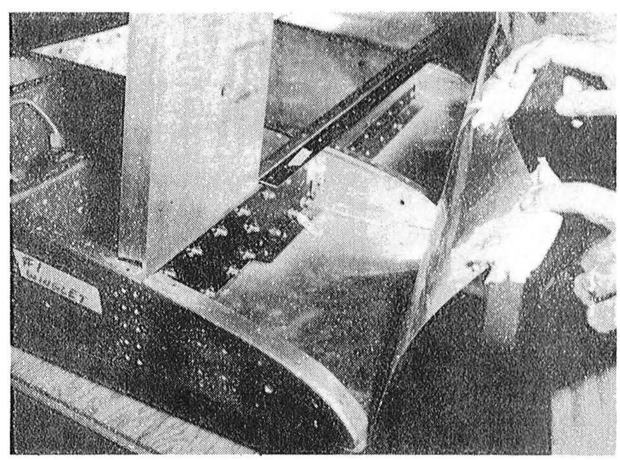

Figure 11. Winglet root modifications.

Figures 12 and 13 show the modifications required on the aircraft wingtip. The rear spar, shown on the left in the figures, was the existing aircraft rear spar. The forward false spar was added to provide an attachment for the winglet front spar. The existing aircraft spar was a formed aluminum channel section to which was added a web doubler. The false spar was also fabricated into a channel section of the same thickness and was fastened to both upper and lower skin panels as well as both outboard ribs. The entire arrangement was designed such that 70 percent of the load was transmitted from the winglet main spar (rear) onto the aircraft rear spar. The integrity of the wingtip modifications was verified by structural analysis.

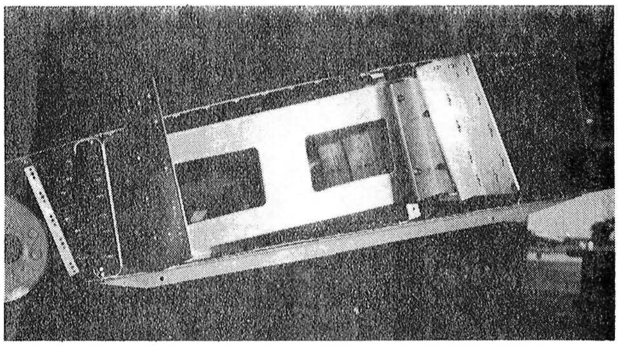

Figure 12. Wingtip attachment fittings.

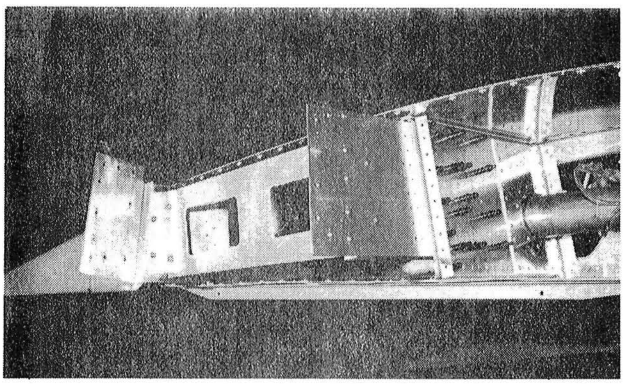

Figure 13. Wingtip spar and attachment fittings.

The maximum winglet root bending moment, predicted to be 3,615 Nm (32,000 in. lb), directly contributes to an increase in the wing root bending moment. The wing root bending is also increased through the addition of the normal force generated by the winglet. The aircraft wing root structure was adequate to withstand the increased loading without modification. The structural integrity of the winglets was verified by analysis and static load tests and was shown to have a positive margin of safety over the limit loads defined in the preceding section.

The weight added to the aircraft wingtips by the winglets and attachment structure causes a concern for the structural dynamics and aeroelastic stability. The test configuration was analyzed for natural frequencies and mode shapes and the results are summarized in Table II. These results agree with measurements made in ground vibration tests[19]. No strong torsional mode was identified for the winglet. The wing and winglet were represented by a finite element model using the Engineering Analysis Language program (EAL), an updated version of the SPAR program. The EAL program generated both natural frequencies and mode shapes, and this data was input to the NASA Flutter Analysis System (FAST) which considered the winglet to be a structure rigidly attached to the wing. The results of the flutter analysis indicated that for flight at sea level an airspeed of M = .8 is required to induce flutter. It was concluded that the wing/winglet assembly for this aircraft was free from flutter due to its low speed operation.

Table II. Weight and Natural Vibration Characteristics

	WEIGHT, N (lb)	1st BENDING, Hz	1st TORSION, Hz
WING ONLY	2224 (500)	6.7	19.17
WINGLET ONLY	285 (64)	29.4	-----
WING + WINGLET (MODIFIED)	2669 (600)	5.4	14.93

Conclusions

The use of wingtip devices (winglets) on a light general aviation aircraft presents a substantial structural design problem as a result of the large normal forces generated by the devices. The loading on the winglets was found to be several times higher than indicated by preliminary estimates from classical airfoil theory. This high loading condition, when compared to that of the "clean" wing, requires a thorough design, analysis, and ground verification test to assure flight integrity. These design procedures should include load predictions, stress, structural dynamics and flutter analyses.

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