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WINGLETS DEVELOPMENT AT ISRAEL AIRCRAFT INDUSTRIES

I. Darel; Y. Eliraz and Y. Barnett
Israel Aircraft Industries Ltd.
Ben-Gurion Int. Airport, Israel

Abstract

The first wind tunnel tests for the development of winglets at IAI were conducted on the ARAVA STOL transport aircraft in late 1974. On this aircraft the aim of the design was to improve the take off weight limitations with one engine inoperative, without compromising cruise performance. The flight tests confirmed the wind tunnel results at the design point and a substantial increase in the permissable take off weight was achieved. The overall cruise performance was improved as well. Following the successful winglet development on the ARAVA, a new program was started in 1978 on the IAI Westwind business jet. This design was special in that the winglets were installed on wing tip tanks. The design aim for the Westwind was greater fuel efficiency, and take off weight limitations gains were a secondary objective. As a result, a new Westwind 2 was tested and received certification, with greater fuel efficiency. This paper presents details of winglet geometry, wind tunnel and flight tests and performance improvements due to installation of winglets.

I. Notation

C_D	-	Drag coefficient
C_L	-	Lift coefficient
$C_{L\alpha}$	-	Lift change with angle of attack
C_l	-	Rolling moment coefficient
$C_{l\beta}$	-	Rolling moment change with sideslip
C_n	-	Yawing moment
$C_{n\beta}$	-	Yawing moment change with sideslip
h	-	Winglet height
SR	-	Specific range
W	-	Weight
β	-	Angle of sideslip
δ	-	Ratio of pressure at altitude to sea-level
ϕ	-	Roll angle
δ_a	-	Aileron deflection
δ_R	-	Rudder deflection

II. Introduction

Winglet development at IAI began with the ARAVA STOL transport. The first wind tunnel tests were conducted in late 1974. On the ARAVA, the design goal was to improve the single engine climb performance, without compromising cruise performance. Following the successful winglet development on the ARAVA, a new program was launched in 1978 to install winglets on the Westwind business jet. This design was special in that the winglets were installed on wing tip tanks. Greater fuel efficiency was the design aim and single engine climb performance was a secondary goal. Each program will be described here separately with details of wind tunnel and flight testing.

III. ARAVA

In late 1974, tests were being conducted in the IAI (Israel Aircraft Industries) 8.5 ft x 12 ft low-speed wind tunnel on an ARAVA model with various wing-tip modifications (e.g., curved and extended tips) in an attempt to reduce induced drag. At that time information on winglet work being conductedin the U.S. was first publicized (1).

That work was aimed at reducing the induced drag of subsonic transports cruising at 0.82 Mach. It was realized at IAI that there existed a potential for applying this concept to a low-speed STOL aircraft, such as the ARAVA, to improve its climb performance.

This paper describes the IAI approach for the selection of a winglet configuration intended to be flight tested on the ARAVA. It presents the major effects of the installation on the aerodynamic characteristics and the steps taken to meet the design objectives.

Wind Tunnel Testing

The wind tunnel testing phase leading to the selection of winglet configuration for flight test evaluation consisted of several hundred runs in three series of tests. The runs were made in the IAI 8.5 ft x 12 ft low-speed wind tunnel on the ARAVA 1/8 scale model. Fig.1 shows the ARAVA model installed in the tunnel with one of the early winglet configurations.

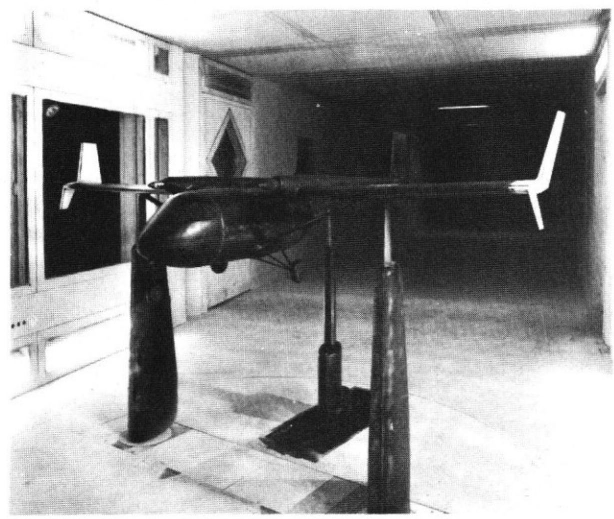

Fig.1-Early ARAVA model in the IAI low-speed wind tunnel

The initial winglet configuration had lower winglet height equal to one half of the upper winglet. Both the upper and lower winglets had a small roll-out angle. In the initial series of tests, the height of the upper winglet was parametrically reduced to 2/3, 1/2 and 1/3 of the basic size. The lower winglet height was also reduced to maintain a constant ratio of upper/lower winglet height. The drag reduction obtained from these tests is shown in Fig.2 for constant values of lift coefficient. It is seen that significant induced drag reduction is obtained only at the larger values of the lift coefficient, those corresponding to the climb condition. Another important observation is that the drag reduction is not proportional to the winglet height. The lateral characteristics are shown in Fig.3, for sideslip angles up to 15 deg. The winglets

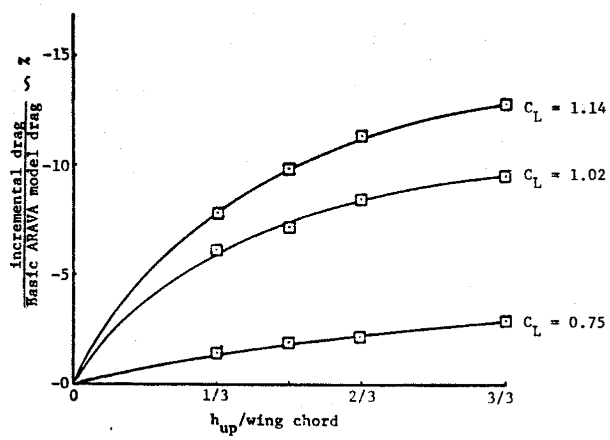

Fig.2-Effect of winglet height on the total drag, wind tunnel tests with ARAVA model.

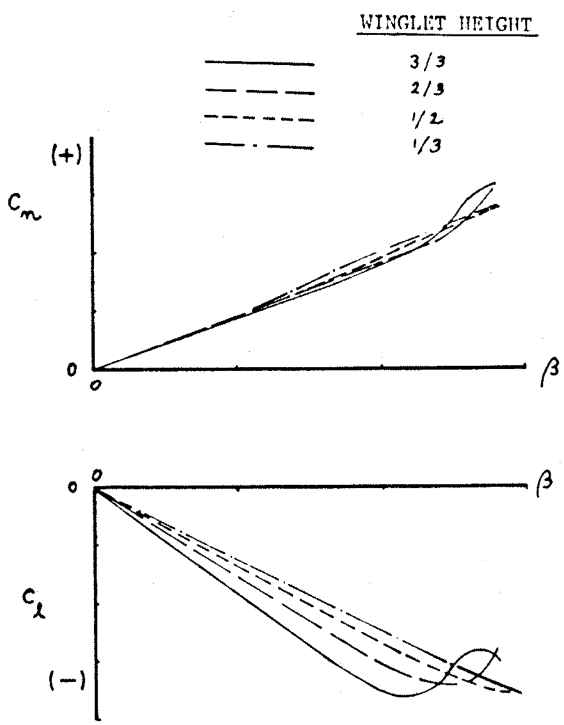

Fig.3-Effect of winglet height on lateral characteristics, wind tunnel tests with ARAVA model.

increased the dihedral effect ($C_{l\beta}$) while reducing the directional stability ($C_{n\beta}$). The reduction of $C_{n\beta}$ is probably caused by the forward tilt of the upper winglet side force which, for a straight wing, lies forward of the airplane center of gravity. We see, also, that with the maximum winglet height, there is a lateral instability above a certain sideslip angle. The angle of sideslip corresponding to this instability is progressively increased as the winglet height is reduced, the behavior being similar to the variation in maximum lift coefficient with reduced aspect ratio of a wing. With a winglet height of 1/3 of the basic size, the instability is completely eliminated.

The maximum change in longitudinal stability was a forward shift in the neutral point of about ½% of the wing chord. Maximum lift was increased by 6% with the largest winglet tested.

In addition to the problem of the lateral instability at moderate angles of sideslip, an additional undesirable characteristic is the large increase in the ratio $|C_{l\beta}/C_{n\beta}|$. With the maximum height winglets this ratio was increased by a factor of 2.5, judged to be excessive from the standpoint of the dutch roll oscillation mode. On the other hand, it was evident that a significant reduction in induced drag can be obtained only if the winglet is made large enough. Much of the remaining wind tunnel testing was concentrated on finding a solution to the lateral stability problems while retaining the size of the winglets large enough to be an effective drag reducing device.

Additional testing was carried out, during which the roll-out angles and span lengths of both the upper and lower winglets were parametrically varied. Special emphasis was placed upon increasing the span of the lower winglet in order to neutralize the large dihedral effect contribution of the upper winglet. The results of these parametric tests are shown in Fig.4. As expected, either increasing the span or the roll-out angle of the upper winglet increased the dihedral effect, while the dihedral effect was reduced when the span or roll-out angle of the lower winglet was increased. The following additional general trends were observed in the data:

(a) Increasing the span of either the upper or lower winglet resulted in a drag reduction,

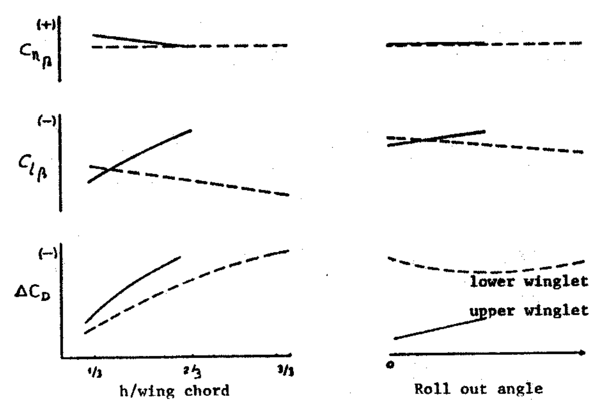

Fig.4-Effect of winglet span and roll-out angle, wind tunnel tests with ARAVA model.

(b) Whereas increasing the roll-out angle of the upper winglet further decreased the drag, the drag level was fairly insensitive to changes in the lower winglet roll-out angle.
(c) The directional stability was found to be essentially insensitive to change in either the upper or lower winglet roll-out angle or when the lower winglet span was increased; however, when the upper winglet span was increased, $C_{n\beta}$ decreased.

From the parameteric tests, it was found that increasing the span of the lower winglet produced a large enough reduction in drag that enable the reduction in the upper winglet height. The cumulative result of these changes resulted in reducing the winglet dihedral effect, while at the same time increasing $C_{n\beta}$, with a resulting drag reduction almost as large as that obtained with the initial winglet configuration. But now the ratio $|C_{l\beta}/C_{n\beta}|$ was considerably reduced: 1.5 compared with 2.5. The only remaining problem, that of early winglet stall during sideslip, was improved by toe-ing out the upper winglet a few degrees. Fig.5 presents the lateral characteristics of the model with and without toe-out, showing the effectiveness of this modification. There was no drag penalty due to incorporating the toe-out.

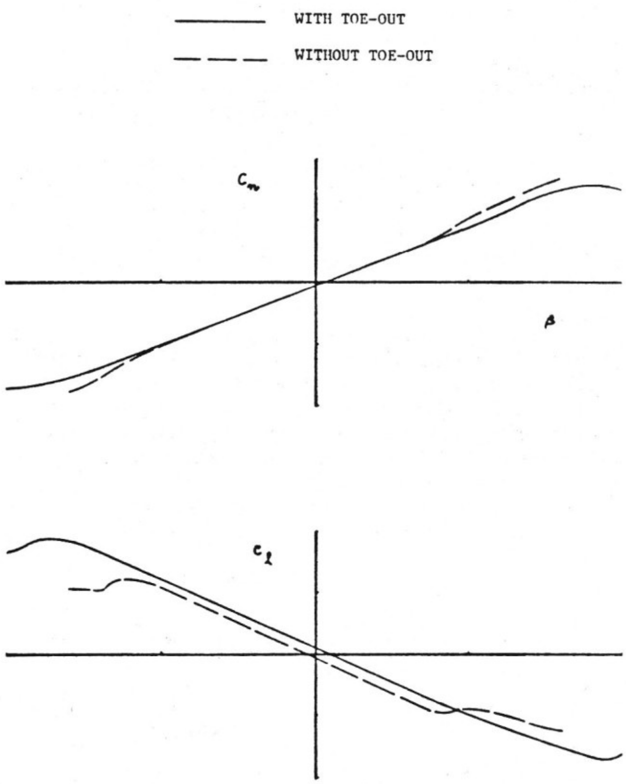

Fig.5-Effect of upper winglet toe-out on lateral characteristics, wind tunnel tests with ARAVA model.

Flight Tests

General. The final winglet configuration that emerged from the wind tunnel tests is shown in Fig.6. The winglets were installed on an aircraft that had previously been tested, and whose aerodynamic characteristics were well established.

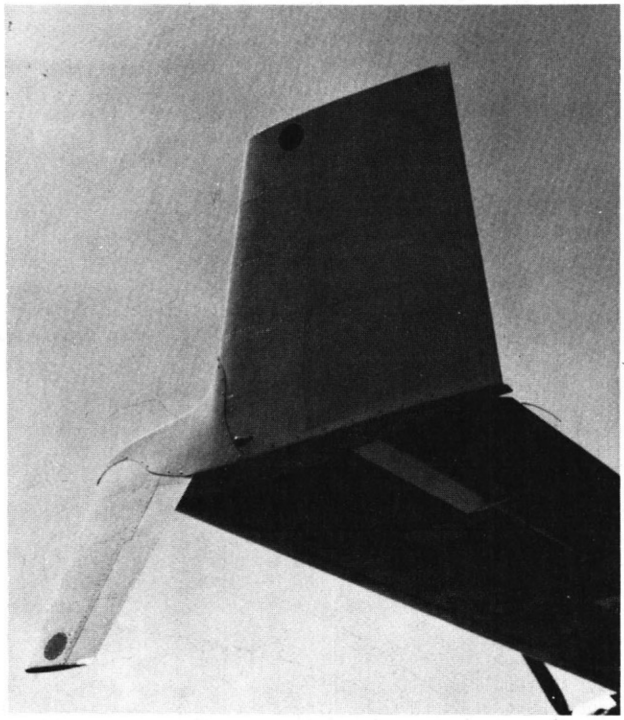

Fig.6-Winglets installation on the ARAVA aircraft, flight test configuration (left wing).

The aircraft was instrumented with advanced flight test equipment, and during flight all required parameters were telemetered to a ground station and monitored in real time by ground test engineers. The main objectives at the flight tests were fourfold:
(a) To determine the drag reduction obtained by winglets in flight in the presence of strong power effects, control movements and production tolerances.
(b) To explore the lateral characteristics, in the light of the wind tunnel test results and the FAR requirements.
(c) To obtain the trim drag during single engine flight, in the climb conditions specified by the FAR.
(d) To demonstrate that such a configuration is easy and safe to fly, as much so as the standard ARAVA.

Twin Engine Drag. Twin engine drag polars were obtained at level flight for take-off, cruise and landing flap settings. The drag reduction of the take-off configuration (10^{o} flaps) is presented in Fig.7, compared with wind tunnel data. The induced drag coefficient of this configuration is reduced due to the winglets by 20% at some range around the climb-out lift coefficient. There is good correlation between wind tunnel and flight test data at the extremes of the presented range. The difference in the middle is not completely understood at present. The relative drag reduction in that figure exceeds the 10% value.

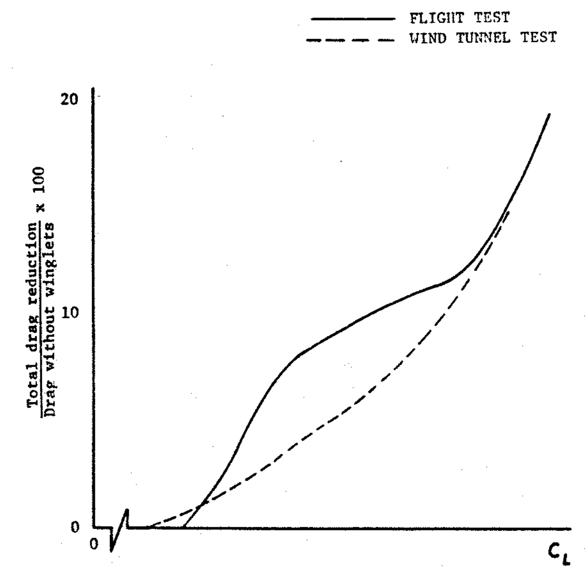

Fig.7-Total drag reduction due to winglets, comparison of wind-tunnel and flight test data, take-off flaps.

Stalls. Wind tunnel data showed an increase in the maximum lift coefficient due to the winglets. This could be expected since the winglets cause an increase in the wing-tip loading at a given angle of attack.

Generally speaking, the reduction in the demonstarted stall speed due to the winglet was more than that indicated by wind tunnel data. The stall characteristics were good, as much so as the standard ARAVA.

Longitudinal Stability. Wind tunnel data indicated a slight reduction in the longitudinal stability due to installing the einglets. This was not observed during the flight test, and it is assumed that for the tested configuration, the destabilizing effect caused by the higher lift curve slope of the wing is countered by a stabilising contribution from the reduction in the downwash on the tail assisted by the effect of variations in power.

Lateral-Directional Characteristics. Lateral and directional characteristics, both static and dynamic, were as good as those of the standard ARAVA. There are some variations of the aerodynamic coefficients, as was predicted by wind tunnel tests and theoretically. In order to estimate the variation of the dynamic derivatives due to the winglets, a method of computation was developed. In this method we used as an input the load data at the wing-tip and the winglets as was measured in the wind tunnel. This load was defined as a function of the angle of attack and the side slip angle. The required derivatives were then calculated, using simplified linear equations. The calculations showed approximately a 10% reduction in the dynamic derivatives due to yaw rate (C_{lr}; C_{nr}; C_{yr}), the same reduction in C_{np} while indicating a 20% increase of the roll-damping (C_{lp}) and a much greater increase in C_{yp}. Flight tests results of the roll characteristics and flight at high side slip angle provided some interesting data.

Roll Characteristics. The addition of wing-tip winglets to an existing planar wing has a combined effect on the roll characteristics. The additional wing load at the tip gives rise to better aileron effectiveness, but at the same time increasing the wing-tip contribution to the roll-damping. This damping is further increased due to positive interaction between the winglets and the load at the wing-tip: Basically, the roll-damping is the outcome of asymmetric load distribution over the span of the rolling wing, where as the load on the down-going wing-tip is increased (while decreased on the up-going wing-tip).

This extra load strengthens the tip vortices, thus increasing the load on the winglets. Since the upper winglet's normal force is directed inwards, and the lower winglet's normal force is directed outwards, the increased load on the down-going wing-tip winglets produces a rolling moment which opposes the rolling motion of the wing. The roll control of the ARAVA is provided by aileron/ spoilers system, where the spoilers are located inboard of the ailerons, and are not supposed to be affected by the winglets. Therefore, the aircraft with the winglets should require more aileron in order to achieve a given roll rate. Flight tests verified this analysis, as shown in Fig.8. It presents a comparison between stabilized roll tests with and without the wing-tip winglets. The stabilized non-dimensional roll velocity is presented versus aileron input.

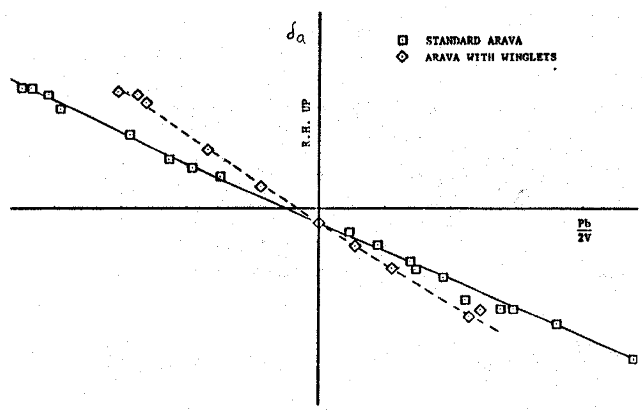

Fig.8-The effect of winglets installation upon the non-dimensional roll rate, flight test.

The Aileron Reversal. Initial flight tests at high side slip angle revealed an unusual characteristic which was defined as Aileron Force Reversal. This phenomenon was discussed in detail in ref.2, and is reviewed here because of its importance. The aileron force reversal was encountered during steady heading, high side slip flight tests. The nature of which was a sudden change in the direction of the aileron force, in such a way that the pilot had to apply aileron pressure against the bank while continuing to keep its heading. Through the use of tufts over the wing-tip and the winglets, the problem was related to abrupt flow separation from the outer, upper portion of the windward aileron, induced by separation near the leading edge of the upper winglet root section.

A solution was believed to be obtained by the installation of a boundary layer fence, as was proved later in flight tests. Fig.9 gives visual illustration of the effect of the fence. The upper picture is of the wing-tip in a right side slip without the fence, where the separated region is clearly defined. The lower picture illustrates the effect of the fence, which confined the separated flow to the immediate vicinity of the winglet, thus allowing the aileron to remain effective.

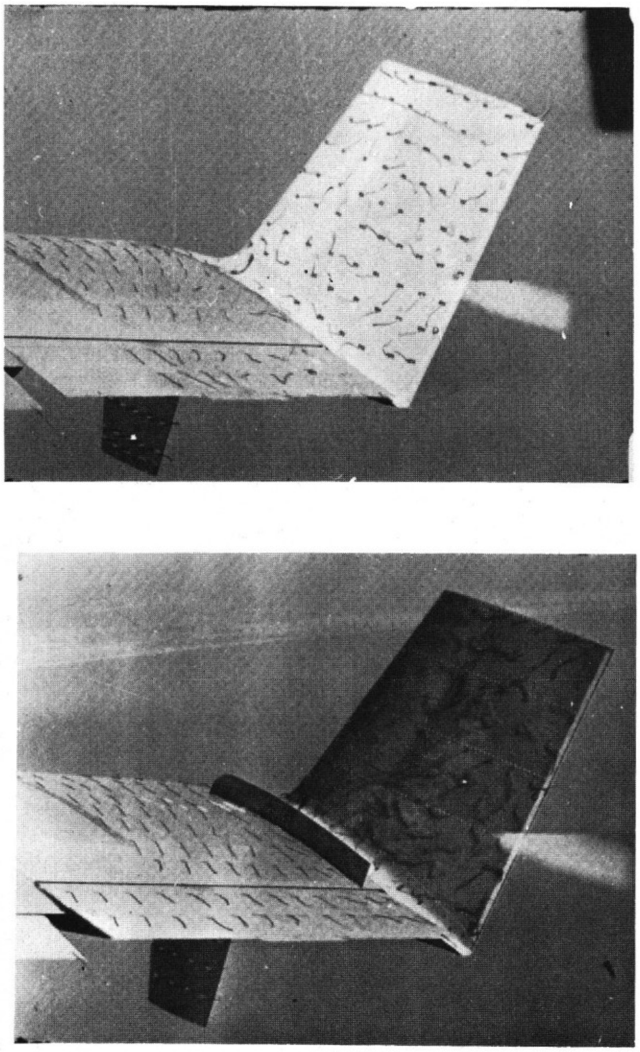

Fig.9-Airflow over the windward wing-tip at high sideslip angle, before and after the installation of the fence (tufts photographs during flight tests).

IV. WESTWIND 2

The installation of winglets on the Westwind business jet was designed to increase the fuel efficiency of the aircraft. Inasmuch that for business jets long range is desireable it was decided to retain the tip tank installation. The resulting winglet-tiptank combination is a new configuration that so far has not appeared on any other aircraft. Apart from winglets,the new Westwind model, designated Westwind 2 would also have a new high speed airfoil. This new airfoil designated IAI 54-12 is a NACA 64A212 (Westwind 1 airfoil) with a modified leading edge and forward upper surface designed to improve high speed characteristics[3]. In this paper we discuss the effect of winglets only with details of wind tunnel testing. Flight testing was done on the Westwind 2 prototype which had both winglets and the modified airfoil. However, this paper will present the flight tests results with emphasis on winglet effects only.

Details of Winglet Geometry

The installation of the winglets on the tiptanks, allows for some noteworthy geometrical features. First of all, the winglet root chord is approximately equal to the wing tip chord. This would not be possible had the winglet been installed on the wing tip itself. A second feature comes from the fact that by being installed on the tiptank the effective winglet span is greater than the geometric span. The basic Westwind wing has a 12% thickness-chord ratio, and no sweep. The winglet was given a thinner section thickness (10%) and the winglet itself had a specially designed high speed airfoil designated IAI 1-10 giving it a higher critical Mach number than the wing itself. In addition it was felt that the tiptank would reduce the interference between the wing and winglet flow fields. Mainly for asthetic reasons the winglet was given a sweep of 40°. Winglet span was the only parameter which was left open for determination by Wind Tunnel test. The Winglet planform had no twist, for ease of manufacture, and zero toe out. Fig.10 shows the winglet planform geometry as installed on the tip tank, and Fig. 11 shows the Westwind 2 in flight.

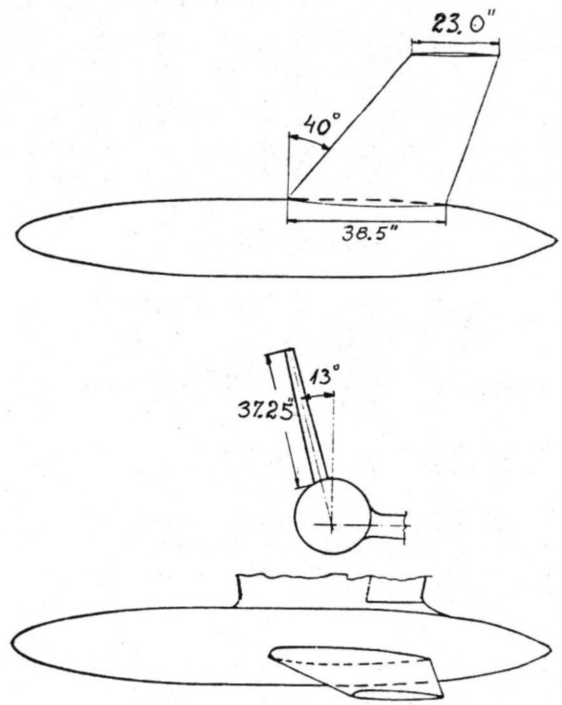

Fig.10-Winglet installed on tip tank.

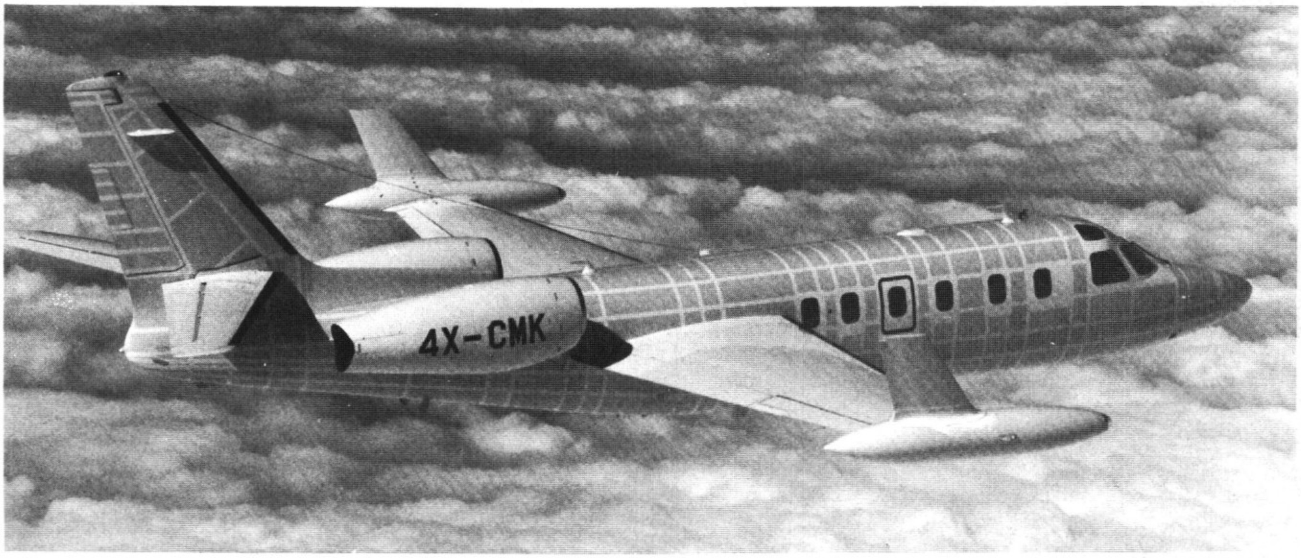

Fig.11-Westwind 2 in flight.

Wind Tunnel Tests

The wind tunnel test program was designed to determine the span of the winglet and the overall aerodynamic characteristics of the aircraft with the desired winglet planform. All the wind tunnel tests were performed in the IAI low speed tunnel on a 1/10 scale aircraft model. Three winglets heights were tested, in terms of wing semispan the winglet heights were 13.7%, 17.2% and 20.7%. The configuration with 17.2% was selected because the additional benefits from a higher winglet weren't justifiable as against the increased loads and structural weight.

The effect of the winglets on the overall aerodynamic characteristics were determined in the cruise configuration and also with flaps extended. From comparison of the lift curves of the aircraft with and without winglets we found that the winglets increased $C_{L\alpha}$ by 4.6%, this corresponds to an increase in effective aspect ratio of 23%. At the same time the winglets give a small increment in maximum lift of $\Delta C_{LMAX} = 0.04$. Another benefit was a small increase in static stability at the higher lift coefficients. This stability increment was slightly less than a 1% MAC rearward shift of the neutral point. The main winglet benefit is in drag and Fig.12 shows ΔC_D vs C_L for several flap settings. In cruise, for $0.2 \leqslant C_L \leqslant 0.6$ drag reductions of up to 30 counts were found. With flaps deflected drag reductions are even more pronounced and will give a large improvement in take-off weight limitations. The reduction in cruise drag would provide a 3-4% increase in fuel efficiency, however, additional benefits due to improved climb capability (large fuel savings in climb and higher cruising altitudes) boost the overall gain to about 6%. Wind tunnel testing in sideslip indicated practically no change in side force and yawing moment coefficients, however, as was to be expected a large increase in $C_{L\beta}$ was found of up to 60%. Tests were performed up to large sideslip angles, and no adverse effects due to flow separation were found. The ratio of $C_{l\beta}/C_{n\beta}$ went up from 0.66 to 1.15. It was expected that the dutch roll characteristics of the Westwind 2 would be different from those of Westwind 1. It was felt that the winglets would increase the roll power of the ailerons due to the increased loading of the wing tip. On the ARAVA, aileron control force reversal was experienced due to flow separation at the winglet-wing tip junction at large sideslip angles. It was felt that this

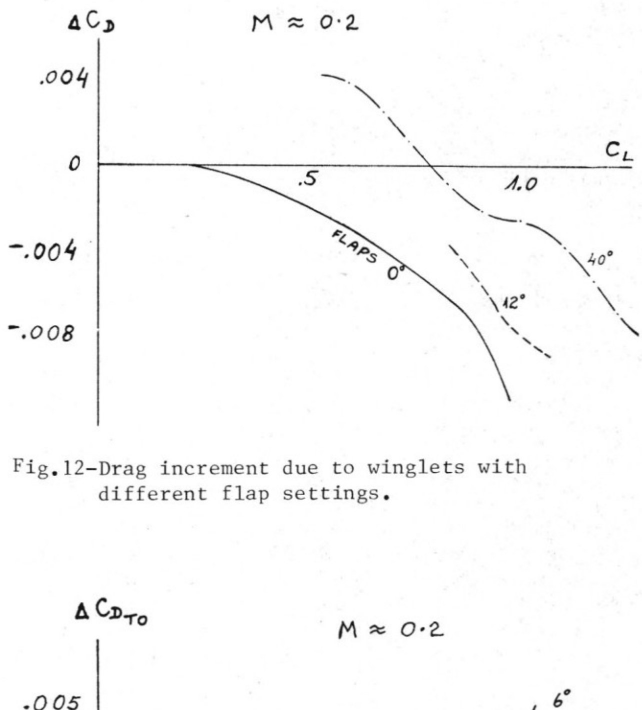

Fig.12-Drag increment due to winglets with different flap settings.

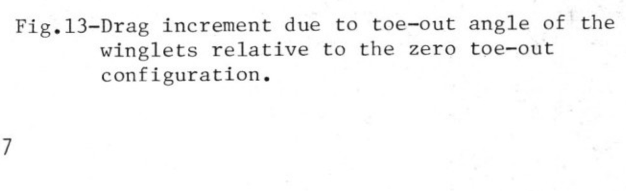

Fig.13-Drag increment due to toe-out angle of the winglets relative to the zero toe-out configuration.

phenomena would not occur on the Westwind 2 because of the presence of the tip tank. All this was later borne out by flight test. Aileron power was tested in the wind tunnel and a 16% increase was measured. This increase is beneficial though not significant since the Westwind has no deficiency in aileron power. Finally some tests were performed to determine the optimum toe-out angle of the winglets. Fig.13 shows the drag increment relative to the zero toe-out configuration as ΔC_{DT_O} vs C_{L_O} for toe-out angle of 3^o and 6^o, and toe-in of -3^o. In all cases, deviation from zero increases the drag. This result is obviously due to the influence of the wing tip tank since in all other installations of winglets directly on the wing tip such as the ARAVA some amount of toe-out is usually necessary.

Flight Test Results

Flight testing of the Westwind 2 was carried out during the certification procedure. The aircraft used was a fully instrumented prototype, however, as already mentioned the prototype was fitted with the modified airfoil as well as winglets. As a result, it is not possible to isolate the winglets effect in the high Mach and in the low speed (stall) regimes. However, some important winglet effects were found and will be discussed here.

The effect of the winglets on the drag was examined by determining the low speed drag polars. In this regime the airfoil contribution was expected to be very small.

Early flight test results indicated that only part of the expected reduction was being obtained even at high C_L. In-flight flow investigations indicated local flow separation at wing-tip tank-winglet junctions and over the rear of the tip tank.

The solution to this problem was obtained by installing short rows of vortex generators in the affected areas. Following a trial and error procedure for arranging the vortex generators, a configuration was arrived at giving results meeting the expectations from wind tunnel tests. Fig.14 shows the drag increment between Westwind 1 and 2 before and after installation of vortex generators. Lateral-directional dynamic stability was checked throughout the altitude - airspeed envelope. It was found that above 20000 ft, a mild dutch roll divergence was encountered. Fig.15 shows flight tests time histories of rudder input and resulting roll and sideslip angles. Mild dutch roll divergence is quite common on jet aircraft and yaw dampers are invariably installed. On the Westwind II it was demonstrated that either yaw damper or autopilot separately were capable of damping oscillations. It was furthermore demonstrated that with the proper technique the pilot can take out the oscillations himself.

An extensive evaluation of Westwind 2 cruise performance was carried out. The beneficial effects of the winglets are found at speeds for maximum range. Fig.16 shows a comparison of the specific range parameter δ x SR at maximum range speeds vs W/δ, for Westwind 1 and 2.

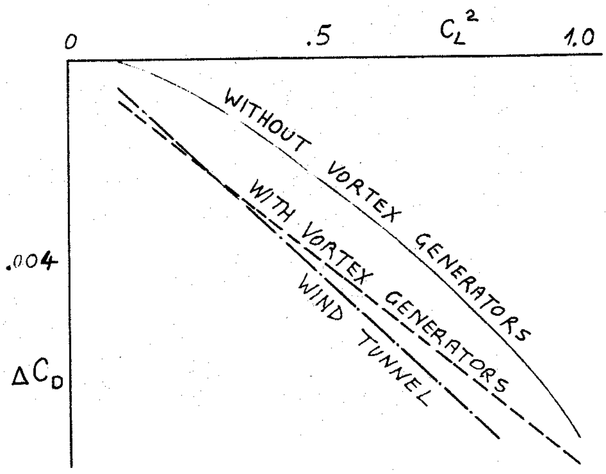

Fig.14-Drag increment between Westwind 1 and 2 from flight test before and after installation of vortex generators.

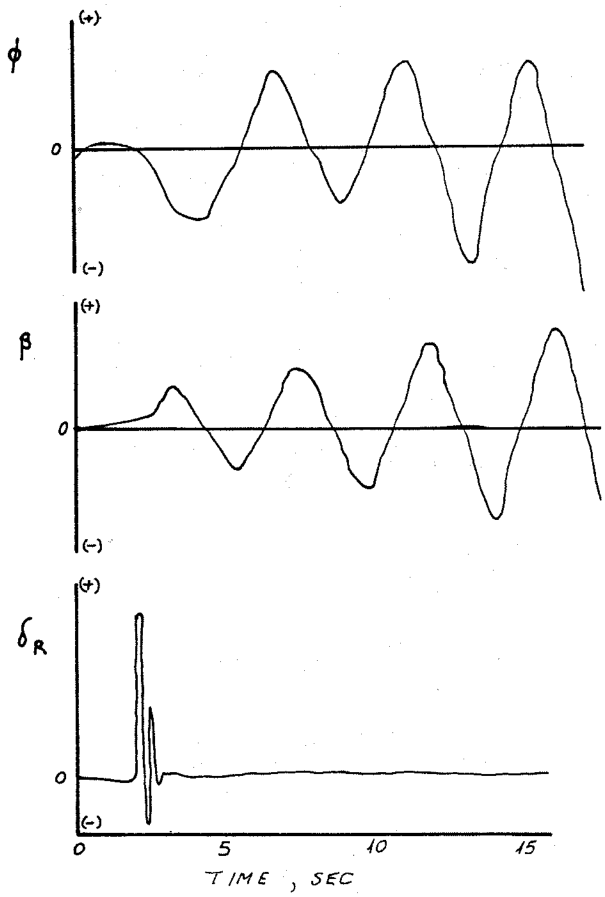

Fig.15-Flight test time histories of rudder input and resulting dutch roll.

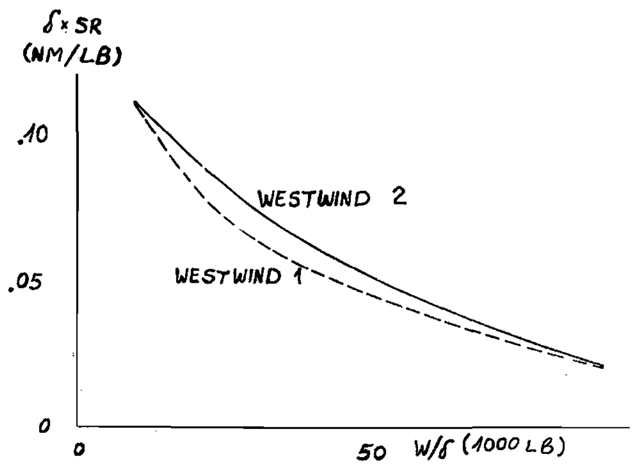

Fig.16–Specific range δ x SR versus W/δ of Westwind 1 and 2 for long range cruise.

At the lowest W/δ, C_L is too small to produce winglet benefits. As W/δ increases the winglets begin to work. It should be remembered that increasing W/δ corresponds to increasing optimum cruise Mach number. Although no wind tunnel tests were performed at high Mach numbers, it was felt that at higher Mach there is less winglet benefit due to compressibility effects at the wing-tip tank-winglet junction. This explains why Fig.16 shows less winglet benefit at high W/δ. The overall maximum range of Westwind 2 was increased by about 6% over that of Westwind 1.

V. CONCLUSIONS

Two aircraft programs involving winglets have been described here on two widely differing aircraft. It was shown that in each case performance benefits can be obtained. Most of the problems likely to be encountered with winglet installations have been discussed.

Analytical methods can be very useful in setting up an optimum winglet planform. A very comprehensive wind tunnel program is needed to investigate performance and handling qualities aspects. It was shown that in both programs the flight tests confirm the good performance as predicted. At the same time it was necessary to provide solutions to local airflow separations that were encountered only in flight.

VI. REFERENCES

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