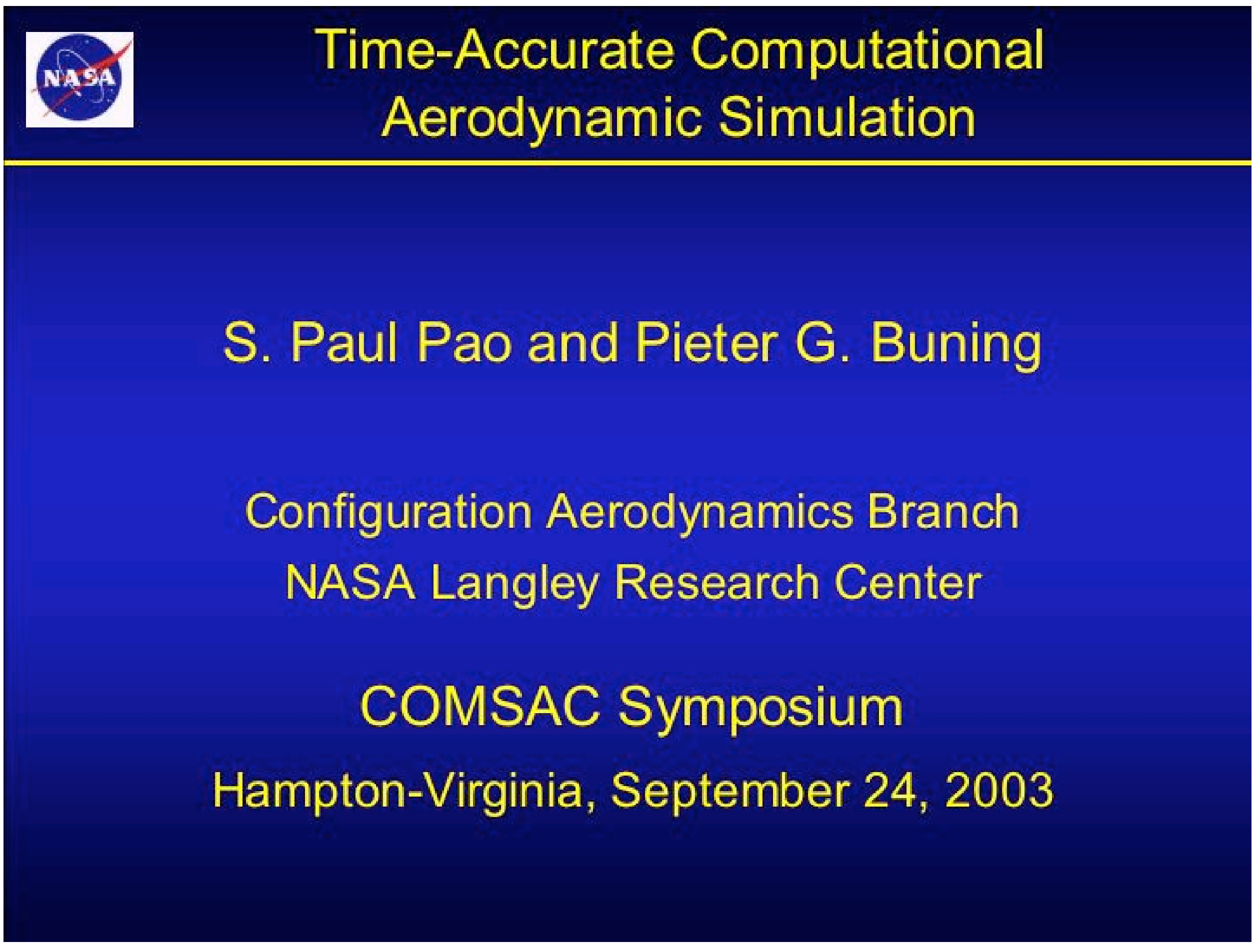
Abstract:

Time accurate CFD may offer a faster approach to S&C aerodynamic database population than the conventional point by point steady state CFD. We would directly simulate α-, β-sweeps or other configuration movements typically of measurement sequence in wind tunnels. A second objective is to demonstrate potential applications to assessment of S&C dynamic derivatives by simulating vehicle motions such as free to roll, and nonlinearity such as the trends of aerodynamic forces near CL-max or flow hysteresis.



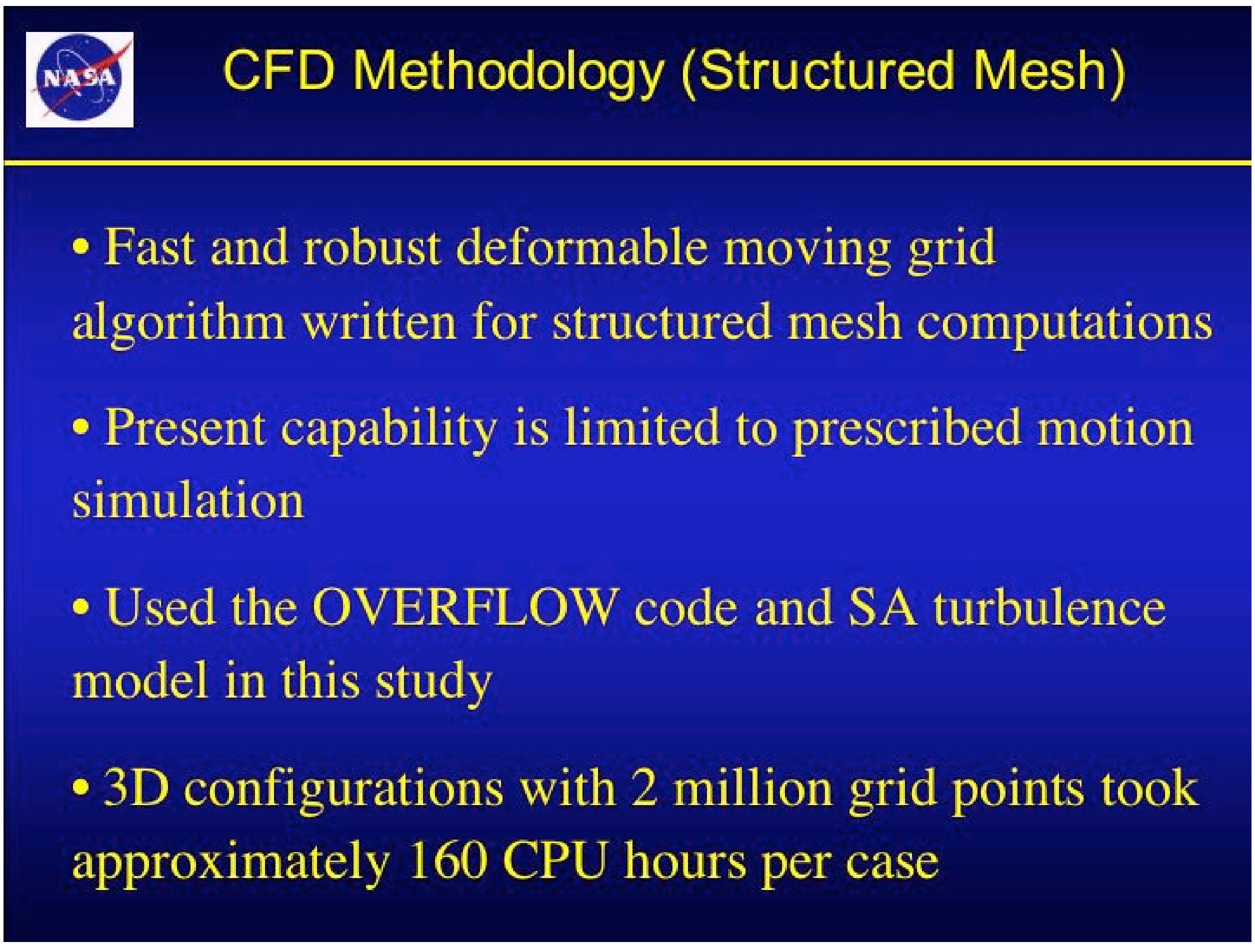
Outline

- Unsteady Motion simulation:
  - Oscillating pitch motion
  - β - sweep at finite rate
  - Periodic body axis roll motion at $\nu = 0.05$
- Database population by continuous sweep
- Summary and future work

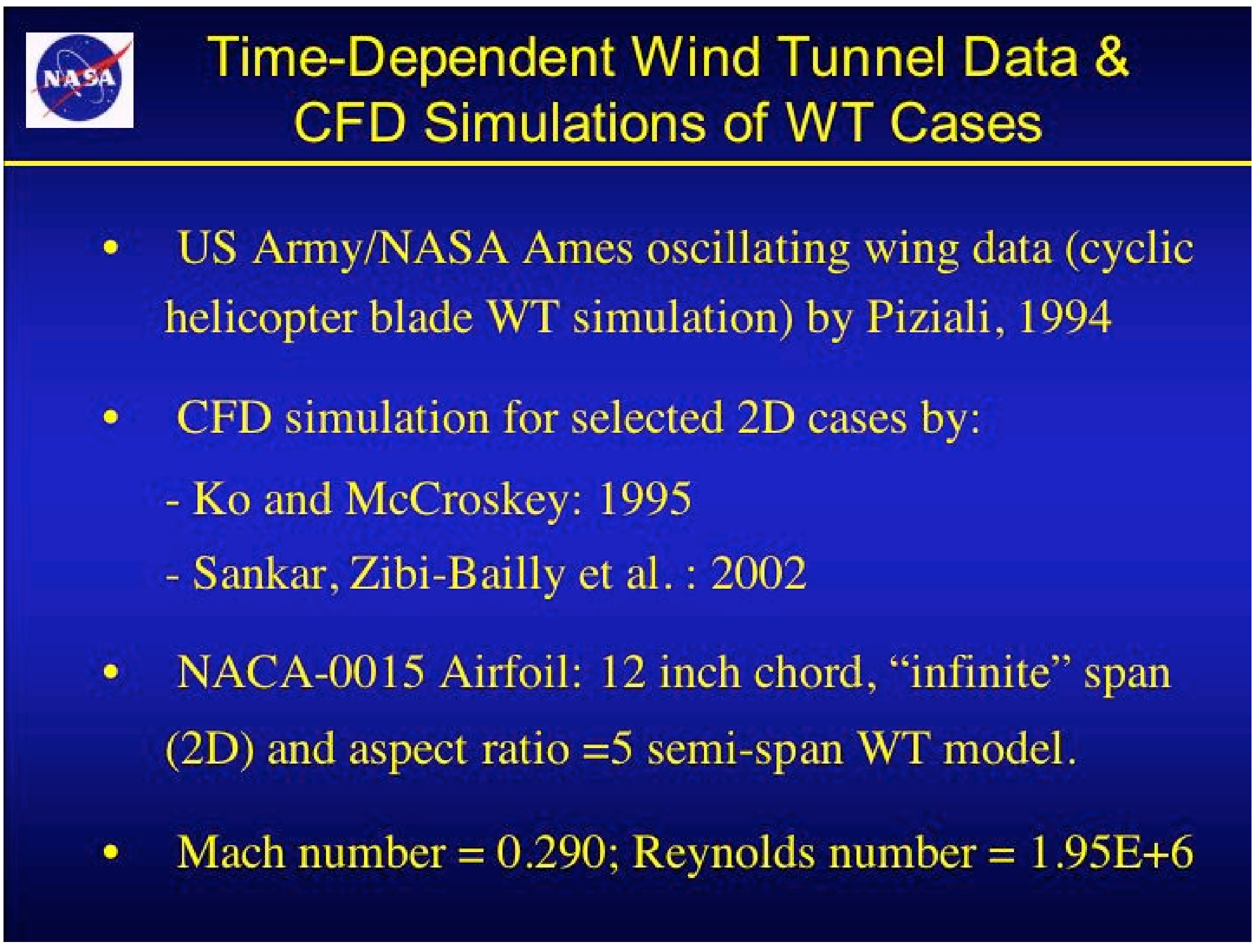
Why Time-Accurate CFD

- Simulate unsteady motion, maneuver, and aero-elasticity
- Provide an alternate approach for efficiency static S&C database population
- Can provide high density continuous data which may not be practical to obtain by steady-state CFD
- Can separate "lumped" dynamic derivatives by direct CFD motion simulation of the relevant components
- Offer a better quantitative assessment of S&C coefficients when the situation involves flow separation

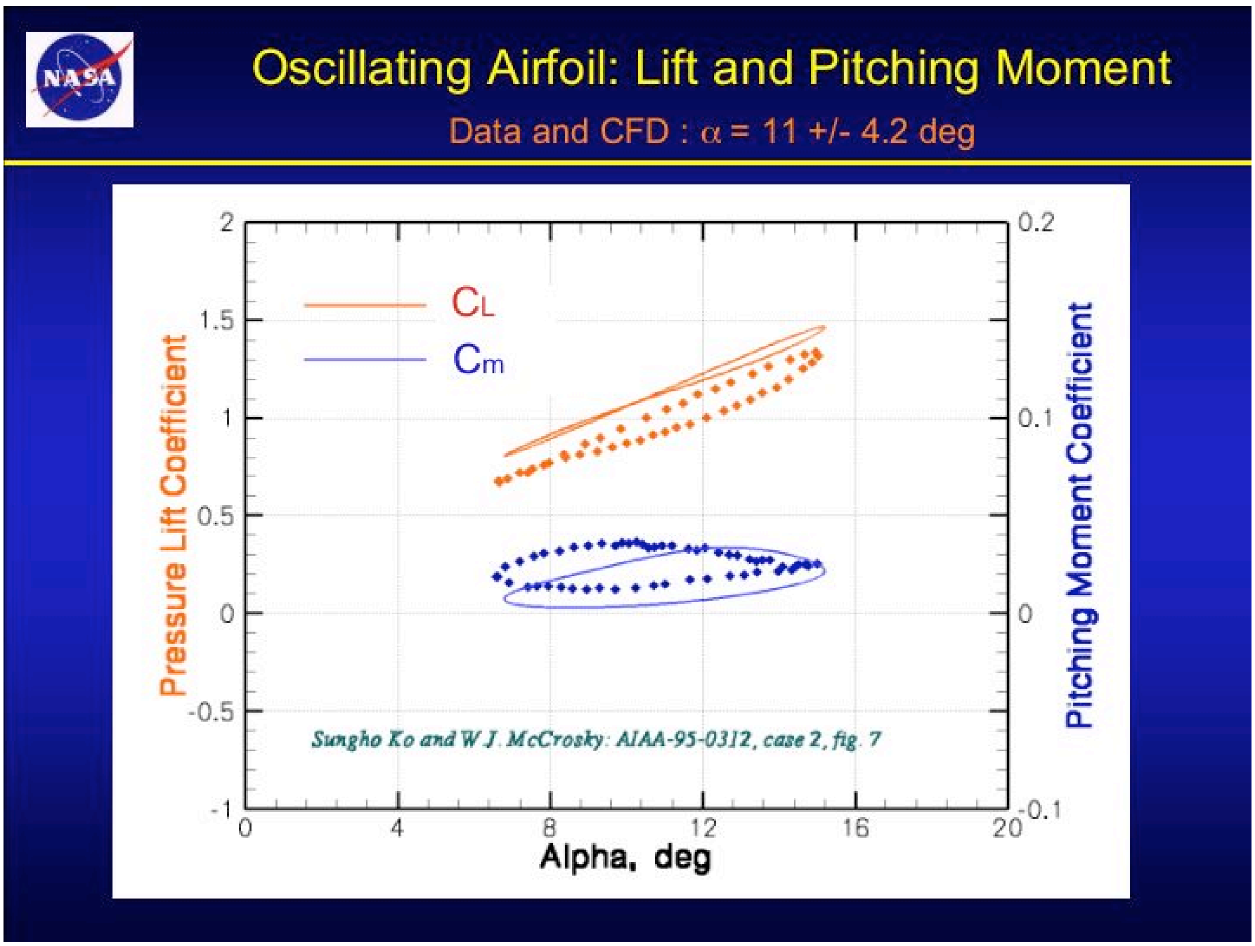
Moving grid algorithm must be efficient and robust for the user. The specifics include simple I/O, maintenance of good grid quality throughout thousands of computational cycles, and fast grid transformation such that grid motion time is a fraction of the time required for a single Navier-Stokes iterative step.



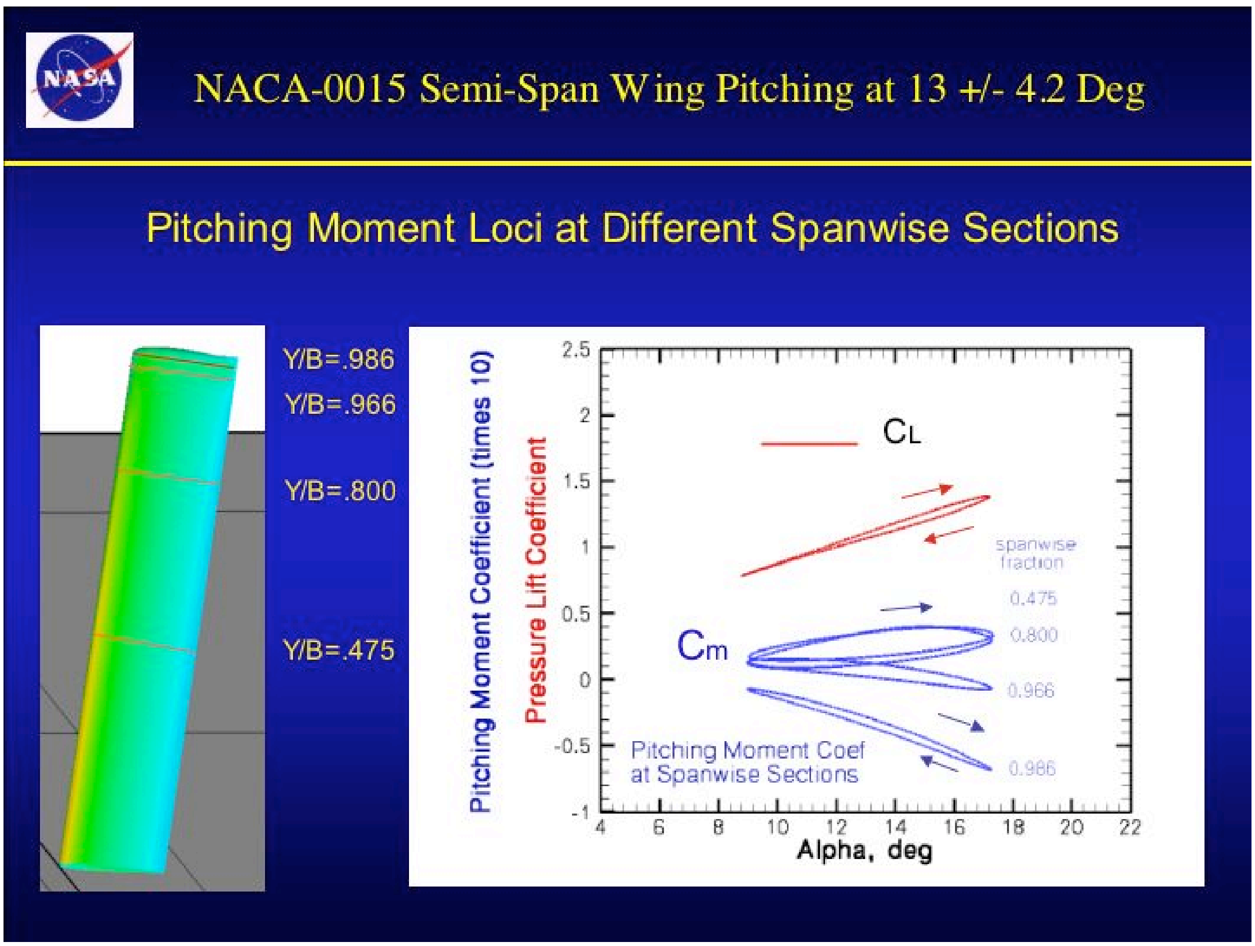
For obvious reasons, the helicopter aerodynamics research community had produced some of the most comprehensive time-accurate wind tunnel measurements and CFD analysis. We have chosen the original data by Piziali and the associated CFD studies as our reference for comparison.



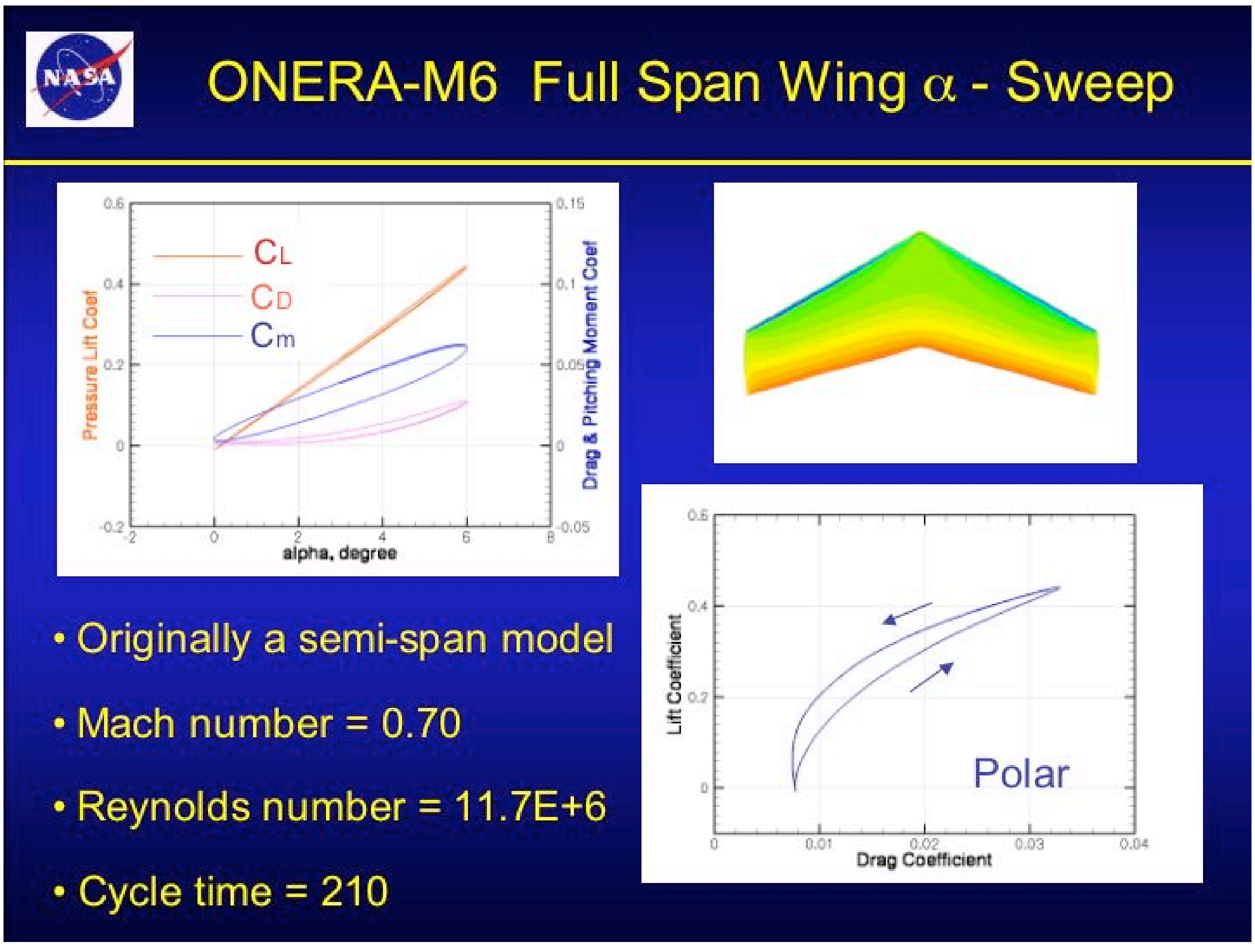
Although the lift and pitching moment comparison are close, there are distinct differences between CFD and measurement. For example, the lift coefficient is higher than the measured data and the hysteresis loop is narrower for the CFD solution. The loop shape of the pitching moment are also different. However, this is typical for comparisons between CFD results using several other codes and the experimental data by Piziali.



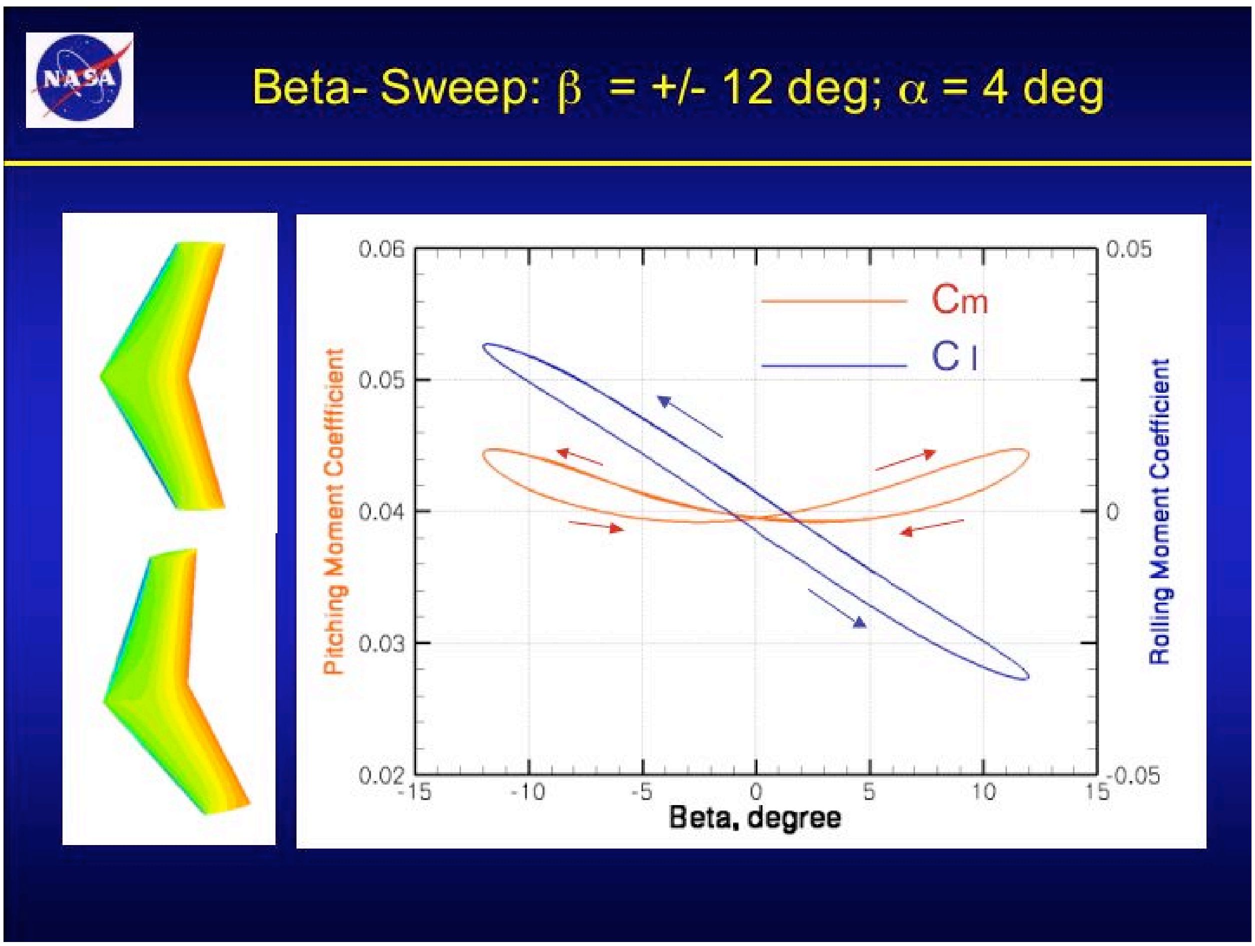
Three dimensional unsteady CFD simulation is rarely available in the literature on account of the computational expenses and the difficulties in obtaining converged solutions. These are not fundamental obstacles and we should see much more often applications of 3D time accurate to practical problems in aerodynamics and S&C in the near future. This example demonstrates the distinct change in aerodynamic behavior in the spanwise direction. The pitching moment sign and slope near the wing tip are different from those for all the inboard stations.



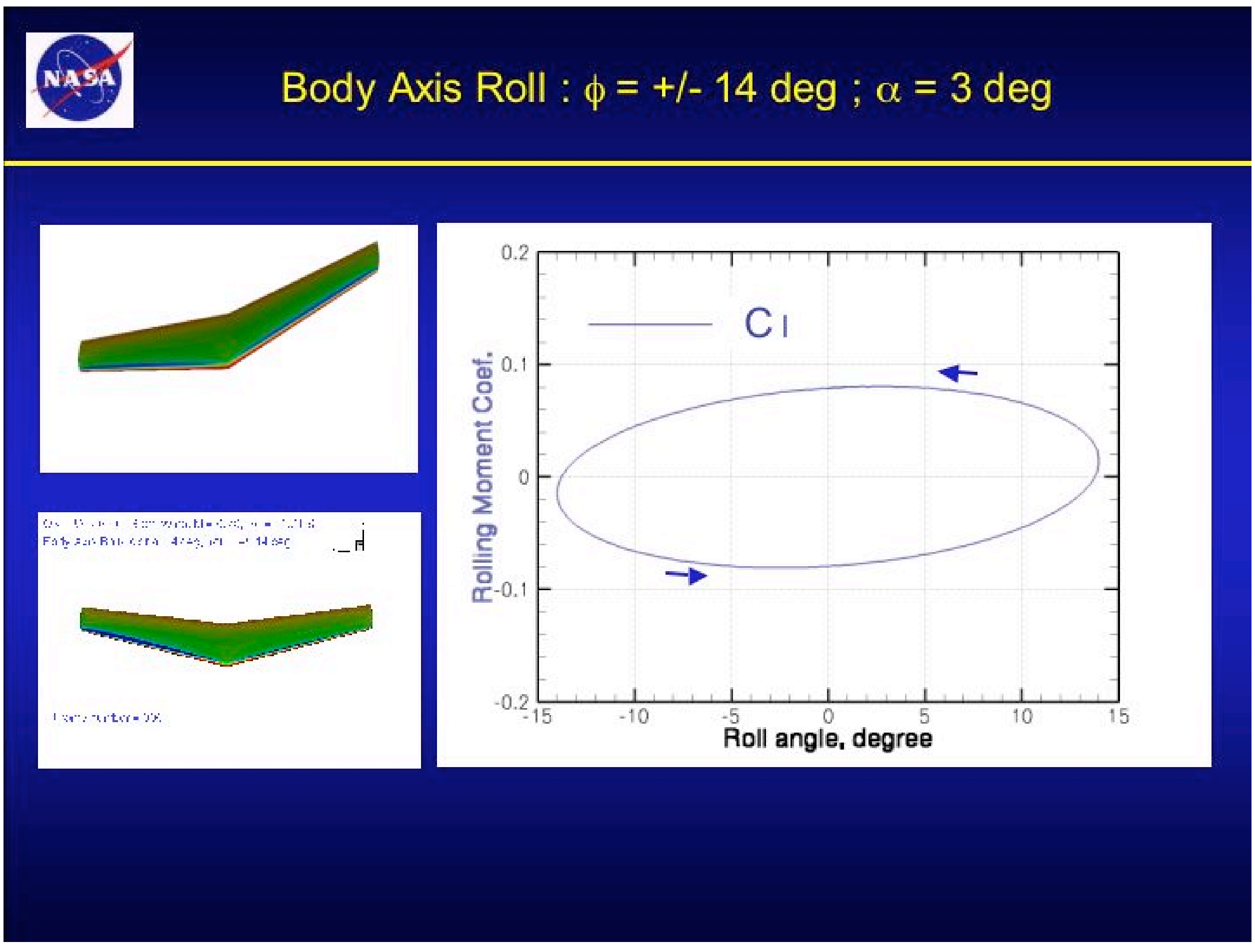
Although we don't have data to compare with, this is to demonstrate feasibility a continuous alpha sweep at a high subsonic Mach number. The lift and drag coefficient information is also plotted as a drag polar. The nondimensional time of T=210 for the angle of attack to go from 0 to 6 deg and back is relatively fast: less than one second in terms of wind tunnel length and time scales.



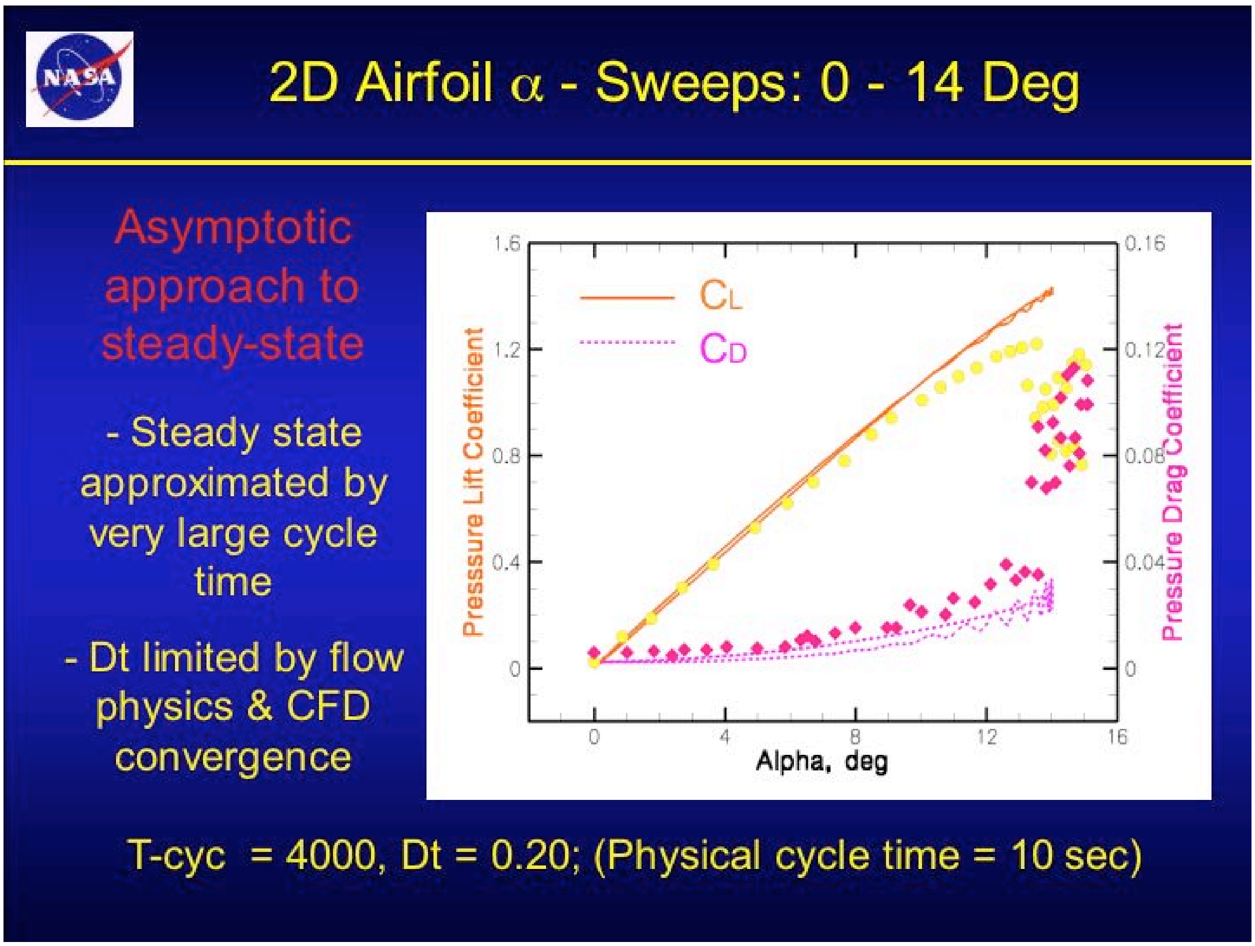
The subject of interest for this finite rate beta sweep simulation is the rolling moment coefficient. The figure shows a narrow hysteresis loop with nonlinear slopes of Cl-beta for beta greater than about +/- 8 degrees.



The rolling moment response of the ONERA-M6 wing to a periodic body axis roll motion is classical. From this Cl versus Φ locus, we can determine the roll damping dynamic derivative for the given roll rate from the slopes of the curve at $\Phi = 0$.



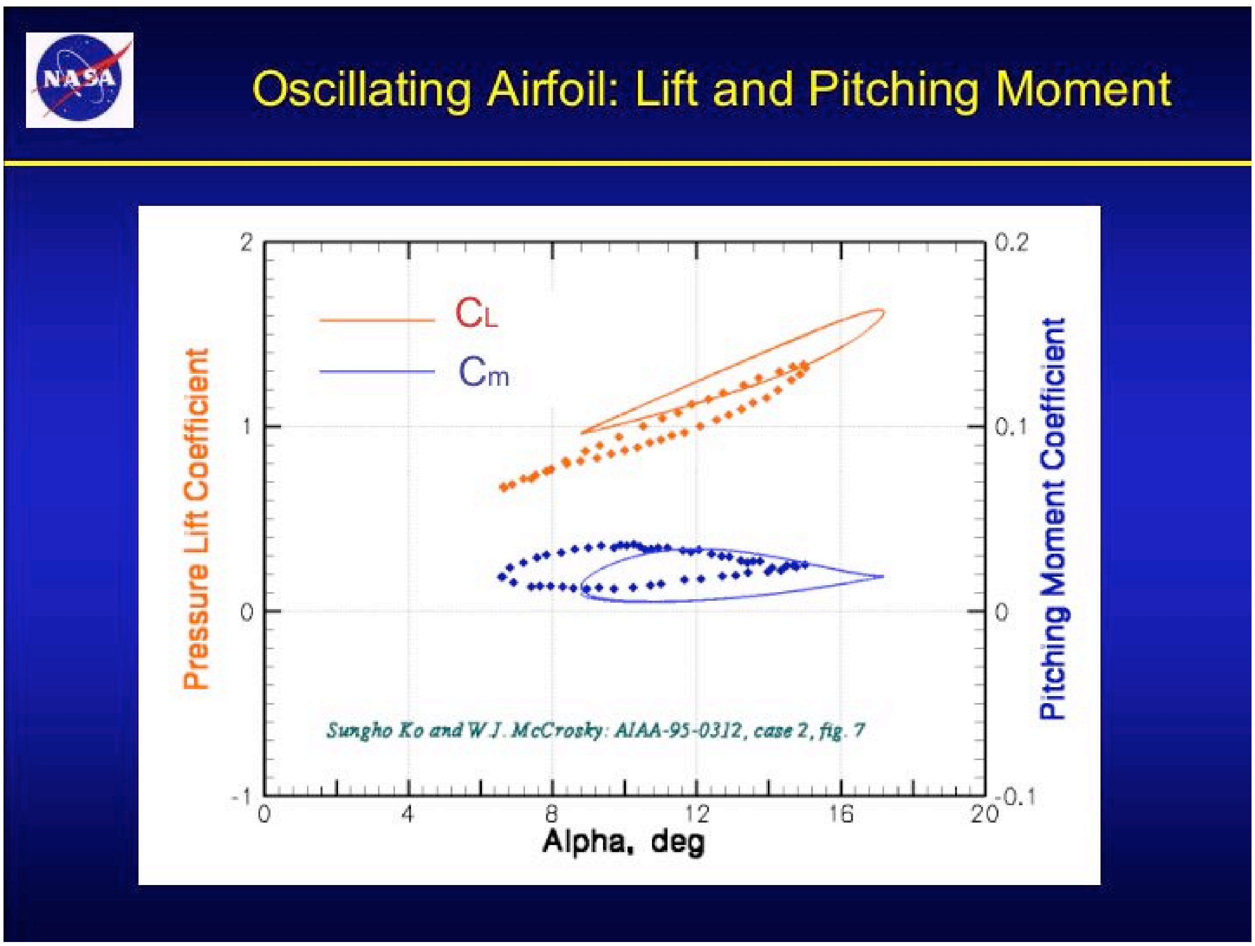
The nondimensional cycle time needs to be sufficiently large for steady-state simulations such that hysteresis due to motion dynamics is not present. A sequence of calculations at different cycle time ranging from 100 to 4000 indicated that cycle time above 1000 will do well. On the other hand, the time step size is governed by flow physics. The nondimensional time unit is the time required for a fluid particle to travel the distance of one chord. At DT=0.2, we are tracking a fluid particle only five times over the airfoil at it moves nominally according to the prescribed free stream velocity. As a result, a complete cycle required 20000 time steps. From a CFD point of view, it is equivalent to computing 10 independent steady state solutions for the same wing configuration.



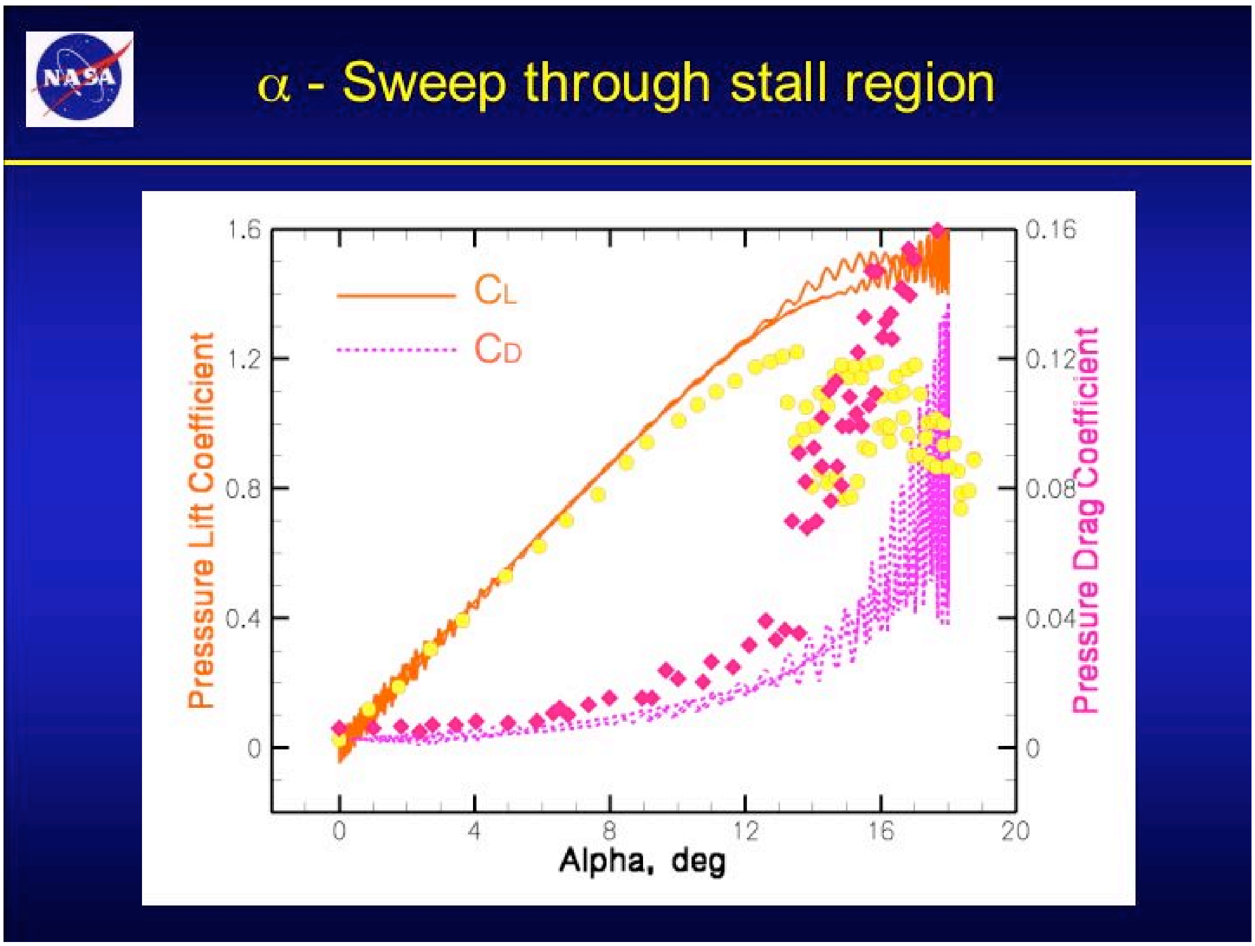
Interesting CFD Observations

- α - shift of forces and moments between CFD and WT measurement
  - numerical algorithm and turbulence model
  - WT measurement assumptions
- α - sweep through NACA-0015 stall region
  - mimic measurement uncertainty in C_L, C_D
  - turbulence model may affect $C_{L\,max}$

The computed lift and moment coefficient curve shapes are now practically the same. One of the explanations could be that the CFD flow separation is delayed by 2 degrees in alpha versus the wind tunnel experiment. At this time, it is not entirely clear what is the cause of this discrepancy. The experiment was done with an infinite span wing, not a true two dimensional representation. Further investigation could repeat this simulation using an infinite span CFD configuration. Instead of URANS, we may have to use DES or other hybrid techniques.



This preliminary example is to demonstrate the unsteady behavior of CFD in the stalled regime. An intriguing feature is the repeatability of the large amplitude oscillation in lift and drag as we repeated the time cycles. The lift and drag data from the experiment did not come from a balance but instead was integrated values from an array of pressure transducers. Assuming that the suction peak on the airfoil may not be perfectly captured by the fixed position pressure transducers, the lift would be lower and the drag would be higher than their respective actual values.



What Have We Learned

- Successfully simulated oscillating 2D airfoil and 3D semi-span wing and showed good agreement with wind tunnel data
- Demonstrated unsteady flow simulation for periodic pitch, yaw, and roll motions of a generic wing at a high subsonic Mach number
- Demonstrated the potential for static S&C database population by continuous sweep in α and β with an efficiency equal to or better than using steady state CFD
- High density S&C data computed without additional cost
- Stall region solutions showed very significant nonlinear effects which are difficult to capture in point-wise steady state CFD calculations

Future Work

- Validate time-dependent method for complex configurations and improve efficiency
- Develop close loop moving grid capabilities coupled to 6-DOF motion and structural deformation
- Use LES/DES/PANS codes to enhance accuracy for separated flow and vortex interaction
- Implement similar grid motion algorithm for unstructured mesh