Experiments on the relationship between shape and effectiveness for three-dimensional boundary layer trips at supersonic speeds
by Stephen Edward Berger

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering
Montana State University
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Abstract:
Measurements to determine the effects of size and shape on the performance of three-dimensional boundary layer trips were made in the Montana State University Supersonic Wind Tunnel. Seventeen trips, representing four basic shapes, were examined. Experiments were conducted in the areas of Schlieren photography, drag force, wake turbulence, velocity profiles, and spanwise turbulent wake profiles behind paired trips. The results indicate that the planform shape and the forward rake angle of a trip have as much bearing on its effectiveness as the previously-known dependence on roughness height and frontal area. Trips of wedge planform were found to exhibit the best combination of desired performance characteristics. Standard trips were found to produce a previously undocumented, fully turbulent, distorted wake that bloomed away from the wall as the flow proceeded downstream. The spanwise wake influence of paired trips was not influenced by their relative spacing and orientation.
EXPERIMENTS ON THE RELATIONSHIP BETWEEN SHAPE AND EFFECTIVENESS FOR THREE-DIMENSIONAL BOUNDARY LAYER TRIPS AT SUPersonic SPEEDS

by

Stephen Edward Berger

A thesis submitted in partial fulfillment of the requirements for the degree of
Master of Science in Mechanical Engineering

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Bozeman, Montana

May 1988
APPROVAL

of a thesis submitted by

Stephen Edward Berger

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

Date Chairperson, Graduate Committee

Approved for the Major Department

Date Head, Major Department

Approved for the College of Graduate Studies

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Signature  
Date  

Stephanie E. Begna  
10 May 1988
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<tr>
<td>A</td>
<td>Frontal area of trip</td>
</tr>
<tr>
<td>A.C.</td>
<td>Alternating current</td>
</tr>
<tr>
<td>$C_p$</td>
<td>Constant pressure specific heat</td>
</tr>
<tr>
<td>$C_d$</td>
<td>Drag coefficient</td>
</tr>
<tr>
<td>D.C.</td>
<td>Direct current</td>
</tr>
<tr>
<td>DPP</td>
<td>Dynamic Pressure Probe</td>
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<tr>
<td>DVM</td>
<td>Digital voltmeter</td>
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<tr>
<td>F</td>
<td>Fahrenheit</td>
</tr>
<tr>
<td>$F_d$</td>
<td>Drag force</td>
</tr>
<tr>
<td>FFT</td>
<td>Fast Fourier transform</td>
</tr>
<tr>
<td>Gm</td>
<td>Gram</td>
</tr>
<tr>
<td>k</td>
<td>Roughness height</td>
</tr>
<tr>
<td>KHz</td>
<td>Kilocycles per second</td>
</tr>
<tr>
<td>L</td>
<td>Length of trip at the base</td>
</tr>
<tr>
<td>L'</td>
<td>Length of trip at the top</td>
</tr>
<tr>
<td>M</td>
<td>Mach number</td>
</tr>
<tr>
<td>$M_t$</td>
<td>Test section Mach number</td>
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<tr>
<td>mV</td>
<td>Millivolt</td>
</tr>
<tr>
<td>mG</td>
<td>Milligram</td>
</tr>
<tr>
<td>MSU</td>
<td>Montana State University</td>
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<td>P</td>
<td>Pressure</td>
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<tr>
<td>PVC</td>
<td>Polyvinyl Chloride</td>
</tr>
<tr>
<td>R</td>
<td>Gas constant for air</td>
</tr>
<tr>
<td>Re</td>
<td>Reynolds number</td>
</tr>
<tr>
<td>Re'</td>
<td>Unit Reynolds number</td>
</tr>
<tr>
<td>Re'k</td>
<td>Trip Reynolds number (Re')(k)</td>
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<td>RMS</td>
<td>Root mean square</td>
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<td>S</td>
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<td>STK</td>
<td>Stock</td>
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<td>SWT</td>
<td>Supersonic Wind Tunnel</td>
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<td>T</td>
<td>Temperature</td>
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<td>U</td>
<td>Free-stream velocity in X-direction</td>
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<td>v.</td>
<td>Versus (in comparison to)</td>
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<td>W</td>
<td>Width of trip</td>
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<td>X</td>
<td>Streamwise coordinate axis</td>
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<td>Trip location</td>
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<td>Y</td>
<td>Coordinate axis normal to the wall</td>
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<td>( \tilde{Y} )</td>
<td>Compressible transformed distance</td>
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<td>Z</td>
<td>Spanwise coordinate axis</td>
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<td>( \alpha )</td>
<td>Half-angle</td>
</tr>
<tr>
<td>( \gamma )</td>
<td>Ratio of specific heats</td>
</tr>
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<td>( \delta )</td>
<td>Boundary layer thickness</td>
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\( \delta^* \)  
Boundary layer displacement thickness

\( \epsilon \) 
Re\(_k^*\) when \( X_t = X_k \)

\( \theta \)  
Boundary layer momentum thickness:
Paired-trip orientation in chapter 9

\( \phi \)  
Rake angle of trip

\( \rho \)  
Density

\( d( ) \)  
Differential quantity

\( P-(\ ) \)  
Plate trip-designator

\( S-(\ ) \)  
Standard trip-designator

\( STR-(\ ) \)  
Strake trip-designator

\( W-(\ ) \)  
Wedge trip-designator

\( (\ )_\delta, (\ )_e \)  
Property at the boundary layer edge

\( (\ )_k \)  
Property at \( X = X_k, Y = k \) in a smooth-wall laminar boundary layer

\( (\ )_o \)  
Stagnation property

\( (\ )_t \)  
Property at the onset of transition:
Property at the stagnation point of a pitot tube in chapter 7

\( (\ )_w \)  
Property at the base of the boundary layer (wall)

\( (\ )_{aw} \)  
Adiabatic-wall property

\( (\ )_{xk} \)  
Property at \( X = X_k \)

\( (\ )' \)  
RMS value of a property
Measurements to determine the effects of size and shape on the performance of three-dimensional boundary layer trips were made in the Montana State University Supersonic Wind Tunnel. Seventeen trips, representing four basic shapes, were examined. Experiments were conducted in the areas of Schlieren photography, drag force, wake turbulence, velocity profiles, and spanwise turbulent wake profiles behind paired trips. The results indicate that the planform shape and the forward rake angle of a trip have as much bearing on its effectiveness as the previously-known dependence on roughness height and frontal area. Trips of wedge planform were found to exhibit the best combination of desired performance characteristics. Standard trips were found to produce a previously undocumented, fully turbulent, distorted wake that bloomed away from the wall as the flow proceeded downstream. The spanwise wake influence of paired trips was not influenced by their relative spacing and orientation.
CHAPTER 1

INTRODUCTION

Methods of artificially forcing a laminar boundary layer to become turbulent are important both for designers of flight vehicles and for aerodynamic research. In flight vehicle design, it is often necessary to create a turbulent boundary layer ahead of engine inlets and control surfaces in order to prevent unwanted boundary layer separation. In research, particularly for high-speed flow experiments on scale models in wind tunnels (e.g., at Mach numbers greater than 10), it is often impossible to obtain any turbulence at all without resorting to artificial means.

The primary method for inducing turbulence in supersonic or hypersonic laminar boundary layers is by the use of individual protuberances, of roughness height \((k)\) as tall as or taller than the laminar boundary layer thickness, distributed on the surface of a flight vehicle or scale model. Large protuberances are required because the temperature gradient in a high-speed, compressible boundary layer creates such low densities near the wall that low-height roughnesses, such as a band of grit or a
knurled surface, are totally ineffective as turbulence promoters. These large, three-dimensional protuberances, known as "trips", have been studied by numerous investigators for the purpose of optimizing their effectiveness, which is defined by the following criteria:

1. The onset of transition from laminar to turbulent flow should occur as close to the trip as possible, ideally at the trailing edge.

2. The trip should not substantially increase the total drag on the flight vehicle or scale model.

3. The effect of the trip should be confined to the boundary layer: it should not cause substantial distortion of the free-stream flowfield.

4. The turbulence induced by the trip should exhibit the same characteristics as natural (free flight) turbulence at a reasonable distance downstream of the trip. Specifically: the velocity profile, heat transfer characteristics, boundary layer thickness, momentum thickness, and displacement thickness of the trip-induced boundary layer should be similar to those found in a naturally-turbulent boundary layer. This requirement is especially critical in wind tunnel experiments.
Despite the extensive amount of research on the performance of trips, little work has been done on the relationship between trip geometry and trip effectiveness. An investigation was therefore undertaken for the purpose of determining the effect of trip geometry on trip effectiveness in supersonic flow.
CHAPTER 2

REVIEW OF PREVIOUS EXPERIMENTAL FINDINGS

Summary of Previous Findings

Due to the lack of a definitive theory on the performance of three-dimensional protuberances in supersonic boundary layers, the bulk of the useful work on the subject of trip effectiveness has been experimental.

Typical of research on trips in low-speed flow is the work of Klebanoff and Tidstrom (1) who, in a study of transition behind a two-dimensional trip, concluded that tripped transition is a stability-governed phenomenon. Specifically, disturbances which are unstable according to the laminar boundary-layer stability theory are greatly amplified within a "recovery zone" (defined as the region in the area downstream of the trip where the mean flow is distorted by the presence of the trip itself). That is, the apparent action of the trip is to create a destabilizing influence on the flow in the recovery zone so that existing (i.e., not trip-induced) unstable disturbances are amplified faster than the natural (untripped) rate. These investigators also found
that transition behind two-dimensional tripping elements changes gradually as the free-stream unit Reynolds number is increased, but transition behind a three-dimensional element changes suddenly when the unit Reynolds number reaches a critical value.

Experimentation on trip effectiveness at supersonic and hypersonic speeds began in the 1950s. Van Driest and McCauley (2), in an experiment using spherical tripping elements on a 5-degree half-angle cone at Mach 1.9 and 3.67, concluded that the horseshoe vortex generated by the tripping element is the mechanism that creates early transition. The horseshoe vortex is said to "contaminate and break down the surrounding vorticity field". Transition was observed to move close to the trip location "suddenly" at a critical trip Reynolds number $Re'_k$, defined as $((Re')_\delta)(k)$, where $\delta$ is the smooth-wall boundary layer thickness at $x_k$. The critical trip Reynolds number also corresponded to the lowest transition Reynolds number in all cases presented. The critical trip Reynolds number was found to be proportional to $Re_{xk}^{1/4}$, where $Re_{xk}$ is the free stream smooth-wall Reynolds number at the trip location. The $1/4$-power relationship was shown to be valid for different trip heights, trip locations, and edge Mach numbers. The significance of these findings is that,
given the flow parameters, the trip location, and the proportionality constant, it should be possible to determine \( k \) such that the critical, or 'effective' trip Reynolds number criterion is met and transition occurs at the lowest possible local Reynolds number. Lateral trip spacing was found to have little effect on the location of the onset of transition, as long as the lateral separation was large enough to prevent interference between the horseshoe vortices behind each trip throughout the transition zone. Additionally, the vortex strength was found to persist in the laminar sublayer of the turbulent boundary layer after transition.

Van Driest and Blumer (3) extended the findings of Reference (2) to include the effects of heat transfer and the values of the proportionality constant for flat plates and cones. The relationship is given as:

\[
k/X_k = 33.4 \left[ 1 + 0.9 \left( \frac{T_w}{T_{aw}} - 1 \right) + 0.28 \left( \frac{T_{aw}}{T_0} - 1 \right) \right] \text{Re}^{3/4}
\]

For flat plates, the proportionality constant is 44.0.

Whitehead (4), in a study of flowfield and drag characteristics of various tripping elements in a Mach 6.8 flow over a flat plate, also noted the horseshoe-vortex phenomena seen by Van Driest and McCauley. Although Whitehead's observations were presented qualitatively
(the primary goal of the experiment was to determine the effect of trip size and shape on drag), he specifically noted that lateral trip spacing had little or no influence on trip effectiveness as long as the spacing was greater than 3 trip widths. Regarding drag, Whitehead observed that the extent of boundary-layer separation at the leading edge influences trip-induced drag at constant trip height and width. Additionally, he found that the relationship between trip-induced drag and trip height becomes constant above about $k = 26$ for cylindrical and wedge-shaped trips, but not for spherical trips. An incidental finding in this paper is that the horseshoe vortex appears to vanish ahead of the wedge-planform trip (it does not appear in the oil-stain photographs).

Potter and Whitfield (5), in an experiment on tripped flows on the exterior of a sharp-lipped tube at hypersonic Mach numbers, found that disturbances in the boundary layer ahead of the trip (which lead to early transition) may arise from the trip bow shock/boundary layer interaction, with free-stream turbulence as a forcing parameter. They noted that the transition process behind large trips can produce distortions in the flow outside the natural boundary layer which persist well downstream of the trip location. These undesirable side-effects result in flow characteristics that do not simulate natural turbulence.
and, if too severe, may defeat the purpose of the trip. These investigators also found that three-dimensional elements are more effective than two-dimensional elements in hypersonic flow (2-d elements become less and less effective at increasing Mach numbers). Even so, the minimum trip height required to move the onset of transition to the trip location was found to increase exponentially with the Mach number.

The major contribution of this paper is the development of an empirical correlation between trip location ($X_k$), trip height ($k$), desired location of transition onset behind the trip ($X_t$), location of transition on the smooth (untripped) surface ($X_{to}$), and a "disturbance parameter" ($Re'_{k/\epsilon}$). The Potter-Whitfield correlation can be used in principle to determine the trip size required to locate transition anywhere between the trip position and the location of smooth-wall transition.

Pate (6), in an experiment on flow over a 5-degree half-angle cone at Mach 3 and 4, investigated the effect of free-stream disturbances on tripped transition by performing the same series of experiments in two different wind tunnels. The purpose of his investigation was to determine whether or not the differences in free-stream disturbances that exist in different wind tunnels would invalidate the Van Driest-Blumer or Potter-Whitfield
correlations. Pate concluded that the absolute location of transition behind a given trip in a given flow was definitely influenced by the free-stream disturbance level. However, the correlations of Potter-Whitfield and Van Driest-Blumer were shown to remain valid. An additional and important finding was that the performance of different trips relative to each other remained unchanged.

An investigation by Nestler and McCauley (7) had a similar conclusion as that of Potter and Whitfield regarding the bow shock-boundary layer interaction as the generator of early transition, at least in the case of large, bluff trips. Unlike other investigators, however, they found that lateral spacing has a maximum critical value as well as having a minimum critical value. These investigators used multiple rows of cube-shaped trips in their experiments and found that the Van Driest-Blumer correlation (which was developed for a single row of spherical trips) was reasonably valid for some other combinations of trip shape, trip size, trip spacing, and nose bluntness.

Strike (8) performed a series of experiments on spherical and serrated tripping elements over a 6-degree half-angle cone at hypersonic (Mach 8) speeds. He concluded that three staggered rows of spherical trips are as effective in causing early transition as a single row with
twice the roughness height. This discovery is important in
that many of the undesirable effects of trips on the
flowfield are caused by excess roughness height. He also
found that staggered rows of trips provide better lateral
uniformity in the downstream heat transfer and flow
properties, that large trips create upstream influences on
the heat transfer and pressure properties, and that
flowfield disturbances persist for a much greater distance
downstream of a single row of large trips than behind
staggered rows of smaller trips.

Whitfield and Iannuzzi (9) conducted experiments on a
4.5 degree half-angle cone at very high Mach numbers (14 to
16) and found that the roughness height required for
effective tripping increased exponentially with the Mach
number (see Potter and Whitfield above). They postulated
that the use of very large trips (in an attempt to move
transition forward at high Mach numbers) may be
self-defeating. That is to say, large trips distort the
flowfield so severely that it may not be possible to trip
the boundary layer at hypersonic Mach numbers without
unacceptable distortion.

McCaulley, Saydah and Bleuche (10) measured the flow
over a 6-degree half-angle cone at Mach 10 and a Re' of
1.6X10^6/ft, using spherical trips and varying both the
angle of attack and the wall temperature. The results of
their experiments confirmed the Van Driest-Blumer correlation (but with a different proportionality constant) under hypersonic conditions.

**Implications for This Investigation**

The findings of the investigators cited above were used to establish the scope of the present investigation. The implications of previous work in the field of trip effectiveness, and the application of these findings to the present investigation, can be summarized as follows:

1. The fact that three-dimensional trips are much more effective than two-dimensional trips in supersonic and hypersonic flows is well-established. Therefore, experiments on two-dimensional trips can be dismissed out of hand in the present investigation.

2. The performance of spherical trips has been exhaustively investigated and documented. It would therefore serve no purpose to experiment on spherical trips in the present investigation.

3. Despite the fact that many of the trips in actual use are of rectangular planform and frontal profile (referred to as "standard" trips in this investigation), the data on the effectiveness of trips of other than spherical shape is very sparse. It is safe to say that the optimum trip shape for effective
tripping action has not been determined. Therefore, a study of the relationship between trip shape and trip effectiveness has the best potential for contributing to the body of knowledge on this topic.

4. Most of the data contained in previous experiments was derived from surface measurements, or by means of single-point hot-wire anemometry. A need therefore exists for obtaining continuous data throughout the boundary layer, particularly in regard to velocity and turbulence profiles.
CHAPTER 3

OUTLINE OF THE INVESTIGATION

Goals

The primary goal of this investigation was to determine the relative effect of different trip shapes on trip effectiveness, with the aim of determining the "best" shape. An equally important goal was to determine the best roughness height \( k \) for the trip or trips of "best" shape, in the hope that this roughness height would be smaller than that of a spherical or a standard trip of equivalent performance.

Scope of the Investigation

During the design of the investigation, it was determined that all the aspects of trip effectiveness listed in Chapter 1 should be explored. Therefore, experiments were devised for the measurement of drag force, turbulence intensity, and flowfield disturbance behind each of the trips in the investigation. An additional experiment was performed on the effect of trip spacing and orientation on trip effectiveness. Recently, experiments in a hypersonic (Mach 8) wind tunnel on the
effectiveness of some of the trips in this study have become available for comparison (Reference (11)).

**Trips**

The trips used in the investigation are listed in Table 1. The trips fall into four categories: strakes; flat plates; wedges; and standard trips. Nomenclature used to describe trip features is as shown in Figure 1.

**Table 1. Trip Identification and Dimensions**

<table>
<thead>
<tr>
<th>Trip No.</th>
<th>k</th>
<th>L</th>
<th>L'</th>
<th>φ(deg.)</th>
<th>α(deg.)</th>
<th>W</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Plates:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P-1</td>
<td>1.25</td>
<td>1.25</td>
<td>0.75</td>
<td>45.0</td>
<td></td>
<td>17.0</td>
</tr>
<tr>
<td>P-2</td>
<td>1.25</td>
<td>1.25</td>
<td>1.25</td>
<td>90.0</td>
<td></td>
<td>5.7</td>
</tr>
<tr>
<td>P-3</td>
<td>0.25</td>
<td>1.75</td>
<td>1.75</td>
<td>90.0</td>
<td></td>
<td>17.0</td>
</tr>
<tr>
<td>P-4</td>
<td>1.25</td>
<td>0.75</td>
<td>0.75</td>
<td>90.0</td>
<td></td>
<td>9.5</td>
</tr>
<tr>
<td><strong>Wedges:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>W-1</td>
<td>0.50</td>
<td>1.25</td>
<td>0.75</td>
<td>90.0</td>
<td></td>
<td>17.0</td>
</tr>
<tr>
<td>W-2</td>
<td>0.50</td>
<td>1.25</td>
<td>0.25</td>
<td>90.0</td>
<td></td>
<td>5.7</td>
</tr>
<tr>
<td>W-3</td>
<td>1.25</td>
<td>1.25</td>
<td>0.75</td>
<td>90.0</td>
<td></td>
<td>17.0</td>
</tr>
<tr>
<td>W-4</td>
<td>1.25</td>
<td>0.75</td>
<td>1.25</td>
<td>90.0</td>
<td></td>
<td>9.5</td>
</tr>
<tr>
<td><strong>Standard Trips:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S-1</td>
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<td>0.95</td>
<td>15.0</td>
<td></td>
<td>0.75</td>
</tr>
<tr>
<td>S-2</td>
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<td>2.00</td>
<td>0.70</td>
<td>30.0</td>
<td></td>
<td>0.75</td>
</tr>
<tr>
<td>S-3</td>
<td>0.25</td>
<td>1.25</td>
<td>0.31</td>
<td>15.0</td>
<td></td>
<td>0.75</td>
</tr>
<tr>
<td>S-4</td>
<td>1.25</td>
<td>0.50</td>
<td>0.33</td>
<td>15.0</td>
<td></td>
<td>0.75</td>
</tr>
<tr>
<td>S-5</td>
<td>0.90</td>
<td>1.60</td>
<td>1.08</td>
<td>60.0</td>
<td></td>
<td>0.90</td>
</tr>
<tr>
<td>S-6</td>
<td>0.90</td>
<td>1.60</td>
<td>1.36</td>
<td>75.0</td>
<td></td>
<td>0.90</td>
</tr>
<tr>
<td>S-7</td>
<td>0.90</td>
<td>1.50</td>
<td>0.00</td>
<td>30.0</td>
<td></td>
<td>0.95</td>
</tr>
<tr>
<td>S-8</td>
<td>0.30</td>
<td>1.50</td>
<td>1.33</td>
<td>60.0</td>
<td></td>
<td>0.90</td>
</tr>
<tr>
<td><strong>Strakes:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>STR-1</td>
<td>1.00</td>
<td>1.90</td>
<td>0.00</td>
<td>27.76</td>
<td>14.74</td>
<td>1.00</td>
</tr>
</tbody>
</table>
Figure 1. Geometry and Nomenclature for Trip Construction

The trips were constructed from Lexan or PVC plastic, the material having been chosen for its ease of machineability and its suitability for operation at the temperatures encountered in the MSU SWT.

Facilities and Equipment

All of the experiments in the test matrix were performed in the MSU Supersonic Wind Tunnel (SWT). The SWT is an open-circuit, continuous-flow facility, using
air as the working fluid and producing a nominal test section Mach number of 3.0 over a Re' range of 580,000 to 1.7 million per inch. Figure 2 illustrates the main features of the SWT, which is fully described in Reference (12).

Figure 2. Major Components of MSU SWT (Reproduced from (12))

General-purpose data acquisition for the test matrix was obtained by the use of the SWT Automated Data Acquisition System. The system, which provides probe control and data capture capability for SWT operations, was redesigned specifically for this investigation.
A complete description of the Data Acquisition System is found in Reference (13).

In addition to the general-purpose equipment listed above, a number of sensors and devices were custom-built for this investigation. These are described in the chapters corresponding to their application.

**Test Matrix**

Due to the comprehensive nature of this investigation, and the large number of trips to be examined, it was determined early in the planning stage that all of the trips could not be examined for all aspects of trip performance. The test matrix was therefore organized so as to "screen out" a portion of the test group in each stage of the investigation. The early stages of the matrix were purely qualitative, thereby providing rapid means to perform the screening-out procedure. The later stages were used to obtain data more amenable to quantitative analysis, but only on the best-performing trips.

The test matrix was constructed as follows:

1. Tare measurements performed for the purpose of obtaining laminar boundary layer properties and transition data required in subsequent stages.
2. Photographic studies of the boundary layer downstream of each trip in the test series by means of the SWT Schlieren system.

3. Drag force measurements on each trip in the test series, using a purpose-built load sensor.

4. Quantitative turbulence measurements in the boundary layer downstream of the "best" trips, as determined by the results of items 2 and 3 above, using an experimental Dynamic Pressure Probe (DPP).

5. Flow-velocity studies (boundary layer profiles) downstream of the trips not screened out after stages 3 and 4, using a pitot tube and the Automated Data Acquisition System.

6. Turbulence profiles in the wake of paired trips, to determine the effects of trip spacing and orientation on turbulence generation.

A Note on Presentation of the Test Data

In order to preserve the continuity of presentation, the experimental procedures and the results for each stage in the test matrix are described in separate chapters.
Boundary Layer Properties

Laminar and turbulent boundary layer measurements were made at the centerline of the SWT nozzle surface ("floor") and at the centerline of the sidewall ("wall"), using a .004 in. diameter pitot tube. These measurements were taken for the purpose of establishing the streamwise rate of growth of $\text{Re}^*$, $\delta$, $\delta^*$, and $\theta$, under laminar and turbulent conditions, for use in later stages of the test matrix. Full boundary layer profiles were also taken for comparison with trip-induced profiles generated later in the test matrix.

The floor data were taken over the range $X = 8.64$ in. to $X = 18.64$ in. ($X$ measured downstream from the nozzle throat) at 1/2 in. intervals. The wall data were taken at 1 in. intervals from $X = 11.14$ in. to $X = 18.14$ in. Data runs were made at $P_o = 350$ mm. Hg (laminar) and at $P_o = 600$ mm. Hg (turbulent). $T_o$ was 100° F for all data runs.
Measurements were made by traversing the pitot tube from the surface (wall or floor) to a point well past the edge of the boundary layer, in .004 in. increments. The data points were captured by an earlier version of the SWT Automated Data Acquisition System (functionally similar to the system described in (13)), and reduced to useable form by means of the computer program listed in Appendix A.

**Turbulence Transition**

Measurements were taken to establish the stagnation pressure ($P_0$) at which turbulence first appears at a given $X$-station in the SWT. These measurements were used for positioning trips, in later stages of the test matrix, at locations of known laminar flow in the smooth-wall boundary layer. The data were also required to establish the stagnation conditions which provide the longest run of laminar flow in the SWT.

The transition data were taken by setting a hot-film anemometer in the boundary layer at a given $X$-station and observing its RMS A.C. signal as the SWT $P_0$ was swept. The total temperature ($T_0$) was maintained at 100° F. The anemometer signal indicates the level of velocity and density fluctuation (turbulence), and can thus be used to detect both the onset and the completion of turbulence transition.
Results

Boundary Layer Properties

Variations of the laminar ($P_o = 350$ mm. Hg) boundary layer edge properties $\delta$, $\theta$, and $\delta^*$, as functions of the $X$-station are shown in Figures 3 through 5. The wall data points in each of these figures exhibit considerable scatter, which is attributed to excess motion of the pitot probe due to mechanical problems with the SWT Z-Axis actuator.

Included in the figures are simple correlations for the variation of the edge properties in the downstream direction. These correlations were used for calculations in later stages of the test matrix.

Figures 6 and 7 are plots of the variation in $Re'$ in the streamwise direction, on the floor and wall respectively. The data in these plots, consistent with previous measurements made in the SWT (see (12)), were considered valid for the purposes of this investigation.
Figure 3. Laminar Boundary Layer Thickness on the SWT Floor and Wall
Figure 4. Laminar Boundary Layer Momentum Thickness on the SWT Floor and Wall

- Wall
- Floor

\[ 0.000551x \]

\[ 0.002047 + 0.0002441x \]
Figure 5. Laminar Boundary Layer Displacement Thickness on the SWT Floor and Wall
Figure 6. Unit Reynolds Number Distribution on the SWT Floor
Figure 7. Unit Reynolds Number Distribution on the SWT Sidewall
Wall v. Floor Thicknesses

It is evident from the figures that the boundary layer grows faster on the wall than on the floor. This result was expected, and is consistent with the characteristics of the SWT nozzle design.

Figure 8 depicts the Mach number distribution in a Laval nozzle of the type used in the SWT. As shown, the test section Mach number ($M_t$) is achieved much sooner on the wall centerline than on the floor. Low (14), among others, has shown that the boundary layer is thicker at higher Mach numbers: hence the faster rate of growth on the wall, where the Mach number is increasing at a higher rate.

![Figure 8. Mach Number Distribution in a Representative 2-Dimensional Laval Nozzle (from {16})](image-url)
Turbulence Transition

Figure 9 is a plot of the onset and completion of transition as functions of both the X-station and $P_0$. Except for a few anomalous points, the plot indicates a monotonic decrease of the transition-onset $P_0$ from a value of about 400 mm. Hg at the 10 in. station to about 325 mm. Hg at the 20 in. station.

Figure 9. Onset and Completion of Transition to Turbulence in the MSU SWT
The "useable approximation" lines shown on the figure were developed by Demetriades from the data of this investigation and also from earlier measurements documented in references (12) and (15). Based on the indications of Figure 8, it was determined that the best conditions for conducting laminar-flow experiments on trips during the remainder of the test matrix would be obtained by using a $P_0$ of 350 mm. Hg, a $T_0$ of 100 °F, and a trip location $X_k$ of about 10 in.
Experimental Apparatus and Procedures

Photographic examination of the boundary layer downstream of the trips was performed by means of the SWT 8 in. Schlieren system. The Schlieren, as described in References {12}, {16} and {24}, is an optical device that uses the principle of diffraction to produce visible images of density gradients in the SWT.

Figure 10 illustrates the method used to align the trip centerlines parallel to the floor during attachment to the SWT floor. The trips were secured to the floor by Cyanoacrylate glue.

The trips were located at the 9.64 in. X-station, a site chosen to provide the longest downstream laminar run. The smooth-wall boundary layer edge Mach number at this station is 2.98 and Re' is 83,350 per in. at the test stagnation conditions (Pq = 350 mm. Hg, Tq = 100° F).

Schlieren photographs were taken using both "continuous" (1/50 sec.) and "spark" (2 microsecond) exposures. The continuous exposures present the average density gradients in the boundary layer, while the spark
photographs "freeze" the flowfield image and therefore present a more detailed picture of boundary layer turbulence.

The depth of field of the Schlieren system is essentially the distance between the concave mirrors, which is much larger than the width of the SWT test section. Therefore, the Schlieren is not a qualitative instrument. For example, a narrow turbulent wake behind a trip cannot be easily detected. However, a turbulent wake that spreads laterally behind the trip can be detected in continuous photographs by the disappearance of the characteristic bright band that defines a laminar boundary layer. The spark photographs supplement this evidence by revealing

Figure 10. Method Used to Align Trips With the SWT Flow
the eddies and granularity of density characteristic of turbulent flow.

Results

Calibration Photographs

Figure 11 shows calibration photographs of laminar ($P_o = 350$ mm. Hg) and transitional ($P_o = 620$ mm. Hg) flow in the SWT. The extreme left side of the transition-flow photograph demonstrates the bright-line diffusion and turbulent bursts characteristic of turbulence onset in a boundary layer.

Trip Photographs

Figures 12 through 20 are photographs of the flow behind the trips. Trip P-2 was not photographed due to resonant flutter that detached it from the SWT floor. A qualitative analysis of the photographs yields the following observations:

1. Trips W-1, W-3, S-5 and S-6 appear to be most effective in generating turbulence. The former are the wedges that present the largest frontal area to the oncoming flow. The latter have the largest frontal area of the standard trips and also have the least amount of rake at the upstream face.
Figure 11. Spark Photos of Tare Flow at $P_o = 620$ mm. Hg (top left) and 350 mm. Hg (top right). Continuous-Exposure Photo of Tare Flow at $P_o = 350$ mm. Hg (bottom right). Trip W-3 at Same position and Schlieren Settings, No Flow (bottom left)
Figure 12. Trip P-1 at Continuous (top) and Spark (bottom) Exposure
Figure 13. Trips P-3 (left) and P-4 (right) Taken with Continuous (top) and Spark (bottom) Exposure
Figure 14. Trips W-1 (left) and W-2 (right) Taken with Continuous (top) and Spark (bottom) Exposure
Figure 15. Trips W-3 (left) and W-4 (right) Taken with Continuous (top) and Spark (bottom) Exposure
Figure 16. Trips S-1 (left) and S-2 (right) Taken with Continuous (top) and Spark (bottom) Exposure
Figure 17. Trips S-3 (left) and S-4 (right) Taken with Continuous (top) and Spark (bottom) Exposure
Figure 18. Trips S-5 (left) and S-6 (right) Taken with Continuous (top) and Spark (bottom) Exposure
Figure 19. Trips S-7 (left) and S-8 (right) Taken with Continuous (top) and Spark (bottom) Exposure
Figure 20. Continuous (top) and Spark (bottom) Photos of Trip STR-1
2. The degree of rake appears to have some effect on the performance of the standard trips. Trips S-1 and S-2 are identical in frontal area, but the blunter S-2 is considerably more effective in promoting turbulence. A similar comparison can be made between the highly-raked S-7 and the blunt S-5 and S-6 trips.

3. The narrow wedges, the plates, and standard trips S-1 and S-3 are the least effective in promoting turbulence.

4. The strake (STR-1) is about as effective as S-7.

Bow Shock Instability on Large, Blunt Trips

Figure 21 illustrates an interesting phenomenon discovered during the Schlieren flow survey. The two spark photos in the figure were taken at exactly the same flow conditions, but at different times. The bottom photo shows a large compression fan ahead of the trip (S-5), and the bright line is lifted from the floor a considerable distance ahead of the trip, which indicates early boundary layer separation. In the top photo, the compression fan is smaller, more condensed, and closer to the trip. The boundary layer separation is also closer to the trip and changes in the shape of the bow-shock wave, although small, appear as far downstream as the photos cover.
Figure 21. Evidence of Flow Instability over the S-5 Trip Observed with Spark Photography
This phenomenon has been observed by Demetriades (17) on supersonic flow over a spike mounted in front of a blunt cylinder. An unstable bow shock of this type can cause significant pressure oscillations on the face of the trip, possibly leading to instability if the trip were used on an actual flight vehicle.
CHAPTER 6

DRAG FORCE MEASUREMENTS

Introduction

As outlined in Reference {18}, theoretical calculation of form drag is possible only for a limited number of cases. The flow around the trips examined in this investigation is so complex that prediction of the drag load from first principles is basically out of the question. It was therefore decided to measure the drag experimentally.

Experimental Apparatus and Procedures

Microbalances

The confined space of the SWT test section and the small magnitude of the expected drag forces dictated the use of a force measuring system similar to the skin friction balance described in Reference {16}. The microbalances used in this investigation were more modest in design than the highly precise, very expensive devices described in the literature, but were expected to be sufficient for the purposes of comparing the drag loads among the trips.
The principal features of the microbalances are illustrated in Figure 22 below and described on the following page.

Figure 22. Principal Components of the Microbalance
In essence, a microbalance is a housing and a set of linkages that connect a load cell to a trip. The Kulite BG series miniature load cells used in the microbalances each employ a cantilever beam with a strain gage mounted on the fixed end to sense a force applied to the free end. Two microbalances, one using a 10-gram and the other a 50-gram load cell, were built for the investigation.

The load cell in each microbalance is mounted on a stand and connected to a tubular rod by means of a small wire link. One end of the rod is free to pivot about a pin joint: the other end, to which a trip is attached, protrudes from a small hole in the inner body of the microbalance housing. The link wire is attached to the trip support rod as close to this end as possible in order to minimize the error in measurement caused by different centers of pressure on different trips.

In use, the microbalance is inserted into a hole bored in a two-piece plastic window that replaces the normal SWT sidewall, and is shimmed so that the end of the inner body is flush with the window surface. The longitudinal axis of the trip is aligned with the air flow by means of index marks, the flow is started, and the drag force is measured by electronic means.
Trip Installation

Figure 23 illustrates the methods used to attach the trips to the 10-gram and 50-gram microbalances. The trips mounted on the 50-gram microbalance were secured by set screws to an extension threaded into the support rod. The trips for the 10-gram device, being much smaller, were glued to a fitted brass base, .005 in. thick, which had been brazed to a pin. The pin was then glued into the support rod.

Figure 23. Methods of Trip Installation on the Microbalances
The trips were shimmed during installation to achieve a uniform gap of about .005 in. at the base. Figure 24 illustrates typical trip mountings.

![Figure 24. Trip S-2 Mounted on the 50-Gram Microbalance (left). Trip P-1 Mounted on the 10-Gram Microbalance (right)](image)

**Installation in the SWT**

The microbalances were installed on the centerline of the SWT sidewall with the trip-support rod at the 9.19 in. X-station. The location of the trailing edge of each trip was between $X = 9.19$ in. and $x = 9.57$ in. As previously mentioned, care was taken to insure that the trips were aligned with the flow. The SWT was operated for about 1 hr. with a dummy plug installed in the microbalance port to ensure thermal equilibrium.
When re-starting the SWT with a microbalance in place, the balance was retracted far enough to shield the trip from the flow, then carefully lowered into place. This procedure was necessary both to protect the microbalances from sudden loads and to ensure that the drag force on a particular trip did not exceed the range of the load cell.

Figure 25 depicts the location of the microbalance in the SWT. The "crack" in the 2-piece window, necessary for access to the test section, was placed well downstream of the microbalance site.
Data Acquisition

The Microbalance was connected to signal conditioning and data-capture equipment as shown in Figure 26.

Figure 26. Microbalance Data Acquisition Block Diagram

The pressure station provided both the 10 VDC excitation to the microbalance and a 10X amplification of the load cell signal. Both microbalances were "set" to eliminate play in the linkages, then the no-load output was carefully zeroed at the start of each data run.
A separate zero-shifter was required for the 10-gram microbalance due to a severe no-load offset in the load cell output. The 50-gram microbalance was zeroed at the pressure station.

Both the steady-state (D.C.) and the fluctuating (A.C.) microbalance outputs were recorded on X-Y plotters. Steady-state signals were also recorded by hand from digital voltmeter readings for later analysis.

Calibration

The microbalances were calibrated as described in Appendix B. Calibration was performed not only to obtain the load v. output curve for each microbalance and verify the repeatability of each device, but also to address the following concerns:
1. The sensitivity of the microbalance to the location of the center of pressure on a trip.
2. The effect of tunnel vibration on the microbalance.
3. The degree of hysteresis in the microbalance output.

The center-of-pressure sensitivity was an issue only for the 50-gram microbalance, which was to be used for the majority of the trips. The sensitivity was measured by performing a series of static calibrations and varying the point of application of the test load between calibrations. The range of variation represented the height of the
tallest trip and the base of the trips as installed on the device. The results, depicted in Figure 27, show an 8 percent variation in the output v. load sensitivity of the instrument due to changes in the point of application of the load. This represented the absolute extremes that could arise during the experiment, and it was felt that the actual results would show less variation.

The vibration issue was addressed by operating the microbalance with a hollow cover placed over the end of the trip support rod, thereby protecting it from the flow but leaving it free to move. A lead weight of the same mass as trip S-1 was attached to the end of the support rod during the test. The A.C. signal was recorded while the SWT $P_o$ was cycled twice between 600 and 300 mm. Hg, in the belief that changes in the SWT vibration level arise from changes in the compressor load. The D.C. signal was recorded in like manner.

The results for the 50-gram microbalance are depicted in Figure 28, and are summarized as follows:

1. The steady-state (D.C.) output is insensitive to vibration. The difference in the signal between runs is attributable to play in the microbalance linkage. This play does not exist during data runs because the flow provides a constant one-way load on the device.
Figure 27. D.C. Signal v. Load for 4 Calibration Runs with the 50-Gram Microbalance
Figure 28. Tare A.C. and D.C. Outputs for the 50-Gram Microbalance (2 runs)
2. The fluctuating (A.C.) output was also insensitive to vibration, except for a "jump" in the reading that occurred during each test run. The reason for this behavior could not be determined, and it was decided to reserve judgment on the validity of unsteady drag measurements until actual data could be obtained.

The 10-gram microbalance was not tested for vibration due to problems described in the next few paragraphs.

The hysteresis issue was addressed by operating each microbalance, with a trip attached, in the SWT and recording the signal on an X-Y plotter while cycling the stagnation pressure. The degree of hysteresis in such a test is evident from the difference between the plotter traces.

Figure 29 is a typical hysteresis trace produced by the 50-gram microbalance. As the plot shows, the maximum relative error from hysteresis is about 3 percent, and is about as large as the expected error from the uncertainty in the location of the center of pressure.

Figure 30 is a typical trace produced by the 10-gram microbalance. The plot, which represents three complete cycles and two others that were interrupted by flow breakdown, evidences severe hysteresis and zero-drift. Traces produced with other trips were equally bad.
Included on the plot is a trace of the drag force measured on the same trip with the 50-gram microbalance. It should be noted here that, although not evident in Figure 30, the level of hysteresis produced by the 50-gram microbalance with this trip was virtually undetectable.

Consequently, it was decided to perform all the drag force measurements with the 50-gram microbalance.

Figure 29. Typical Hysteresis Trace for the 50-Gram Microbalance (Trip S-3)
Results

Steady-State Drag

The data on the steady-state drag of all the trips examined in this stage of the investigation are depicted in Figures 31 and 32 on the following two pages.
Figure 31. Drag Force v. Stagnation Pressure for Standard, Wedge and Strake Trips
Figure 32. Drag Force v. Stagnation Pressure for Low-Drag Trips
Figure 31 contains the drag force data on the standard trips, the wedges, and the strake. Figure 32 contains the data on the two plates examined, plotted with the low-drag group from Figure 31 for comparison purposes.

Twelve of the original 17 trips were examined in this stage of the test matrix. Trips P-2 and P-3 were eliminated from consideration after the Schlieren survey. Trip S-4 was too large to fit on the microbalance. Trips S-5 and S-6 could not be tested because their drag loads exceeded the load cell's operating range.

The drag curves reveal the following general characteristics:
1. A linear increase in the drag with increasing \( P_0 \) in the laminar-flow range.
2. A sudden increase in the slope of the drag curves at the onset of transitional boundary layer flow for trips S-3 and S-8. These are the only trips in the test set that were completely immersed in the laminar boundary layer. The increase in slope at transition also appears on the curves for taller, bluff trips \((k > \delta, \ W >> 0)\), but is nearly absent for the plates and narrow wedges \((W \text{ very small})\).
3. A roll-off in the drag-curve slopes as the boundary layer becomes fully turbulent.
The magnitudes of the measured drag forces ranges from 70 grams for trip S-7 at 600+ mm. Hg to about 2 grams for trip S-3 at 300 mm. Hg. The following trends are evident:

1. The total drag on a standard trip of given k and W depends on the bluntness of the upstream face. Trips S-5 and S-6, which were off the scale in drag force, have the same width and roughness height as trip S-7. The reason for this trend is evident in the Schlieren photos. The highly-raked S-7 has essentially an attached oblique shock at its front face, while the other two trips produce detached normal shocks. The pressure rise across a normal shock is known to be greater than that across an oblique shock; therefore the pressure drag is higher for equivalent frontal areas. A similar argument can be made for S-2 v. S-1, which differ only in degree of rake.

2. The total drag on a trip of given width and planform depends on the roughness height, as evidenced by W-3 v. W-1.

The changes in the character of the drag at transition are even more evident in Figures 33 and 34. These are plots of the measured drag normalized with the SWT stagnation pressure.
Figure 33. Drag/Po v. Pq for Standard, Wedge and Strake Trips
Figure 34. Drag/$P_\infty$ v. $P_\infty$ for Low-Drag Trips
The total drag on an object immersed in a gas flow consists of viscous drag (skin friction) and the pressure drag. The pressure drag is given by:

\[ F_d = C_d A \frac{\gamma}{2} P M^2 \quad (1) \]

The static pressure (P) in (1) is given by:

\[ P = P_0 \left(1 + \frac{\gamma - 1}{2} M^2\right)^{-\gamma/\gamma - 1} \quad (2) \]

The Mach number at a given position in the SWT is essentially constant over all \( P_o \), being affected only by changes in the boundary layer thickness. The frontal area of a trip (A) and the ratio of specific heats (\( \gamma \)) are also constant. Therefore, the pressure drag can be given by:

\[ \text{(constants)} \times (C_d) \times (P_o) \quad (3) \]

where the drag coefficient (\( C_d \)) may also depend on \( P_o \).

If it is assumed that the pressure drag is much larger than the viscous drag (very reasonable for all the trips except the narrow wedges and plates), then a plot of drag/\( P_o \) should reveal whether or not the drag is independent of \( P_o \).

As shown by the figures, the drag on all of the trips appears to be either independent of \( P_o \) or very nearly linear in \( P_o \) (i.e., drag/\( P_o \) is essentially a straight line) in the laminar-flow range. As expected, these relationships change during transition.
It is interesting to note that most of the curves appear to level off as the flow becomes fully turbulent at the trip station.

Figures 35 through 38 are plots of the drag coefficients \( (C_d) \) v. \( Re \) for the trips. The evidence of Figure 35 and also of W-3 in Figure 37 supports the findings of Whitehead (4) that the drag coefficient on fixed-width trips becomes essentially constant as \( k/\delta \) approaches 2 or greater for trips in laminar flow. The increasing order of \( C_d \) for S-1, S-2 and S-7 in Figure 35, and for S-3 and S-8 in Figure 36, again demonstrates the effect of rake angle on drag for standard trips.

**Measured v. Theoretical Drag**

An effort was made to calculate the theoretical drag on some of the trips for comparison with the experimental data.

The full theoretical wave drag calculation was not undertaken. Instead, a highly simplified approach was used to obtain the pressure drag on the wedge trips only.

The wedges were assumed to be immersed in a uniform supersonic flow at the trip-station Mach number, and at zero angle of attack. The pressure on the forward faces of the trips was obtained from oblique shock theory; the back pressure was measured by placing a pitot tube in the dead-air region directly behind each trip.
Figure 35. Drag Coefficient v. Re$^\delta$ for Large Standard Trips
Figure 36. Drag Coefficient vs. $Re_\delta$ for Small Standard Trips
Figure 37. Drag Coefficient v. $Re_\delta$ for Wedge Trips
Figure 38. Drag Coefficient v. Re_6 for Thin Wedges and Plates
The skin friction drag was obtained from simple laminar viscous theory, and was calculated for both the wedges and the plates. All calculations were made at an assumed $P_0$ of 350 mm. Hg.

Table 2 is a comparison of calculated v. measured drag for the wedges and plates. The values agree in the qualitative ordering of the forces as one goes from the most (W-3) to the least (P-1) "air resistant" trip. Quantitatively, the difference between measured and calculated drag is reasonable (about 25 per cent) for the larger trips, but poor for the thin wedges and plates.

Table 2. Calculated v. Measured Drag for Selected Trips

<table>
<thead>
<tr>
<th>Trip</th>
<th>Calculated drag (Gm.)</th>
<th>Measured drag (Gm.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W-1</td>
<td>11.71</td>
<td>9.25</td>
</tr>
<tr>
<td>W-2</td>
<td>2.33</td>
<td>3.60</td>
</tr>
<tr>
<td>W-3</td>
<td>27.49</td>
<td>34.00</td>
</tr>
<tr>
<td>W-4</td>
<td>5.29</td>
<td>8.60</td>
</tr>
<tr>
<td>P-1</td>
<td>0.81</td>
<td>3.40</td>
</tr>
<tr>
<td>P-4</td>
<td>0.98</td>
<td>3.65</td>
</tr>
</tbody>
</table>
Unsteady Drag

A fluctuating (unsteady) drag component, manifested as an A.C. voltage signal, was present in the microbalance output when the boundary layer became turbulent at the trip location. Consequently, it was possible to plot the RMS value of the fluctuating drag $v. P_0$ as was done in Figure 39 on the following page.

It is apparent that when the boundary layer was laminar ($P_0$ less than 350-400 mm. Hg), the RMS component of the drag was close to the value shown in the tare measurement of Figure 28. At transition, the RMS signal increased abruptly due to buffeting of the trip by the turbulent flow. The drag fluctuations seen on the plots appear to be random and limited to low frequencies. However, the load cell frequency response is limited to 1000 Hz; therefore higher frequency drag fluctuations would not appear on the plots.

Figure 40 is a plot of the ratio of the RMS value of the unsteady drag to the steady drag, as a function of the SWT $P_0$, for selected trips. Also shown on the plot are data from a skin friction balance. This data was only of passing interest for the present investigation, since a body that has transitional flow at the trip station would likely not require a trip in the first place.
Figure 39. Unsteady Drag v. $P_0$ for Three Standard Trips
Figure 40. Normalized Unsteady Drag v. $P_o$ for Selected Trips
The unsteady drag results are, however, potentially useful for the technology of transition detection. If the beginning of the RMS force rise is noted in each of the plots of Figures 39 and 40, the transition onset points can be cross-plotted on a transition graph such as that of Figure 9. These points, clustered around $P_0 = 400$ mm. Hg and $X = 8.7$ in., fall very close to the "onset" line of Figure 9, and tend to confirm the onset predictions of that figure, which were developed by a different detection method. Additionally, there appears to be a correlation between the roll-off of the unsteady drag force and the end of transition to turbulence.

Trip Selection

As a result of the findings of both the drag force and the Schlieren stages of the test matrix, all of the plates and the narrow wedges were eliminated from further consideration in the investigation. The remaining wedges (W-1 and W-3) and all of the standard trips were carried into the next stage of the experiment.
CHAPTER 7
TURBULENCE MEASUREMENTS

Introduction

Quantitative measurements of the turbulence generated behind the remaining trips in the test set were required for comparison to naturally-generated turbulence. The usual method of obtaining these measurements is by hot wire anemometry, as described in References {16}, {19} and {23}.

For this investigation, it was decided to attempt qualitative turbulence measurements with a new instrument, a wide-band Dynamic Pressure Probe (DPP). The DPP, although experimental as used in this investigation, is potentially far superior to the current hot wire technology for the following reasons:

1. The DPP has a much better frequency response, given by the manufacturer as flat to the resonant frequency of 1.5 MHz and far exceeding the known boundary layer turbulence frequency limit of 500-600 KHz. The typical hot wire output, as described in (16), falls off by 98+ percent at 10 KHz. A frequency-compensating amplifier is therefore required for hot wire anemometry. The
DPP, which requires no such biasing in its amplification circuitry, is therefore much simpler to use.

2. The property sought in turbulence measurements is $dU/U$, the ratio of the fluctuating velocity to the time-averaged velocity in the streamwise direction. The DPP gives this property directly. The hot wire data requires prolonged analysis to obtain the same result.

3. Hot wires are notoriously fragile in high speed flows. The DPP is much more resistant to mechanical damage by dust particles in the air stream or by accidental contact with the SWT floor or test models.

The pressure transducer used in the DPP, a Kulite model CQ-030-100G, is rated by the manufacturer as a dynamic device only. That is to say, the manufacturer does not recommend its use for time-averaged (steady state) pressure measurements. As a DPP, the transducer must be able to measure both the fluctuating and the time-averaged pressures simultaneously. Therefore it was not assured, at the start of this stage of the test matrix, that the device would really work. Fortunately, qualitative turbulence measurements behind the trips had been taken by Demetriades (Reference {20}), which could be used as back-up data.
Principle of Operation for the Dynamic Pressure Probe

Direct measurements of the velocity ratio $dU/U$ can be made with a fast-response (dynamic) pitot probe if the sensitivity of the probe to velocity fluctuations, as a function of the flow properties, is known. Derivation of the sensitivity relation proceeds from the following basic equations.

The Rayleigh Supersonic Pitot Equation for $M > 1$:

$$ P_t = P \left( \sqrt{\frac{\gamma-1}{\gamma}} M^2 \right)^{\gamma/\gamma-1} \left[ \frac{2\gamma}{\gamma+1} M^2 - \left( \frac{\gamma-1}{\gamma+1} \right)^{-1/\gamma-1} \right] $$

The Isentropic Pressure Ratio for $M \leq 1$:

$$ P_t = P \left( 1 + \frac{\gamma-1}{2} M^2 \right)^{\gamma/\gamma-1} $$

The Adiabatic Energy Relation:

$$ UdU + C_p \ dT = 0 $$

The Adiabatic Temperature Ratio:

$$ \frac{T}{T_0} = 1 + \frac{\gamma-1}{2} M^2 $$

The Definition of the Sonic Velocity:

$$ C^2 = \gamma RT $$
Differentiation of (4) gives the following relationship for $M > 1$:

$$\frac{dP_t}{P_t} = \frac{dP}{P} + 2 \left[ \frac{\gamma}{\gamma - 1} - \frac{2\gamma(\gamma+1)M^2}{(\gamma-1)^2(2\gamma M^2 - \gamma + 1)} \right]$$

(9)

Differentiation of (5) gives the following relationship for $M \leq 1$:

$$\frac{dP_t}{P_t} = \frac{dP}{P} + \frac{2\gamma M^2}{2 + (\gamma - 1)M^2}$$

(10)

Combining (6) and (8), recognizing that $C_p/R$ is equal to $(1 - \gamma)M^2$, and rearranging gives:

$$\frac{dT}{T} = (1 - \gamma)M^2 \frac{dU}{U}$$

(11)

Differentiating (7) leads to the following:

$$\frac{dT_o}{T_o} = \frac{dT}{T} + \frac{(\gamma - 1)M^2}{1 + \left(\frac{\gamma - 1}{2}\right)M^2}$$

(12)

In adiabatic flow, $T_o$ is constant, therefore $dT_o/T_o$ is zero. Combining (9), (11), and (12), and rearranging, gives the following connection between $dP$, $dU$, and $dP_t$ for $M > 1$ and $\gamma = 1.4$:

$$\frac{dP_t}{P_t} = \frac{dP}{P} + \left[ 7 - \frac{35M^2}{7M^2 - 1} \right] \left[ 1 + \frac{M^2}{5} \right] \frac{dU}{U} = \frac{dP}{P} + S \frac{dU}{U}$$

(13)

For subsonic flow, (9) is replaced by (10), giving:

$$\frac{dP_t}{P_t} = \frac{dP}{P} + \frac{7 M^2}{5} \frac{dU}{U} = \frac{dP}{P} + S \frac{dU}{U}$$

(14)

where $S$ is defined as the "sensitivity coefficient".
Equations (13) and (14) establish the relation between the quantities $dP_t/P_t$, $dP/P$, and $dU/U$ over the entire range of Mach numbers for which the assumption of ideal-gas behavior is valid (generally taken as Mach 6 and below). Note that at $M = 1$, the supersonic and subsonic sensitivity coefficients are equal.

If it is now assumed that the pressure fluctuations inside a turbulent boundary layer are much smaller than the velocity fluctuations then, since $S$ is of order unity or higher for $M > 0.845$, it is legitimate to simplify equations (13) and (14) by dropping the $dP/P$ term. Doing so leads to the following relationships:

$$\frac{P'_t}{P_t} = S \frac{u'}{U}; \quad \frac{u'}{U} = \frac{1}{S} \frac{P'_t}{P_t}$$

(15)

Where $p'_t$ and $u'$ are the RMS magnitudes of the velocity fluctuations, and $S$ is as defined in (13) or (14), depending on whether the local velocity is subsonic or supersonic.

The formulas (15) establish that the velocity fluctuations at a point in the flow can be found by measuring the local Mach number (thus $S$), $P_t$, and $p'_t$.

Figure 41 is a plot of the sensitivity coefficient as a function of the local Mach number for $\gamma = 1.4$ (air).
Figure 41. Sensitivity Coefficient v. Mach Number for Air
Experimental Apparatus and Procedure

Dynamic Pressure Probe

The design of the Dynamic Pressure Probe (DPP) is illustrated in Figure 42. The device is essentially a sting and fin that houses the Kulite pressure transducer, its wiring, and a standard pitot tube for calibration.

Figure 42. Major Features of the DPP Design

Calibration of the DPP was somewhat involved, due to the extreme temperature sensitivity of the pressure transducer. Additionally, the device was initially very
susceptible to electronic noise. Considerable effort was required before the DPP could be made into a useful instrument. A detailed exposition of this effort, too lengthy to be included here, is found in Appendix C.

**Data Acquisition**

Two modes of data capture were used for DPP measurements. Figure 43 is a block diagram of the real-time mode used to obtain quantitative data. Figure 44 is a block diagram of the system used to store data on magnetic tape for spectral analysis.

**Data Reduction**

The DPP produces two signals simultaneously: a D.C. voltage proportional to the time-averaged (steady-state) pressure and an RMS A.C. voltage proportional to the fluctuation of the pressure about the mean value. Reduction of these voltages to the desired property, \( \frac{dU}{U} \), is very straightforward and proceeds as follows:

\[
\frac{dU}{U} = \frac{1}{S} \left( \frac{dP_t}{P_t} \right)
\]

(16)

where:

\[
S = \frac{7}{5} M^2
\]

(17)

and:

\[
S = \left( 7 - \frac{35M^2}{(7M^2 - 1)} \right) \left( 1 + \frac{M^2}{5} \right)
\]

(18)

for \( M \leq 1 \) and \( M > 1 \) respectively.
Figure 43. Block Diagram of the DPP
Electronic Configuration
Figure 44. Block Diagram of the DPP Data Storage System
The DPP outputs are related to the pressures as follows:

\[ \text{D.C. Output} = (\text{D.C. gain}) (A \ Pt + B) \]  
\[ \text{A.C. Output} = (\text{A.C. gain}) (A \ dPt) \]

where A and B are the calibrated slope and intercept for the DPP output v. pressure characteristics.

Therefore:

\[ \frac{dP_t}{Pt + B/A} = \frac{(A.C. \ OUTPUT)(D.C. \ GAIN)}{(D.C. \ OUTPUT)(A.C. \ GAIN)} \]  

If B (the no-load D.C. offset) is purposely adjusted so that \( (B/A) \) is \( \ll Pt \) (i.e., B nearly zero), then (21) becomes:

\[ \frac{dP_t}{Pt} = \frac{(A.C. \ OUTPUT)(D.C. \ GAIN)}{(D.C. \ OUTPUT)(A.C. \ GAIN)} \]  

and:

\[ \frac{dU}{U} = \frac{A.C. \ OUTPUT \times D.C. \ GAIN \times 1}{D.C. \ OUTPUT \times A.C. \ GAIN \times S} \]  

In practice, the local Mach number is determined from \( Pt \) by the methods contained in Appendix A, the sensitivity coefficient is calculated, and the value of \( dU/U \) is determined from (23).

**Tare Measurements**

The first task in this stage of the experiment was to obtain tare data on natural turbulence in the SWT floor boundary layer. This task was accomplished by
placing the DPP as far downstream as possible from the SWT throat (at X = 20 in.) and traversing it through a known turbulent boundary layer.

Two traverses were made: the first with the SWT at $P_0 = 604$ mm. Hg, $T_0 = 100^\circ$ F (natural turbulence) and the second at the same stagnation conditions, but with the turbulence enhanced by injecting air into the upstream boundary layer. The DPP output was recorded by hand from voltmeter readings and also by analog traces on X-Y plotters.

DPP data was also recorded on tape for spectral analysis. The taped data consisted of boundary layer traverses and samples of the DPP signal with the device fixed in either the location of maximum boundary-layer turbulence intensity or in the free stream.

**Results**

Figures 45 and 46 are the analog traces of the DPP A.C and D.C signals for the natural-turbulence and enhanced-turbulence data runs. The A.C. signal pattern is very similar to hot-film and hot wire traces produced by other investigators in the SWT (see, for example (20)). The D.C. signal pattern is likewise similar to existing SWT pitot traces. The traces can only be compared qualitatively, but the similarities are encouraging.
Figure 45. Analog Trace of the DPP A.C. Signal in a Turbulent Boundary Layer (2 runs)

Figure 46. Analog Trace of the DPP D.C. Signal in a Turbulent Boundary Layer (2 Runs)
The frequency spectra in Figure 47 were produced by feeding the taped DPP A.C. signal through a Rockland FFT wave analyzer. These spectra are in qualitative agreement with hot-film data produced in the SWT, including the "bump" at 200 KHz in the free stream.

\[ P_0 = 600 \text{ mm. Hg} \]
\[ T_0 = 100 \text{ Deg. F} \]
\[ X = 17.64 \text{ in.} \]
\[ Y = 0.150 \text{ in.} \] (Peak Signal)

\[ P = 600 \text{ mm. Hg} \]
\[ T_0 = 100 \text{ Deg. F} \]
\[ X = 17.64 \text{ in.} \]
\[ Y = 0.500 \text{ in.} \] (Free Stream)

Figure 47. DPP Frequency Spectra (Tare Measurements)

The reduced data from the natural-turbulence tare measurement is plotted in Figure 48. Included in the figure is reduced hot-wire data from Reference (21).
The scatter in the hot-wire data makes a definitive comparison difficult, but the general agreement between the two data sets is obvious.

Figure 48. $\frac{dU}{U}$ v. $Y/\Delta$ from DPP Data Plotted with Hot-Film Data from (21)
DPP Failure

The next task in the test matrix was to survey the boundary layer behind the trips and produce plots for comparison with Figure 48. Unfortunately, the DPP failed the day after the tare data was taken. Examination of the device revealed a hole in the pressure diaphragm on the face of the transducer. The exact cause for the failure was not determined, but was thought to be a hot spot generated by the electronic circuitry.

The failure occurred at a critical time in the test matrix and, since the manufacturer of the transducer quoted a six-month delivery time for a replacement, it was decided to use the back-up data for trip screening.

Trip Selection

The turbulence data taken by Demetriades (20) was used to make a further screening of the trips at this stage of the test matrix. The sum of all the previous stages in the investigation pointed to the wedge-planform trips, particularly W-1, as having the best combination of effective tripping action and low drag. The large standard trips (S-5 and S-6) were seen to produce the best "pure" tripping action, but at a substantial cost in drag. Consequently it was decided to perform the velocity field survey on the W-1 and S-5 trips only.
CHAPTER 8
BOUNDARY LAYER PROFILES

Introduction

Having lost the benefit of quantitative data on boundary layer turbulence behind the trips due to the failure of the DPP, an additional test stage was needed. The shape of the velocity profile is a distinct characteristic that can be used to differentiate between a laminar and a turbulent boundary layer. Additionally, normalized velocity profiles of the same type (laminar or turbulent) are easily compared for similarity. Consequently, it should be possible to determine both the degree of turbulence generation behind a trip and its similarity to natural turbulence by comparing the tripped and naturally-turbulent velocity profiles.

Experimental Apparatus and Procedures

The velocity profiles were measured by traversing a .006 in. diameter pitot tube from the SWT floor to a point well into the free stream. The boundary layer thickness was .200 - .400 inches, giving a pitot tube resolution of 1:35 or better. Laminar and turbulent tare profiles (no
trip installed) were made for comparison with the tripped profiles. The tripped profiles were made with the trips installed at the 9.64 inch X-station. Figure 49 illustrates the positioning of the trip and the pitot tube in the SWT.

![Figure 49. SWT Configuration for Boundary Layer Velocity Profiles](image)

Pitot pressures were converted to a D.C. voltage signal by a Kulite XTH-1-190-5A pressure transducer encapsulated in the pitot tube housing. The data was captured on 5 1/4 in. floppy disks by the SWT Automated Data Acquisition System (see Reference {13}) and reduced to quantitative form by the computer program listed in Appendix A. The static pressure used for data reduction was obtained with a 1.125 in. long by .044 in. diameter static pressure probe. The static holes (4 each) were .020 in. in diameter and located .58 in. from the tip.
Results

The data presented here represents normalized boundary layer velocity profiles at the furthest possible normalized distance \((X - X_k)/k\) behind each of the trips surveyed. As described at the end of Chapter 7, trips S-5 and W-1 were the only trips examined in this phase of the test matrix.

Figure 50 depicts the flow behind trip W-1 at \((X - X_k)/k = 29\) and \(Z = 0\) (the plane of symmetry of the trip). Curves 1 and 2 on the plot are the tare profiles for laminar \((Re' = 31,500/cm)\) and turbulent \((Re' = 55,000/cm)\) flow at the same location, but without the trip. The abscissa is normalized with respect to the compressible transformed distance \(\tilde{Y}\), given as:

\[
\tilde{Y} = \int_{0}^{Y} \frac{\rho}{\rho_e} \, dy
\]

and used in the Illingworth - Stewartson transformation (see Reference (18)) used to reduce the compressible boundary layer equations to nearly the same form as those for incompressible flow. The tare profiles are used as standards of comparison for determining whether curve 3, taken with the trip in place, represents laminar or turbulent flow and to test the similarity of the tripped profile to the naturally-turbulent profile.
The correspondence between profiles 2 and 3 of the figure, while not perfect, is good enough to establish that the trip produces a flow behind it very similar to the "natural" turbulent boundary layer.

It should be noted here that the tare laminar profile is not comparable to the Blasius profile, which is valid only for flows with no streamwise pressure gradient. Brower (Reference (22)) has shown that the laminar
nozzle-wall profiles in the SWT are, as expected, of the Hartree type found from Falkner-Skan theory as outlined in Reference (18). Typical data from Brower are included on the plot of Figure 50. The correspondence of curve 1 and Brower's data shows that the tare profile indeed represents an accelerated-flow laminar boundary layer.

Figure 51 represents the velocity profile at 15 trip heights behind S-5, a typical standard trip and the best pure generator of turbulence in the test set. In this figure, the ordinate is normalized with the velocity at the boundary layer edge \( U_e \), but the abcissa is dimensional.

Immediately next to the wall, curve 3 (the tripped profile) coincides with the tare turbulent profile (curve 2) long enough to produce a wall shear stress identical to that of a turbulent boundary layer. Further out, however, the profile loses its similarity to the turbulent case, and is dissimilar to the laminar profile (curve 1) as well. Nevertheless the shape of the curve, if the portion to the right of the "plateau" (at about \( X = .275 \) in.) is ignored, is indeed characteristic of turbulent flow. The dissimilarity of the tripped flow away from the wall is even more apparent in the normalized plot of Figure 52.
Figure 51. Dimensional Boundary Layer Profile Behind Trip S-5

Figure 52 shows a region from about $\tilde{Y}/\theta = 0.25$ to $\tilde{Y}/\theta = 1.3$ in which the velocity has not reached the expected free-stream value. Figure 53 is a "map" of the pitot profiles behind W-5, taken under laminar-flow conditions, which shows that the trip-affected region grows away from the wall and is only weakly attenuated at 16 trip heights downstream. It is interesting to note that the
hot film data of Demetriades (20) shows that the flow in this region is also fully turbulent. Due to the limited size of the SWT test section, it was not possible to determine how far downstream these "wake blooming" turbulence and velocity phenomena persist. However, neither the laminar-flow pitot profile map behind W-1 (Figure 54) nor the hot-film data reveal any such behavior behind that trip.

Figure 52. Normalized Boundary Layer Profile Behind Trip S-5
Figure 53. Velocity Profile Map Behind Trip S-5 (Dashed Line is the Edge of the Turbulence)
Figure 54. Velocity Profile Map Behind Trip W-1
CHAPTER 9

WAKE TURBULENCE PROFILES BEHIND PAIRED TRIPS

Introduction

Practical tripping arrangements require several trips. As described in References (2), (4), (7), (8) and (10), trip spacing and orientation are known to influence the overall performance of a tripping system. With the exception of the Whitehead investigation (4), all of the work cited above was performed with the trips mounted on axisymmetric bodies (cones, primarily) and arranged spanwise in at least one row. Consequently, the lateral downstream influence of each trip was "fenced in" by its neighbors.

It was deemed important for the purposes of this investigation to determine whether or not trip spacing and orientation would effect the lateral downstream spread of trip-generated turbulence in the absence of the "fencing-in" effect. Therefore, a test stage was developed to explore this issue.
Experimental Apparatus and Procedures

This test stage used the same plastic sidewall as the drag force measurements described in chapter 6. A 1 1/2 in. blank plug, free to rotate in the sidewall port, was substituted for the microbalance.

A trip consisting of a right circular cylinder, of diameter = .148 in. and $k = .148$ in., was fixed to the center of the plug. A second identical trip was placed at a distance $S$ (representing center-to-center trip separation) from the plug center. Figure 55 illustrates the major features of the test configuration.

![Figure 55. SWT Configuration for the Paired-Trip Experiments](image)
The sidewall was indexed at 10 degree increments for alignment with an index mark scribed through the trip centers on the plug.

The roughness height of the trip was chosen to coincide with the laminar boundary layer thickness at the center of the plug \((X = 8.82 \text{ in.})\). The cylindrical shape was chosen to avoid shape effects as the trip orientation was varied during the experiments.

Measurements were made at \(S = 2W\) and \(S = 3W\). Stagnation conditions were \(P_o = 350 \text{ mm. Hg, } T_o = 100^\circ F\) for all measurements.

Data acquisition was by means of a hot-film anemometer, driven by the SWT ADP-12/13 hot-film station. The hot-film signal was passed through a Hewlett-Packard RMS voltmeter and captured on an X-Y plotter. Pre-data measurements established that the trips would generate turbulence that was not present in the tare state.

Two sets of experiments were conducted. In the first, the hot-film anemometer was fixed at \(X = 2 \text{ in.}, \ Y = .5 \text{ in.}\), and \(Z \text{ (distance from the sidewall)} = k \text{ (and also } \delta)\). This location was known to be outside the turbulent wake of a single trip from pre-data measurements. The RMS value of the hot-film signal was plotted as the plug was rotated from the trips-abreast position \((\theta = 0^\circ)\) to the in-line position \((\theta = 90^\circ)\). The object of this experiment was to
look for increases in the signal, indicative of a widening of the turbulent wake.

The second set of experiments consisted of fixing the angle \( \theta \), then traversing the hot-film through the wake of the trips. These measurements were intended to determine the rate of turbulence spreading, if any, as a function of the trip orientation for a given trip spacing.

**Results**

Figures 56 and 57 are the results of the hot-film signal v. rotation angle experiments for the 2W and 3W trip spacings respectively. Both figures indicate a point of maximum signal intensity. For the 2W spacing, the maximum occurs at \( \theta = -5 \) degrees (nearly abreast); for the 3W spacing it appears at \( \theta = 70 \) degrees. Both figures show a fall-off in the signal intensity on either side of the maximum point. Repeated runs of the experiments resulted in identical results. The reason for the observed behavior, however, is not known.
Figure 56. Hot-Film RMS Signal Intensity v. Rotation Angle (2W Spacing)
Figure 57. Hot-Film RMS Signal Intensity v. Rotation Angle (3W Spacing)

Figure 58 is an example plot of the wake profiles, in this case behind a single trip. The peak in the hot-film signal at $X = 1$ in. (behind the trip) is obviously caused by the trip itself, and appears to both spread and attenuate as the flow proceeds downstream.
Figure 58. Hot-Film Wake Traverses Behind a Single Trip
The signal peaks at the lateral edges of the wake, not only initially greater than that behind the wake but also much less attenuated downstream, are thought to be caused by the horseshoe vortex observed by numerous investigators, as discussed in Chapter 2. These peaks appear to spread slowly.

A characteristic of Figure 58, common for all the wake profiles taken, is that the width of the turbulent zone is distinctly defined by the abrupt rise in the hot-film signal at each side of the wake. Therefore it is easy to visualize the effects of trip spacing and orientation on the turbulent wake by plotting all of the signal-rise patterns for the same \( S \) on one graph.

The zone widths are shown in Figures 59 and 60 for 2W and 3W spacing respectively. Only the widths for \( \theta = 0^\circ \) and \( \theta = 90^\circ \) are shown: the width patterns for all other rotation angles fell within the bounds of these two extremes.

The width maps reveal the following trends:

1. The width of the wake for both the 2W and 3W spacing is the same as that for a single trip at \( \theta = 90^\circ \).
2. The width of the wake for \( \theta = 0^\circ \) is approximately equal to the single-trip width plus the trip spacing.
3. The lateral growth rate of the wake is basically independent of \( S, \theta \), and the number of trips.
Figure 59. Turbulent Zone-Width Map at 0 and 90 degrees - 2W Spacing
Figure 60. Turbulent Zone-Width Map at 0 and 90 degrees - 3W Spacing

\[ z = 0.148 \text{ in.} \]
CHAPTER 10

CONCLUSIONS

The results of the experiments in this investigation support a conclusion that trip geometry has a definite bearing on trip effectiveness. In particular, the effectiveness of a three-dimensional trip in supersonic flow depends as much on the planform shape and the forward rake angle as it does on the roughness height and the frontal area. Specific findings of the investigation are summarized in the following statements.

1. The principal mechanism that generates forced turbulence behind a three-dimensional trip is the horseshoe vortex. This finding is in line with most of the previous experiments discussed in Chapter 2, and is supported in this experiment by the wake turbulence profiles of Chapter 9.

2. Wedge-planform trips of roughness height $k \approx 26$ and half-angle on the order of 20 degrees meet all the criteria for an effective trip listed in Chapter 1. That is to say, such trips exhibit the best combination of low drag, low flowfield disturbance, and rapid turbulence generation. Unlike the standard trips,
which have equal or better effectiveness in the area of turbulence generation, the influence of the wedge trips is confined to the boundary layer. Flowfield distortions created by the wedge trips also attenuate more rapidly than for standard trips. Therefore the boundary layer behind a wedge trip assumes a natural appearance earlier than that behind a standard trip.

3. Rectangular-planform trips with raked forward faces, denoted as "standard" trips in this investigation, produce a distorted velocity profile behind them that is characterized by a slow rate of streamwise decay and a monotonic streamwise increase in thickness. The flow within this distorted region is also fully turbulent, as evidenced by the hot-film data of Demetriades in Reference (20). It is not presently known how far downstream this distorted, turbulent flowfield persists. This finding has significant potential in the technology of mixing gas flows, and therefore begs further investigation.

4. The precise relationship between k, W, the half-angle, the flow properties, and trip effectiveness for wedge-planform trips has yet to be determined. The commonly-used Potter-Whitfield trip-sizing correlation (see Appendix D) does not apply universally to trips of this shape. Therefore, more research is needed in
order to develop data from which a similar correlation can be developed.

5. The evidence of the experiments of Chapter 9 indicate that the spanwise influence of three-dimensional trips in a uniform flow is independent of the proximity and orientation of neighboring trips. This finding does not apply to flows that are closely confined in the spanwise direction.

6. Drag force measurements are possible using a simple, low-cost device such as the microbalance described in Chapter 6. Through refinement of the design, it may be possible to measure very small forces, for example skin friction, at a fraction of the usual cost and effort for such measurements.

7. Quantitative measurements of the turbulence intensity in boundary layer flow can be simplified greatly by the use of a fast-response pressure sensor (DPP). Further development of such an instrument, with the intent of replacing hot-wire anemometry as a turbulence sensor, is fully justified by the experience of this investigation.
REFERENCES CITED


APPENDIX A

BOUNDARY LAYER PROFILE DATA REDUCTION PROGRAM
Figure 61. Boundary Layer Parameter Calculation Program

100 MSSID = "BOUNDARY LAYER PARAMETER CALCULATION PROGRAM"
20'
20 MSSID = "Calculates thermodynamic properties and velocities in"
20 MSSID = "boundary layers from pitot probe data."
40
60'
70 MAX = 250  'MAX NUMBER OF DATA POINTS - RESET IF RED'D
80'
90 DIM Y(MAX), ZERO(MAX), PT(MAX), VEL(MAX), TEMP(MAX), H(MAX), RHO(MAX), YBAR(MAX)
100 DIM REPRIE(MAX)
110'
120 FLAG$ = ""  'set series-repeat flag to a null string
130 FAST$ = ""  'set "fast" manual node flag to null string
140 RUSHO = ""  'eliminates tabular data file if set
150 PANICS = ""  'only edge-property files made if set
160'
170 This is the entry point for the series-repeat loop:
180'
190 get the filename, output header, stagnation props, x-location,
200 and y-step increment from the user:
210'
220'
230'
240 CLS:KEY OFF  'clr screen
250 LOCATE I,(80-LEN(MSSID))/2:PRINT MSSID  'print pgm. I.D.
260 PRINT:PRINT SPC(15) MSSID:PRINT SPC(15) MSSID
270 PRINT:PRINT:PRINT'
280'
290 IF FLAG0="Y" OR FLAG0="y" THEN 340  'don't need drive popts on repeats
300'
310 INPUT "WHICH DRIVE HAS THE INPUT FILES? (A:/B:/C:) ==> ",INDRIVEO
320 INPUT "WHICH DRIVE GETS THE OUTPUT? (A:/B:/C:) ==> ",OUTDRIVE0
330'
340 INPUT "ENTER THE INPUT FILE NAME (no ',EXT') ==> ",FILEO
350 IF FLAG0="Y" OR FLAG0="y" THEN 560  'save header, etc, in repeats
360 INPUT "SKIP THE TABULATED-DATA FILE? (Y/<CR>) ==> ",'RUSH0
370 IF RUSHO="Y" OR RUSH0="y" THEN 540  'no tab-data file, so no header
380'
390 PRINT
400 PRINT "YOU HAVE THREE LINES (60 COLUMNS EACH) FOR THE OUTPUT HEADER:
410 PRINT
420 PRINT "   1  2  3  4  5";
430 PRINT "   6"
440 PRINT " 1________0________0________0________0________0"
450 PRINT " 0________0"
460 INPUT "LINE 01 ==> ",LINEO1
470 INPUT "LINE 02 ==> ",LINEO2
```
480   INPUT "LINE 03 ==> ",LINE39
490
500   PRINT LINE10 'DEBUG
510   PRINT LINE20 'DEBUG
520   PRINT LINE30 'DEBUG
530
540   PRINT;INPUT "ENTER THE STEP-INCREMENT (oils) ==> ", STEPP
550   INPUT "ENTER THE STAGNATION PRESSURE (oo. Hg) ==> ",PO
560   INPUT "ENTER THE STAGNATION TEMPERATURE (deg. F) ==> ",TSTAG
570
580   INPUT "ENTER THE X-LOCATION (inches) ==> ",XLOC
590   INPUT "ENTER THE LOCAL STATIC PRESSURE (oo. Hg) ==> ",PS
600   INPUT "ENTER THE 'BOUNDARY LAYER THICKNESS' (oils) ==> ",DELTA
610   IF FASTO="Y" OR FASTO="y" THEN 660
620
630   INPUT "USE DEFAULTS? (Y/<CR>) ==> ",FASTO
640   INPUT "EDGE PROPERTY FILES ONLY? (Y/N) ==> ",PANICO
650
660   IF FASTO="Y" OR FASTO="y" THEN 690 'pitot O.D. unchanged for repeats
670   INPUT "ENTER THE PITOT TUBE OUTSIDE DIAMETER (oils) ==> ",OD
680
690   PRINT STEPP,PO,TSTAG,XLOC;STOP 'DEBUG
700
710   OPEN "I",01,INDRIVE0+FILE0*.DAT"
720
730   INPUT 01,PO           'get the stagnation pressure
740
750   FOR N=1 TO 50
760     IF EOF(1) GOTO 810
770     INPUT01,PT(N),ZERO(N)
780     PRINT N,PT(N),ZERO(N) 'DEBUG
790     IF (N MOD 21) = 0 THEN STOP 'DEBUG
800   NEXT N
810   CONTINUE
820   STOP   'DEBUG
830
840   N = N-1 'throw out last increment
850
860
870   SUM = 0: INDEX = 0
880   FOR I=1 TO 20
890   IF ZERO(1) <= 0 GOTO 940
900     SUM = SUM + PT(I)
910     INDEX = INDEX + 1
920   NEXT I
930
940   IF INDEX = 0 THEN PRINT: PRINT" ERROR IN INPUT FILE":PRINT:END
```

N = (INDEX+1)
PRINT "N = " INDEX
WAXPRESS = 0.0
FOR I=2 TO N
PT(I) = PT(I-INDEX)+1
IF PT(I) > WAXPRESS THEN WAXPRESS = PT(I); THISONE = I
NEXT I
PT(I) = SUH/INDEX
N = THISONE
PRINT "N = " N
PRINT: STOP
FOR I=1 TO N PRINT PT(I); " "
PRINT: STOP
FOR I=1 TO N 'SET THE STEP INCREMENT
Y(I) = STEPS(I-1) + OD/2
PRINT Y(I); °
NEXT I
PRINT: STOP
IF FLAG="Y" OR FLAG="y" THEN 1170 'same cal. values for repeats
PRINT: PRINT "ENTER THE CALIBRATION VALUES FOR THE CHANNEL AND GAIN"
PRINT: PRINT "USED TO ACQUIRE THE DATA FOR THIS RUN:" PRINT SLOPE, INTERCEPT; PRINT: STOP
FOR I=1 TO N 'Convert raw pressure data
TEMP = PT(I) - INTERCEPT ' (counts) to cm. Hg
PT(I) = TEMP/SLOPE
PRINT PT(I); " 
NEXT I
PRINT: STOP
CLS 'clr screen
PRINT: PRINT: PRINT SPC(2B) "WORKING"
PRINT: PRINT: PRINT "DATA POINTS PROCESSED:" PRINT
TEHP(O) = .94OSTA6+459.69)
RHO(O) = PS/(2.01647$(TSTA6+459.69))
124

Figure 61—Continued

1370  I = 1,  'need this for Mach no. calc.
1380  
1390  FOR I=1 TO N
1391  
1400  IF PT(I)/PS THEN PT(I) = PS
1410  IF PS/PT(I) < .528282 GOTO 1460  'it's supersonic
1420  
1430  H(I) = 598((PT(I)/PS)^((2/7)-1))  'subsonic Mach no. as
1440  GOTO 1610  'per L&H eqn. 6.2

1460  A = ((1/6)^((5/2)/(5/6))+(5/2)^((7/2)))  'supersonic Mach no.
1470  LOOPSTART HERE  'as per Rayleigh eqn.
1490  B = (78Z) - 1  'the Mach no.
1510  F = A6((5/2)/(7/2)) - (PS/PT(I))  'implicit in the
1520  XX = 3586((3/2)/Z^((7/2))  'solution, therefore
1530  YY = 788^((5/2)/(2/4))  'use Newton's method.
1540  FP = (A^2)(XX-YY)
1550  X = Z-(F/FP)
1560  IF ABS(Z-X) < .0001 GOTO 1590  'it converged

1570  Z=Xs GOTO 1480  'LOOPSTART  'try again
1590  
1600  CONTINUE here if subsonic solution was used
1620  'END routine for Mach no.

1630  PRINT H(I)" ";"STOP  'DEBUG
1640  
1650  the local temperature:
1660  
1670  TEP(I) = (.94+.068(Y(I)/Y(I)))8(TSTAG+459.69)
1680  TEP(I) = TEP(I)/(1+.28H(I)^2)  'units = degrees Rankine
1690  PRINT TEP(I)" ";"STOP  'DEBUG

1700 'the local density:
1710 ' 
1730  RHO(I) = .0522038PS/TEP(I)  'units = lbm/ft^3
1740  PRINT RHO(I)" ";"STOP  'DEBUG

1750 'the local velocity:
1760 ' 
1770  A = 49.01658BR(TEP(I))  'need local Mach no.
1790  VEL(I) = H(I)^8A  'convert to velocity
1800 ' PRINT VEL(I)" ";"STOP  'DEBUG
1810 ' 
1820 PRINT USING"000000";I;"show completion of each iteration
Figure 61—Continued

1830  IF (I MOD 10) = 0 OR I = N THEN PRINT  "clean up output
1840  NEXT I
1850 ,
1860 ,
1870 , new calculate the dimensionless parameters (y-bar and theta)
1880 , integrate numerically by the Trapezoid Rule
1890 ,
1900 , this takes a while, so let user know the prog. hasn't crashed:
1910 ,
1920  PRINT:PRINT SPC(25)"STILL WORKING":PRINT
1930 ,
1940 ,
1950  STH = 0  "this is the cantuqo
1960  CONSTANT = RHO(N)*VEL(N)^2  "thickness calculation
1970 ,
1980  FOR I=2 TO (N-1)  "add up F(2) to F(n-1)
1990  STH = STH + RHO(I)*VEL(I)8*(VEL(N)-VEL(I))
2000  NEXT I
2010 ,
2020  STH = STH + .758*(RHO(I)*VEL(I)^8*(VEL(N)-VEL(I)))
2030 ,
2040  THETA = STEPP*STH/CONSTANT  "units are oils
2050 ,
2060 ,
2070  STH = 0  "this is the Delta-8
2080  CONSTANT = RHO(N)*VEL(N)  "calculation
2090 ,
2100  FOR I=2 TO (N-1)
2110  STH = STH+CONSTANT-(RHO(I)*VEL(I))
2120  NEXT I
2130 ,
2140  STH = STH+.758*(CONSTANT-(RHO(I)*VEL(I)))
2150 ,
2160  DELTASTAR = STEPP*STH/CONSTANT  "units are oils
2170 ,
2180 ,
2190  YBAR(0) = 0  "this is the
2200  YBAR(I) = (STEPP/4)*((RHO(1)+RHO(0))/RHO(N))  "Y-
2210 ,
2220 ,
2225  GBTIT = 0
2230  FOR I=1 TO N  "jump Y' calc. lot time thru
2235  IF I=1 THEN 2360  "jump Y' calc. lot time thru
2240  ENDS = ((RHO(0)/2)+RHO(1))/RHO(N)
2250  FACTOR = 1.58*(RHO(1)/RHO(N))
2260  IF I=2 THEN 2330
2270 ,
2280 ,
FOR J=2 TO (I-1)
    FACTOR = FACTOR + (2*N/RH0(J)/RHO(N))
NEXT J

YBAR(I) = (STEPP/2)*(ENDSTFACTOR) 'units are oils

m = (1.09E-068*(TEKP(I)^1.5))/(TEMP(I)+198.6)

REPRIME(I) = 4.8*l248*Ka(I)*VEL(I)/HU 'Re'' calc. (in SI)

PRINT USING"0000000";I 'show the iterations as before

IF (I MOD 10)=0 OR I=N THEN PRINT '10 per line

IF DOTIT=0 AND VEL(I)>=.998VEL(N) THEN DELTA=Y(I)/DOTIT=1

NEXT I

calculations are complete, so output the data:

use defaults if the "fast" flag is set:

IF FASTO = 0Y0 OR FASTO = Y THEN OUTFILE0=FILE0:600 TO 2340

PRINT:PRINT

INPUT "ENTER THE OUTPUT DATA FILE NAME (no '.EXT' ==> ",OUTFILE0

CLOSE 81 'close the input file

IF RUSHO=0Y0 OR RUSHO=Y0 THEN 4020 'no tab-data file wanted

OPEN *0,02,OUTDRIVES+OUTFILE0".OUT" 'open the tab-data output file

IF FASTO=0Y0 OR FASTO = Y THEN SEEIT0=0 AND GOTO 2610 'default = no echo

PRINT "ECHO OUTPUT TO THE SCREEN ? (Y/N) ==>",SEEIT0

IF SEEIT0 (>Y0 AND SEEIT0=0 THEN 3340 'no screen echo.

CLS 'clr screen

PRINT LINE10;PRINT LINE20;PRINT LINE30

PRINT:*PRINT

PRINT "STAGNATION PRESSURE (cc. Hg): ";PRINT USING"0000000000";PO

PRINT "STAGNATION TEMP. (deg. F): ";PRINT USING"0000000000";STA9

PRINT "DISTANCE FROM THROAT (x, cc.): ";

PRINT USING"000000.000";XLOC22.56

PRINT "STATIC PRESSURE (cc. Hg): ";PRINT USING"000000.000";PS

PRINT "BOUNDARY LAYER THICKNESS (cc.): ";
Figure 61—Continued

2750 PRINT USING"*0000.0000";DELTA0.0254
2760 PRINT "HORIZONTAL THICKNESS (cm): ";
2770 PRINT USING"*0000.0000";THETA0.0254
2780 PRINT "DISPLACEMENT THICKNESS (cm): ";
2790 PRINT USING"*0000.0000";DELTASTAR0.0254
2800 PRINT:PRINT
2810 PRINT:PRINT
2820 PRINT USING"*0000.0000";DELTAS.0234
2830 PRINT "MOMENTUM THICKNESS (cm): ";
2840 PRINT USING"*0000.0000";THETASTAR8.0254
2850 PRINT USING"*0000.0000";THETAS.0234
2860 PRINT "DISPLACEMENT THICKNESS (cm): ";
2870 PRINT USING"*0000.0000";DELTASTAR8.0254
2880 PRINT USING"*0000.0000";DELTAS.0234
2890 PRINT USING"*0000.0000";THETASTAR8.0254
2900 INPUT "PRESS ANY KEY TO CONTINUE ==> ",KEYYO
2910 CLS 'clr screen
2920 PRINT:PRINT
2930 PRINT:PRINT
2940 FOR M TO N
2950 PRINT USING"*00000.0000";Y(I)8.0254;
2960 PRINT USING"*00000.0000";PT(I);
2970 PRINT USING"*00000.0000";H(I);
2980 PRINT USING"*00000.0000";VEL(I)8.3048;
2990 PRINT USING"*00000.0000";TEMP(I)8(5/9);
3000 PRINT USING"*00000.0000";RD(I)816.0185;
3010 PRINT USING"*00000.0000";VEL(I)/VEL(N);
3020 PRINT USING"*00000.0000";Y(I)/Y(N)
3030 IF (I MOD 10)=0 OR I=N THEN PRINT;INPUT "<CR> TO CONTINUE ==> ",KEYYO
3040 NEXT I
3050 CLS
3060 FOR I=1 TO N
3070 PRINT USING"*00000.0000";Y(I)8.0254;
3080 PRINT USING"*00000.0000";PT(I);
3090 PRINT USING"*00000.0000";H(I);
3100 PRINT USING"*00000.0000";VEL(I)8.3048;
3110 PRINT USING"*00000.0000";TEMP(I)8(5/9);
3120 PRINT USING"*00000.0000";RD(I)816.0185;
3130 PRINT USING"*00000.0000";VEL(I)/VEL(N);
3140 PRINT USING"*00000.0000";Y(I)/Y(N)
3150 IF (I MOD 10)=0 OR I=N THEN PRINT;INPUT "<CR> TO CONTINUE ==> ",KEYYO
3160 NEXT I
3170 PRINT:PRINT
3180 PRINT:PRINT
3190 PRINT:PRINT
3200 '
3220 ' FOR I=1 TO N
3230 PRINT USING"00,0000";REPRIHE(I);
3240 PRINT SPC(3);PRINT USING"00,0000";Y(I)/THETA;
3250 PRINT SPC(3);PRINT USING"00,0000";Y(I)/DELTASTAR;
3260 PRINT SPC(3);PRINT USING"00,0000";YBAR(I)/THETA;
3270 IF (I MOD 10)=0 THEN PRINT"INPUT<CR> TO CONTINUE ===>",KEYYO
3280 NEXT I
3290 ' non write all the data to the files:
3300 '
3310 '
3320 ' non write all the data to the files:
3330 '
3340 CLS 'clr the screen
3350 LOCATE 12,1
3360 HSG0 = "WRITING TO THE FILES: THIS TAKES A FEW MINUTES"
3370 OFFSET = ((80 - LEN(HSG0))/2) + 1
3380 PRINT SPC(OFFSET);HSGO;PRINT;PRINT
3390 PRINT02,CHR$(10)
3400 PRINT02,LINE10:PRINT02,LINE20:PRINT02,LINE30
3410 PRINT02,CHR$(10);CHR$(10)
3420 PRINT02,CHRO(10)
3430 PRINT02,"STAGNATION PRESSURE (mm. Hg):";SPC(5);
3440 PRINT02,USING"00000000";PO
3450 PRINT02,"STAGNATION TEMP. (deg. F):";SPC(5);
3460 PRINT02,USING"0000.00";TSTAG
3470 PRINT02,"DISTANCE FROM THROAT (X, cm.):";SPC(5);
3480 PRINT02,USING"00000000";XLOC
3490 PRINT02,"STATIC PRESSURE (mm. Hg):";SPC(5);
3500 PRINT02,USING"00000000";PS
3510 PRINT02,"BOUNDARY LAYER THICKNESS (mm):";SPC(5);
3520 PRINT02,USING"0000.00";DELTA
3530 PRINT02,"MOMENTUM THICKNESS (mm):";SPC(5);
3540 PRINT02,USING"0000.00";DELTA0.025
3550 PRINT02,"DISPLACEMENT THICKNESS (mm):";SPC(5);
3560 PRINT02,USING"00000000";DELTASTAR.025
3570 PRINT02,CHR$(10);CHR$(10)
3580 PRINT02,"B. L. PARAMETERS -vs- DISTANCE FROM THE HALL: I"
3590 PRINT02,"------------------------------------------"
3600 PRINT02,"Y POS. P. PRESS MACH VELOCITY TEMP. DENSITY"
3610 PRINT02,CHR$(10);CHR$(10)
3620 PRINT02,"Y POS. P. PRESS MACH VELOCITY TEMP. DENSITY"
3630 PRINT02,SPC(4);PRINT02,"U/W, V/Delta"
3640 PRINT02,"(m. sec) (m. Hg) M. (m. sec) (KELVIN) (Kg/m^3)"
3650 PRINT02,"------------------------------------------"
3660 PRINT02,"------------------------------------------"
3670 PRINT02,CHR$(10)
3680 "}
Figure 61—Continued

3690 FOR I=1 TO N
3700 PRINT02,USING"00.000",Y(I).0254;
3710 PRINT02,SPC(3);PRINT02,USING"000.0000",PT(I);
3720 PRINT02,SPC(3);PRINT02,USING"0000.0",A(I);
3730 PRINT02,SPC(3);PRINT02,USING"0000.000",VEL(I).3048;
3740 PRINT02,SPC(3);PRINT02,USING"000000",THETA(I).1.3048;
3750 PRINT02,SPC(3);PRINT02,USING"000000",Y(I)/THETA;
3760 PRINT02,SPC(3);PRINT02,USING"000000",Y(I)/DELASTAR;
3770 NEXT I
3780 'non add all the edge properties to files (for plotting later)
3790 XLOC = XLOC2.54 'convert to co.
3800 OPEN "A",01,"VELOCITY.DAT";
3810 PRINT01,XLOC;SPC(5);VEL(I).3048;
3820 CLOSE 01
3830 OPEN "A",01,"HACH.DAT";
3840 PRINT01,XLOC;SPC(5);A(I);
3850 CLOSE 01
OPEN "A",02,"DENSITY.DAT"
"PRINT02,XLOC;SPC(5);:PRINT02,USING"."0000000";RHO(N)$16.0185
CLOSE 02

OPEN "A",02,"TEMP.DAT"
PRINT02,XLOC;SPC(S);TEMP(N)$,(5/9)
CLOSE 02

OPEN "A",02,"PRESSURE.DAT"
PRINT02,XLOC;SPC(S);PRESS
CLOSE 02

OPEN "A",02,"DELTA.DAT"
PRINT02,XLOC;SPC(S);DELTAS.0254
CLOSE 02

OPEN "A",02,"DELTASTAR.DAT"
PRINT02,XLOC;SPC(S);DELTASTAR0.0254
CLOSE 02

OPEN "A",02,"THETA.DAT"
PRINT02,XLOC;SPC(S);PRINT02,USING"."0000000";THETA0.0254
CLOSE 02

OPEN "A",02,"REPRIRE.DAT"
PRINT02,XLOC;SPC(S);PRINT02,USING"0000000.000";REPRIRE(H)
CLOSE 02

last files to write are the normalized profiles:

IF PANICO="Y" OR PANICO="y" THEN 5090 'skip this if in a real hurry

IF FASTS="Y" OR FASTS="y" THEN 4600 'don't need to fix filename

OPEN "O",02,OUTDRIVE+OUTFILE+.NVP

FOR I=1 TO N
PRINT 02,USING"O.000000";Y(I)/Y(H);

Figure 61—Continued

4640 PRINT 02, SP(5); PRINT 02, USING "0.00000"; VEL(I)/VEL(N)
4650 NEXT I
4660 ' 
4670 CLOSE 02
4680 ' 
4690 ' 
4730 OPEN "0", 02, OUTDRIVE0+OUTFILE0+.HUP" 
4740 ' 
4750 FOR I=1 TO N 
4760 PRINT 02, USING "0.00000"; Y(I)/THETA;
4770 PRINT 02, SP(5); PRINT 02, USING "0.00000"; VEL(I)/VEL(N)
4780 NEXT I
4790 ' 
4800 CLOSE 02
4810 ' 
4820 ' 
4860 OPEN "0", 02, OUTDRIVE0+OUTFILE0+.HDP" 
4870 ' 
4880 FOR I=1 TO N 
4890 PRINT 02, USING "0.00000"; Y(I)/Y(I);
4900 PRINT 02, SP(5); PRINT 02, USING "0.00000"; RHO(I)/RHO(N)
4910 NEXT I 
4920 ' 
4930 CLOSE 02
4940 ' 
4950 ' 
4990 OPEN OOB, 02, OUTDRIVE0+OUTFILE9+?NMP° 
5000 ' 
5010 FOR I=1 TO N 
5020 PRINT 02, USING "0.00000"; Y(I)/Y(N);
5030 PRINT 02, SP(5); PRINT 02, USING "0.00000"; H(I)
5040 NEXT I 
5050 ' 
5060 CLOSE 02
5070 ' 
5080 ' 
5090 ' user may have gone to sleep waiting for the ppo. to get this far
5100 ' so rung the bell to wake him/her up;
5110 ' 
5120 PRINT CHR$(7);CHR$(7)
5130 ' 
5140 ' 
5150 ' Now let the user loop back to crunch another data file in the same
5160 ' series of runs (say Po, To, increment, pitot tube, etc) or end
5170 ' the program if the series of files has been crunched;
5180 ' 
5190 ' 
5200 PRINT:PRINT
5210 PRINT "DO YOU WANT TO PROCESS ANOTHER DATA FILE FROM THIS SERIES"
5220 INPUT "(SAME increment, etc) (Y/<CR>) ==> ",FLAG$ 
5230 ' 
5240 IF FLAG$="Y" OR FLAG$="y" THEN 170 'back to series-repeat entry point 
5250 ' 
5260 ' 
5270 ' User says 'don't repeat' so end program. 
5280 ' 
5290 CLS:KEY ON:END
APPENDIX B

MICROBALANCE CALIBRATION
MICROBALANCE CALIBRATION INSTRUCTIONS

Calibration

1. Install the microbalance in the test stand and connect it to the digital voltmeter as shown in Figure 62 below. The signal may be read directly (shown as "no gain" on the figure) or fed through the pressure station. The latter is the recommended method because it provides amplification and zero-load output trimming.

Figure 62. Configuration for Microbalance Calibration
2. Adjust the transducer 'A' power supply trim pot (on the pressure station) until the voltmeter reads 10 volts across the input ports at the mike jack.

3. Apply a maximum rated load (10 grams or 50 grams, depending on the device being calibrated) to the microbalance. The purpose of this step is to remove any 'play' in the mechanism.

4. If desired, adjust the transducer 'A' output trim pot on the pressure station front panel to obtain a zero reading when the transducer is unloaded (zero load).
   NOTE -- adjust the zero-reading with the sling in place.

5. Measure and record the output while applying loads over the entire operating range of the microbalance. Make at least three runs of measurements. Unload the microbalance between runs (by removing the weight and sling) to verify a proper return to the zero-load output (i.e., to check for hysteresis). It is best to vary the order of load application in a random manner during each run rather than always loading the microbalance progressively.
   NOTE -- the SAME DATA ACQUISITION SYSTEM must be used for both the calibration and the actual measurements in the tunnel.
6. Use the average of the output values for the three runs to make a linear-regression curve-fit of the LOAD -VS- OUTPUT relationship (NOT output-vs-load). A quadratic fit usually gives the best correlation. The coefficients will be used to reduce the actual data from the wind tunnel.

Reducing the Actual Data

The zero-load output reading obtained during a data run generally will not be the same as the zero-load value obtained during calibration. If the difference was not compensated for by adjusting the actual zero-load output to match the calibration zero-load output as described in step 4 above, then the following correction is required:

1. If the calibration curvefit was linear, the load -vs- output relationship obtained from calibration is of the form:

   load = A + Bx(output)

   The corrected form for actual data reduction is:

   load = A + Bx(output - offset);
   offset = (actual no-load output) - (cal. output)
2. If the calibration curvefit was quadratic, the load-vs-output relationship obtained from calibration is of the form:

\[ \text{load} = A + Bx(\text{output}) + Cx(\text{output})^2 \]

The corrected form for actual data reduction is:

\[ \text{load} = A + Bx(\text{output} - \text{offset}) + Cx(\text{output} - \text{offset})^2 \]

where offset is defined as in (1) above.
APPENDIX C

DYNAMIC PRESSURE PROBE CALIBRATION
CALIBRATION OF THE DYNAMIC PRESSURE PROBE

The Dynamic Pressure Probe (DPP) proved difficult to calibrate due to the extreme temperature sensitivity of the Kulite CQ-030-100G transducer. Figure 63 is a signal v. time plot of the DPP output that illustrates the problem.

![Figure 63. DPP Signal v. Time for Varied Temperature Environments](image)

At the 100 second point on the plot, the DPP was cooled by spraying the sting and fin (not the transducer) with Freon. As shown, the signal changed by about 100 mV. The remainder of the plot shows the DPP output during actual operation in the SWT. Note that the change in output due to cooling was of about the same magnitude.
as a change in pitot pressure of 170 mm. Hg. This change represents the entire operating range of the device as used for SWT measurements.

Figures 64 and 65 are plots of the DPP D.C. signal in a laminar and a turbulent boundary layer respectively, plotted against standard pitot tube profiles taken under the same conditions.

![DPP v. Standard Pitot Tube Profiles in a Laminar Boundary Layer](image)

Figure 64. DPP v. Standard Pitot Tube Profiles in a Laminar Boundary Layer

The DPP profiles in these plots were fitted to the pitot profiles by scaling the ordinates so that they matched at the edge of the boundary layer. The profiles are in reasonable agreement for the laminar case, but are seriously dissimilar for the turbulent case.
The discrepancies between the DPP and the pitot tube were thought to be caused by the DPP temperature sensitivity, aggravated by a too-rapid traverse through the boundary layer.

The first attempts to calibrate the DPP consisted of placing the transducer in a fixed location in the SWT and comparing its output to the known pitot pressure (obtained by a standard pitot tube) under various stagnation pressures ($P_o$). Repeated runs using this method showed a wide variation in the calculated sensitivity (output v. $P_t$) between calibrations. It is known that the SWT air flow undergoes a transient temperature change during changes in
and it was believed that the temperature sensitivity of the transducer was responding to these changes.

Consequently, a new calibration method was devised to eliminate the temperature effect. The method consisted of placing a streamlined axisymmetric object (a "shield") in the SWT test section. The shield produces a dynamic pressure field at constant \( P_0 \) (hence constant \( T_0 \)), which can be measured and documented with a standard pitot tube. By repeating the process with the DPP, the desired calibration data was obtained.

Figure 66 illustrates the results of 11 calibration runs; seven by the first method and four by the improved method. It is obvious from the figure that the improved method produces much less uncertainty in the sensitivity of the DPP and a closer agreement with specifications.

Figure 67 illustrates the electronic configuration for the improved calibration procedure. In practice, calibration data is taken simultaneously for both the standard pitot tube and the DPP, both of which are at known positions relative to the shield. The data are then matched at the same location in the flowfield to yield the DPP sensitivity.
Figure 66. Calculated DPP Sensitivity for 11 Calibration Runs
During experiments, the temperature effect was minimized by monitoring the DPP output on a chart recorder. Data runs were started only after the DPP output was seen to be constant in time, and each data point was recorded only after the DPP output for that point was stable.
APPENDIX D

COMPARISON BETWEEN TRIP PERFORMANCE AND THE POTTER-WHITFIELD TRIP SIZING CORRELATION
COMPARISON OF TRIP PERFORMANCE WITH THE
POTTER-WHITFIELD TRIP SIZING CORRELATION

In Reference {5}, J. L. Potter and J. D. Whitfield published an empirical method for determining the location of the onset of turbulence transition behind a three-dimensional roughness (a trip), based on the laminar boundary layer profile at the trip location, the trip height, the laminar boundary layer temperature profile at the trip location, and the location of the onset of turbulence transition without the trip (smooth-wall transition). The Potter-Whitfield method has been validated by other investigators since its publication, and is widely used to 'design' effective trips.

The Potter-Whitfield method was developed from transition data taken behind single rows of spherical trips, and the authors caution against using the method to design trips of non-spherical shape. However, the usefulness of the method would be greatly enhanced if it could be shown to apply to three-dimensional trips other than spheres.

Consequently, the Potter-Whitfield method was applied to all the trips of this investigation to determine whether or not their measured performances correlated to the Potter-Whitfield curve.
The method is applied as follows:

1. Given the trip height \((k)\) and the known or calculated laminar boundary layer profile at the trip station \((X_k)\), a roughness parameter \((\epsilon)\) is determined from Figure 27 of the reference. \(\epsilon\) is the roughness Reynolds number \((\text{Re}'_k)\) when the onset of transition is at the trip station.

2. The actual roughness Reynolds number for the trip is calculated from \(k\), the laminar velocity profile at \(X_k\), and the corresponding temperature profile, using equation 13, 14, 15, 16, or 17 of the reference.

3. The ratio \(\text{Re}'_k/\epsilon\) is applied to the performance curve given in Figure 28 of the reference to determine a position parameter, defined as:

\[
(X_t/X_{to})^{1/2} - (\text{Re}'_k/\epsilon)(X_t/X_{to})^{1/2}
\]

where: \(X_t\) is the location of transition onset and \(X_{to}\) is the location of smooth-wall (no-trip) transition.

4. The position-parameter formula and the numerical value given by (d) above can be used to determine the unknown \(X_t\).

5. Conversely: given a desired \(X_t\), the trip station \(X_k\), and the boundary-layer profiles, the method can be used to determine the required trip height \((k)\). This is the usual application of the method.
An important caveat: The Potter-Whitfield method is valid only for the range $X_k < X_t < X_{to}$. Obviously, $X_t = X_{to}$ is the limiting case when $k = 0$ (no trip). The other limit ($X_t = X_k$) has a corresponding "maximum $k$": trips taller than this maximum value will yield calculated $Re'_k/\epsilon$ greater than one, and are meaningless both physically and in the application of the method. Consequently, in comparing the trips to the Potter-Whitfield curve, $Re'_k/\epsilon$ was taken as unity for all trips that were taller than the calculated maximum.

The method used to compare the trips with Potter-Whitfield was as follows:

1. The actual laminar boundary-layer temperature profile (from the tare data) was used to calculate the adiabatic-wall recovery factor and the Prandtl number, as a check on the validity of the tare data itself.

2. The value of $\epsilon$ was taken from Figure 27 of the reference and the actual boundary-layer edge Mach number at $X_k$. As a first approximation, it was assumed that the maximum trip height for Potter-Whitfield was greater than or equal to the boundary-layer thickness.

3. The value of $\epsilon$ from (b) above, the tare flow properties, and equation 16 of the reference were
used to determine $k_{\text{max}}$ for the limiting case
$Re'_{k} = \epsilon$, calculated as .301 Cm.
The actual tare boundary-layer thickness was .315 Cm.
However, the differences in the flow parameters at the
assumed and actual values of $k$ are all $<< 1/10$ of 1
percent; therefore the calculation of $k_{\text{max}}$ was taken as
valid within the error range of the source data.

It transpired that $k$ was greater than $k_{\text{max}}$ for all but
three of the trips (S-3, S-8 and P-3). Therefore, the only
possible comparison between actual trip performance and
Potter-Whitfield for the "tall" trips was to determine
whether or not these trips met the limiting case of
$X_t = X_{to}$.

The location of $X_{to}$ was determined by the first
appearance of transitional turbulence signals in the hot-
film anemometer data of Reference (20) taken behind each
trip (except for the plates, which had previously been
determined to have no influence at all on transition). The
results for the "tall" trips are plotted on Figure 68.
Trips that do not fall on the Potter-Whitfield "suggested
curve" are taken as not correlating with the method.

It should be noted that the above results do not imply
that the "tall" trips which meet the limiting performance
criterion actually correlate with the Potter-Whitfield performance curve: it is probably best to say that the results are indeterminate in these cases. Additionally, it should be noted that the Potter-Whitfield Position Parameter is bounded at both ends for tall trips. The Position Parameter always has a lower bound of zero: also; for $X_t = X_{to}$, $Re'_k/\epsilon$ forced to unity, the maximum value of the Position Parameter is fixed numerically by the value of $(X_k/X_{to})^{1/2}$.

The trips for which $k \leq k_{max}$ produced results as shown on Figure 68. These results can be summarized as follows:

1. The calculated values for Position Parameter v. $Re'_k/\epsilon$ fall directly on the Potter-Whitfield "suggested curve" for trips S-3 and S-8. It can therefore be said that, at least for these trips, the Potter-Whitfield method correlates with actual trip performance.

2. The calculated Position Parameter for trip P-3, which has the same roughness height as S-3, but is known to have no effect on transition, does not fall on the suggested curve. This result is as expected, since it represents the theoretical "worst case". However, it also bears out the point that the Potter-Whitfield method cannot be used for trips of arbitrary shape.
The conclusion to be drawn from this comparison is that more experimentation is needed in order to establish the dimensional parameters under which a trip of a given shape will fit the Potter-Whitfield performance curve. The Potter-Whitfield parameter that contains trip geometry \((\text{Re}_k')\) allows only one length variable \((k)\). Obviously, this is inadequate for trips that cannot be geometrically defined by a single length dimension.
Figure 68. Trip Correlations with the Potter-Whitfield Performance Curve (Plotted on the Original graph from {5})