FLIGHT EXPERIMENTS ON LOCAL AND GLOBAL EFFECTS OF SURFACE ROUGHNESS ON 2-D AND 3-D BOUNDARY-LAYER STABILITY AND TRANSITION

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Abstract

The work cumulated in a series of laminar-turbulent transition flight-test experiments on a swept wing with the goal of validating the *spanwise-periodic distributed roughness elements* (DRE) technology in a Reynolds number range applicable to *SensorCraft* technology. Phase I of the program measured freestream turbulence levels that were nominally 0.05% to 0.06% of the freestream speed and thus established the suitability of the flight environment for the laminarization flights. Phase II of the program did the baseline transition measurements on the airfoil i.e. with and without DRE technology. The region of laminar flow was extended from 30% to 60% chord at a chord Reynolds number of $Rec = 8.1 \times 10^6$ and sweep angle, $\Lambda = 37°$.

1. INTRODUCTION

Establishing the origins of turbulent flow and transition from laminar to turbulent flow remains an important challenge of fluid mechanics. The common thread connecting aerodynamic applications is the fact that they deal with *bounded shear flows* (boundary layers) in *open systems* (with different upstream or initial amplitude conditions). It is well known that the stability, transition, and turbulent characteristics of bounded shear layers are fundamentally different from those of free shear layers. Likewise, open systems are fundamentally different from those of closed systems. The distinctions are trenchant and thus form separate areas of study.

For the classic open system, no mathematical model exists that can predict the transition Reynolds number on a simple flat plate because the influences of freestream turbulence, sound, and surface roughness are incompletely understood. With the maturation of linear stability methods and the conclusions that breakdown mechanisms are initial-condition dependent, more emphasis is now placed on the understanding of the source of initial disturbances than on the details of the later stages of transition.

1.1 Roughness-Induced Meanflow Changes for Laminar Flow Control

There is no dearth of historical work on the role of roughness in stability and transition. Therefore, it is well known that surface roughness generally causes an earlier transition to turbulence and in some cases it can delay transition. Advances in transient-growth theory

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14. ABSTRACT

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for 2-D boundary layers have guided more relevant experimental work in this area. Moreover, the development of nonlinear PSE computations, along with careful experiments in 3-D boundary layers, has validated the important physics of boundary-layer problems. However, some recent surprises have occurred and this forms the justification of the proposed work.

Swept-wing flows have 3-D boundary layers with crossflow which exhibit a different type of instability than that of 2-D boundary layers. Whereas T-S waves react strongly to freestream sound and weakly to freestream turbulence, crossflow vortices are insensitive to sound but very sensitive to freestream turbulence (Bippes 1999). In a low-turbulence environment, the crossflow instability is in the form of stationary co-rotating vortices aligned (almost) with the inviscid streamlines. Recent reviews of the classic stability problems are given by Saric et al (2003) and the details and complete references are contained therein.

In a series of crossflow dominated swept-wing experiments, Saric et al (1998a, b) demonstrated that one could use spanwise-periodic discrete roughness elements (DRE) to favorably modify the boundary-layer by exciting subcritical wavelengths. The subcritical waves would grow early, modify the meanflow, prevent the most unstable modes (critical wavelengths) from growing, and then decay before causing transition.

They excited stationary crossflow wavelengths with small roughness elements whose height was 6 μm and whose diameter was 1 – 2 mm. The critical wavelength was 12 mm and when this spacing was used, transition moved forward as expected. When an 8-mm spanwise spacing was used, essentially full-chord laminar flow was achieved – even beyond the pressure minimum at 71% chord. The nonlinear response of the streamwise vortices created harmonics in wavenumber space – not subharmonics. The higher wavenumber disturbances initially grow and inhibit the growth of low wavenumber disturbances. These higher wavenumber disturbances then decay leaving nothing. This set of experimental results was confirmed with nonlinear PSE by Haynes and Reed (2000) and with DNS by Wassermann and Kloker (2002).

The experiments and computations were done in a modest chord-Reynolds-number range (2.2 to 3.5 million) and the goal has been to extend this to higher chord Reynolds numbers more typical of flight systems. Because of the sensitivity of the crossflow instability to freestream turbulence, it appears to be difficult (but not impossible) to do laminar crossflow experiments at higher Reynolds numbers (>5 million) in wind tunnels because of turbulence. This is justified next.

Flight tests can be very difficult since one does not have the collection of instrumentation available to a wind tunnel. However, if one follows the guidelines of Reshotko for transition research in flight and use the care outlined by Saric (1990), there is a chance for success.

The influence of freestream disturbances must be resolved and an important step is to do careful stability and transition experiments in flight where the disturbance levels are indeed low. These experiments should form the base state for the influence of roughness. A well-known and very successful flight program was conducted by Dougherty (1980). Since the identical model was taken to every supersonic facility, this work actually provided a means to evaluate flow quality in high-speed tunnels. Since then, the achievements have been meager for a variety of reasons – not the least of which is the cost of doing flight experiments.

1.2 Objectives

The objective was to investigate, in a low-disturbance, flight-test environment, the DRE technology on a subsonic swept-wing test article. The test article was designed to be consistent with a *SensorCraft*-type wing section (30° leading-edge sweep). The goals are to quantify the effectiveness of DRE in increasing the extent of laminar flow (i.e. transition location in chordwise direction) on the suction and/or pressure sides beyond the baseline (no-control) case; investigate the robustness and utility of DRE in maintaining laminar flow over the SensorCraft flight envelope i.e., variations in test-article angle-of-attack (*AoA*) over chord Reynolds numbers, $Rec = 7.5 \times 10^6$; gain insight into conducting boundary-layer transition control experiments in a flight environment versus a wind-tunnel environment; and obtain a database that provides additional insight into boundary-layer stability and transition and for validation of prediction tools. The AOA was nominally set at 0° but was adjusted to as much as ±2° using sideslip.

The program planning objectives were: (1) Measure the freestream disturbance environment and establish that the flight test has an acceptable disturbance environment within which one can conduct boundary-layer stability and transition measurements; (2) Develop a map of breakdown due to isolated roughness as a function of Re_k and roughness location (Re_x); (3) Develop the laminarization technology with periodic DRE and determine the sensitivity to roughness at higher Reynolds numbers; (4) Determine how the low-disturbance environment of flight can validate (or invalidate) wind-tunnel experiments; (5) Complement the experiments with stability computations; (6) Provide program guidelines for laminarization and long-range flight. All six objectives were met.

2. TEST RESULTS

The primary objective for Phase I testing was to determine whether the in-flight turbulence intensities were low enough to proceed with the swept-wing experiment. A value less than 0.08% for u'/U_∞ was expected. Experimental results show that the nominal value is between $0.05\%U_\infty$ and $0.06\%U_\infty$.

Basically the target conditions for achieving 70% laminar flow where a chord Reynolds number of $Rec = 7.5 \times 10^6$, at model angle of attack of $AoA = 0°$, and a swept angle of $\Lambda = 30°$. The model (see Figure 1).was fabricated at Tri-Models in Huntington Beach, California and was flown on a Cessna O-2 as an external store.

Figure 1. The swept-wing model hung on O-2. A black powder-coat finish was used to enhance the IR image. The IR camera was mounted in the cabin.

2.1 Initial results with a polished leading edge

The swept-wing model was designed with an accelerated flow to 70% chord. The intent was to make the boundary layer sub-critical to T-S waves but rather unstable to crossflow instabilities. One of the principal result is that we achieved 80% laminar flow with a polished leading edge at Re_c = 8.0 x 10^6, *AoA* = -4° and Λ = 30°. This corresponds to linear stability *N*-factors of well over 16. Background roughness was 0.3 μm rms with 2.2 μm avg peak-to-peak. The linear stability *N*-factor is the log of the unstable disturbance amplitude ratio given by $N = \ln\left(A/A_0\right)$. Where A_0 is the initial amplitude at the first neutral point and *A* is the amplitude at transition. Thus an e^{16} growth is an amplitude ratio of almost 10^6. The IR Thermography for this case is shown in Figure 2.

The colder area denoted by the dark orange color indicates laminar flow while the lighter area denotes turbulent flow. These conclusions were confirmed by placing large roughness elements on the model and tripping the boundary layer. The white marks at the bottom and top of the model are pieces of aluminum tape denoting 40%, 60%, and 80% chord respectively. The light orange color near the top of the model is due to the cabin IR reflection. The diagonal line across mid-span is the reflection of the bottom of the aircraft. The bright area near the top is the forward propeller and forward engine exhaust reflections.

Achieving an *N*-factor greater than 16 with the polished leading edge demonstrates the low-turbulence environment of flight. Results such as these have never been obtained in wind tunnels where *N*-factors of 8-9 have been achieved with *N* = 6 being more common. With 80% laminar flow, there is not much that can be done with DRE for laminar flow control. However, the polished leading edge with 0.33 μm rms can be considered a base state. A more realistic, operational surface would be painted.

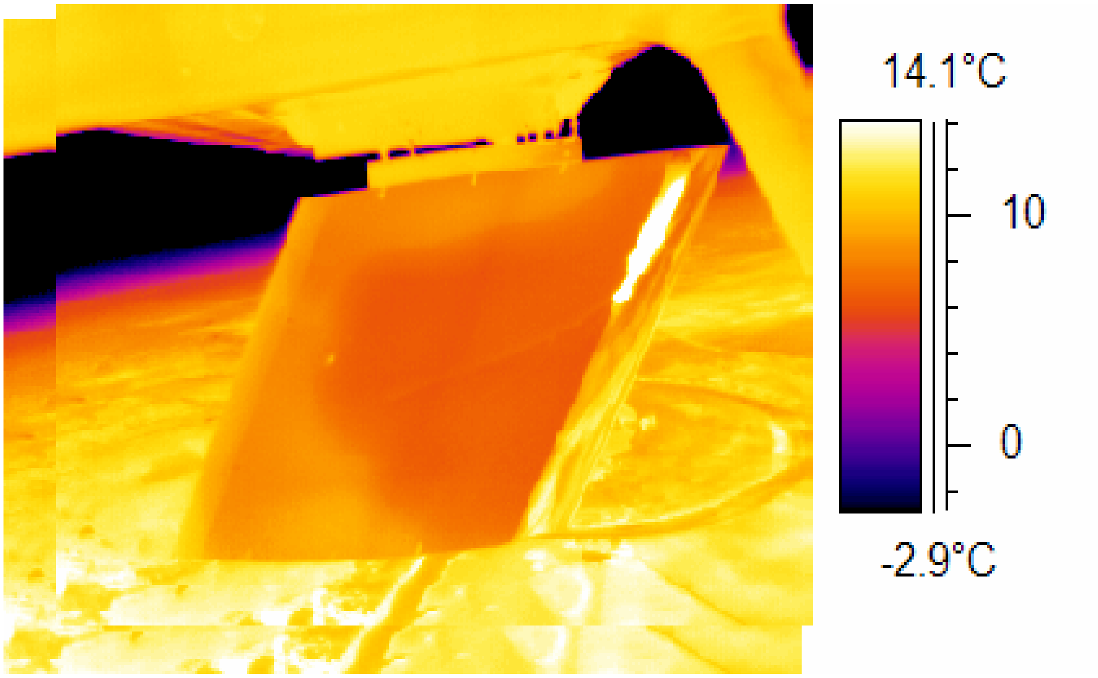

Figure 2. IR image at 170 KTAS, *Rec* = 8.0 x 10^6, *AoA* = -4°, *Λ* = 30°; 3500 ft MSL, Polished LE, No DRE, peak to peak roughness = 4.3 μm; rms roughness = 0.33 μm, *N*-factor > 16 at mid-span, *x/c*)tr = 80%

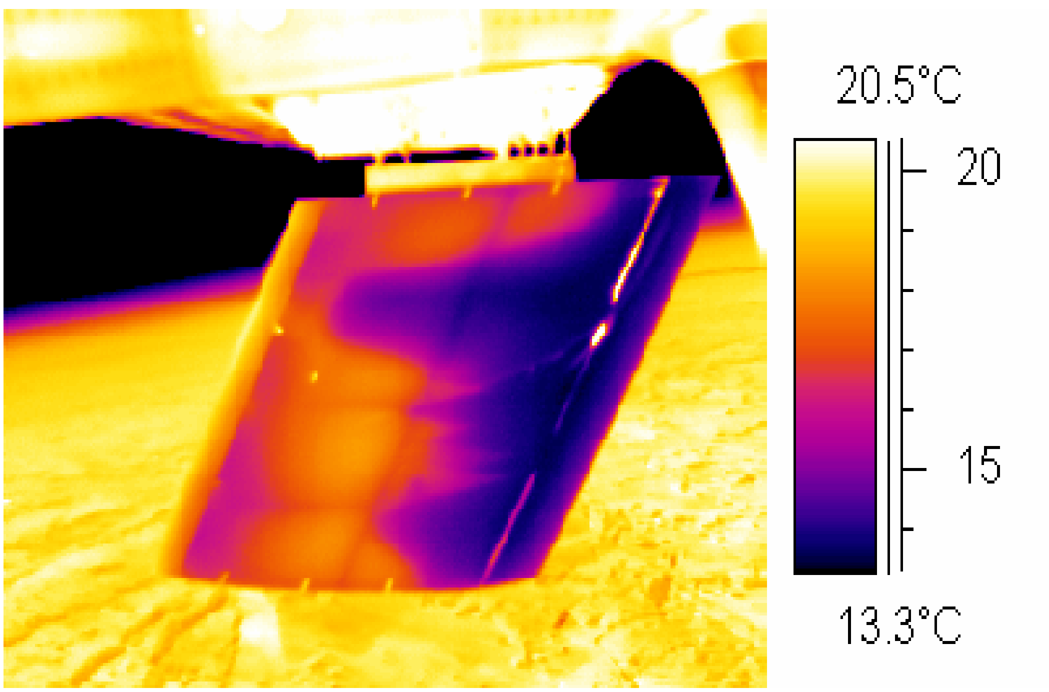

Figure 3. IR thermography at 173 KTAS, *AoA* = -4°, *Rec* = 8.0 x 10^6, no DRE, White painted LE. *x/c*)tr ≈30%.

2.2 Laminarization results with a painted surface

The model surface was painted to achieve a background roughness level of 1.0 µm rms with a 3.8 µm avg peak-to-peak. In this case transition moved forward to 25% to 30% chord under conditions of $Re_c = 8.13 \times 10^6$, $AoA = -4°$, $\Lambda = 30°$ and an N-factor = 8. This is shown in figure 3.

In this case transition moved forward to 30% chord and this is our new base state.

When a double layer of DREs (12 µm high) was used, the transition location moved back to 60% chord. $Re_c = 8.13 \times 10^6$, $AoA = -4°$, $\Lambda = 30°$ and an N-factor = 15. This shown in Figure 4. The region of laminar flow was doubled from the base state and, according to linear theory, the disturbance amplitude was reduced by e^{-7} or $< 10^{-3}$.

This rather remarkable result demonstrates the DRE technology in flight at a chord Reynolds number of 8 million.

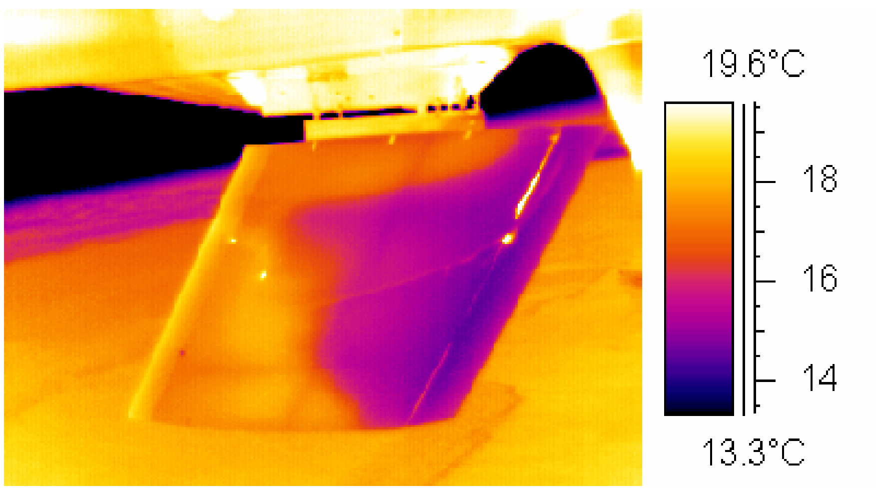

Figure 4. 180 KTAS, $AoA = -4$, $Rec = 8.0 \times 10^6$, White painted LE, DRE x 2 placed at 1% x/c at inboard pressure row, and 1.3% x/c at outboard pressure row, $d = 1$ mm, $\lambda = 2.25$ mm, transition moved to 60% x/c

3. SUMMARY

3.1 Boundary-Layer Stability and the Transition Measurements

Transition due to the crossflow instability has been found to be very sensitive to freestream turbulence and rather insensitive to sound. The reason for going to flight is that the turbulence levels in even the best wind tunnels increase with speed to a level that this turbulence is a significant factor in the transition results, thereby calling into question their applicability to free-air flight conditions. Our freestream turbulence measurements in flight showed u'_{rms} levels of the order of 0.05% U_∞. These were considered low enough even though these numbers included electronic noise.

3.1.1. The most significant lesson learned was in the case of the polished leading edge. We achieved 80% laminar flow at a Re_c of 8 million. The linear stability *N*-factor was 16 in this case. This is an astounding result for the following reasons:

(1) Prior transition results in the carefully conducted flight tests by others were dominated by Tollmien-Schlichting type instabilities which behave quite differently; and as such the present tests are the first crossflow dominated flight tests.

(2) The importance of both surface roughness on the model and freestream turbulence in wind tunnels were not given their proper significance and thus, wind-tunnel transition results were thought to be a “not-too-bad” result;

(3) Although it has long been recognized that crossflow transition was nonlinear, it was thought that linear theory could be used as a rough correlation for transition and generally accepted *N*-factors in wind tunnels were approximately 6 – 8.

3.1.2. The swept-wing model was designed assuming transition at $N = 8$. This implied that linear stability had to be discarded and calculations of the Nonlinear Parabolized Stability Equations (NPSE) were done.

3.1.3. The NPSE results showed the following:

(1) The NPSE could demonstrate the stabilization of the critical mode due to the presence of a roughness-induced mode at a smaller wavelength;

(2) The DRE are only effective when the amplitude control wavelength is not only larger than the critical amplitude, but had to be of a specific ratio;

(3) The optimum position for the control DRE is at the neutral point of the critical wavelength and not at the neutral point of the control wavelength.

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Graduates:

S. Schouten, 2008 "Complete CFD analysis of a velocity XL-5 RG with flight test verification." M.S. Aerospace Engineering, Texas A&M University, March 2008

C.W. McKnight, 2006 "Design and Safety Analysis of In-Flight, Laminar Flow Control, Airfoil." M.S. Aerospace Engineering, Texas A&M University, Aug 2006.

Publications

1. Carpenter AL, Saric WS, Reed HL. 2008 Laminar Flow Control on a Swept Wing with Distributed Roughness. *AIAA Paper No. 2008-7335*
2. Martin ML, Carpenter AL, Saric WS. 2008 Swept-Wing Laminar Flow Control Studies Using Cessna O-2ATest Aircraft. *AIAA Paper No. 2008-1636*
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17. Zuccher S, Saric WS. 2008 Infrared Thermography Investigations in Transitional Supersonic Boundary Layers. *Exps. Fluids* **44**:145-57

Honors & Awards Received

William S. Saric, Promoted to *Distinguished Professor of Aerospace Engineering,* Texas A&M University, 2008

William S. Saric, Elected, *National Academy of Engineering* 2006.

William S. Saric, Elected, *The Academy of Medicine, Engineering, and Science of Texas* 2006.

William S. Saric, Named *Stewart & Stevenson Endowed Professor*, Texas A&M University, 2006

William S. Saric, Recipient of the MMAE Department, *IIT Alumni Recognition Award* 2005.

William S. Saric, Elected *AIAA Fellow* 2005

William S. Saric, Recipient of the AIAA *Fluid Dynamics Award* 2003.

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Transitions

The technology development from this grant has direct impact on the AFRL AEI program and the AFRL SensorCraft/HiLDA program. Bi-weekly telecons are held with AFRL (Dr. Gary Dale) on the technical progress of the program.

New Discoveries

None