Design Parameters for Flow Energizers

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Fourteen geometric configurations of a 75-deg sweep flow energizer were tested on an 18% scale model of a general aviation airplane. The test matrix included variations in camber, overlap, gap, and convergence of the channel between the two surfaces. Cambered flow energizers performed better than their flat counterparts. The only change between the two most promising configurations was the convergence; yet the performance was significantly different, suggesting that convergence must be given careful attention in design. The better of the two configurations had a $C_{L\max}$ about 7.5% greater than the other. It also gave an increase in α_s of approximately 4 deg over the baseline model. However, $C_{L\max}$ was still approximately equal to that of the baseline model. Cruise L/D ratio for the best configuration was less than 2% more than the baseline. At stall, the slope of the $C_m - \alpha$ curve changed sharply from negative to positive. Full-scale flight tests are under way to explore the behavior of flow energizers at full-scale Reynolds numbers and to measure the flowfield in the vicinity of the devices.

Nomenclature

C_L = lift coefficient
$C_{L\max}$ = maximum lift coefficient
C_D = drag coefficient
C_M = pitching moment coefficient
$C_{m\alpha}$ = slope of pitching moment curve vs α
C_ℓ = rolling moment coefficient
C_n = yawing moment coefficient
α = angle of attack
α_s = stall angle of attack

Introduction

FLOW energizers are small surfaces added to an airplane to alter flow characteristics in local regions. They serve much the same purpose as vortex generators, but flow energizers are mounted essentially parallel to a lifting surface rather than perpendicular to it. In this paper all flow energizers discussed will have a shape like that sketched in Fig. 1, that is, a highly swept half-delta planform with a leading-edge sweep angle of 75 deg. Flow energizers of this type develop vortex systems that add energy to the boundary layer and thus reduce or delay separation. Flow energizers have been used in place of the more common fillets at the wing/fuselage and the wing/nacelle junctions to improve handling qualities during landing, reduce separation-induced buffet, and improve stall warning.

Polhamus,[1] Wentz and Kohlman,[2] and Frink and Lamar[3] describe the use of delta-shaped surfaces, similar to those sketched in Fig. 1, to improve the capability of lifting surfaces. Typically, the devices (variously called strakes, leading-edge extensions, and vortex generators) depend on leading-edge sweep angles of 70 deg or more to generate the vortices that effectively increase the lifting capability of the main surface. More recently, similar but smaller devices have been installed on general aviation airplanes to provide higher energy flow near the wing/fuselage and wing/nacelle junctions. Wallis et al.[7] described this application, and they completed a limited wind tunnel test[4] to verify a specific configuration. Several other general aviation companies have expressed interest in the effects produced by such devices, but usable design data are not readily available.

In the spring of 1983, Texas A&M University was funded by NASA Langley Research Center (LaRC) to systematically investigate and identify the parameters that control design of flow energizer installations. The effort was funded as both an experimental and analytical program with the experimental research broken down into two phases: 1) wind tunnel testing of a light twin scale model and 2) full-scale flight testing of the same airplane. The first wind tunnel tests were completed in the fall of 1983 and this paper summarizes the results.[5] Though the objective of the wind tunnel work was limited to an overall estimate of desirable geometric parameters and to a relatively small number of configurations, the initial results should be of considerable interest to designers who contemplate using flow energizers.

The model, furnished by Gulfstream Aerospace Corporation, has a span of 80 in. and is shown mounted in the low speed wind tunnel (LSWT) in Fig. 2. For this series of tests, the model was modified with pressure orifices on the upper and lower surfaces of the left inboard section of the wing, on the left side of the fuselage, and on the right side of the left nacelle. Other changes[6] were made to strengthen the model and provide for the installation of the flow energizers. Data collected during these tests included force and moment measurements from the LSWT external balance, surface pressure data, and flow visualization using smoke and oil flow. Only the force and moment data are discussed in this paper. Trip strips (also shown in Fig. 2) were installed on leading edges to provide uniform boundary-layer transitions for all configurations. These trip strips were lengths of Chartpak tape (0.001 in. thick) fastened to the lifting surfaces at 5% of local chord and at the nose cone break on the fuselage. This precaution was taken so that small differences in measured forces and moments could be consistently compared, since the trip strips guaranteed transition to a turbulent boundary layer at a fixed position. All tests were run at a nominal dynamic pressure of 60 psf to keep the model from vibrating excessively at angles of attack near the stall. The Reynolds number based on model chord was nominally 1.4×10^6 at this dynamic pressure. For each flow energizer configuration, the angle of attack was varied from -4 deg up to the stall angle of attack in 2-deg increments.

Flow Energizer Design Parameters

The factors that affect the performance of a flow energizer configuration are not well understood at this time. Obviously, planform is a major contributor, but for these initial tests only one planform was selected. This choice was based on the work

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of Wallis,[4] which suggested a leading-edge sweep of approximately 75 deg. The only variation in the physical configuration of the flow energizer blades in this first stage of the study was a comparison between flat and cambered profiles. Camber was added to the blade sections by forming the energizers on a form block. The contour of the form block was obtained from the upper surface of the airfoil, starting at 2% chord aft of the leading edge. This initial look at only two blade shapes certainly should be carried further. Unanswered questions include:

1) Should the sweep angle be varied along the leading edge to produce a more robust vortex?

2) Could a simple low-aspect-ratio rectangular surface give similar favorable vortex patterns?

Another important design parameter is the distance between the lower surface of the energizer and the upper surface of the wing. More precisely, gap is defined as the distance from the leading edge of the wing to the chord of the energizer, measured perpendicular to that chord line. Figure 3 illustrates this definition. Evidently, gap plays an important role in controlling the amount of interaction between the vortex generated by the flow energizer and the accelerating flow over the upper surface of the wing.

The third design parameter, also illustrated in Fig. 3, is a measure of the longitudinal position of the flow energizer. Overlap is the percentage of wing chord covered by the energizer blade. Like the gap, overlap affects the vortex flow/accelerating flow interaction, but this parameter alters the streamwise location of this interaction rather than the vertical location affected by the gap. Overlap is a very important factor if the vortex bursts on the aft part of the wing or near one or more of the empennage surfaces. Overlap can be the most important design parameter when the flow energizer operates near the stall.

Finally, a measure of how much the streamlines are "squeezed" together by the venturi effect between the flow energizer and the wing upper surface is important. The parameter chosen was the convergence ratio, obtained by dividing the gap dimension by the distance from the wing upper surface normal to the flow energizer trailing edge. Again, Fig. 3 illustrates the definition. Convergence ratio is an empirical measure of the acceleration imparted to local flow because of the decreasing cross-sectional area between the two surfaces. The definition used for convergence ratio is not completely satisfactory in that it does not fully describe a converging-diverging region like the flat energizer sketched in Fig. 3. Simply considering the shape of this passage leads one to expect poor performance from such flow energizers. All the design parameters except the convergence ratio were investigated by Wallis,[4] but so far as is known by the authors, no systematic attempt to measure this effect has been made before. These first experimental results show that convergence ratio is one of the more important considerations.

To catalog flow energizer configurations conveniently, a systematic notation describing each of the four design parameters was needed. A four-element shorthand[5] was adopted. For example, an F1051.0 configuration was flat, overlapped the local airfoil section by 10% of the local wing chord, had a gap of 5% of the local wing chord, and had a

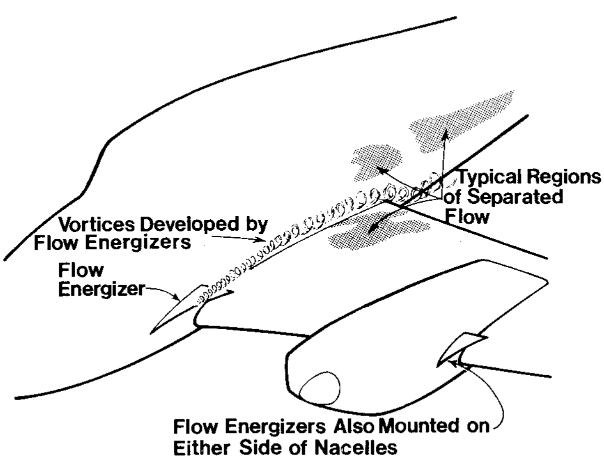

Fig. 1 Typical flow energizer installation.

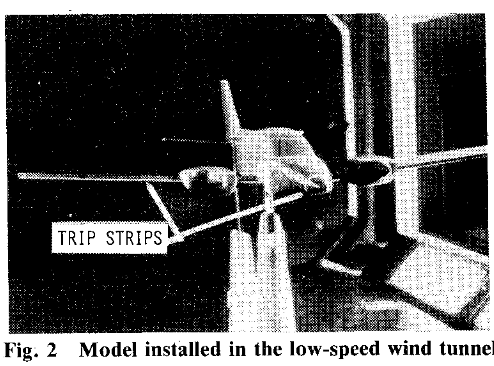

Fig. 2 Model installed in the low-speed wind tunnel.

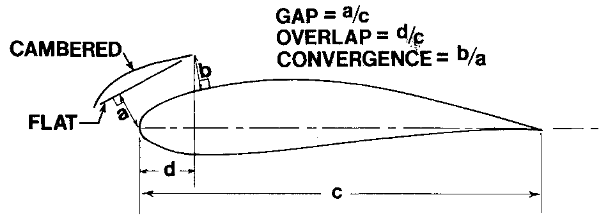

Fig. 3 Definition of gap, overlap, and convergence.

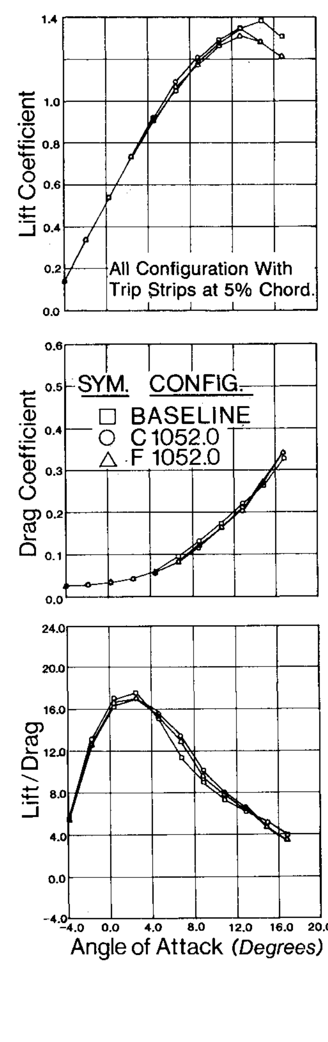

Fig. 4 Comparison of poorly optimized flow energizer configurations.

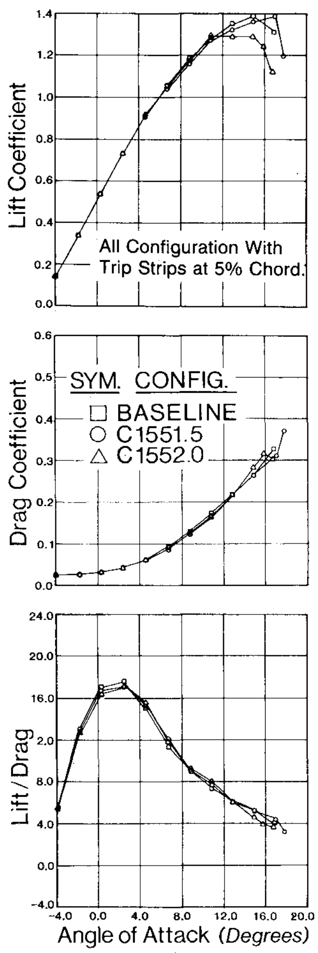

Fig. 5 Comparison of promising flow energizer configurations.

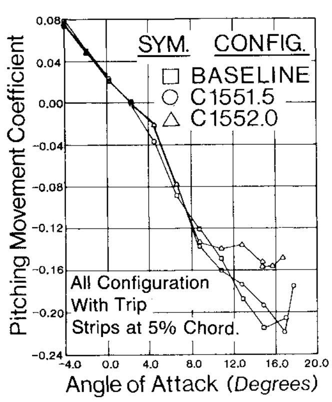

Fig. 6 Comparison of pitching moment coefficients.

convergence ratio of 1.0. This notation allowed easy reference to each of the fourteen configurations tested.

Wind Tunnel Results

First, the wind tunnel data showed that flow energizers are likely to degrade performance unless careful attention is paid to their placement. Only one of the fourteen flow energizer configurations tested produced a $C_{L\max}$ greater than the baseline airplane and a higher stall angle of attack. Even this $C_{L\max}$ improvement was so small that it is within the measurement errors. Figure 4 shows that indiscriminant choice of a flow energizer configuration may penalize the vehicle design. Increases in drag coefficient and decreases in L/D stand out in these data. The lift curve is essentially unchanged for all three configurations below about 5-deg angle of attack. Both the flat and cambered flow energizers gave the same stall angle of attack, about 2 deg less than the baseline model. The addition of either energizer had a negligible effect on the angle of attack for best L/D, and both configurations degraded the L/D ratio by 2 to 3% at cruise (approximately -2-to 0-deg angle of attack). These results for 10% overlap substantially agree with Wallis, et al. in their earlier study.[7] Similar results were obtained with an overlap of 15% and a gap of 2%. If the designer is careless with energizer placement, these data show that performance will be penalized.

As expected, cambered flow energizers outperformed flat ones in every case. The experimental results confirmed the expectation that the converging-diverging passage created by mounting a flat energizer above the cambered upper surface of the wing (see Fig. 3) would be aerodynamically inefficient. Figure 4 shows typical data for a pair of energizers that differ only in camber. Above about a 4-deg angle of attack, the drag coefficient for the cambered energizer shows slightly less drag, and the lift coefficient is greater than for the flat one. Obviously, the L/D ratio shows these combined effects, especially at higher angles of attack. At approximately 9-deg angle of attack, the cambered energizers give an increase of roughly 9% in L/D compared to the flat ones. The improvement in L/D is relatively unimportant at these angles of attack, but the difference between flat and cambered devices is noteworthy. These data also agree well with the previously cited paper[7] and suggest that the designer using flow energizers should camber them.

The results shown in Fig. 4 were typical of the first 12 energizer configurations tested and were not encouraging. However, when flow energizers C1551.5 and C1552.0 were run, the results were dramatically better. Figure 5 summarizes the results for these two configurations. Recall from the previous discussion that the only difference between these two configurations is the convergence ratio.

Even though the difference in convergence ratio is small, every one of the primary performance measures is affected. Even the lift curve is significantly altered. With a convergence ratio of 1.5, C_L flattens out at approximately 10-deg angle of attack and remains essentially unchanged until stall occurs at approximately 15 deg, the same as the baseline. Still, $C_{L\max}$ for configuration C1552.0 is 6% less than for the baseline. On the other hand, configuration C1551.5 has a $C_{L\max}$ about the same as the baseline, and the stall angle of attack is 17 deg. Clearly, the convergence ratio for these small appendages had a noticeable impact on the model's stall angle of attack. The data indicate that flow energizers carefully optimized for a given configuration may give increases in stall angle of attack but they have little effect on the maximum lift coefficient. Given the small size of these devices, it is not surprising that $C_{L\max}$ is unaffected. However, increasing the stall angle of attack, even without decreasing stall speed, may help separate minimum control speed and stall speed, thereby reducing the probability of a departure. If not, flow energizers of the type tested may be limited to controlling buffet level and to improving handling qualities.

The behavior of the drag curve and the flattening of the lift curve for configuration C1552.0 implies that the vortices produced by the energizers are bursting early. Better flow visualization techniques are being developed to explore this hypothesis and will be used in future tests.

The cruise performance with flow energizers installed was degraded only slightly in comparison with the baseline. At $L/D_{\max}$ both configuration C1551.5 and C1552.0 reduced this key performance parameter only about 2%. For cruise angles of attack, the loss in L/D was even less. Of course, it must be remembered that the baseline comparison was made to a configuration that had no fillets of any kind (see Fig. 4). No tests were run with fillets installed, and the degradation in L/D is likely to be more pronounced for optimized fillets on the baseline model. This comparison will also be made in later tests.

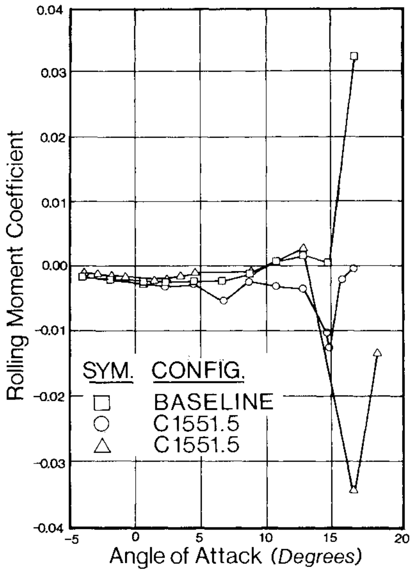

Fig. 7 Comparison of rolling moment coefficients.

In sum, the performance measures of merit associated with configuration C1551.5 are promising, especially if some means of increasing $C_{L\max}$ to go with the increase in angle of attack can be found. Of course, performance alone is not enough; one must also be concerned with any changes in stability and controllability.

Though these wind tunnel tests were aimed primarily at performance measures of merit, static moment data were also recorded. The pitching moment curve of Fig. 6 raises questions about the effects of flow energizers on static longitudinal stability.

Again, the importance of careful selection of a convergence ratio is emphasized by the results. Configuration C1551.5 and C1552.0 both caused changes in the slope of the pitching moment curve. C1551.5 gave slightly more longitudinal static stability than the baseline for angles of attack between approximately 5 and 9 deg. The improvement is small, however, and may be more than offset by decreased static stability around 12-deg angle of attack. In both of these cases, static stability persisted up to the stall angle of attack. But the most noteworthy feature of Fig. 6 is the near neutral stability produced by the off-optimum choice of convergence ratio in configuration C1552.0. At 9-deg angle of attack, roughly 2 deg before C_L flattened out, the slope of the pitching moment curve approached zero. This behavior once again suggests vortex bursting, perhaps near the horizontal tail, starting at about 9-deg angle of attack and moving forward to affect the wing's lifting ability at about 11 deg. This hypothesis still must be confirmed with better flow visualization than was available for this initial series of tests.

The lateral-directional handling qualities may also be altered by the addition of flow energizers. For the application of the energizers considered in this paper, this handling qualities aspect is particularly significant at and near the stall. How different are the rolling and yawing moments? The static moment coefficient data suggest that careful evaluation of the stall behavior may be in order. Figure 7 illustrates the measured increments in rolling moment between the baseline and the C1551.5 configurations. The rolling moment coefficient measured in different runs has opposite signs at the higher angles of attack. Model vibration was a significant problem and may have been the cause of these differences, especially near the stall angle of attack. Whether or not this increment is peculiar to the wind tunnel model remains to be seen; at least, the data suggest that flight tests should cautiously approach the stall with flow energizers installed. It should be noted that this large difference in rolling moment coefficients is mostly due to a large increase in rolling moment for the baseline configuration. The changes in rolling moment coefficient for the C1551.5 configuration are an order of magnitude less than for the baseline model. This fact, plus the docile stall characteristics of the actual airplane with no fillets as it approaches the stall, leads the authors to believe that the rolling moment data from the wind tunnel may not reflect the behavior of the airplane.

Conclusions and Recommendations

Even at this early stage of the study of flow energizer design criteria, the following conclusions can be drawn:

1) Cambered energizers provide the best overall performance promise. Even a relatively crude way of cambering the energizer blades gave better L/D ratios and higher maximum C_L than flat ones. Any designer contemplating the use of flow energizers should plan to use cambered shapes. How to optimize camber for these devices needs further study.

2) The data from this series of tests confirm that overlaps on the order of 15% of the local chord and gaps on the order of 5% are more likely to produce the vortex strengths needed. Considerably more study of the bursting locations of the vortex interactions is required to better understand why the forces and moments behave as they do. These data are especially needed to interpret changes in moment coefficients.

3) Convergence ratio is a very important design parameter in choosing a flow energizer configuration. The differences between configurations C1551.5 and C1552.0 were greater than for any of the other measured differences. Several convergence ratios must be examined in flight where the Reynolds number effects are not present.

Acknowledgments

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