Exploration of a Slotted Airfoil Laminar-Flow-Control Concept

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Objectives

To better understand the aerodynamics and explore the practicality of the Slotted, Natural-Laminar-Flow (SNLF) airfoil concept via wind-tunnel tests.

To compare the SNLF concept with Laminar-Flow Control (LFC) using suction.

To develop and validate design tools for both SNLF and LFC airfoils.
Motivation

Recent reawakened interest in laminar-flow technologies owing to rising fuel costs.

Provide data to better to assess the practicality of the SNLF concept.

Drag reduction potential without the complexities of active LFC approaches such as suction.

DLR LFC (Suction) Airfoil
Passively achieve drag reductions roughly equivalent to LFC concepts without power, complex active mechanisms, and extensive ducting.

Pfenninger, Zurich, 1946
Slot Suction, $R = 1.0$ to $6.0$ million
Technical Approach

Explore the effect of different positions and deflections of the aft element of the S414 SNLF airfoil.

Examine high-lift behavior as well as aileron/flap viability.

Measure the drag penalty associated with the aft element mounting brackets.

Validation of theoretical design and analysis tools.

Comparison of the SNLF and LFC concepts.
Impact

If found practical, the SNLF airfoil concept could have a major impact on laminar-flow wing design for many different categories of flight vehicles.

The SNLF concept promises performance benefits comparable to LFC, but with less complexity and lower cost.
Penn State Low-Speed, Low-Turbulence Wind Tunnel

[Diagram of the wind tunnel with labels for various components such as Stator, Fan, Driveshaft, Data-acquisition station, Honeycomb Screens, Test section, Breathor, Contraction, Test-section detail (2:1), 224-kW (300-hp) motor, Dust screen, Rapid expansion, Perforated plate, and Settling chamber.]
Penn State Low-Speed, Low-Turbulence Wind Tunnel

- Test Section Size: 3.3 ft by 5.0 ft
- Max Test Speed: 220 ft/sec
- Reynolds Numbers: 0.06 to 2.0 million
- Turbulence Intensity: below 0.045%
Qualification of the Penn State Low-Speed, Low-Turbulence Wind Tunnel - Comparison w/ NASA Langley Low-Turbulence Pressure Tunnel

Excellent agreement: $R = 60,000$ to $460,000$
Excellent agreement: $R = 700,000$ to $1,500,000$
SNLF Airfoil Model
Baseline Aerodynamic Characteristics
2009 and 2013

S414  \( R = 1.0 \times 10^6, \ M = 0.10, \) transition free

PSU Exp. 2013
PSU Exp. 2009
Baseline Pressure Distributions

\[ \Delta x/c = 0, \Delta y/c = 0, \delta = 0 \]

-○- \( \text{aoa} = -2.1 \) degrees
-□- \( \text{aoa} = 0.0 \) degrees
-△- \( \text{aoa} = 4.1 \) degrees

Aft element operates in fore element flowfield. Its pressure distribution changes very little.
Baseline Pressure Distributions

\[ \Delta x/c = 0, \Delta y/c = 0, \delta = 0 \]

- \( \circ \) - \( \text{aoa} = 9.1 \) degrees
- - \( \square \) - \( \text{aoa} = 12.2 \) degrees
- - \( \diamond \) - \( \text{aoa} = 15.7 \) degrees
Aft Element Position and Deflection Schedule

<table>
<thead>
<tr>
<th>Position</th>
<th>δ</th>
<th>F</th>
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<tbody>
<tr>
<td>1</td>
<td>0  1  5 10  -5  -10  -15</td>
<td></td>
</tr>
<tr>
<td>1+F</td>
<td>0</td>
<td>3.5 22.5 17</td>
</tr>
<tr>
<td>2</td>
<td>0  5 10</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>2  5</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>
Baseline Pressure Distributions

\[ c_l \approx 0.52 \]

\[ \Delta x/c = 0, \Delta y/c = 0, \delta = 0 \]
Pressure Distributions

\[ c_l \approx 0.49 \]

\[ \Delta x/c = 0, \Delta y/c = 0, \delta = -5 \]
Pressure Distributions

$c_l \approx 0.50$

$\Delta x/c = 0$, $\Delta y/c = 0$, $\delta = +5$
Aerodynamic Characteristics

S414  $R = 1.0 \times 10^6$, $M = 0.10$, transition free

- PSU Exp. Baseline
- Aft Element = +5 deg.
Baseline Pressure Distributions

$c_l \approx 0.52$

$\Delta x/c = 0, \Delta y/c = 0, \delta = 0$
Pressure Distributions

\[ c_l \approx 0.57 \]

\[ \Delta x/c = -0.0083, \Delta y/c = 0, \delta = 0 \]
Pressure Distributions

\[ c_l \approx 0.50 \]

\[ \Delta x/c = +0.0167, \Delta y/c = 0, \delta = 0 \]
Aerodynamic Characteristics

S414  $R = 1.0 \times 10^6$, $M = 0.10$, transition free

- PSU Exp. Baseline
- Aft Element: $\Delta(x/c) = 0.0167$, $\delta = 0$ deg.
Pressure Distributions

\[ c_l \approx 0.56 \]

\[ \Delta x/c = +0.0167, \Delta y/c = 0, \delta = +5 \]
Aerodynamic Characteristics

S414, R = 1.0 \times 10^6, M = 0.10, transition free

- PSU Exp. Baseline
- Aft Element: \Delta(x/c) = 0.0167, \delta = 0 \text{ deg.}
- Aft Element: \Delta(x/c) = 0.0167, \delta = +5 \text{ deg.}

\( c_x \) vs. \( x/c \)

\( c_m \) vs. \( \alpha \)

\( c_d \) vs. \( \alpha \)

\( c_a \) vs. \( \alpha \)
Tab Simulating a Simple Flap

Tab was taped on aft element.

Tab chord was 10% of total airfoil chord, 30% of aft-element chord.

Deflections of -17, 0, 3.5, 22 degrees.

No pressure orifices on tab.
Aerodynamic Characteristics-
Tab Simulating a Simple Flap

S414  R = 1.0 \times 10^6, M = 0.10, transition free

- PSU Exp., Flap = 0 deg.
- Flap = +22.5 deg.
- Flap = -17 deg.
Fluorescent Oil Flows

\[ \alpha = +3.0 \text{ deg.} \]
Aft Element Mounting Bracket

\[ \alpha = -3.0 \text{ deg.} \]
Baseline Pressure Distributions
Theory vs. Experiment

$c_l \approx 1.35$

- $\Delta x/c = 0, \Delta y/c = 0, \delta = 0$
- MSES
- OVERFLOW
Aerodynamic Characteristics
Theory vs. Experiment

$S4.14 \quad R = 1.0 \times 10^6, \quad M = 0.10, \text{ transition free}$

- PSU Wind Tunnel
- MSES
- OVERFLOW, Coder-Maughmer Transition

$c_2$ vs. $x/c$
DLR LFC (Suction) Airfoil

α relative to the zero-lift line

DLR SUCTION AIRFOIL

DLR AIRFOIL 16.53%
Suction Airfoil Pressure Distribution

$c_l \approx 0.45$

- FLUENT, Langtry-Menter
- DLR Experiment
At $c_l = 0.5$, Pfenninger gives the losses as 0.0007 at $R = 1 \times 10^6$, compressor and windmill, $\eta = 0.85$
SNLF concept works

Theory is reliable except for maximum lift and stall characteristics

While scheduling of aft element for ailerons/flaps is possible, a simple flap/aileron on aft element seems more suitable

Aft element mounting bracket drag is not excessive

S414 stall characteristics are undesirable

DLR LFC airfoil wind-tunnel data have been compared with results from theoretical methods used for design

The LFC airfoil design methodology is being complimented with an analysis method (modified MSES)
Next steps

Design a new SNLF airfoil based on understanding gained during Phase I, including improved stall characteristics.

Conduct wind-tunnel investigation to validate codes and determine maximum lift and stall characteristics, which are beyond current theoretical capabilities.

Perform design studies to explore Reynolds and Mach number limits of SNLF applications.

Refine and validate LFC design methodologies; design new LFC airfoil to same specifications as new SNLF airfoil.

Perform conceptual design studies of an unmanned air vehicle with both SNLF and LFC airfoil concepts to determine practical issues and potential benefits.
Dissemination of Results

