Flight Tests of a Supersonic Natural Laminar Flow Airfoil

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Outline

- Background and previous research
- F-15B IR system
- Experiment overview
- Flight test results
  - Transition with Mach number
  - Transition with Reynolds number
  - Transition due to roughness elements
- Summary
- Questions
Background

- NASA has a current goal to eliminate barriers to the development of practical supersonic transport aircraft
- Drag reduction through the use of supersonic natural laminar flow (S-NLF) is currently being explored as a means of increasing aerodynamic efficiency
  - Tradeoffs work best for business jet class at M<2
- Conventional high-speed designs minimize inviscid drag at the expense of viscous drag
  - Existence of strong spanwise pressure gradient leads to crossflow (CF) while adverse chordwise pressure gradients amplifies and Tollmien-Schlichting (TS) instabilities
- Aerion Corporation has patented a S-NLF wing design (US Patent No. 5322242)
  - Low sweep to control CF
  - $dp/dx < 0$ on both wing surfaces to stabilize TS
  - Thin wing with sharp leading edge to minimize wave drag increase due to reduction in sweep
- NASA and Aerion have partnered to study S-NLF since 1999
- Series of S-NLF experiments flown on the NASA F-15B research test bed airplane
- Infrared (IR) thermography used to characterize transition
  - Non-intrusive, global, good spatial resolution
  - Captures significant flow features well
Previous Research

- Supersonic Natural Laminar Flow (SSNLF)
  - Bi-convex test article
  - Demonstrated extended runs of S-NLF up to $Re_c = 10$ million at Mach 1.8

- Supersonic Boundary Layer Transition (SBLT)
  - Large chord flat-plate test article
  - Measured plate pressures and local inflow conditions up to Mach 2.0
  - Pressure data used to help design follow on S-NLF test article

Timeline:
- SSNLF: 1999
- SBLT phase 1 (flat-plate): 2002
- SBLT phase 1 (flat-plate): 2010
F-15B IR System

- **Camera**
  - L3 Cincinnati 640x512 NC
  - 640x512 Indium-Antimonide (InSb) focal plane array with 28 micron pitch
  - Mid-wave (3-5 micron spectral range)
  - 13 mm lens
  - Simultaneous 14-bit digital and RS-170 analog output

- **Camera pod**
  - Streamlined pod mounted on starboard armament rail
  - Silicon window with anti-reflection coating
  - Right-angle prism to redirect image to camera

- **Onboard Recorders**
  - 8 mm (Hi-8) recorder for analog output
  - Digital Design Corp. VAADR-1 unit
S-NLF Test Article
Strong Back Side

- Strong Back
- Conical probe
- Instrumentation Bay
F-15B Test Configuration

- IR Camera Pod
- S-NLF Test Article
- CLIP

NASA
Roughness Elements

- Roughness elements installed during select flights to investigate effects on transition
- Trip dots
  - 19 dots were installed near leading edge of the test article
  - Dots were formed from aluminum and polyimide adhesive tapes with thicknesses of 2, 3, and 4.5 mil (0.051, 0.076, and 0.114 mm)
- 2-D steps
  - Created from 30 inch (76 cm) strips of 4.5 mil (0.114 mm) thick adhesive backed vinyl film
  - Leading edge located approximately 8.5 inches (21.6 mm) back from leading edge
  - Layered to create addition step heights of 13.5 and 22.5 mil (0.343 and 0.572 mm)
IR Image Transformation

- IR images have perspective distortion (foreshortening)
  - Wide-angle lens
  - Camera pod mount position
- Calibration grid applied to test article for image registration
- Control point pairs used to transform distorted image into reference perspective
- Transformation applied frame-by-frame to IR video

Analog IR image from flight
Target image with control points
IR image with control points
Transformed IR Image

Flight = 452  Mach = 1.714  Hp = 43898  Re_{ft} = 2.805e+06

- Camera Pod Shock
- Turbulent Wedge
- CF Transition
- Shock Train
Transition with Mach Number

M=1.1, 42 kft (12.8 km), accelerating

M=1.4, 49.5 kft (15.09 km), accelerating

M=1.55, 49.5 kft (15.09 km), accelerating

M=1.7, 49.5 kft (15.09 km), steady state
Reynolds Number Effects $M=1.7$

- $M=1.7$, $Re_{ft}=2.14$ million/ft (0.652 million/m)
- $M=1.7$, $Re_{ft}=2.67$ million/ft (0.814 million/m)
- $M=1.7$, $Re_{ft}=3.49$ million/ft (1.06 million/m)
- $M=1.7$, $Re_{ft}=4.31$ million/ft (1.31 million/m)
Trip Dots $M=1.7$

$M=1.7, \text{Re}_f=2.21 \text{ million/ft (0.674 million/m)}$

$M=1.68, \text{Re}_f=2.67 \text{ million/ft (0.814 million/m)}$

$M=1.71, \text{Re}_f=3.49 \text{ million/ft (1.06 million/m)}$

$M=1.7, \text{Re}_f=4.31 \text{ million/ft (1.31 million/m)}$
2-D Steps $M=1.7$

(upper 0.343 mm, lower 0.114 mm)

$M=1.7$, $Re_{ft}=2.14$ million/ft (0.68 million/m)

$M=1.73$, $Re_{ft}=2.67$ million/ft (0.814 million/m)

$M=1.69$, $Re_{ft}=3.49$ million/ft (1.06 million/m)

$M=1.69$, $Re_{ft}=4.31$ million/ft (1.31 million/m)
Flight 452

Mach = 1.102  Hp = 41672 ft  Re_{ft} = 2.074e+06  \text{T}_{RTD} = -5.14^\circ F
Flight 454

Mach = 1.100  Hp = 41688 ft  Re_{ft} = 1.974e+06  T_{RTD} = 9.88 °F
Flight 456

Mach = 1.103  Hp = 41882 ft  Re_{ft} = 1.970e+06  T_{RTD} = -9.10 °F
Summary

- IR thermography was used to characterize the transition front on a S-NLF test article at chord Reynolds numbers in excess of 30 million.
- Changes in transition due to Mach number, Reynolds number, and surface roughness were investigated.
  - Regions of laminar flow in excess of 80% chord at chord Reynolds numbers greater than 14 million.
- IR thermography clearly showed the transition front and other flow features such as shock waves impinging upon the surface.
- A series of parallel oblique shocks, of yet unknown origin, were found to cause premature transition at higher Reynolds numbers.
Questions?