Experimental Study of Airfoil Performance with Vortex Generators

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The canard airfoil from the Voyager aircraft was tested in Ohio State University's subsonic wind tunnel. This highly optimized laminar flow section had good clean airfoil performance, but suffered severe lift and drag penalties with early boundary-layer transition. These performance penalties resulted from a midchord boundary-layer separation. An experimental program was conducted to document this problem and then to design and test vortex generators in order to improve the tripped airfoil performance while having the least effect on the clean airfoil. A set of properly designed vortex generators were found to increase the lift and reduce the drag of the contaminated airfoil. A brief study documented a significant drag rise due to a rough surface in the turbulent boundary-layer region.

I. Introduction

HIGH-performance advanced canard configuration aircraft are starting to appear in the fleet. These airplanes include the small single-engine Quickie and the two-place pusher Vari-Eze in the home-built field. Business-class canard aircraft include the multipassenger twin turboprop Beech Starship and the Piaggio Avanti. Perhaps the largest aircraft of this type is the 110-ft-span Voyager, an around-the-world point design. All of these high-performance aircraft have canard (or forward wing) surfaces and airfoils designed specifically for the task.

One of the first of these aircraft to fly was the Quickie, a tandem-wing, home-built aircraft. Because of its small size, low speed, and airfoil shape, the aircraft had a substantial amount of laminar flow on its flying surfaces. As more of these aircraft came into service, pilots began to report a new phenomena: When encountering a light rain, the aircraft changed pitch trim, tending to nose down, and required more back stick pressure to maintain level flight.

There has been sufficient documentation of these pitch trim problems to ensure that it is a fundamental concern and not just a local problem due to inaccurate wing construction. The problem results partly because these advanced configuration aircraft require the stabilizing surface to operate at high lift coefficient. Efficient laminar flow airfoils with high lift-to-drag ratios at high lift coefficient give these aircraft excellent performance. However, if this laminar flow is destroyed, by rain for example, the thickened turbulent boundary may separate early and cause a decrease in lift. This loss of lift on the forward stabilizing surface causes a nose-down change in pitching moment.

Obara and Holmes[1] have measured the transition location on a natural laminar flow airfoil in flight. During these tests, the presence of visible moisture on the wing was found to cause a reduction in the amount of laminar flow achieved. In Ref. 2, Van Dam discusses not only the effect of contamination on the extent of laminar flow, but also the loss of aerodynamic performance. Computational results with an airfoil found on many of the early canard designs show the loss in lift, reduction in lift curve slope, and large drag rise due to early boundary-layer transition. These results show that with early transition the resulting turbulent boundary layer reaches the pressure recovery region with a boundary-layer displacement and momentum thickness that is two to four times thicker than in the natural transition case. This boundary layer then separates early, causing a large loss in airfoil performance. Experimental results by Althaus[3] show this loss in performance on a laminar flow sailplane airfoil. Using a simulated insect contamination pattern, early boundary-layer transition caused a severe loss in lift, reduction in lift curve slope, and drag rise.

Aircraft have been built using canard airfoils that are susceptible to large lift losses due to leading-edge contamination. For these aircraft to operate safely, either the canard airfoil must be replaced or a fix must be found. Vortex generators have been used in many fluid flows to prevent or delay separation. Pearcey[4] presents an extensive survey of the field and some vortex generator design information. Vortex generators seem to be a logical choice as a method to correct the flow separation problem on these canard airfoils.

To examine and develop an aerodynamic fix for this problem of canard lift loss due to roughness, a two-dimensional model of the canard airfoil to be used on the Voyager around-the-world aircraft was fabricated. Care was taken to use the same construction technique as was used on the flight vehicle. The model was of full-scale chord including the elevator control surface. Tests in the 3×5 ft subsonic wind tunnel at Ohio State University were conducted at 70 mph, close to the approach speed of the Voyager.

These tests measured the lift, drag, and control authority of the canard surface in a clean configuration and with a trip strip to represent the roughness due to rain. A series of vortex generators were designed and tested and proved to control this lift loss. The vortex generators were designed such that the clean airfoil suffered only a small drag increase due to their presence.

II. Experimental Apparatus

Tunnel and Model

These tests were conducted in Ohio State University's subsonic wind tunnel located at the Aeronautical and Astronautical Research Laboratory. The tunnel is of conventional design with an approximately 3×5 ft test section, 8 ft in length. The tunnel operates at speeds of 0–220 ft/s at a Reynolds number of up to 1.3×10^6/ft. The tunnel is of open return type and uses four turbulence screens and honeycomb

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in the settling chamber to reduce the tunnel turbulence. The tunnel will accommodate airfoils mounted mounted vertically in the test section or three-dimensional models, strut-mounted using an internal strain gage balance. Tunnel speed, Reynolds number, and Mach number are measured through facility pressure transducers.

A model of the Voyager canard airfoil was built for this test (see Fig. 1). The model has a chord of 22 in., identical to that of the full-scale aircraft. The model span is 39 in. Care was taken to build the model using the same construction techniques as were used on the actual aircraft. The model was constructed by hot-wire cutting a foam core, which was then wrapped with fiberglass and epoxy. The model is equipped with a 25% chord simple flap that on the full-scale aircraft acts as the elevator. To save weight, the surface of the Voyager canard was not filled and sanded aft of the 55% chordwise location on the upper surface and the 65% chordwise location on the lower surface. These were the predicted boundary-layer transition locations at cruise. To test the aerodynamic effect of this fairly rough surface finish, half of the model span was finished in this way, leaving the aft portion of the airfoil rough, and the other half of the span was given a smooth surface finish all the way back to the trailing edge.

The model was instrumented with over 40 surface static pressure taps on the model centerline. Taps were provided on both the main element and flap and were concentrated near the leading edge of each element. A simple technique was used to simulate the effect of leading-edge roughness due to rain or insect debris on the airfoil. A 0.25 in. wide strip of 0.012 in. thick duct tape was applied at the 5% chordwise station on the upper surface. The backward-facing edge of the duct tape was ragged, formed by the tearing of the tape. This rough edge created additional disturbances in the boundary layer. This technique was chosen over the more traditional carborundum grit method, since the tape is easy to prepare and is widely used as a roughness simulator in canard aircraft flight testing.

Standard tunnel instrumentation was used for this test. Pressure measurements were made using a Scanivalve system capable of measuring 48 pressures. No cutoff valves were used for this test. A single traversing total pressure probe was used to measure the airfoil wake. The probe was located approximately one chord length downstream of the model trailing edge and was traversed automatically by the computer system.

To enable the measurement of the drag difference between the smooth and rough trailing-edge surfaces, the probe was modified to allow wake surveys to be taken either on the model centerline or 8 in. above or below the centerline. Unless otherwise indicated, all data were taken on the model centerline.

Data Acquisition and Reduction

Data acquisition and reduction was accomplished primarily on the laboratory's Harris H100 computer. The airfoil lift and moment coefficients were determined from the integrated surface pressure measurements. The tunnel speed and Mach number were determined from pressures measured by the facility's transducers and as a check by the Scanivalve transducer. The airfoil drag coefficient was determined by an integration of the wake momentum deficit measured by the wake total pressure probe. With the exception of the pressure distributions, all data presented here have been corrected for wind tunnel wall effects.[5]

III. Results and Discussion

Clean Airfoil

Initially, the airfoil was tested to establish its basic performance with natural transition and with transition fixed at the 5% station. All tests were run at a nominal chord Reynolds number of 900,000 and a Mach number of 0.075. These conditions were chosen since they closely simulate the flight conditions during takeoff and landing. Although the tunnel is capable of chord Reynolds numbers of over 2×10^6, tests at higher Reynolds numbers were not conducted.

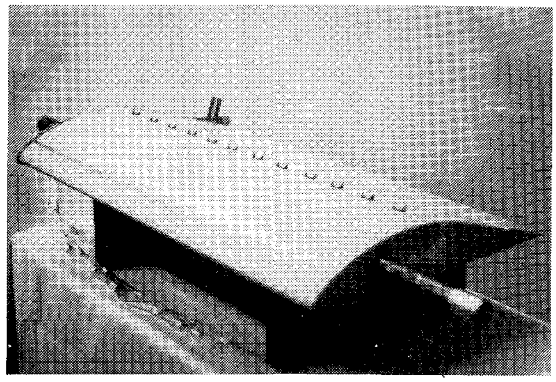

Fig. 1 Voyager canard airfoil model ($C=21$ in. and span $=39$ in.).

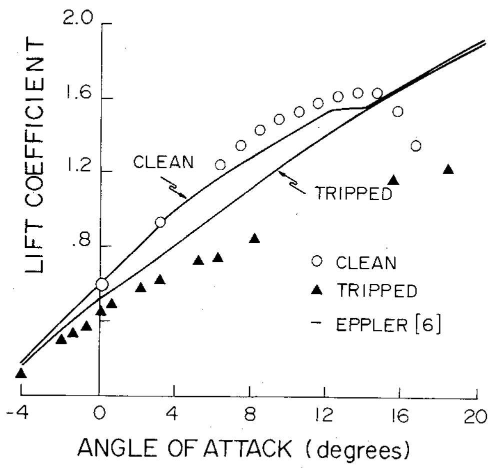

Fig. 2 Experimental and theoretical lift performance of the airfoil clean and tripped.

In Fig. 2, the measured lift performance of the airfoil is shown along with the theoretical prediction.[6] As can be seen from the experiment, at the design point of an angle of attack of 3 deg, the lift drops from 0.9 to 0.55 when the boundary layer is tripped. This penalty increases as the angle of attack is increased. With the model tripped, the code does a poor job of predicting lift. Eppler and Somers[6] does show a lift loss, but not the magnitude measured in the tunnel. Significant upper surface separation is predicted by the code for the tripped case.

The drag polars for the airfoil are shown in Fig. 3. For an airfoil operating at a Reynolds number of only 900,000, the drag with natural transition, slightly less than 0.010, is very good. This is particularly true since prior experience has shown that laminar flow airfoils suffer a drag rise due to the presence of surface pressure taps. Sublimating chemical tests showed that, at the design lift coefficient, the upper surface transition was at $x/c=0.53$. With the boundary layer tripped, the drag increases rapidly above a $C_{\ell,\max}$ of 0.6. This indicates that the upper surface separation becomes significant for these cases. Reference 6 does a good job of predicting the clean airfoil drag, but does not predict the tripped airfoil drag well, since the separation zone is not properly modeled.

The moment coefficient about the airfoil quarter chord was measured clean and tripped. A severe effect is seen when the boundary-layer trip is installed, giving a more nose-up pitching moment. Since these theoretical methods do not model the large separation zone, the pitching moment is not predicted well. Even the clean airfoil case compares poorly, since significant regions of separated flow occur here even at moderate angles of attack.

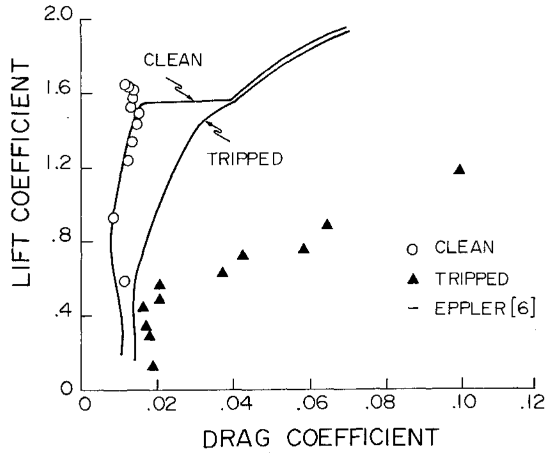

Fig. 3 Experimental and theoretical drag performance of the airfoil clean and tripped.

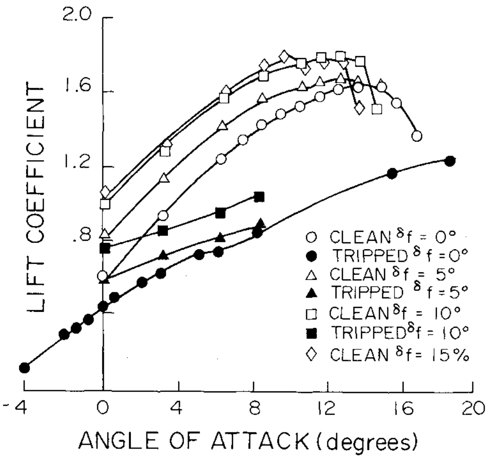

Fig. 4 Experimental effect of elevator deflection on lift, clean and tripped.

Figure 4 shows the effect of flap deflection on the airfoil clean and with the boundary layer tripped. In addition to the large loss in lift and reduction in lift curve slope seen with the boundary-layer trip, a loss in elevator effectiveness is shown. Only limited data were taken with the boundary layer tripped, but it can be seen that as the angle of attack increases from 0 to 8 deg, a loss in elevator effectiveness is indicated. This is probably due to the large trailing-edge separation at the higher angles of attack. Note that at the design point of $C_\ell = 0.9$, over 10 deg of flap deflection would be required to restore the lift loss due to the trip. Unfortunately, a 15 deg flap deflection with the airfoil tripped was not run, but based on the clean data elevator, effectiveness is lost for deflections above 10 deg.

Pressure distributions from theory and experiment for the natural transition and tripped cases are compared in Fig. 5. The theory due to Smetana et al.[7] is shown here where the uncorrected lift coefficients have been matched. The pressure distributions compare well except for some discrepancies near the trailing edge, probably due to the presence of the flap system. Also shown is a measured pressure distribution with boundary layer tripped and at the same angle of attack. It is clear that tripping the boundary layer causes a large separation region on the aft portion of the upper surface, as indicated by the region of almost constant pressure. The increase in drag and reduction in lift seen earlier are due to this effect.

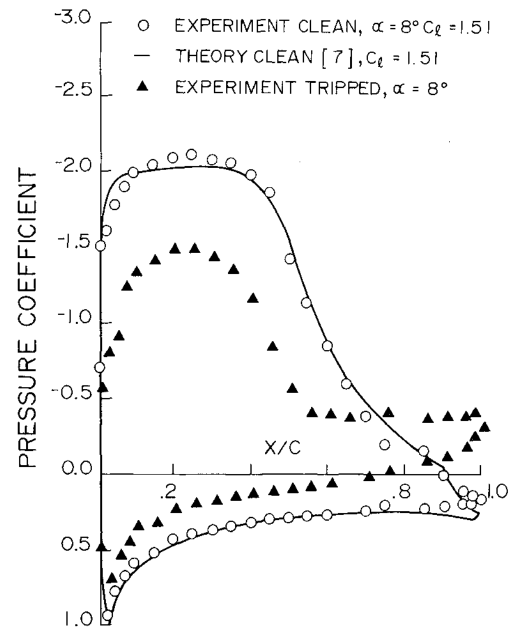

Fig. 5 Experimental and theoretical pressure distributions, clean and tripped.

Airfoil with Vortex Generators

In an attempt to restore the airfoil lift lost due to the early transition and roughness from the duct tape strip (the leading-edge roughness simulator), vortex generators were used. The purpose of the vortex generators is to introduce vortices into the flow ahead of the separation point to energize the boundary layer and thus to prevent the flow separation. As seen in Fig. 6, three types of vortex generators were used. The vortex generators were built in pairs as shown in the figure. By using brass sheet metal and folding up on the dotted line as indicated, two vortex generators, generating vortices of opposite sign, are constructed. The vortex generators are essentially very-low-aspect-ratio wings positioned on the airfoil surface protuding up and out of the boundary layer. Each vortex generator is at a 20-deg angle of attack. The small vortex generators of Fig. 6a are 0.4 in. long and extend up from the surface 0.15 in. Figure 6b shows the large vortex generators, which are a slightly larger version of those in Fig. 6a. Vortex generators with a delta-shaped planform are shown in Fig. 6c. These extend 0.4 in. up from the airfoil surface. The small vortex generators were placed chordwise at both the 17 and 45% chord location, each pair approximately 3 in. apart. The large vortex and delta vortex generators were only tested at the 45% chord location.

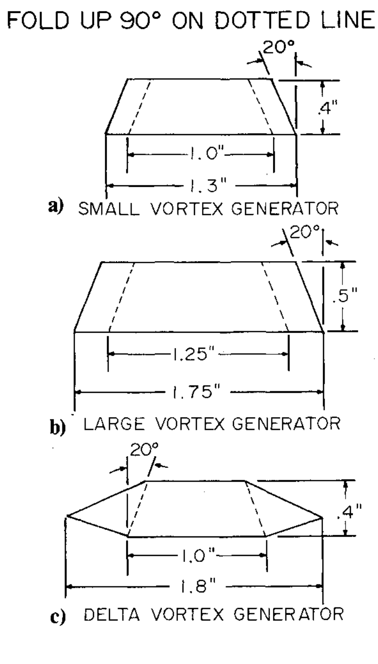

Fig. 6 Various vortex generators used.

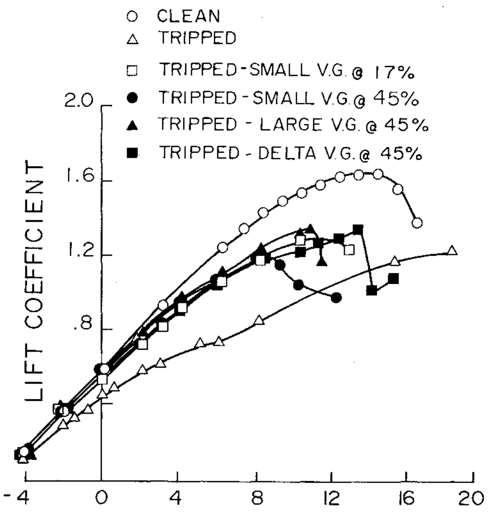

Fig. 7 Effect of vortex generators on lift with the airfoil tripped.

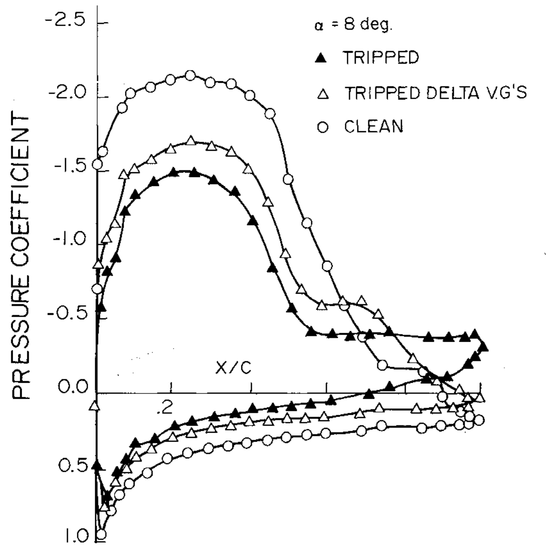

Fig. 8 Effect of vortex generators on the measured pressure distributions for the tripped airfoil.

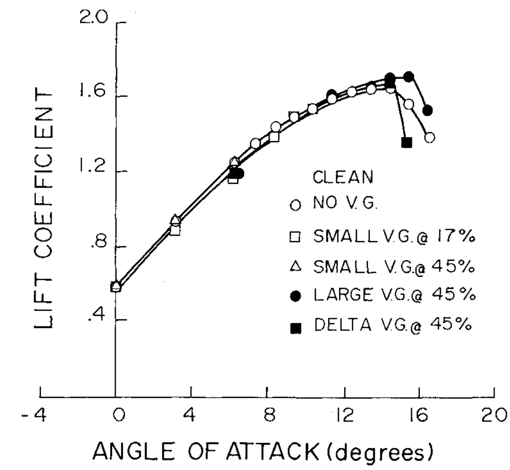

Fig. 9 Effect of the vortex generators on the clean airfoil lift.

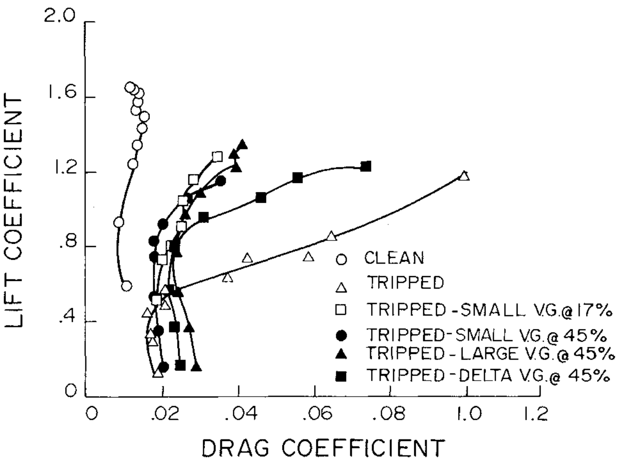

Fig. 10 Effect of vortex generators on drag with the airfoil tripped.

The primary function of the vortex generators was to keep the flow attached on the airfoil when the boundary-layer trip was present. This could be seen in the pressure distributions or in the lift performance of the airfoil. Figure 7 shows the lift performance of the airfoil with natural transition, and tripped with and without vortex generations. All of the vortex generators do a good job at a low angle of attack of restoring the lift loss due to the boundary-layer trip. The airfoil was designed for a canard cruise C_ℓ of 0.9. At this condition, the vortex generators return the lift within approximately 0.1 of the natural transition level, depending on the vortex generators used. A significant loss in $C_{\ell,\max}$ is seen even with the vortex generators, although enough lift at these high angles has been restored so as not to affect seriously the aircraft operation. Some difference in maximum lift is seen, depending on which vortex generator configuration is used, with the large and delta configurations providing slightly higher values.

The effect of the vortex generators can be seen in more detail in Fig. 8. Here the pressure distribution is shown for the tripped airfoil with and without vortex generators. The boundary layer still separates at about the 55% station, but due to the vortex generators it reattaches again at about the 70% station. No reattachment occurs without the vortex generators. Even with the separation bubble present, much of the lift is restored.

Measurements were taken to ensure that the vortex generators did not seriously affect the airfoil lift with no trip strip (see Fig. 9). The vortex generators are seen to have little affect on the untripped model lift and actually increase the maximum lift slightly. A small reduction in the angle of attack for zero lift is also indicated, due to the effect of the vortex generators on the boundary-layer displacement thickness on the upper surface. Overall, the vortex generators are seen to have an insignificant affect on the lift.

In Fig. 10, the drag polars are shown for the airfoil with natural transition, tripped, and with the various vortex generators attached. The clean airfoil drag with natural transition is seen to be less than 0.010 (100 counts) around the design C_ℓ of 0.9. With the airfoil tripped and no vortex generators attached, a drastic drag increase is seen above a lift coefficient of 0.6. This drag rise was controlled by all of the vortex generators tested. While some configurations reduced the drag more than others, this is not very significant since the vortex generators were designed to maintain lift at an acceptable drag penalty. It is assumed that these tripped conditions will occur infrequently.

The key to our recommendation for a vortex generator configuration for this airfoil can be explained using Fig. 11. Since it is assumed that the airfoil will operate the majority of the time without early boundary-layer transition, the goal is to protect against lift losses due to a boundary-layer trip, while suffering as small a losss in natural transition airfoil performance as possible. As can be seen from Fig. 11, the delta vortex generator configuration shows only a 10 drag count in-

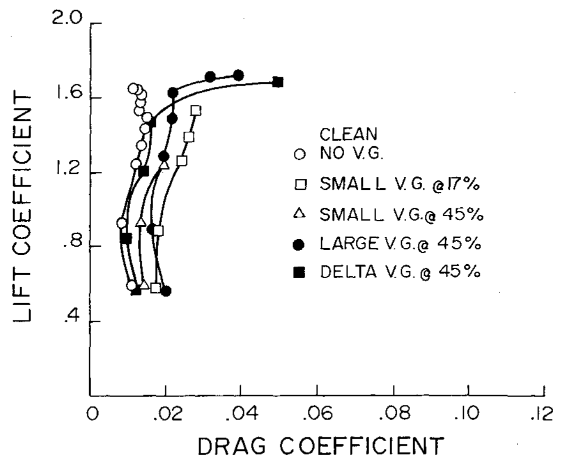

Fig. 11 Effect of the vortex generators on drag with the airfoil clean.

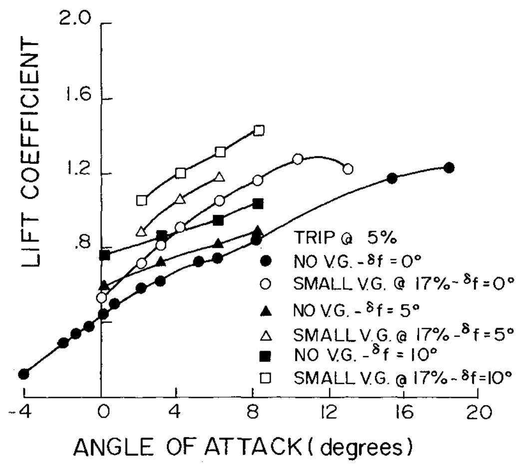

Fig. 12 Effect of elevator deflection on lift with and without vortex generators and with trip.

crease at the design C_ℓ over the airfoil with natural transition and no vortex generators. The next best vortex generator configuration has almost a 40 drag count increase at a lift coefficient of 0.9. The delta vortex generators were designed to keep the vortex generator span load approximately constant. According to Taylor,[8] this provides the strongest vortex with the least drag penalty. The delta vortex generators performed even better at reducing the drag penalty than was expected.

The effect of flap deflection on the lift of the tripped airfoil, with and without vortex generators, is shown in Fig. 12. Only data for the small vortex generators at 17% chord location are available. The vortex generators increase the lift and the lift curve slope with flap deflection, as expected. An improvement in elevator effectiveness is also seen.

Using the modified wake survey probe described earlier, drag data were taken near the design C_ℓ, 8 in. above and below the centerline. This gave a measure of the effect on the drag of not smoothing the airfoil surface in the turbulent boundary-layer region (see Sec. II for a description of the model finish). These measurements showed that leaving the aft portion of the airfoil surface rough increased the drag almost 17% over the completely smooth model. Since it was felt that the actual aircraft canard was even rougher than the model tested, some additional qualitative tests were performed. Several strips of 0.005 in. thick, 0.5 in. wide tape were applied spanwise on the aft portion of the rough half of the model. This showed a 30% increase in drag over the smooth airfoil surface. While these tests were not carefully controlled, they do show the importance of having a smooth surface over the entire airfoil.

IV. Summary

A longitudinal control problem has been observed on many canard aircraft when the canard suffers early boundary-layer transition due to surface contamination. This particular program concerns the Voyager aircraft, which made the first nonstop, unrefueled flight around the Earth in December 1986. The goal of this program was to document the effect of leading-edge transition on the Voyager canard, and, if necessary, to recommend an aerodynamic fix.

An extensive wind tunnel program was conducted on a full-scale section of the canard airfoil. The airfoil was tested with natural transition, tripped at the 5% chord location and with various vortex generator configurations. The effect of leaving a rough, unfinished surface on the airfoil in the turbulent boundary-layer region was also evaluated. Several conclusions were reached:

1) An extremely severe loss in airfoil lift and an increase in drag were observed with the boundary layer tripped. This loss in performance was due to flow separation on the upper surface at the beginning of the pressure recoverey.

2) For the tripped airfoil, all four vortex generator configurations increased the lift and reduced the drag.

3) The delta planform vortex generators caused only a very small increase in drag on the airfoil with natural transition. Since on the tripped airfoil these vortex generators also restored the necessary lift and improved the drag, we recommend this configuration.

4) It is clear from the tests that a rough airfoil surface, even on the aft portion of the airfoi in the turbulent boundary-layer region, causes a significant drag rise.

The changes to the Voyager aircraft suggested here have been made. The delta-shaped vortex generators have been installed and the aft surfaces of both the main wing and canard have been filled and smoothed. While no quantitative flight test results are available, some pilot reports are. The aircraft appears to perform better with regard to cruise speed than before. The drag savings accomplished by smoothing the aft part of the wing and canard appear to have more than cancelled the slight drag rise due to the vortex generators. In addition, the pilots report an improved elevator stick force feel that they attribute to the vortex generators.

During part of its record breaking flight, the Voyager did encounter rain. The addition of the vortex generators greatly improved the longitudinal handling qualities of the aircraft under these conditions.

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