Characteristics of a supersonic laminar boundary layer over a rough wall
by Joseph Michael DSa

A thesis submitted in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in Mechanical Engineering
Montana State University

Abstract:
The characteristics of a supersonic laminar boundary layer over a rough wall were investigated. The boundary layer was produced by, a slender body of revolution at Mach 3 and the roughness consisted of random distributed and two dimensional periodic overlays. Results reported here cover mean flow profiles needed to validate and characterize the flow and detect changes in the profile caused by roughness. The critical roughness needed to cause profile distortions is based on the Reynolds number defined by local properties rather than free stream properties. The height of the distributed roughness needed to cause profile distortions caused great difficulty in interpreting the profile data. The two dimensional periodic overlay with a roughness height greater than the critical roughness height caused an upstream movement of transition. The two dimensional overlay also caused an outward displacement of the boundary layer edge with a simultaneous decrease in the boundary layer thickness causing a distinct distortion of the boundary layer profile and an increase in the surface skin friction.

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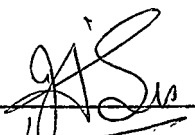
Signature 

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JOSEPH MICHAEL D'SA

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NOMENCLATURE

Symbol		Description
c_{f1}	:	Friction coefficient (wall viscosity)
c_{f2}	:	Friction coefficient (stream viscosity)
k	:	Roughness height
k_1	:	Critical height for destabilization/transition
M	:	Mach number
P	:	Pressure
P_T	:	Pitot pressure reading
R	:	Gas constant
Re'	:	Unit Reynolds number
Re_θ	:	Momentum Reynolds number
$Re_{e,T}$	:	Critical Reynolds number for destabilization (based on roughness height and stream properties)
$Re_{k'}$	:	Critical Reynolds number for destabilization (based on roughness height and conditions at that height)
T	:	Temperature
T_{op}	:	Local stagnation temperature at pitot tube
u	:	Velocity
x	:	Axial Coordinate (measured from trailing edge forward)
y	:	Coordinate normal to the surface
$\tilde{y}$	:	Transformed coordinate normal to the surface

Symbol		Description
γ	:	Specific heat ratio
δ	:	Boundary layer thickness
δ^*	:	Displacement thickness
θ	:	Momentum thickness
μ	:	Viscosity
ν	:	Kinematic Viscosity
ρ	:	Density
$( )_o$	:	Stagnation (supply) conditions
$( )_e$	:	Boundary-Layer edge conditions
$( )_k$	:	Conditions at roughness height
$( )_w$	:	Conditions on wall surface

ABSTRACT

The characteristics of a supersonic laminar boundary layer over a rough wall were investigated. The boundary layer was produced by a slender body of revolution at Mach 3 and the roughness consisted of random distributed and two dimensional periodic overlays. Results reported here cover mean flow profiles needed to validate and characterize the flow and detect changes in the profile caused by roughness. The critical roughness needed to cause profile distortions is based on the Reynolds number defined by local properties rather than free stream properties. The height of the distributed roughness needed to cause profile distortions caused great difficulty in interpreting the profile data. The two dimensional periodic overlay with a roughness height greater than the critical roughness height caused an upstream movement of transition. The two dimensional overlay also caused an outward displacement of the boundary layer edge with a simultaneous decrease in the boundary layer thickness causing a distinct distortion of the boundary layer profile and an increase in the surface skin friction.

CHAPTER I

INTRODUCTION

The purpose of the present investigation was to determine the characteristics of a supersonic laminar boundary layer over a rough wall.

There are a number of factors such as pressure gradient, surface heat transfer, bluntness, curvature and roughness that could affect the characteristics of a laminar boundary layer. The question of how roughness affects transition of a laminar boundary layer has been addressed by many researchers in the past. For instance, van Driest with McCauley (1) and later with Blumer (2) investigated the effects of three dimensional roughness on transition of supersonic laminar boundary layers, while Whitfield and Iannuzzi (3) investigated similar effects up to a Mach number of 12 to verify the hypersonic extensions of these effects proposed by Potter and Whitfield (4). Roughness, for all the above researchers, consisted of spheres glued to a smooth surface in an array. Only recently, Reshotko and Leventhal (5) and Kendall (6) worked with distributed random roughness (sandpaper) to study disturbances caused by roughness in laminar low speed boundary layers. The question of how random distributed or two dimensional periodic roughness affects characteristics

of a supersonic laminar boundary layer has been given little attention in the past.

There were three questions which were of considerable importance to the present investigation. First of all, it was necessary to determine the critical size of roughness that would show profile distortions compared to the profiles of the smooth (no roughness) surface. Second, how does roughness (above the critical size) affect the point of transition? And third, why does surface skin friction have to be greater for a rough (roughness above critical value) surface compared to a smooth surface?

The question concerning the critical size of roughness has been addressed in the past for low speed flows. According to Fiendt (7), the critical Reynolds number necessary to show profile distortions is defined by free stream properties as

$$Re_{e,T} = \frac{u_e k}{\nu_e} = 120.$$

On the other hand, Reshotko (5) and Kendall (6) motivated by Smith and Clutter (8) state that the critical Reynolds number is defined by local properties as

$$Re_k = \frac{u_k k}{\nu_e} = 100.$$

Thus it was necessary to determine which of the two Reynolds numbers is applicable for laminar supersonic

flows.

The question of why skin friction increases for a rough (roughness greater than the critical value) surface compared to a smooth surface in a supersonic laminar boundary layer has been given little attention in the past.

Although results on how roughness affects the point of transition for three dimensional roughness in laminar supersonic boundary layers have been reported (1), none have been reported for random distributed or two dimensional periodic roughness for similar boundary layers.

CHAPTER II

DESIGN OF THE EXPERIMENT

The criteria to be met in designing this experiment were as follows:

a) The external condition had to be uniform and the ratio of the roughness height k to the boundary layer thickness be constant (or nearly so) over the measured length of the model so that the profile distortion be constant.

b) The range of the Reynolds number Re_θ had to lie below the transition value (thought to be 400-800) and yet be high enough to detect profile distortions.

c) The ratio of k/δ had to be large enough to detect profile distortions compared to the smooth wall case.

The test model was a sharp nosed body of revolution. In this way, the cylindrical surface, unlike a flat surface, would be void of side wall interference. The sharp nose would suppress any bluntness phenomena (e.g. entropy gradients) and the small ogive angle would not allow a large pressure drop across the weak shock from the nose. Calculations show that a model like the one mentioned when placed in the test section of the wind tunnel would have a boundary layer thick enough to avoid resolution problems with miniaturized sensors and yet thin

enough to avoid phenomena peculiar to axisymmetric boundary layers (9).

CHAPTER III

DESCRIPTION OF MODEL AND WIND-TUNNEL

The wind-tunnel and model are pictured on Figures 1 through 3. The MSU Supersonic Wind Tunnel (MSU/SWT) is configured to operate continuously with Mach 3.0 nozzle discharging into a 3.1" x 3.2" (7.87 cm. x 8.13 cm.) test section. The stream unit Reynolds number Re' range varies from about 20,000 to 60,000 per cm.

The model consisted of a sharp ogive-cylinder combination with an overall length of 12.6" (32.0 cm). The ogive tip formed a cone 5.2° in half angle, with the purpose of avoiding significant shock waves reflecting on the model surface by sidewall reflection. The ogive was 4.6" (11.68 cm.) long and was detachable from the 8" (20.32 cm.) long cylindrical afterbody. Several afterbodies had been built, and the design allowed for rapid disassembly and reinstallation of the desired afterbody in the SWT without removing the entire model. The ogive-afterbody junction was designed to be flush for each afterbody choice. The entire model was suspended by two vertical actuator struts, while two additional struts supported the sensor probe in use. The model-probe arrangement could be moved vertically in unison (for example, when starting the tunnel, they were moved to the tunnel ceiling to prevent

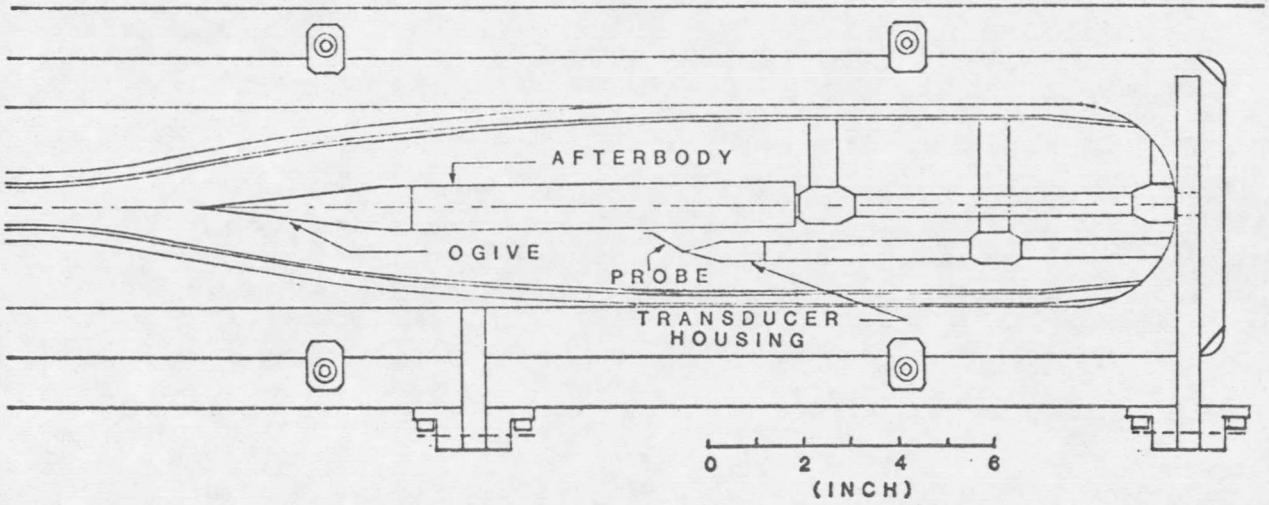

Figure 1 Placement of the Model and Probe in the Test Section (to scale