

Computational and Physical Aspects of UAV Vortical Flows

**Aerodynamic Issues Of Unmanned Air Vehicles
University of Bath, UK, Nov 4-5, 2002**



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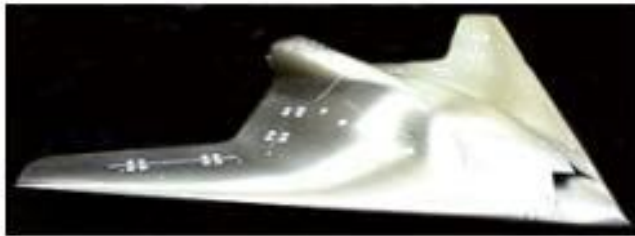
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Broad Range of Mission Requirements & Concepts



UAV/HALE



UCAV's



MAV's



Prediction Challenges



Unconventional Design

Configuration

- Broad range of vehicle size
- Sensor-suite dictated
- High-aspect-ratio wings
- High-aspect-ratio swept wings
- Joined wings
- Delta wing platforms
 - Moderate sweep ($\Lambda > 60^\circ$)
 - Low sweep ($\Lambda < 60^\circ$)



Flow Conditions

- Incompressible to transonic
- $10^4 < Re < 10^6$
- Laminar-transitional flows
- High-altitude
- Low drag aerodynamics

Extreme Flight Conditions



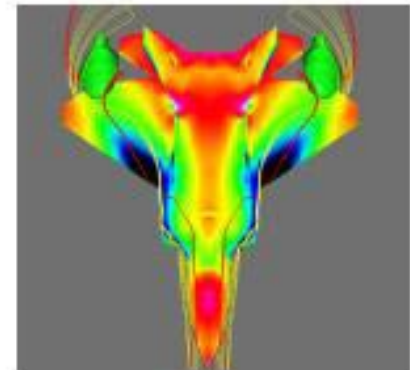
Viscous Flow Simulation for Air Vehicles



Modeling Hierarchy

Reynolds Averaged Navier-Stokes Eqs. (RANS)

- Full aircraft simulation
- 1 or 2-equation models
- 2nd-order algorithms

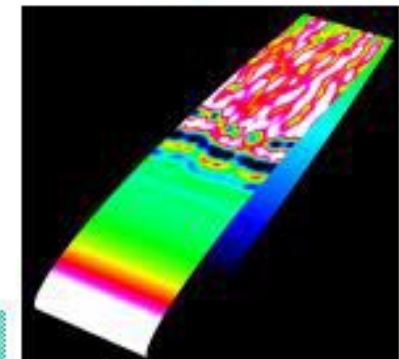


STEADY

Hybrid approaches

Large-Eddy Simulation (LES)

- Component flow analysis
- Spatio-temporal turbulent large-scale structure
- Sub-grid scale models

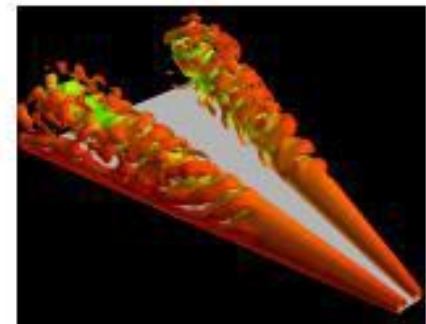
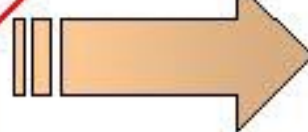


UNSTEADY

High-order algorithms

Direct Numerical Simulation (DNS)

- Transitional flows
- Flow control devices
- Micro Air Vehicles (MAV's)



Flow Control

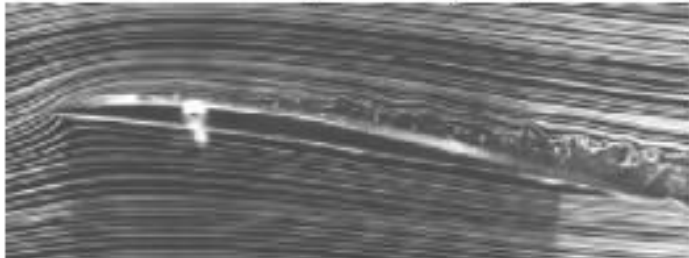


Prediction of Low-Re Airfoil Flows

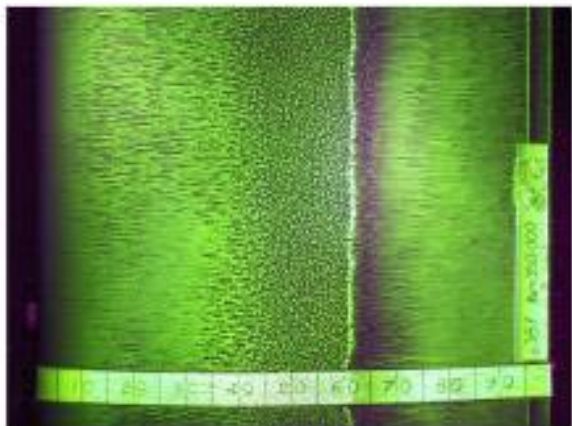


Experiment

Mueller et al, $Re = 47,000$, $\alpha = 8^\circ$

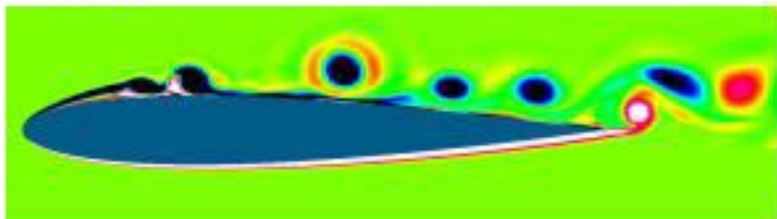


Selig et al, $Re = 3.5 \times 10^6$, $\alpha = 2^\circ$

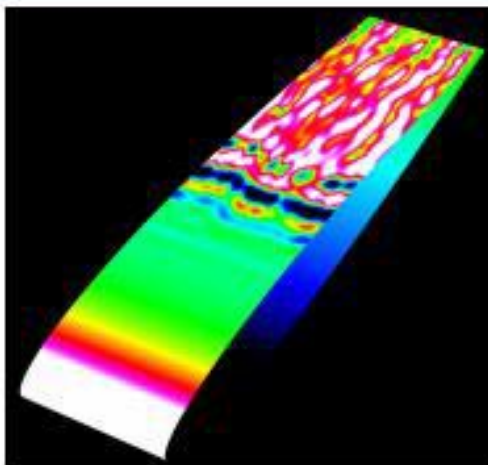


Computation

2-D



3-D



$Re = 1.0 \times 10^5$, $\alpha = 5^\circ$

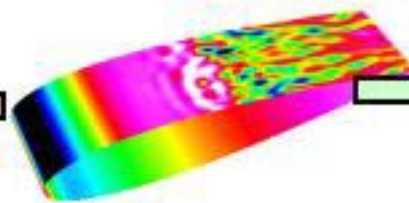


Impact of Scheme Accuracy on Prediction of Transitional Flows

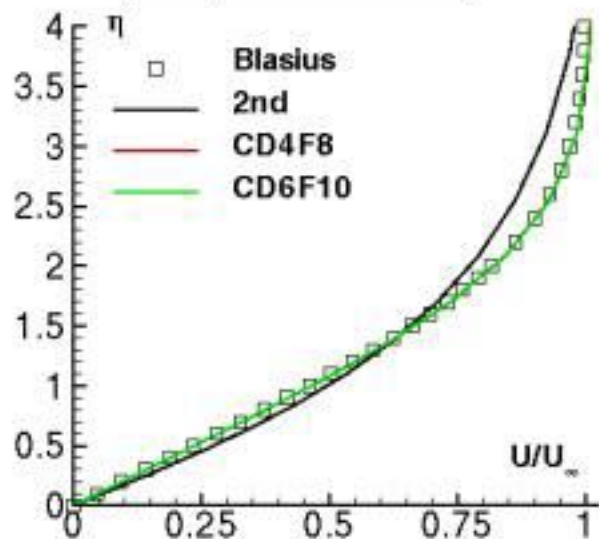


Base flow prediction:
Boundary layer

Growth of instabilities:
Shear layer

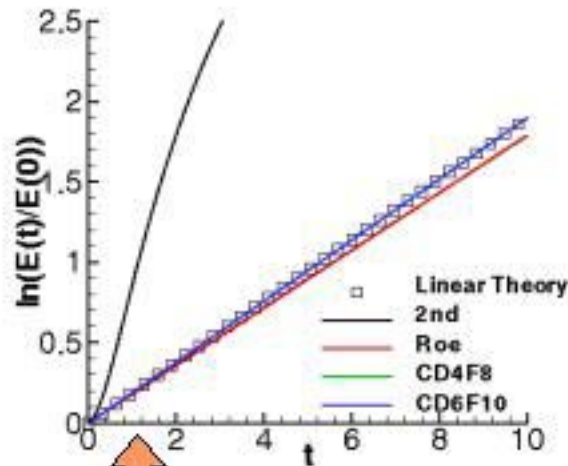


$$Re_x = 1.45 \times 10^5$$

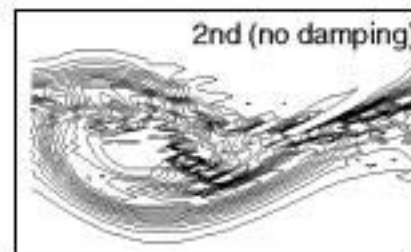
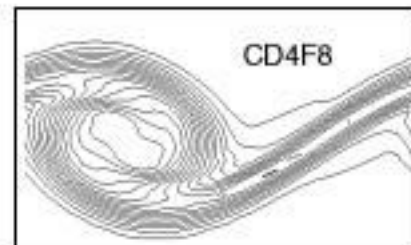


12 points in b/l

$$U = 0.5 (1 + \tanh(y))$$
$$M_\infty = 0.05$$



Grid: 29 X 45



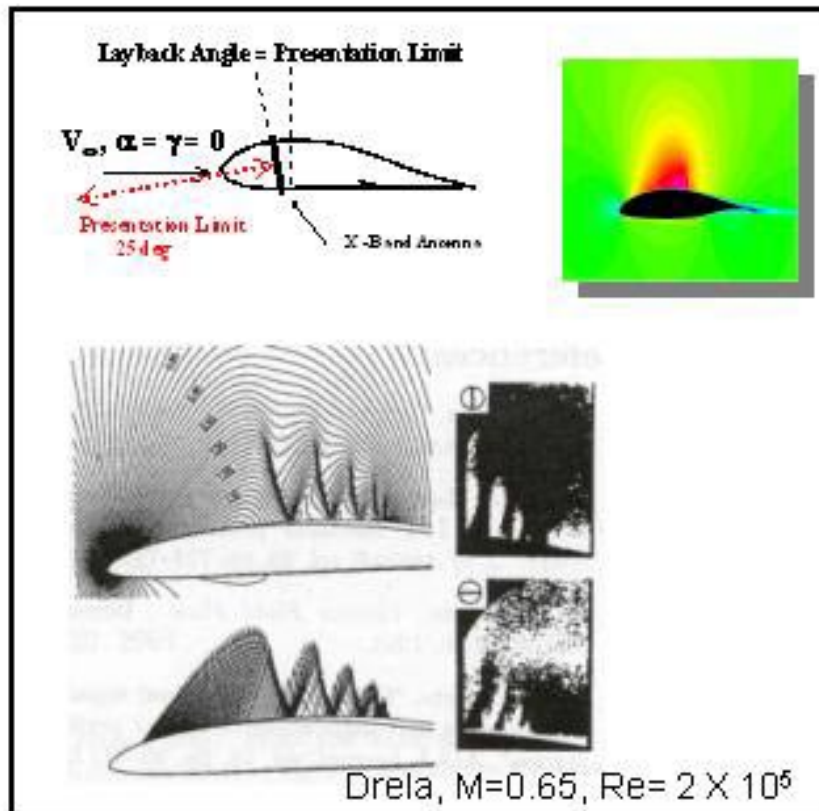
$$E(t) = \int_0^L \int_{-\infty}^{\infty} (\hat{u}^2 + \hat{v}^2) dy dx$$



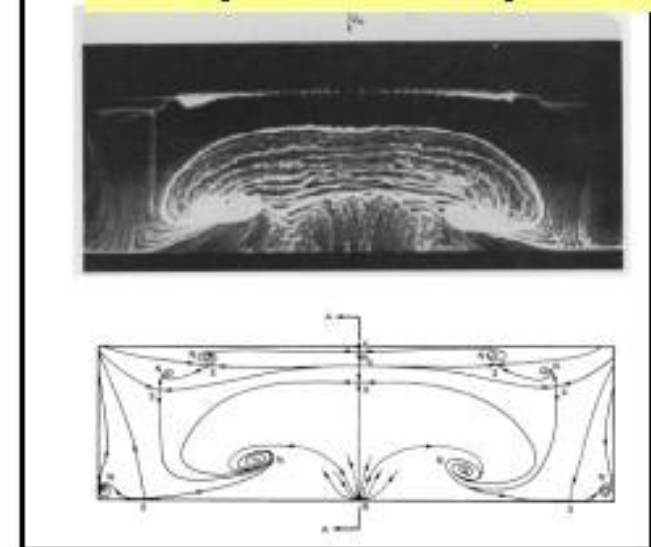
Compressibility and 3-D Effects



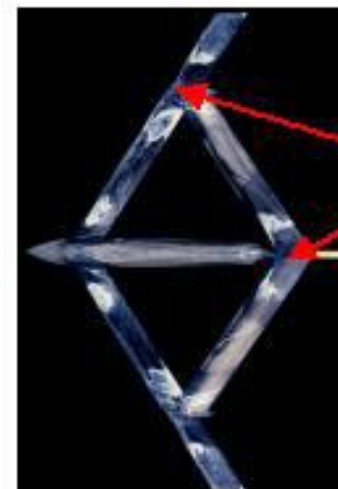
Shock / B.L. Interactions



Complex 3-D Separation



Peake & Tobak



Juncture flows



Issues for the Accurate Prediction of Low-Re High-AR Wing Sections



- *Separation and transition* must be captured accurately
- *High-resolution unsteady* tools required
- *RANS low-order* procedures not suitable for transitional flows
- Coupling of transition with body motion
(implications for aeroelasticity and vehicle dynamics)
- *Crossflow instability* for swept wings
- Effect of gusts, crosswinds and aircraft dynamics
- Hysteresis effects
- Complex 3-D separation and juncture flows
- Transonic shock b/l interactions
- Surface heating effects on low-Re aerodynamics





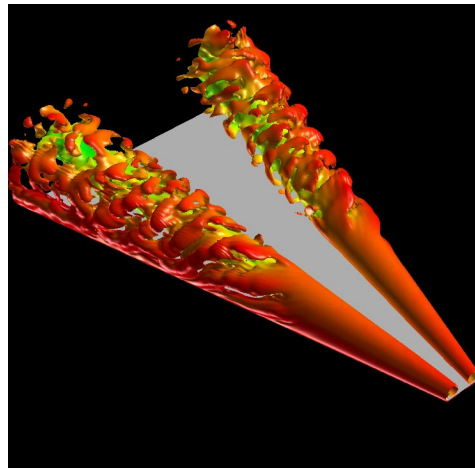
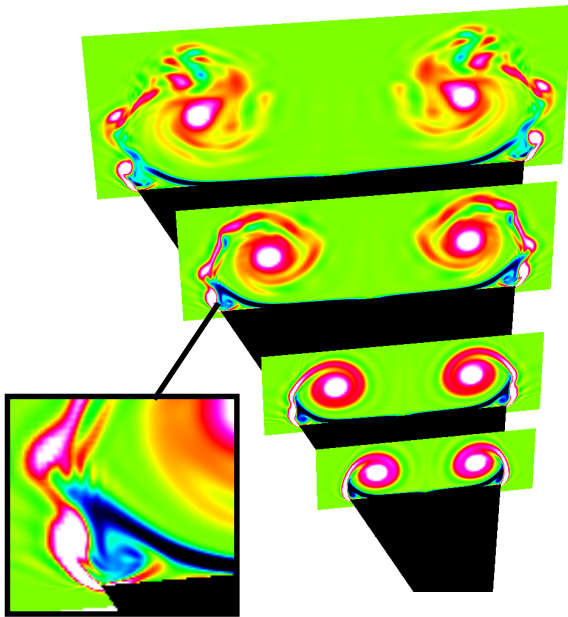
Delta Wing Platforms



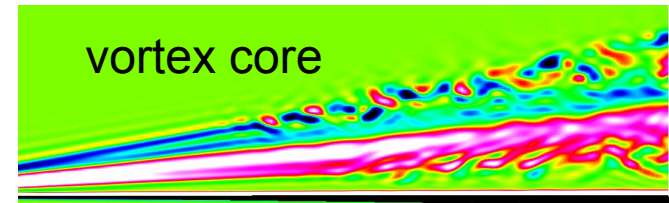
Flow Challenges

- Leading-edge vortex formation
- Feeding sheet structure
- Vortex wandering
- Vortex core dynamics
- Vortex asymmetries
- Interaction of multiple vortices
- Vortex breakdown & stall
- Hysteresis effects
- Dynamic motion effects
- Multiple time scales
- Reynolds number effects
- Unsteady loading (buffeting)
- Effect of wing platform leading and trailing edge shaping
- Shear-layer and boundary layer transition
- Flow structure for moderate sweep

Shear Layer Structure on Delta Wings



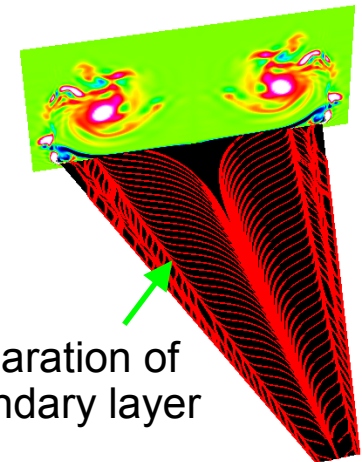
$$\Lambda = 75^\circ, \text{Re} = 50,000, \alpha = 25^\circ$$



What is the origin of vortical sub-structures?

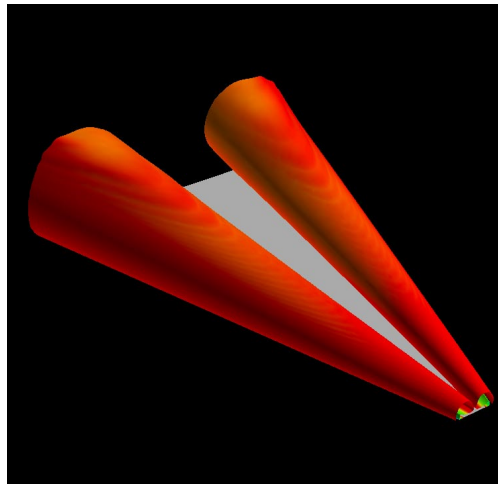
- Experimental disturbances
- Interaction of S/L with secondary flow, trailing-edge separation and breakdown
- Shear-layer instability modes
- Steady vs unsteady substructures

What is the relation of the surface flow pattern to the S/L transition process?



Laminar separation of surface boundary layer

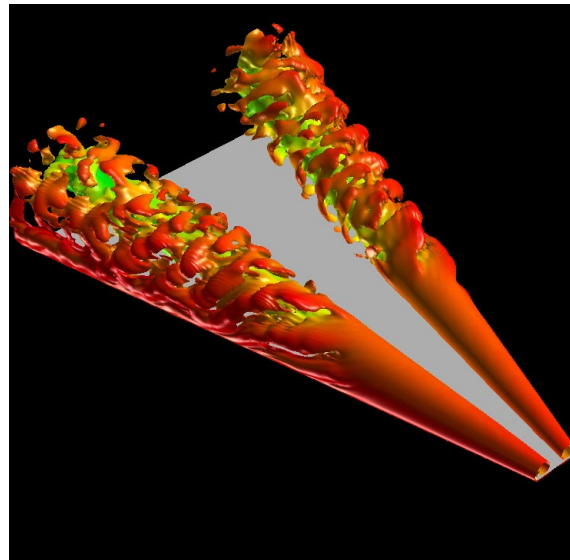
Moderate-Re Flows on Delta Wings: Evolution of Shear Layer



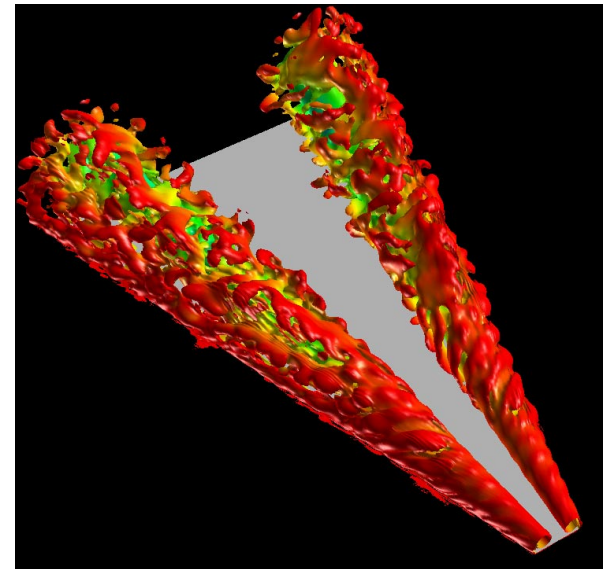
$Re = 10^4$

$\Lambda = 75^\circ, \alpha = 25^\circ$

$Re = 5 \times 10^4$



$Re = 10^5$



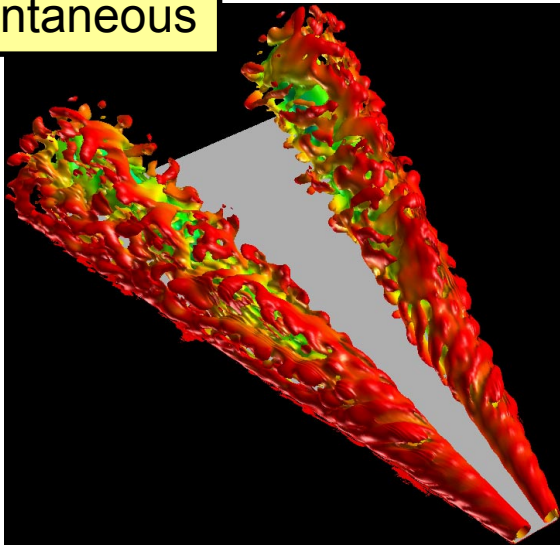
Increasing Re

Complex flow field evolution in transitional regime

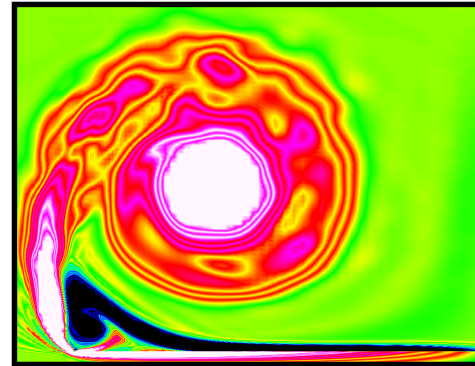
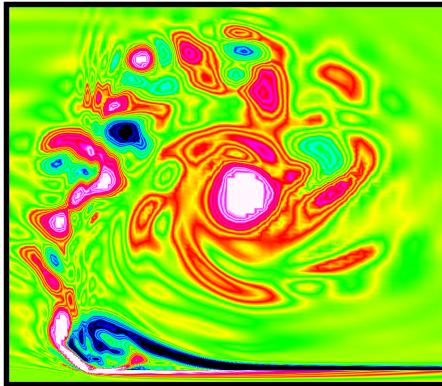
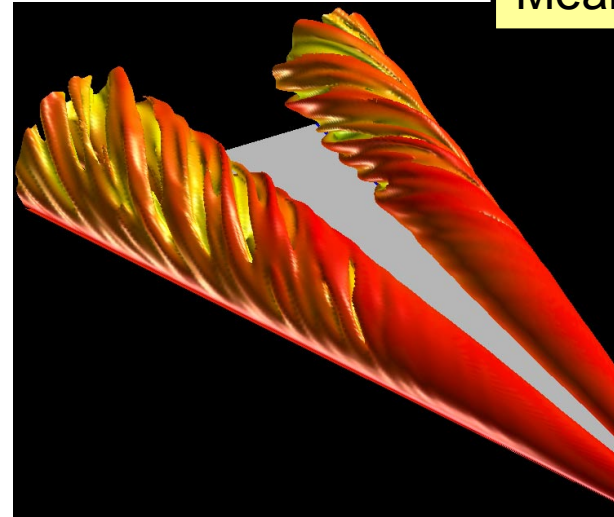
Instantaneous and Mean Representations of Transitional Shear Layer

$$\Lambda = 75^\circ, \text{Re} = 100,000, \alpha = 25^\circ$$

Instantaneous



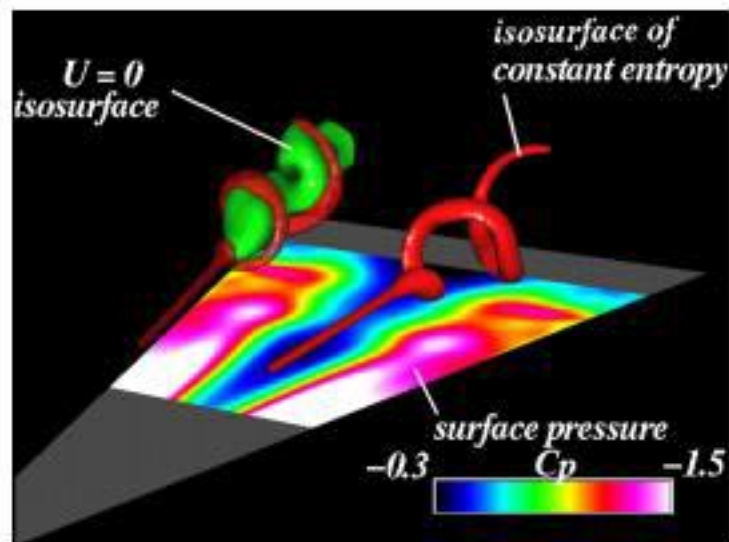
Mean



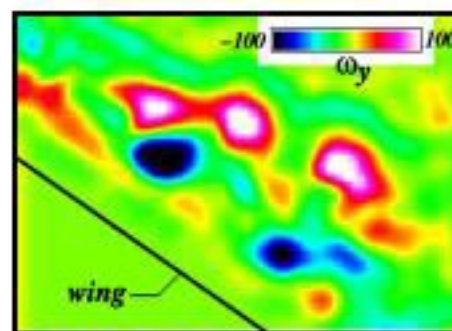
Are steady & unsteady sub-structures distinct phenomena or simply different representations of transitional/turbulent shear-layer dynamics ?



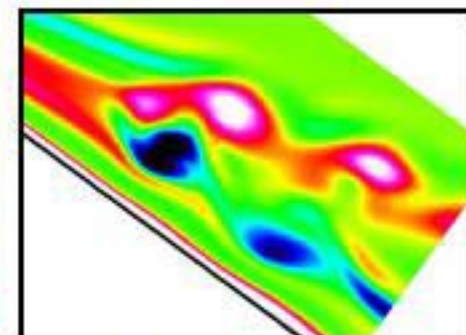
Physics of Vortex Breakdown



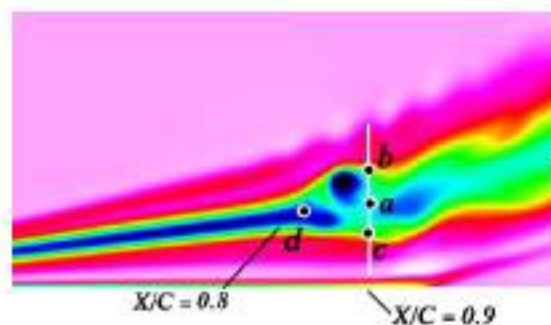
Experiment



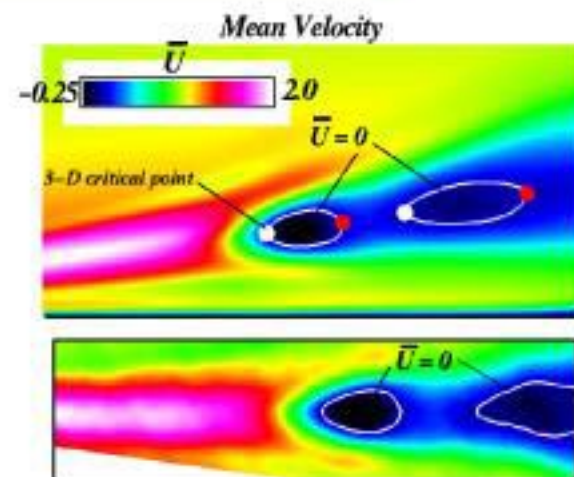
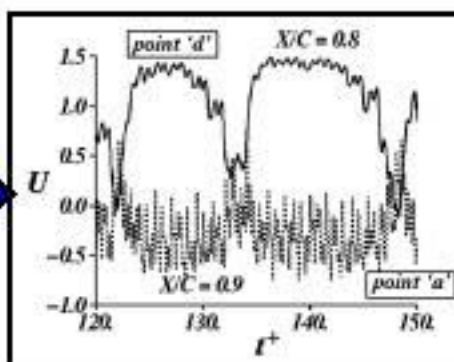
Computation



Instantaneous structure



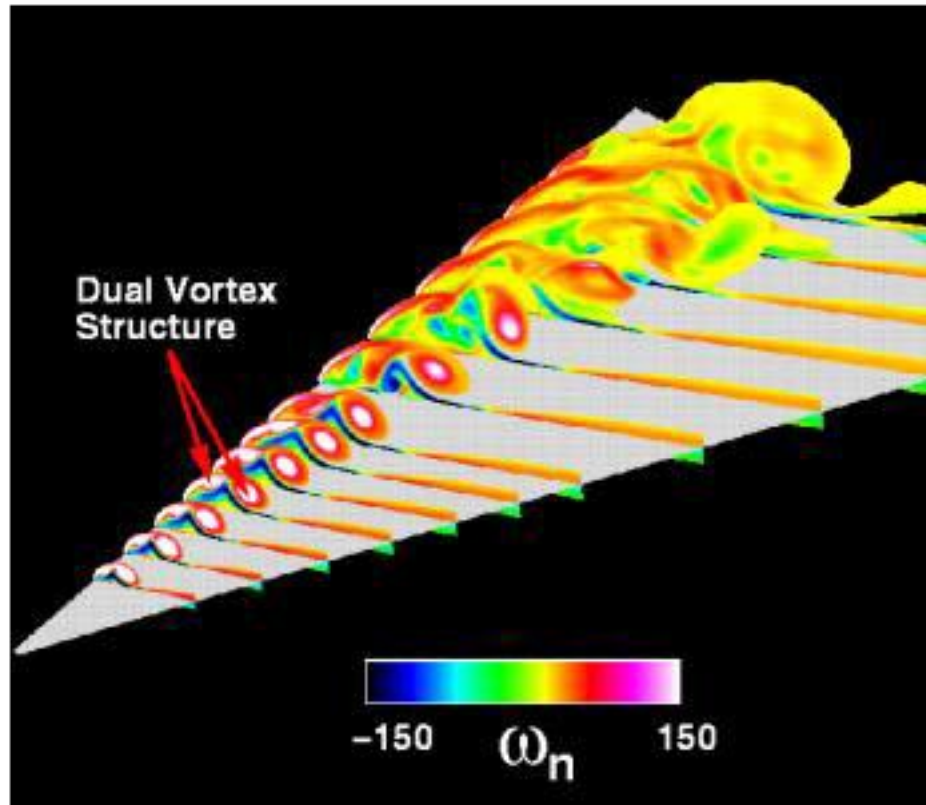
Breakdown fluctuations



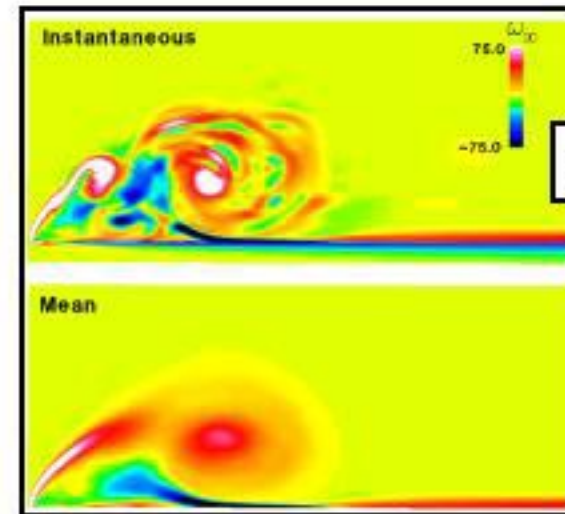
Mean Flow



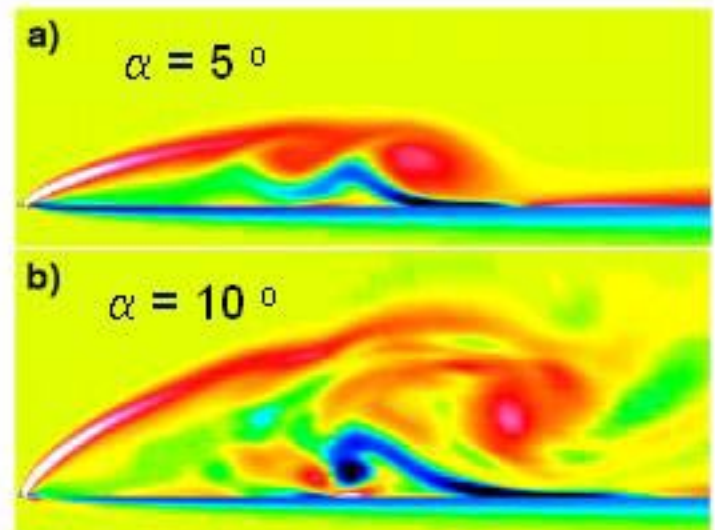
Delta Wing Flow Structure for Moderate Sweep Angles



$\Lambda = 50^\circ, \alpha = 10^\circ, Re = 20,000$

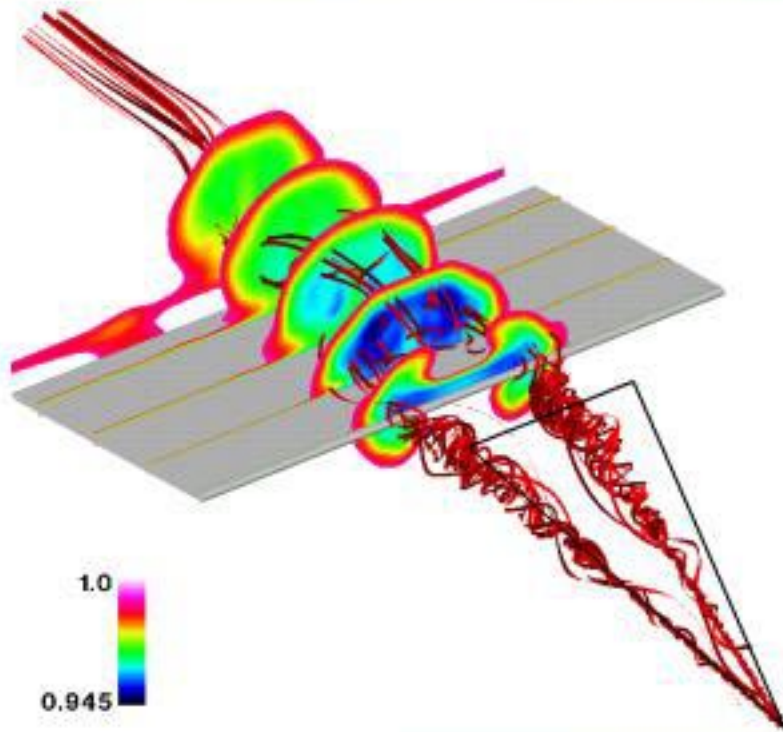


$\alpha = 15^\circ$

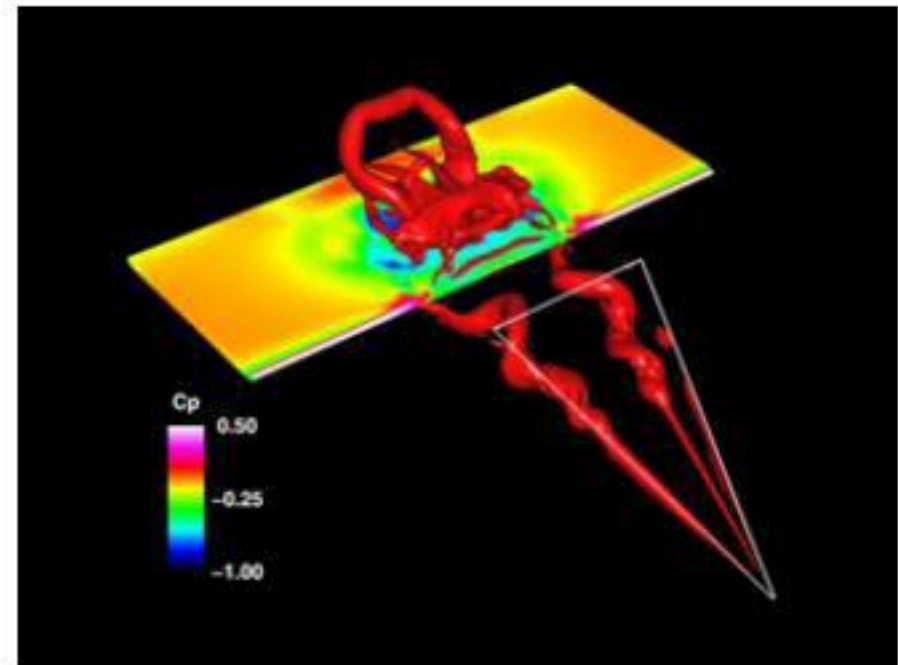




Physic of Vortex/Surface Interactions



Pt



Physical Mechanisms:

- spiral instability
- fin leading-edge separation
- breakdown fluctuations
- vortex distortion & splitting
- Feedback between breakdown and fin separation region



Some Key Issues



- Need to reinvigorate vortex flow research with emphasis on UAV applications
- Unconventional flight conditions/configurations demand combined experimental / numerical approaches
- Flows are inherently unsteady, possibly transitional and always three-dimensional
- High-fidelity unsteady numerical tools suitable for the nearly-incompressible to the transonic regimes are required
- Simulation of coupled phenomena is essential, *i.e.* fluid-structure interactions, flow control and vehicles dynamics
- High-fidelity tools needed to guide more affordable design approaches