FLIGHT-TEST OF TURBULENT SKIN-FRICTION REDUCTION BY RIBLETS

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1. SUMMARY

Plastic riblet film developed by the 3M Company was flight tested on the upper surface of the wing of a T-33 airplane. Increments in the average skin friction of the riblet surface relative to a smooth surface were determined by rakes of pitot tubes at 83 percent chord. For optimum combinations of groove spacing and Reynolds number, average skin-friction reductions of about 6 percent were observed. The local scaling relationship implied by earlier NASA data was found to apply in an average sense over the length of the test surface, and the riblets were found to remain effective in the adverse pressure gradient on the aft portion of the wing. Finite-difference calculations of the boundary-layer development, with a modification to the eddy viscosity to account for the riblet effect, were found to be helpful in interpreting the data.

2. INTRODUCTION

Riblets, or longitudinal surface grooves, have been shown to be effective in reducing the skin friction of turbulent boundary layers in wind tunnel tests at NASA Langley (Refs. 1 and 2) and elsewhere. Fig. 1 illustrates the symmetrical, saw-tooth riblet form that has proved most effective so far and shows a sample of the measured values of $D/D_p$, the ratio of the friction drag of the specimen to the drag of a corresponding smooth specimen. These NASA data show a clear correlation between the drag-reduction effectiveness of the riblets and the riblet spacing $s^+ = s u_c/\nu$ expressed in turbulent-boundary-layer wall units.

Based on this correlation, a riblet spacing of about 0.002" should be optimum for drag reduction on current subsonic jet transport airplanes. In an effort to develop such a surface for aircraft applications, the 3M Company, in cooperation with NASA, has developed a method of molding riblets into thin plastic films with adhesive backings. It has been estimated at Boeing that a riblet surface of this type could reduce the total cruise drag of a transport airplane by 2 to 3 percent, resulting in a somewhat smaller percentage saving in fuel consumption. Before such a surface can be put into service on airplanes, however, numerous practical difficulties must be overcome, and some remaining questions concerning aerodynamic effectiveness must be answered. There are still relatively few data for transonic Mach numbers, for the kinds of pressure gradients usually encountered on aerodynamic surfaces, or for three-dimensional flows.

In an effort to answer some of these aerodynamics questions, Boeing has carried out flight-test measurements of the drag reduction of experimental riblet materials produced by 3M. The test was aimed at the near-term practical goal of applying riblets to production airplanes, and its scope was limited to simple measurements of the drag reduction.
obtained. The longer-term goal of providing a more general understanding of the riblet effect was not addressed.

3. TEST SURFACE AND INSTRUMENTATION

The basic experimental technique was to measure boundary-layer mean-velocity profiles behind test specimens placed on the upper surface of one wing of a T-33 jet trainer, as shown in Fig. 2. Increments in skin-friction drag between different specimens tested on different flights were inferred from increments in the measured boundary-layer momentum thickness \( \theta \). All else being equal, an observed decrease in \( \theta \) should correspond to the same percentage decrease in an average of the skin friction upstream of the measurement station. This can be a sensitive method of detecting increments in skin friction, provided that changes in pressure distribution are small and essentially two-dimensional so that they can be accounted for approximately. It was for this reason that the wing surface was chosen in preference to the fuselage, even though longer specimens could have been tested on the fuselage. Three-dimensional
Fig. 2  Test surface and instrumentation on T-33 airplane.

effects are much more important in the fuselage boundary layer, and changes would have been very difficult to account for.

As shown in Fig. 2, the test surface was instrumented with pressure belts to measure the static-pressure distribution and boundary-layer pitot rakes to measure boundary-layer mean-velocity profiles at x/c = 0.83. The boundary layer on the test surface was tripped at x/c = 0.05 by a row of epoxy discs of 0.05" diameter and 0.008" thickness on 0.10" centers that remained in place for all flights. The inboard half of the test surface served as a reference surface and was covered with a smooth plastic film on all flights. Data from the reference surface were used to correct for unavoidable small changes in test conditions from one flight to another as will be explained in Section 4. The outboard half of the test surface was covered with a smooth plastic film on one flight (the reference flight) and with various configurations of riblet films on succeeding flights. In each case the leading edge of the plastic film specimen was positioned at x/c = 0.07, far enough behind the trip discs to ensure that the boundary layer was turbulent over the entire test specimen. For each riblet configuration tested, the measured values of e for up to 15 different flight conditions (speeds and altitudes) were compared with the values measured under corresponding conditions during the reference flight with a smooth surface. Fig. 3 illustrates the observed change in the measured boundary-layer velocity profile for a typical condition where $\frac{e}{\theta_{smooth}} = .955$, a 4.5 percent reduction in $e$. (Note that at the first measured point is much greater than the sublayer thickness, and that the higher velocity with riblets does not imply that $au/ay$ at the wall was greater).
Typical Boundary Layer Survey Data With Riblet Coatings

Condition 13

\[ M = 0.70 \quad C_L = 0.08 \quad R/ft = 4.27 \times 10^6 \]

\[ x/c = 83\% \quad \bar{c}_{avg} = 76 \text{ in.} \]

\[ \frac{\theta}{\theta_{smooth}} = .955 \]

4. TEST CONDITIONS

One goal of the test was to cover the entire favorable range of \( s^+ \). To this end we used riblet specimens of two different groove spacings (\( s = 0.0013'' \) and 0.003'') in combination with test conditions that covered the widest range of unit Reynolds number of which the airplane was routinely capable. The 15 nominal flight conditions that were attempted on each flight are listed in Table 1 and shown in Fig. 4, and corresponding chordwise pressure distributions, averaged from the two pressure belts are shown in Fig. 5. Covering a wide range of Reynolds number required a wide range of lift coefficients. One feature all of the pressure distributions have in common, however, is that on the upper surface there is little or no adverse pressure gradient forward of 40 to 50 percent chord.
Table 1 Nominal flight conditions

<table>
<thead>
<tr>
<th>Cond</th>
<th>M</th>
<th>C_L</th>
<th>Hpft</th>
<th>R/ft x 10^6</th>
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<tr>
<td>1</td>
<td>.625</td>
<td>.43</td>
<td>34050</td>
<td>1.55</td>
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<td>2</td>
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<tr>
<td>3</td>
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<td>.50</td>
<td>32250</td>
<td>1.45</td>
</tr>
<tr>
<td>4</td>
<td>.625</td>
<td>.30</td>
<td>26800</td>
<td>2.00</td>
</tr>
<tr>
<td>5</td>
<td>.70</td>
<td>.20</td>
<td>23000</td>
<td>2.52</td>
</tr>
<tr>
<td>6</td>
<td>.50</td>
<td>.375</td>
<td>22350</td>
<td>1.80</td>
</tr>
<tr>
<td>7</td>
<td>.45</td>
<td>.45</td>
<td>22000</td>
<td>1.64</td>
</tr>
<tr>
<td>8</td>
<td>.70</td>
<td>.15</td>
<td>17000</td>
<td>3.04</td>
</tr>
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<td>9</td>
<td>.55</td>
<td>.25</td>
<td>18250</td>
<td>2.28</td>
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<tr>
<td>10</td>
<td>.70</td>
<td>.12</td>
<td>12400</td>
<td>3.50</td>
</tr>
<tr>
<td>11</td>
<td>.35</td>
<td>.40</td>
<td>8400</td>
<td>1.93</td>
</tr>
<tr>
<td>12</td>
<td>.625</td>
<td>.12</td>
<td>7550</td>
<td>3.57</td>
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<tr>
<td>13</td>
<td>.70</td>
<td>.08</td>
<td>4100</td>
<td>4.43</td>
</tr>
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<td>14</td>
<td>.55</td>
<td>.15</td>
<td>7400</td>
<td>3.16</td>
</tr>
<tr>
<td>15</td>
<td>.45</td>
<td>.20</td>
<td>6100</td>
<td>2.67</td>
</tr>
</tbody>
</table>

Because of unavoidable variations in atmospheric conditions and aircraft weight, the nominal flight conditions were never matched exactly. Thus in comparing results from different flights, as in comparing the riblet test surfaces with the smooth test surface on the reference flight, the question arises as to how to account for these small differences in flight conditions. Several methods were tried, including using the measured pressure distributions in conjunction with numerical calculations of boundary-layer development. However a very simple method using the measured momentum thicknesses on the reference surface proved to be the most satisfactory in the sense of producing the least scatter in the final data plots. It is based on the assumption that a change in flight condition, between a given flight and the reference flight, would change both values of momentum thickness (on the test surface and the reference surface) by the same factor if the test surface had been smooth on both flights. The momentum thickness ratios reported in Section 5 were thus corrected by the formula:

\[
\frac{\theta_{\text{riblet}}}{\theta_{\text{smooth}}} = \frac{\theta_{\text{riblet flight}}}{\theta_{\text{reference flight}}} \times \frac{\theta_{\text{reference flight}}}{\theta_{\text{riblet flight}}} = \frac{\theta_{\text{reference}}}{\theta_{\text{riblet}}} \times \frac{\theta_{\text{riblet}}}{\theta_{\text{reference}}} \]


Fig. 4  Nominal speed - altitude schedule.
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Fig. 5 Pressure distributions corresponding to nominal flight conditions.
The first ratio on the right can be regarded as the primary measurement of the riblet effect. The second term is a correction that would ideally take on a value of unity if flight conditions were identical on the two flights.

5. EXPERIMENTAL RESULTS

Data were taken on six flights, including the reference flight. The configurations of the test surface for all of these flights are listed in Table 2.

Table 2 Test-surface configurations

<table>
<thead>
<tr>
<th>Flight</th>
<th>Film Type</th>
<th>Coverage x/c to x/c</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Smooth</td>
<td>0.07 0.83</td>
<td>Reference surface</td>
</tr>
<tr>
<td>2</td>
<td>Riblets; s = .003&quot;</td>
<td>0.07 0.83</td>
<td>Large grooves; full surface</td>
</tr>
<tr>
<td>3</td>
<td>Riblets; s = .0013&quot;</td>
<td>0.07 0.83</td>
<td>Small grooves; full surface</td>
</tr>
<tr>
<td>4</td>
<td>Riblets; s = .0013&quot;</td>
<td>Smooth; 0.07 0.50 0.50 0.83</td>
<td>Small grooves; divided surface</td>
</tr>
<tr>
<td>5</td>
<td>Riblets; s = 0.0013&quot;</td>
<td>0.07 0.83</td>
<td>Small grooves; yawed 15°</td>
</tr>
<tr>
<td>6</td>
<td>Riblets; s = 0.0013&quot;</td>
<td>0.07 0.83</td>
<td>Film perforated; 0.02&quot; diameter holes on 0.25&quot; centers</td>
</tr>
</tbody>
</table>

Reynolds Number Scaling

The basic scaling of the riblet effect with groove spacing or Reynolds number was investigated on flights 2 and 3, with riblet film covering the test surface from 7 percent chord to the rake location at 83 percent. The simplest global way of presenting the data is to plot the e ratios (corrected as described in Section 4) versus $R_s = \frac{V_0}{\mu}$, as is done in Fig. 6. The data for the two different groove spacings overlap around $R_s = 400$ and define both the low and high ends of the favorable range. For $R_s$ above about 300 the e ratios of Fig. 6 display a trend very similar to that of the NASA flat-plate $C_f$ ratios of Fig. 1. Over the range of Reynolds number covered by our test, the global parameter $R_s$ is close enough to being proportional to the wall-region scale $s^*$ that the basic trend is not distorted. Over a wider range of Reynolds numbers, however, we would expect the wall-region scaling to be more general.
Fig. 6 Measured θ ratios for two different riblet spacings.

In the NASA wind-tunnel experiments, a local value of s* is easy to define because the test specimens were relatively short, so that C_f, and thus s*, were nearly constant along the length of a specimen. In our test, C_f varied considerably over the length of a test specimen, and thus the only simple way to define a single wall-region scale is by averaging s*. Because we did not measure C_f directly, we relied on the boundary-layer calculations described in Section 6 to define s*. In Fig. 7 the calculated distributions of s* for a range of flight conditions show that s* varied by roughly a factor of two over the length of the test specimen.

In Fig. 8 the data from flights 2 and 3 are plotted versus s*, the calculated s* averaged over the length of the test specimen. For comparison the scatter band of the NASA C_f ratios is indicated by the dashed lines. In making this comparison we should point out that θ ratios and C_f ratios are roughly comparable in this case because the modification was in effect over nearly the entire surface over which the growth in θ took place. In the most favorable range of s*, between 10 and 20, there is a noticeable shift upward of the T-33 scatter band relative to the NASA scatter band. At least part of the shift is due to the fact that the trend of the data is concave upward, and the s* value for each T-33 data point represents an average of a range of local s* values. The T-33 data show a favorable effect (drag reduction) over the range of s* between about 6 and 25, with optimum drag reduction averaging about 6 percent for s* between 10 and 15.

Pressure-Gradient Effect
To investigate the effectiveness of riblets in an adverse pressure gradient, we devised the configuration tested on flight 4, in which a smooth plastic film replaced the riblets aft of x/c = 0.50, which is
<table>
<thead>
<tr>
<th>COND.</th>
<th>$M_\infty$</th>
<th>$C_L$</th>
<th>$R_{1/4} \times 10^6$</th>
<th>$%_{\text{smooth}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>.625</td>
<td>.12</td>
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<td>.955</td>
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<tr>
<td>1</td>
<td>.625</td>
<td>.43</td>
<td>1.5</td>
<td>.970</td>
</tr>
</tbody>
</table>

Fig. 7 Computed local $s^+$ for $s = 0.0013''$.

Fig. 8 Measured $\theta$ ratios compared with NASA $C_f$ ratios.
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...where the adverse pressure gradient begins on the T-33 wing under most flight conditions. The measured \( \theta \) reductions, shown in Fig. 9, are less than half as large as those shown in Fig. 8, where the riblet film extended all the way to the boundary-layer rake at \( x/c = 0.83 \). Thus the riblets aft of \( x/c = 0.50 \) in the configuration of Fig. 8 were effective in spite of the adverse pressure gradient.

![Graph showing \( \theta \) ratios with riblets on forward portion of test surface only.](image)

**Fig. 9** Measured \( \theta \) ratios with riblets on forward portion of test surface only.

**Effects of Misalignment and Perforations**

Also investigated (Flight 5) was the effect of applying the riblets in an orientation yawed 15 degrees from the flight direction. In Fig. 10 the benefit is seen to be reduced by more than half relative to Fig. 6, which is a somewhat stronger effect of yaw than was observed by NASA (Refs. 1 and 2). On flight 6, the riblet film was perforated with 0.020" diameter holes on 0.25" centers, which is currently being considered as a method of allowing for the escape of cabin pressurization air that may leak around rivets in fuselage skins. Relative to Fig. 6, the benefit, shown in Fig. 11, was reduced by about half, indicating that smaller perforations will be needed if the full benefit of riblets is to be realized on pressurized parts of an aircraft.

6. **BOUNDARY-LAYER CALCULATIONS**

The boundary-layer calculations carried out in the course of this study served two main purposes:
Fig. 10 Measured $\theta$ ratios for riblets yawed 15° from flight direction.

1) They provided an estimate of $s^+$ along the length of each test specimen so that the experimental results could be plotted versus $s^+$ in Figs. 8 and 9, and

2) They established a curve-fit for the effect of riblets on eddy viscosity so that the boundary-layer code can be used as a convenient tool for estimating the benefit of riblets in future applications.

We used the three-dimensional finite-difference computer program developed at Boeing reported in (Ref. 3), running the code in a special mode in which it performs only a two-dimensional integration, solving the equations for an infinite swept wing with taper effects. The mean equations of motion solved were thus equivalent to those used by Bradshaw (Ref. 4) for tapered wings, except that boundary-layer thickness was assumed to scale with $c^{0.8}$ rather than linearly. The turbulence model was a three-dimensional version of the eddy-viscosity model of Mellor and Herring (Ref. 5).

As part of this study we developed a modification to the eddy-viscosity to model the effect of riblets. Because the riblet effect has been shown experimentally to scale with turbulent-boundary-layer wall units, the same dimensional arguments can be applied as to the case of distributed surface roughness. The result (see Rotta, Ref. 6) is that the eddy-viscosity is modified only in the inner layer, and the modification takes the form of a shift $\Delta y^*(s^+)$ in the normal coordinate expressed in wall units. For surfaces that produce only small changes in local skin friction, such as riblets or sand-grain roughness with $k^+ < 25$, the change in skin-friction is directly proportional to $\Delta y^+$. Thus if the percentage change in skin-friction is known, the corresponding $\Delta y^+$ can
Fig. 11 Measured $\theta$ ratios for riblet film with perforations.

be determined directly from the known behavior of the eddy viscosity model. For the range of $s^+$ greater than about 10, we used a curve-fit through the middle of the NASA flat-plate data of Fig. 1 in this way to determine $\Delta y^+(s^+)$. For the lower range of $s^+$, we determined the curve by trial-and-error so as to obtain the best overall prediction of our own data from the T-33. The resulting composite curve is shown in Fig. 12 along with a curve for standard sand-grain roughness for comparison.

The curve $\Delta y^+(s^+)$ of Fig. 12 is defined in the computer program as a table of discrete values at small intervals in $s^+$. When the effects of riblets are to be computed, the code is run in the conventional way, but with the riblet spacing $s$ as an additional input. In its calculation of the eddy-viscosity, the code determines the appropriate $\Delta y^+$ as a function of $s^+$ by interpolation of the table.

With this representation of the riblet effect in place, we ran the code for all the flight conditions of flights 1 through 4. Measured static pressures, interpolated from the spanwise locations of the pressure belts to the location of the outboard pitot rake, were used as inputs. The predicted momentum thicknesses for flight condition 1 with the smooth film (flight 1) and 0.003" riblets (flight 2) are shown in Fig. 13 along with the measured values at the rake location. Because the cross-flow angles predicted in the calculations were small, they were ignored, and the predicted velocity magnitudes were used to define $\theta$. In this particular case the increment in $\theta$ due to riblets was well predicted, although the absolute level of $\theta$ was underpredicted by a few percent. Fig. 14 compares the predicted and measured increments, relative to flight 1, for all of the conditions on flights 2, 3, and 4. For the larger riblet spacing on flight 2, values of $s^+$ were predominantly in the
Fig. 12 Empirical function used to modify eddy viscosity model for boundary-layer calculations. Corresponding function for sand-grain roughness included for comparison.

Fig. 13 Calculated and measured $\theta$ for a typical flight condition with and without riblets.
Fig. 14 Comparison of calculated and measured $\theta$ ratios.

higher range where we used NASA data to establish the $\Delta y^*$ curve (see Fig. 8). The corresponding correlation between calculations and measurements in Fig. 14a is quite close. There is somewhat more scatter in the correlation for the smaller riblet spacing on flight 3, shown in Fig. 14b. In spite of the greater scatter, this correlation provided the basis on which we defined the $\Delta y^*$ curve for low values of $s^*$ in Fig. 12. For the configuration of flight 4, with riblets only on the forward portion of the test surface, the comparison (Fig. 14c) shows that the drag reductions in this case were, on the average, overpredicted for a greater fraction of the conditions than in the previous cases.
7. CONCLUSIONS

Plastic riblet films tested on the T-33 were found to provide a skin-friction reduction that correlated with an average wall-unit parameter $s^*$. A favorable effect was found for the range of $s^*$ from about 6 to 25, with an optimum drag reduction averaging about 6 percent in the range of $s^*$ between 10 and 15. For $s^*$ above 10, the general form of the correlation with $s^*$ was very similar to the correlation with local $s^*$ defined by NASA flat-plate data. The drag reduction was found to remain effective in the adverse pressure gradient on the aft portion of the test surface. Effectiveness of the riblets was found to be reduced by misalignment in yaw and by perforations of the plastic film. Finite-difference boundary-layer calculations were carried out, showing that reasonable predictions of the effect of riblets can be obtained with a simple modification to a conventional eddy-viscosity model.

REFERENCES


NOMENCLATURE

c = local chord of wing

$C_f = 2\tau_w/(\rho e U_e^2)$; skin friction coefficient

$C_L = L/(1/2\rho_e V_e^2)$; lift coefficient

$C_p = (p - p_\infty)/(1/2\rho_e V_e^2)$; pressure coefficient

D = drag of a riblet flat-plate specimen

D_{fp} = drag of a smooth flat-plate specimen
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\[ H_p \] pressure altitude, ft.

\[ k \] sand-grain roughness size

\[ M \] Mach number

\[ R \] Reynolds number

\[ R_s = \frac{s V_\infty}{v_\infty} \] riblet-spacing Reynolds number

\[ s \] riblet spacing, in.

\[ u \] velocity magnitude in boundary layer

\[ U_e \] velocity at edge of boundary layer

\[ U_m = \frac{U_m}{\rho W}; \] friction velocity

\[ V_\infty \] flight velocity

\[ x \] longitudinal distance from leading edge

\[ y \] distance normal to wing surface

\[ \Delta y^+ \] shift used to modify eddy viscosity for riblet effect

\[ \nu \] kinematic viscosity

\[ \theta = \int_0^\infty \rho u \left( \frac{1 - u}{U_e} \right) dy \] boundary-layer momentum thickness based on velocity magnitude

Superscripts

\[ + \] denotes length expressed in wall units \( u_c/U_e \)

\[ \bar{\text{overbar}} \] denotes average over length of riblet specimen

10. ACKNOWLEDGMENTS

We wish to thank the following individuals who made the flight-test possible. G. W. Brune designed the pitot rakes and helped with the early stages of test planning. F. J. Marentic, T. L. Morris, and L. F. Vangen of 3M manufactured the riblet film and helped apply it to the airplane. J. A. Terhune, the test pilot maintained the prescribed flight conditions with such skill that the resulting data correlations are comparable to those obtained in wind tunnels.