



Roughness Based Crossflow Transition Control: How Does the Saric *Vaccine* Work?

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SWIFT Flight Experiments

Receptivity to Surface Roughness Can Have Large Impact on Transition Location.
(Carpenter, Saric and Reed. SWIFT experiments, 2008)



RMS Height (μm)	Peak to Peak Height (μm)	Approx. Transition Location (x_{tr}/c)
1.0 (Painted LE)	3.8	0.3
0.3 (No paint)	2.2	0.8
Painted LE + controlled roughness at subcritical wavelength	12+	0.6



Flow Configuration

SWIFT experiment (Carpenter, Saric and Reed, 2008)

Test Point 27:

- Reynolds number = 7.15×10^6
based on freestream velocity and streamwise chord
- Angle of attack = -4.69 degrees.

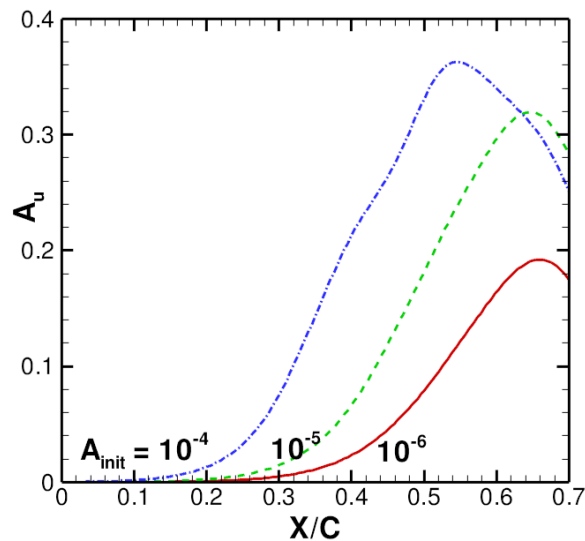


Analysis Codes

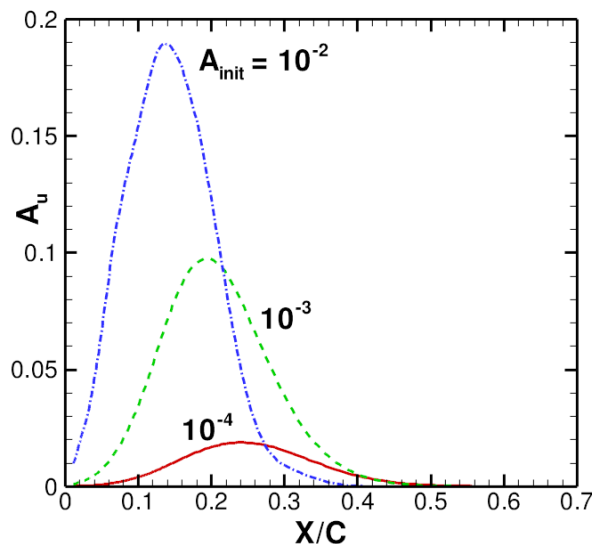
- Mean Flow: Boundary-Layer Code
----- infinite span assumption
- Stationary Crossflow Vortices:
Langley Stability and Transition Codes.
(LASTRAC) ----- nonlinear PSE.
- Linear Secondary Instability:
2-D eigenvalue analysis code.
- Nonlinear Growth of Secondary Instability:
LASTRAC.



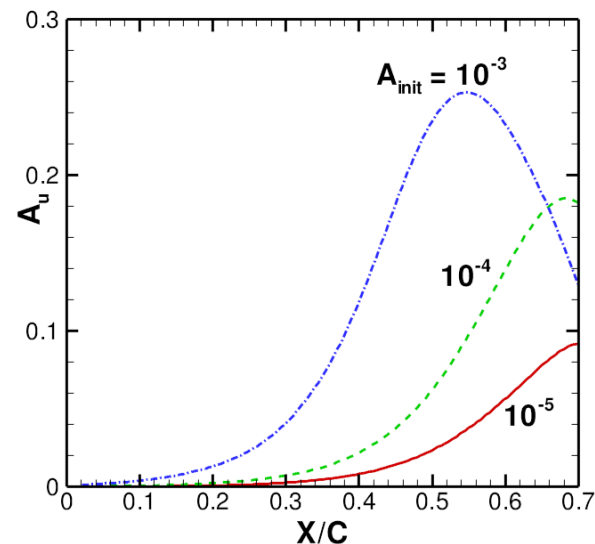
Growth of Stationary Crossflow Vortex with Different Spanwise Wavelengths



5 mm

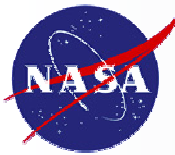


2.25 mm

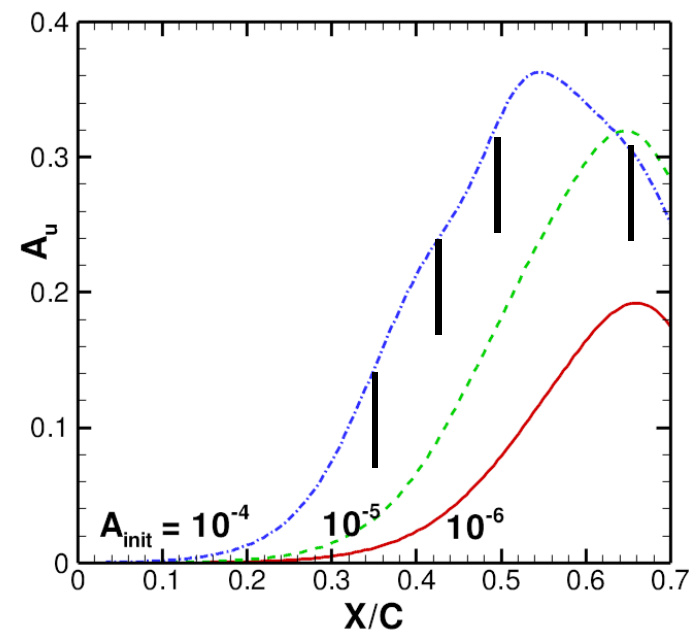
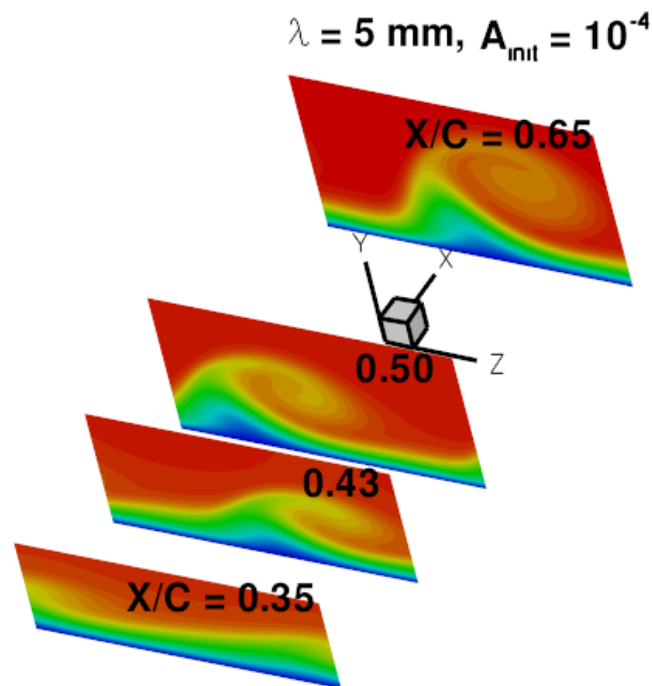


10 mm

Nonlinear evolution of stationary crossflow vortex amplitude for different wavelengths



Nonlinear Evolution of Stationary Crossflow Vortex



Chordwise velocity contours

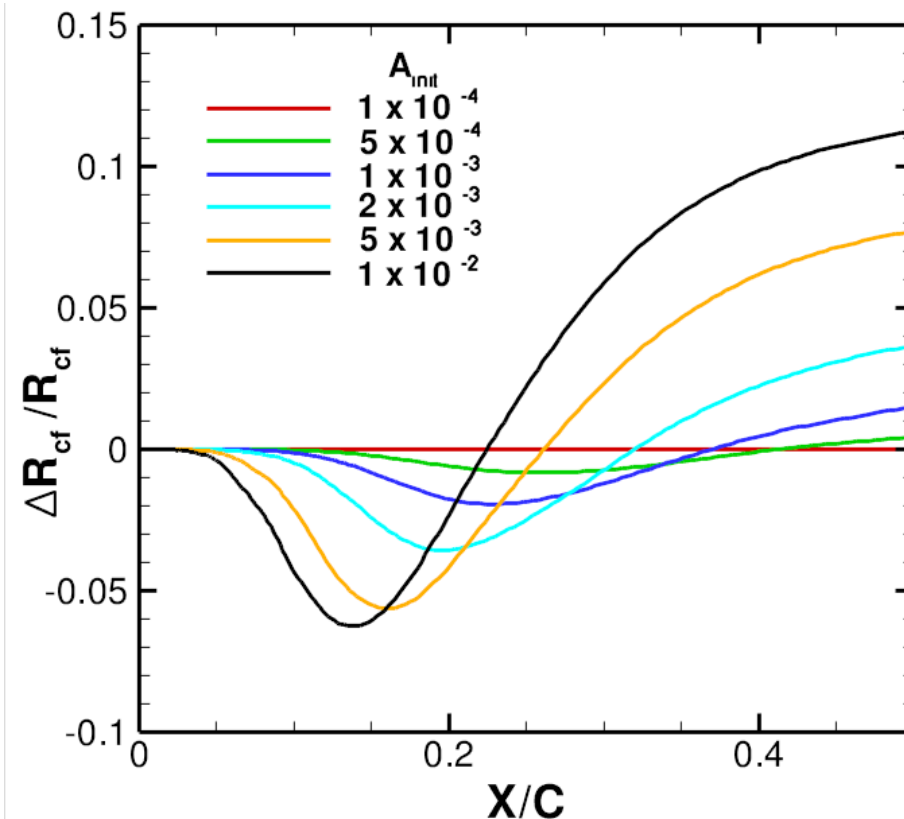


Target and control modes

- Most amplified stationary crossflow instability:
4.5 mm in wavelength ($N \approx 12$) – Target Mode.
- First Harmonic of above:
2.25 mm in wavelength ($N \approx 5.6$) – Control Mode
- 2.25 mm mode is used to control 4.5 mm mode.
 - Large initial amplitude of 2.25 mm and growth modify the mean state
 - 4.5 mm growth delayed and suppressed



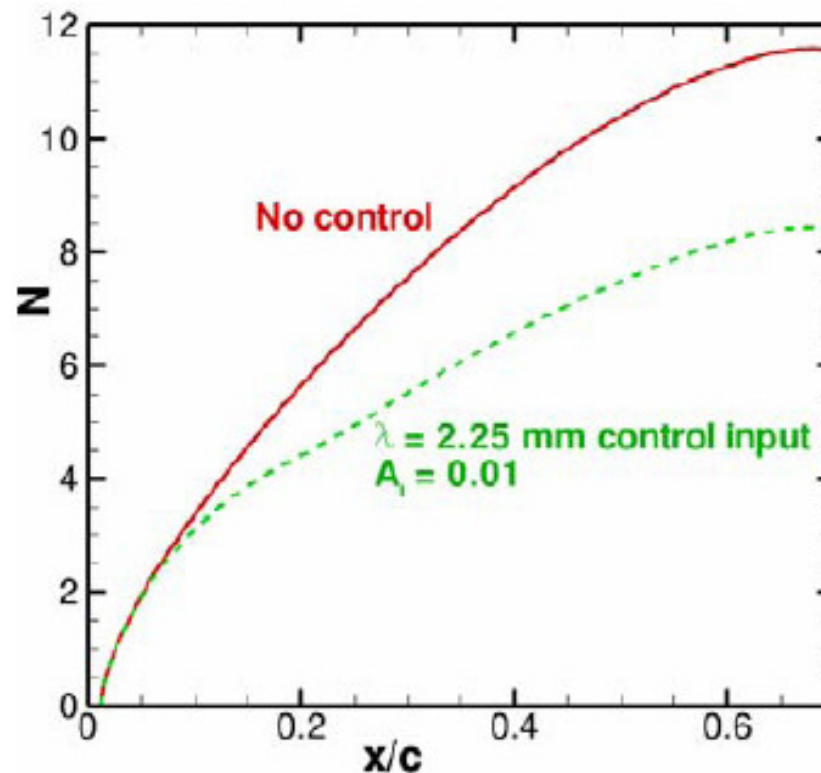
Effect of Control Input on Crossflow Re



- Moderate reduction in crossflow Reynolds number near peak of control mode
 - Correlates with reduced growth of target mode in this region
- Increase in crossflow Reynolds number downstream of initial peak of control mode
 - Does not correlate with reduced growth of target mode in this region



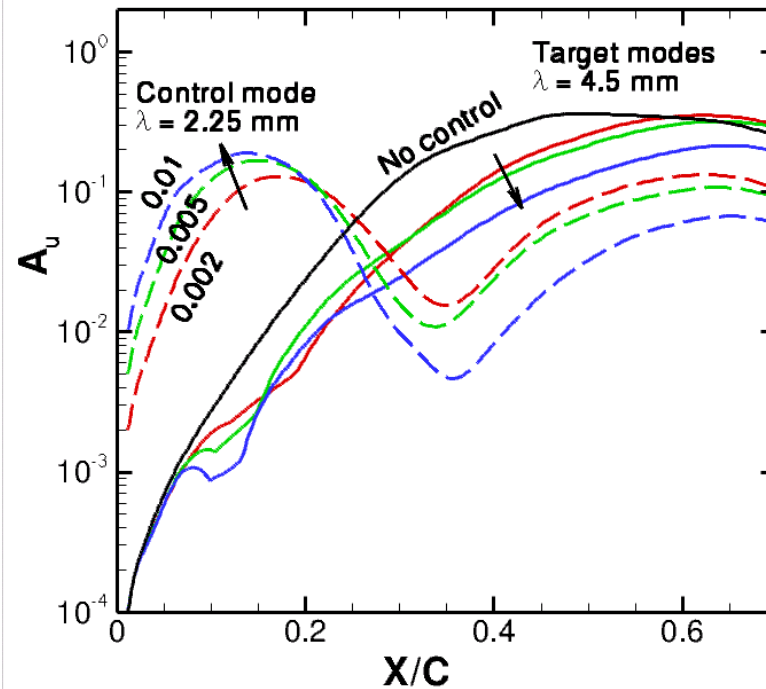
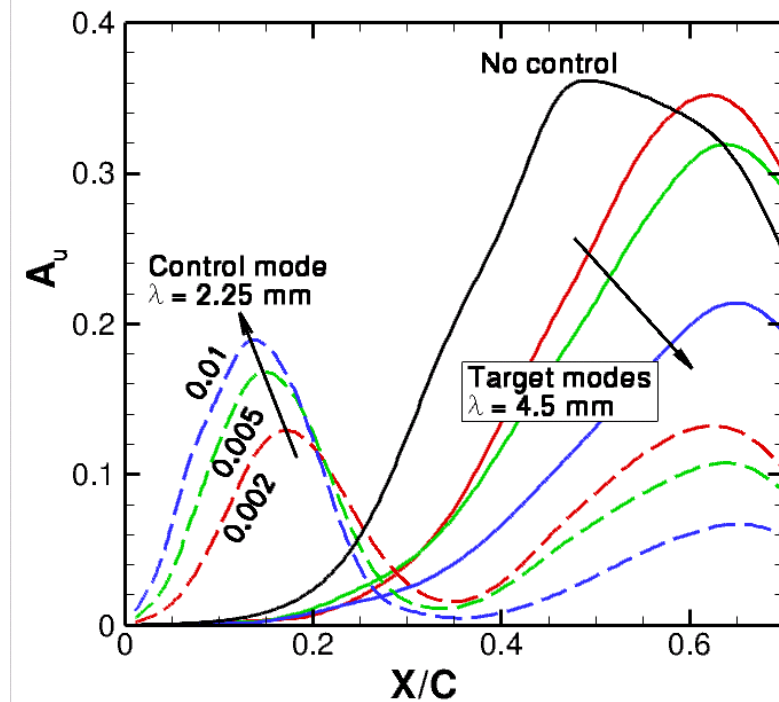
Effect of Control Input on Linear Stability of Spanwise Averaged Basic State



- Basic state modification due to the control mode $\Rightarrow$ significant reduction in peak N-factor relative to the uncontrolled case ($\Delta N \approx 3.2$ near $x/c=0.6$) for the 4.5 mm mode.



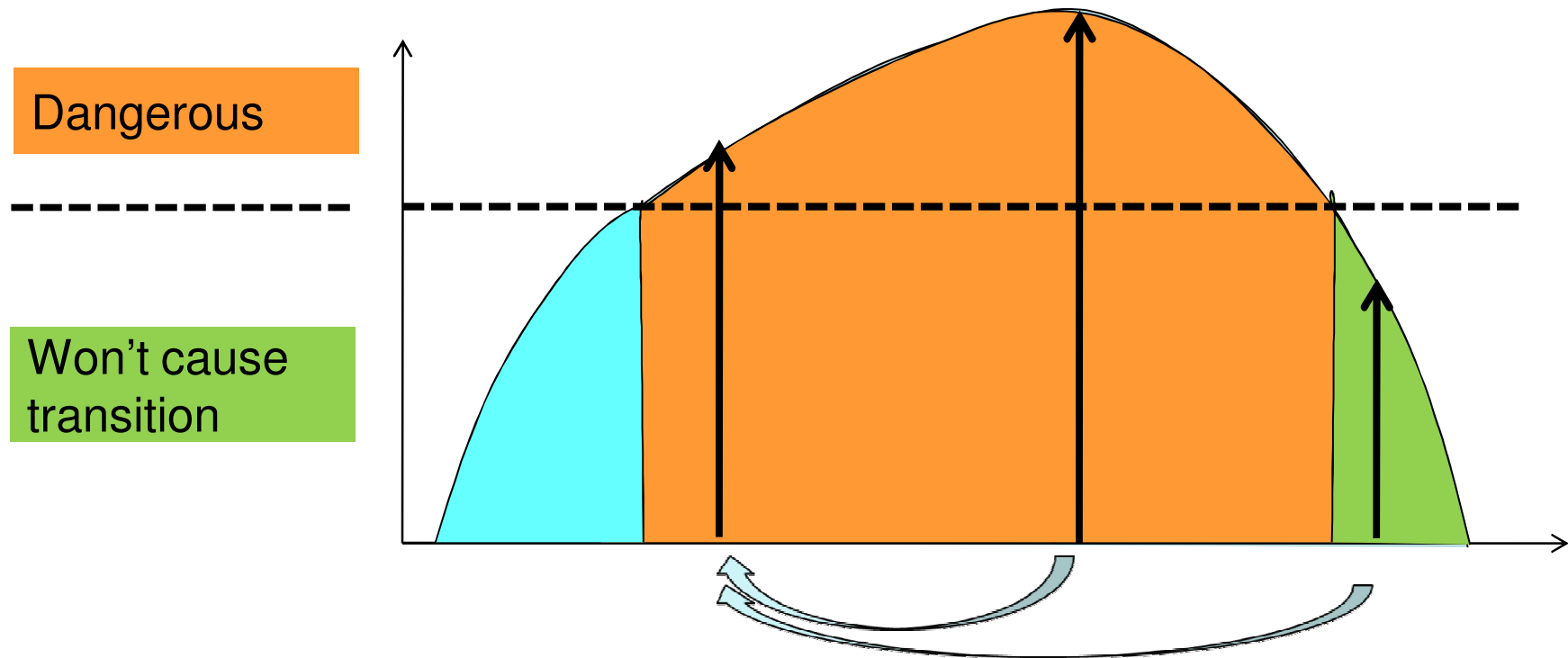
Effect of Control Input on Target Mode Amplitude



- Target mode Amplitude progressively reduces as control amplitude increases.
- Logarithmic scale plot: control does not take effect until its amplitude becomes sufficiently large.



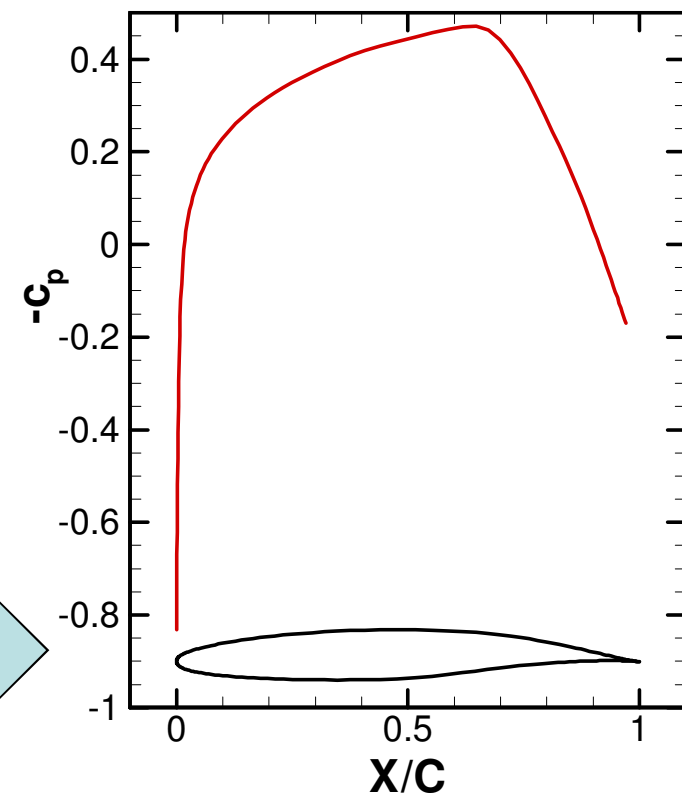
Difference Mode Interaction between Control and Target Modes





Flow Configuration

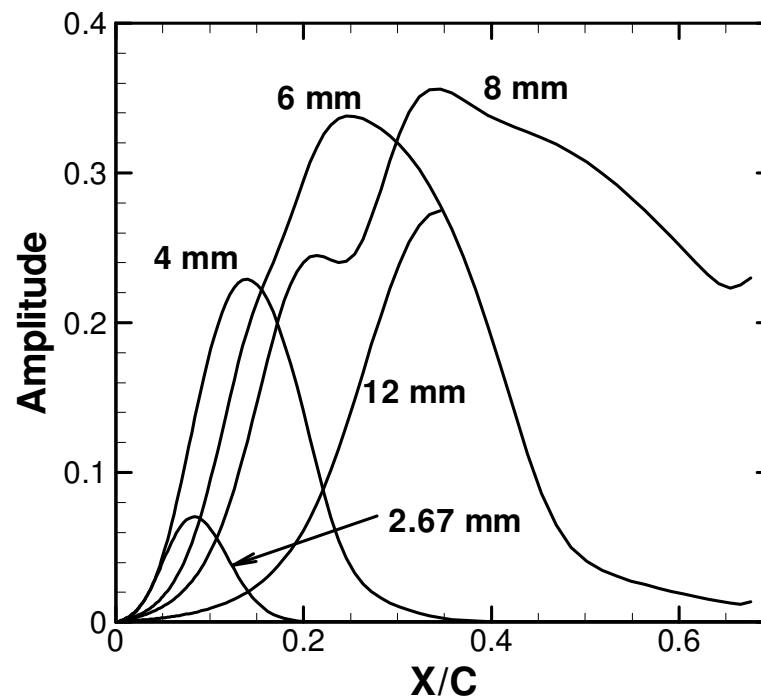
- Flow Configuration designed for natural laminar flow for $x/c < 0.6$ (Texas A & M Univ.)
 - TAMU-003T-75 (v.90) airfoil, 9.3% thick
 - $\Lambda = 30$, $\alpha = 0$
 - $M_\infty = 0.75$, $Re_c = 17 \times 10^6$
 - 40,000 ft. (flight altitude)
- Present study
 - Off-design condition $\alpha = -1^\circ$ for laminar flow control study
- Euler solution
 - provided by Belisle et al.  (TAMU)





Uncontrolled Crossflow Transition

- Linearly most unstable: 8 mm stationary crossflow vortex
- Max. amp. in nonlinear evolution: ~38% of freestream velocity
- Modes most likely to lead to transition: ~ 6 – 12 mm



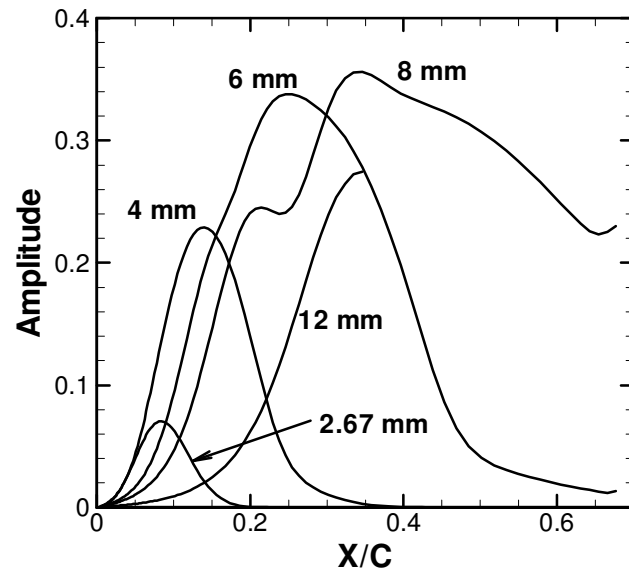
Nonlinear evolution of fundamental mode amplitudes at a $A_{init} = 10^{-3}$



Selection of Control Input

Basic Requirement for Control Input

1. Must be able to reduce target mode growth
2. Must not be too unstable to cause transition itself

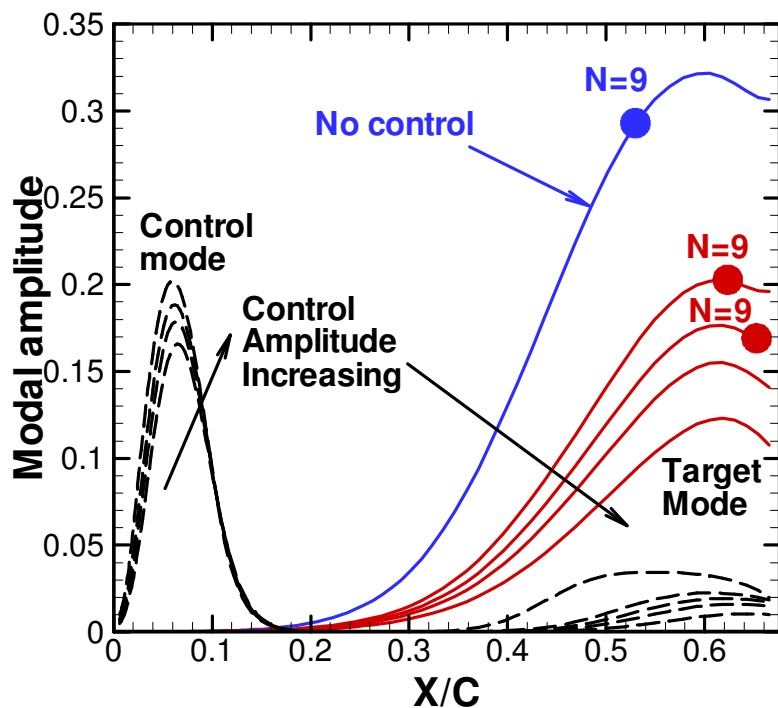


Candidates for Control Mode

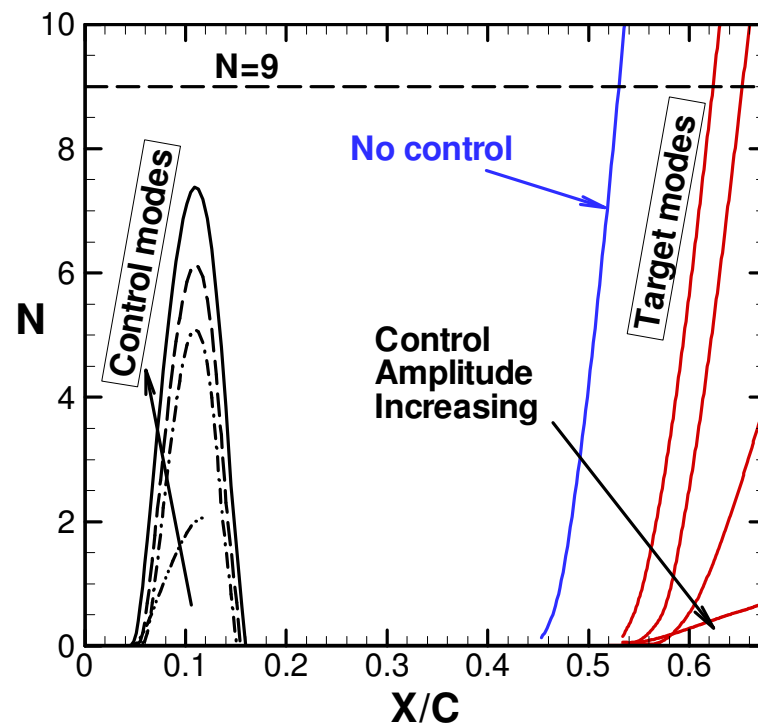
- $\lambda = 2.67$ mm
 - Does not amplify much
 - Acts over short chordwise distance
- $\lambda = 4$ mm
 - Moderate amplification
 - Acts over longer chordwise distance



Effect of Control: 2.67 mm controlling 8 mm



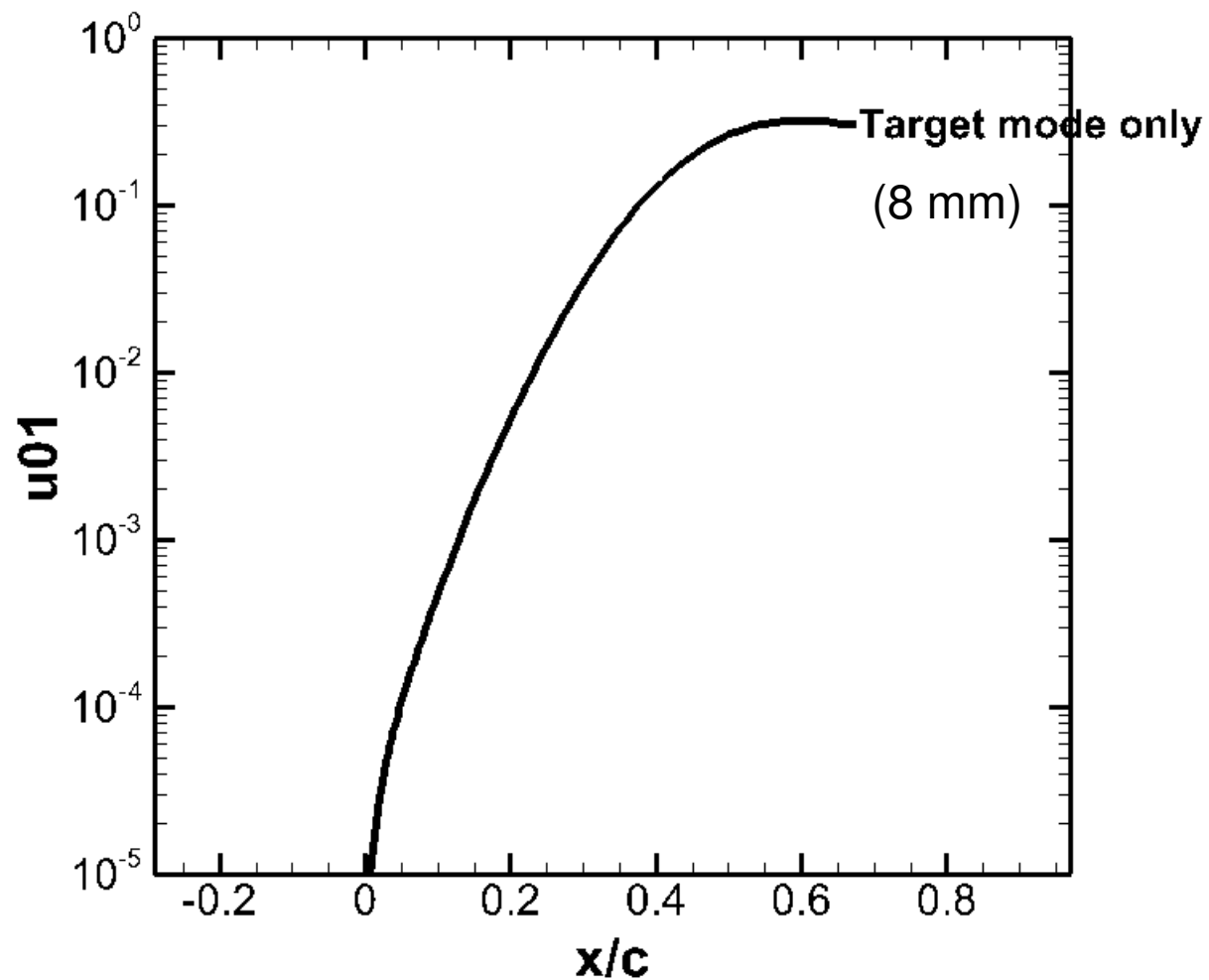
8 mm primary crossflow
vortex amplitude



8 mm secondary instability N-factor

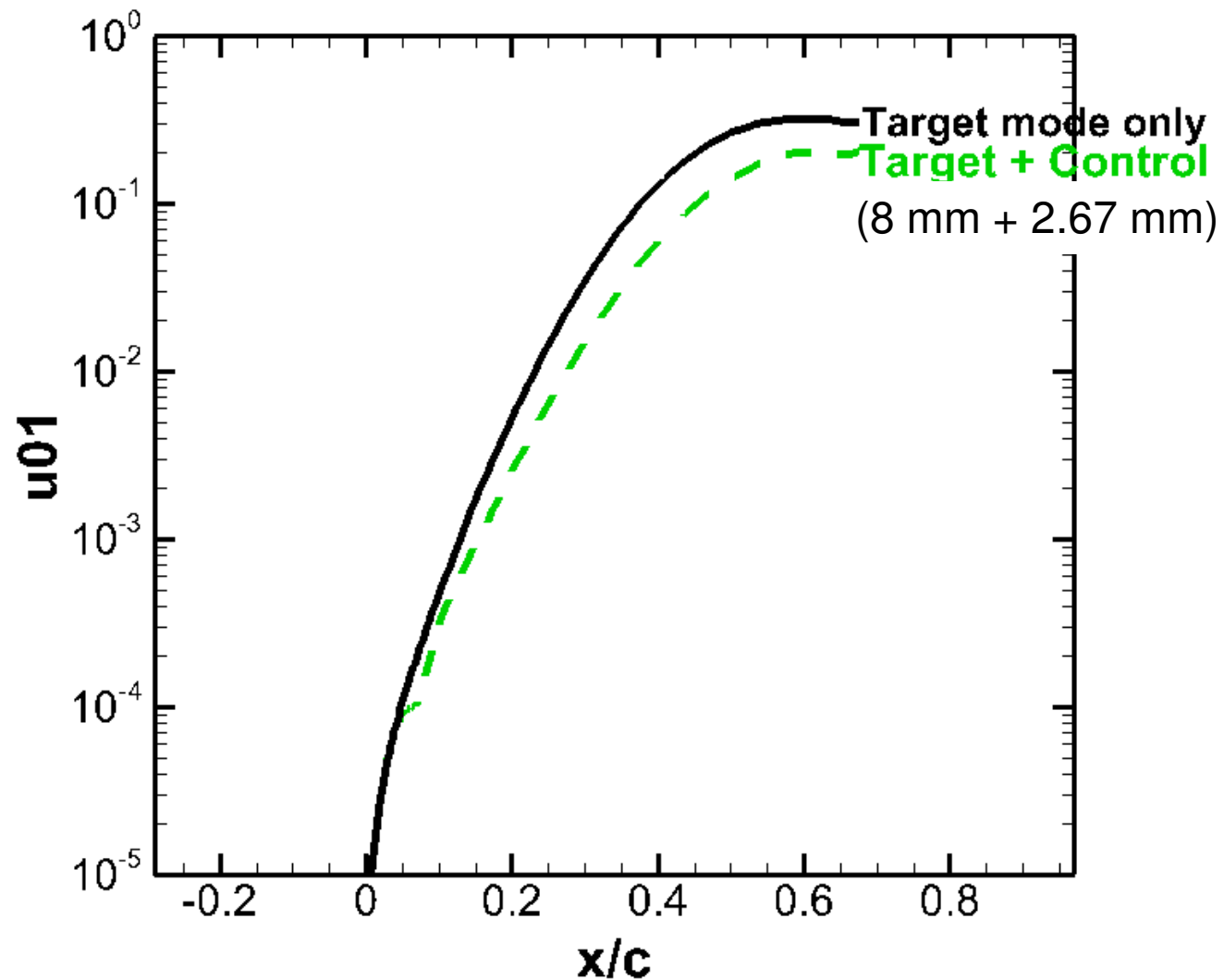


Target Mode (8 mm) Evolution



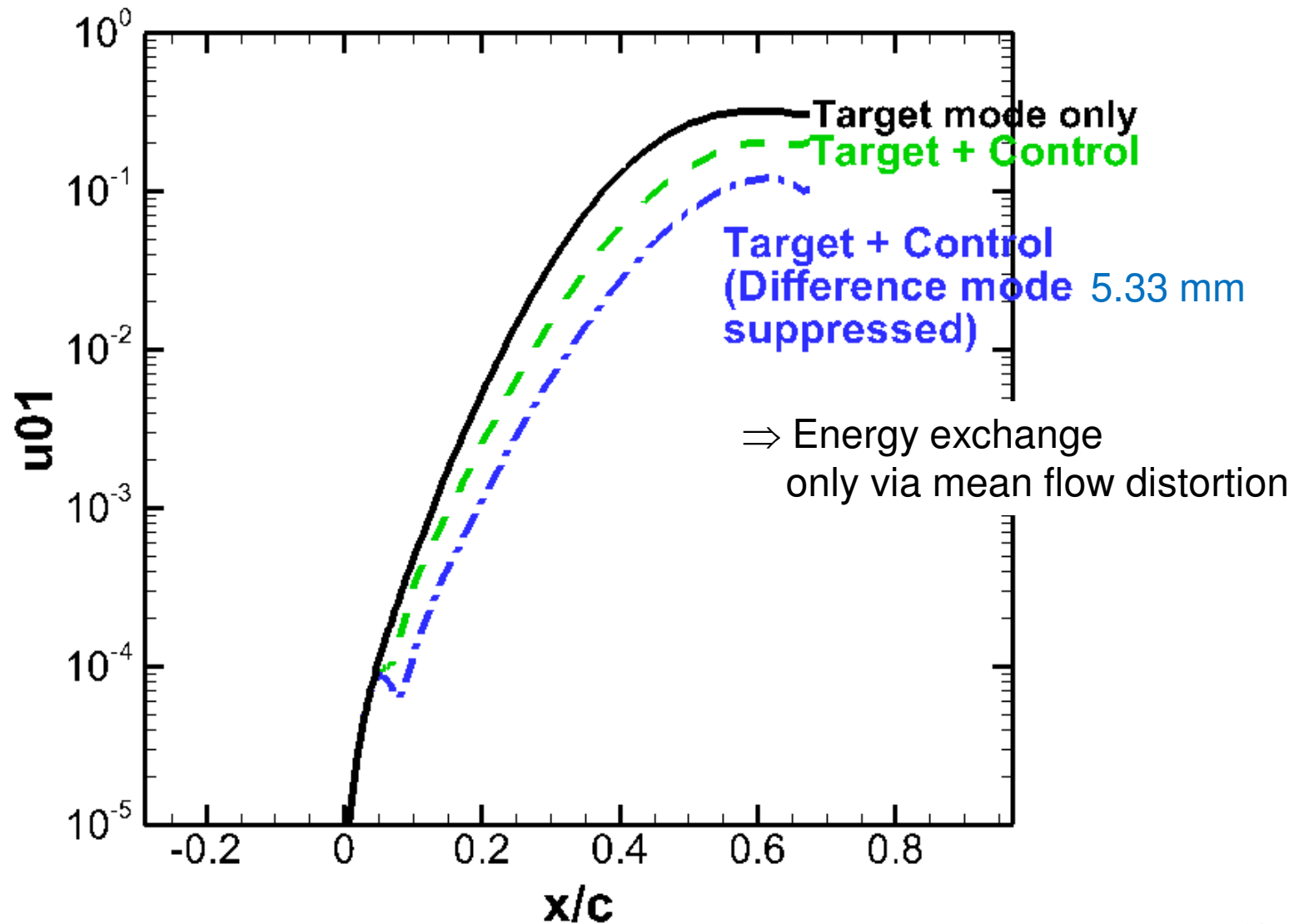


Target Mode (8 mm) Evolution



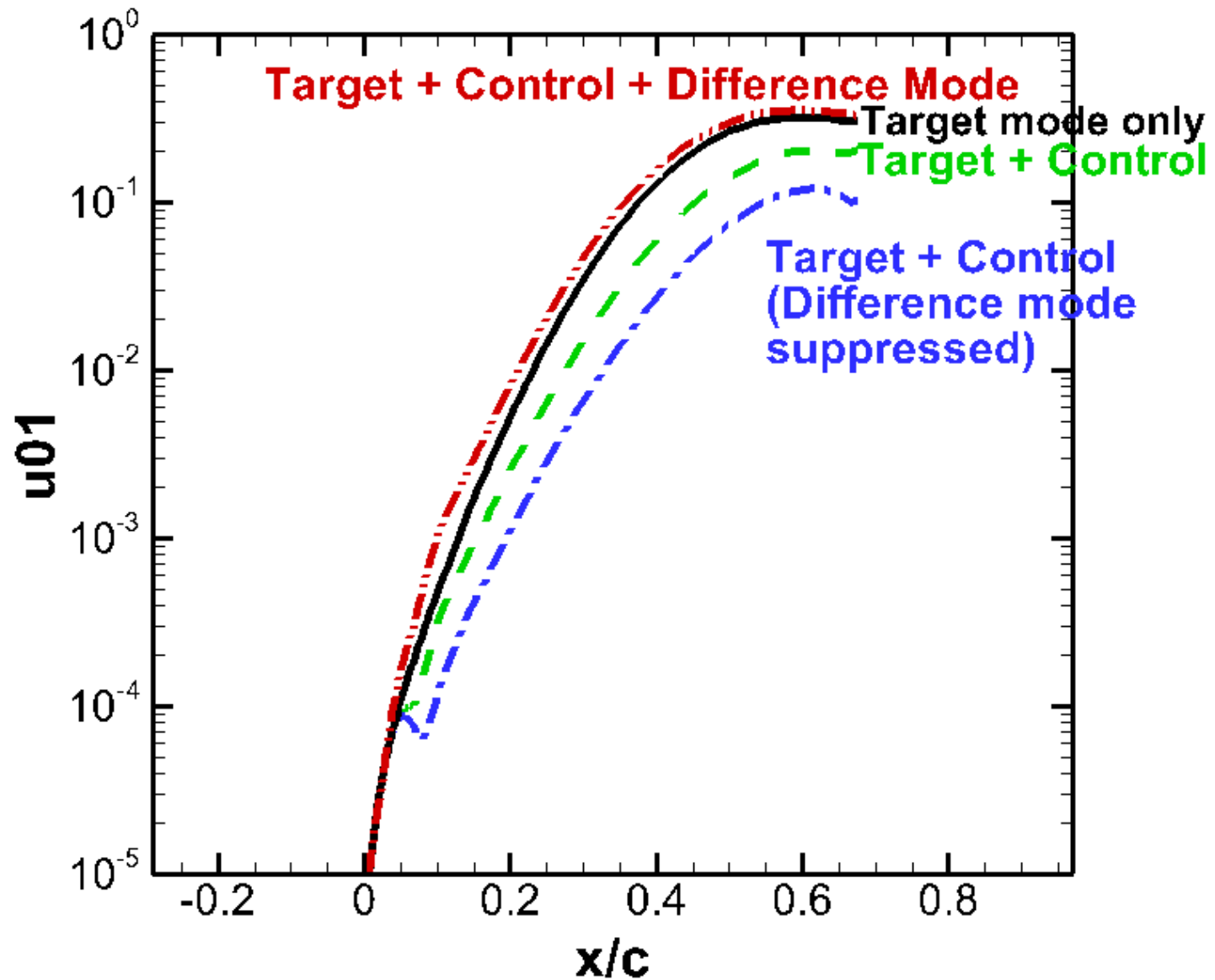


Target Mode (8 mm) Evolution





Target Mode (8 mm) Evolution





Summary

- **Mean flow modification by DREs is a significant aspect of the mechanism behind the control action**
- **However, triadic interaction via difference mode between the control and target modes can also exert a comparable influence on target mode evolution**



Extra Charts



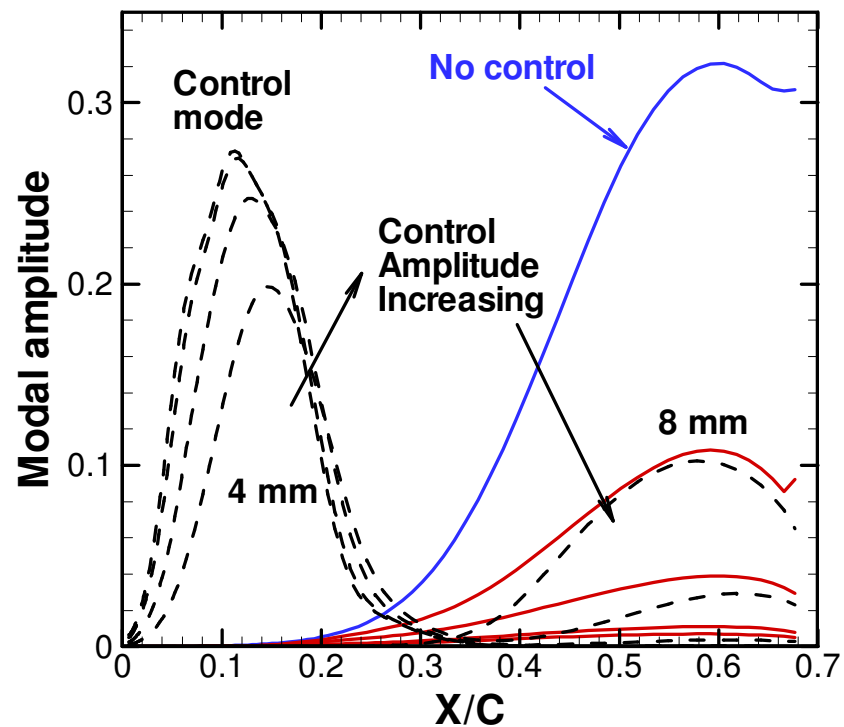


4 mm mode as control input

What to do to avoid exciting unwanted modes?

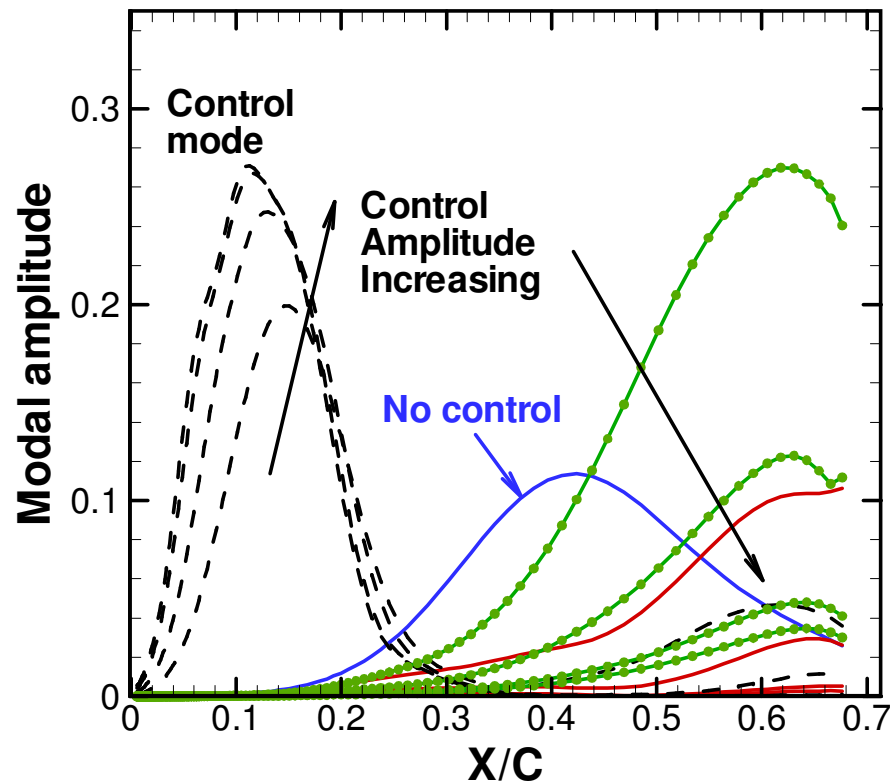
- try 4 mm mode as control input
- does control 8 mm mode well
- but reaches large amplitude itself

- Dashed lines: 2.67 mm
 - Solid lines: 8 mm
- 





Effect of 4 mm Mode on 6 mm Mode



dashed lines: 4 mm; solid lines: 6 mm; dots: 12 mm

quadratic interactions:

$$\exp(i2\pi/4) \exp(-i2\pi/6) = \exp(i2\pi/12)$$

$$\exp(i2\pi/6) \exp(i2\pi/12) = \exp(i2\pi/4)$$

$$\exp(i2\pi/4) \exp(-i2\pi/12) = \exp(i2\pi/6)$$



Summary

- $Re = 17 M \Rightarrow \lambda = 6 - 17 \text{ mm}$ can potentially cause transition
- DREs at $\lambda = 2.67 - 4 \text{ mm}$ reduce the growth of naturally dominant stationary crossflow instability modes at high Re
 - Indirectly also weaken the secondary instability growth
- Overcontrol (i.e. premature transition) can be avoided if control input is suitably small (o.k. if surface is sufficiently smooth)
- Possibility of exciting unwanted modes exists
 - Interactions between short wavelength control and target modes could lead to significant growth of longer waves
- DRE control at high Reynolds numbers is a delicate balance between reducing target mode amplitude and avoiding overcontrol



Interaction of 2.67 mm and 4 mm modes

Possible Bad Scenario:

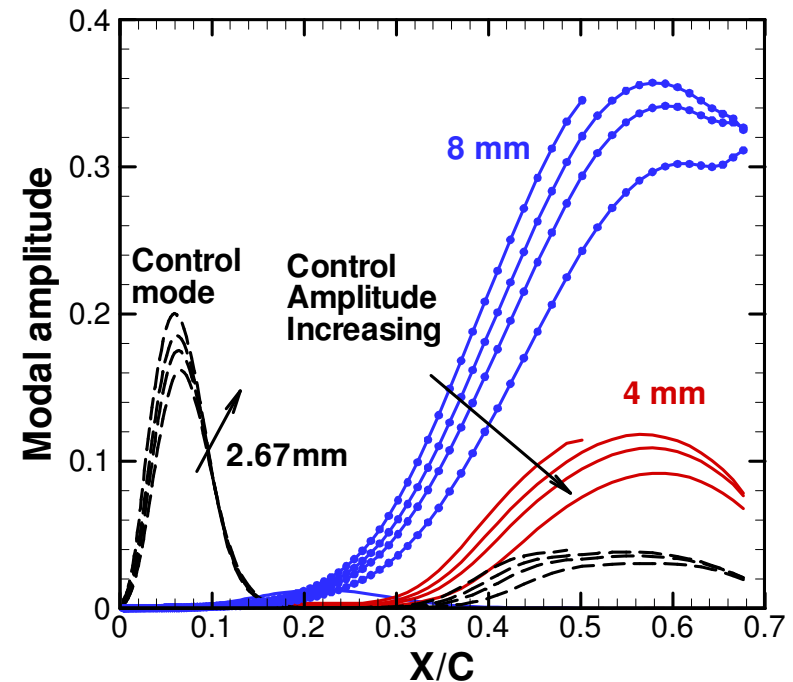
- 2.67 mm mode used as control input
- significant initial presence of 4 mm
- quadratic interaction:

$$\exp(i2\pi / 2.67) \exp(-i2\pi / 4) = \exp(i2\pi / 8)$$

leading to



- dashed lines: 2.67 mm
- solid lines: 4 mm
- dots: 8 mm





Interaction of 2.67 mm and 4 mm modes

Possible Bad Scenario:

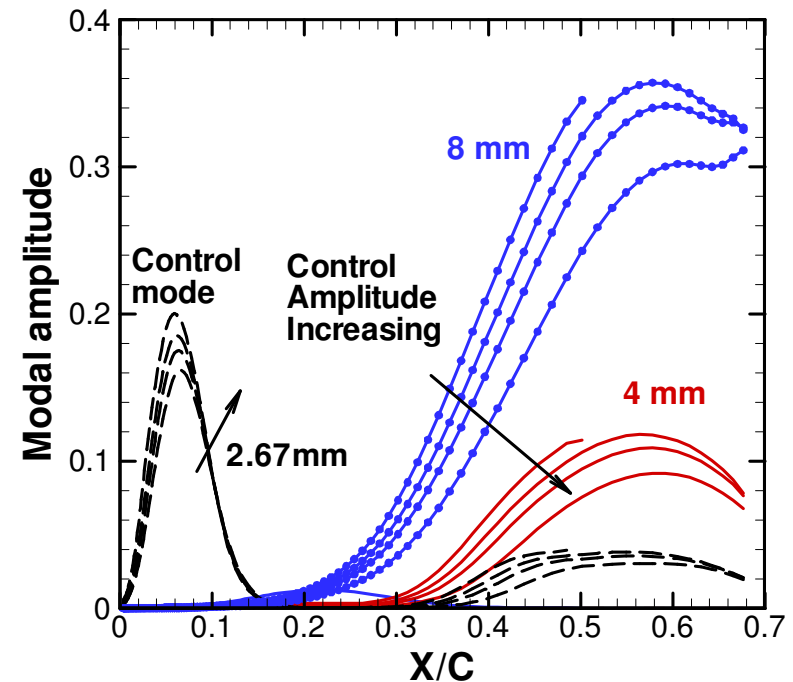
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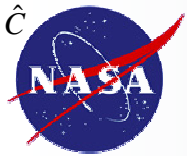
$$\exp(i2\pi / 2.67) \exp(-i2\pi / 4) = \exp(i2\pi / 8)$$

leading to



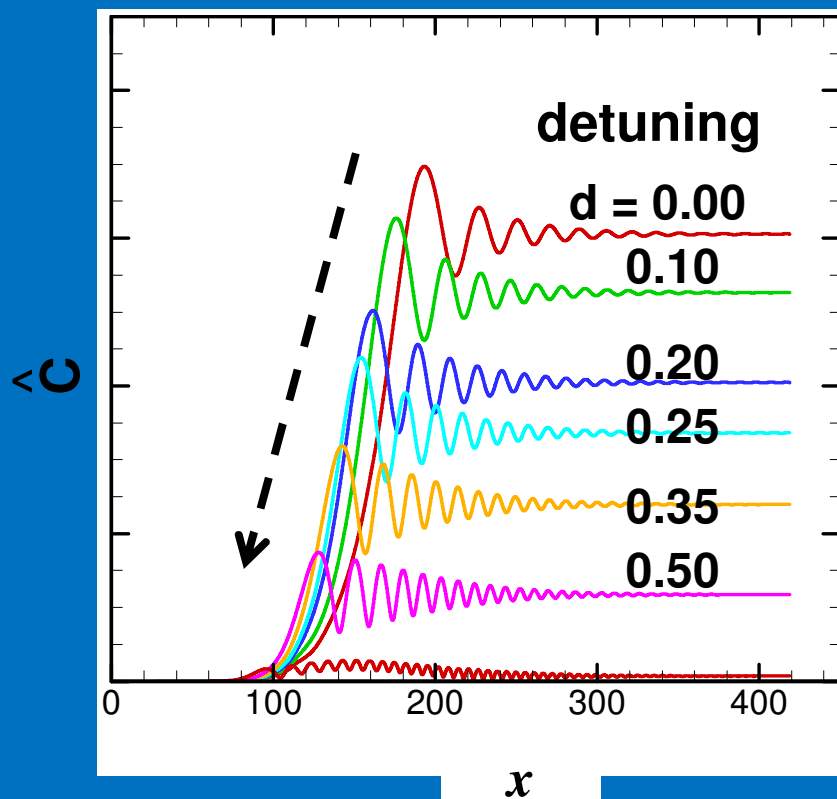
- dashed lines: 2.67 mm
- solid lines: 4 mm
- dots: 8 mm



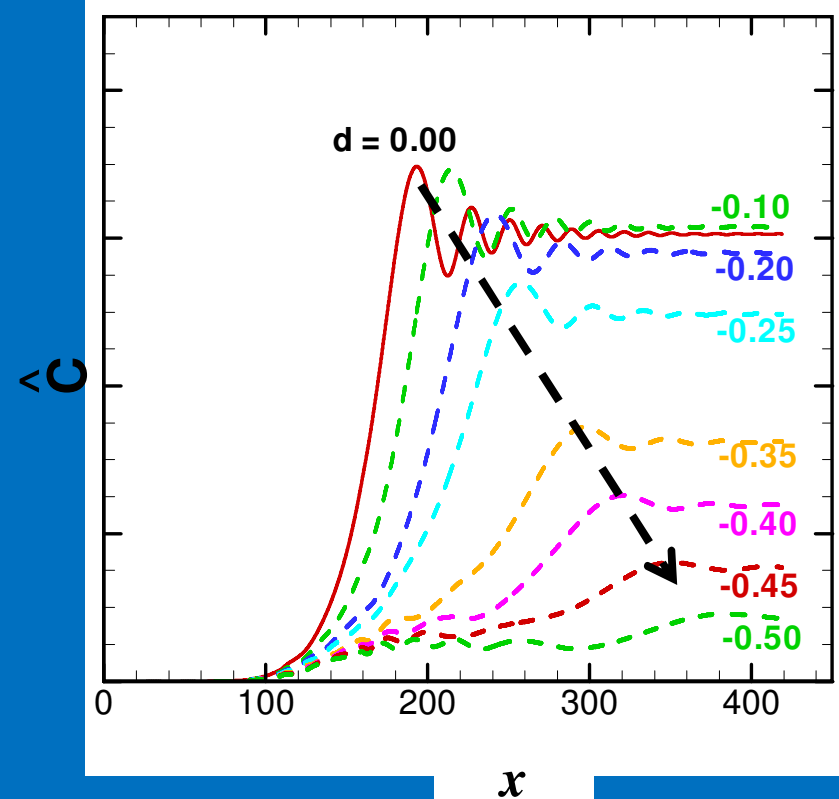


Distributed Receptivity due to Coherent Waviness Swept Hiemenz Flow ($Re = 400$, $\beta = 0.4$, $f = 0$)

$$\alpha_w > \alpha_{l.b.}$$



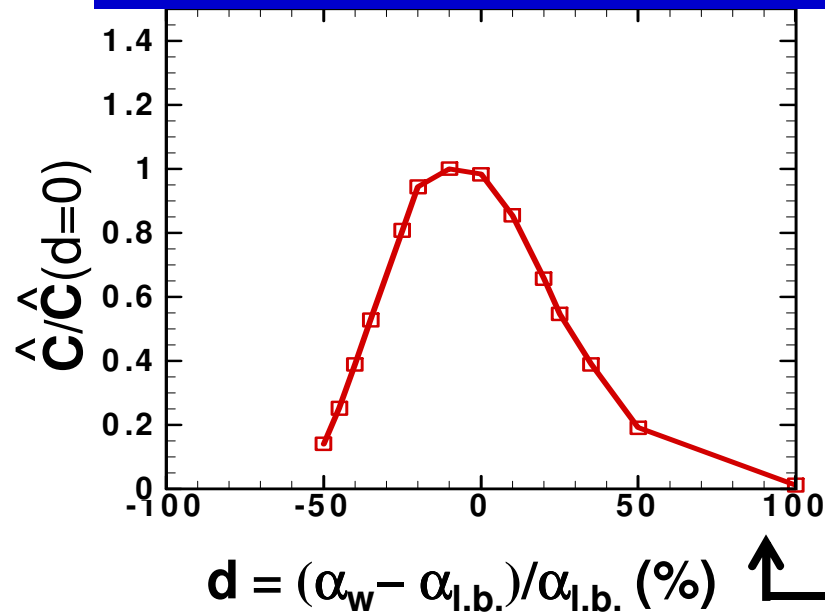
$$\alpha_w < \alpha_{l.b.}$$



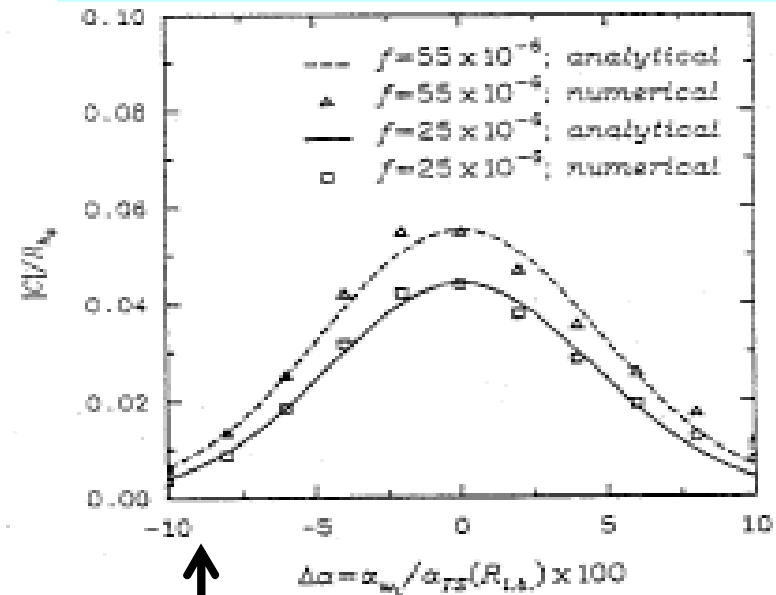


Distributed Receptivity due to Coherent Waviness

Swept Hiemenz Flow ($Re = 400$, $\beta = 0.4$, $f = 0$)



TS Receptivity Choudhari (1992)



- Crossflow modes sensitive to larger spectral bandwidth

- Consistent with theory: $\hat{C}/\hat{C}(d=0) = \text{Exp}[-(\Delta\alpha/d)^2]$

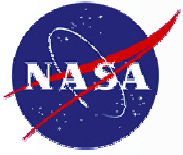
$$d^2 = |D_\alpha|^2 / \text{Im}(D_\alpha)$$

Desynchronization factor $D_\alpha = d\alpha/dx$ at $x = x_{l.b.}$

- Crossflow modes: $\text{Im}(D_\alpha) \ll \text{Re}(D_\alpha)$ (TS modes: $\text{Im}(D_\alpha) > \text{Re}(D_\alpha)$)

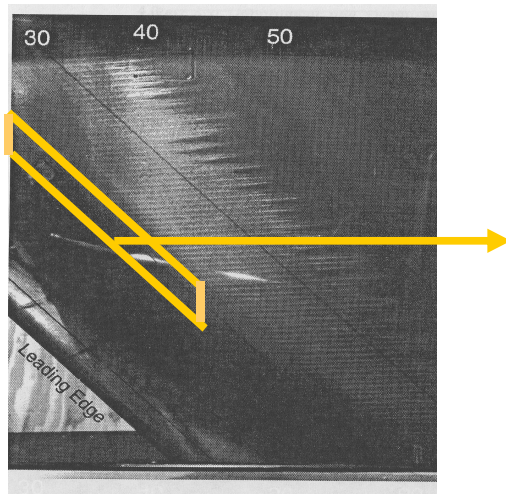


- Unique roughness database on NASA-Boeing HLFC wing
- Significance?
 - Characterization of disturbance environment (“input” to transition process) important aspect of “rational” transition prediction. Roughness database represents first cut at quantifying broadband roughness on realistic configurations
 - RMS height perturbation in range of crossflow wavelengths $\leq 1\mu$; nearly white spectrum
- Need larger, better database
- Need improved (stochastic) prediction techniques to exploit the database

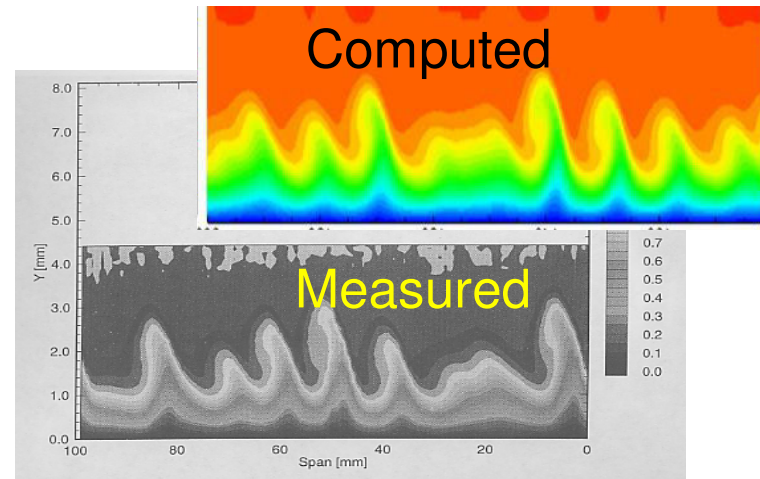


Spanwise Periodic Roughness Elements in a Swept-Wing B.L.

Stationary Crossflow Transition on NLF-0415(b) swept-airfoil
(Reibert et al. 1996, Carrillo et al., 1998)

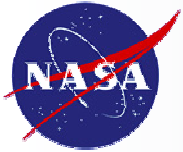


Flow-visualization on wing surface



Flow-visualization on swept wing
(Natural roughness -- Carrillo et al., 1998)

- **Crossflow development dominated by nonlinear effects**
- **Transition delayed via controlled roughness**



Roughness based Control of Crossflow Transition

- **Control mechanism transparent to (nominal) e^N methods**

=> higher fidelity transition prediction based on
3-stage approach for design of roughness
based LFC

I. Receptivity

+

II. Linear and nonlinear PSE

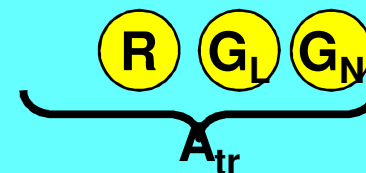
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III. Secondary instability



Hierarchical prediction approach

Primary Amplitude Criterion: F^*



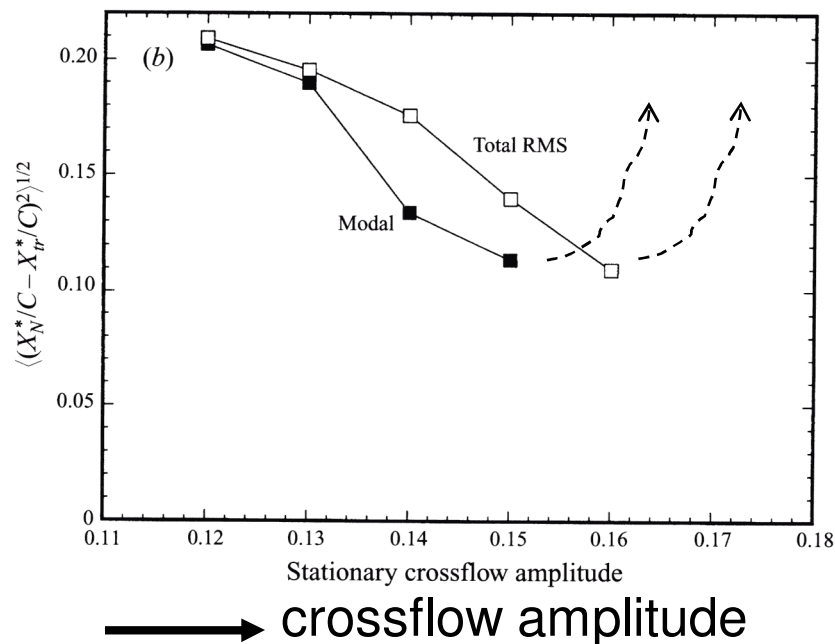
Secondary N-factor: $A_{primary}$



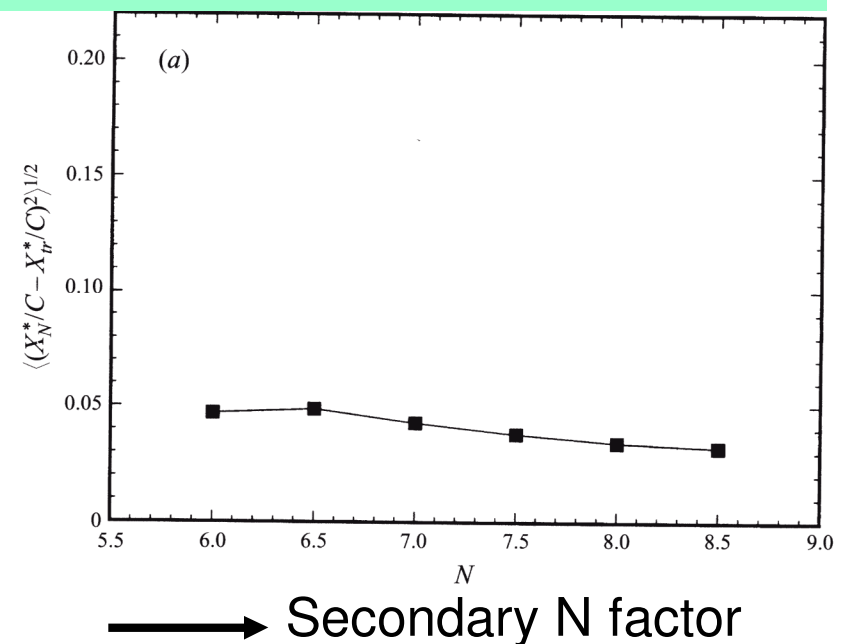


Transition correlation: Nonlinear Amplitude Criterion vs. Secondary N-factor correlation

Based on primary amplitude



Based on primary amplitude
+ secondary N factor



- Inclusion of secondary instability => relatively robust correlation (Secondary N-factor somewhat smaller at Re=3.2M, but impact on prediction small)
- Finite fetch for secondary evolution
=> $x_{tr} \neq$ onset of secondary instability
- Temporal & spatial predictions for secondary instability amplification



Broadband Initial Spectrum, $Re=2.4M$

Uncontrolled

Control via 8mm

