

Control of Crossflow-induced Transition

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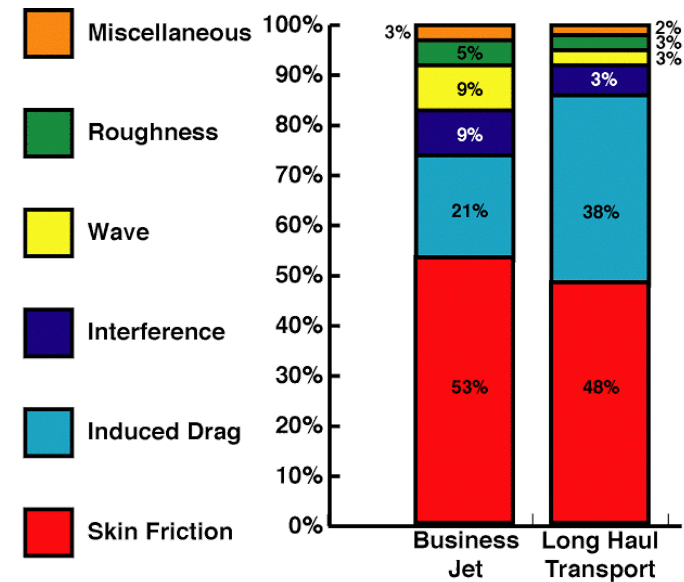
Outline

- **Motivation**
- **Discrete Roughness Elements (DRE) technology**
 - Demonstration at high Re_c
- **Experimental Glove Design**
- **Computational assessment**
 - Linear and Non-linear PSE
 - Secondary Instability [Partial Differential Eigenvalue Problem]
- **Effect of surface curvature on crossflow instability**
- **Concluding remarks**

Why Laminar Flow?

- Skin-friction is 50% of total drag
 - BL transition delay will result in substantial reduction in fuel burn
 - fuel saving
 - reduced environmental impact
- Laminar flow is an important element of drag reduction programs in US and Europe
 - Suction Laminar Flow Control (LFC)
 - Natural Laminar Flow (NLF)
 - Discrete Roughness Elements (DRE)

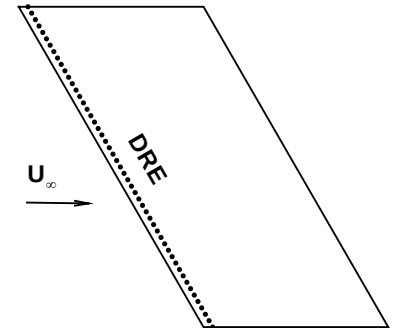
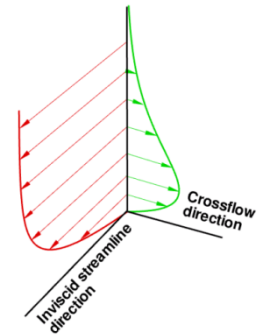
Aircraft Drag Budget



Washburn (2011)

Discrete Roughness Elements (DRE)

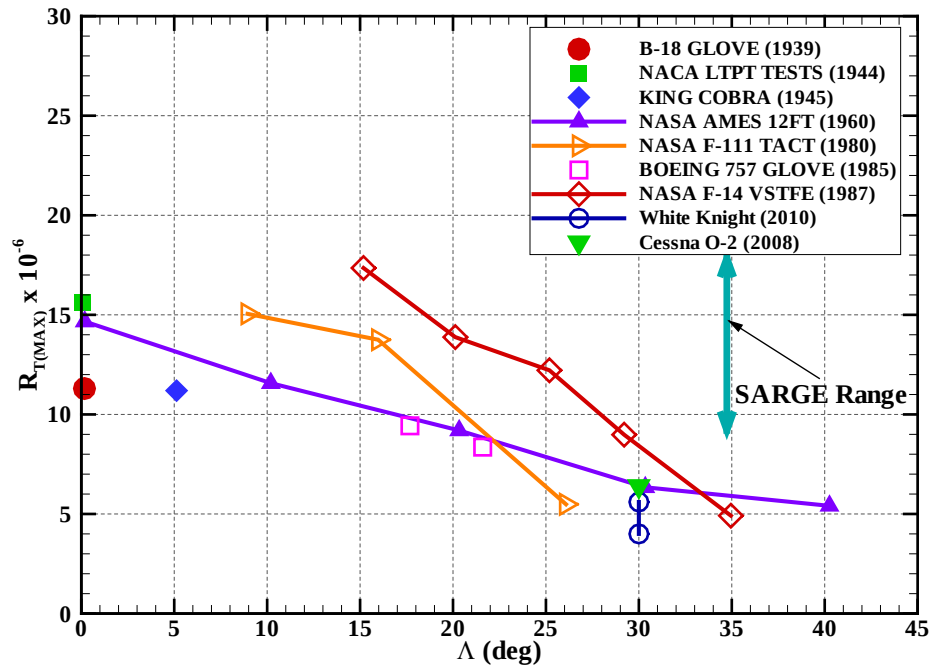
- Swept wing boundary layer transition
 - Crossflow instability (stationary and traveling modes)
 - Tollmien-Schlichting (TS) instability
- DRE concept of Saric et al. (1998, 2008, 2011)
 - Traveling crossflow not relevant in flight due to low turbulence levels
 - Design such that transition subcritical to TS waves
 - Stationary crossflow-induced transition can then be delayed by suitably placed roughness elements near the wing leading-edge
- DRE concept demonstrated in flight at low Re_c (8×10^6)
- Will DRE work at C_L , Mach and Reynolds numbers relevant to transport aircraft?
 - Subsonic Aircraft Roughness Glove Experiment (SARGE)
 - Project Goal: Increase Re_{tr} by 50% as compared to NLF



Previous NLF Experiments



Maximum Transition Reynolds Numbers

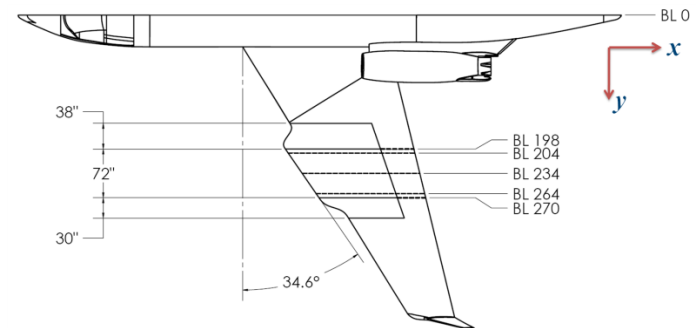


- SARGE promises $2 \times Re_{tr}$ ever achieved in an NLF experiment at 35° sweep
- DRE could further increase Re_{tr} up to 15×10^6

Experimental Glove Design

- Subsonic Aircraft Roughness Glove Experiment (SARGE)
- Gulfstream-III (G-3) as the baseline aircraft
- Laminar Flow Glove designed by Texas A&M University
 - Glove upper surface designed for DRE experiment
 - Ref: AIAA-2012-0870

- ✓ Mach number range: .66 - .75
- ✓ Section $C_L \sim .5$
- ✓ Sweep Angle = 34.6°
- ✓ Re_c range: $15 - 30 \times 10^6$

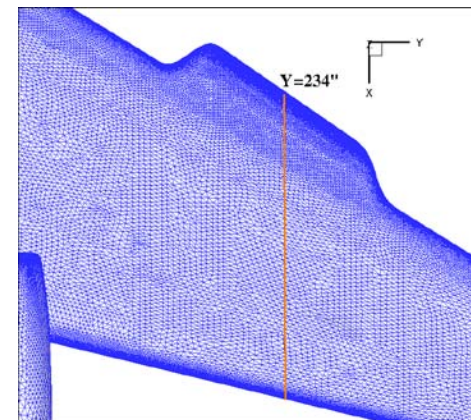
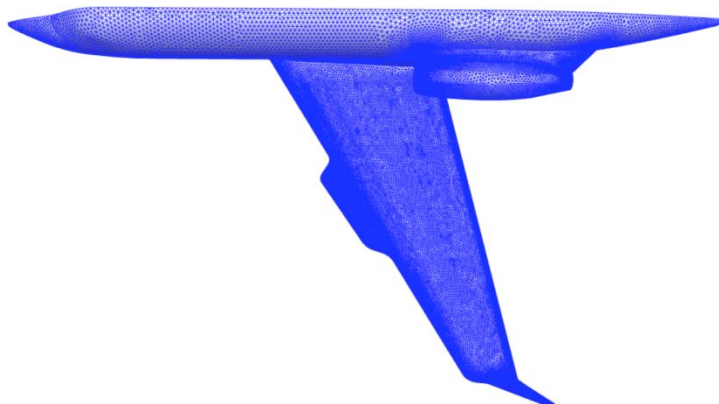


Computational Assessment

- Mean Flow
 - [FUN3D](#), Unstructured-grid Navier-Stokes
 - [Overflow](#), Overset, structured-grid Navier-Stokes
 - [BLSTA](#), Quasi-3D boundary-layer solution
- Stability Analysis
 - [LASTRAC](#), Langley Stability and Transition Analysis Code
 - LST and Linear PSE
 - Non-linear PSE (NPSE)
- Secondary Instability Analysis
 - 2D Partial-differential eigenvalue problem

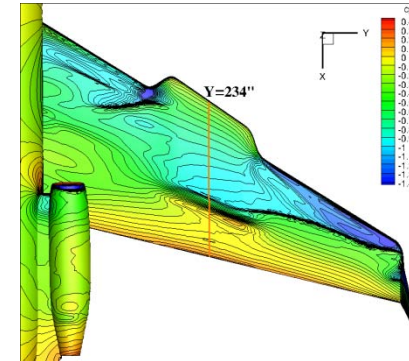
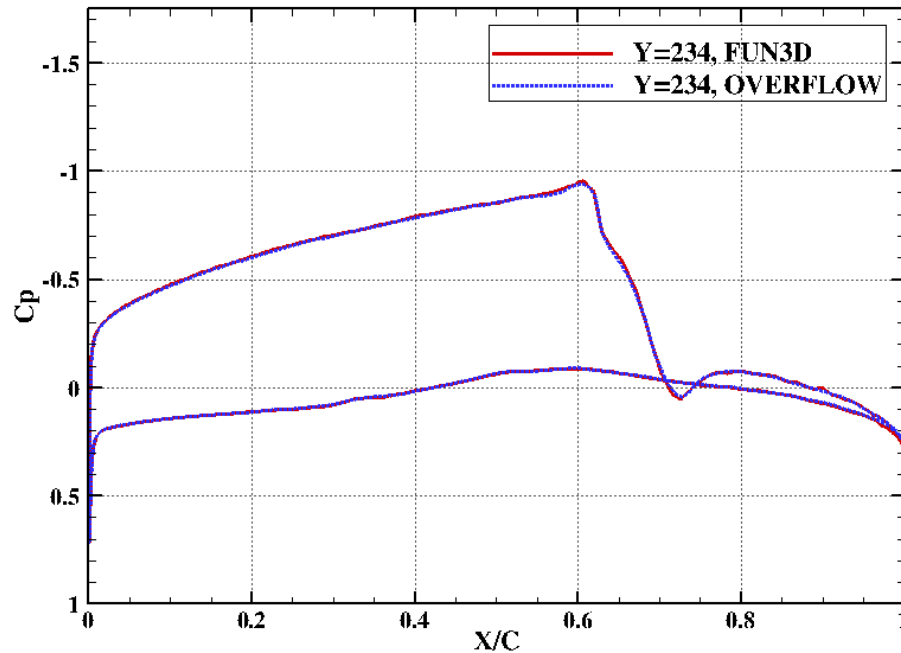
Flight Conditions for the Computations

- Mach number = 0.75
- Reynolds number = 24.2×10^6 (based on chord at $Y = 234$ in)
- Glove mid-span ($Y=234$ in) chord = 14.43 ft
- Aircraft Angle of Attack = 3.4°

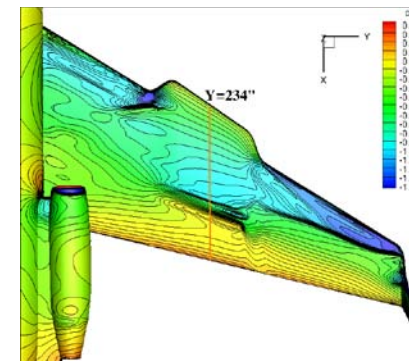


Cp Distribution Computed Using FUN3D and OVERFLOW

Glove Mid-span (Y = 234 in)



FUN3D

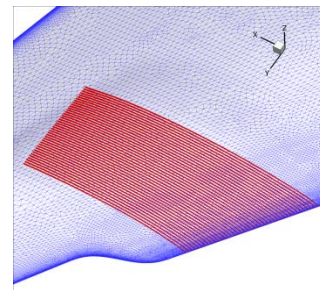
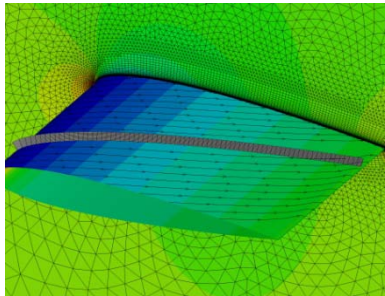


OVERFLOW

- Upper surface favorable pressure-gradient should
 - minimize TS instability
 - enhance crossflow instability

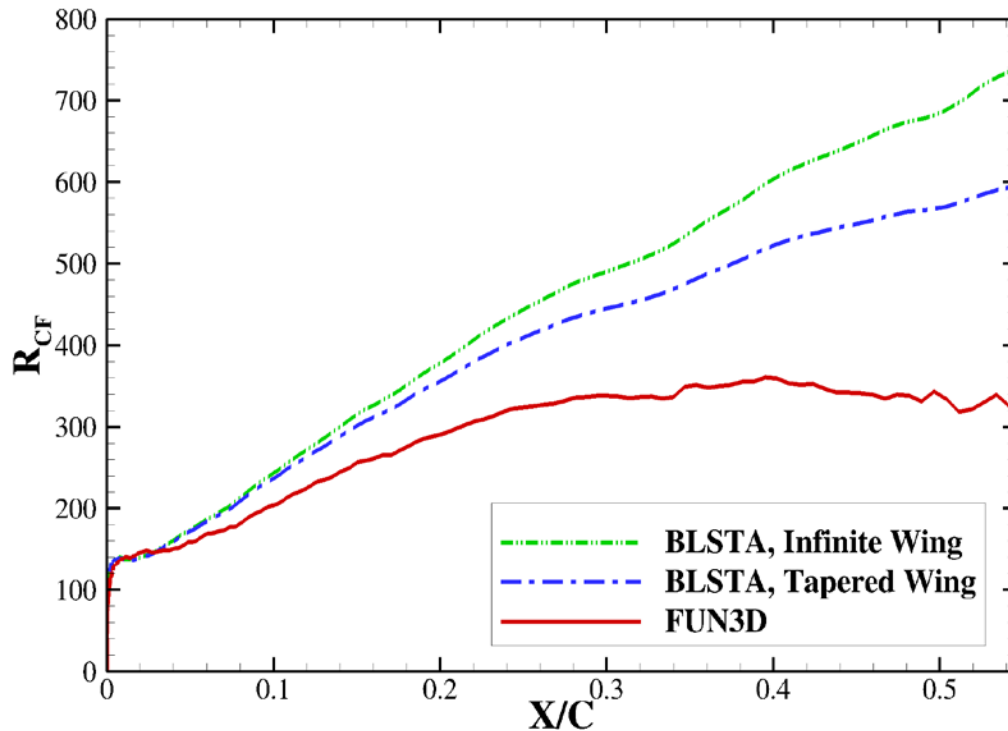
Choices for BL Mean Flow

- Infinite-swept wing assumption
 - Use C_p distribution in an infinite-swept BL code
- Conical flow assumption for a tapered wing
 - Use C_p distribution in a BL code using conical similarity
- BL profiles from unstructured-grid Navier-Stokes solution
 - Interpolate (linear) solution from tetrahedral grid to a structured BL grid



- Navier-Stokes solution, or a fully 3D BL code, needed to correctly compute glove boundary layer

Crossflow Reynolds Number Variation at $Y = 234$ in



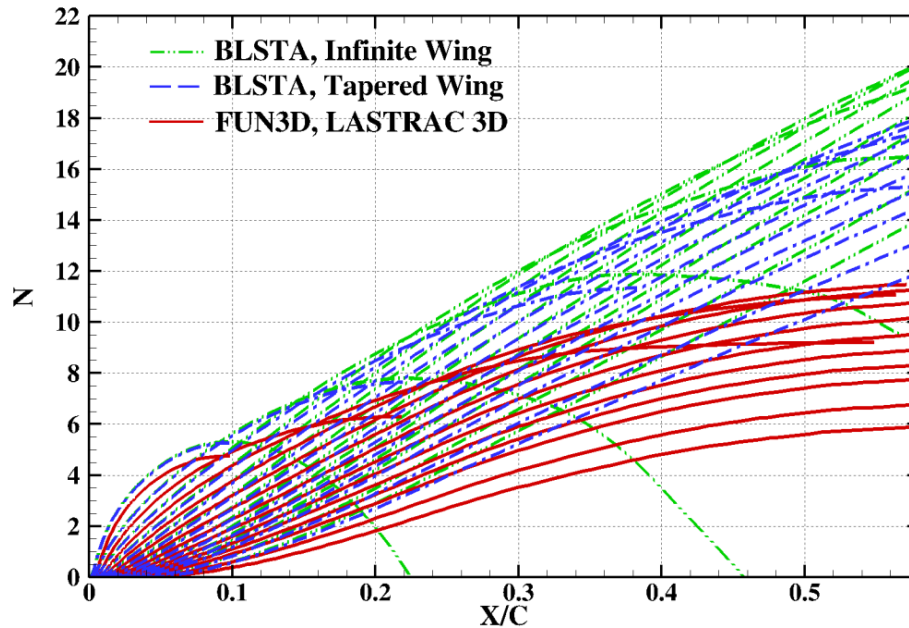
BLSTA : Quasi-3D Boundary Layer Solution
FUN3D: Navier-Stokes Solution

Lower crossflow [in FUN3D case] will yield lower N factors

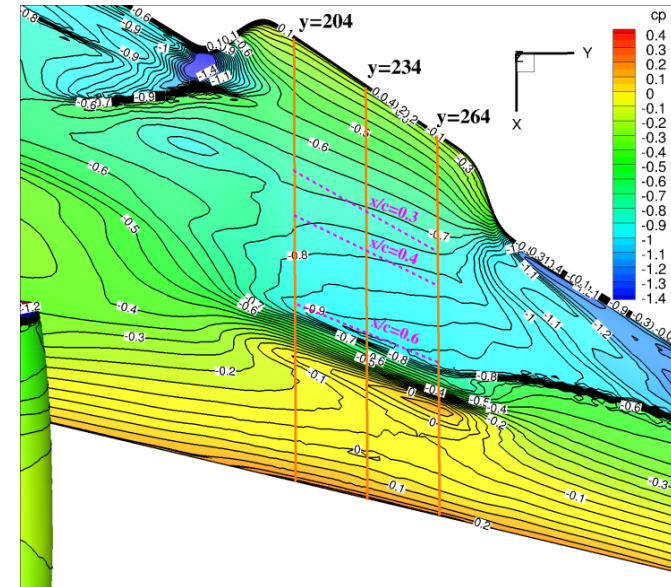
➤ Suggests NLF design using fully 3D methods

LST N Factors for the Wing-glove

N Factors ($y = 234$ in)



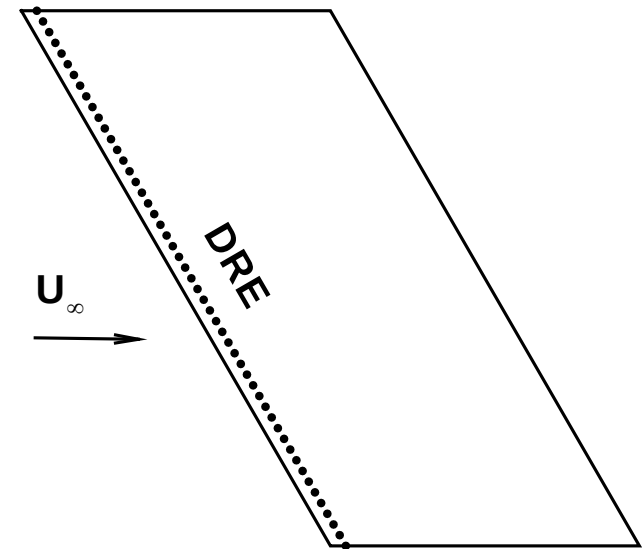
Isobars



- N factor decreases by about 8 compared to infinite-swept wing case
- Un-sweeping of the isobars → Reduced crossflow → Lower N factors

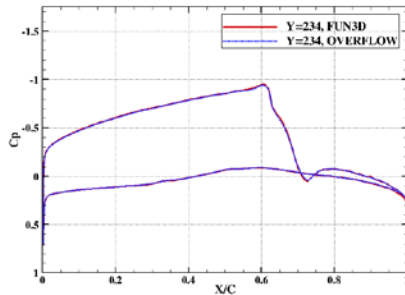
What do DREs do?

- Swept wing transition in quiet (flight) environment
 - Transition dominated by stationary crossflow vortices
 - Can design TS out of the problem
- Placing roughness array near leading edge
 - Transition is delayed
- Roughness (DRE) spacing
 - Control mode has shorter wavelength than target mode (most unstable crossflow instability)
 - Roughness height $6-12 \times 10^{-6}$ m
- Leading edge surface roughness
 - Polished surface: 0.3×10^{-6} m
 - Painted surface: $3 - 4 \times 10^{-6}$ m



DRE Control of Stationary Crossflow Disturbances

- Infinite-swept wing assumption
 - Use glove mid-span C_p in a BL code to compute boundary layer profiles

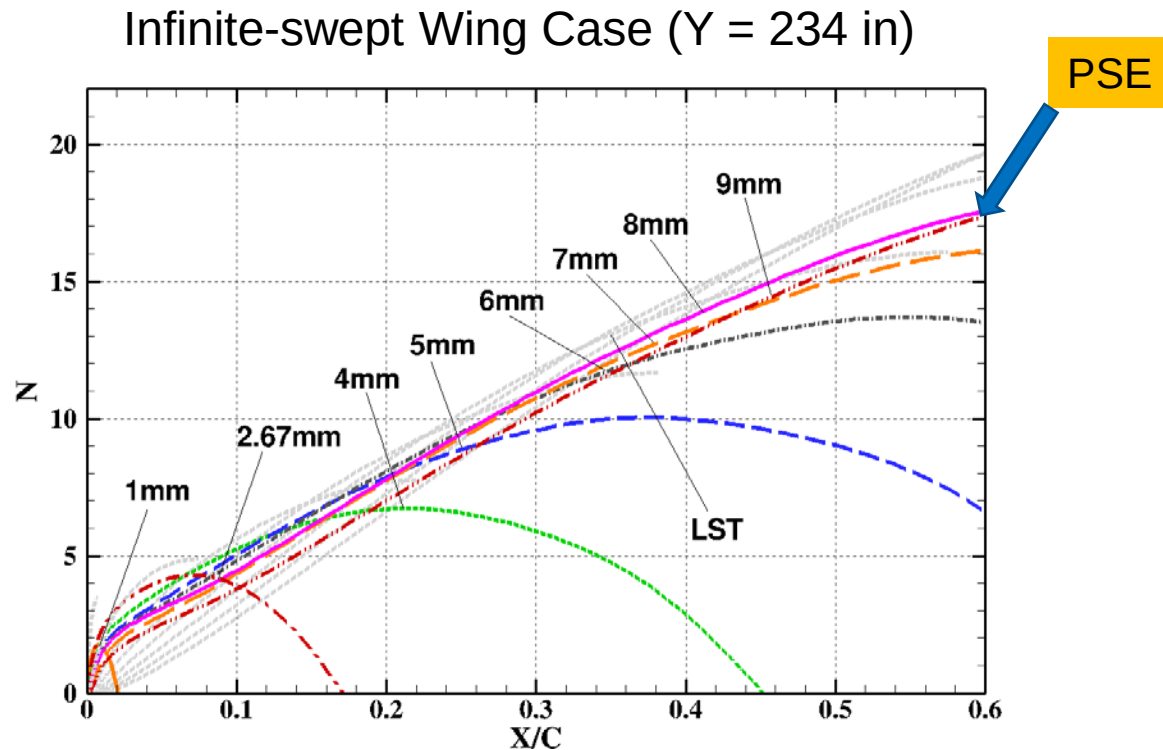


$M = 0.75$, $Re_c = 24.2$, LE sweep = 34.6°

- Perform linear PSE computations to select “target” and “control” modes
- Perform NPSE for these modes, with assumed initial amplitudes
- Perform secondary instability analysis

If NLF transition is at $x/c = 0.3$, DRE control should move it to $x/c = 0.45$

PSE N Factors for Stationary Crossflow Disturbances

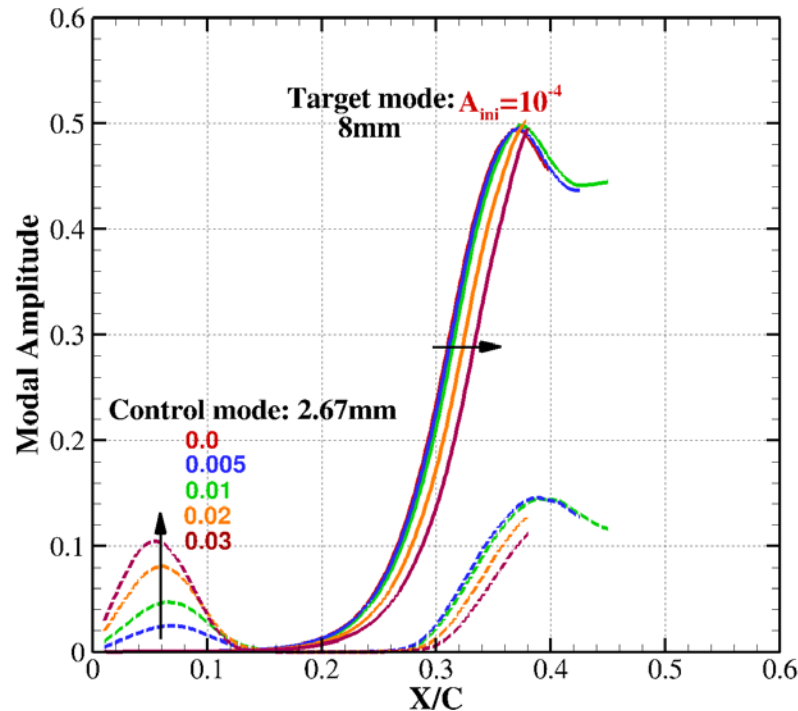


- Most amplified and hence the “target” mode has a wavelength of 8mm
- Possible “control” modes: 2.67mm or 4mm
 - Control mode must grow sufficiently to modify the mean flow and influence “target” mode
 - Control mode must not induce transition by itself

Amplitude Growth of Stationary Crossflow Disturbances



Initial amplitude of target mode = .01%

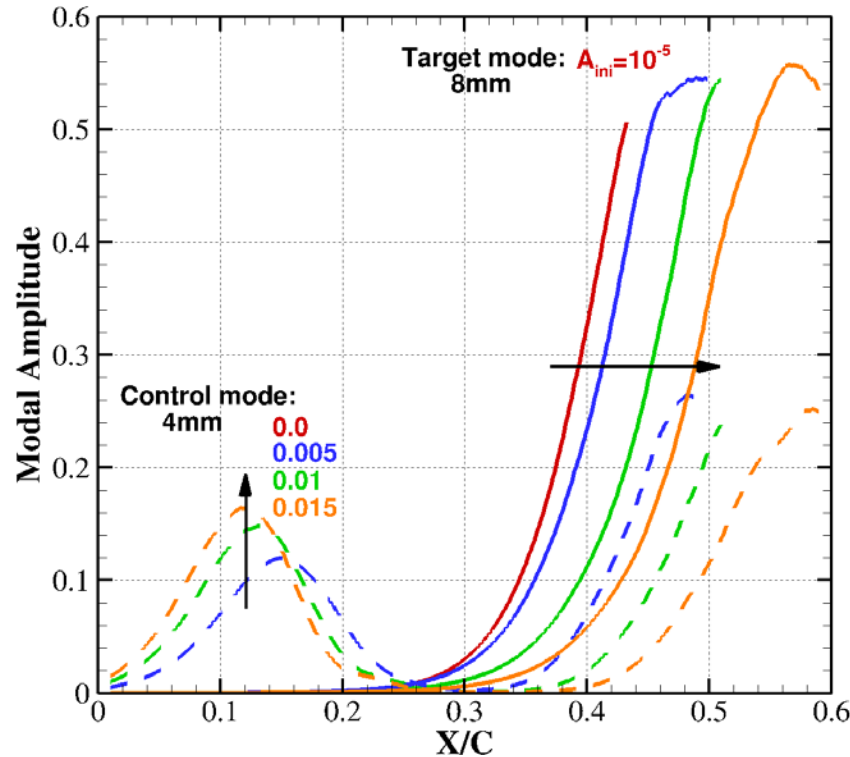


- DRE control of 8 mm (target) mode with 2.67 mm (control) mode
- For control amplitude of .03, expected transition delay is rather small

Amplitude Growth of Stationary Crossflow Disturbances



Initial amplitude of target mode = .001%



Chordwise velocity component

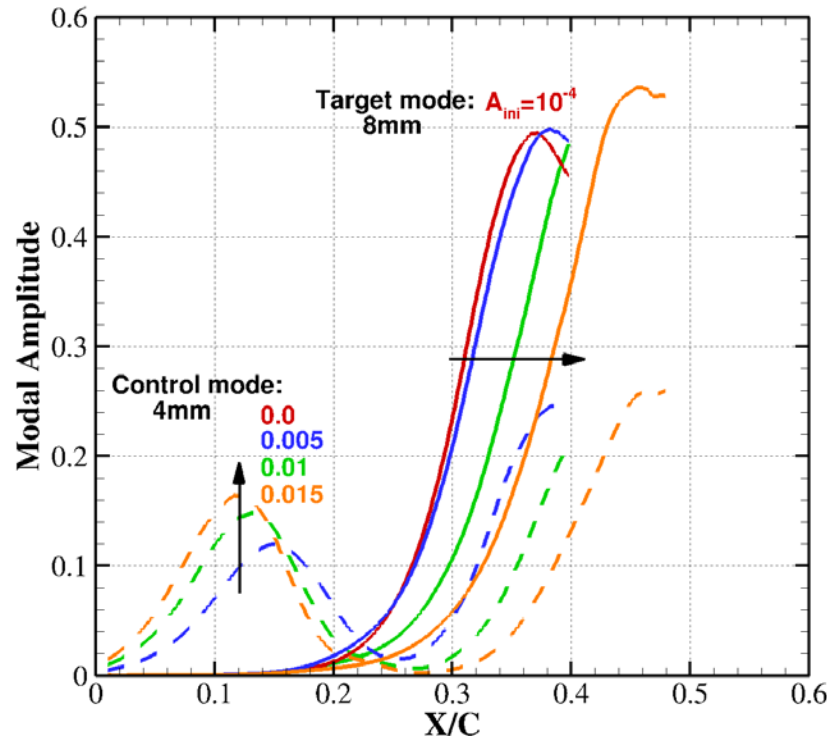
- DRE control of 8 mm (target) mode with 4 mm (control) mode
- For control amplitude of .015, transition could move from $x/c = 0.4$ to 0.5
 - An increase of 25%

Amplitude Growth of Stationary Crossflow Disturbances



Initial amplitude of target mode = .01%

Chordwise velocity
component



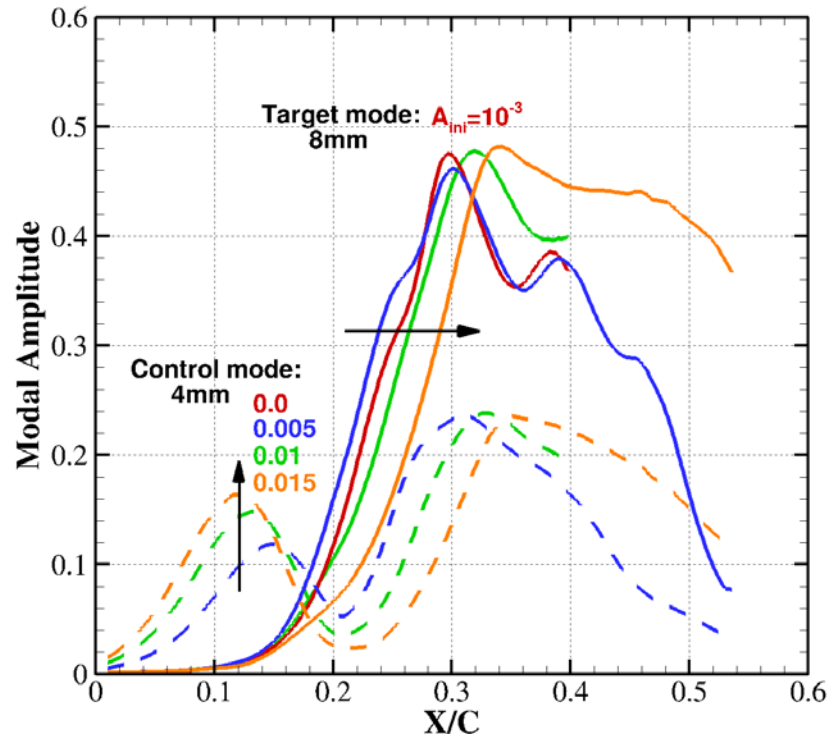
- DRE control of 8 mm (target) mode with 4 mm (control) mode
- For control amplitude of .015, transition could move from $x/c = .32$ to $.39$
 - An increase of 22%

Amplitude Growth of Stationary Crossflow Disturbances



Initial amplitude of target mode = .1%

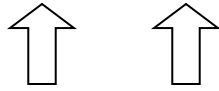
Chordwise velocity component



- DRE control of 8 mm (target) mode with 4 mm (control) mode
- For control amplitude of .015, transition could move from $x/c = .25$ to .29
 - An increase of 16%

2D/PDE-based Eigenvalue Analysis

$$\psi = \phi_0 + \phi$$



Mean, Perturbation

$$\phi_0 = \phi_0(y; x, z) \longrightarrow \text{1D eigenvalue problem (classical LST)}$$



Slow varying

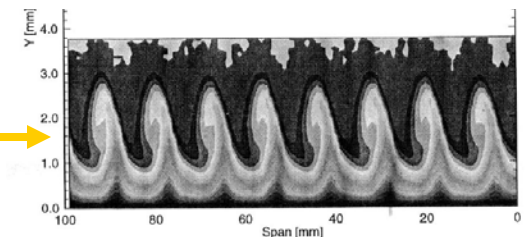
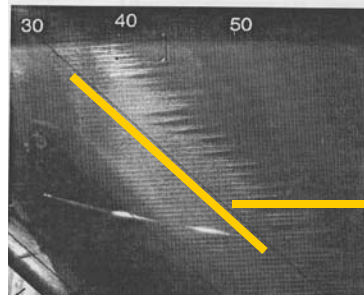
$$\phi_0 = \phi_0(y, z; x) \longrightarrow \text{2D eigenvalue problem (e.g., Lin \& Malik 1996; Malik et al. 1999)}$$



Slow varying

Flow-visualization on wing surface

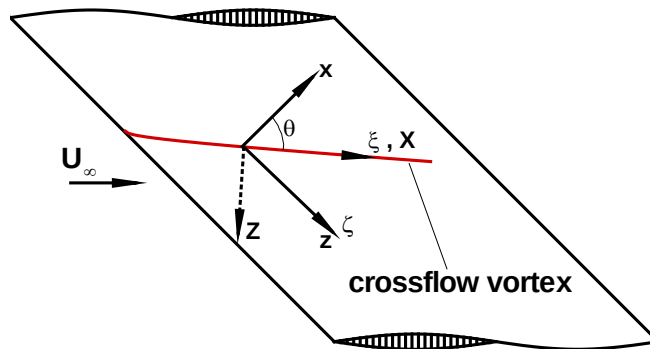
-- Reibert et al., 1996



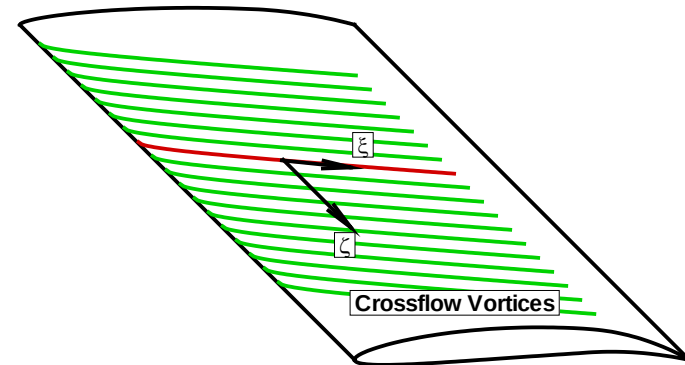
Coordinate System for Secondary Instability Analysis



3 coordinate systems



Selected coordinate system



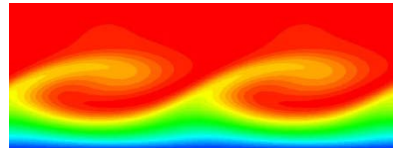
- *For the selected vortex aligned non-orthogonal (ξ, ζ) coordinate system:*
 - base flow is 'slow' varying in ξ , and is periodic in ζ
 - allows secondary instability to be periodic in z (ζ) and grow in X (ξ)
 - suitable for spatial stability analysis
 - this selection of coordinate system results in 'bi-global' stability problem
 - x-z coordinate system will result in 'tri-global' stability problem



Numerical Aspects of 2D Eigencalculation

- y -discretization: 4th order finite difference
- ζ -discretization: Fourier
- Resulting matrix size: $5N_y N_\zeta \times 5N_y N_\zeta$, with banded structure

Overall Solution Procedure for Secondary Instability Analysis



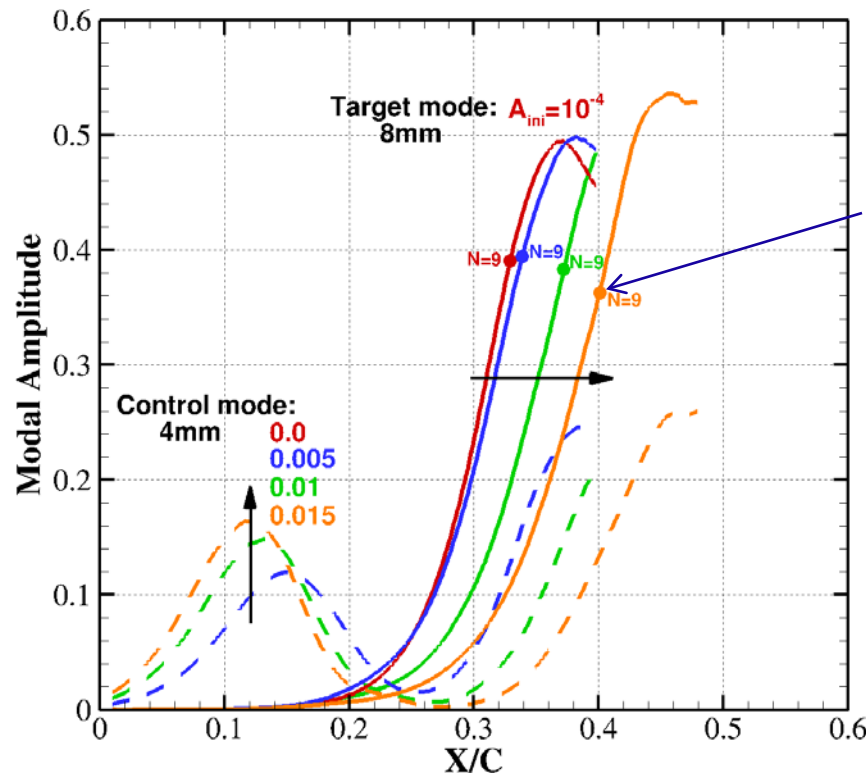
Basic flow for secondary analysis

1. **Basic flow:** B.L. + NPSE for given wavelength+initial amplitude of primary (stationary crossflow) mode
 - Resolution: 121→251 points in y + 32→64 modes in ζ
2. Global (temporal) search of eigenvalues with Arnoldi method to provide initial guesses for marching
 - Multiple families of modes,
classified based on energy production budget
3. “Local” marching solutions over appropriate frequency range
4. Secondary N-factor calculation

Secondary Instability of Stationary Crossflow Disturbances



Initial amplitude of target mode = .01%



Chordwise velocity component

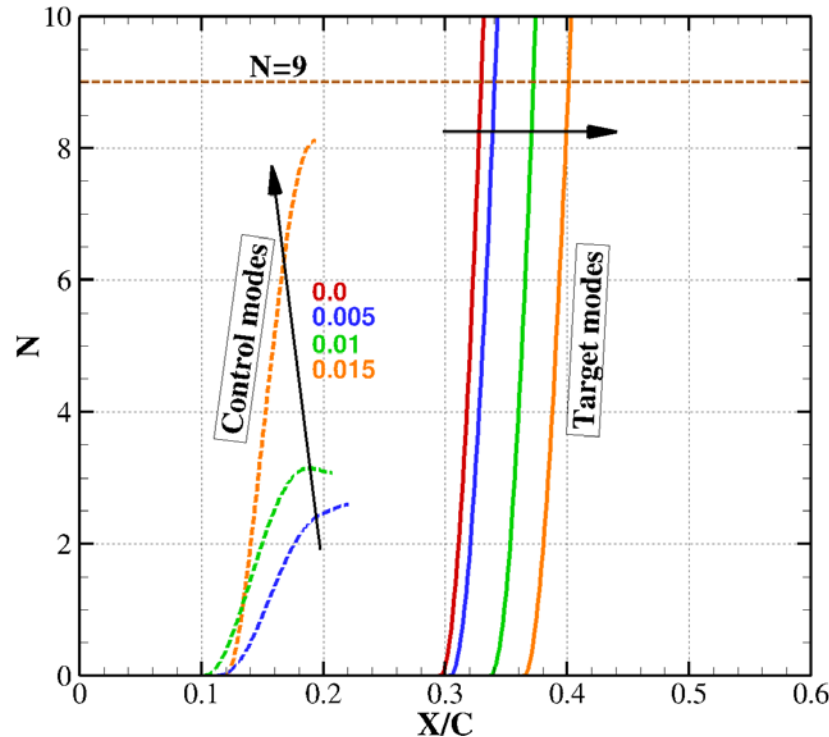
Secondary N factor

- DRE control of 8 mm (target) mode with 4 mm (control) mode
- Based on an N factor of 9, transition would move from $x/c = .33$ to $.40$
 - An increase of 21%

Secondary Instability of Stationary Crossflow Disturbances



Initial amplitude of target mode = .01%



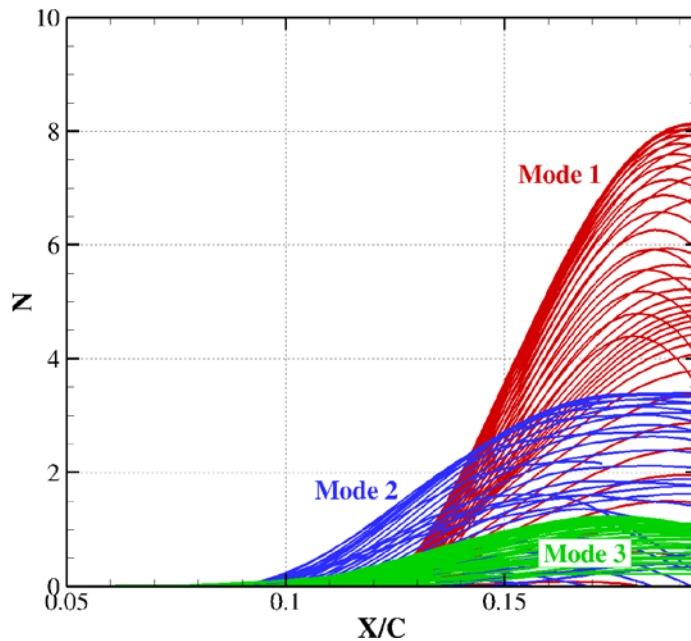
Secondary N factor

- DRE control of 8 mm (target) mode with 4 mm (control) mode
- An N factor of 7-9 yields essentially the same $(x/c)_{tr}$ for the target mode
 - But an N = 7 will result premature transition due to the control mode

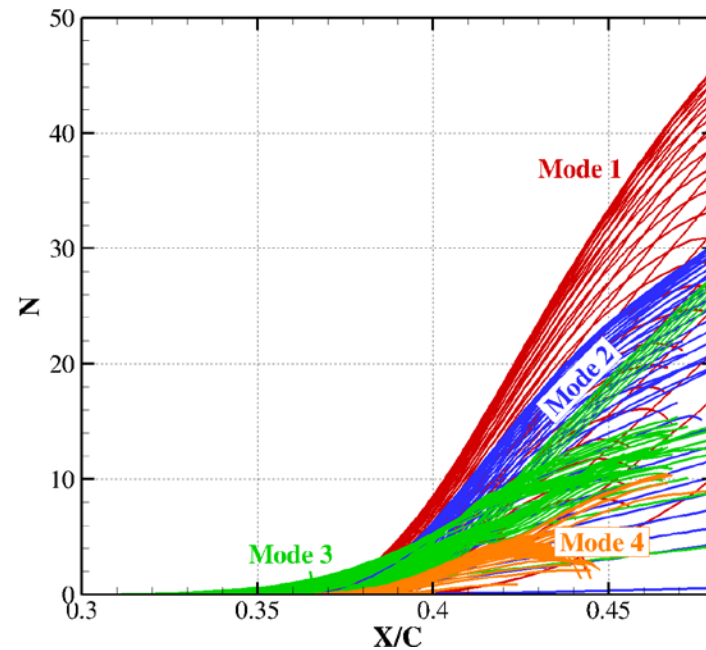
Secondary Instability of Stationary Crossflow Disturbances



Control Mode (4 mm)



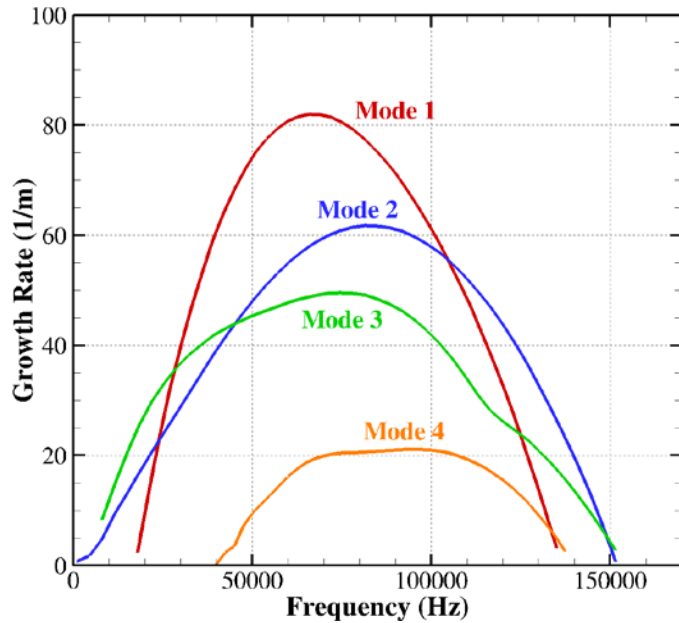
Target Mode (8 mm)



- Multiple secondary instability modes [both sinuous and varicose]
- In Malik et al. (1999) terminology
 - Mode 1 for target mode is a “z-mode” (i.e., aligns with spanwise shear)
 - Mode 1 for control mode is a “y-mode” (i.e., aligns with wall-normal shear)

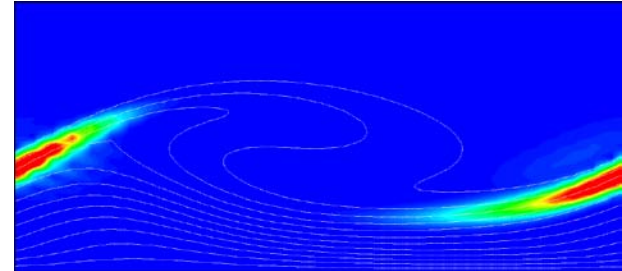
Secondary Instability Modes for Target (8mm) Mode

$x/c = 0.3856$

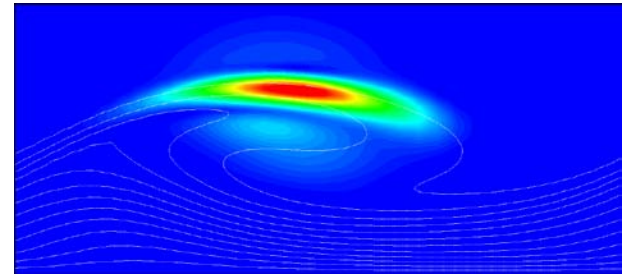


- High frequency disturbances

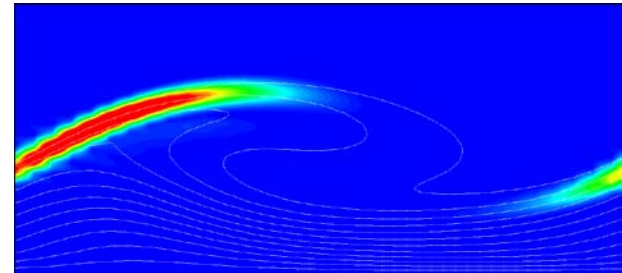
Mode 1



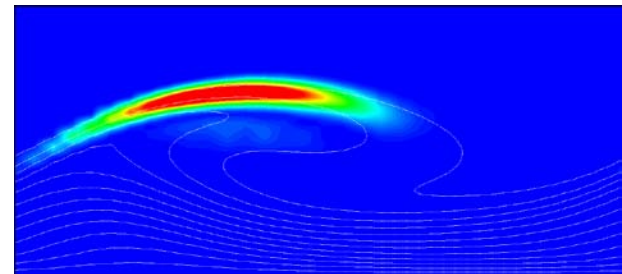
Mode 2



Mode 3

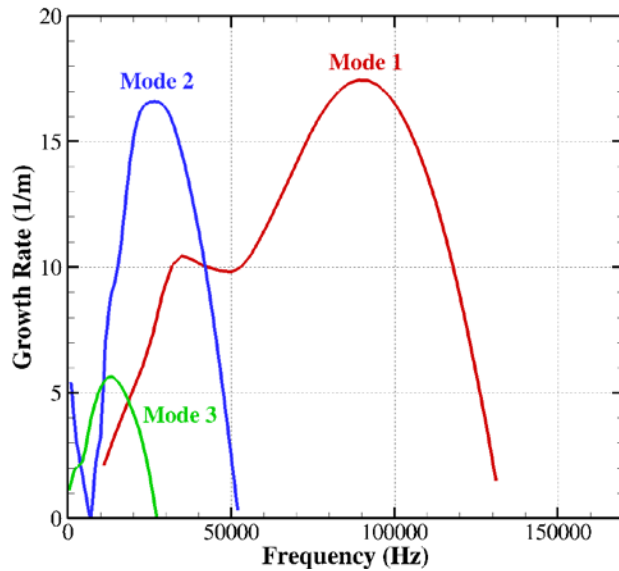


Mode 4



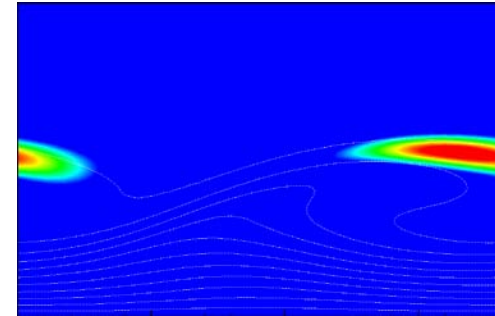
Secondary Instability Modes for Control (4mm) Mode

$$x/c = 0.126$$

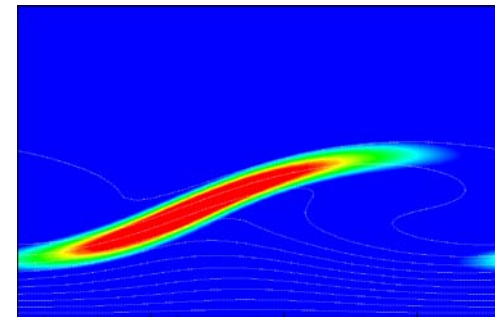


- High frequency disturbances

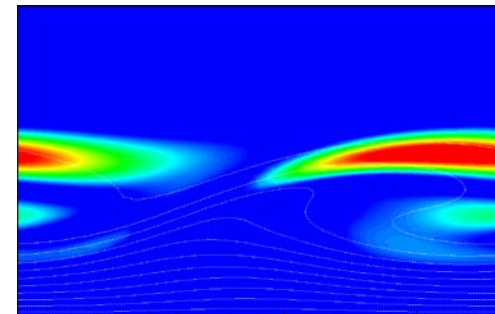
Mode 1



Mode 2

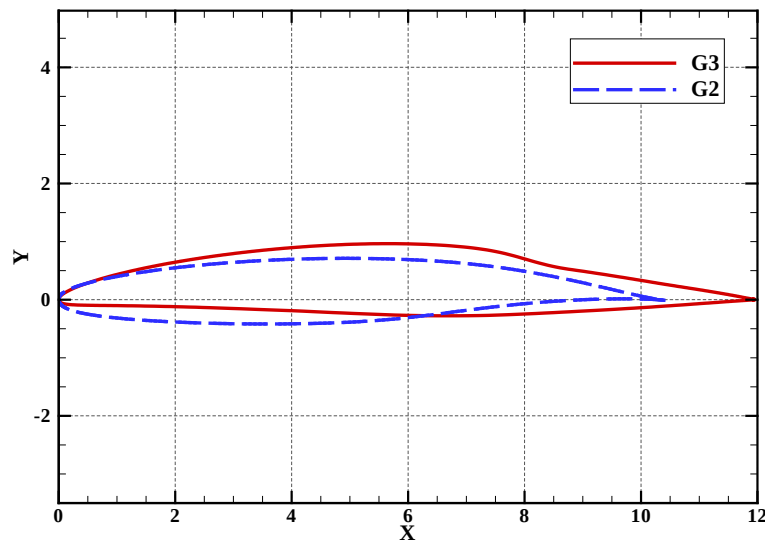


Mode 3

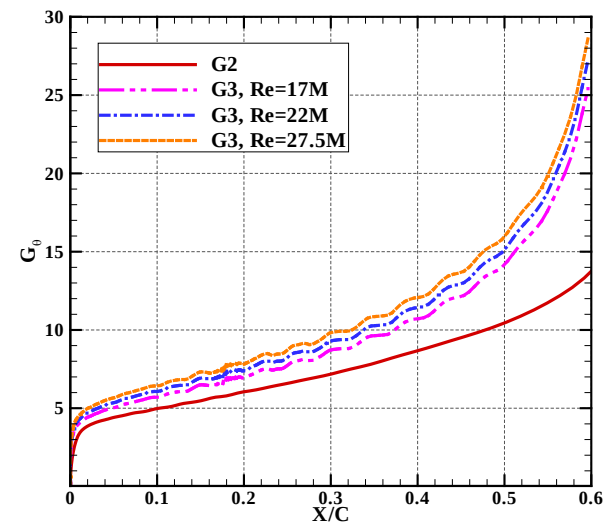


Effect of Surface Curvature on Crossflow Instability-1

- During the design process, two earlier gloves were designed
 - G-2 aircraft (AIAA-
 - G-3 aircraft (AIAA-2011-
- Upper surface “Gortler number” much larger for the latter design



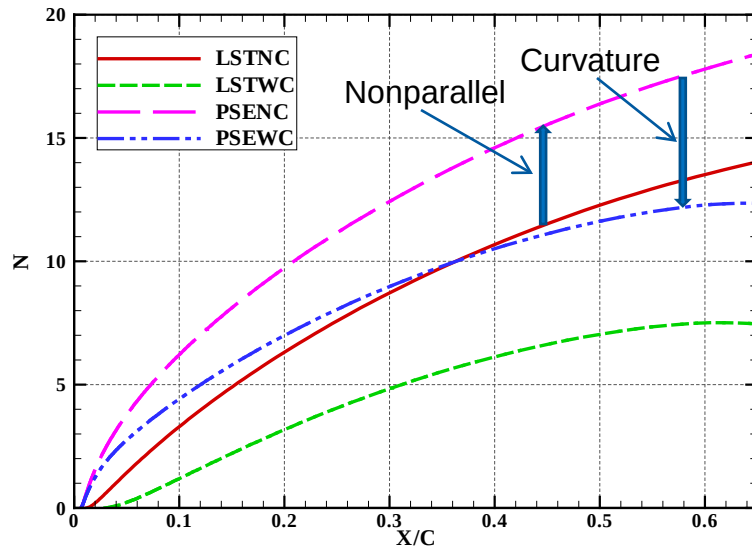
Chordwise geometry (ft)



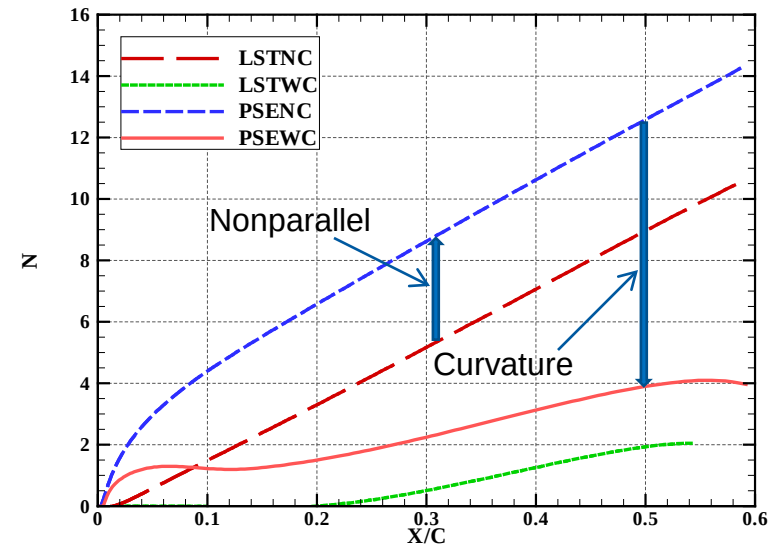
Gortler number, $G_\theta = Re_\theta \sqrt{\theta \kappa}$

Effect of Surface Curvature on Crossflow Instability-2

- Nonparallel effect destabilizing, surface curvature stabilizing
 - For G-3, stabilizing effect of surface curvature much larger than destabilizing effect of nonparallel mean flow
 - Use of LST too conservative for NLF design (based on stationary crossflow)
- Use surface curvature as an NLF design parameter
- Provided transition induced by stationary crossflow disturbances only, which is also a necessary condition for DRE control



G-2 N factors [$Re_c = 17 \times 10^6$]



G-3 N factors [$Re_c = 22 \times 10^6$]

Concluding Remarks

- DREs at $\lambda = 4$ mm delays the growth of naturally dominant stationary crossflow instability mode ($\lambda = 8$ mm) at $Re_c = 24.2 \times 10^6$
 - Delays secondary instability growth and, hence, transition
 - Project goal of increasing Re_{tr} by 50% will likely not be achieved
- DRE control at high Reynolds numbers is a delicate balance between reducing target mode amplitude and avoiding over-control
- Missing Physics (from the analysis)
 - Surface Roughness
 - Receptivity (initial amplitudes of control and target modes assumed, not computed)
- DNS Required for Definitive Conclusions
- Both varicose and sinuous modes of high frequency secondary instability are computed
 - Sinuous mode dominant for the target mode
 - Varicose mode dominant for the control mode
 - Which mode dominates is related to the crossflow vortex wavelength, and Re