High Order DNS and LES for Wing Tip Vortex and Flow Control

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Outline

1. Introduction

2. Governing Equations and Numerical Algorithm

3. DNS and LES Results

4. Summary and Concluding Remarks

Introduction

Engineering importance

- ♦ Wing tip vortex flows dominate the wakes of lifting vehicles

- ♦ Such flows are unsteady and very complicated, are considered to be the cause of noise, vibration and detectable signals, which could affect other objects (aircraft, propeller etc) following at a close distance

- ♦ Tip vortex can generate a low pressure core which could cause cavitation to damage blades of propeller or turbine machinery. The long lasting, strong low pressure core is also a main cause of damage of hurricane. Tip vortex is important to taking off and landing of an flight vehicle.

- ♦ Blade/vortex interactions can directly affect the performance of the rotorcraft such as propeller, helicopter etc

- ♦ The drag induced by wingtip vortex is significant

Tip vortex control is of great engineering importance

Governing Equations

- The conservation form of 3-D compressible Navier-Stokes equations in generalized curvilinear coordinates

$$\frac{1}{J}\frac{\partial Q}{\partial t}+\frac{\partial\left(E-E_v\right)}{\partial\xi}+\frac{\partial\left(F-F_v\right)}{\partial\eta}+\frac{\partial\left(G-G_v\right)}{\partial\zeta}=0$$

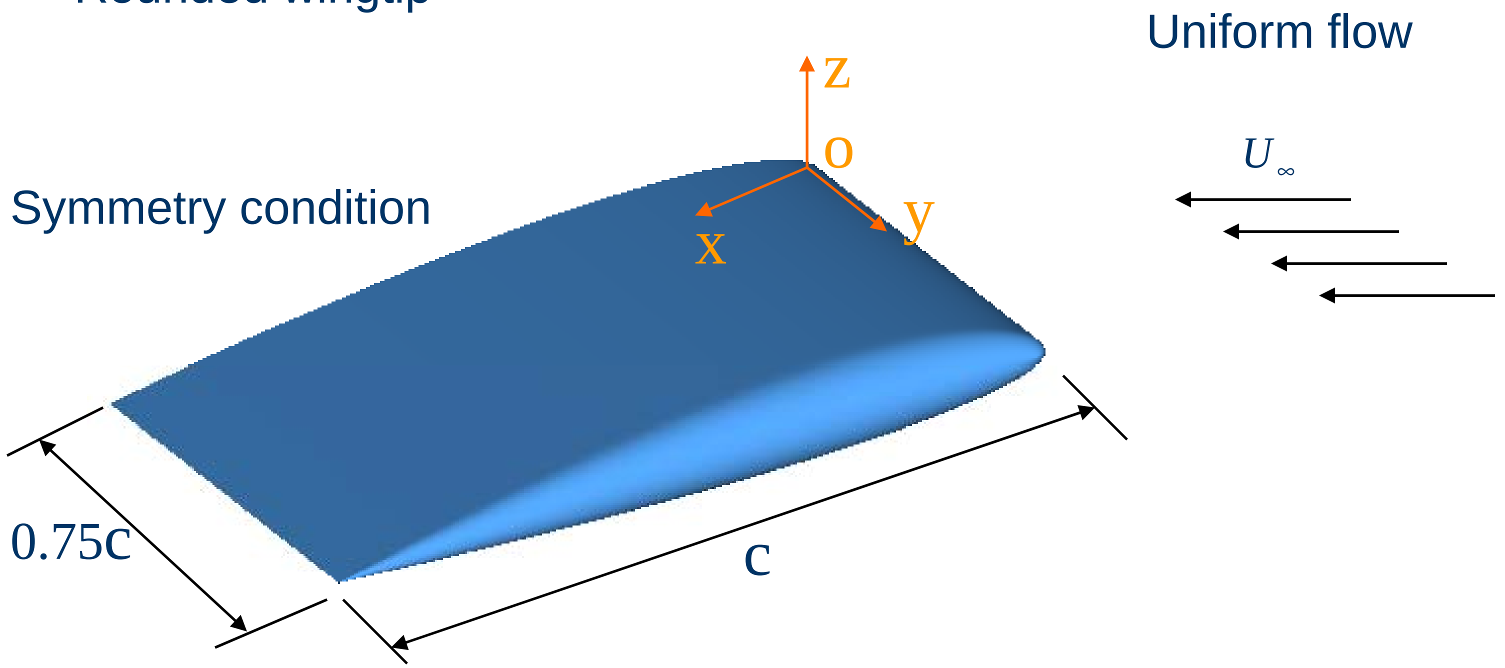
- Filtered Structure Function Subgrid Model (Ducros et al. 1996)

Numerical Algorithm

- ♦ Second order Euler backward in time
- ♦ Sixth order compact central difference for spatial discretization
- ♦ LU-SGS implicit solver (Yoon, 1992) for time advancing
- ♦ High order compact filtering to suppress numerical oscillation
- ♦ Parallel computing based on domain decomposition and Message Passing Interface

Flow configuration

Geometry: Rectangular half wing
NACA0012 wing section
Rounded wingtip

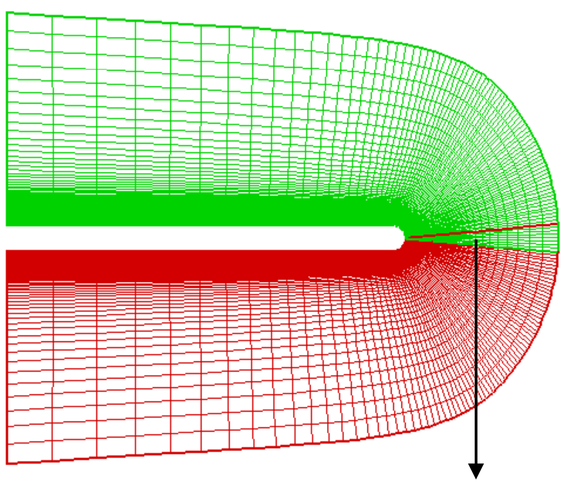


$$Re_c = 4.6\times10^6,\quad M_\infty = 0.2,\quad \text{Attack angle}\ \alpha = 10^\circ$$

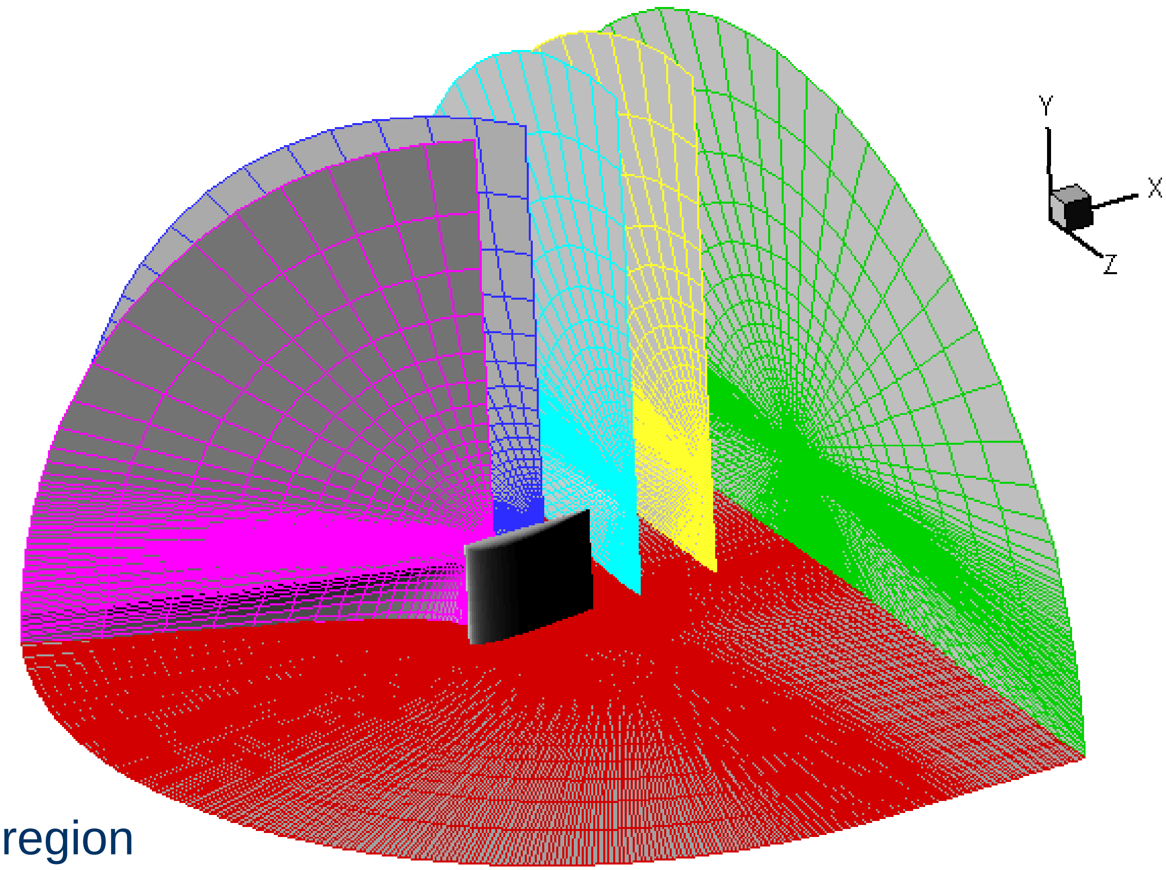
Grid distribution

Grid number: 1024x160x160 (26 millions), one block

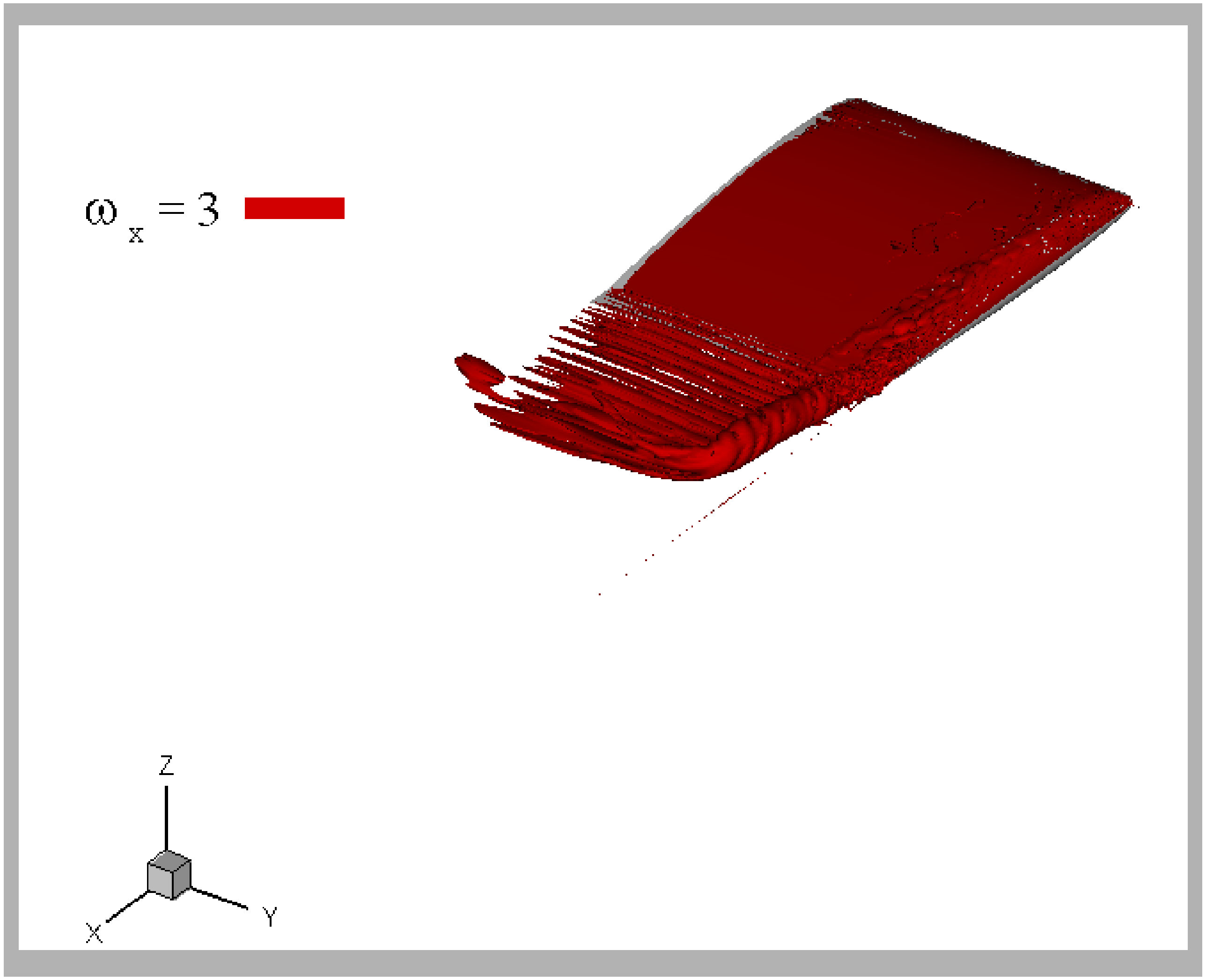
Streamwise: $\Delta x^+_{\min} = 17.5$
Spanwise: $\Delta y^+_{\min} = 35$
Wall-normal: $\Delta z^+_{\min} = 2.6$



Grid overlapped region
5 grid points



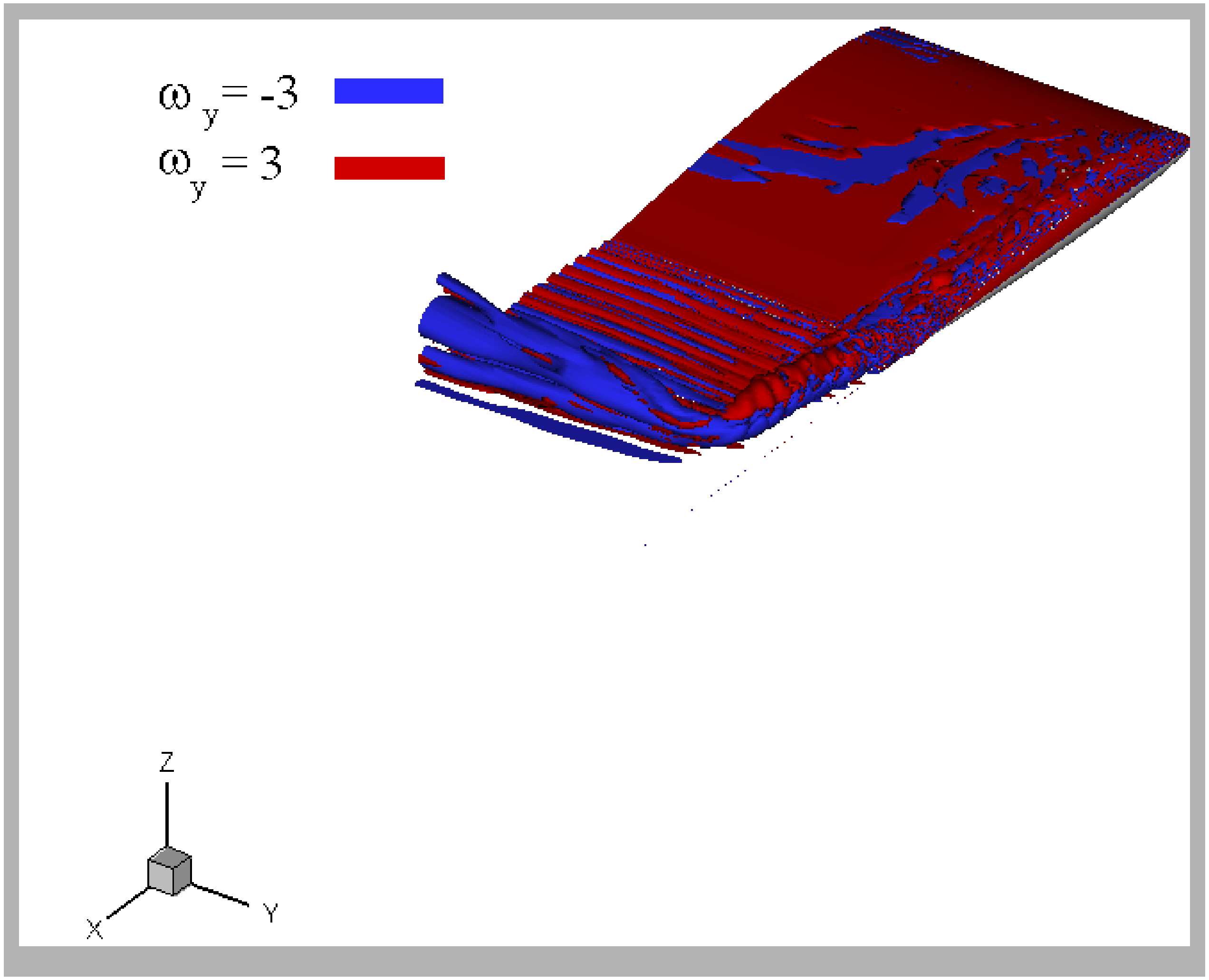
DNS results – instantaneous flow field



Animation: Iso-surface of vorticity component ω_x=3

- The iso-surface of axial vorticity starts from the wing tip in the form of small vortical structures and evolves into a smooth (laminar) vortex tube in the further downstream of the wake.
- On the suction side of the wing, the flow near the tip region is highly 3D and turbulent. Small vortical structures are clearly seen inside and around the tip vortex.
- Near the trailing edge, spiral wake surrounding the tip vortex is formed as the wake is skewed and laterally stretched and curved by the rotating velocity field associated with the tip vortex.

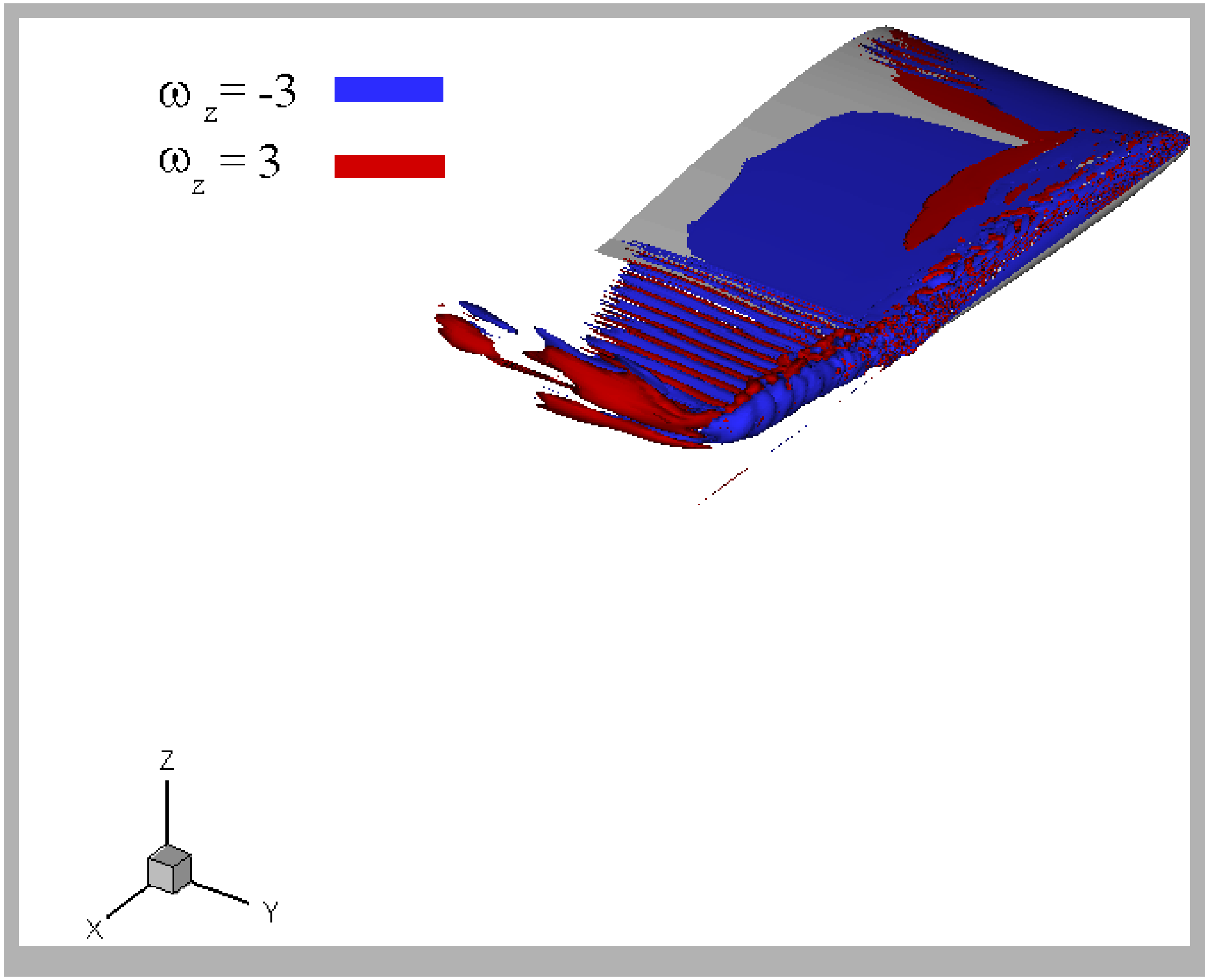
DNS results – instantaneous flow field (Cont'd)



Animation: Iso-surface of vorticity component $\omega_y = \pm 3$

- Along the wing tip vortex in the wake, the iso-surfaces of positive and negative spanwise vorticity are parallel to each other in a vertical layout representing a typical spiral motion of velocity field.

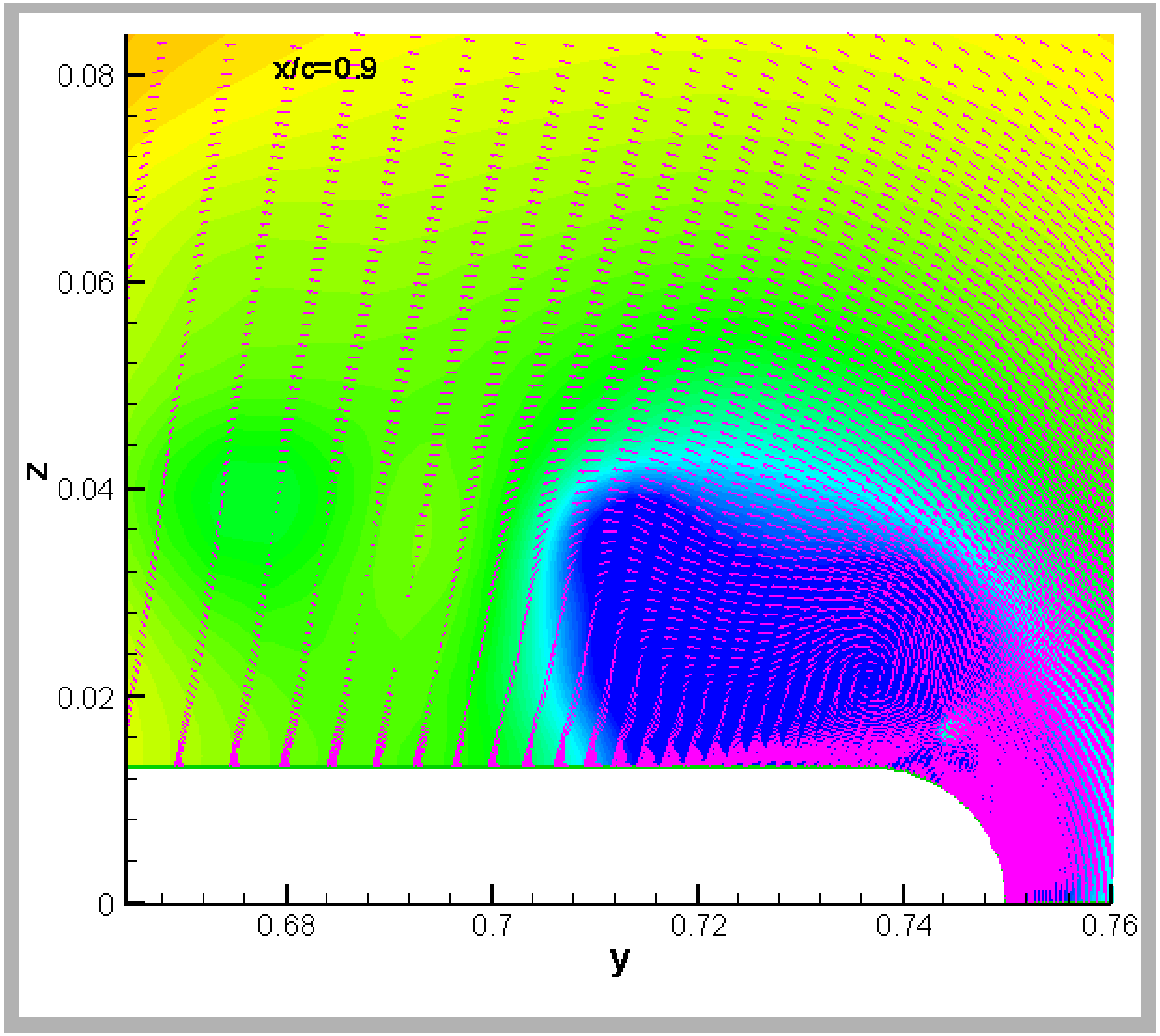
DNS results – instantaneous flow field (Cont'd)



Animation: Iso-surface of vorticity component $\omega_z = \pm 3$

- Along the wing tip vortex in the wake, the iso-surfaces corresponding to the positive and the negative *z*-component of vorticity are parallel to each other in a horizontal layout representing a typical spiral motion of velocity field.

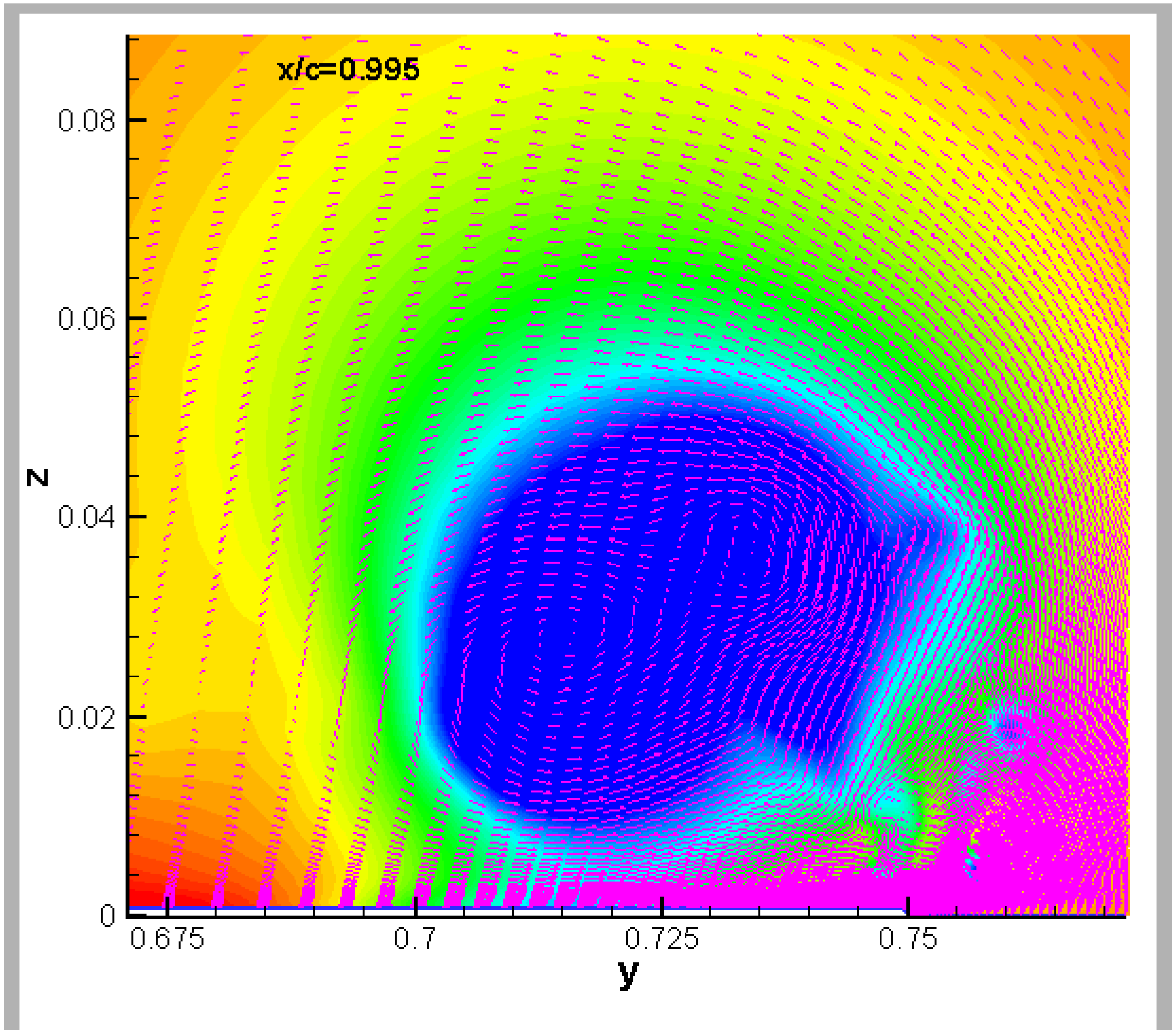
DNS results – instantaneous flow field (Cont'd)



- The vortex structures are highly unsteady. The core area of the primary vortex is very unstable and the outer edge of the primary vortex is not smooth.
- The shear layer separates from the rounded wing tip and rolls up generating the primary vortex.
- Near the junction of the wing and the rounded tip, the secondary vortex is induced by the primary vortex and the secondary vortex rotates in the opposite direction of the primary vortex.
- The vorticity of small vortices shedding from wing tip shear layer has the same sign as the primary vortex

Animation: Pressure contours and velocity vectors in the cross-section at x/c=0.9

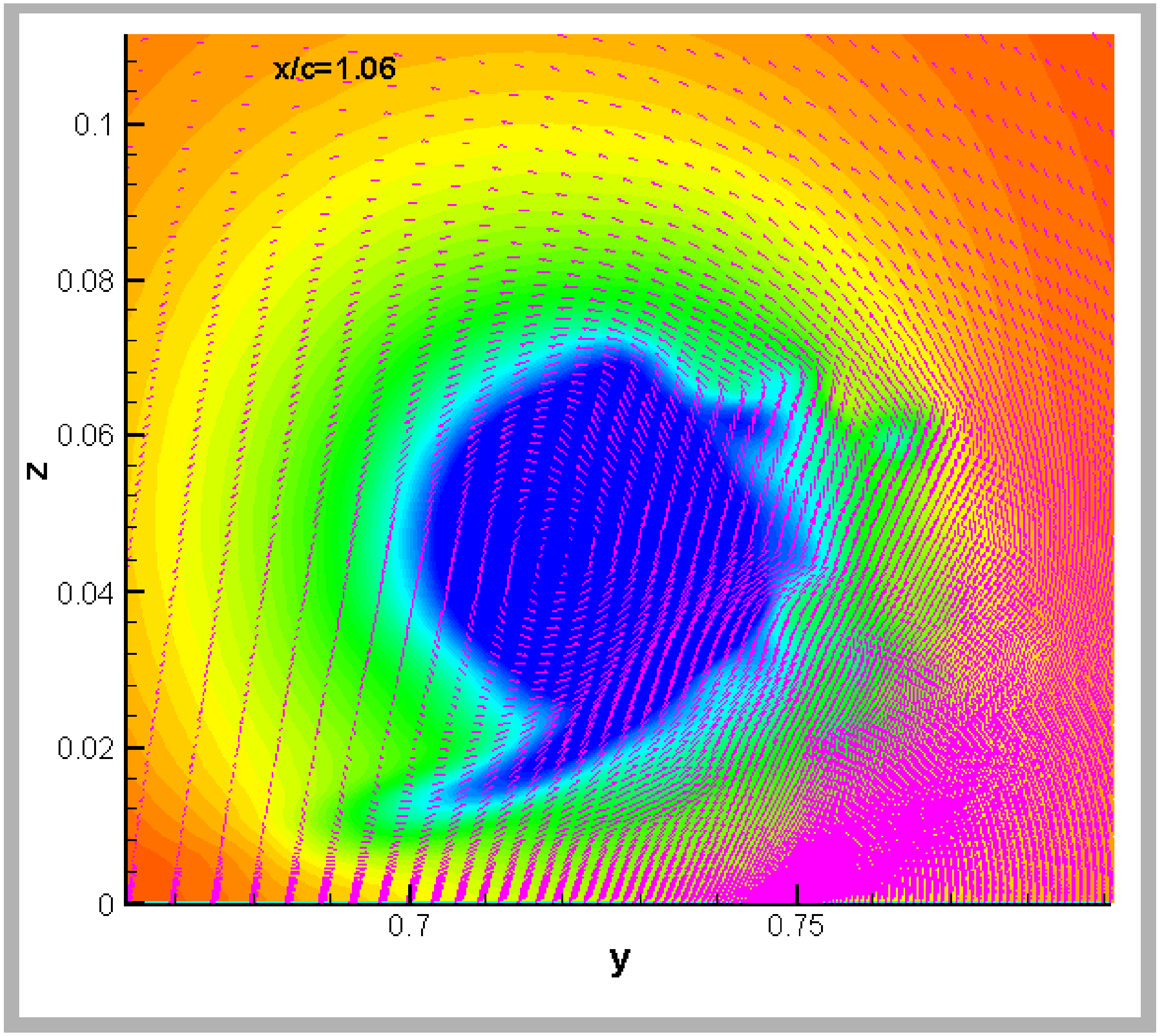
DNS results – instantaneous flow field (Cont'd)



- The center of the primary vortex moves upward away from the surface of the wing and the vortex core grows.
- The secondary vortex also grows. It rolls up and merges into the primary vortex. The secondary vortex brings unsteadiness and instability into the core of the primary vortex.
- The interaction between the primary and the secondary vortices leads to the generation of small vortical structures in the core area.

Animation: Pressure contours and velocity vectors in the cross-section at x/c=0.995

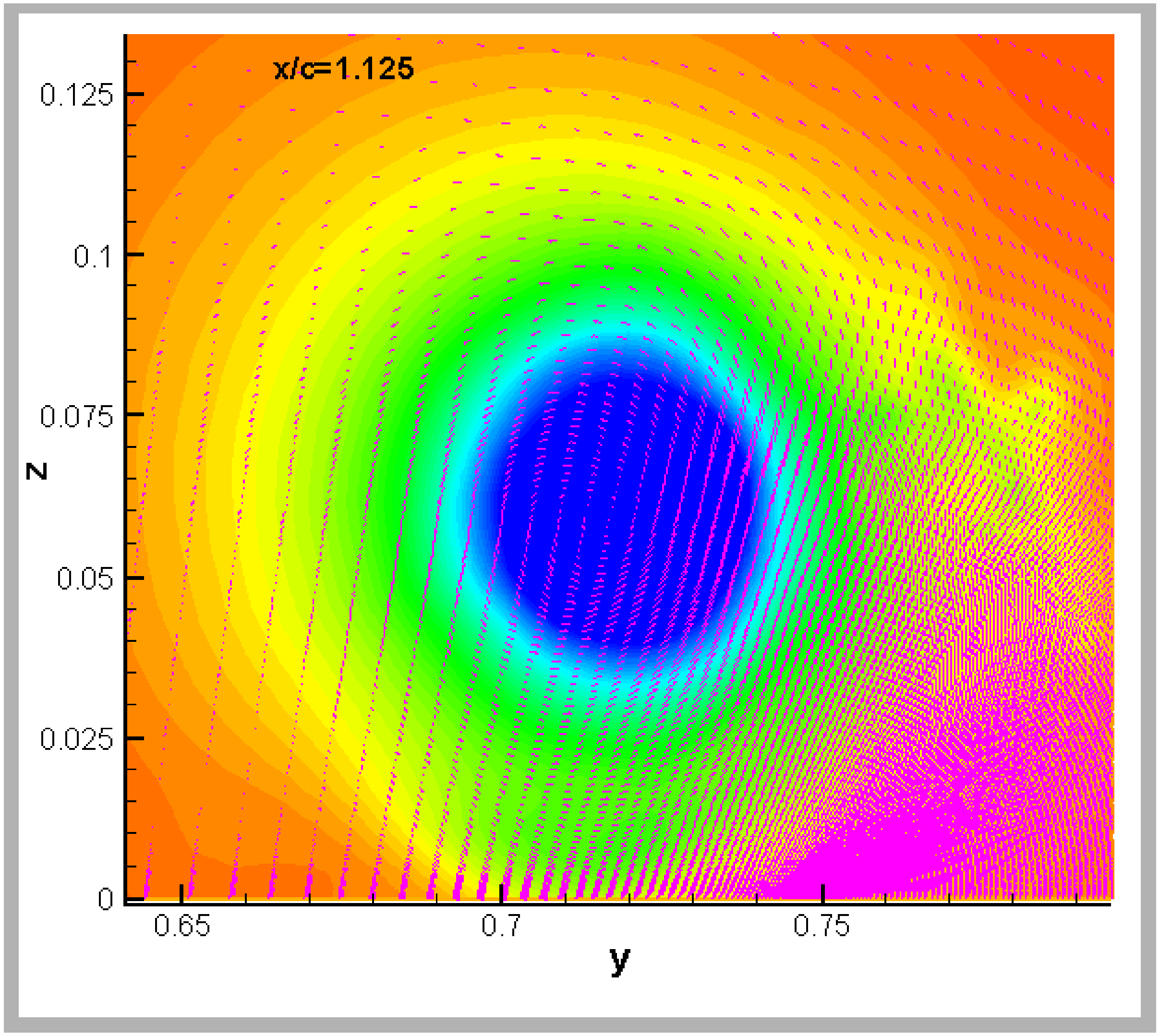
DNS results – instantaneous flow field (Cont'd)



- At the Immediate down-stream of the trailing edge, there is not any newly generated secondary vortices due to the absence of wall. The visible secondary vortical structures are actually the secondary vortices shed from the wing surface at the upstream location and convected downstream.
- The secondary vortices become weaker while traveling downstream, thus introduces less disturbance to the core of the primary vortex. The primary vortex is able to maintain an unbroken core all the time at this location.

Animation: Pressure contours and velocity vectors in the cross-section at x/c=1.06

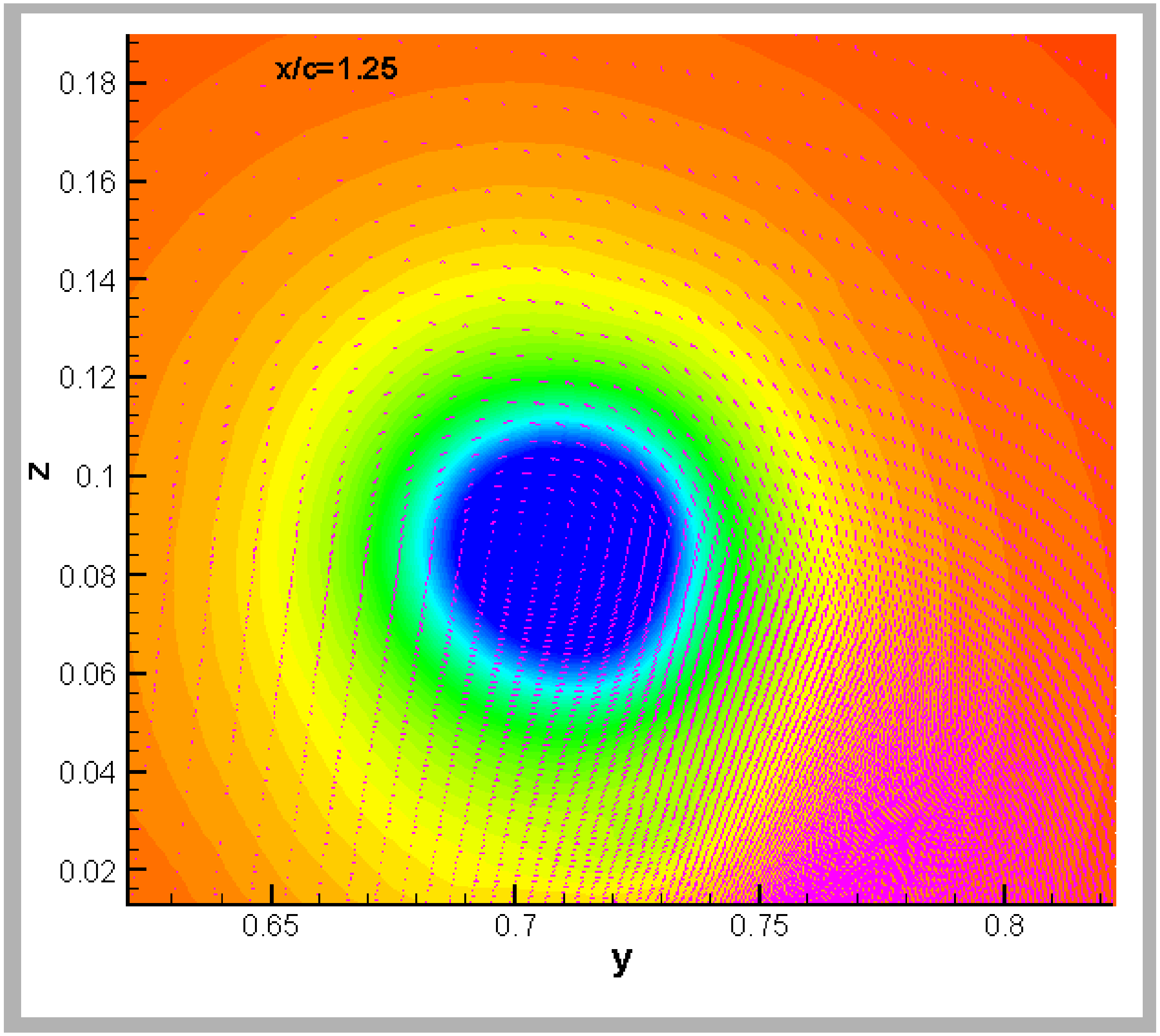
DNS results – instantaneous flow field (Cont'd)



- Further downstream from the trailing edge of the wing, the secondary vortex is barely seen, because they are significantly dissipated while they are convected downstream.
- Because of the disappearance of the secondary vortex and the absence of the shear layer, no more disturbance is input to the primary vortex. The primary vortex is stabilized and is able to maintain a shape of a smooth regular circle.
- Sometimes, the trailing edge wake (from the lower left corner of the plot), being entrained by the primary vortex, rolls up into the primary vortex. When this happens, the shape and the position of the vortex core are affected.

Animation: Pressure contours and velocity vectors in the cross-section at x/c=1.125

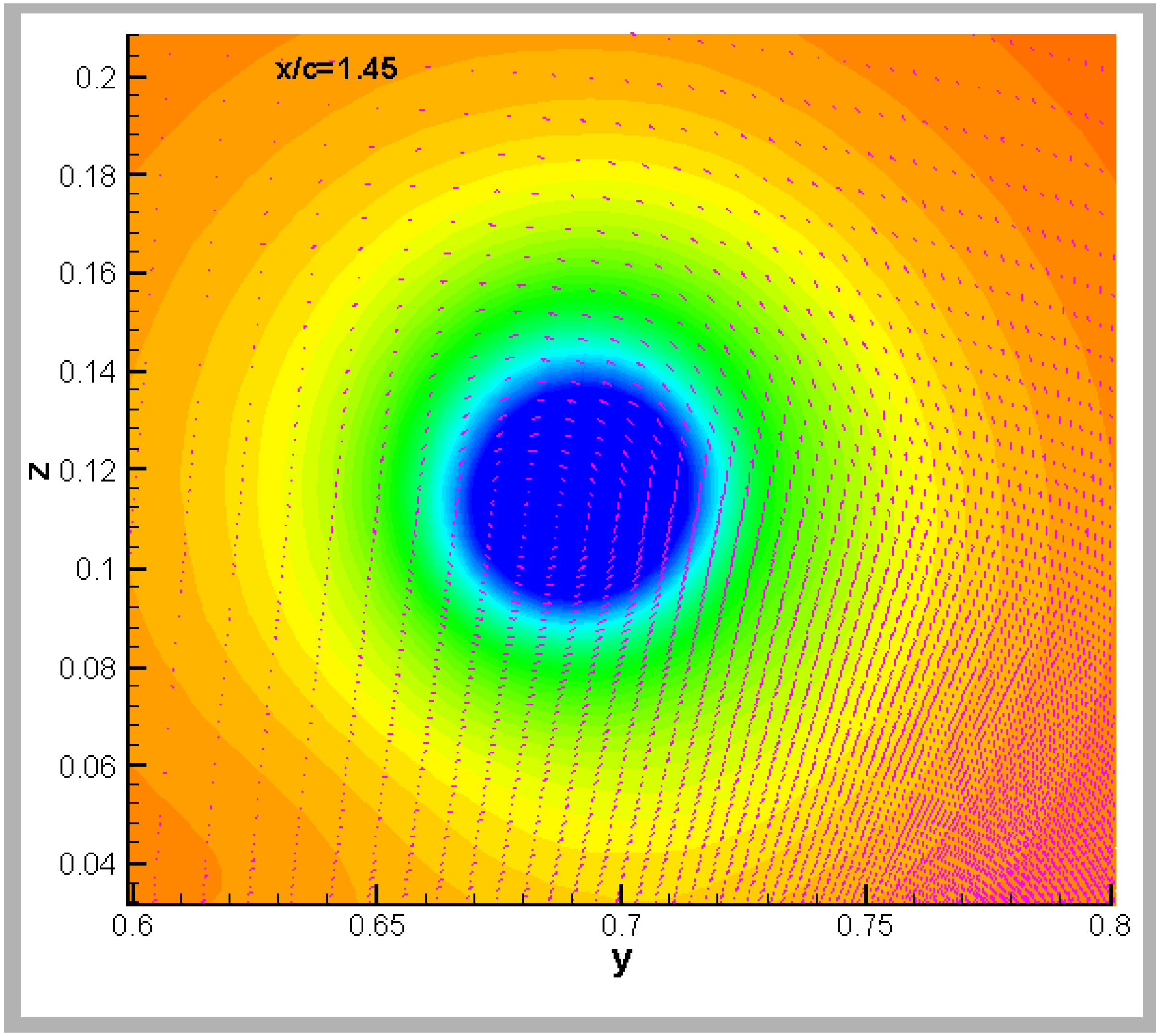
DNS results – instantaneous flow field (Cont'd)



- Due to the reasons that have been discussed in the previous slide, as one goes to a further downstream location, the primary vortex becomes more stable (relaminized) .

Animation: Pressure contours and velocity vectors in the cross-section at x/c=1.25

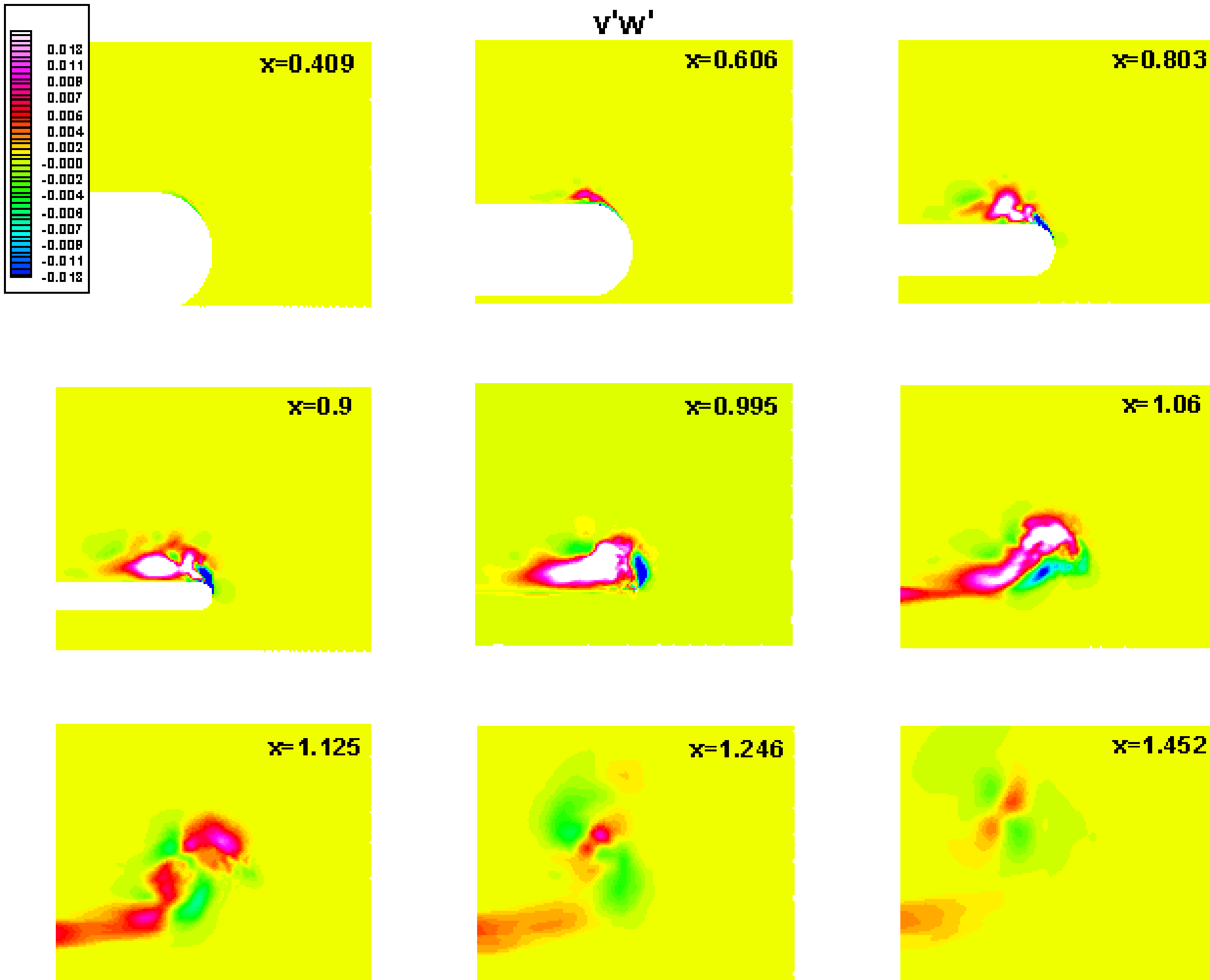
DNS results – instantaneous flow field (Cont'd)



- The primary tip vortex becomes more stable .

Animation: Pressure contours and velocity vectors in the cross-section at x/c=1.45

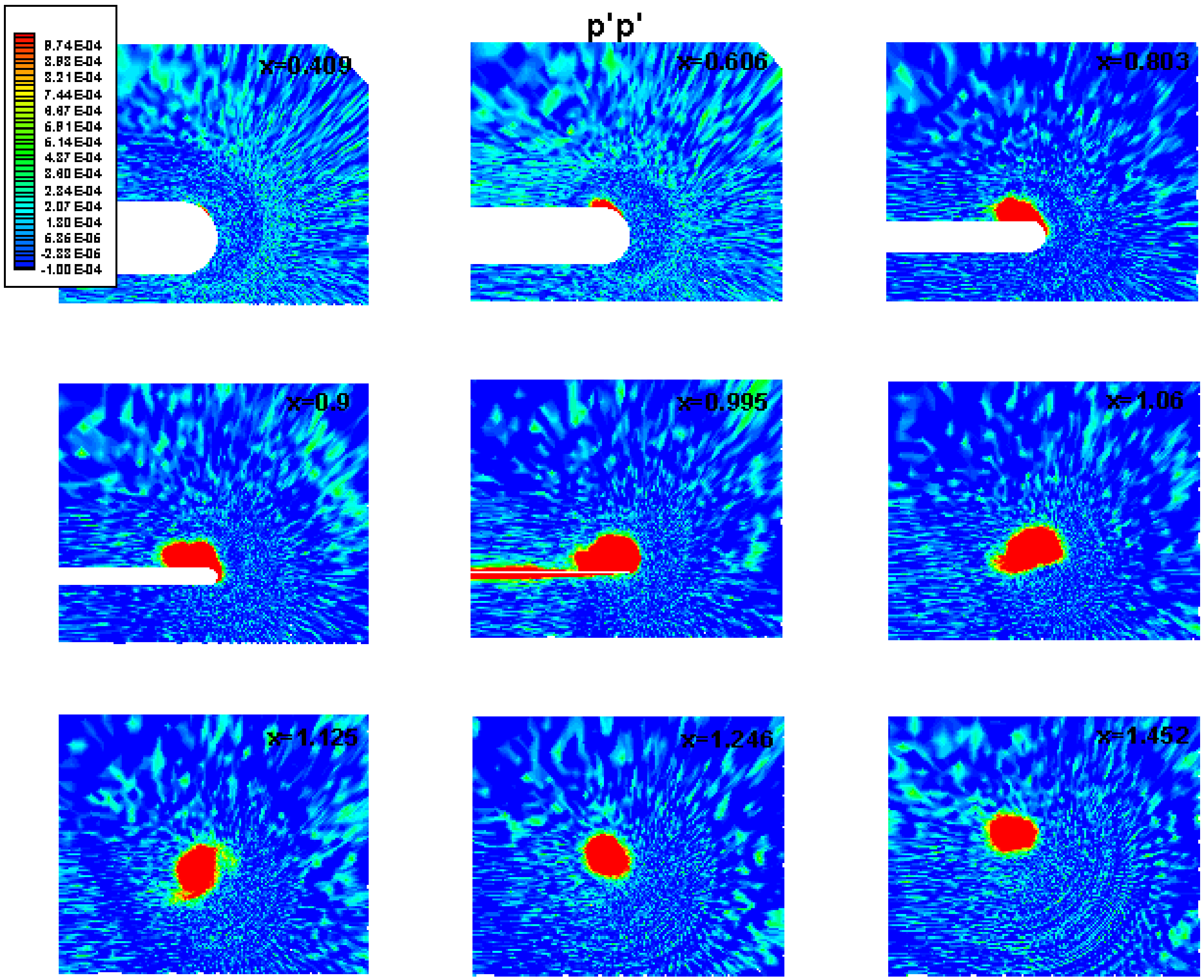
DNS results – Reynolds shear stress (Cont'd)



The contours of the *v'w'* component of Reynolds stress show four-leaf clove pattern which was also observed in the experiments (Chow, et al, 1997). This pattern becomes more clear in the wake where the distortion effect of the shear layer vanishes.

Contours of the *v'w'* component of Reynolds stress in cross-sections at different axial locations

DNS results – Acoustic wave



Contours of RMS p' in cross-sections at different axial locations

The distribution of pressure perturbation reveals the propagation of acoustic waves away from the wingtip. The pressure perturbations are closely associated with the fluctuations in the tip vortex and the separated turbulent shear layer. The formation of the wingtip primary vortex is considered as a major source of noise.

Preliminary Analysis of Tip Vortex Feature

1. Why the tip vortex is turbulent originally?
1) Wall surface is the resource of turbulence generation
2) Interaction of primary and secondary vortices

2. Why the tip vortex is relaminarized and stable after shedding?

1) There is no wall surface in the wake (no turbulence source)
2) The velocity in the tip vortex center becomes larger because of the rotation and the velocity profile of mean flow becomes jet-type (no deflection point) which is invicidly very stable.
3) The secondary vortex is quickly dissipated and does not disturb the primary vortex.

Concluding Remarks

- High Reynolds number ($4.6x10^6$) complex flow associated with the formation of the wingtip vortex and its initial development and interaction with the near wake has been simulated by DNS. The high order, high resolution compact scheme enables this simulation to capture the major features using only about 24 million grid points.

- On the suction side of the wing surface, the rolling up of the separated shear layer at the rounded wingtip creates the primary tip vortex. The rotational flow field of the primary tip vortex induces the counter-rotating secondary vortex near the wing surface. The separated shear layer contains high level of fluctuations and wraps up the secondary vortex into the primary vortex. The shear layer fluctuations and the secondary vortex contribute high energy to the vortex core to produce small vortical structures within the core region which is highly turbulent. Therefore, the turbulence inside the primary tip vortex is not created by the tip vortex itself. The turbulent shear layer and the interaction between the primary and the secondary vortices are the major sources of turbulent activity in the core.

- The primary tip vortex is generated near the wingtip onboard the suction surface and is convected downstream. The rotation of the tip vortex produces low pressure in the core region. The favorable axial pressure gradient accelerates the axial flow and produces axial velocity surplus. Instantaneous axial velocity can reach as high as $2.0U_\infty$. On the other hand, counter-rotating secondary vortex contribute to axial velocity deficit.

Concluding Remarks (Cont'd)

- In the near wake region, there is no more energy input from the shear layer and secondary vortex due to the absence of the wall surface. In the wake, the small vortical structures convected from the upstream dissipate rapidly. This is not only because of lack of turbulence source, but also because the mean flow profile is jet type without deflection point due to rotation which is strongly inviscid stable. The quick dissipation of secondary vortex is another reason to make tip vortex relaminized quickly.

- The near field wake is screwed and laterally stretched and curved by the rotating primary vortex. Wake disturbances contributes to the fluctuation of the primary vortex and dissipate quickly when traveling downstream. In further downstream, the tip vortex becomes more stable and flow in the core region is more axisymmetric.

- On the cross-sections that are intersected with the wing, peak values of velocity fluctuations are found over the suction side of the wing where the shear layer separates from the rounded wingtip. The high level fluctuations are wrapped up into the vortex core and convected downstream. In the wake region, the peak of velocity fluctuation appears in the center of the vortex core and fluctuation level decreases rapidly downstream along the axial direction.

- Pressure perturbation field shows that the noise source locates in the tip region and acoustic waves propagate away from the wingtip. The fluctuations inside the tip vortex contribute to the pressure perturbations.

Acknowledgment

This work was sponsored by the Office of Naval Research (ONR) and monitored by Dr. Ron Joslin under grant number N00014-03-1-0492. The authors also thank the High Performance Computing Center of US Department of Defense for providing supercomputer hours.

DIRECT NUMERICAL SIMULATION FOR FLOW SEPARATION CONTROL NACA0012 AIRFOIL

(supported by AFOSR under grant F49620-01-1-0028)

Contributed by

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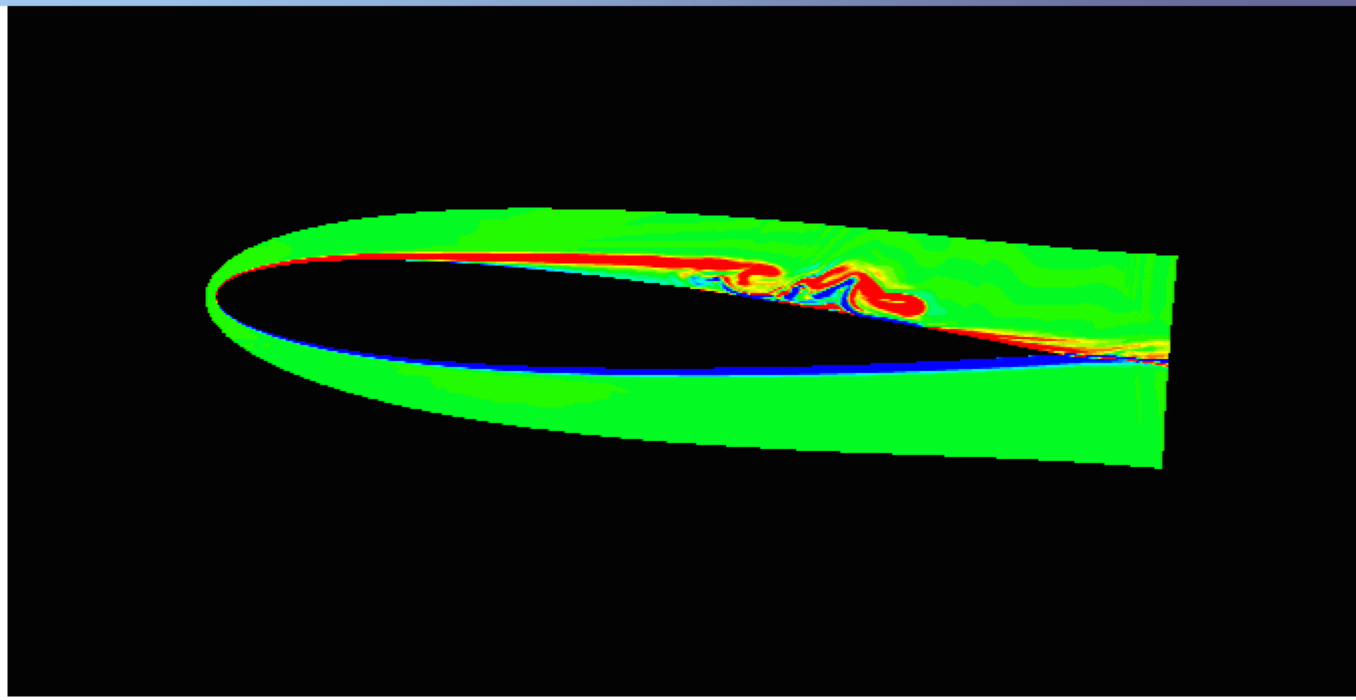
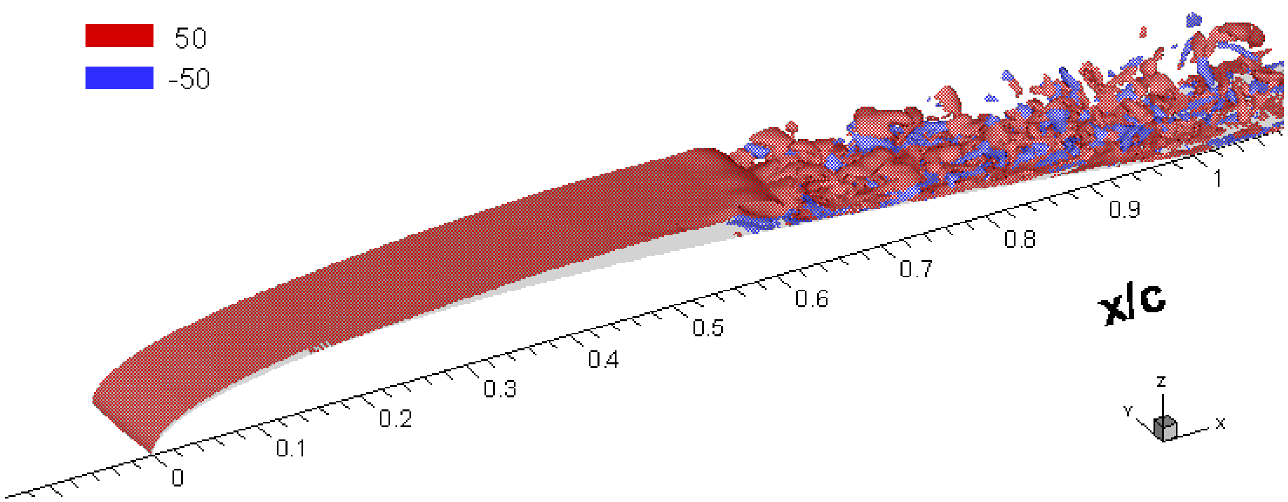
University of Texas at Arlington

No Blowing

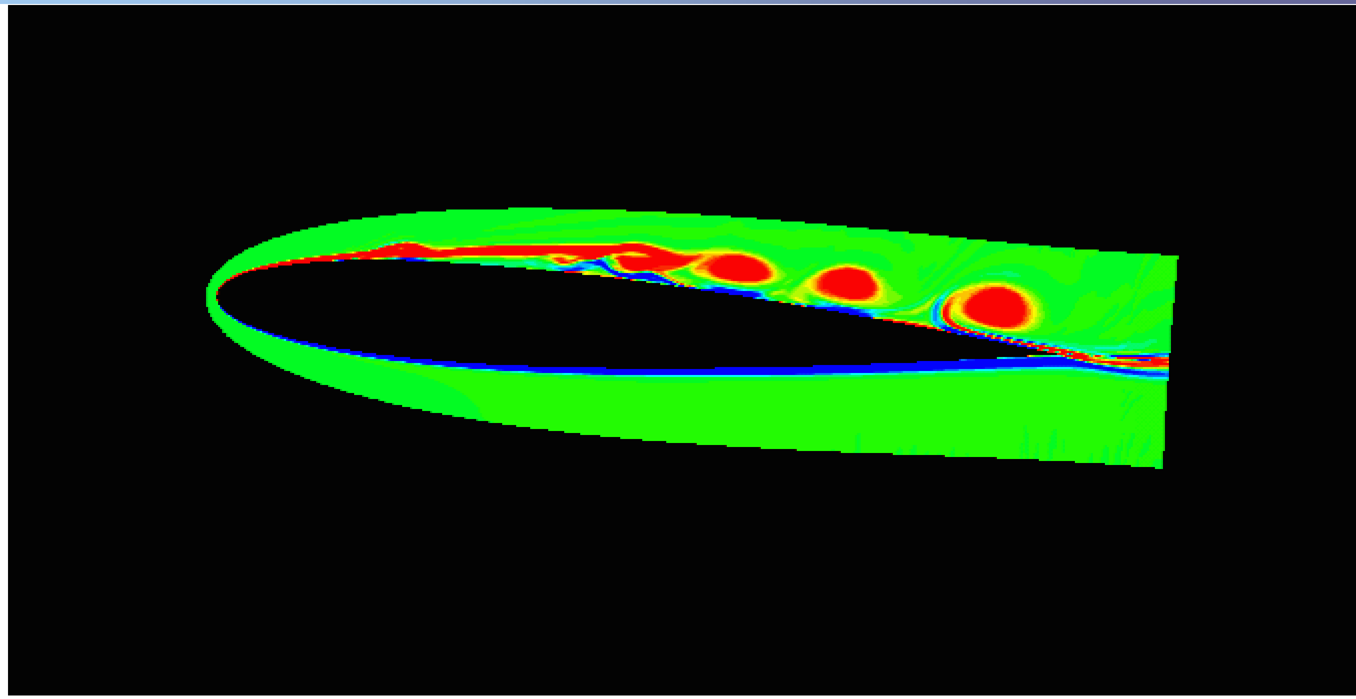
Spanwise vorticity

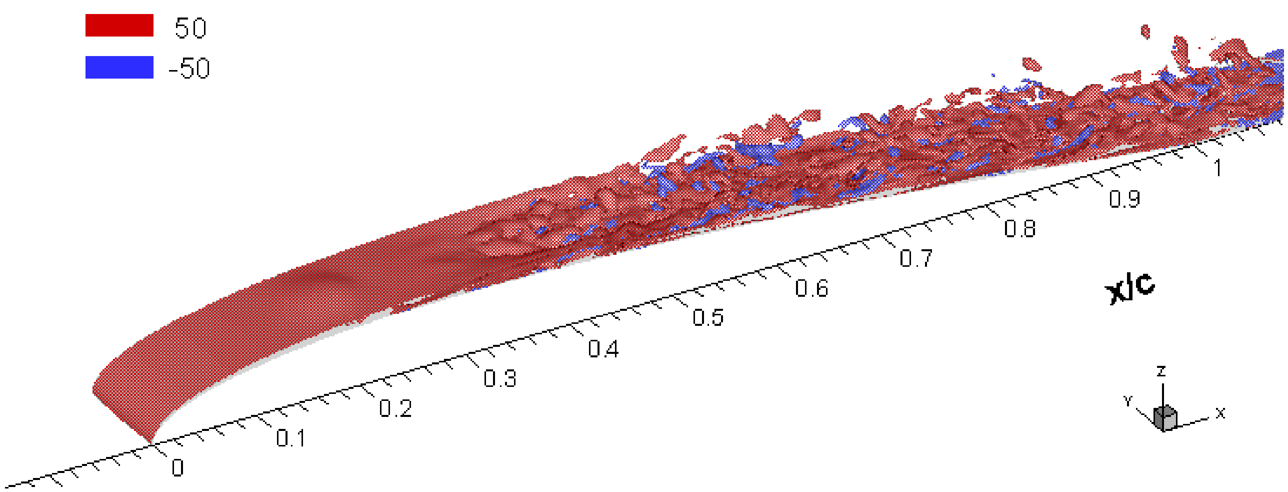




Pulsed Wall Normal Blowing

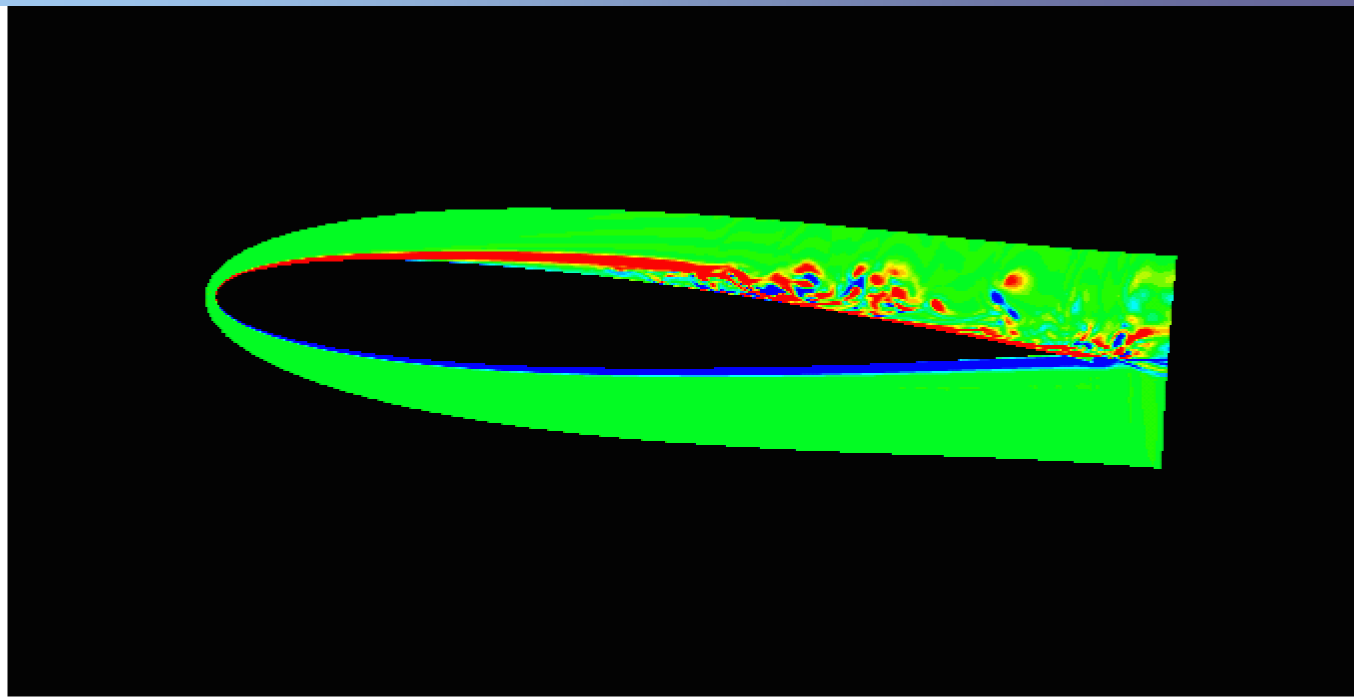
Spanwise vorticity

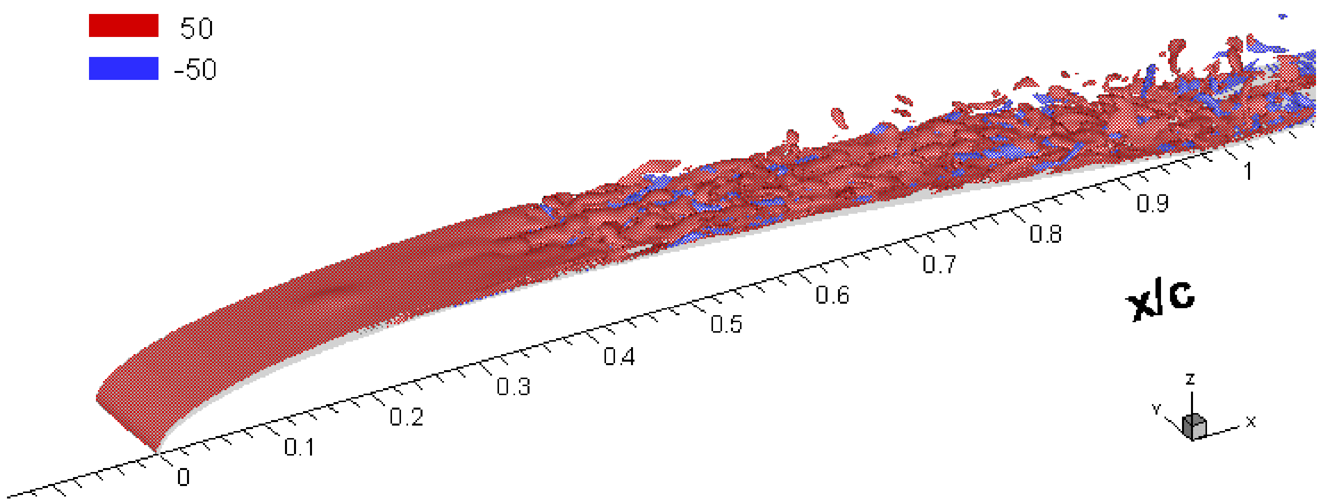


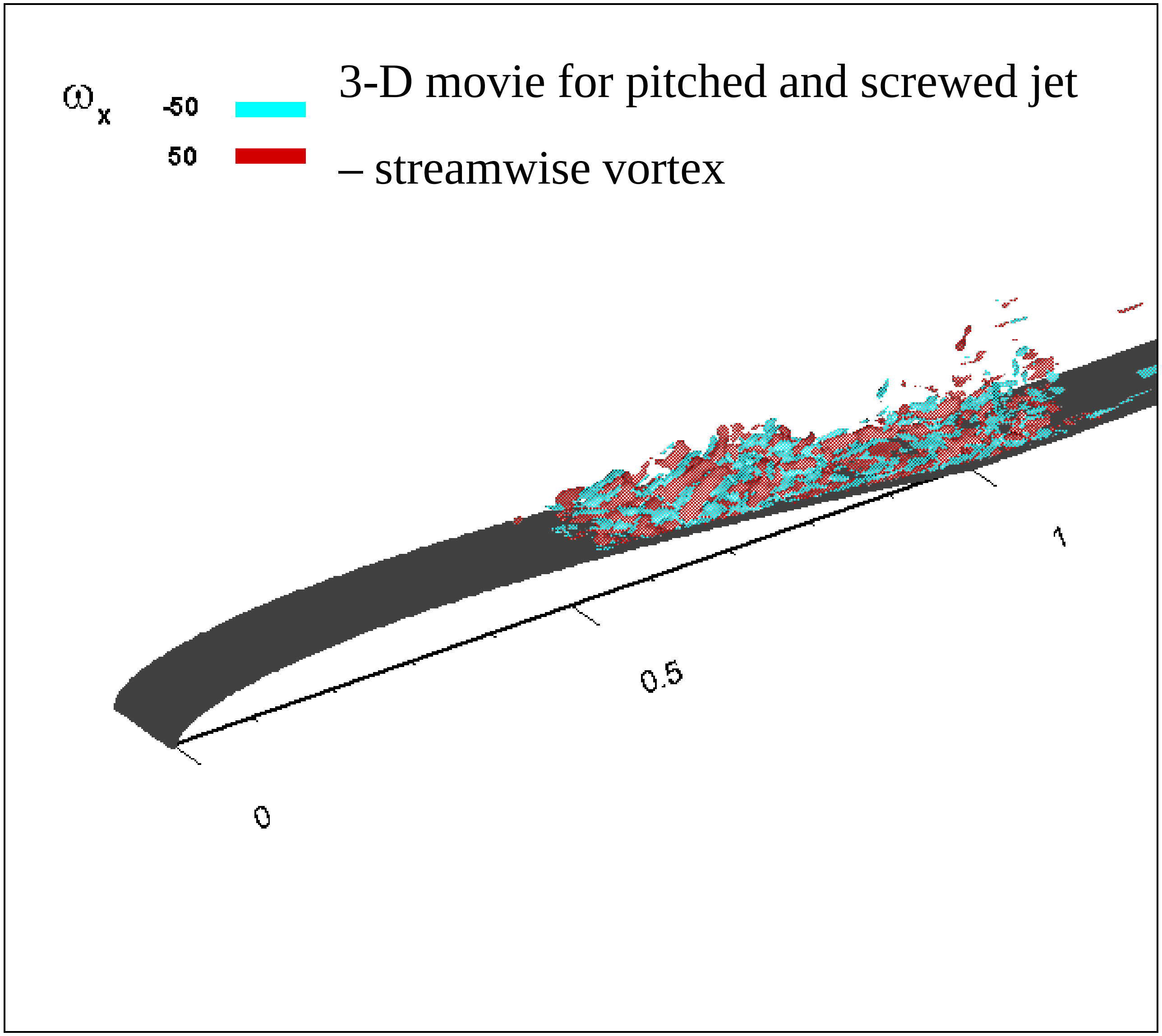


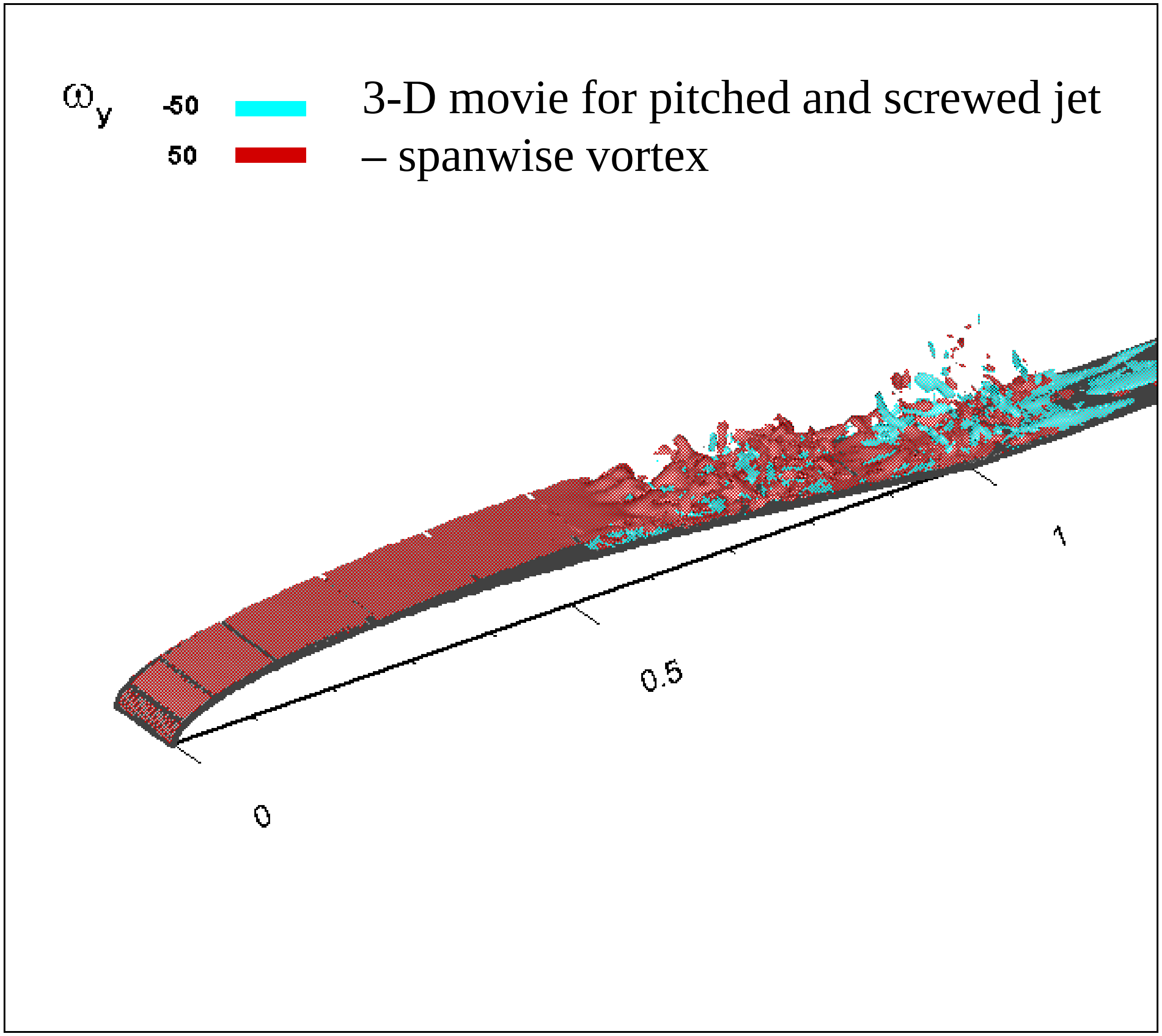
Pulsed Blowing at 30 Pitch Angle

Spanwise vorticity






ω_x
-50
50
3-D movie for pitched and screwed jet
– streamwise vortex
0
0.5
1


ω y
-50
50
3-D movie for pitched and screwed jet
– spanwise vortex
0
0.5
1

DIRECT NUMERICAL SIMULATION FOR FLOW SEPARATION CONTROL NACA0012 AIRFOIL

(supported by Lockheed Maritn)

Contributed by

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University of Texas at Arlington

August, 2002

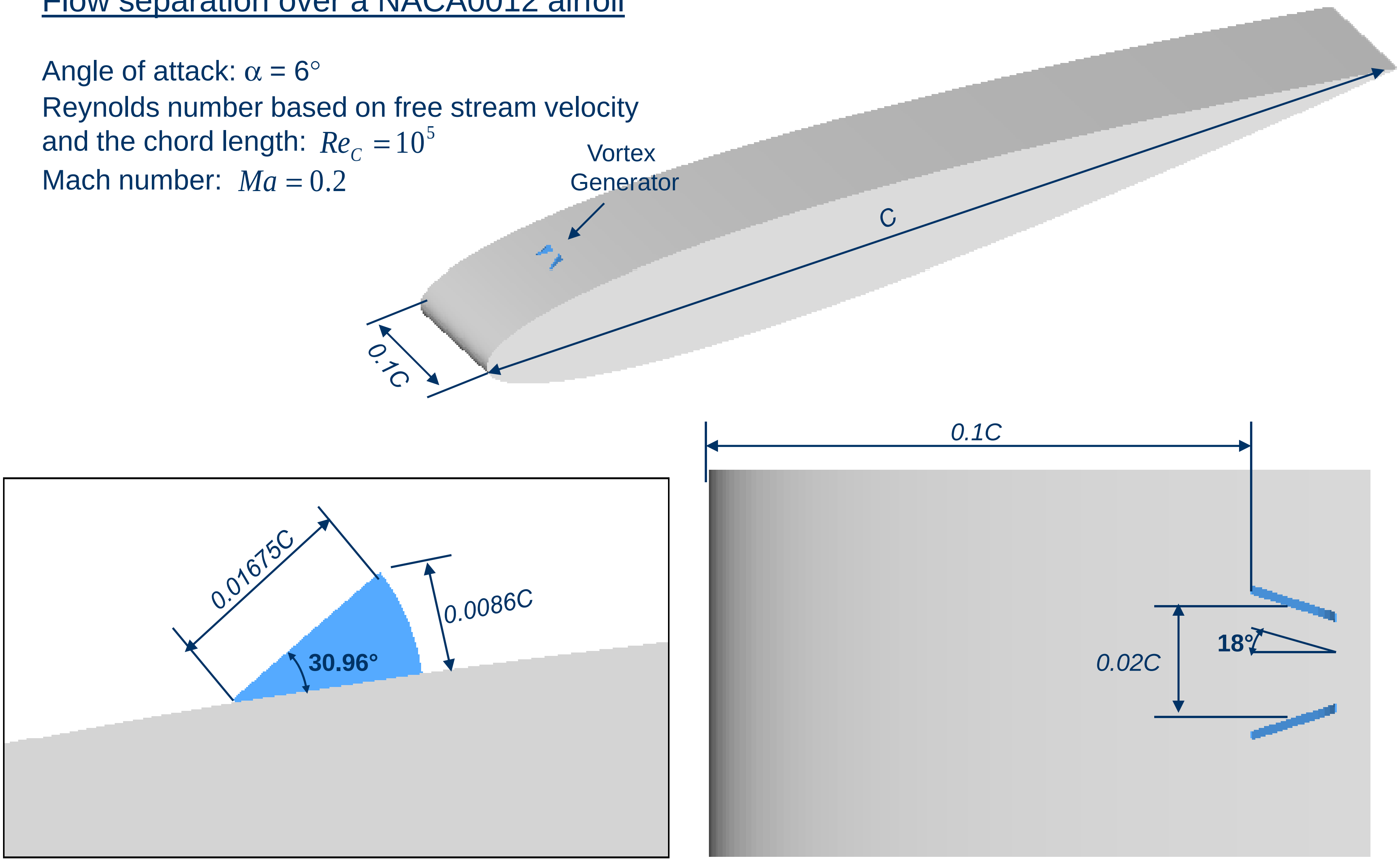
IV. Problem Formulation

Flow separation over a NACA0012 airfoil

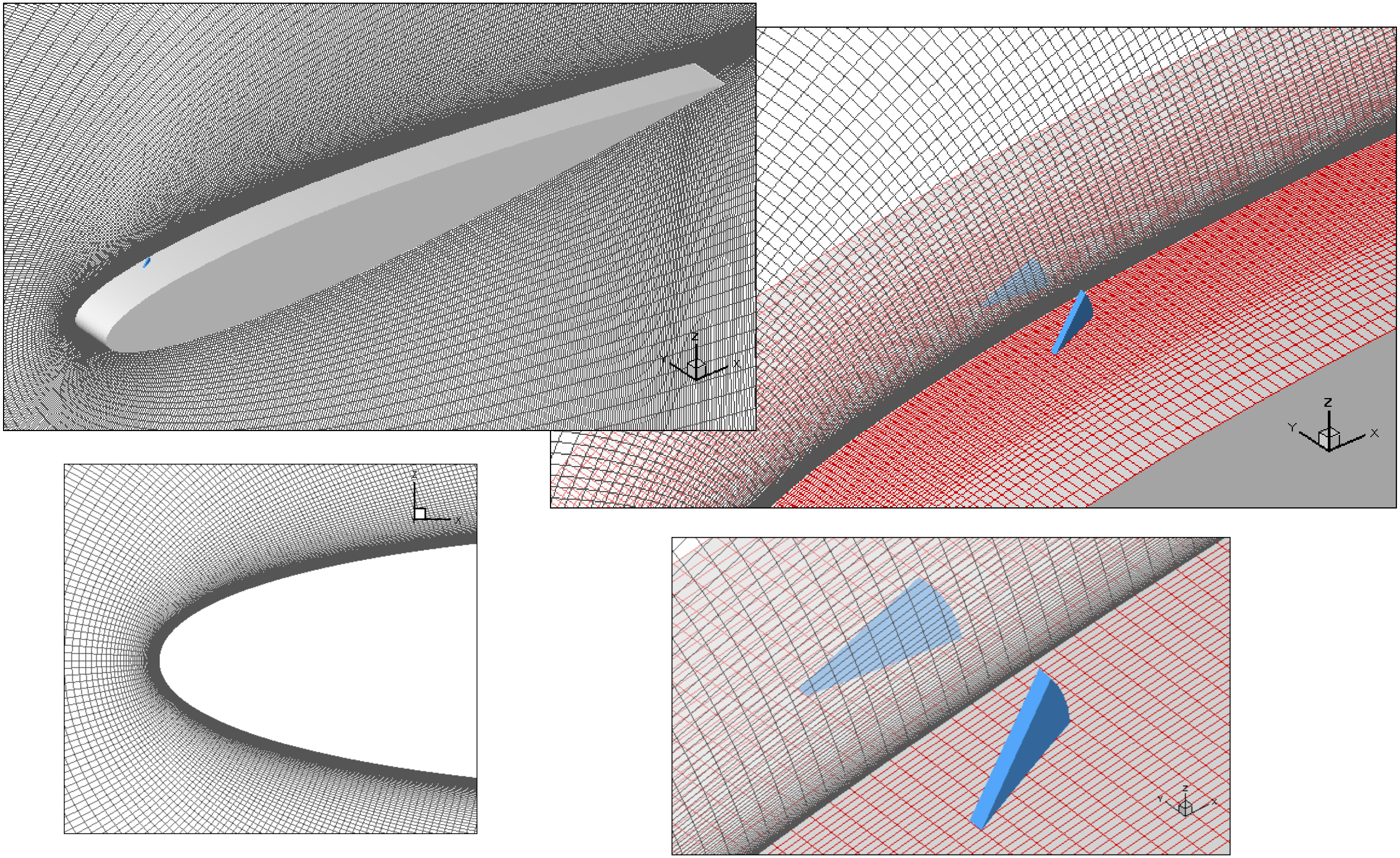
Angle of attack: $\alpha = 6°$

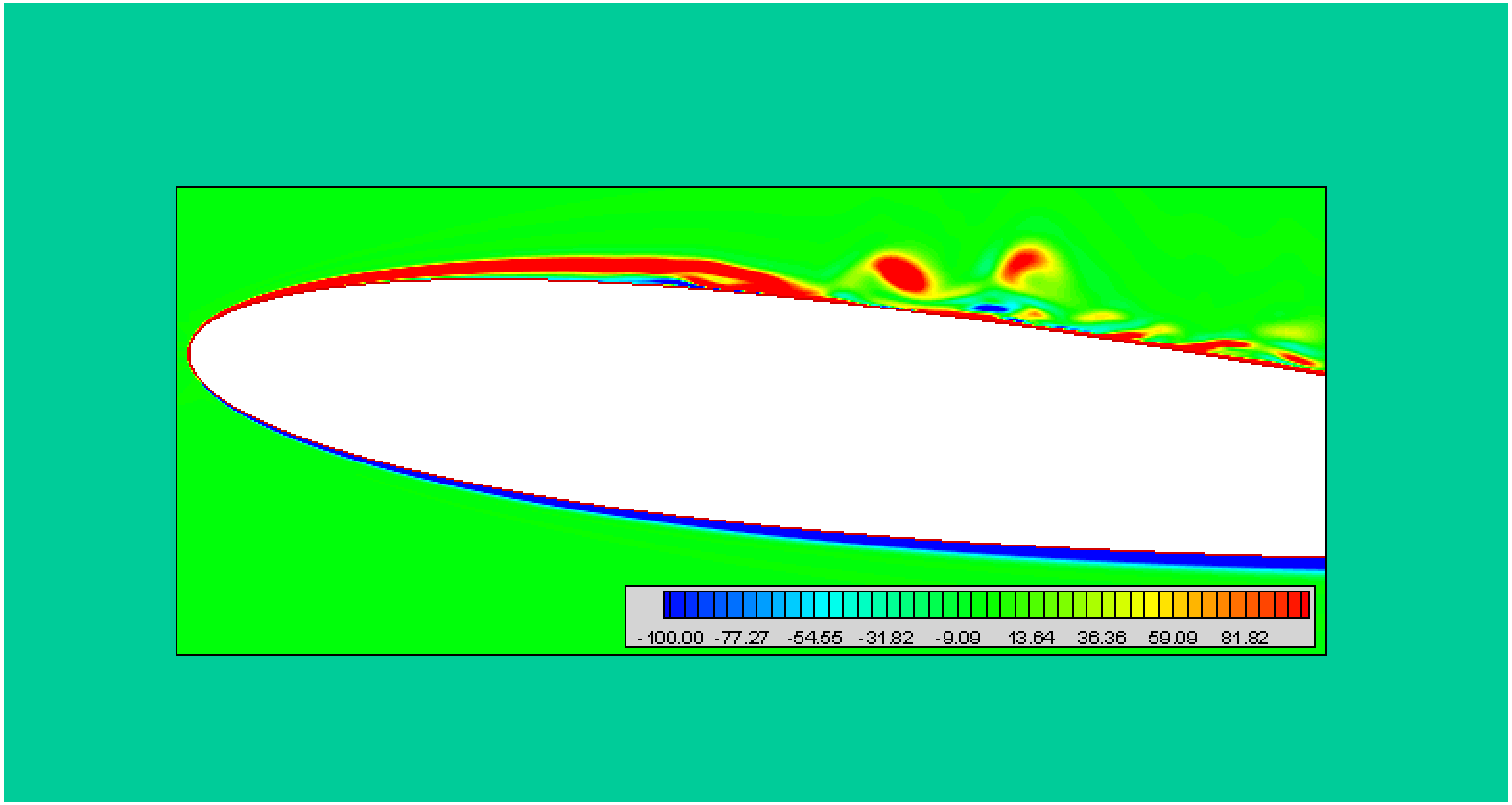
Reynolds number based on free stream velocity and the chord length: $Re_C = 10^5$

Mach number: $Ma = 0.2$



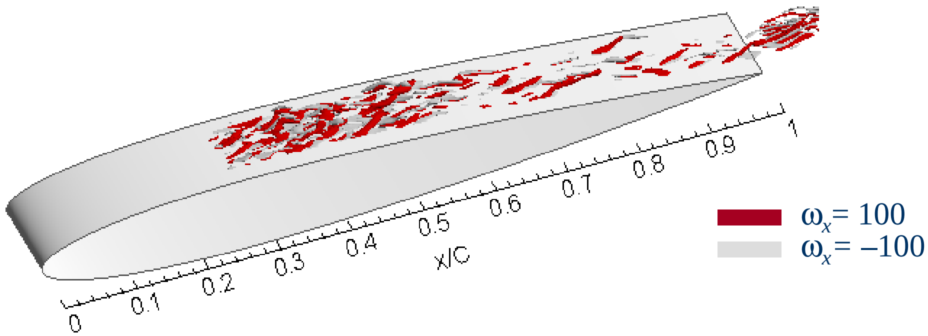
Number of grid points: 840×90×120



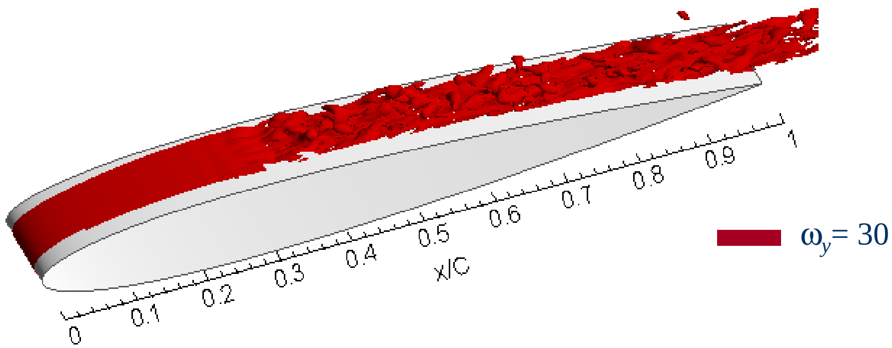


Animation. Contours of instantaneous spanwise vorticity on the mid-plane

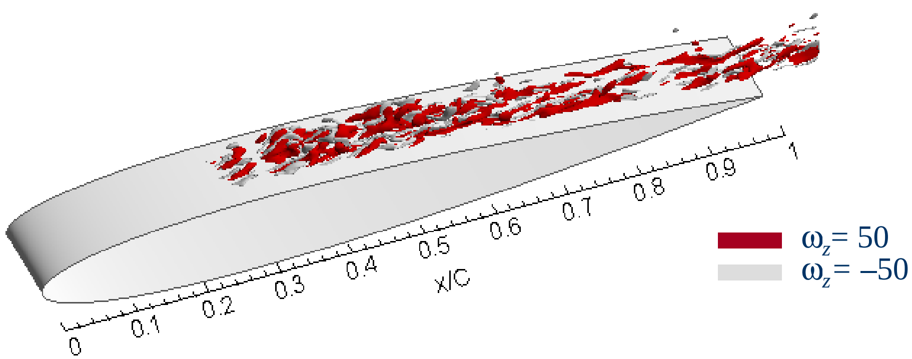
Instantaneous Flow Field (Cont'd)



Isosurfaces of streamwise vorticity



Isosurfaces of spwanwise vorticity



Isosurfaces of wall-normal vorticity

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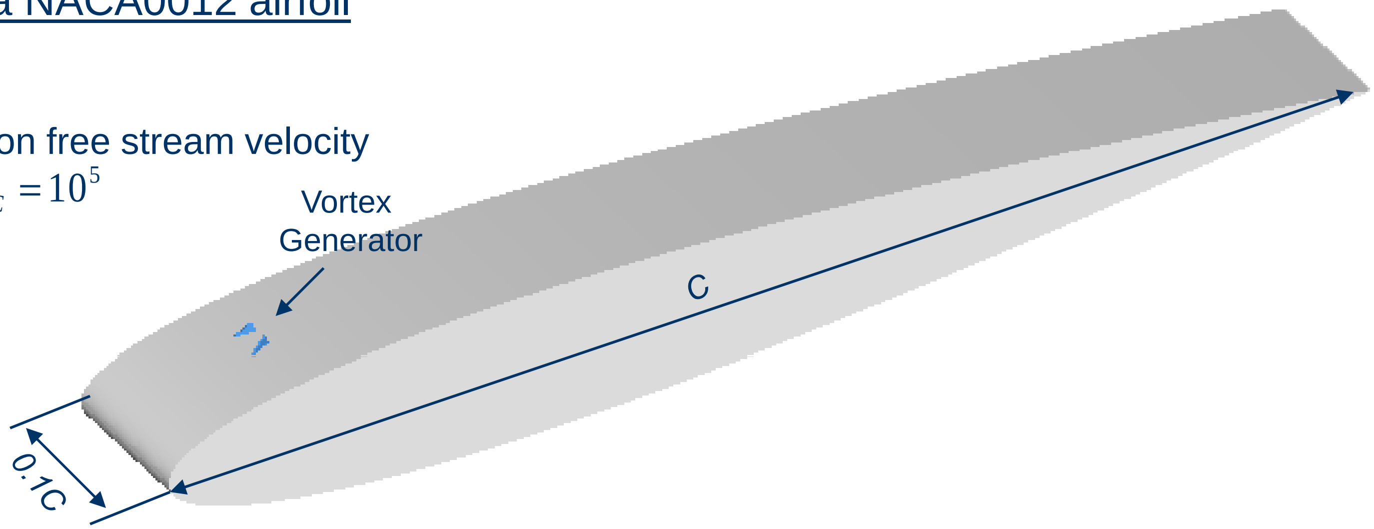

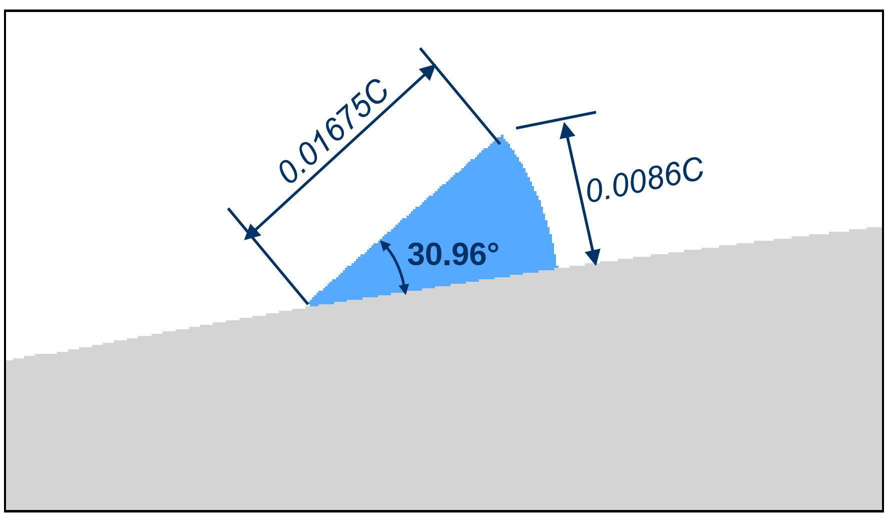

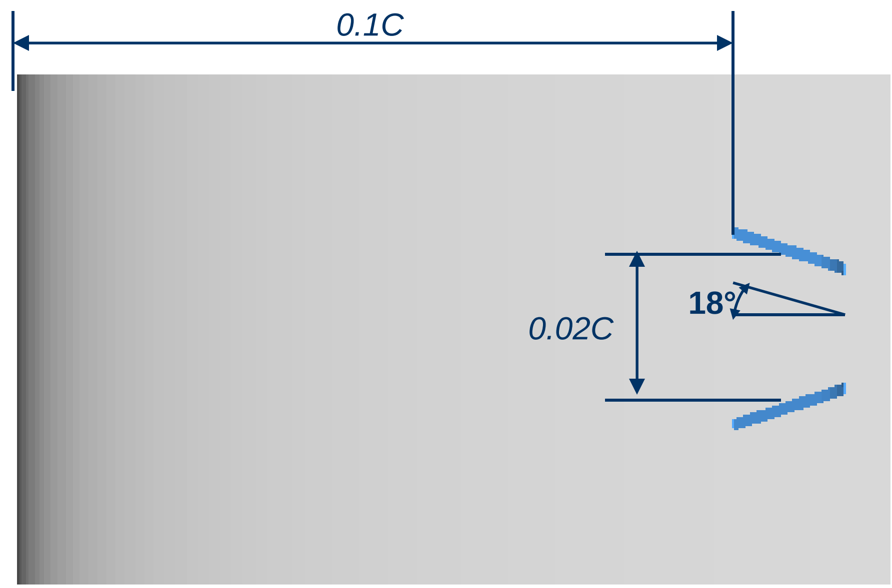

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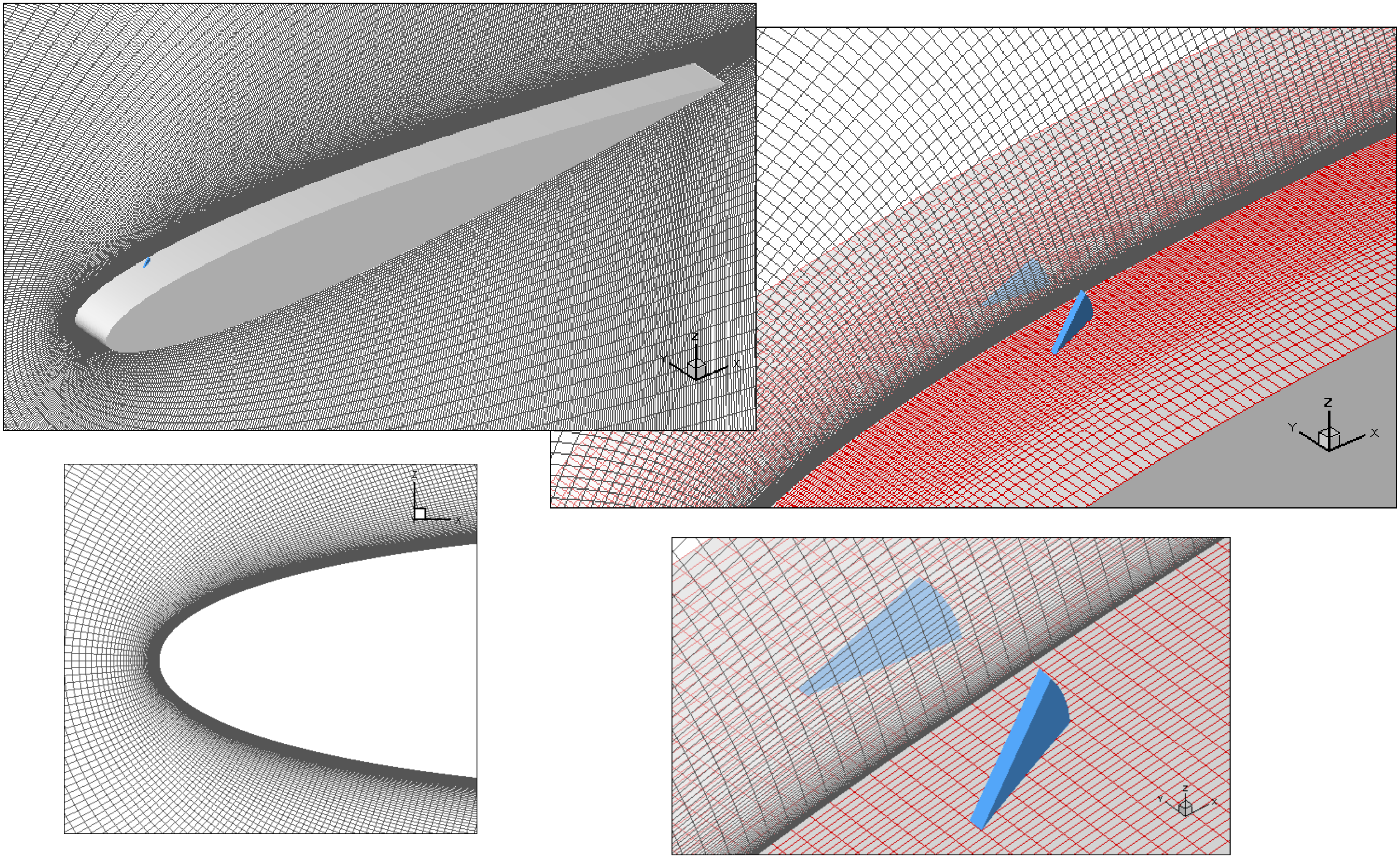
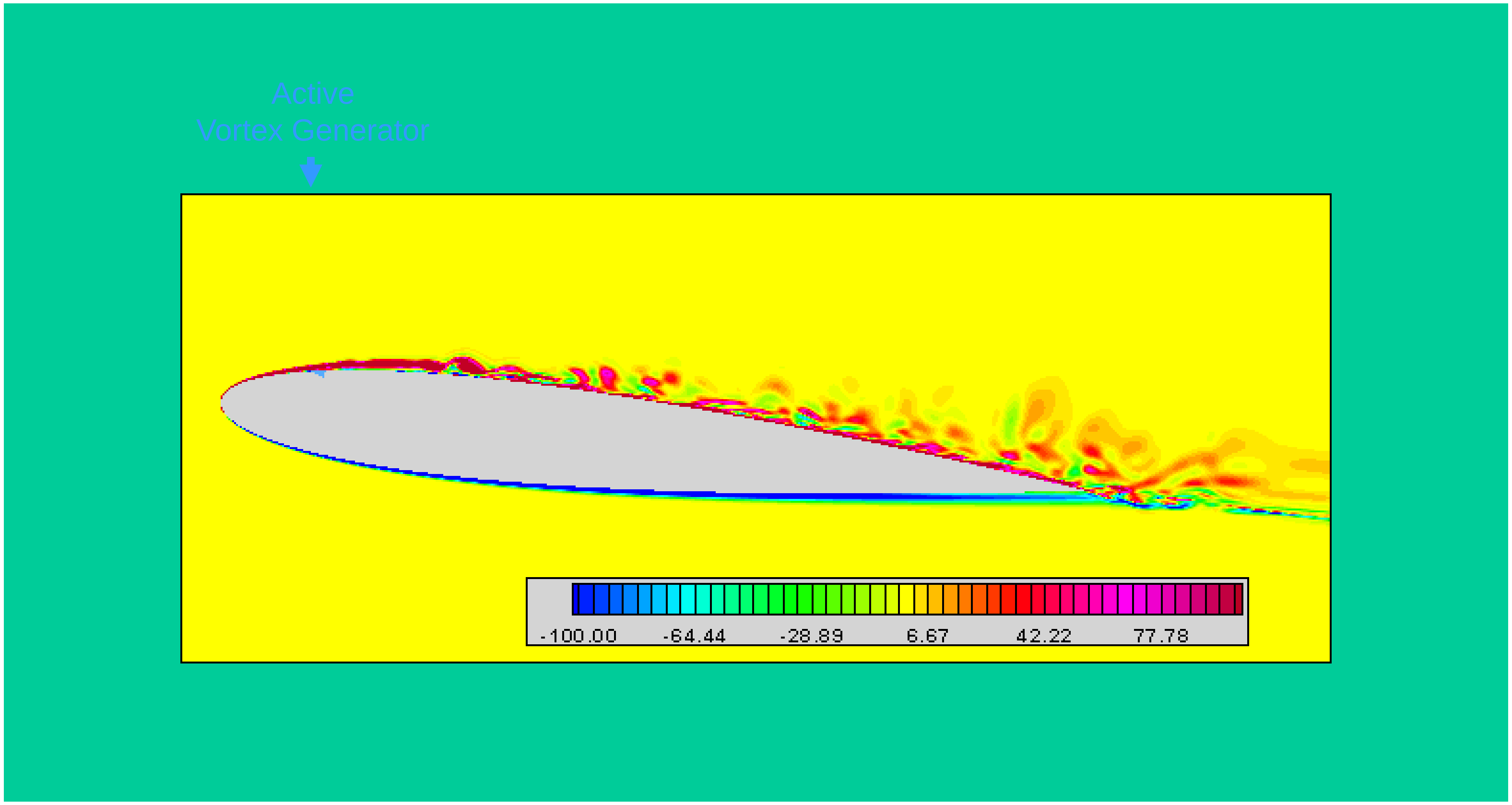


Instantaneous Flow Field (Cont'd)



Animation. Contours of instantaneous spanwise vorticity on the mid-plane

Thank You