TURBULATOR GEOMETRY INFLUENCE ON TRIPPING EFFECTIVENESS BASED ON LOW-SPEED WIND-TUNNEL DATA

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Abstract

An experiment was conducted to determine the relative tripping effectiveness of different turbulator-tape geometries. Oil-flow photographic data were obtained in a low-speed wind tunnel for the upper surface of a Wortmann FX-63-137 airfoil two-dimensional wing section. Meaningful flowvisualization data were obtained for several turbulator geometries that demonstrate different degrees of effectiveness for each turbulator configuration tested. A statistical compilation of the data quantitatively illustrate increased tripping effectiveness for a specific configuration tested, over the standard Z-patterned tape currently in use.

1. Introduction

The present investigation was performed to assess the effectiveness of different turbulator geometries in a controlled ground-test experiment using a wing model employing a Wortmann FX-63137 airfoil. The selection of this airfoil was based on (1) the extent of laminar flow expected over the upper surface, and (2) the use of this airfoil in a previous study whose results will be discussed below. While different types of turbulator-tape geometries are considered effective in promoting boundary-layer transition to avoid laminar separation, several geometries are considered to be more effective for a given application. Z-patterned tape is commonly used in many ground and flight applications, with 90° and 60° wedge patterns on the tape leading edge (or both leading and trailing edges) being the most common.

Numerous experiments have been conducted using oil-flow visualization to qualitatively understand the boundary-layer behavior over aerodynamic surfaces. Since the effect of the oil flow on the boundary-layer motion should be minimal for the model locations and freestream conditions of interest in this study,[1] meaningful observations and quantitative measurements of the relevant flow topologies can be made with this technique.

The study was based on obtaining data that are more precise than those obtained in a previous investigation of these effects. The previous investigation[2] was a practical test conducted using a larger model of the same FX-63-137 airfoil and a special ground-test rig mounted atop an automobile. Very little differences were observed between the limited number of Z-pattern turbulator geometries tested ($Re = 0.34 \times 10^6$ to 0.36×10^6), and it was recommended that more precise data obtained in a wind tunnel may demonstrate effects that could not be observed in this earlier test. In addition, while the previous study provided qualitative observations, the present study includes quantitative data measurements with a comparison of run-to-run variability using smooth-wall transition data, and a statistical treatment of the results obtained.

Figure 1. Wortmann FX-63-137 Airfoil

2. Experimental Arrangement

A plastic, two-dimensional wing model was constructed using a spline fit of published coordinate points for the FX-63-137 airfoil.[3] A chord of 6.0 inches (152.4 mm) and span of 24.0 inches (609.6 mm) were selected to provide a reasonable simulation scale, compatibility with the Villanova University 24-inch Open Circuit Wind Tunnel constraints, and a model scale large enough to enable use

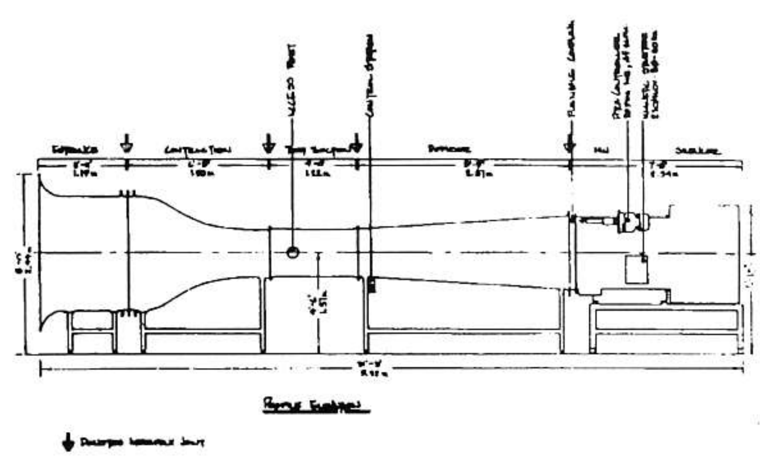

Figure 2. Open Circuit Wind Tunnel

of commercially available tape thickness for turbulator fabrication. The model was finished in white for these flow-visualization tests and was polished to provide an aerodynamically smooth surface. The airfoil profile is shown in Figure 1.

The Villanova University 24-inch Open Circuit Wind Tunnel[4] is shown schematically in Figure 2. While a quoted turbulence of 2% was associated with this facility, implying a relatively high turbulence factor,[5] the smooth-wall transition data discussed in the following sections demonstrate transition characteristics that agree with published results for this wing section. In addition, since the primary focus of this study is not to define airfoil performance characteristics, but to parametrically assess different turbulator geometries at a fixed freestream condition, the test facility was deemed appropriate for this study. The 24 x 24 inch test section walls were constructed of 3/4-inch Plexiglas to facilitate model photography, and provide easy model access. Model positioning was limited to angle-of-attack adjustments, measured using a vernier reading of the model mounting end-plate (disc) relative to the fixed test-section wall.

The use of Z-patterned tape is commonly found in both ground and flight applications,[5-10] and most patterns incorporate either 90° or 60° patterns on the tape leading edge with either a straight trailing edge, or on both leading and trailing edges. While the previous study[2] examined 60°, 90°, 120°, and 180° (flat) leading-edge wedge angles (Figure 3), the current study incorporated the testing of six different patterns as shown in Figure 4 (the flow direction is from the top of the figure toward the bottom). Configurations 1 and 6 were produced using standard pinking shears and have a wedge angle of approximately 116°. The other patterns were produced using non-standard shears to easily produce the patterns illustrated. The leading-edge arcs shown for configurations 2, 4, and 5 are approximately circular in planform. The selection of these candidate patterns evolved from preliminary wind-tunnel test runs performed to optimize the photographic settings and oil-flow application procedure used for the subsequent primary wind-tunnel runs.

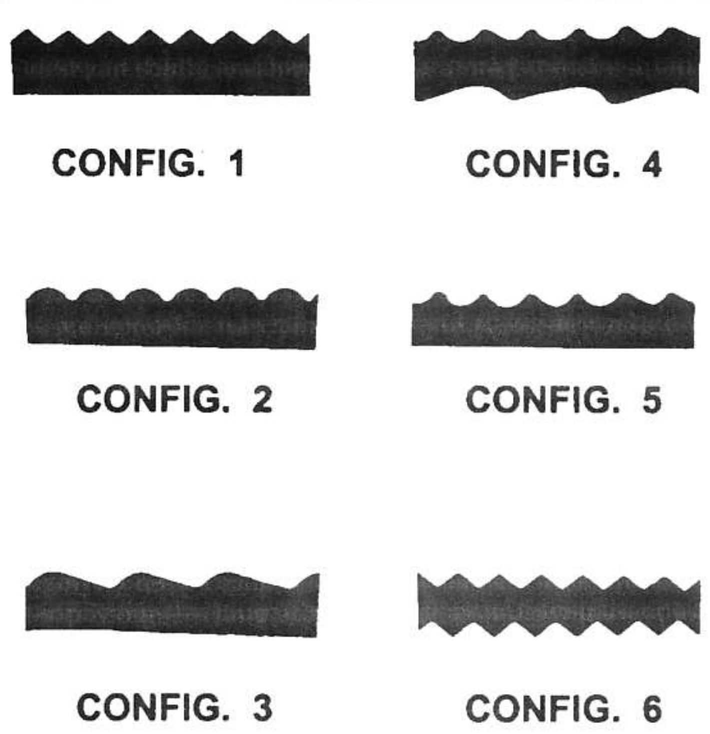

Figure 4. Present Study Turbulator Patterns

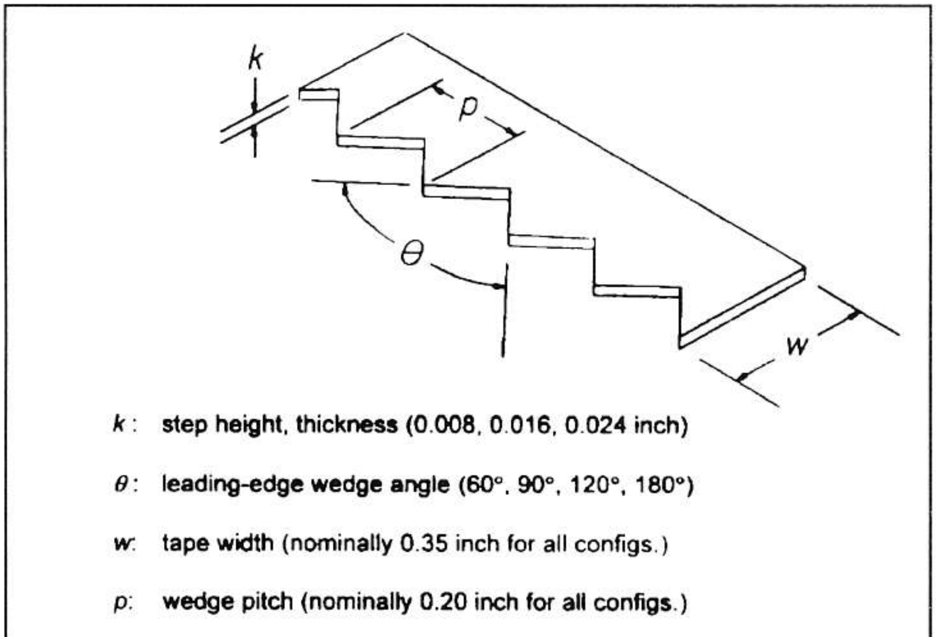

Figure 3. Previous Study[2] Turbulator Patterns

Final turbulator-tape patterns were pre-cut from Scotch (3M) "Super Strength Packaging Tape." This tape provided a high-contrast color for photographic resolution, and turbulator step height (tape thickness) could be varied by using multiple layers of tape and verifying the composite thickness with a micrometer. The nominal thickness of a single layer of tape was 0.0030 inch (0.076 mm).

In order to obtain valid and meaningful data, a consistent procedure was used to apply the oil film, conduct the test run, and photograph the results. Prior to each run, a thin coat of oil was brushed over the upper wing surface in spanwise strokes. The selected oil was used (dark) SAE 10W-40 motor oil, based on the successful results obtained in prior ground and flight-test applications.[10-13] For additional photographic contrast, a small amount of dark blue food coloring was added to the oil. The ambient temperature during the test was approximately room temperature, therefore the mixture of additional thinning agents was not necessary during this test. Resulting oil-flow patterns were photographed during and immediately after each run to record the fresh streaks before any significant "wind-off" effects could perturb the streak pattern.

3. Oil-Flow Visualization Data Assessment

A test matrix was developed to conduct all wind-tunnel entries in a methodical, logical, and efficient order, and to maximize the usefulness of the information obtained in order to further modify the matrix for maximum run efficiency and data accuracy as the test proceeded (i.e., to maximize the output per run while collecting a complete, valid, and meaningful database). The primary test sequence involved: (1) smooth-wall (no turbulator) runs at zero angle of attack, and at various Reynolds numbers to determine where, and if, natural transition occurs; (2) selecting a nominal Reynolds number to conduct trip-height (k) effects for a nominal turbulator pattern, and establishing the height that is marginally effective for specific trip locations (x); and (3) selecting a nominal trip location to conduct runs that parametrically vary trip geometry (the main focus of this study). Preliminary runs were conducted to establish test requirements for photographic lighting, camera placement, and appropriate run times. For camera convenience, the model was mounted inverted. The nominal test conditions achieved were $Re_{c\infty}=0.35\times10^6$ (u_∞ = 110 ft/s, 33.5 m/s).

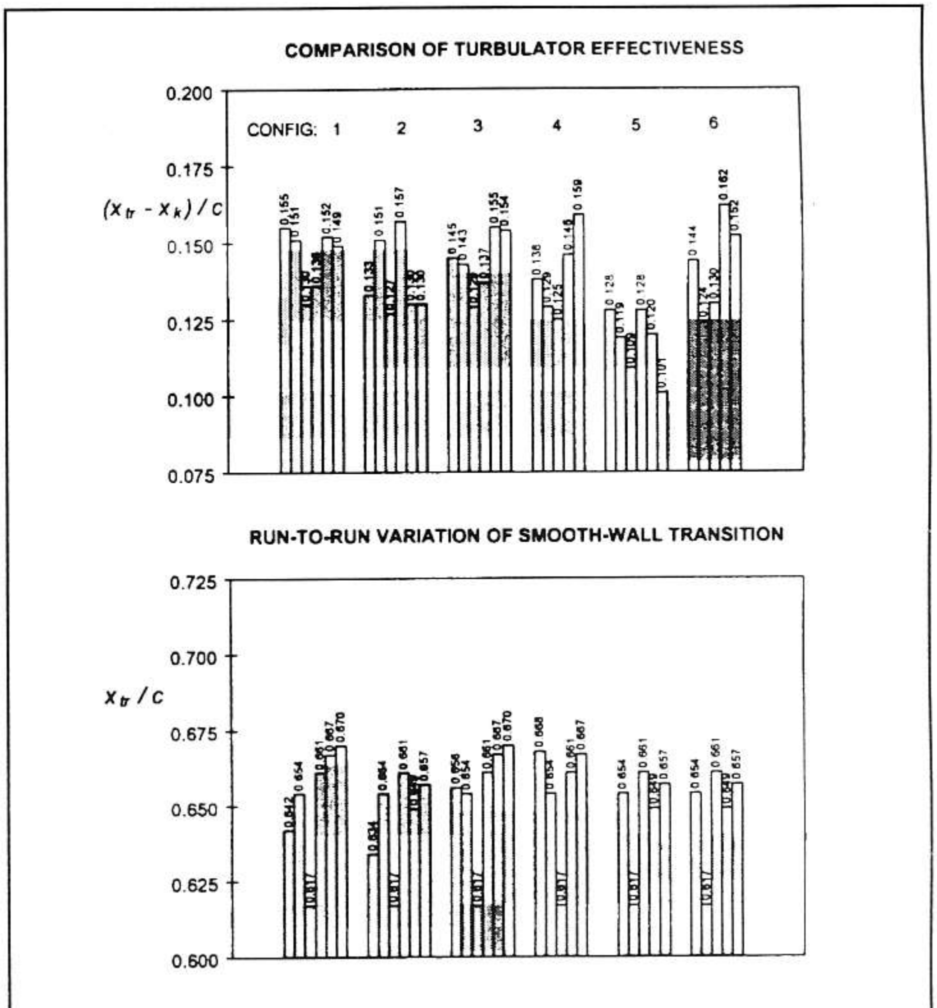

Figure 5. Turbulator Effectiveness and Run Variability

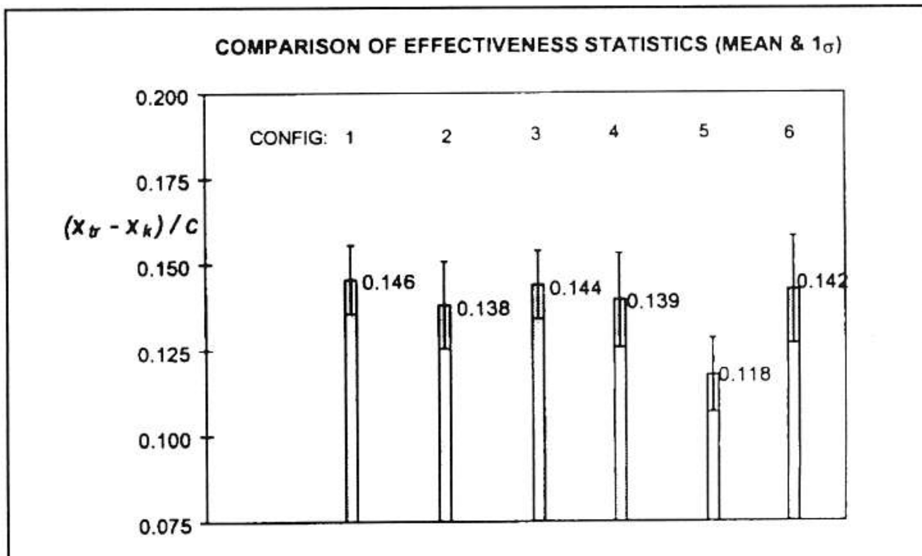

Figure 6. Turbulator Effectiveness Statistics

After the smooth-wall runs were conducted, runs with turbulators were performed by applying the turbulator to the left side of the model and leaving the right side with no turbulator. This served the important purpose of assessing any runto-run variability during the test, and provided tare references for comparison with "turbulator-on" flow patterns. This was achievable due to the predominantly two-dimensional flow over the airfoil at zero angle of attack. The repeatability of smooth-wall transition location was demonstrated for all smooth-wall runs (no turbulator on model), and the right side of the wing for all other "turbulator-on" runs performed. In addition, the smooth-wall transition location measured for this installation arrangement, $x/c \approx 0.63\text{-}0.67$, agrees with published data for the FX-63-137 airfoil at similar Reynolds numbers.[14]

After primary runs were completed with a single turbulator configuration on the left side of the model, additional repeat runs were conducted to demonstrate data repeatability. In addition, runs with three turbulator configurations on the left side were performed to determine if the "two-dimensionality" of the flow provided minimal spanwise effects in order to obtain more configuration data per run. While this was demonstrated, it was carefully implemented, since close examination of the photo details do indicate spanwise effects on a small scale (of the order of the turbulator pattern's spanwise pitch, p), therefore the spanwise extent of a given configuration was always significantly larger (approximately several inches) than this small-scale effect (on the order of several millimeters).

4. Turbulator Effectiveness Comparisons

The definition of turbulator effectiveness used in this study is the distance downstream of the turbulator leading edge where the flow becomes fully turbulent, as evidenced by the thinner oil film over the airfoil surface, $(x_{tr} - x_k)/c$, with smaller distances indicating greater effectiveness (all x are measured from the wing leading edge). In Figure 5, a comparison of turbulator effectiveness is shown for the 6 configurations tested. The bottom of Figure 5 also shows the run-to-run variability (x_k for the smooth, right side of the model) for each corresponding run at the top of Figure 5. This was provided to give an indication of the variability experienced and assigned to each run. All runs shown were obtained at $Re_{cx} = 0.35\text{x}10^6$, $\alpha = 0$, $x_k/c = 0.43\text{-}0.44$, and $k = 0.006$ inch (0.15 mm). For procedural consistency, the same analyst performed the examination of each photo in an attempt to minimize any additional variability due to photo interpretation.

The mean and standard deviation of effectiveness for each configuration were calculated and are shown in Figure 6. While the standard configurations (configurations 1 and 6) show similar performance, slight differences are shown for configurations 2 through 5. Configuration 5 clearly demonstrates significantly more effectiveness than the other configurations considered. The standard deviation bounds for configuration 5, based on the data shown in Figure 5, barely overlap the bounds of any other configuration tested.

It is unknown why configuration 5 is so much more effective than configuration 4, unless the trailing edge of the configuration-4 turbulator provides a canceling effect to the tripping generated by the leading-edge pattern (configurations 4 and 5 incorporate the same leading-edge pattern).

5. Conclusions and Recommendations

An assessment of the data obtained shows that the turbulator configurations studied demonstrate different tripping effectiveness. One configuration (configuration 5) provided results that clearly demonstrate greater tripping effectiveness compared to standard Z-patterned turbulators (configurations 1 and 6). Application of turbulators with increased effectiveness may provide benefits in overall aerodynamic performance for glider and general aviation, marine/hydrodynamic applications, and control-surface development in unmanned or micro aerial vehicles (UAV, MAY), since these vehicles are expected to operate in low to very low Reynolds number conditions[15] where the control of laminar flow separation, and efficient aerodynamic performance, may require further development work.

It is recommended that as additional data on turbulator-tape geometry effects become available from future ground and flight tests, and to the extent that any sign)ficant effects are demonstrated, these results should be gathered, correlated and made available to the soaring/aerodynamics community. It is also recommended that infrared (IR) thermography techniques, successfully used in ground and flight-test visualization of global transition patterns,[16] be incorporated in future studies as these imaging systems are perfected, miniaturized, and become more affordable.

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