TRANSITION DUE TO SURFACE STEPS IN THE PRESENCE OF FAVORABLE PRESSURE GRADIENTS

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The influence of favorable pressure gradients on the allowable size of surface steps for laminar flow wings can have a beneficial effect on manufacturing tolerances. However, generally-applicable guidelines for including the effects of pressure gradient on the allowable size of surface steps do not exist in the literature. A series of experiments has been undertaken, in a low-speed wind tunnel and a novel propelled-model facility, to obtain data to determine manufacturing tolerances for laminar flow aircraft. Building on that work, new models were designed and tested to extend the ranges of applicable Reynolds number and pressure gradient to include many future aircraft concepts. In the case for an unswept wing with a pressure gradient of K=0.5x10^{-7} the allowable Re_k was found to be approximately an order of magnitude greater than that from a wind tunnel with very good flow quality designed for boundary layer studies. This is the first reporting in what will be a series of papers related to this test program.

NOMENCLATURE

U_e	edge velocity
U_∞, U	freestream velocity
Cp	coefficient of pressure
ν	kinematic viscosity
ν_k	kinematic viscosity at height k
c	chord
s	streamwise distance along surface, measured from leading edge
x	chordwise distance
k	excrescence height
u_k	velocity in boundary layer profile at height k
Re_k	excrescence height Reynolds number
Re_{xk}	excrescence location Reynolds number
Re_{tr}	transition Reynolds number
K	nondimensional pressure gradient
Cf	skin friction coefficient

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INTRODUCTION

It is widely appreciated that aircraft designed to exploit laminar flow for wing drag reduction, such as SensorCraft concepts like the one shown in Figure 1, require tighter manufacturing tolerances than may be otherwise typical. [1] These tighter tolerances come from concern regarding surface excrescences—often steps—causing premature transition of the laminar boundary layer. The tighter tolerances can have the effect of increasing manufacturing costs and complexity; hence there is a need to understand the required tolerance accurately enough to strike a balance between the requirements for laminar flow and cost-effective manufacturing. Because laminar flow wings have a favorable pressure distribution over a relatively large portion of the chord, some skin seams inevitably are placed in regions of favorable gradient. By determining the specific relation between favorable pressure gradient and allowable step heights, manufacturing tolerances for laminar flow aircraft can be made less severe.

Figure 1 SensorCraft concept designed for laminar flow

The existing literature focuses almost exclusively on the allowable heights of excrescences in the absence of a pressure gradient (flat plate flow) and therefore the findings are not directly applicable to excrescences in pressure gradients on airfoils. In this work, the goal was to conduct experiments that accounted for pressure gradient effects on transition movement, without being specific to a particular geometry. Therefore, the results could be used to generate tolerance criteria applicable to any aircraft configuration. In order to make the results generally applicable, the results and the parameters on which they depend were nondimensionalized. The excrescences examined were two-dimensional (spanwise invariant) step excrescences, both forward-facing and aft-facing. Excrescence geometries were defined primarily by their height, k. The nondimensionalized excrescence height was expressed as an excrescence Reynolds number, Re_k, and the location of transition was expressed as a Reynolds number, Re_{tr}.

BACKGROUND

The first program to investigate the allowable heights of excrescences in the presence of pressure gradients was called Manufacturing Tolerances for Laminar Flow and given the acronym MeaTLoaF. MeaTLoaF examined unswept two-dimensional step excrescences, with a broad range of pressure gradients, utilizing the Washington State University (WSU) Contractionless Boundary Layer Wind Tunnel [2]. The tunnel is capable of unit Reynolds numbers ranging from zero to 0.2 x 10^6 per foot. The position of the upper wall of the test section was variable and therefore determined the static pressure variation over the test plate. The test article was a flat plate with a super ellipse leading edge. It had provisions to accept full-span excrescence inserts at 4 different chord-wise locations, to affect different excrescence location Reynolds numbers, Re_{xk}. Pressure gradients ranging from strongly adverse to strongly favorable, measured with static pressure taps on the test article, were tested in order to obtain data on the effects of pressure gradient on transition movement. The transition location was determined from skin friction distribution measurements obtained with Preston tubes.

The results for zero pressure gradient cases matched well with the data in the literature, which supports the validity of the wind tunnel experiment. The results for favorable pressure gradients showed that for even very small pressure gradients, there was a significant increase in the allowable step heights. However, the results of the study were limited to a maximum transition Reynolds number (Re_{tr}) based on surface streamwise length of less than 10^6 – not high enough to encompass the entire range of interest for flight applications.

To extend the results to flight applications an approach for testing at higher Reynolds numbers was sought. This was complicated by the practical limitation of many test facilities. The criterion for a test facility was the ability to obtain flight-representative Reynolds numbers with a low disturbance environment conducive to transition testing. The facility that was eventually identified and selected for the study was the Towing Wind Tunnel [3] (TWT) at Tohoku University's Sunrise Beach Research Facility in Hyuga, Japan.

An exploratory test [4] at TWT was conducted using the same model and instrumentation approach used in the earlier wind tunnel testing at WSU. This flat plate model was mounted at a slight angle of attack to produce a mildly favorable pressure gradient on the test surface. With freestream velocities ranging from 20 to 40 m/s, the measurable transition Reynolds number was 0.2 - 2.9 million. Instead of simply extending results to higher Reynolds numbers, the exploratory TWT test yielded an unexpected result. The results implied that a "free-air" environment, different from that of even a wind tunnel with very good flow quality designed for boundary layer studies, has the potential for substantial reduction in required manufacturing tolerances. One would expect free-air to be better, but the profound differences seen in the exploratory test data were not expected. Because of the possibility for dramatic reduction in manufacturing tolerances, the Surface Excrescence Transition Study (SETS) program to more thoroughly investigate the excrescence effects at higher Reynolds numbers at the Towing Wind Tunnel was initiated.

TEST FACILITY

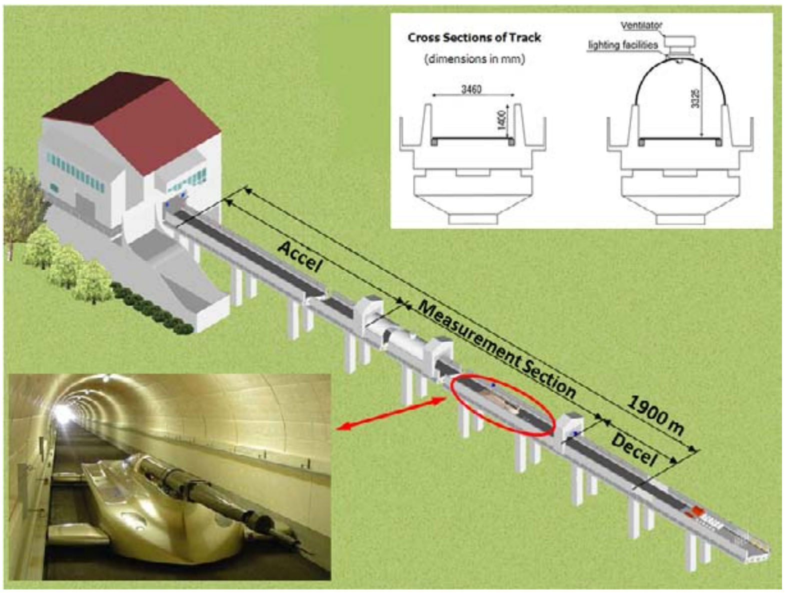


Figure 2 Towing Wind Tunnel

The Towing Wind Tunnel (Figure 2) is not a conventional wind tunnel, but rather a unique propelled-model facility featuring an approximately 2-km long track on which the battery-powered 'HART' vehicle runs (HART = Hyuga Aerodynamic Research facility by Towing). The facility was constructed on a former MAGLEV railway testing track [5]. The track is 3.46m wide and 6.9 km long, however, only the first 1900m of the track is currently used by the TWT. Models are placed on the HART vehicle and supported by a hydraulically actuated support arm to minimize vibrations. The 515 meter measurement region is covered by an insulated hood to minimize sound reflection and heat convection and to reduce the effect of winds. The surface of the test track is paved asphalt. The HART vehicle runs on 8 pneumatic tires and has 4 additional pneumatic tires which track against the vertical sidewalls to keep the vehicle centered on the track. The maximum speed of the HART vehicle is 30 m/s during manned operation and 50 m/s during unmanned operation.

TEST ARTICLE DESIGN

Aerodynamic Design

The objective of the model aerodynamic design was to create models that achieved near-constant chordwise and spanwise dimensionless pressure gradient (K) distributions. For the favorable pressure gradient models, the nominal target K-values were K_A=0.5x10^{-7} and K_B=1x10^{-7}, for the Gradient-A and Gradient-B models, respectively. For Gradient-Zero, the nominal target K-value was K_0=0. The models were designed to attain their respective K values before or at the step location, 19 inches aft of the leading edge, measured along the surface. Dimensionless pressure gradient K is given by the following equation.

$$K = \frac{\nu}{U_e^2}\left(\frac{dU_e}{dx}\right) \quad (1)$$

Because the model was tested in an incompressible regime, Bernoulli's formula was used to manipulate Equation 1 in order to obtain the pressure gradient as a function of Cp, as shown in Equation 2. The design tools used in this work were more conveniently employed with an output targets expressed in Cp than edge velocity.

$$K = \frac{-\nu}{2U_\infty \left(1 - C_p\right)^{3/2}} \frac{dC_p}{dx} \quad (2)$$

The models were designed to maintain laminar flow throughout the test portion of the model in the absence of any excrescence. The approach taken with Gradient-Zero—a flat plate—resulted in the primary design task being that of the leading edge. In order to maintain laminar flow on the flat plate the leading edge needed to be designed such that the curvature maintained continuity in the second derivative at the junction of the leading edge and the flat plate. This was done by using a superellipse with a semi-diameter ratio of 1/6.

The initial design for both of the favorable pressure gradient models (Gradient-A and Gradient-B) was done using XFLR5, a panel-code coupled with a two-equation lagged dissipation integral boundary layer formulation. While this method is relatively inaccurate, it provided a way to quickly manipulate the geometry and make rapid Cp calculations in

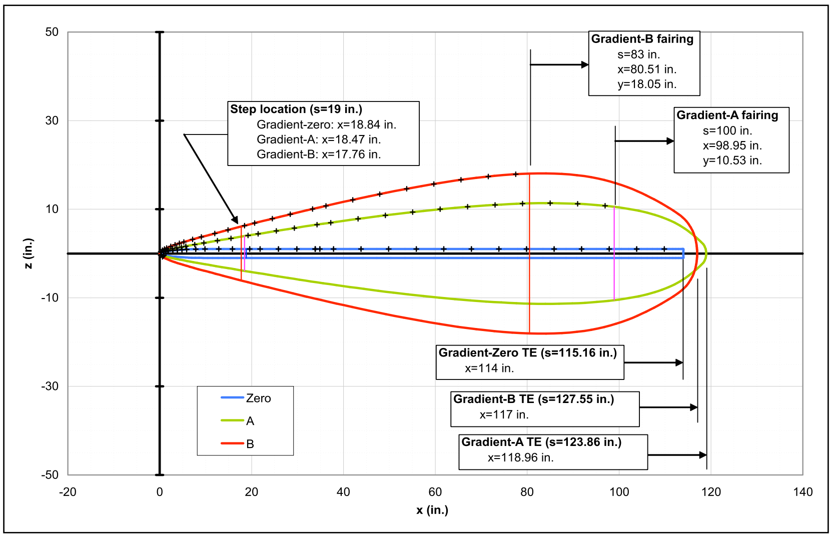


Figure 3 Model shapes and static pressure orifice locations

order to acquire a rough outer mold line (OML) shape for both models. The OML was then used to create a 2-D Navier-Stokes model using GRIDGEN. This grid was then run through a 2-D/3-D RANS flow solver called CFL3D [6]. Based upon the RANS results the curvature of the OML was further manipulated using a NURBS modeling package called Rhino. This process was repeated for each model until an OML (Figure 3) that provided the desired pressure distribution was found.

Achieving the desired Reynolds number resulted in models with large chords. Model span was limited by the hooded test section height of TWT. Splitter plates were used to maximize the two-dimensional character of the flow of the resulting low aspect ratio models. To size the 2 splitter plates a 3-D Navier-Stokes model was created in Gridgen and analyzed with CFL3D. An iterative process was used to size the splitter plates, increasing the lateral extent of these surfaces progressively until the spanwise uniformity of the pressure was achieved within 5%. CFL3D simulations of the test article with splitter plates show that the model maintains 2-D flow through the central 80% of the span. Figure 4 shows the design Cp and K for the Gradient-A model at several spanwise locations.

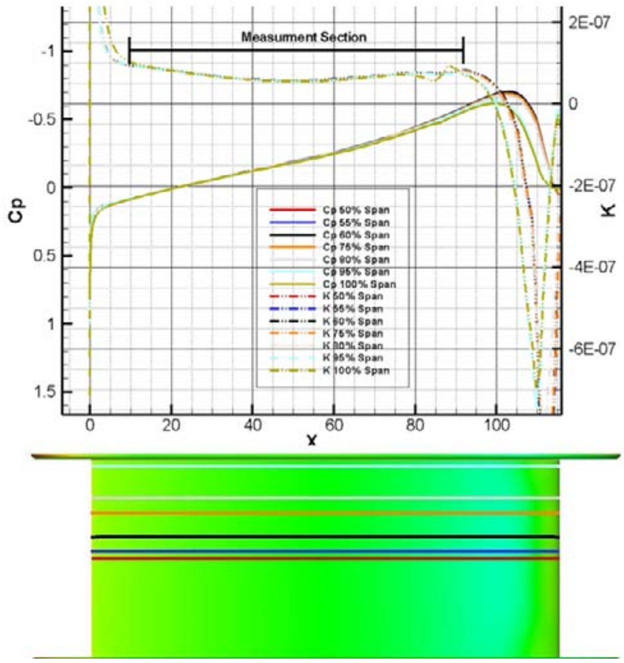


Figure 4 Gradient-A design Cp distributions at various span stations

Achieving the desired pressure distributions the Gradient-A and Gradient-B models resulted in those test articles having very broad aft ends, creating a bluff body shape. Because the testing was to take place at such low dynamic pressures, concerns arose regarding the stability of the flow separating off the aft end of each model. In order to investigate whether the models exhibited significant vortex shedding 2-D time-accurate models for both the Gradient-A and Gradient-B models were created. In order to minimize analysis time and computational resources, the unsteady analysis was performed in 2-D. The 2-D analysis used a Detached Eddy Simulation coupled with a Spalart-Alamaras turbulence model. This 2-D unsteady analysis is very conservative. The analysis showed the Gradient-B model is the limiting case because its shedding vortices are much stronger than that of the Gradient-A model. Therefore the temporal lift variation of the Gradient-B model was analyzed. The frequency of the vortex shedding was found to be less than that of the Tolmien-Schlichting waves and therefore will not induce early transition.

Stagnation point movement due to low frequency vortex shedding was examined to determine if it would affect transition location. Figure 5 displays the center of the stagnation point and maximum stagnation point travel due to the vortex shedding. It was seen the stagnation point travel due to the vortex shedding is a maximum of 0.03 inches and will not induce early separation. A similar analysis was performed for the Gradient-A model with comparable results.

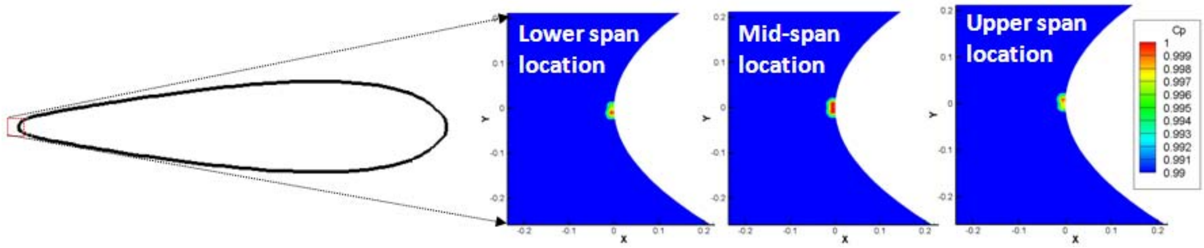


Figure 5 Gradient-B stagnation point travel

Early runs in the TWT focused on determining if the models met the Cp and K design goals by measuring clean plate pressure distributions at all the velocities in the test matrix. Figures 6 show the speed averaged Cp of the 3 models, as measured at TWT. For each model the average of the pressure distributions at each speed is shown. Figure 7 shows the speed averaged K for each model. This latter figure shows the objective of uniform pressure gradients over the measurement section (s ≥ 20 inches) of each model was achieved. The final pressure gradient values for the Gradient-Zero, Gradient-A, and Gradient-B models were $K_0 = 0.2x10^{-7}$, $K_A = 0.5\ x10^{-7}$, $K_B = 0.6\ x10^{-7}$. The Gradient-Zero model had a non-zero K due to the blockage/displacement effects of the model and the HART vehicle in the shrouded test area of TWT.

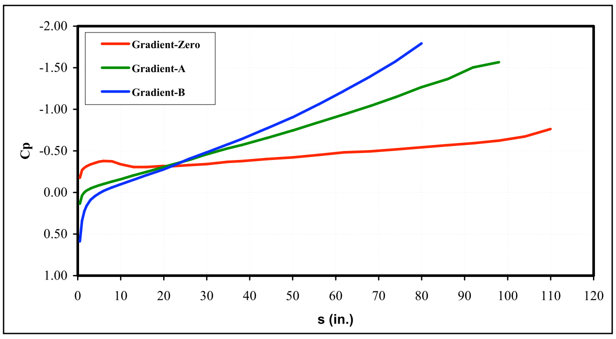


Figure 6 Model comparison of speed averaged pressure distribution (Cp)

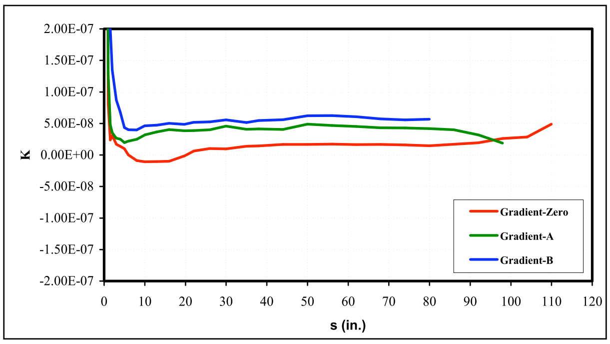


Figure 7 Model comparison of speed averaged pressure gradient (K)

Test Article Construction

The models have 6 major components. An aluminum support frame and the upper and lower splitter plates are common to all 3 models. A leading edge assembly and 2 surface panels are specific to each of the 3 models. The general arrangement of the model is shown in Figure 8. The majority of the test article components were CNC machined from CAD models. The leading edge and midsection assemblies were made from aluminum-6061. The area surrounding the step location was stainless steel, to ensure the tolerance, perpendicularity, and rigidity of the step excrescence. The measurement side and non-measurement side skins are a fiberglass layup. The skins on the non-measurement side include access panels for instrumentation and step adjustment. The measurement side skins have no access panels so as not to disturb the boundary layer being measured. A Laser Tracker inspection of the fiberglass skin panels showed the worst-case OML

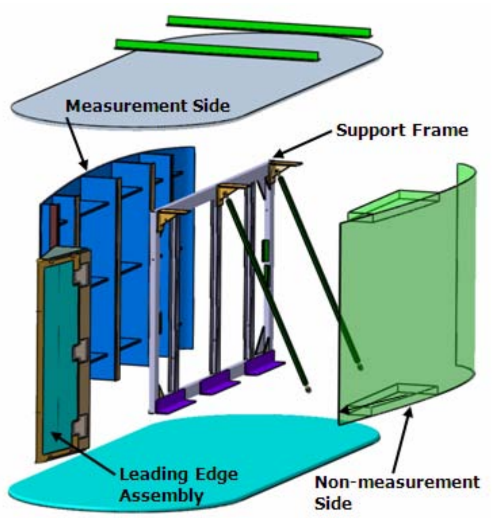


Figure 8 General arrangement of test article (Gradient-A shown)

variation was less than 0.010 inches (0.25 mm). The maximum OML variation was seen at the edges of the model at the interface of the splitter plate, which is outside the measurement region. Significantly tighter tolerances were held throughout the measurement region.

The leading edge assembly incorporates a moving assembly such that 0.001 inch (0.025 mm) incremental step heights can be created. Step height (k) range is ±0.250 inches (6.35 mm) (positive height for a forward facing step, negative for aft facing). The step height is uniform for the entire span of the test article. The lower splitter plate serves as the interface between the model and the mounting hardware on the HART carrier vehicle. Turnbuckles and struts were used to stabilize the upper and lower splitter plates. Figure 9 shows the Gradient-A model mounted on the HART vehicle.

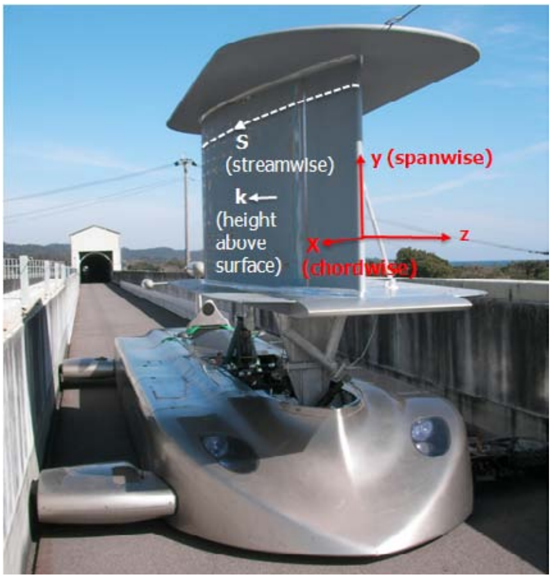


Figure 9 Gradient-A model on HART vehicle

Instrumentation

Static pressure orifices were installed in each of the three models. The majority of these are located in 2 chord-wise rows at 25% and 75% span (0% span being closest to the lower splitter plate). On the Gradient-Zero model each chord-wise row has 32 pressure orifices. The Gradient-A and Gradient-B models have fewer, 30 and 27 respectively, due to shorter measurement surfaces dictated by their boat tail close-outs. Each model has a few orifices on the non-measurement side, near the leading edge, mirroring those on the measurement side. These were used to assess the angle-of-attack (AoA) of the model. When pressures from the orifices on the two sides of the model were equal the model was at zero AoA and the stagnation point was on the leading edge. The components of the pressure system included a Scanivalve DSM 3400 and three ZOC22/TCU units. The range of the transducers was +/-10 in H_2O. The DSM 3400 logged 2 scans/second on all 96 channels simultaneously. In addition to the static pressure orifices the pressure system was used for the 18 Preston tubes and the Pitot probe

A probe traversing system, called Boundary Layer Data System (BLDS), was used to obtain total pressures and hot wire measurements in the boundary layer. The BLDS is a light weight (0.75 lb), fully self-contained device with internal power and memory. It records time-stamped position, local dynamic pressure, static pressure and temperature data at each point. Figure 10 is a plan view of BLDS mounted on the model in the vicinity of the excrescence location (vertical metallic component). The three probes are: 1) a boundary layer probe (hot-wire or total pressure) which traverses on the vertical stage housed inside the streamlined fairing; 2) a total pressure probe, mounted at the top of the streamlined fairing; and 3) a stationary probe at the surface of the model containing a static orifice. For this test a light trigger was designed to start the data collection on the BLDS device once

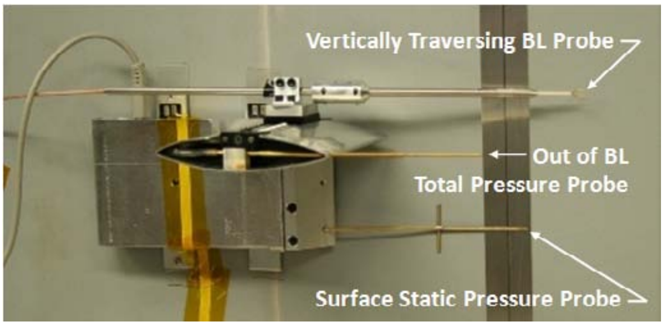


Figure 10 Boundary Layer Data System

the HART vehicle entered the hooded test section. The data is stored onboard the BLDS in non-volatile memory until after the run when it is downloaded onto a laptop computer for viewing and analysis. The BLDS attaches to the models with double-sided structural adhesive tape, and thus can be placed at virtually any position on the models. The BLDS used by the SETS program is similar in concept to in-flight boundary layer velocity profile measurement devices that have been developed previously [7, 8].

Preston tubes measure stagnation pressure inside the boundary layer, close to the model surface. By calculating a pressure differential between the stagnation and local static pressure, wall sheer stresses can be calculated. Preston tubes of three different sizes, 0.020, 0.025 and 0.032 inch, were used to determine skin friction distributions on the models. The ratio of inner diameter to outer diameter of each was 0.6. The appropriate tube diameter is dependent on the flow conditions, most importantly, the boundary layer thickness. The Preston tubes were sized using output from IBL [9], a 2-D boundary layer code. Input to the code was the CFD predicted pressure distributions and nominal flow conditions. The Preston tubes were mounted on the models nominally along a 15-degree half-angle line extending from the point where the leading edge meets the splitter plate, both upper and lower surface. This configuration of Preston tubes was the standard configuration used, though other arrangements were sometimes used. Thus there were typically two spanwise and chordwise varying rows of Preston tubes, with 7 Preston tubes each (the last centerline Preston tube being shared by both rows). The two rows were designated as inboard and outboard, with the inboard row being the row closest to the lower splitter plate.

Model vibrations could be a source of flow fluctuations. As such two accelerometers were attached to the model to measure the k-component (wall normal direction) and the s-component (stream-wise direction). Each accelerometer had its own power supply with internal rechargeable battery, which worked simultaneously as an amplifier with adjustable gain. The voltage signal from the power supply/ amplifier output was recorded directly to a LogBook-based data acquisition. Although not presented in this paper the vibration spectra revealed low power over a broad range of frequencies. They did not show any sharp peaks for the frequency range where unstable T-S waves can be present.

A standard four-channel constant temperature hot-wire anemometer (AA Lab System AN-1005) was used for flow velocity measurements. Hot-wires were used in conjunction with the BLDS and were also mounted to the model with stationary fixtures. Hot-wire results are not presented here but will be the subject of a later paper.

Shakedown Tests

An extensive checkout of the Gradient-Zero and Gradient-A models and systems was conducted in the Northrop Grumman Corporation (NGC) 7-x10-ft Wind Tunnel prior to shipping these components to the TWT in Japan. The NGC 7-x10-ft WT is a low-speed wind tunnel originally designed for the X-21 Laminar Flow Research program, and was built for the purpose of conducting low-speed laminar flow testing. The facility is a closed circuit tunnel providing test section Reynolds numbers up to 2.4 million per foot. The primary objective of the shakedown tests was to provide an end-to-end check of the instrumentation and data acquisition systems and their integration with the models. Data obtained during the shakedown test was used to examine the performance of the model and instrumentation systems. However, obtaining boundary layer transition data in the 7-x10-wind tunnel was not a primary objective of the shakedown testing and was not pursued beyond what was necessary to accomplish the primary objectives. The short timeframe between completing fabrication of the Gradient-B model and its TWT entry did not permit a shakedown test. The value of shakedown testing was proven when the

Gradient-B model was tested at the TWT. A small gap in the vicinity of the excrescence resulted in air flow from inside the model making the results suspect. As such no Gradient-B results are reported.

TWT TEST RESULTS

The test matrix investigated the parameter space of pressure gradient (K), velocity (U), and excrescence height (k). The measurands relevant to the results presented in this paper are boundary layer velocity profiles, Preston tube (total) pressure, and model surface (static) pressure.

The BLDS device was used to measure boundary layer velocity profiles at the step location on each of the models, for the zero step configurations. These local velocity profiles were used to reduce the dimensioned step heights, k, into dimensionless Re_k values (see Equation 3 and Figure 11).

$$Re_k = \frac{u_k k}{\nu_k} \qquad (3)$$

The velocity component of the profile is calculated by converting the moving pressure probe and out-of-the-boundary layer total pressure probe readings into u/u_e by simple division. Because the primary end-use of the velocity profiles is the calculation of Re_k, the velocity profiles are then re-dimensioned with the average u_e from the profile. The final form of the velocity profiles is k in inches and U in meters per second. Thus, the necessary parameter for the Re_k calculation, namely u_k, can be easily extracted.

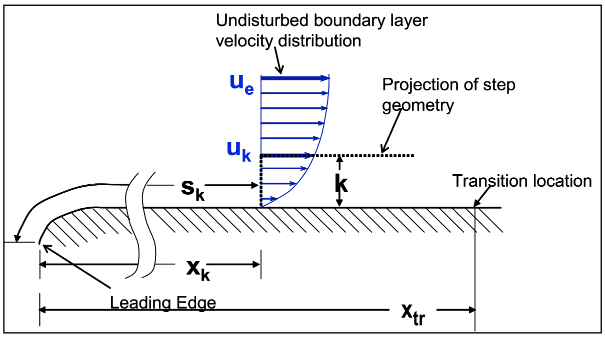
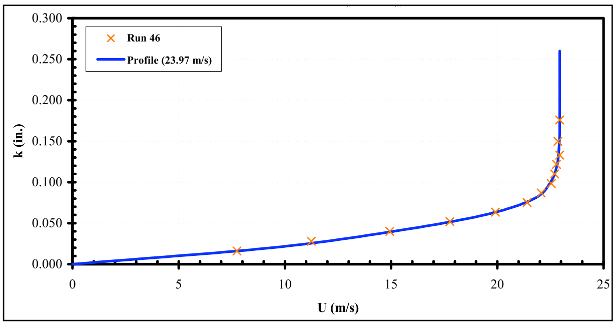
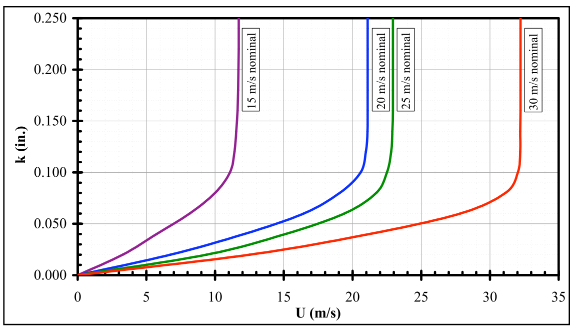


Figure 11 Illustration of velocity profile and u_k

Figure 12 shows a representative boundary layer velocity profile for the Gradient-Zero model. The profile is defined using approximately 15 data points acquired from the BLDS. Figure 13 gives the boundary layer velocity profiles for the Gradient-Zero model at all the nominal test velocities. These results and companion results from the Gradient-A and Gradient-B models show that the boundary layers have linearly growing velocity profiles and increasing (and freestream velocity sensitive) displacement thicknesses.





Skin friction coefficient (Cf) was calculated from Preston tube measurements and the static pressure at the same chordwise location. There are different calibrations to calculate skin friction coefficient and

locity profile for

Figure 13 Boundary layer velocity profile for which calibration to use is dependent on the boundary layer state. Poll's calibration was used for laminar flow and Patel's calibration was used for turbulent flow.

Figure 14 is a plot of Cf versus location (s) on the Gradient-A model at 16.38 meters/sec, and an R_{ek} of 1886. Step location (s = 19 inches) is indicated with the vertical blue-dashed line. The dashed green and red laminar and turbulent lines are the Cf calculations from IBL and are on the plot only to serve as references for skin friction coefficient. The solid green line is Cf data from clean model (no step) runs at the same velocity. Transition was defined as the location where Cf reached a value 50% greater than the clean model value. The vertical blue and magenta lines indicate transition location, based on the 50% increase in Cf, for both the inboard and outboard Preston tube locations.

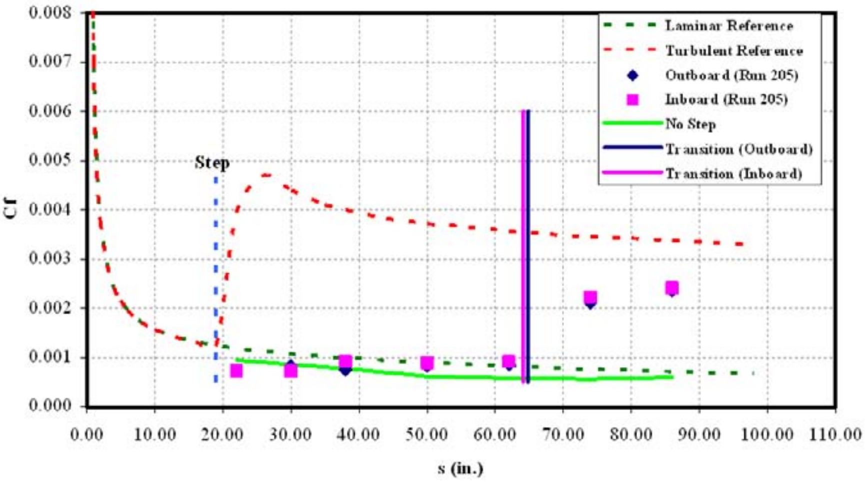


Figure 14 Skin friction coefficients vs. location for Gradient-A model at 16.38 meters/sec and Rek = 1886

EXCRESCENCE RELATIONS

The excrescence relations, Re_k versus Re_{tr}, were developed from the skin friction results. Figure 15 shows the excrescence relations for a forward facing step on the Gradient-A model ($K=0.5x10^{-7}$). The closed symbols on the plot represent measured transition locations. The open symbols represent runs wherein transition was not measured on the plate (i.e. the flow was all laminar for that condition). The transition Reynolds number value of the open symbols is shown at the end of the measurement section of the model. The trendlines are shown to follow these open symbols – this is a very conservative use of the open symbol data since the open symbols do not represent measured transition locations. When compared to the results from the MeaTLoaF program (lower left of Fig 15) it can be seen the allowable Re_k for an unswept wing with a pressure gradient of $K=0.5x10^{-7}$ is approximately an order of magnitude greater than those from a wind tunnel with very good flow quality designed for boundary layer studies.

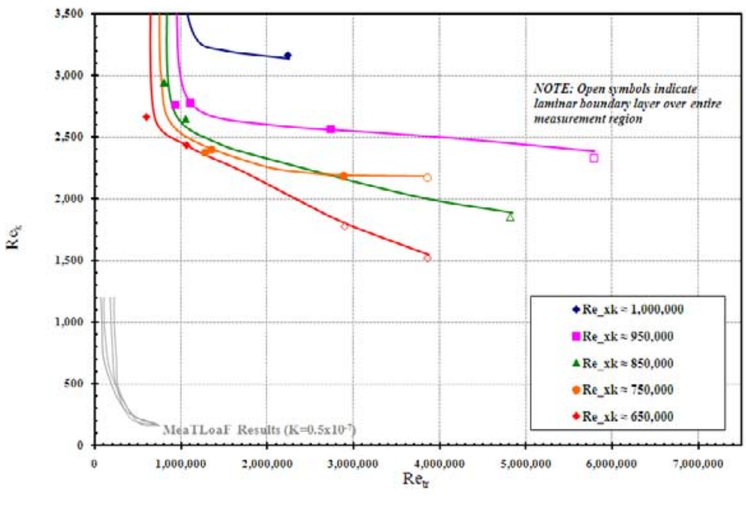


Figure 15 Re_k versus Re_{tr} for forward facing step on Gradient-A Model ($K=0.5x10^{-7}$)

CONCLUSIONS

The results of the SETS program have allowed the transition relations, Re_k as a function of Re_{tr}, to be extended to significantly higher Reynolds numbers. These relations are applicable to current and future laminar flow aircraft and can be used as a basis for determining the required manufacturing tolerances. The allowable height of step excrescences obtained in the SETS program are significantly larger than previous studies have indicated. This will allow for loosening of tolerances on laminar flow aircraft which could contribute to more practical applications of the technology.

FUTURE RESEARCH DIRECTIONS

The reliable, practical implementation of laminar flow on future aircraft requires understanding the effects of all types of surface excrescences likely to result from manufacture and operations, in the presence of the pressure gradients and other characteristics of the wing that effect the boundary layer. Building on this work for two-dimensional excrescences, examination of three-dimensional excrescences as well as multiple excrescences could provide important insight. The effects of compressibility and wing sweep remain to be understood, as do the influence of more complex pressure gradients like those on a real wing. With the experimental approach used in the current work, all of these effects can be examined. Additionally, this data represents an opportunity to examine whether existing boundary layer stability computational methods can be used to model or predict the effects of surface excrescences on boundary layer transition.

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