Experimental study of tip vortex flow from a periodically pitched airfoil section

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AIAA SciTech2016 Meeting, San Diego, CA, Jan., 2016

Supported by
Transformational Tools and Technology (TTT) Project
Advanced Air Vehicles Program

Outline of talk:

Introduction

Experimental Facility

Results and Discussion

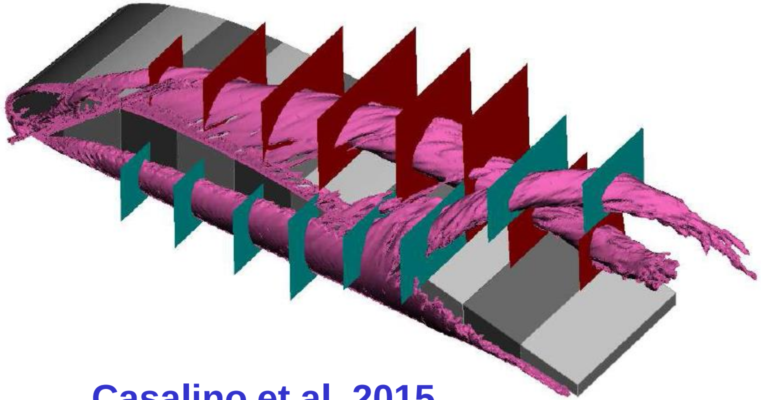
Summary

Introduction

Tip Vortex pertains to numerous applications:

-- Tip clearance loss in turbomachinery
-- Noise from rotorcrafts
-- Air traffic control
-- Performance of all lifting surfaces

Wing tip vortex in cloud from Boeing 767



Casalino et al. 2015

From Wind turbine

Background & Objective:

'Side project' utilizing existing facility and hardware

Database for numerical simulation
Start with simple geometry – fundamental study
This paper is a status report

Most results are for stationary airfoil
Shed light on some conflicting observations in the literature regarding vortex characteristics.

Experimental facility

Wind Tunnel

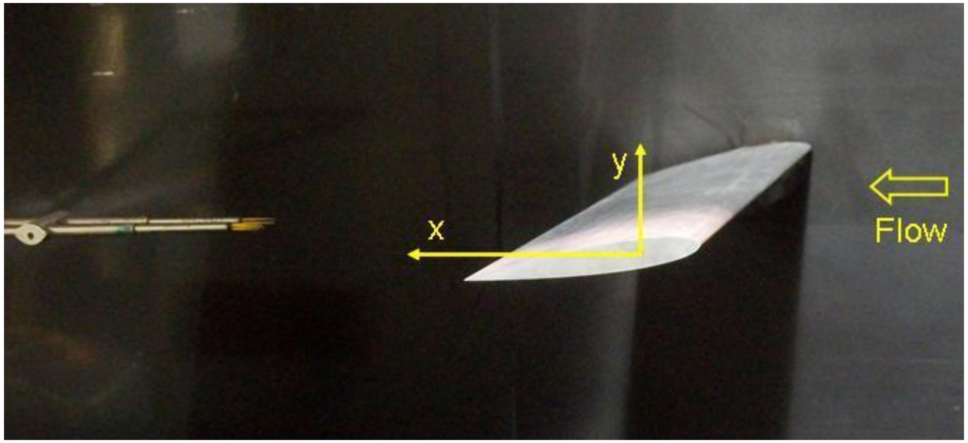
View of airfoil inside tunnel

Oscillation mechanism

Test section: 76.2cm wide x 50.4cm high
Max speed about 11 m/s

Experimental Procedure

Airfoil and hot-wire probe arrangement

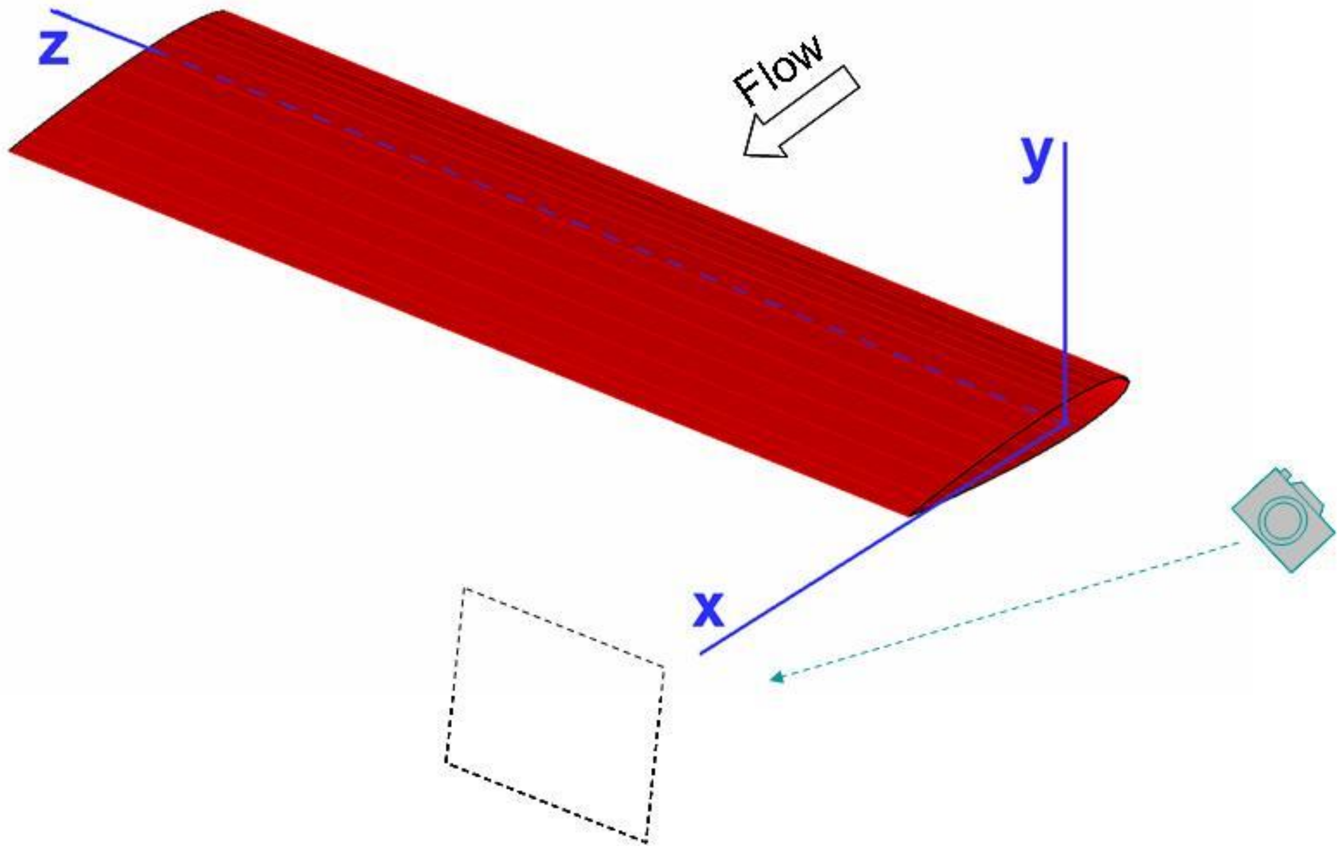


Airfoil: 7.62cm chord x 25.4cm span, supported at ¼-chord
Support rod connected to oscillation mechanism outside
Oscillation (in pitch) possible up to about 16 Hz, amplitude adjustable

All data for $U_\infty \approx 8$ m/s, $Re_C \approx 40\times10^4$

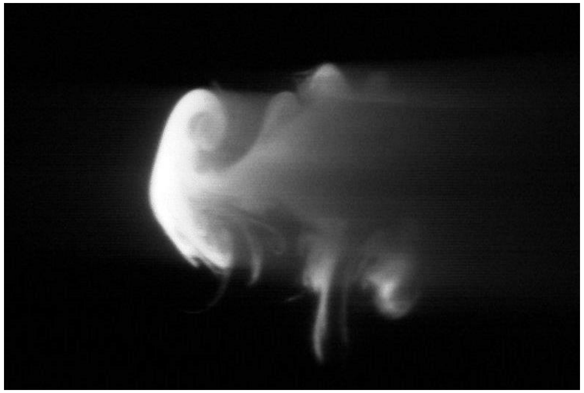
Most data in the following for stationary airfoil

Perspective in flow Visualization

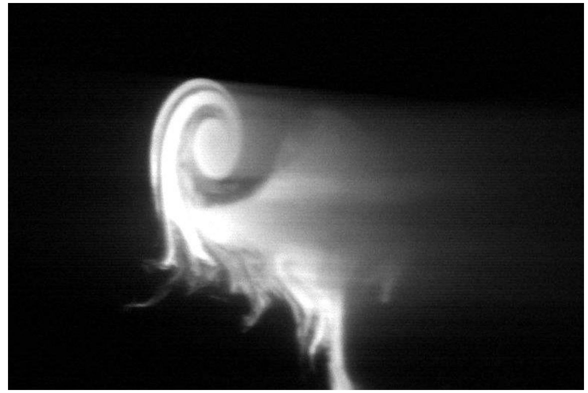


Flow visualization for stationary airfoil with varying α

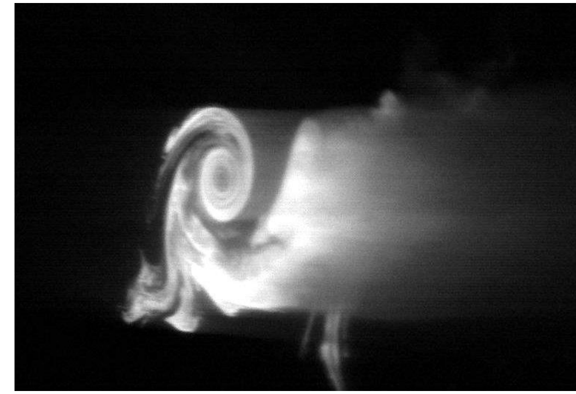
α=5°



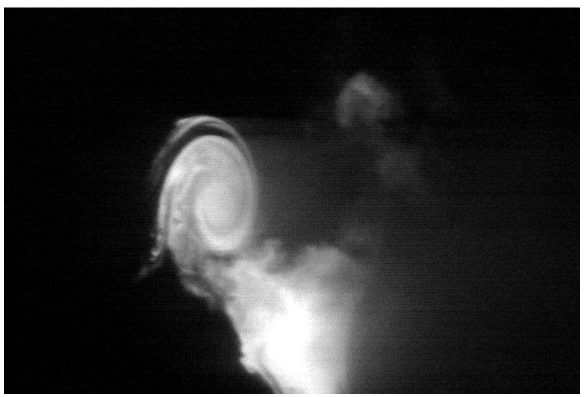
α=10°



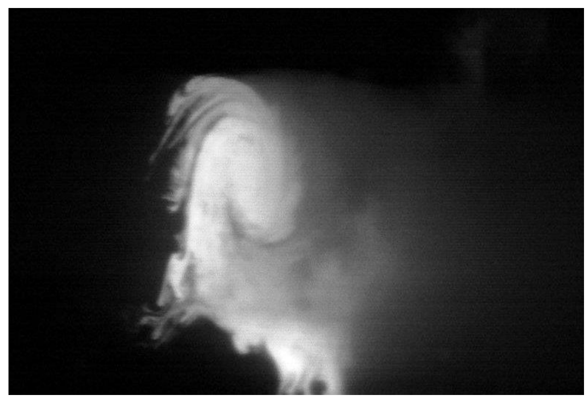
α=15°



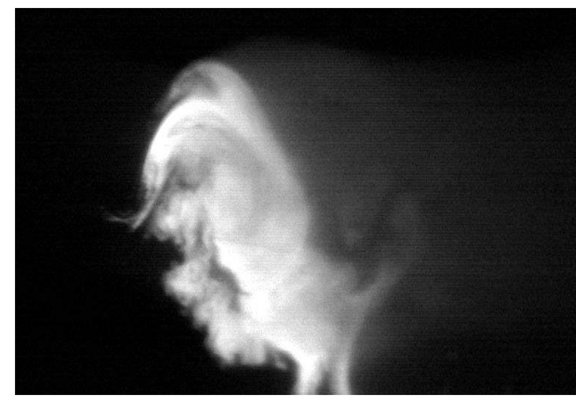
α=20°



α=25°



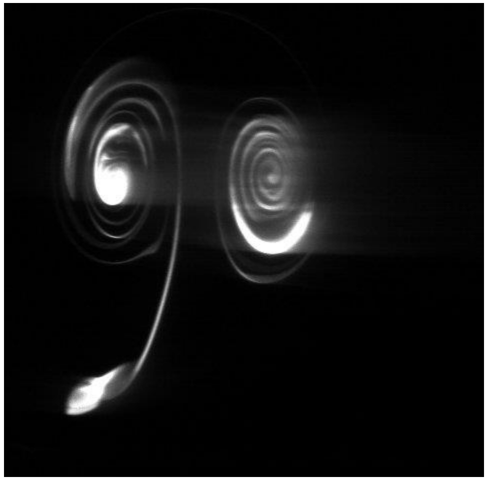
α=35°



A tube of cool smoke (about 6” diameter) is introduced from upstream of inlet to pass over airfoil tip. Laser sheet illuminated cross-section of flow at $x \approx 3.2$.

Earlier tries of flow visualization with ‘warm’ tube of smoke
(back-up slide, not in paper)

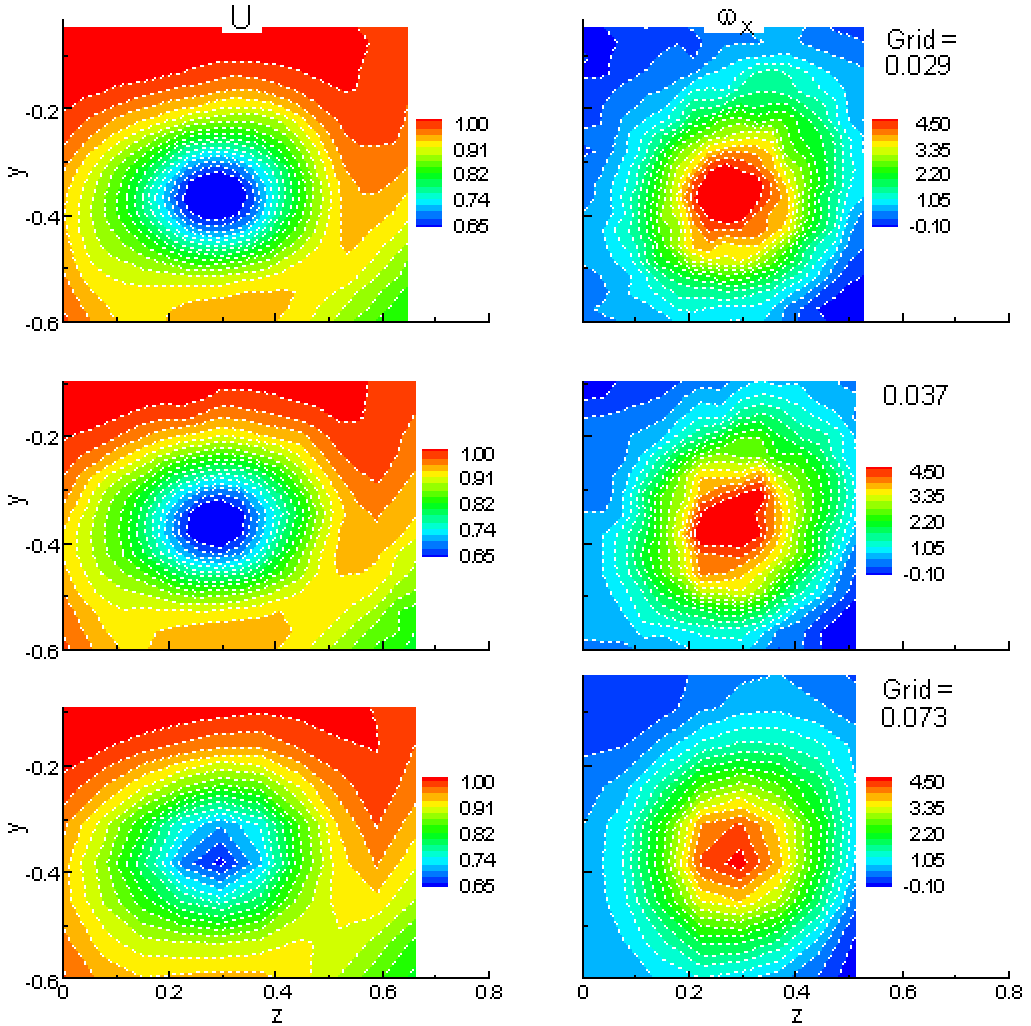
Global view of Smoke streak inside tunnel from upstream with no airfoil

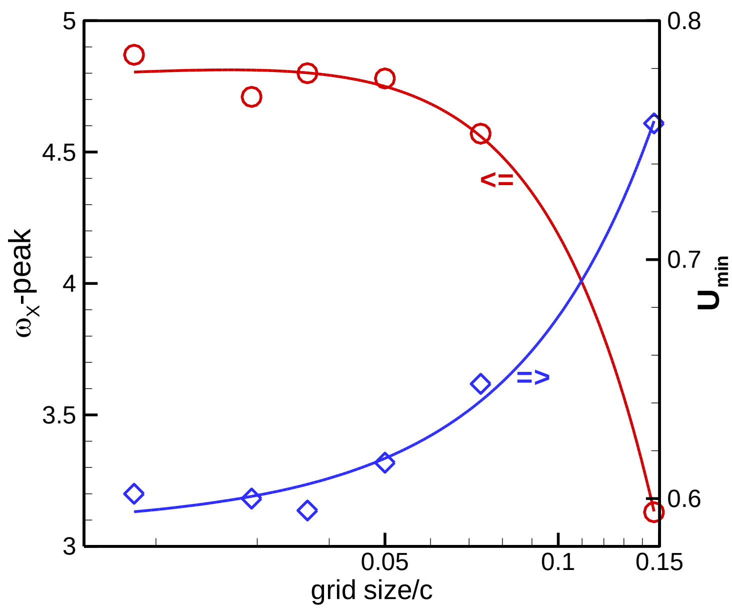


Cross-sectional view with no airfoil (Nice vortices!)

Smoke temperature was about 125°F at entrance to inlet. Buoyancy effect accentuated through contraction section to produce ‘mushroom’ vortex.

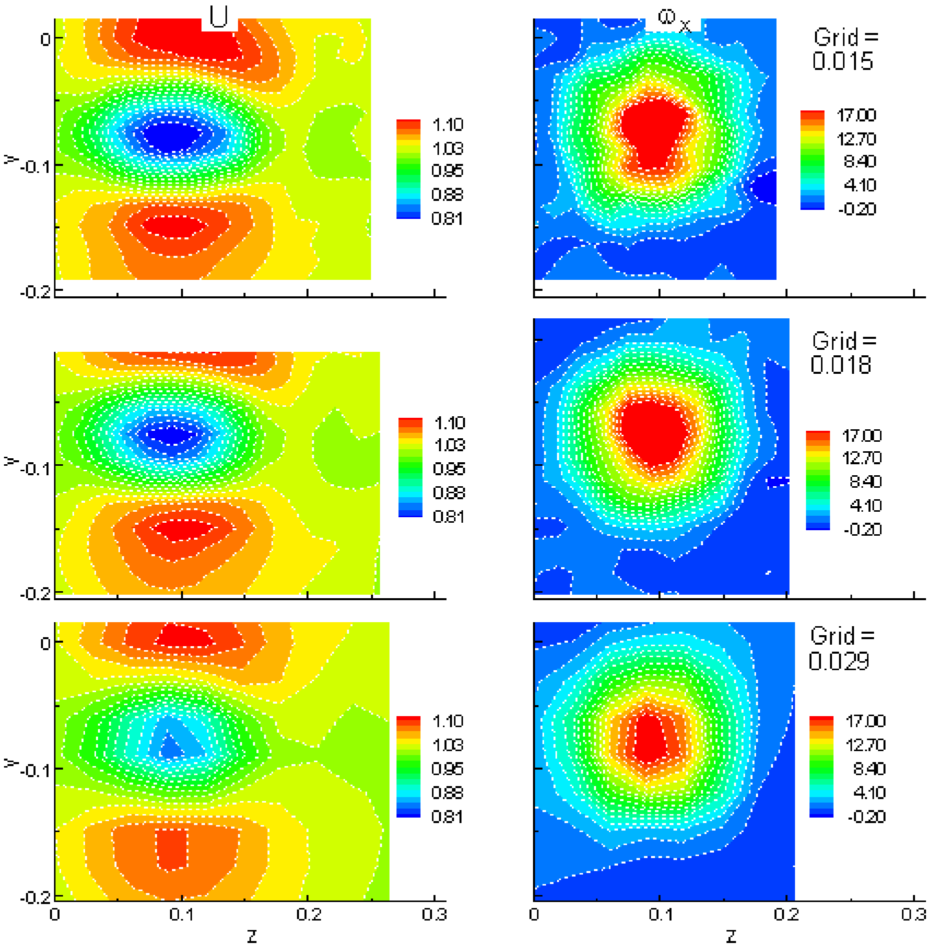
Grid sensitivity of *U* and ω_x contours at *x*=3.2, α=25°

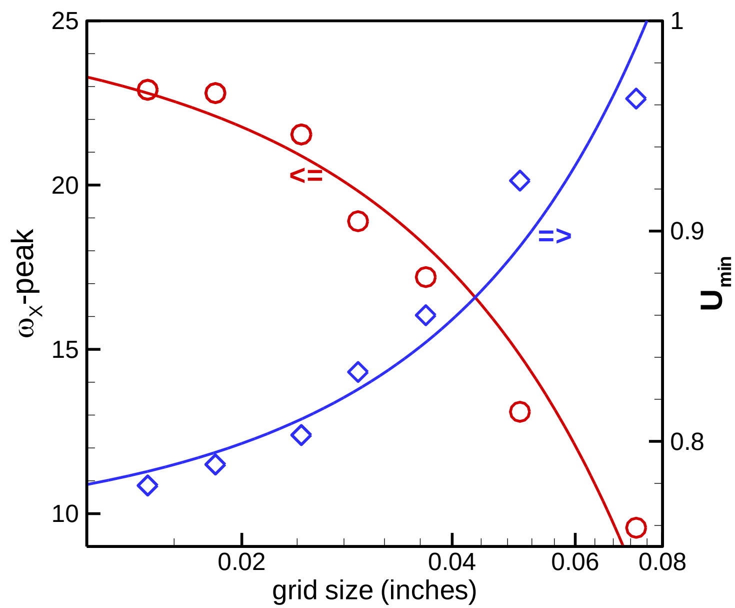




Here, approximat grid size of 0.037x0.037 is sufficient to capture peak *U* and ω_x amplitudes.

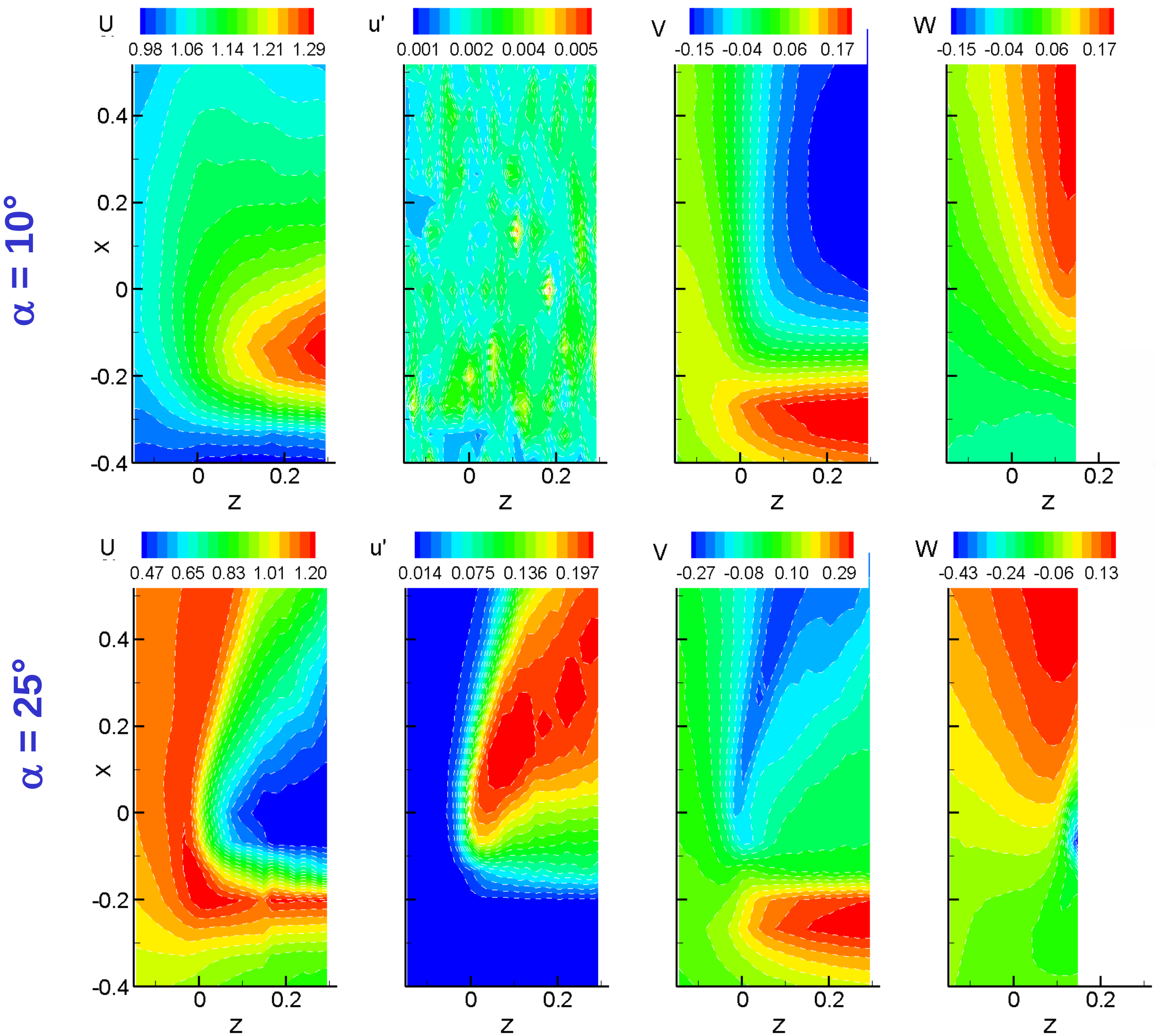
Grid sensitivity of U and ω_x contours, x=3.2, α=10°

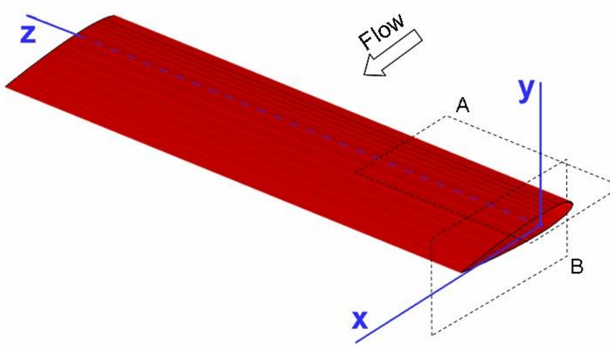




Here, grid size 0.015x0.015 is barely sufficient to capture the peak U and ω_x amplitudes.

Contours of various properties on plane ‘A’

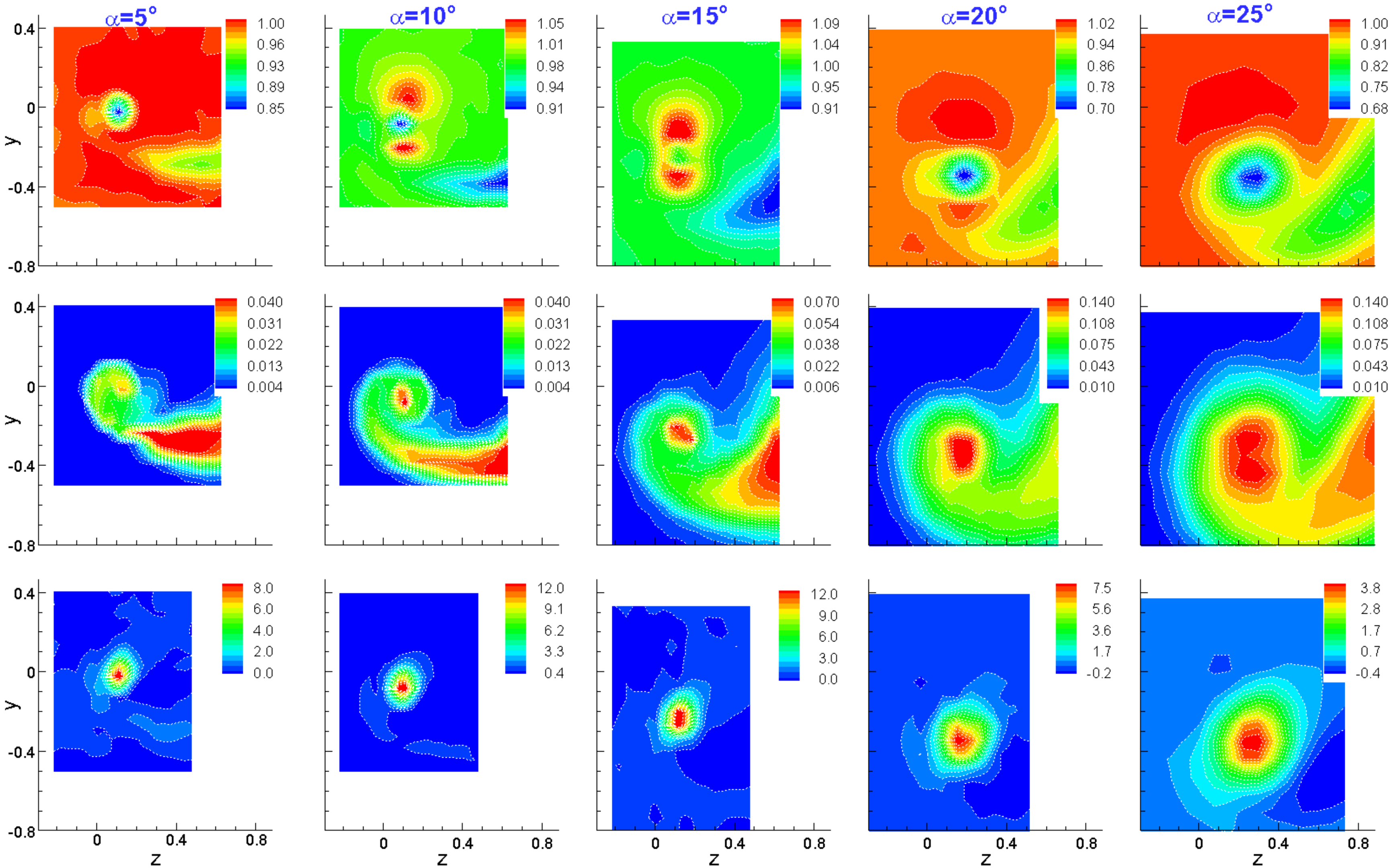




These data might be helpful in numerical simulation

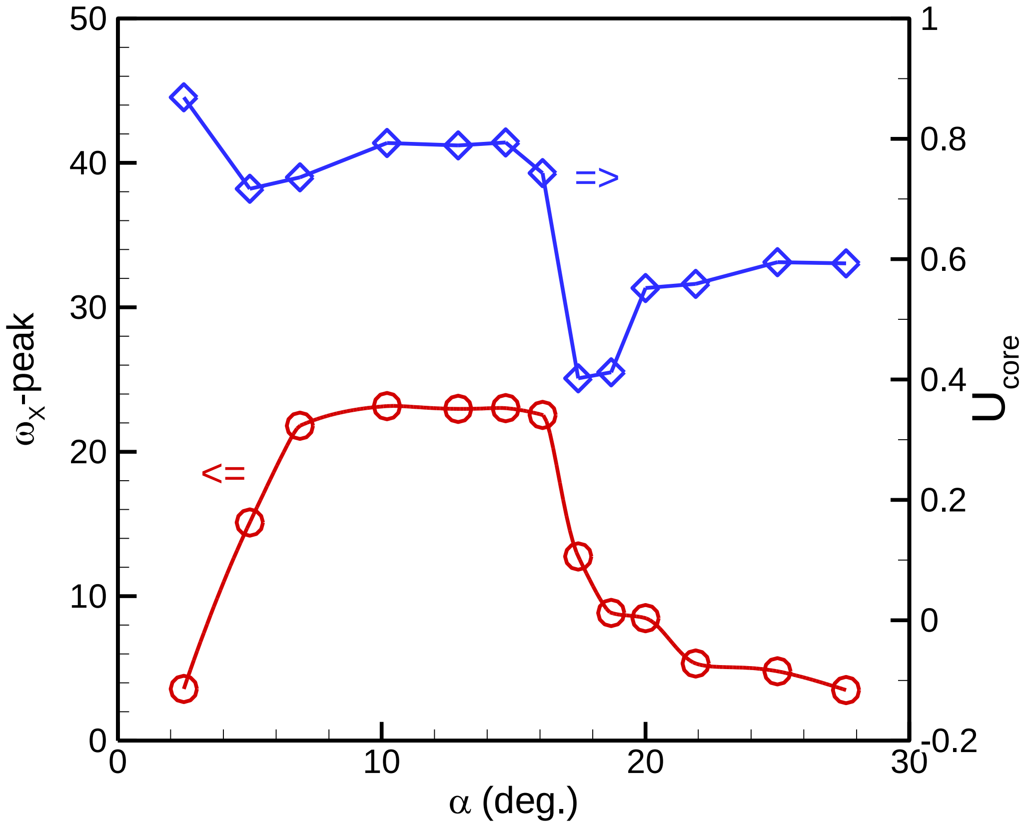
Field properties at x=3.2 for different α

(U, u' and ω_x from top to bottom rows)



Tip vortex best described by ω_x data. Mean velocity has deficit ('wake') at vortex center

Properties at the vortex center versus α; z =3.2



Literature data on ω_X-peak (α = 10°)

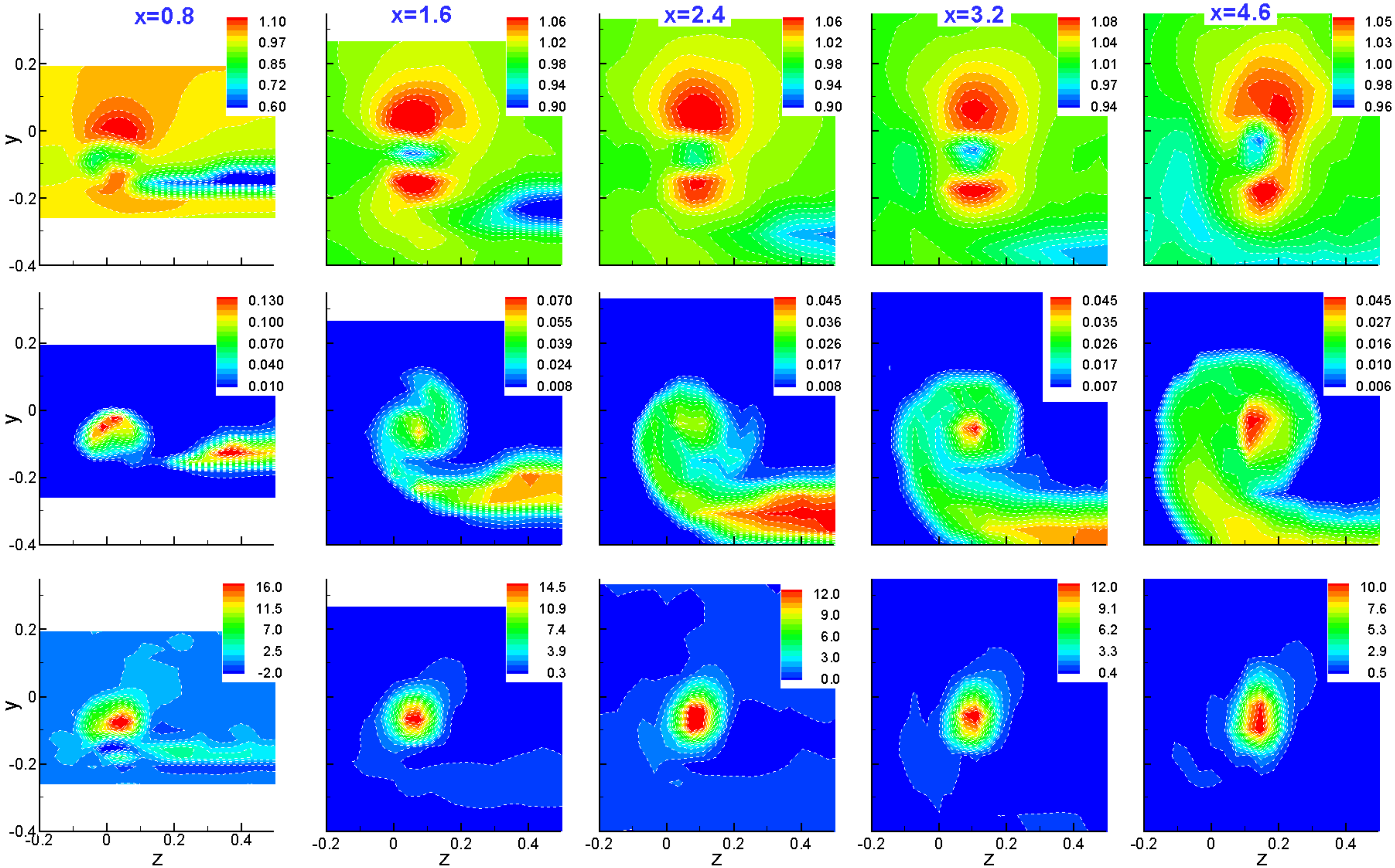
Reference	airfoil	ω_X-peak
Chow et al 1997	0012	--
Ramaprian et al 1997	0012	26
Birch et al 2004	0015	26
Present	0012	23
Birch et al 2004	cambered	40

ω_X-peak may have some *Re* dependence but is likely quite sensitive to airfoil shape

All properties exhibit a rapid change around α=16°
Transition is likely tied to onset of stall

Field properties for α=10° at different x

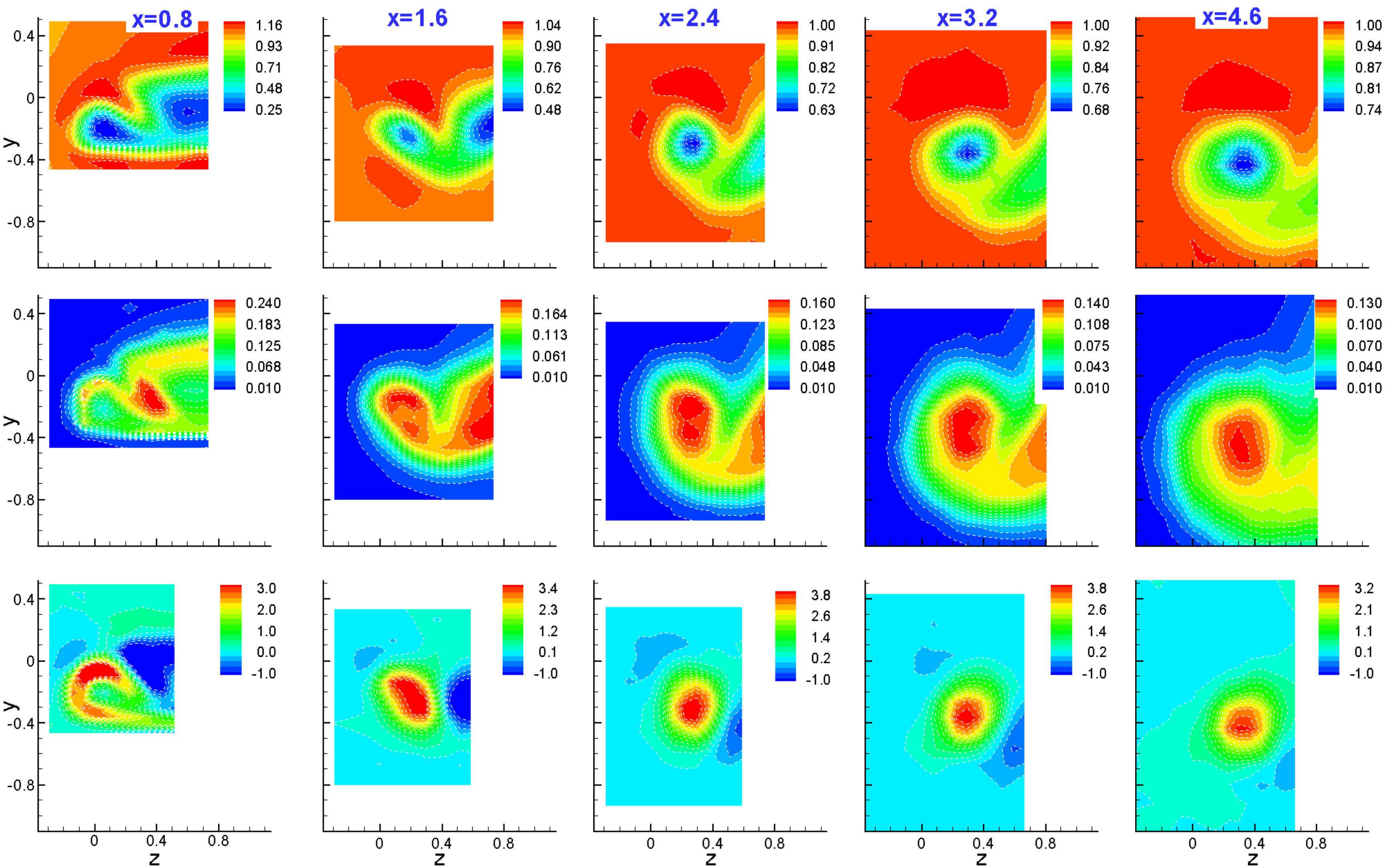
(*U*, *u'* and ω_x from top to bottom rows)



Tip vortex best discerned from the ω_x data.

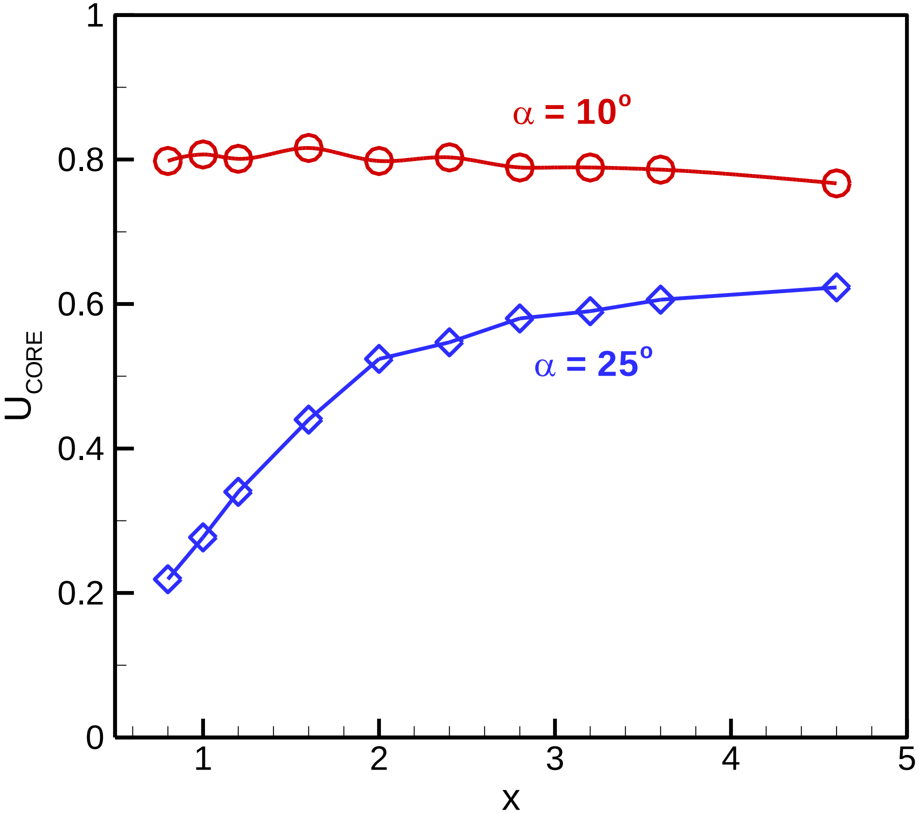
Field properties for α=25° at different x

(U, u' and ω_x from top to bottom rows)



Tip vortex is best visible from the ω_x data. Mean velocity defect at vortex center traces to airfoil wake

U_{core} (minimum U at vortex center) versus x



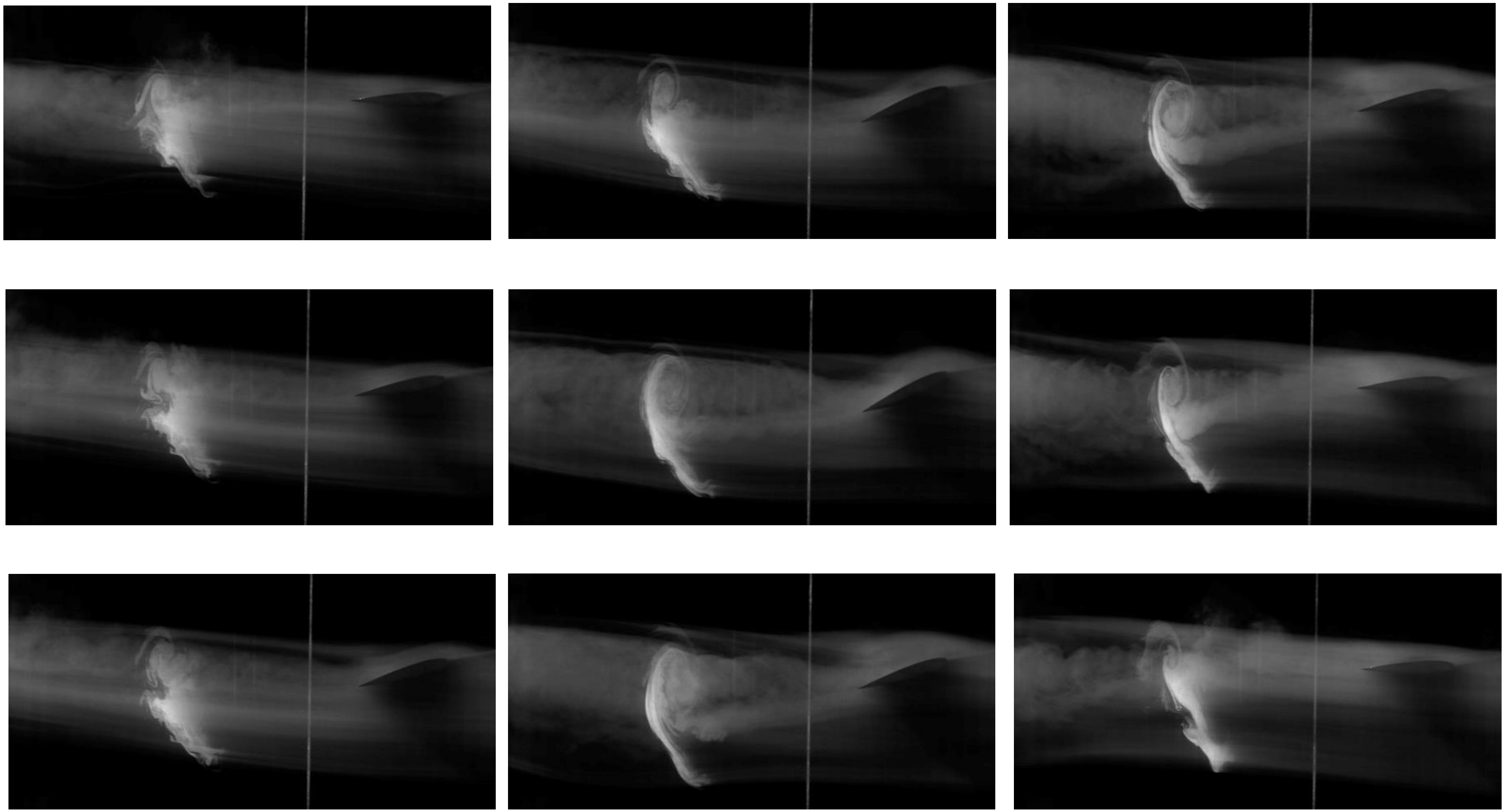
Different observations in literature (α = 10°)

Reference	U_{CORE}	Rex10^{-5}
Chow et al 1997	excess 1.77	46.0
Devenport et al 1996	deficit 0.86	5.3
Birch et al 2004	about ≈1.0	2.0
Ramaprian et al 1997	deficit ≈0.7	1.8
Present	deficit ≈0.78	0.4
Present rounded end (not in paper)	deficit 0.79	0.4

A velocity deficit is observed at all conditions of present experiment
Deficit or excess might be *Re* dependent (??)
In present case, deficit traces to wake from airfoil; part of wake is ingested in the vortex core

Sequence of flow Visualization pictures of periodically pitched airfoil

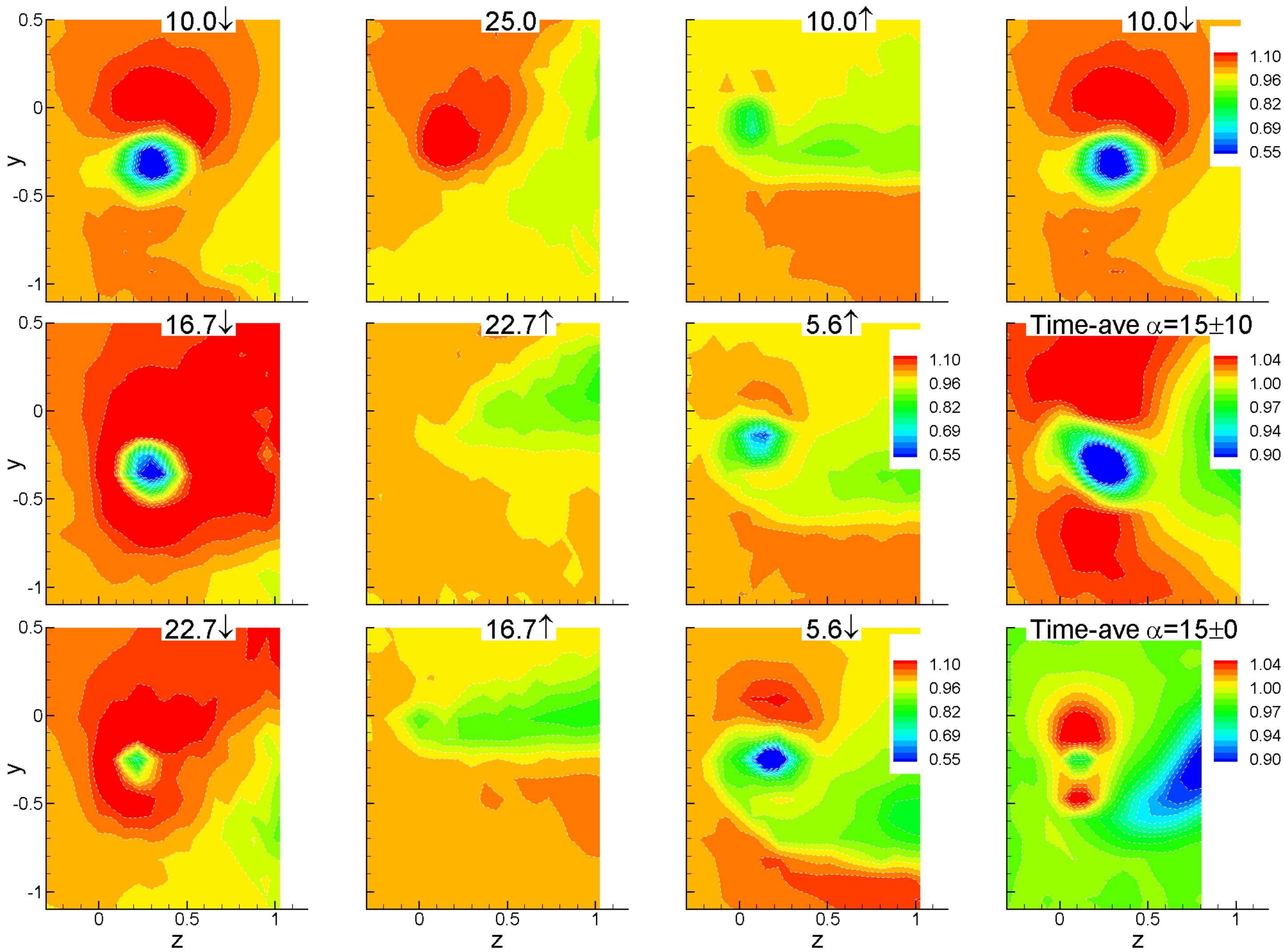
From movie clip k=0.2 (f=6.5 Hz), α=15°±10°



Wrapping of the shear layers from top and bottom surfaces of airfoil visible in some frames.

U-contours for periodically pitched airfoil

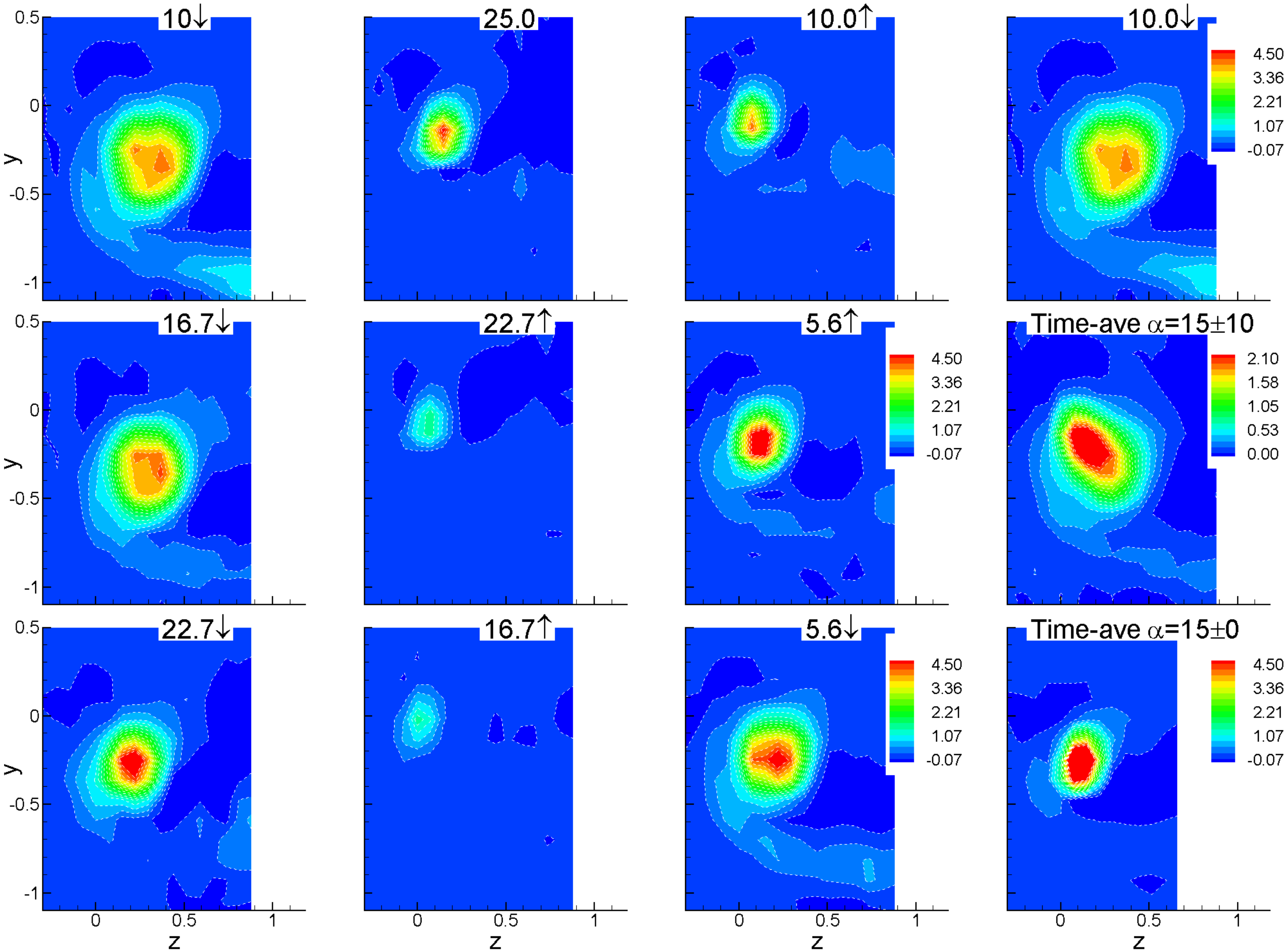
k=0.2 (*f*=6.5 Hz), α=15°±10°



Vortex is more organized when α is increasing.

ω_x-contours for periodically pitched airfoil

k=0.2 (f=6.5 Hz), α=15°±10°



Vortex is more organized when α is increasing.

Summary

-- ω_x superior descriptor of tip vortex although other properties (*U*, *u'*) do identify overall shape.

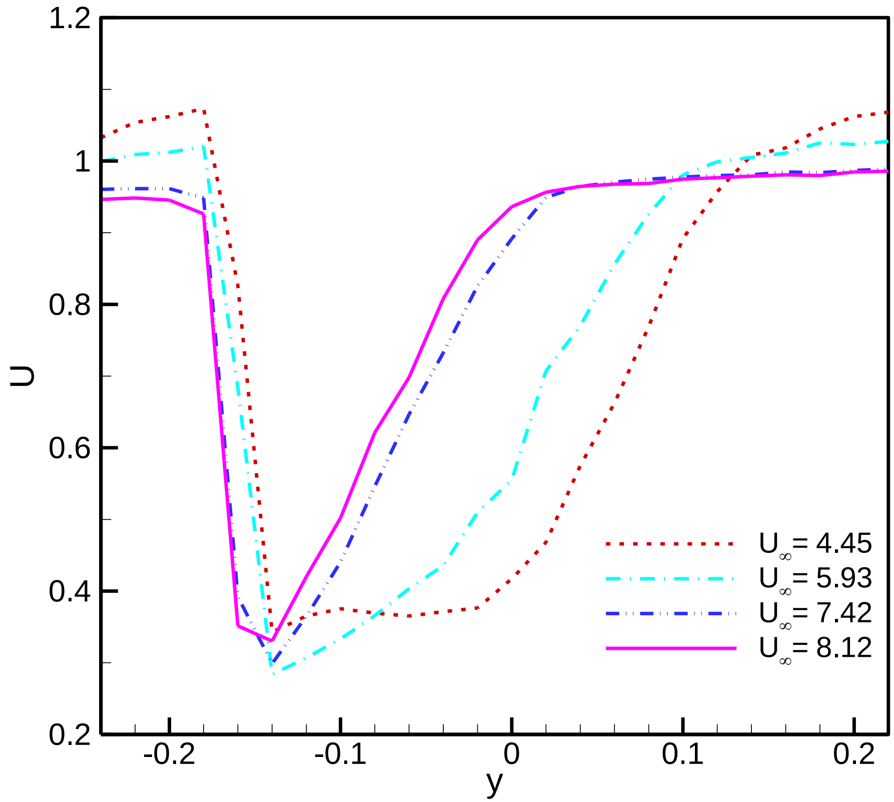
-- In present case, vortex is laminar up to $\alpha \approx 16°$ and becomes turbulent at higher α. Transition linked to onset of stall.

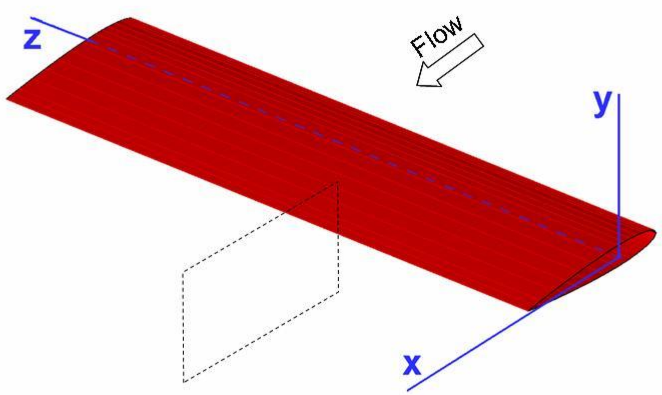
-- For all cases, vortex core is marked by *U*-deficit (wake-like profile). At small α, excess velocity (jet-like profile) is seen above and below vortex. Both deficit in core and excess outside can be traced to airfoil wake.

-- With periodic oscillation, phase-averaged data documented at *x*=3.2. Vortex seen more (or less) organized depending on pitch-down or pitch-up phase.

Additional data (in hand) to be included in a NASA TM: k=0.08, 0.2, 0.33 for α=15°±10° and for α=15° ±5°, ±10°, ±15° for k=0.2

U-profiles just downstream of airfoil one chord away from tip
α =10°, *x* =0.8, *z* =1.0





These profiles show that at the operating speed (8.12 m/s) there is no massive laminar separation that otherwise occurs at low speeds.