EFFECTS OF ELEVATED FREE-STREAM TURBULENCE ON ACTIVE CONTROL OF A SEPARATION BUBBLE

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The Effects of elevated free-stream turbulence (FST) on the natural and periodically excited separation bubbles were studied experimentally, due to the relevance of this flow to low-pressure turbine blades at low Reynolds numbers.

A bubble was formed at the leading edge of a flat plate and the FST level was altered by placing a grid across the flow at different locations upstream of the plate. The mixing across the separated shear-layer, forming the free boundary of the bubble, increased due to the elevated FST and due to nominally two-dimensional periodic excitation, both flattening and shortening the bubble. Periodic excitation at frequencies that were at least an order of magnitude lower than those associated with the initial shear-layer instability, were very effective at low FST, because the amplitudes of the excitation frequency and its harmonic were amplified over the bubble.

High frequency excitation ($F^+ \approx 3$, based on the length of the baseline low FST bubble) had a major effect close to the separation location, while farther downstream the excited fluctuations rapidly decayed in the reattachment region. Low frequency excitation, that generated waves comparable to the length of the unperturbed bubble ($F^+ \approx 1$) were less effective and their magnitude decayed at a slower rate downstream of reattachment.

An increase in the level of the FST reduced the net effect of the periodic excitation on the mixing enhancement and subsequent reattachment process, probably due to a destructive interference between the nominally 2D excitation and the random (in space and time) FST, reducing the spanwise coherence and therefore the effectiveness of the current control strategy. However, even at the reduced effectiveness of 2D periodic excitation at elevated FST, it accelerated the reattachment process and the recovery rate of the reattached boundary layer, enhancing the boundary layer resistance to repeat separation and reducing its momentum loss further downstream.

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Effects of
Elevated Free-stream Turbulence on
Active Control of a
Transitional Separation Bubble

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Outline

- Scope and Motivation
- Experiment
- Free-Stream Turbulence
- FST Effect on Bubble
- AFC Effect on Bubble at Various FST
- Conclusions

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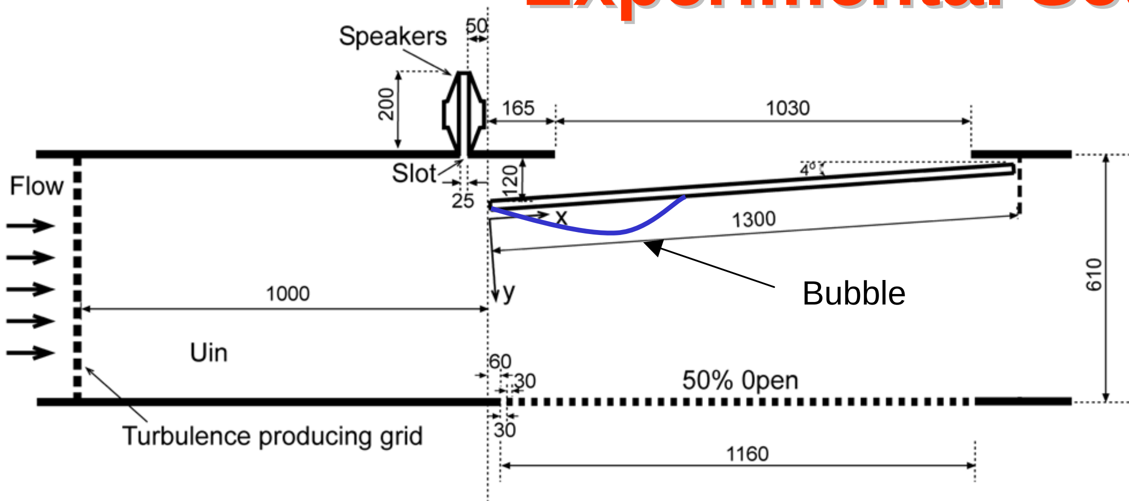
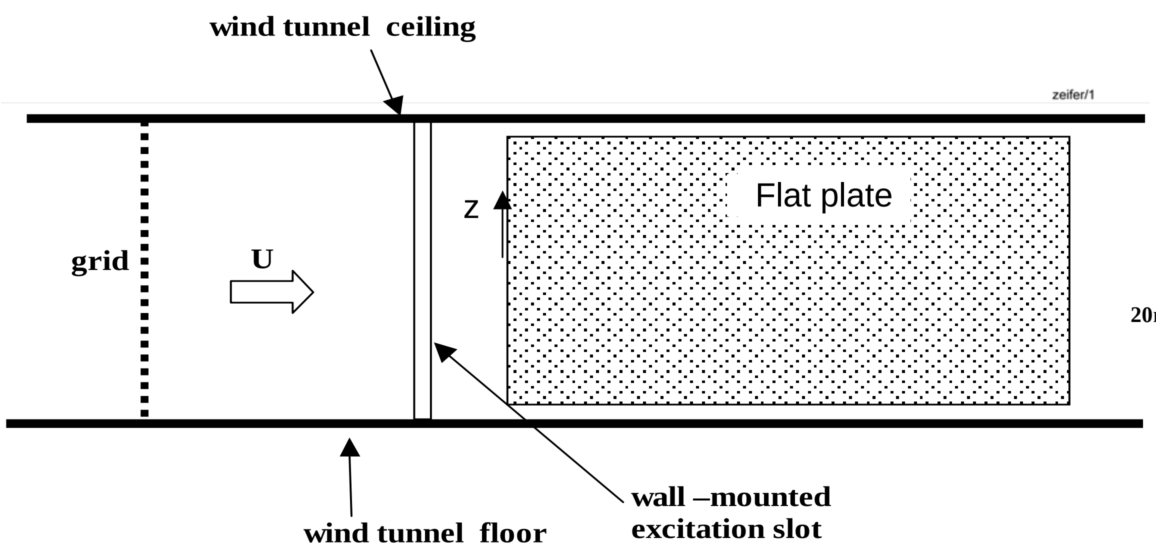
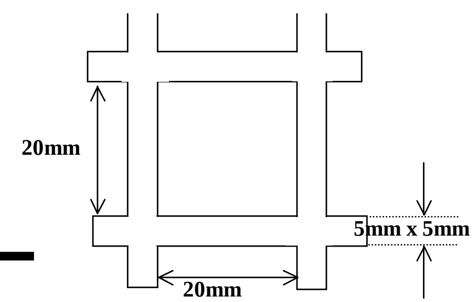
Motivation

- Laminar, transitional and turbulent Separation bubbles appear at low Re and where surface discontinuity
- Degrade performance and induce unsteadiness
- Elevated FST is known to shrink bubbles
  (Hillier & Cherry, '81, Nakamura & Ozono, '87, Saathoff et al, '97)
- Active Flow Control (AFC) using 2D periodic excitation is known to shrink bubbles
  (Sigordson, '85, '95, Kiya et al, '93)
- Elevated Free Stream Turbulence (FST) is known to "overshadow" natural 2D "Structures" and lead to 3D flows
  (Chandrsuda et al, '77, Cherry et al, '84)
- The efficacy of AFC with Elevated FST have not been studied yet in detail (…to the best of our knowledge)

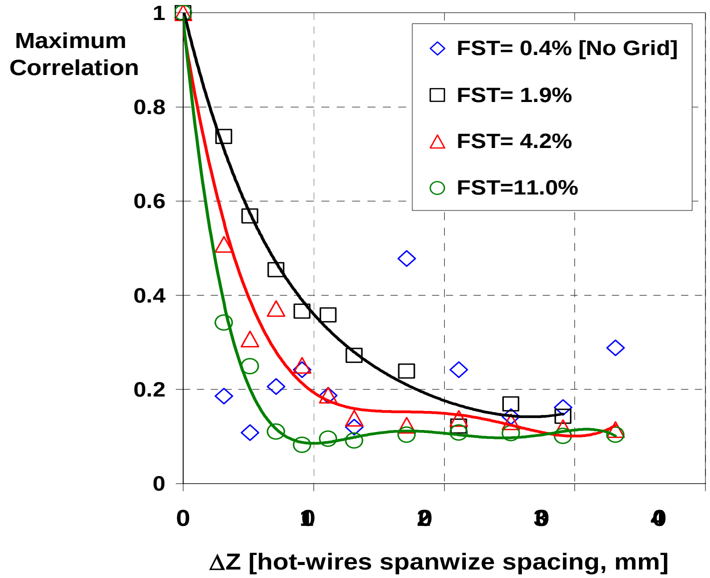
Experimental Set-up

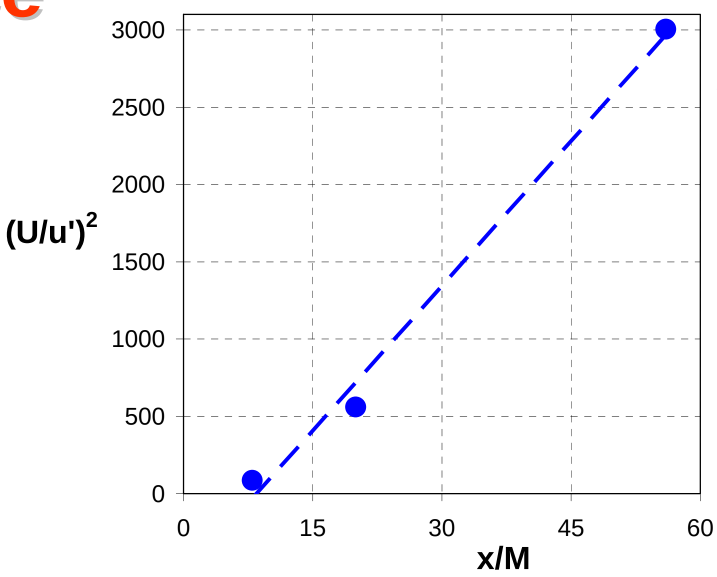




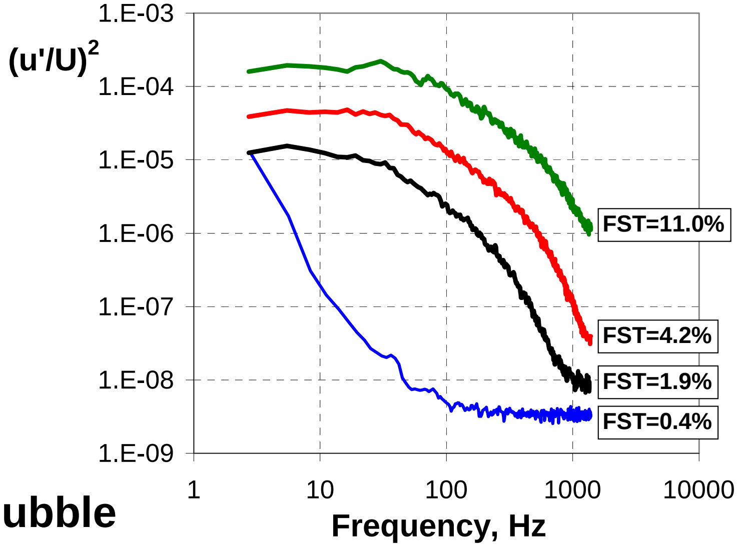


Free-stream Turbulence



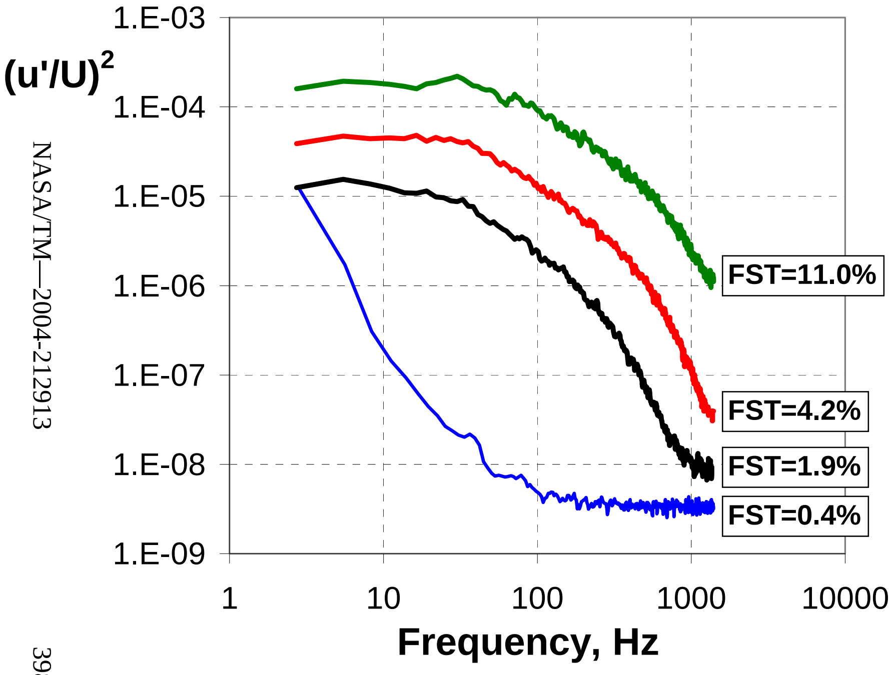


Grid x	Tu %	Lx cm	Lz cm
No	0.4	Large	Large
-150cm	1.9	2.0	1.4
-60cm	4.2	1.2	0.7
-30cm	11.0	0.8	0.4

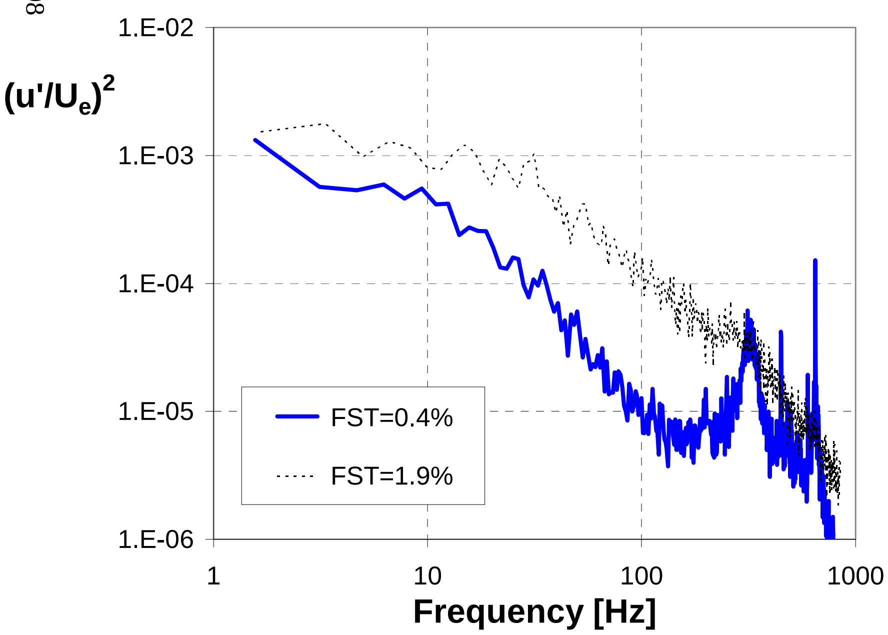


FST decreases and Scales increase over bubble

FST Effects on Shear layer Spectra



Free-Stream



Separated shear Layer

(note smaller Freq. Range)

Ue – local free stream velocity

X=10mm

Initial KH instability ~700Hz

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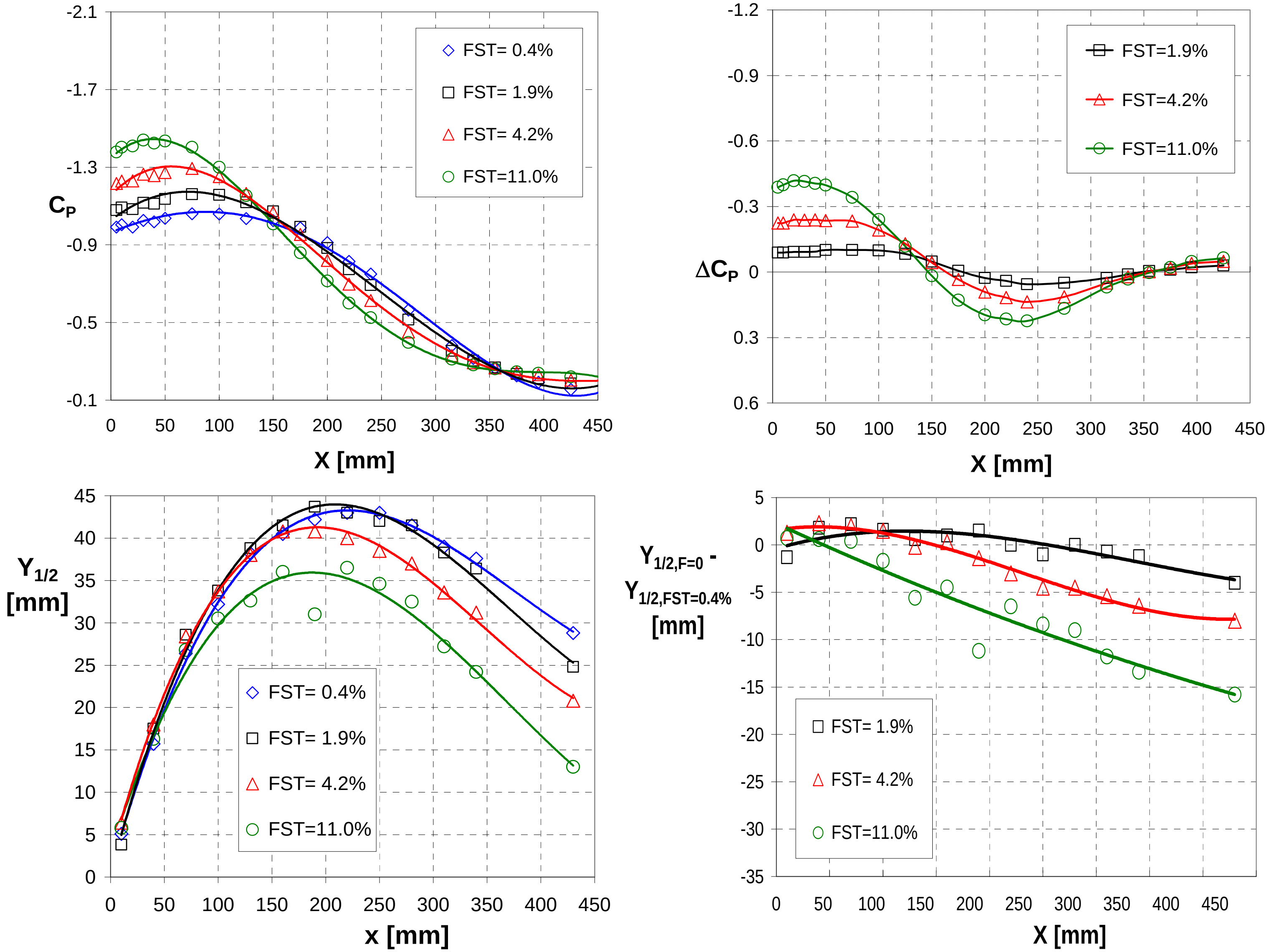
FST Effects on Unforced Bubble



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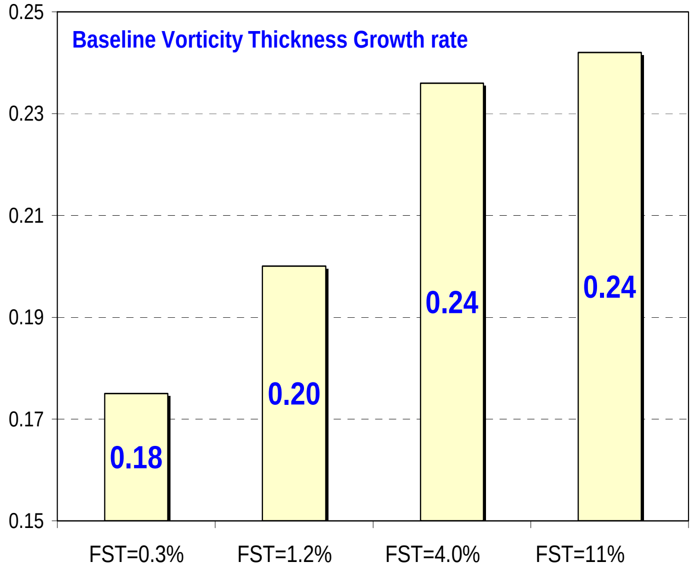
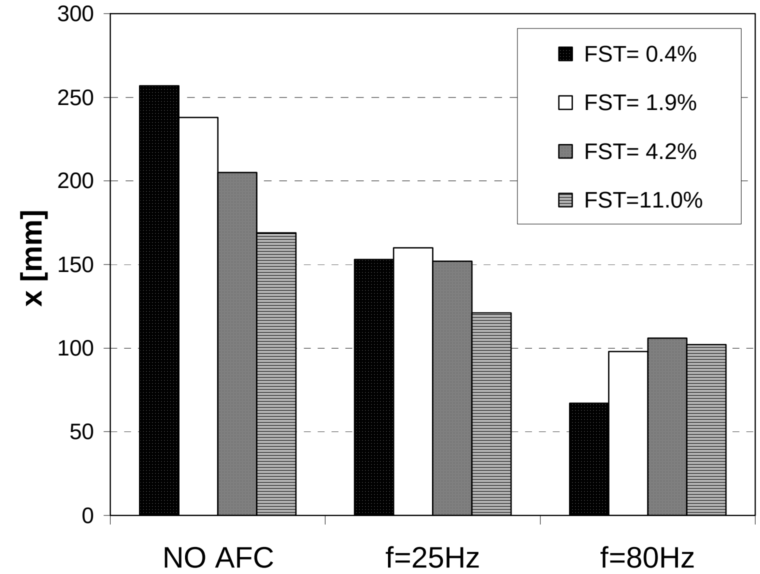
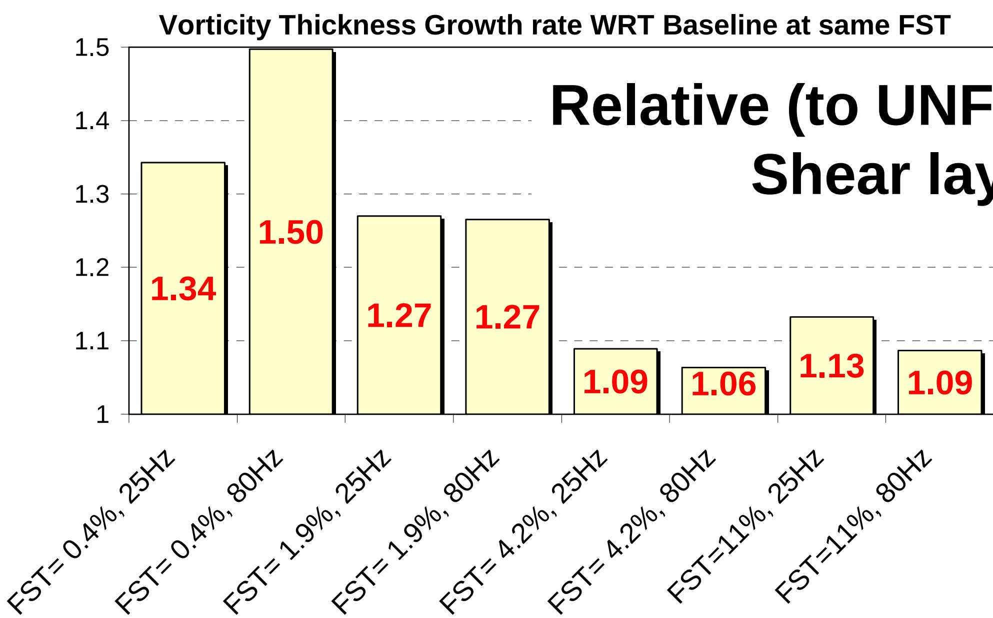
FST and AFC Effects on Reattachment

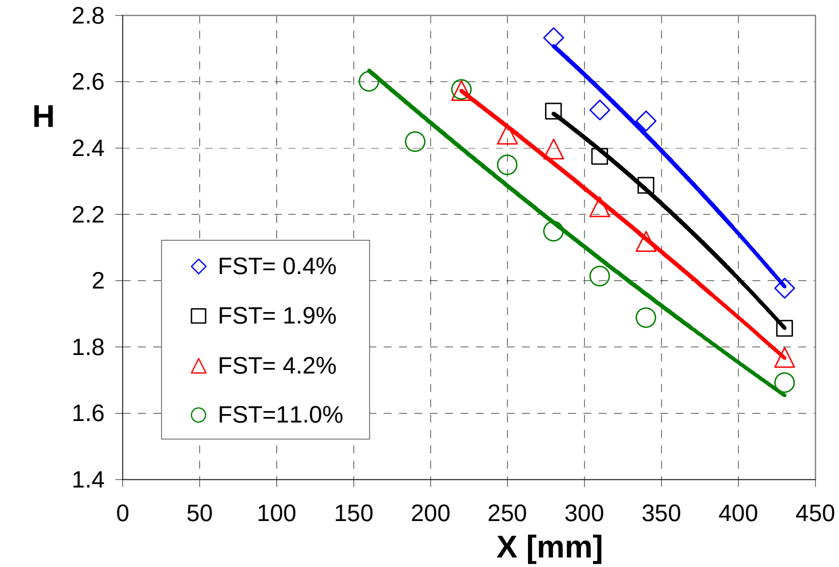


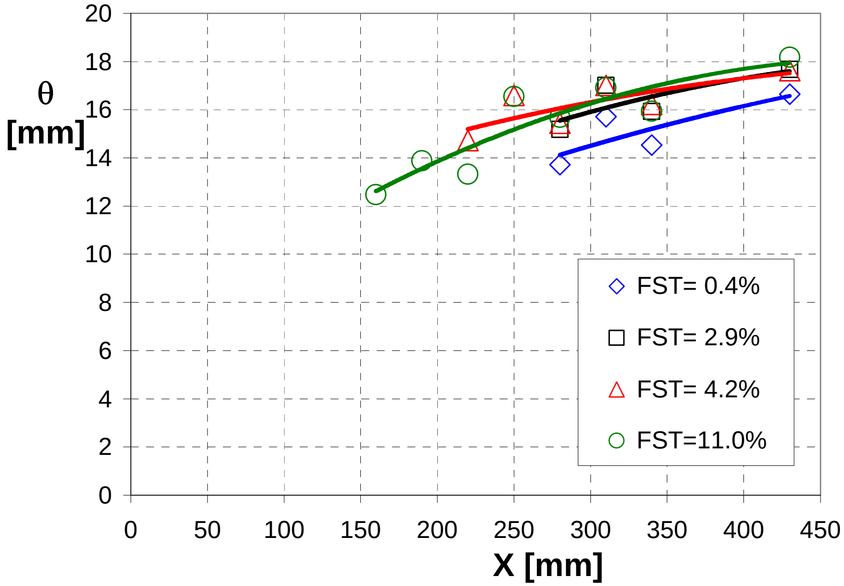


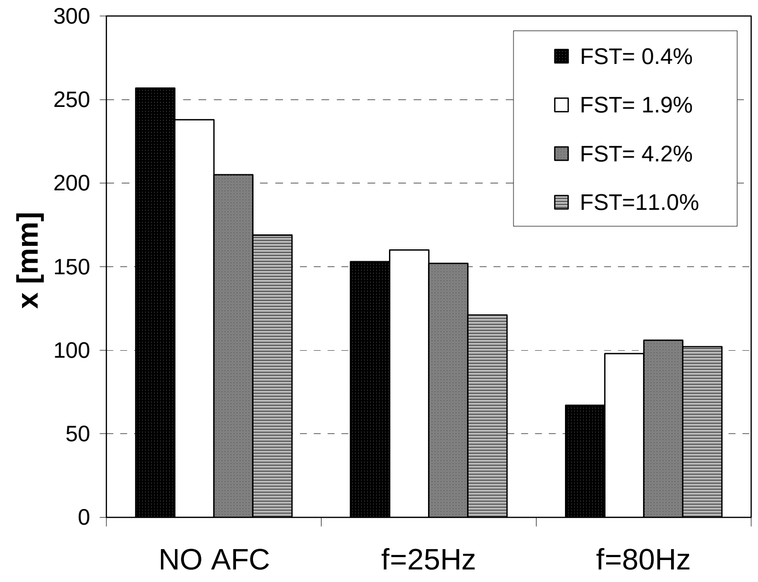


Relative (to UNFORCED, same FST data) Shear layer spreading rate

Unforced BL Recovery





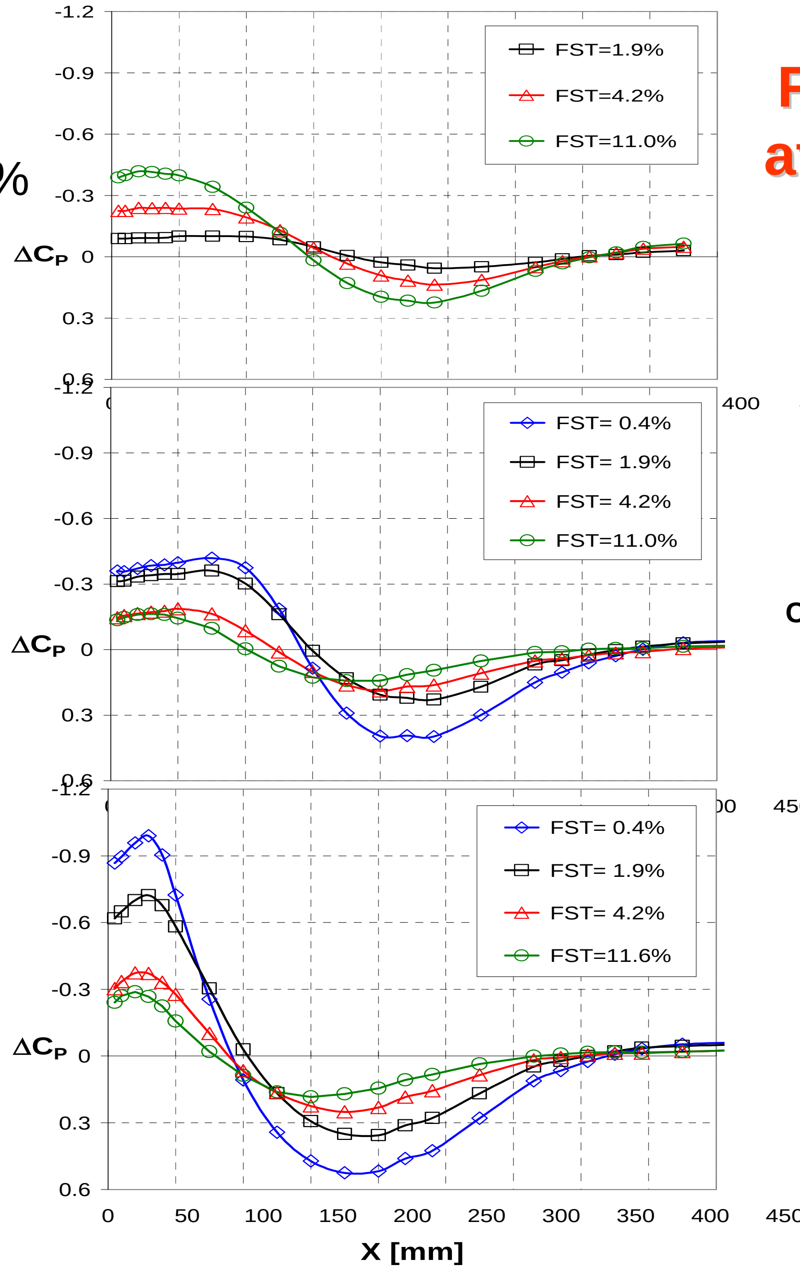


FST Effect on ΔC_p at Fixed Frequency

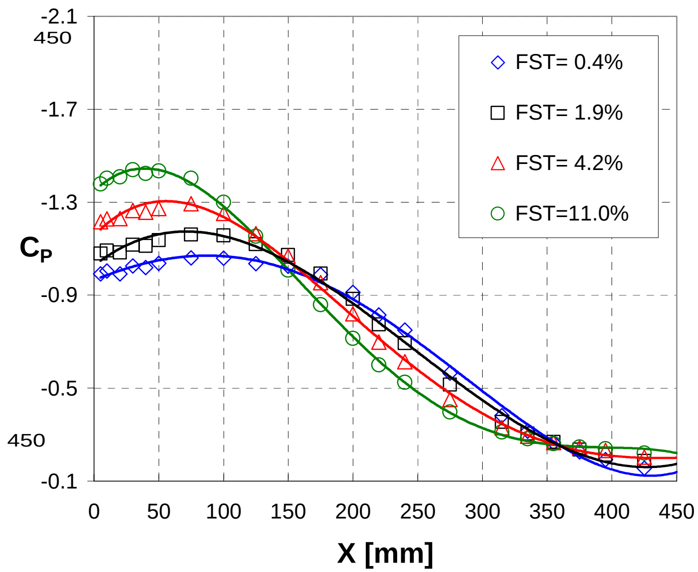
ΔC_p ref.
FST=0.4%
F=0

ΔC_p
F=25Hz

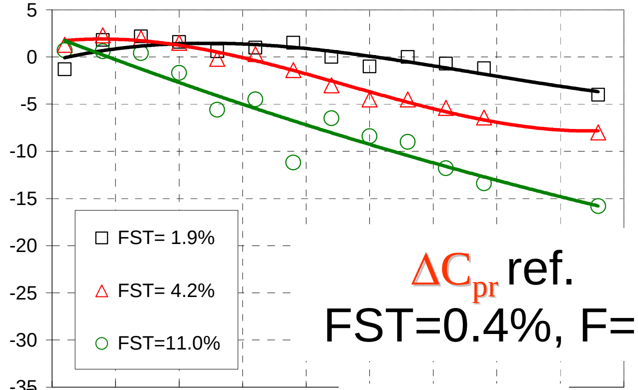
ΔC_p
F=80 Hz



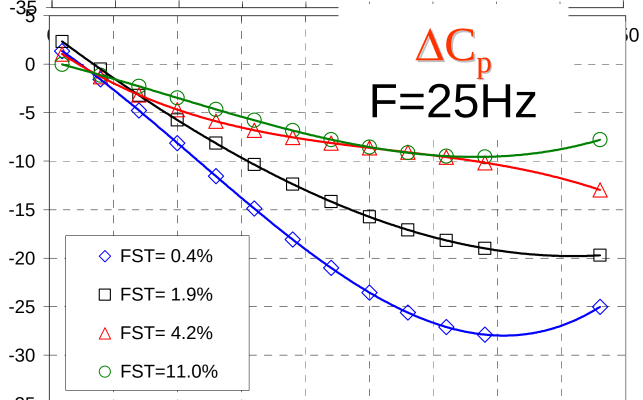
Unforced Pressures



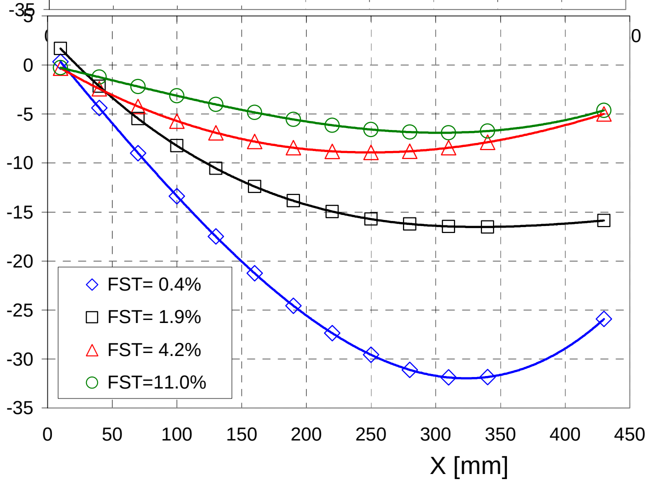
FST Effect on $Y_{1/2}$ at Fixed Frequency



ΔC_{pr} ref.
FST=0.4%, F=0

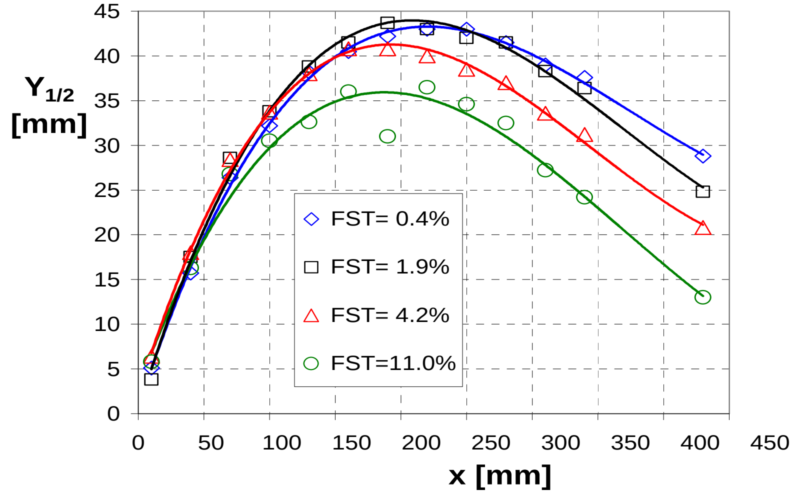


ΔC_p
F=25Hz



ΔC_p
F=80 Hz

Unforced, $Y_{1/2}$



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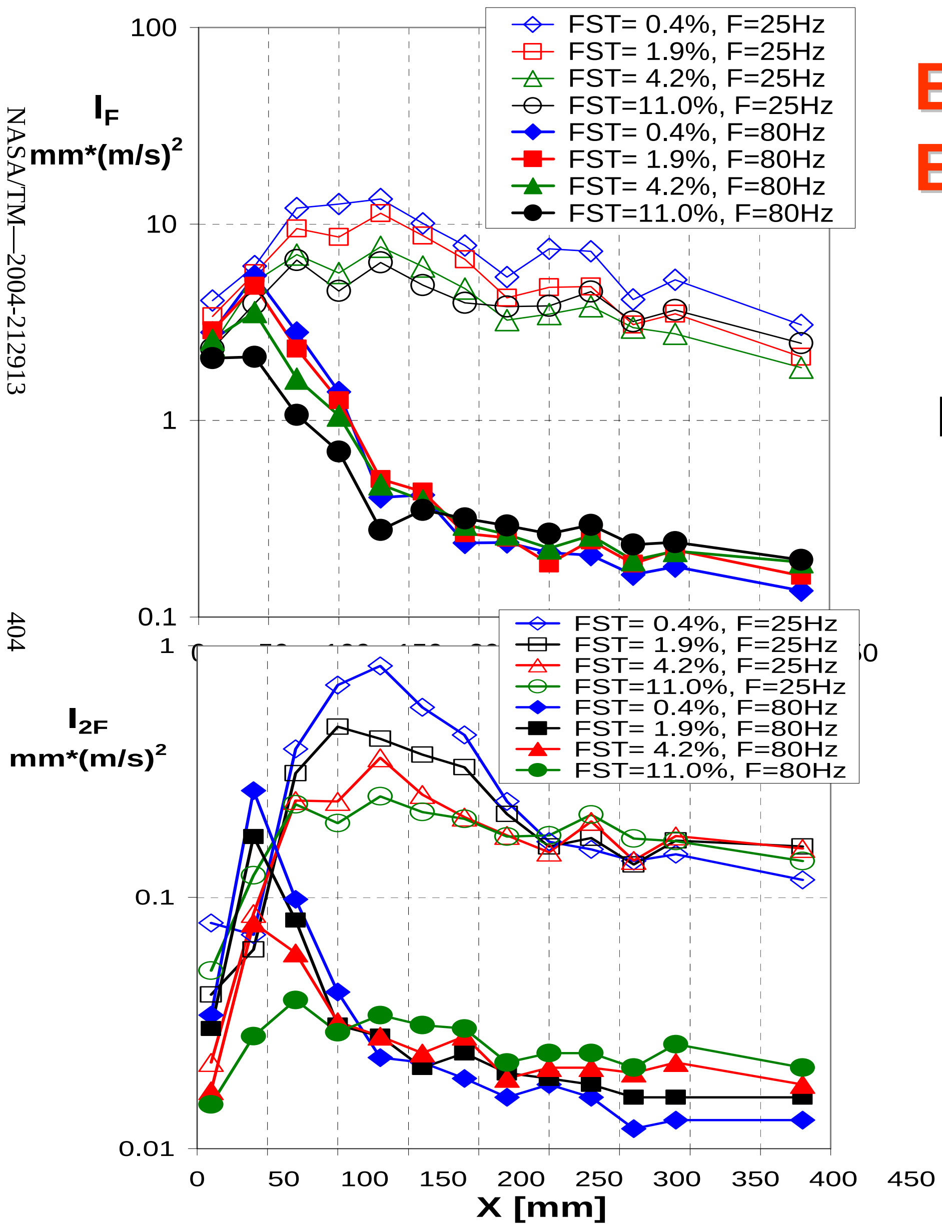
Evolution of Excitation Momentum



Fundamental

$$I_F \equiv \int_{y=0}^{\delta} \left(u'_F\right)^2 dy$$

Harmonic

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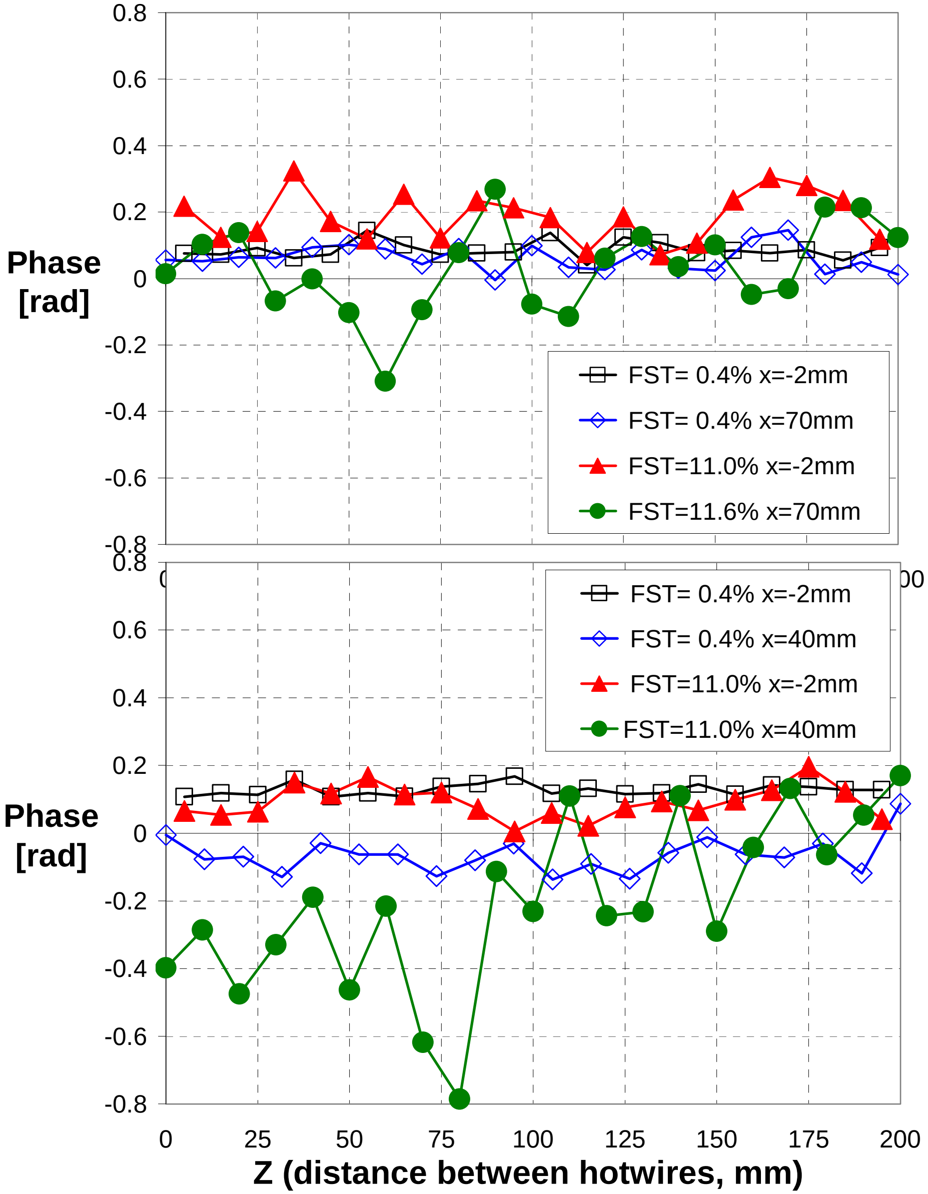
Spanwise Coherence of Excitation at x of Peak magnitude



F=25 Hz

F=80 Hz

FST Effects on AFC of Separation Bubble

Conclusions

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- Elevated F.S.T. Reduces Bubble size and the potential for improvement by AFC
- AFC using $F^{+} \approx 1$-3 effective for reducing bubble size at Elevated F.S.T.
- These F^{+} are an order of magnitude lower than the initial separated shear-layer instability frequency, AFC not transition related
- The amplitudes of the fundamental excitation frequency and its harmonic were significantly amplified over the bubble
- Destructive interaction between the Nominally 2D Excitation and Random FST distorts the Excitation Spanwise Coherence – Reducing the Effectiveness of AFC
- Effectiveness maintained at low frequencies that interacts with the bubble Global instability at elevated F.S.T. and are of significantly larger scale WRT FST scales