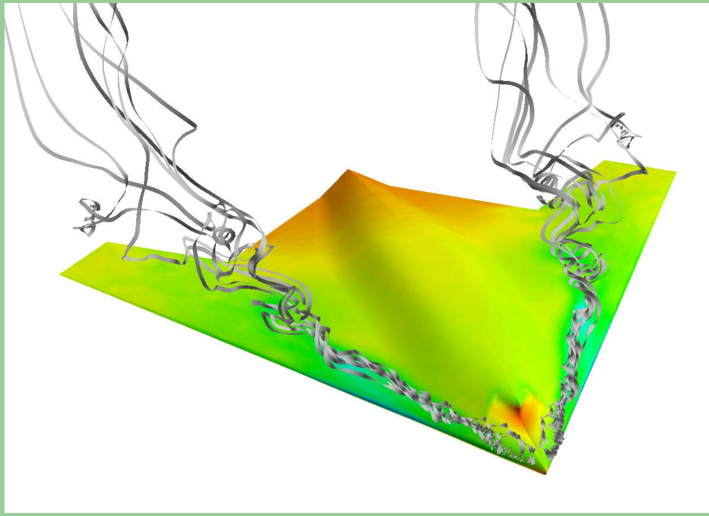
Comparison of Numerical Predictions and Wind Tunnel Results for a Pitching Uninhabited Combat Air Vehicle

Russell M. Cummings, Scott A. Morton, and Stefan G. Siegel

Department of Aeronautics
United States Air Force Academy
USAF Academy, CO



Outline

- Introduction
- Dynamic Stall/Lift
- UCAV Configuration
- Experimental Results
- Numerical Method
- Static Results
- Pitching Results
- Conclusions

Introduction

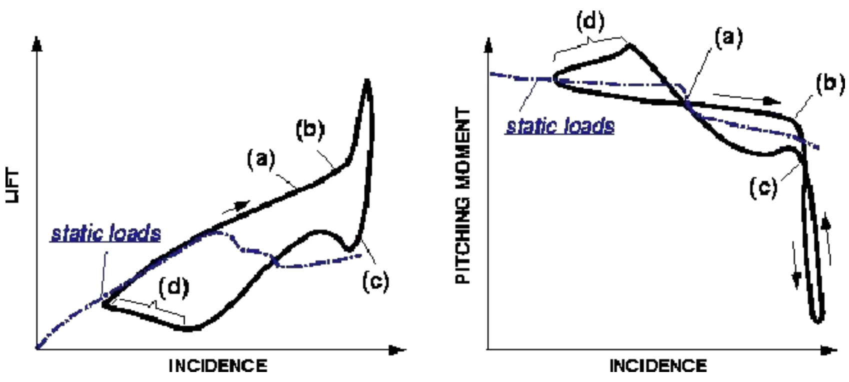
- UCAV's are playing an important role in current military tactics
- Predator and Global Hawk are becoming essential elements of current operations
- X-45A represents future configurations

Introduction

- Some issues to explore in order to take advantage of a UCAV's uninhabited state:
  - High g maneuvering
  - Compact configurations
  - Novel control actuation
  - Morphing wings
  - MEMS-based control systems
  - Semi-autonomous flight
  - Increased use of composites
  - Novel propulsion systems
  - Dynamic stall/lift

Dynamic Stall/Lift

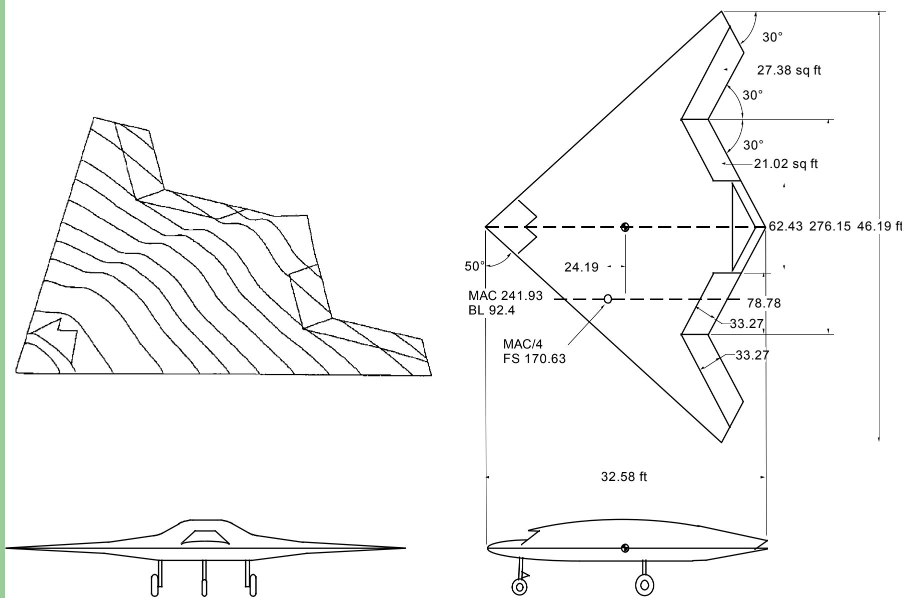
a—separation begins
b—leading-edge vortex forms
c—full stall
d—reattachment and return to static state



From http://hodgson.pi.tu-berlin.de/~schatz/PIZIALI/osc.html

- Utilizes rapid pitch-up and hysteresis to produce increased lift
- A great deal of work has been done on airfoils and simple wings
- Very little work has been done on UCAVs

UCAV Configuration



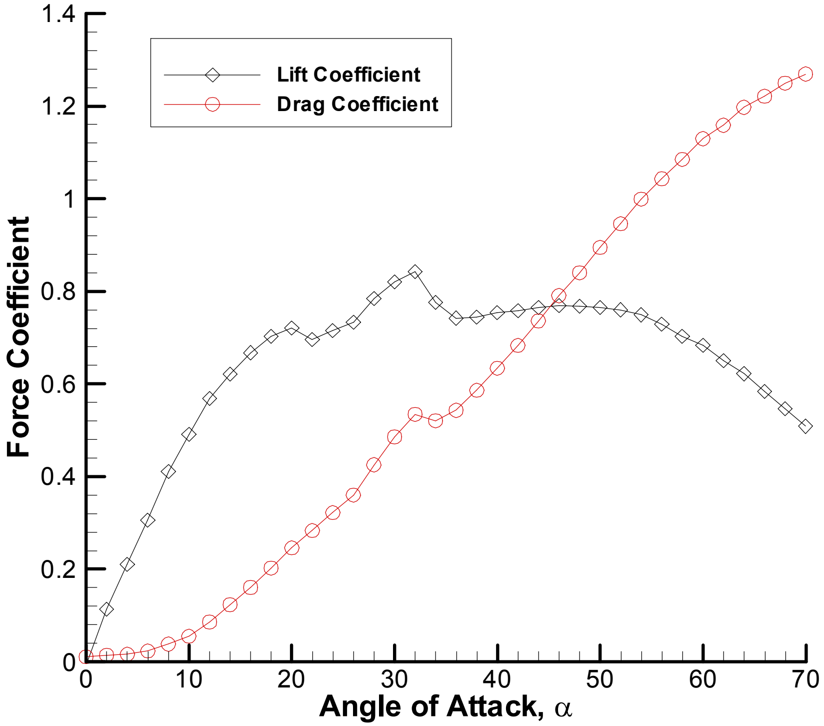
Boeing 1301 UCAV

- Straight, swept leading edge with 50^o sweep
- Aspect ratio of 3.1
- Round leading edges
- Blended wing & body
- Top/front engine inlet
- B-2-like wing planform
- Low observable shaping

Experimental Results

- 1:46.2 scale model
- Academy 3 *ft* × 3 *ft* open return low-speed wind tunnel
- Less than 0.05% freestream turbulence levels at all speeds
- Freestream velocity of 20 *m/s* (65.4 *ft/s*)
- Chord-based Reynolds number of 1.42×10^5

Static Testing



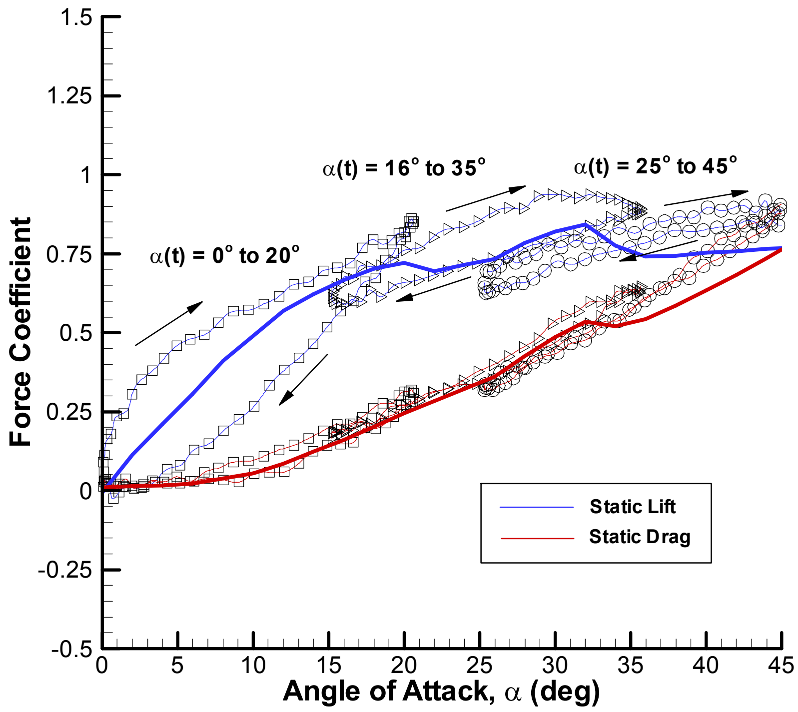
- Linear lift characteristics up to 10º to 12º
- Stall occurring at about 20º
- Lift re-established up to 32º, where an abrupt loss of lift takes place
- Effect of leading-edge vortices and vortex breakdown?

Dynamic Testing

- The configuration was pitched at 0.5, 1.0, and 2.0 Hz (k = 0.01, 0.02, and 0.04)
- Center of rotation at the nose, 35% MAC, and the tail
- The pitch cycles were completed for three ranges of angle of attack:
  - $0^o < \alpha < 20^o$
  - $16^o < \alpha < 35^o$
  - $25^o < \alpha < 45^o$

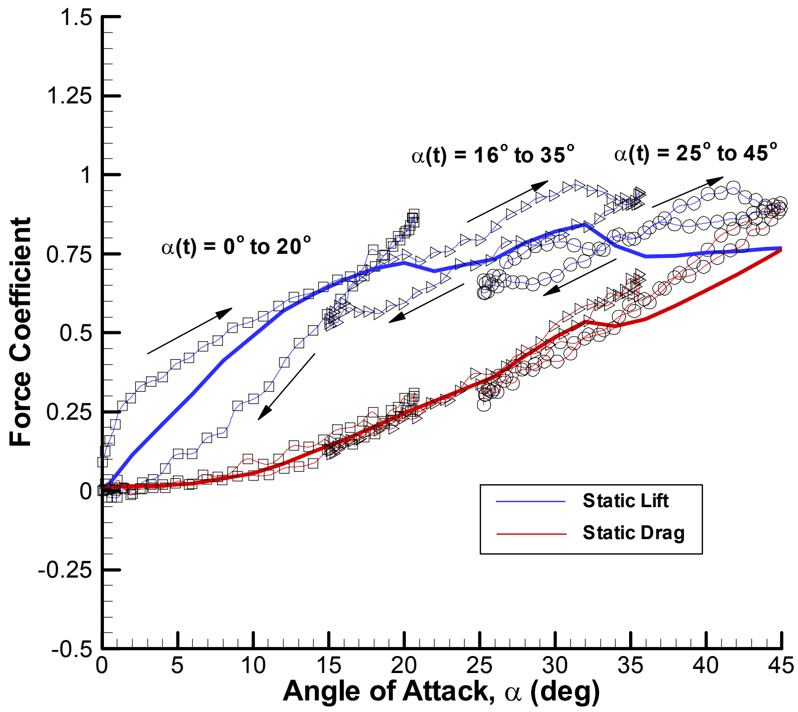
$$\alpha(t) = \alpha_\circ + m(1 - \cos(\omega t))$$

Pitching About 35% MAC @ 2 *Hz*



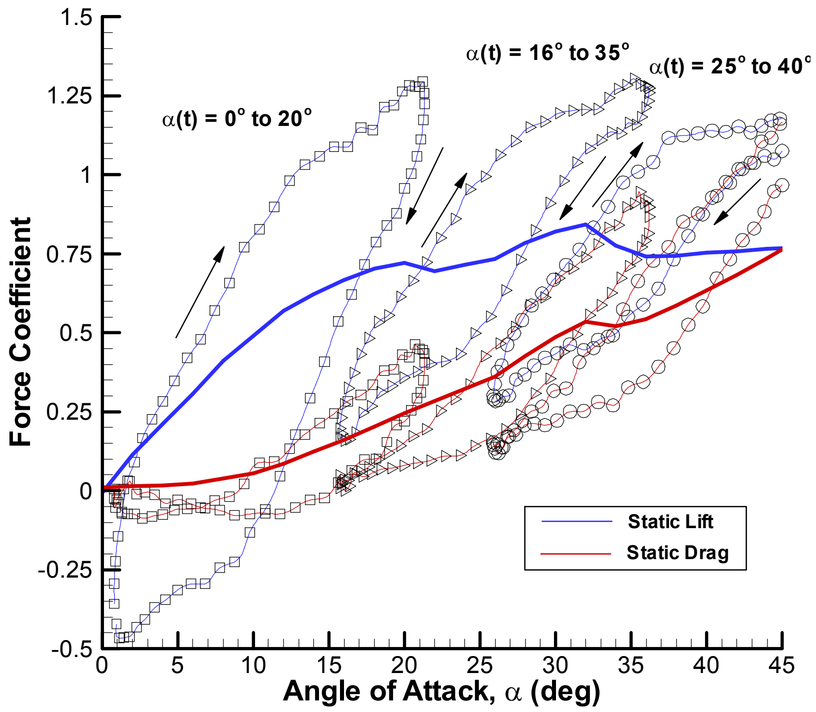
- Dynamic lift is greater than static lift during pitchup
- Pitchup lift is also greater post stall
- Dynamic lift is less than static lift during pitchdown
- Little impact on drag

Pitching About Nose @ 2 *Hz*



- Similar results to pitching about 35% MAC
- Slightly less effective at producing lift during pitchup
- Essentially identical results in post-stall region

Pitching About Tail @ 2 *Hz*

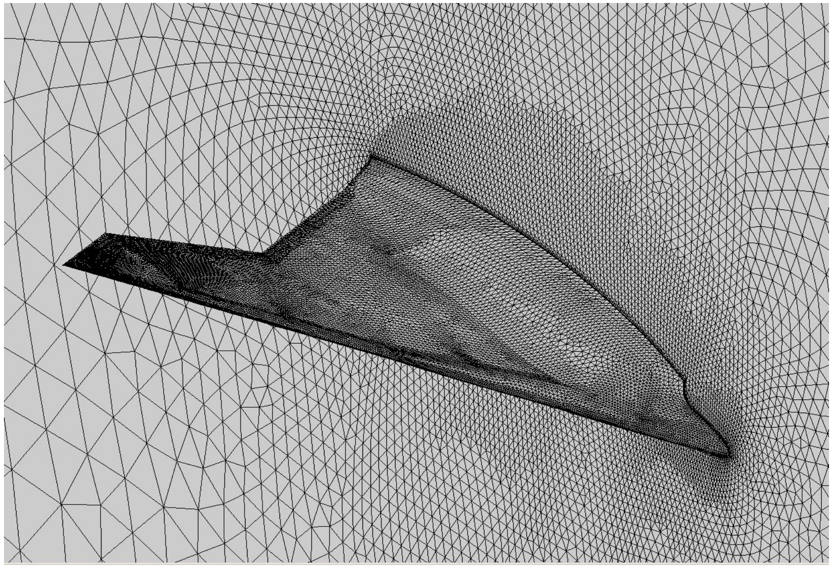


- Drastically different than previous results
- Much more lift at higher angles of attack in pitching cycle
- Reduced lift at lower angles
- Significant impact on drag

Numerical Method

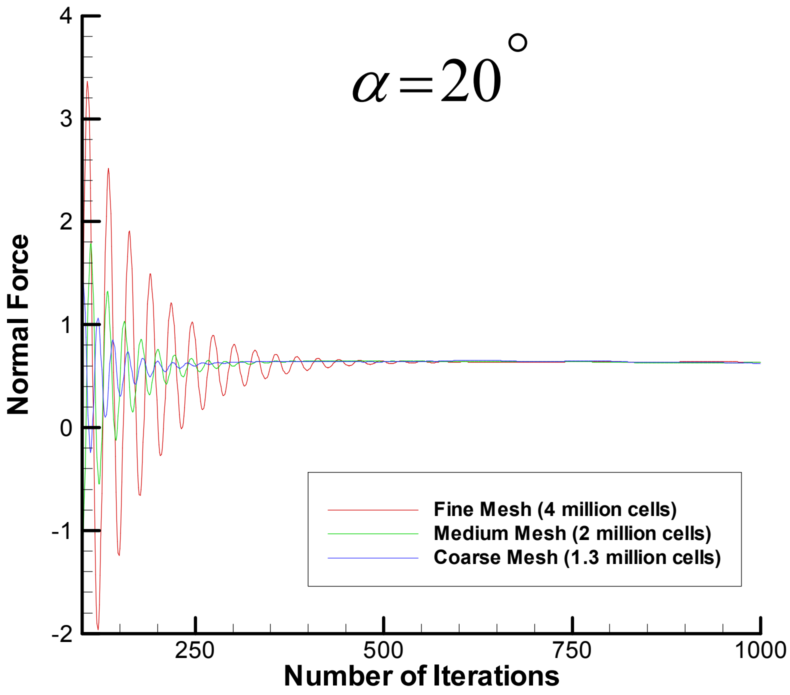
- Cobalt Navier-Stokes solver
  - Unstructured mesh
  - Finite volume formulation
  - Implicit
  - Parallelized
  - Second-order spatial accuracy
  - Second-order time accuracy with Newton sub-iterations
- Run on Academy 64 processor Beowulf cluster, Origin 2000, and USAF HPC computers
- Laminar flow with freestream conditions set to match Reynolds number of wind tunnel experiment

Mesh and Boundary Conditions



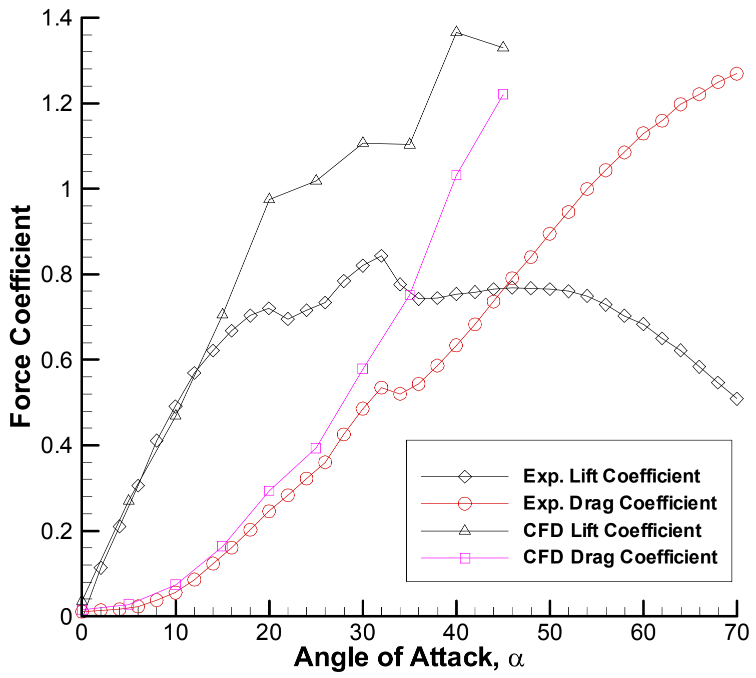
- Three unstructured meshes:
  - Coarse (1.3 million cells)
  - Medium (2 million cells)
  - Fine (4 million cells)
- Half-plane model
- No-slip on surface
- Symmetry plane
- Freestream inflow
- Inlet covered to match model
- No sting modeled

Mesh Convergence



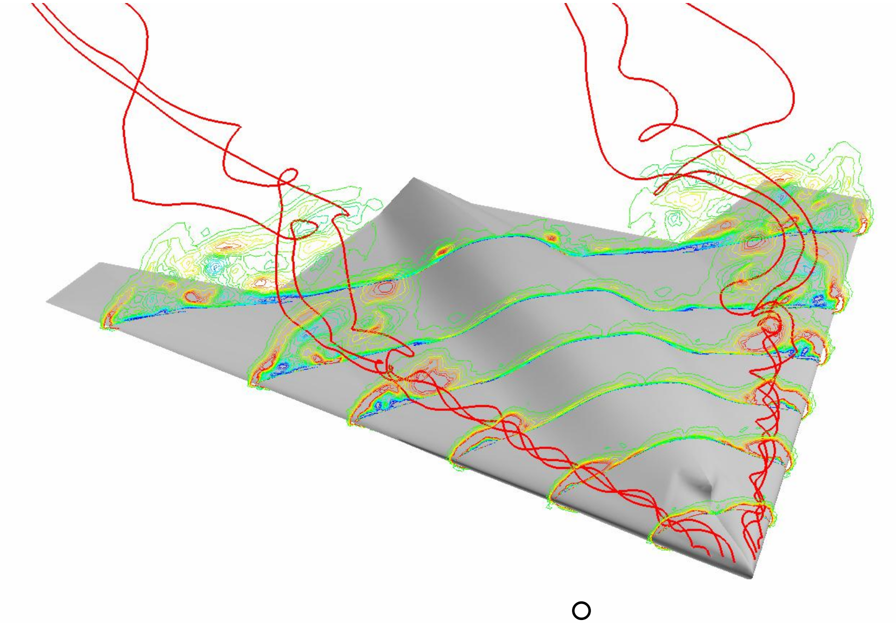
- Steady results from all three meshes yield identical forces
- High angle of attack flowfields will be unsteady
- Use 2 million cell mesh for following calculations
- Detailed time step study to follow for unsteady flow

Steady-State Static Results



- Good results in linear angle of attack range
- Qualitatively similar results in post-stall region
- Lift and drag are significantly over-predicted in post-stall region

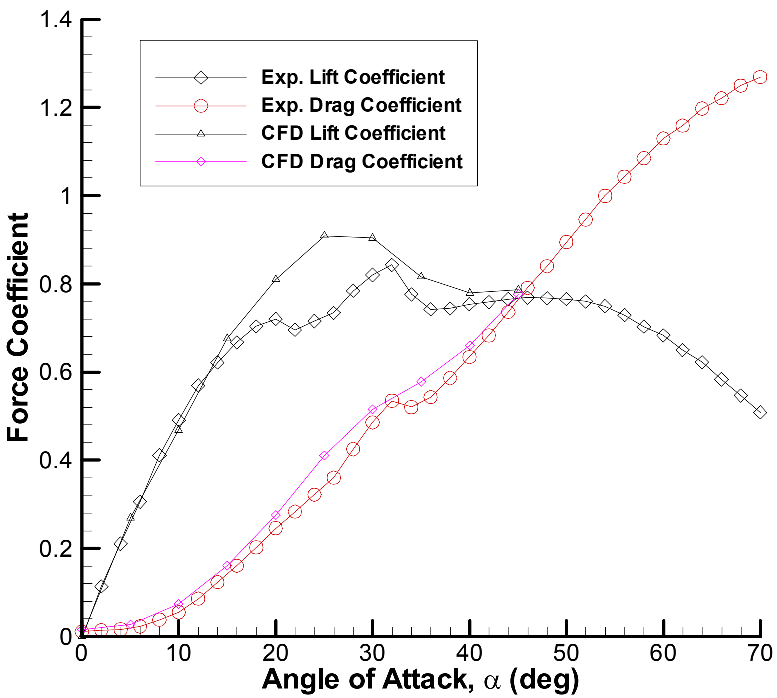
Steady-State Static Results



$\alpha = 20^\circ$

- Wide shallow vortices
- Vortex breakdown fairly far back on configuration
- Vortical structures behind breakdown maintain lift on aft of vehicle
- Rounded leading edge creates weaker vortices that breakdown sooner

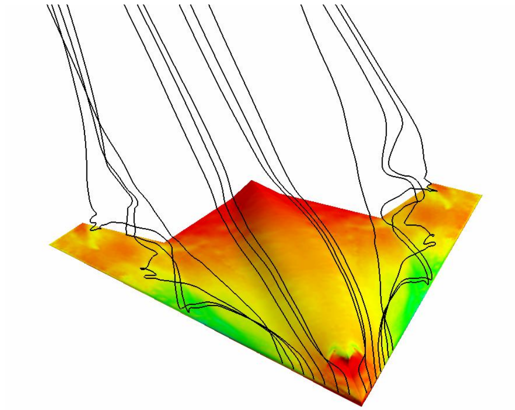
Time-Accurate Static Results



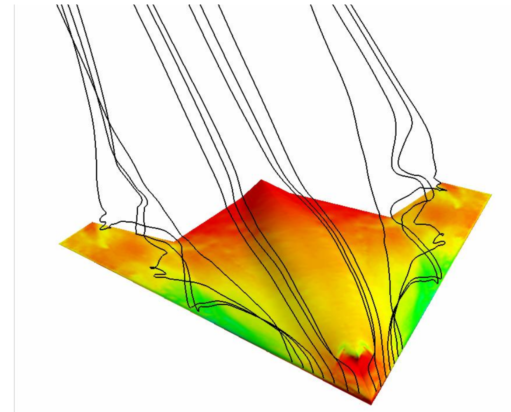
- Flowfields in post-stall region are unsteady
- Time-accurate results match experiment much more closely
- Fairly good modeling of flowfield, including drag, up to $\alpha=45^o$
- Differences in lift from $\alpha=20^o$ to $\alpha=30^o$ (sting, surface roughness, transition ?)

Time-Accurate Static Results

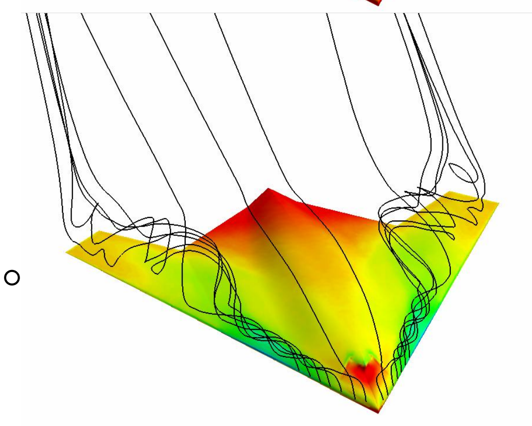
$\alpha = 5^\circ$



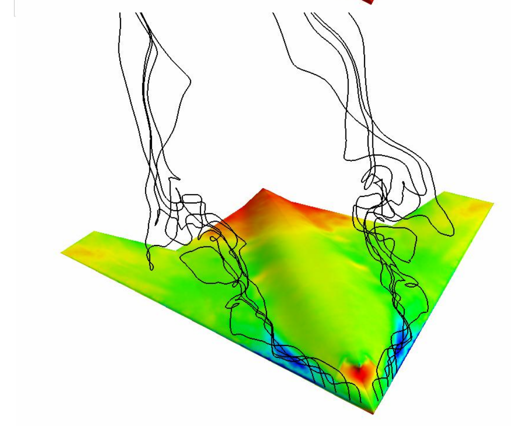
$\alpha = 10^\circ$



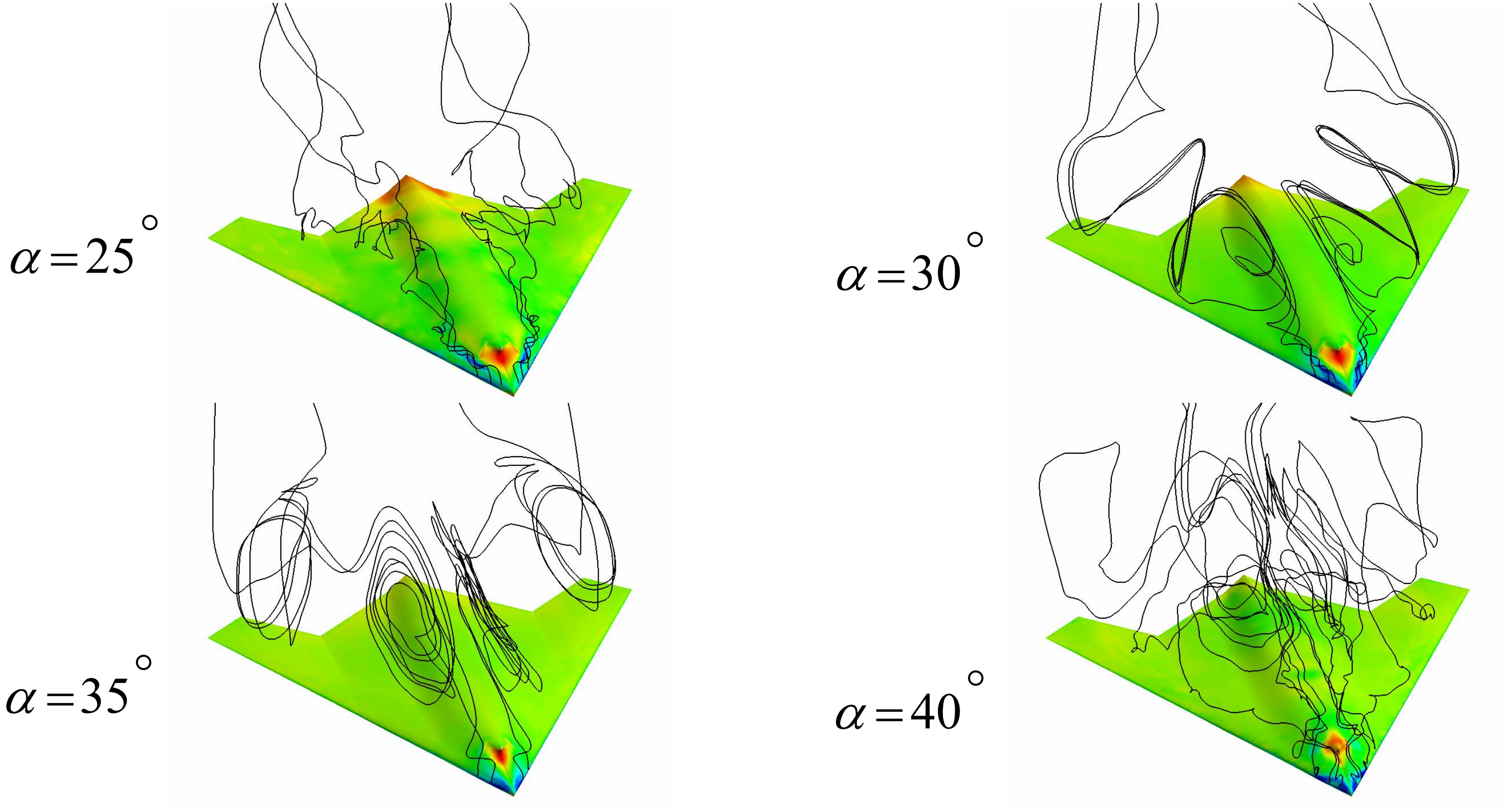
$\alpha = 15^\circ$



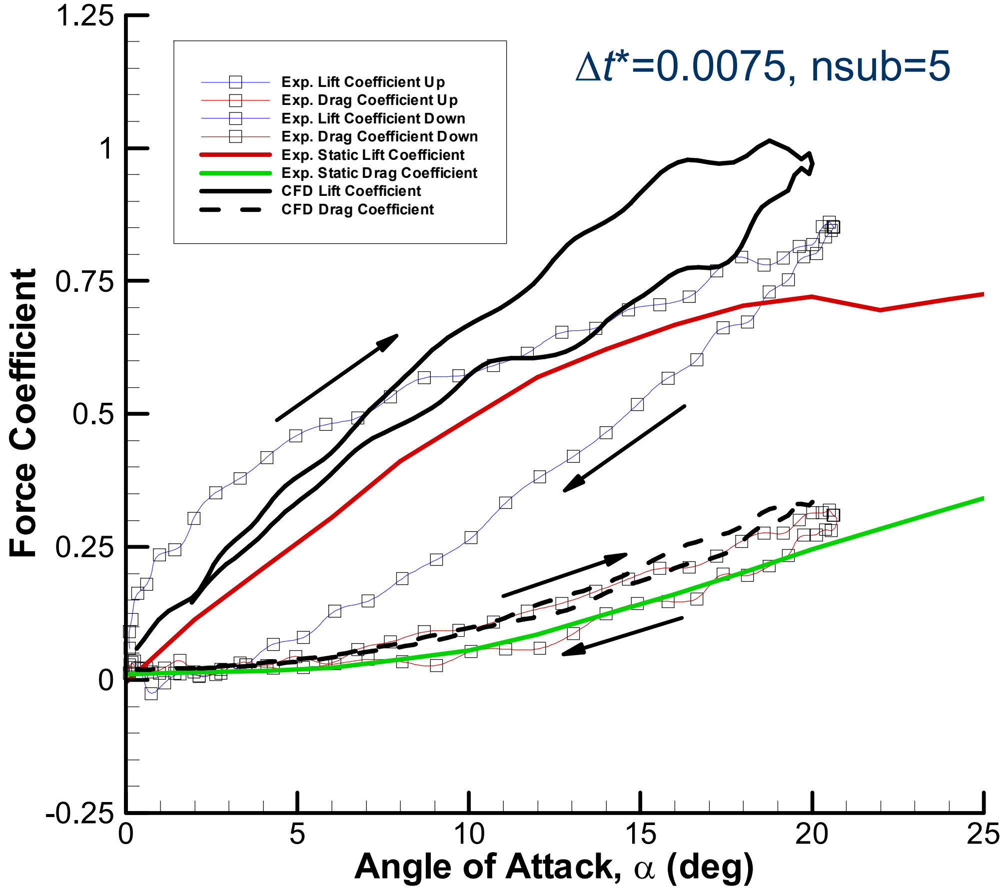
$\alpha = 20^\circ$



Time-Accurate Static Results



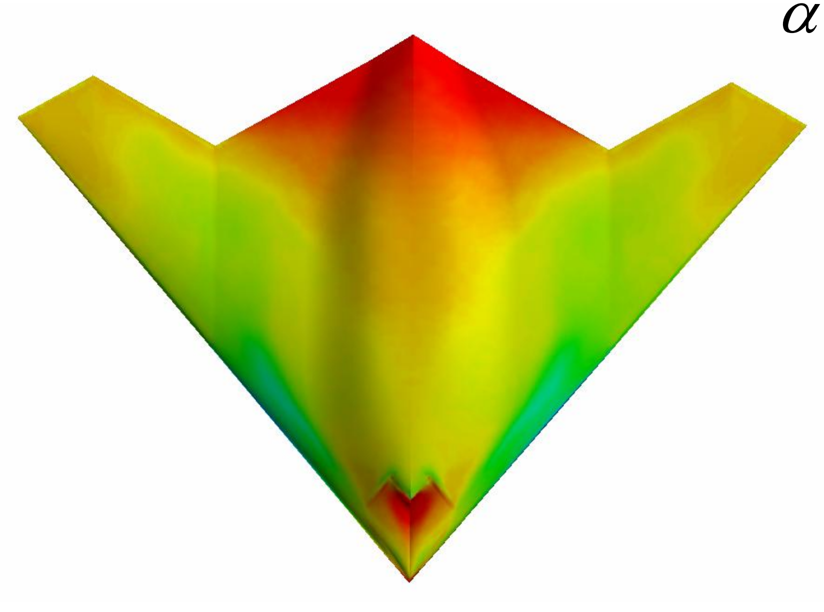
Dynamic Pitching Results



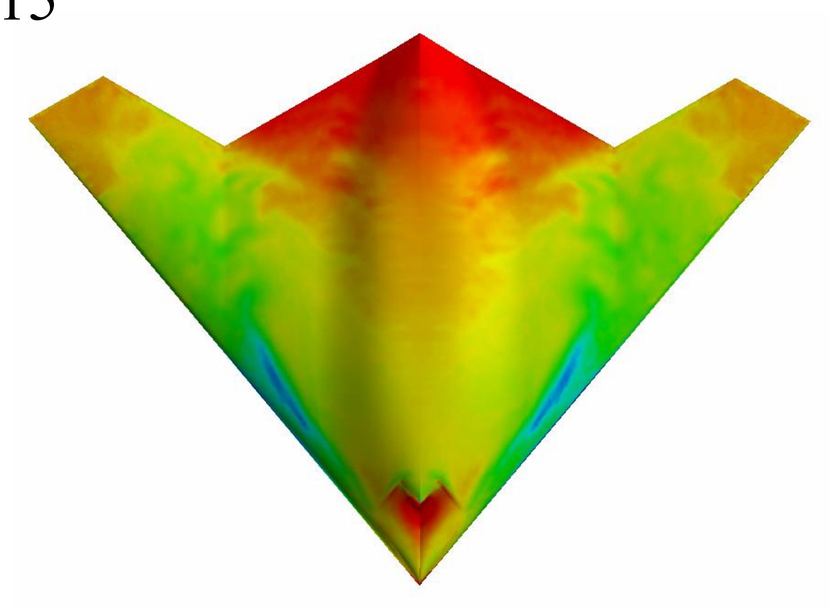
- Pitchup doesn't capture full lift increase at low α
- Overprediction of lift also seen in pitchup case
- Drag is fairly well modeled during pitchup
- More cycles required

Dynamic Pitching Results

$\alpha = 15^\circ$



Static Pressure



Pitching Pressure

Conclusions

- A generic UCAV configuration has been wind tunnel tested both statically and pitching
- The configuration generates increased dynamic lift during pitchup maneuver
- Numerical simulation helps to understand causes of wind tunnel results
  - Stronger leading-edge vortex during pitchup
  - Leading-edge vortex persists to very high angles of attack
  - Vortex breakdown causes the non-linearities in lift
- Collaboration between experimentalists and computationalists leads to greater understanding of aerodynamics

Questions?