



Nonlinear Development and Secondary Instability of Traveling Crossflow Vortices

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Motivation

- Transition study is needed because a substantial drag reduction is required for future commercial jets
- Swept wing boundary layer susceptible to crossflow instability
- Crossflow instability leads to crossflow vortices (or equivalently waves)
 - Stationary, found in quite environments, due to surface roughness
 - Traveling, found when turbulence level is sufficiently high
- Large amplitude crossflow vortices lead to secondary instability
- Secondary Instability of crossflow vortices leads to breakdown
- Breakdown could happen via interaction of stationary and traveling crossflow vortices (see e.g. Malik et al 1994)



Objectives

- **Investigate secondary instability of traveling crossflow vortices in isolation from stationary vortices.**
- **What initial amplitude of traveling crossflow vortex is needed to trigger strong secondary instability?**
- **How does this threshold amplitude compare with that of stationary crossflow vortex?**



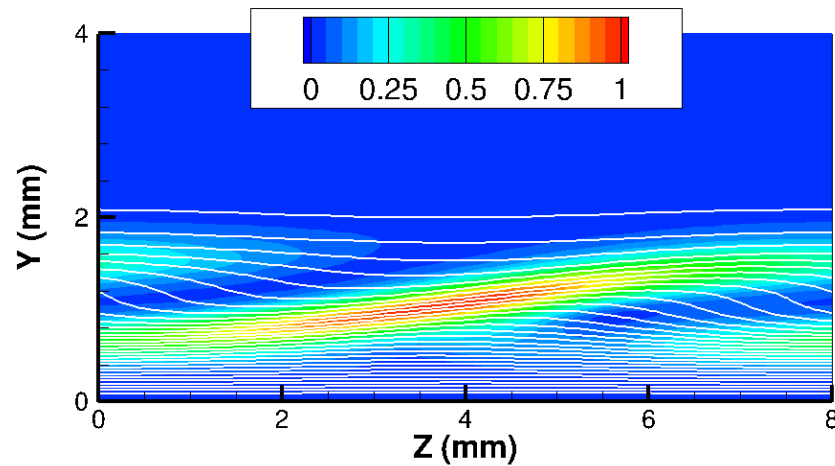
Flow Configuration

- Swept wing with laminar flow airfoil TAMU-003T-75(v.90)
 - Belisle et al AIAAPaper 2010-4381
 - Sweep angle: 30 degrees
 - Realistic flight conditions
 - Mach: 0.75
 - AoA: 0 degrees
 - Re based on chord length: 17 million
 - Altitude: 40,000 ft (12200 m)
 - Freestream temperature: 390 R (217 K)
- Off-design AoA of -1 degree used in present study to enhance crossflow instability

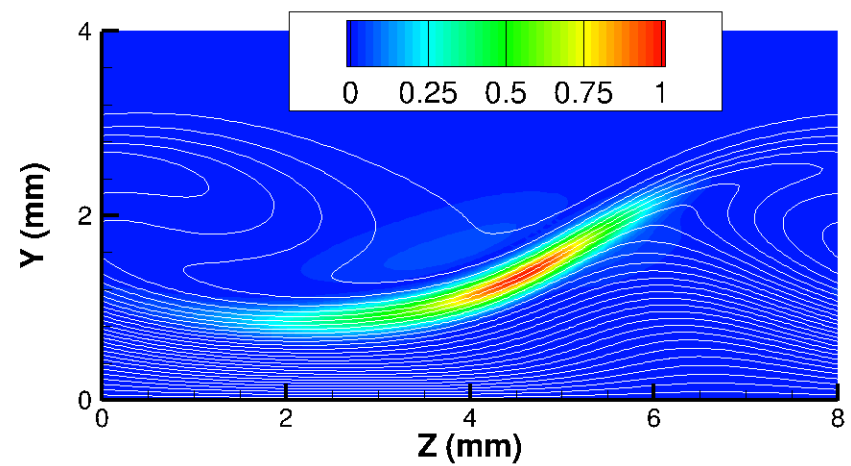


Finite Amplitude Crossflow Vortex and Secondary Instability

Traveling

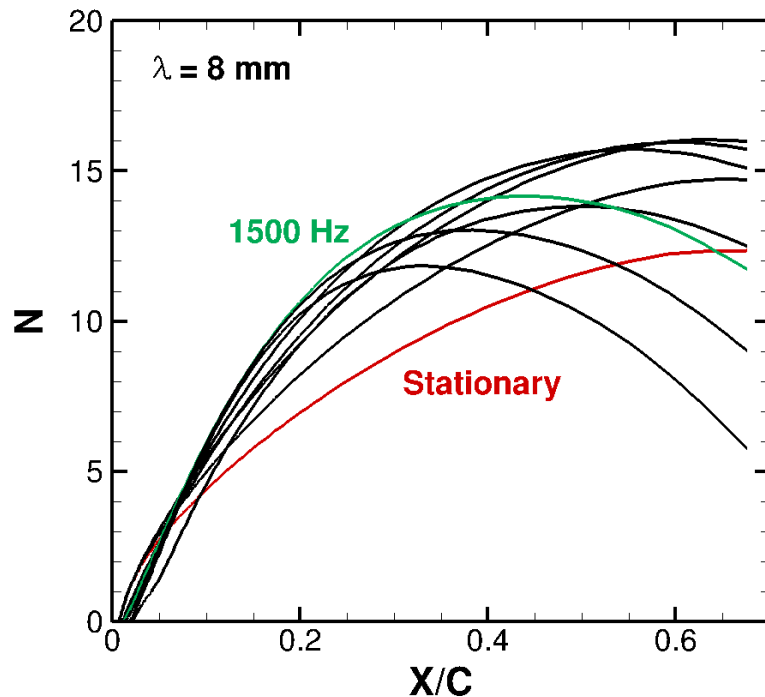


Stationary

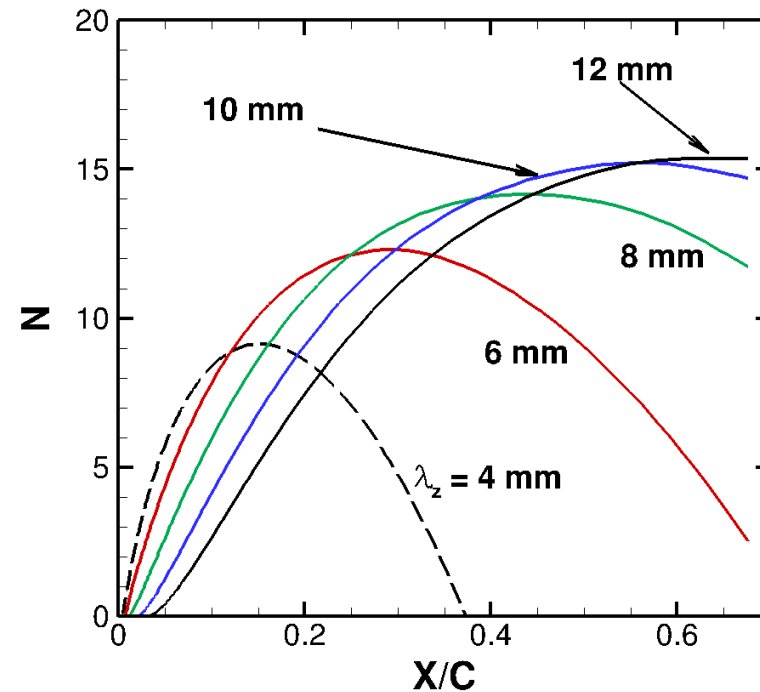




Linear Traveling Crossflow Instability



$f = 0 \sim 2,250$ Hz, $\Delta f = 250$ Hz
 $\lambda_z = 8$ mm



$f = 1,500$ Hz

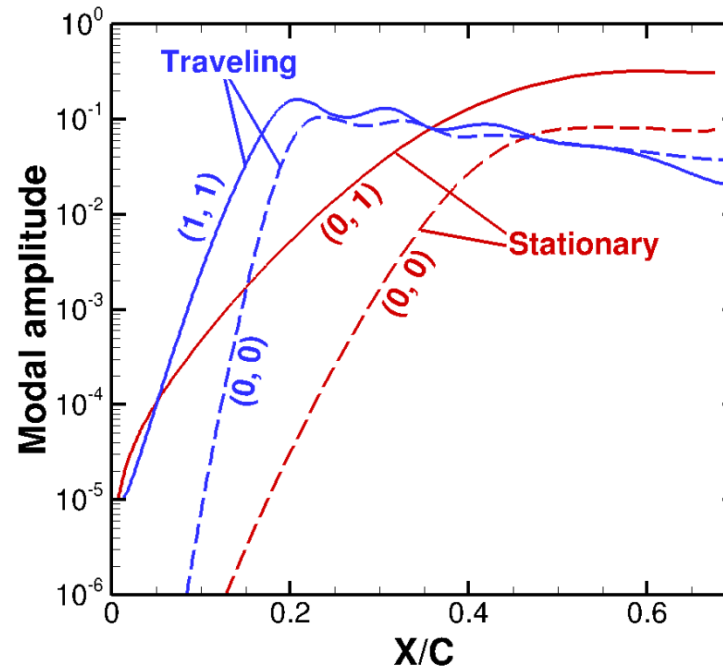
Peak frequency: 1,500 Hz

Focus: 8 mm for comparison with well-studied for stationary case



Nonlinear Evolution of Crossflow Vortices

(Choudhari et al., 2013)



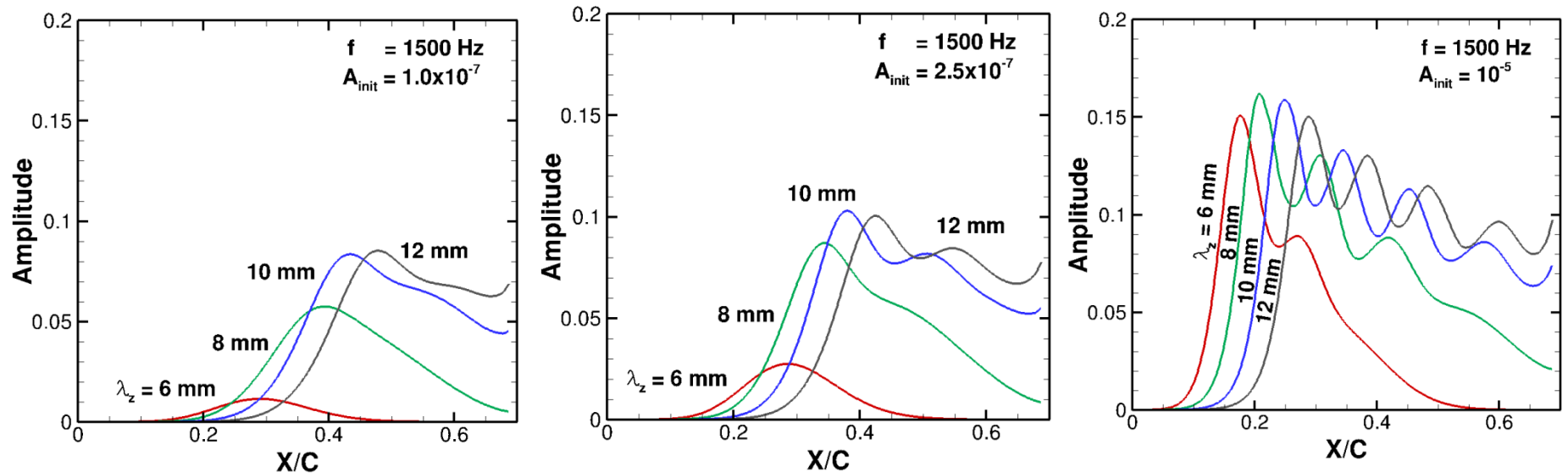
$f = 0$ and 1,500 Hz, $\lambda_z = 8$ mm, $A_{init} = 1e-5$

Comparison with stationary

- Traveling crossflow vortex saturates at half the amplitude of stationary
- Mean flow correction reach comparable amplitudes for both
- Similar results obtained for different configurations by Malik et al 2013, Wassermann & Kloker 2003 $\longrightarrow$ generality of results.



Nonlinear Evolution: Initial Amplitude Effect

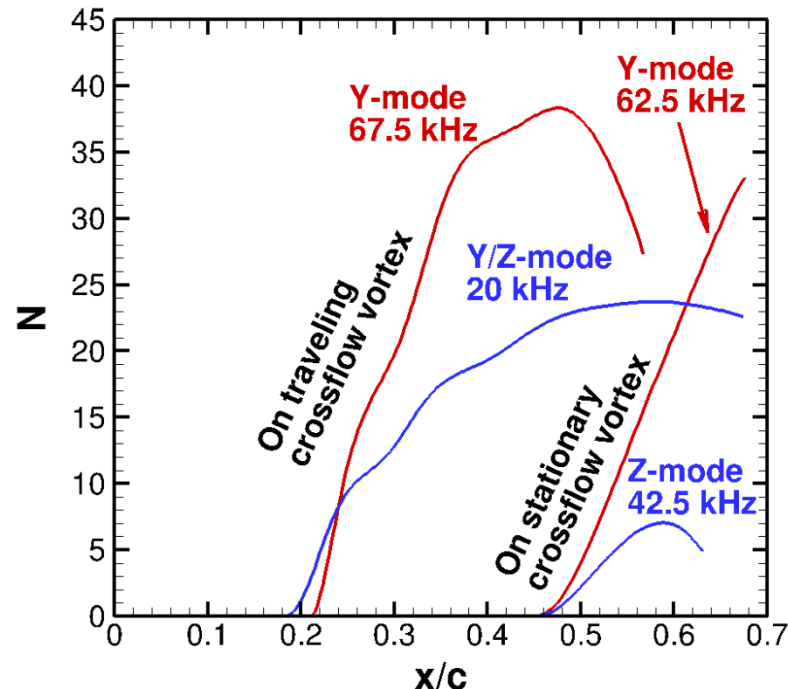


$f = 1,500$ Hz

- Higher A_{init} $\longrightarrow$ higher maximum amplitude at smaller X/C
- Higher A_{init} $\longrightarrow$ shorter wave reach overall maximum amplitude
- Oscillatory behavior at sufficiently high A_{init}



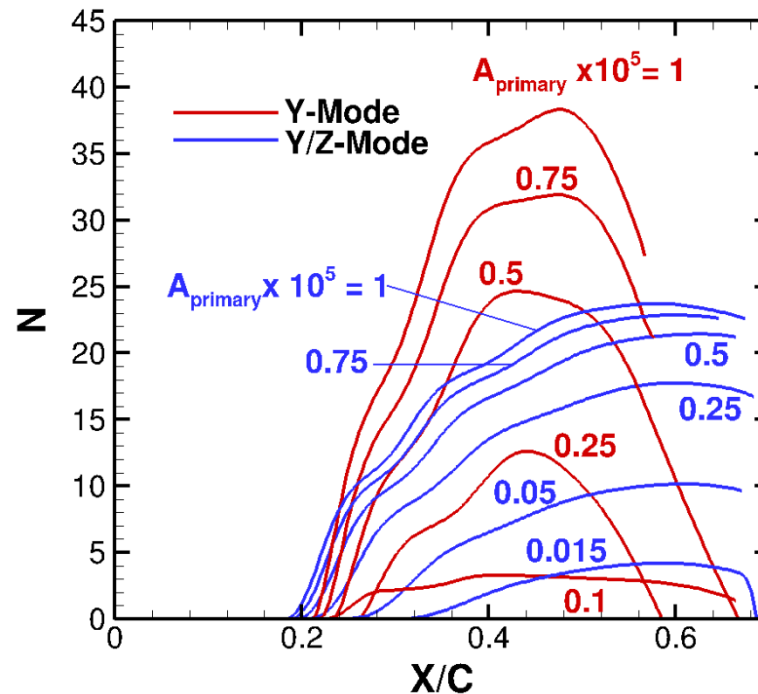
Secondary Instability on Crossflow Vortices



- Primary waves (crossflow vortices) $A_{init} = 1e-5$
- Spanwise wavelength: 8 mm
- Peak N-factor modes shown
- Y modes dominate
- Large N-factors for both cases



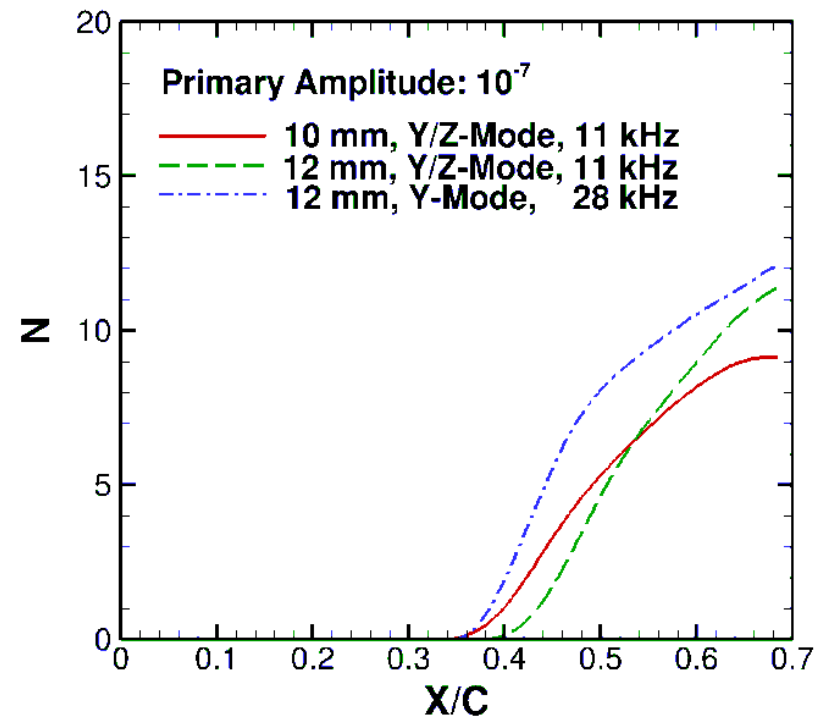
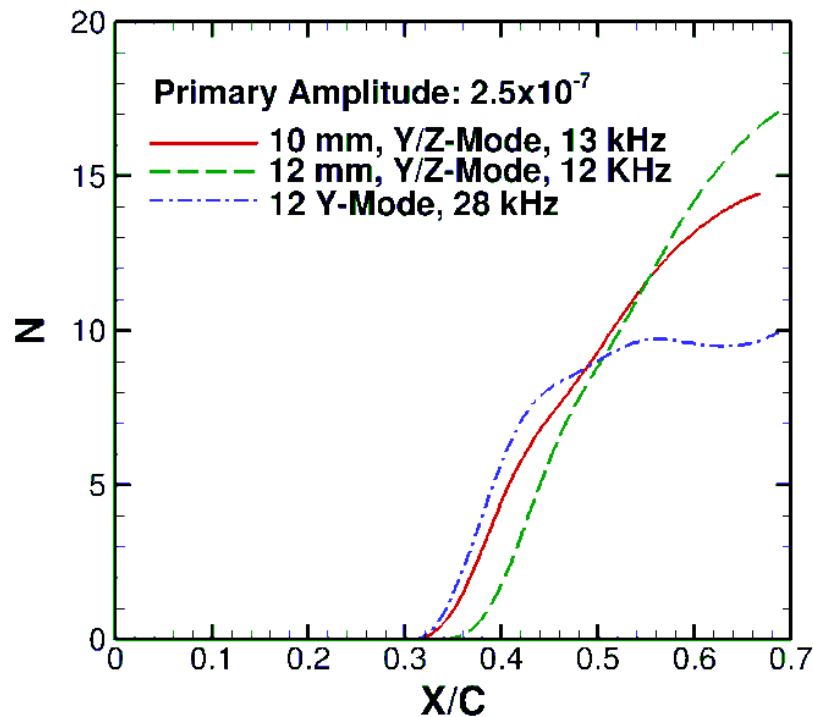
Secondary N-Factors: Effect of Initial Crossflow Vortex Amplitude



- Spanwise wavelength: 8 mm
- Frequency: 1,500 Hz
- Y mode dominates for large primary A_{init}
- Y/Z mode dominates for small primary A_{init}
- For Y mode, $N < 3.3$ when $A_{\text{init}} < 0.100\text{e-}5$
- For Y/Z mode, $N < 4.2$ when $A_{\text{init}} < 0.015\text{e-}5$



Secondary Instability of Crossflow Vortices with Longer Spanwise Wavelengths



- Significant growth
- Re-emergence of Y-mode
- Reduction of primary amplitude pushes instability downstream



Primary A_{init} Required for $N_{secondary} = 10$

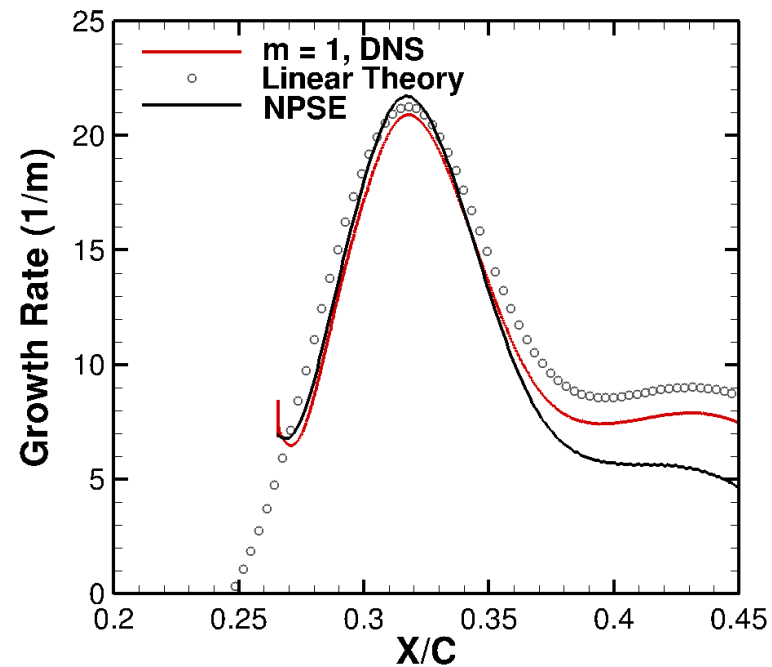
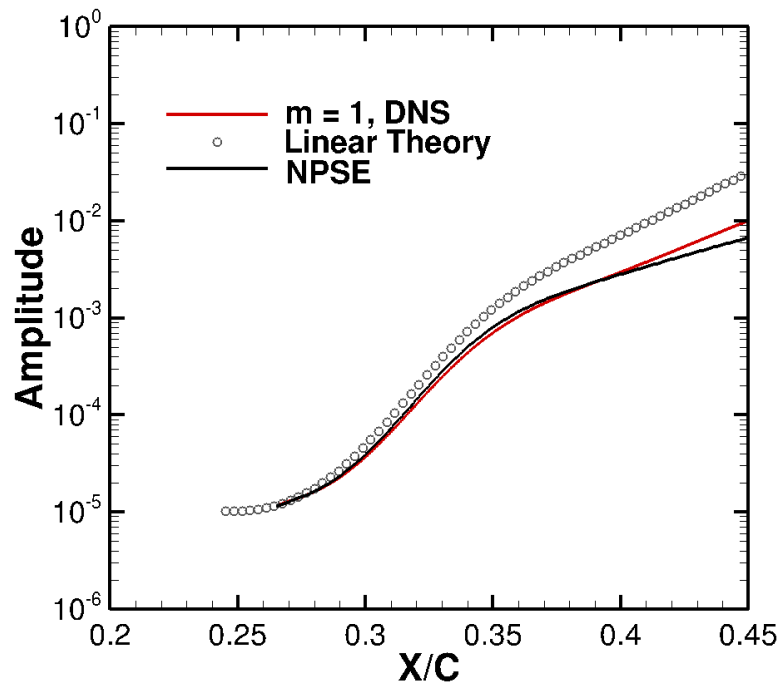
Primary Wave Type	Primary A_{init}	Sec. N at $X/C = 0.54$
Stationary	1.00e-5	10
Traveling (1,500 Hz)	5.00e-7	9.7

Initial amplitude required of the traveling crossflow vortex for secondary instability to reach an N-factor of 10 at the same chordwise location as that of a stationary vortex is more than one order of magnitude lower.



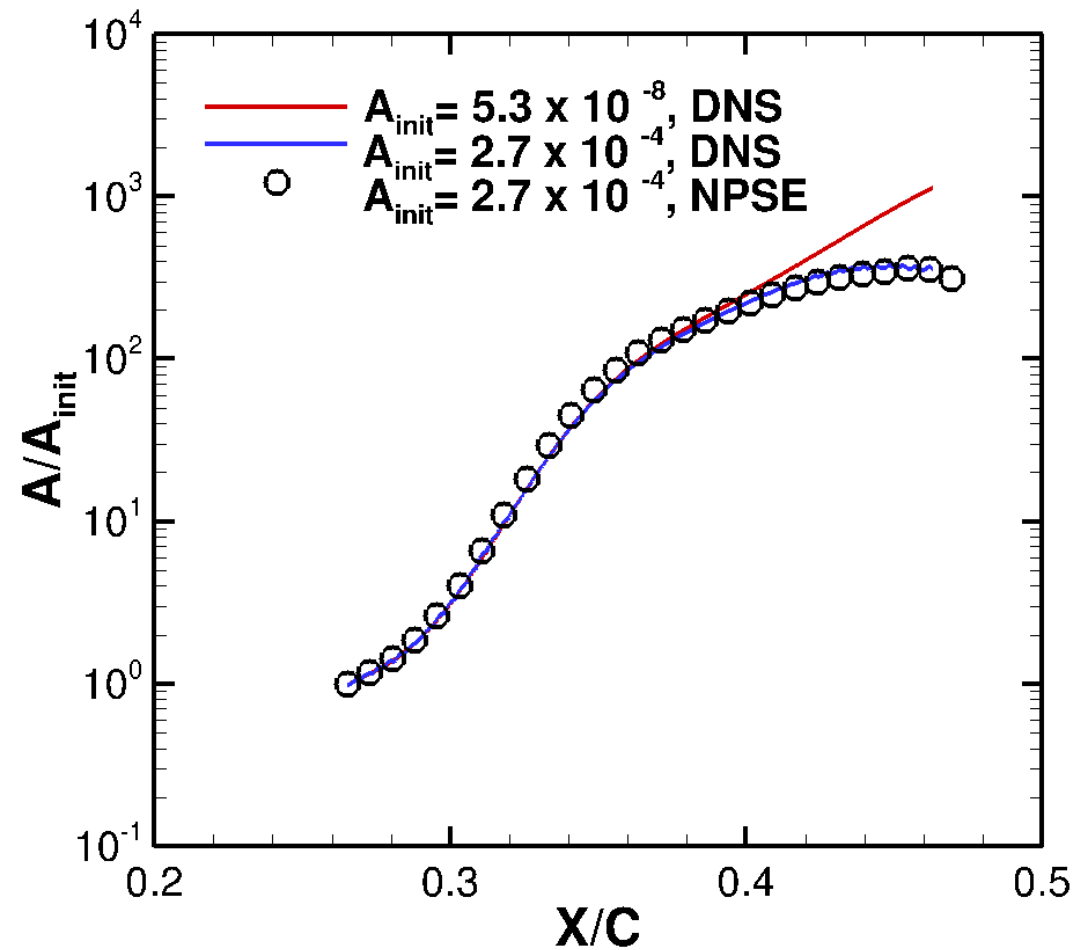
Comparison: LSIT, NPSE and DNS

- Primary $f = 1,500 \text{ Hz}$, $A_{\text{init}} = 5e-7$
- Secondary (Y/Z mode) $f = 13.5 \text{ kHz}$, $A_{\text{init}} = 1e-5$



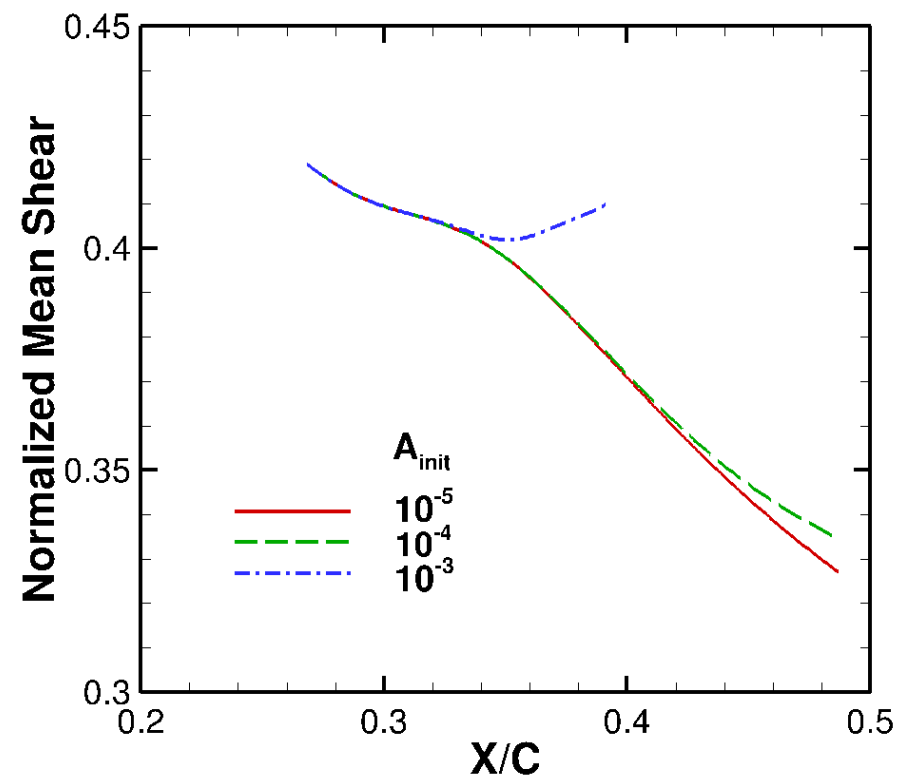
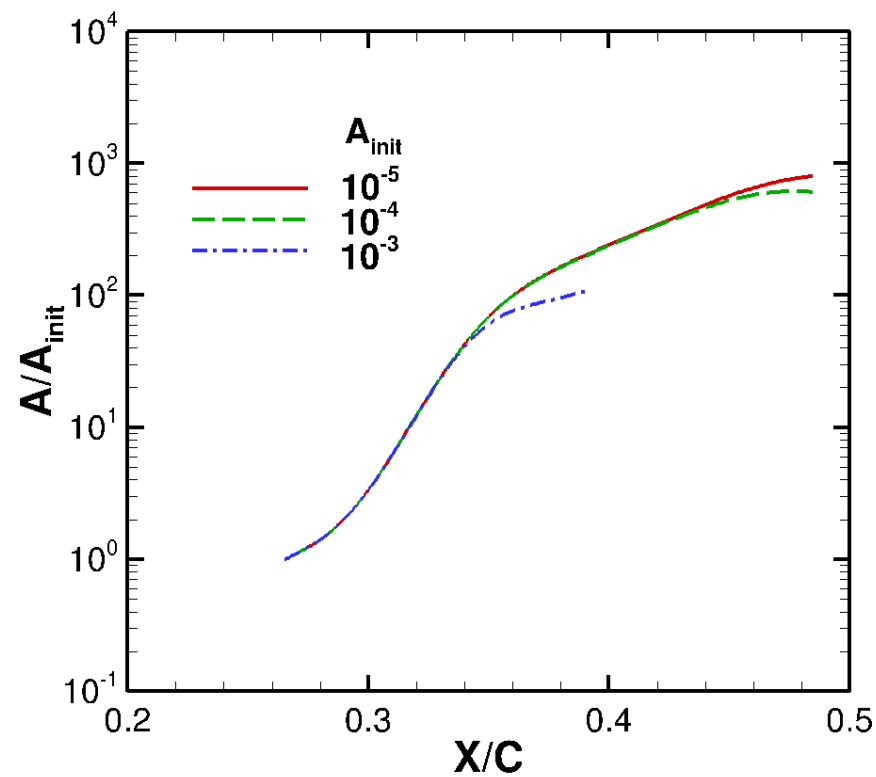


Comparison: LSIT, NPSE and DNS





Nonlinear Development of Secondary Instability





Summary

- Carried out parametric study of secondary instability on traveling crossflow vortices
- Strong oscillatory behavior after saturation
- Even with lower saturation amplitude compared with stationary counterpart, traveling crossflow vortices support secondary instability in much the same way as stationary and resulting secondary instability is at least as strong.



Summary (continued)

- For 8mm, 1,500 Hz primary wave
 - Y mode dominates when primary amplitude is large
 - Y/Z mode dominates when primary amplitude is small
 - When $A_{init} < 1.5e-7$, both become insignificant
- At lower primary wave initial amplitude, dominant primary wave shift to modes with larger spanwise wavelengths and region of secondary instability shift downstream
 - Lower primary A_{init} implies smaller freestream turbulence and breakdown via stationary waves become important