Numerical Simulation of Dynamic Stall

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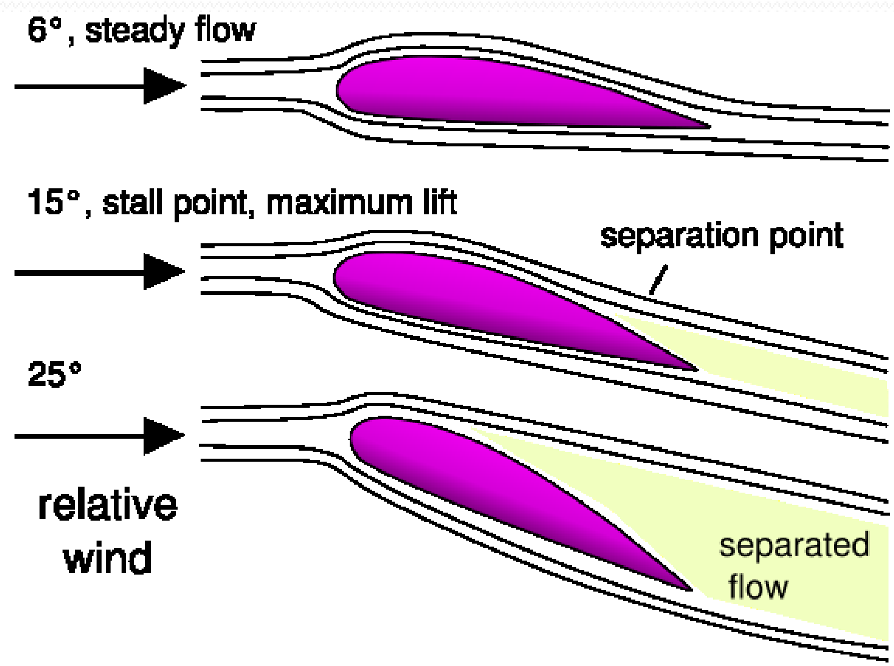
Introduction

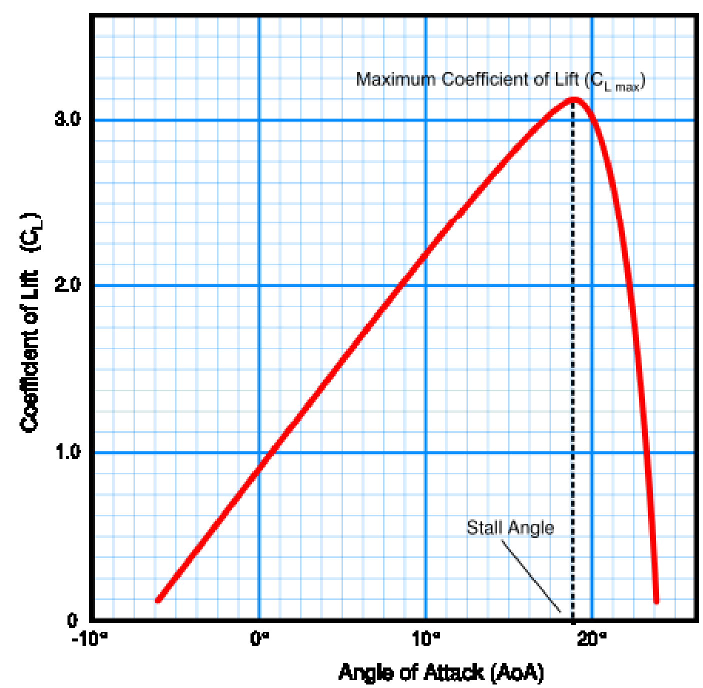
- **Aim:**

  To study the dynamic stalling of helicopter rotor blades
- **Relevance:**
  - Dynamic Stalling limits helicopter performance
    - High forward flight speeds
    - High *g* maneuvers
  - Results in high torsional air-loads and sudden loss of lift
  - Unsteady aerodynamics: time dependent angle of attack and incoming flow velocity
- Prediction requires solution to **Navier Stokes equations** with an appropriate turbulence model
  - Boundary layer transition and separation
  - Vortex formation
  - Locally supersonic flow causing shock – boundary layer interactions

Aerodynamic Stall

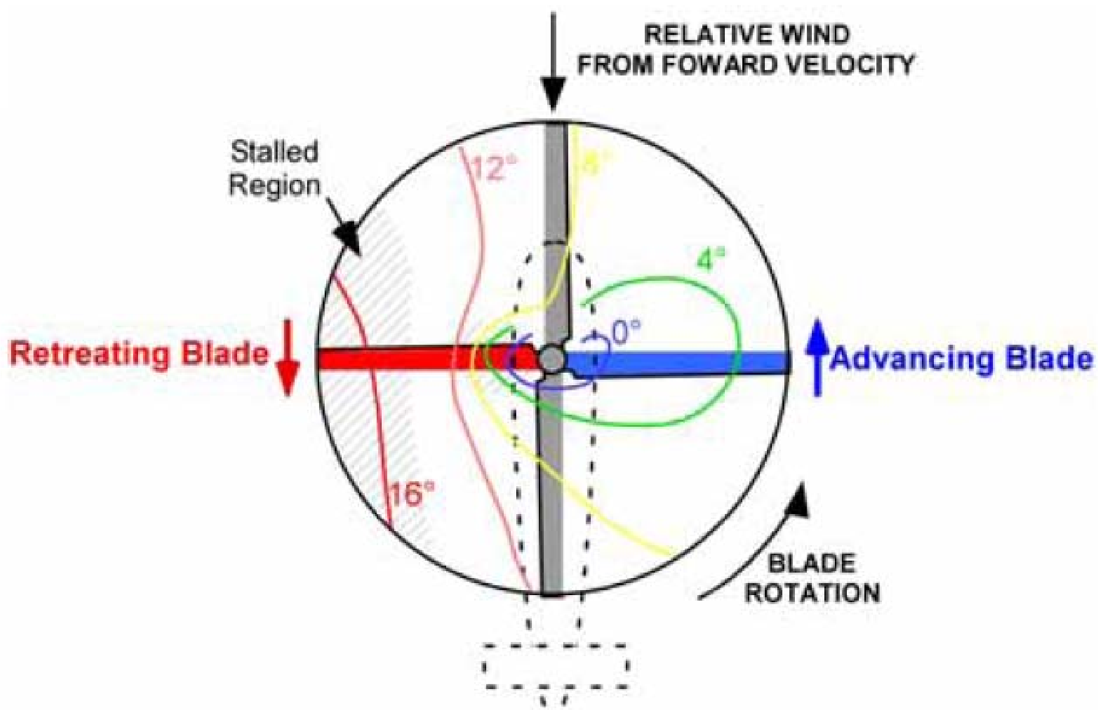
- “Stall” – Sudden loss of lift resulting from flow separation

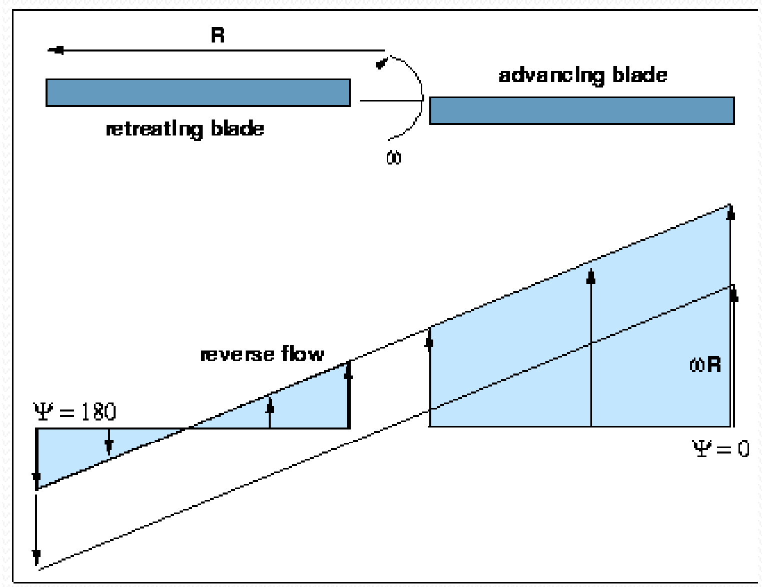




Unsteady Flow

- Flow seen by rotor cross-section is unsteady
  - Variation in the angle of attack
  - Unsteady wake flow from preceding blade
  - Varying speed of incoming flow



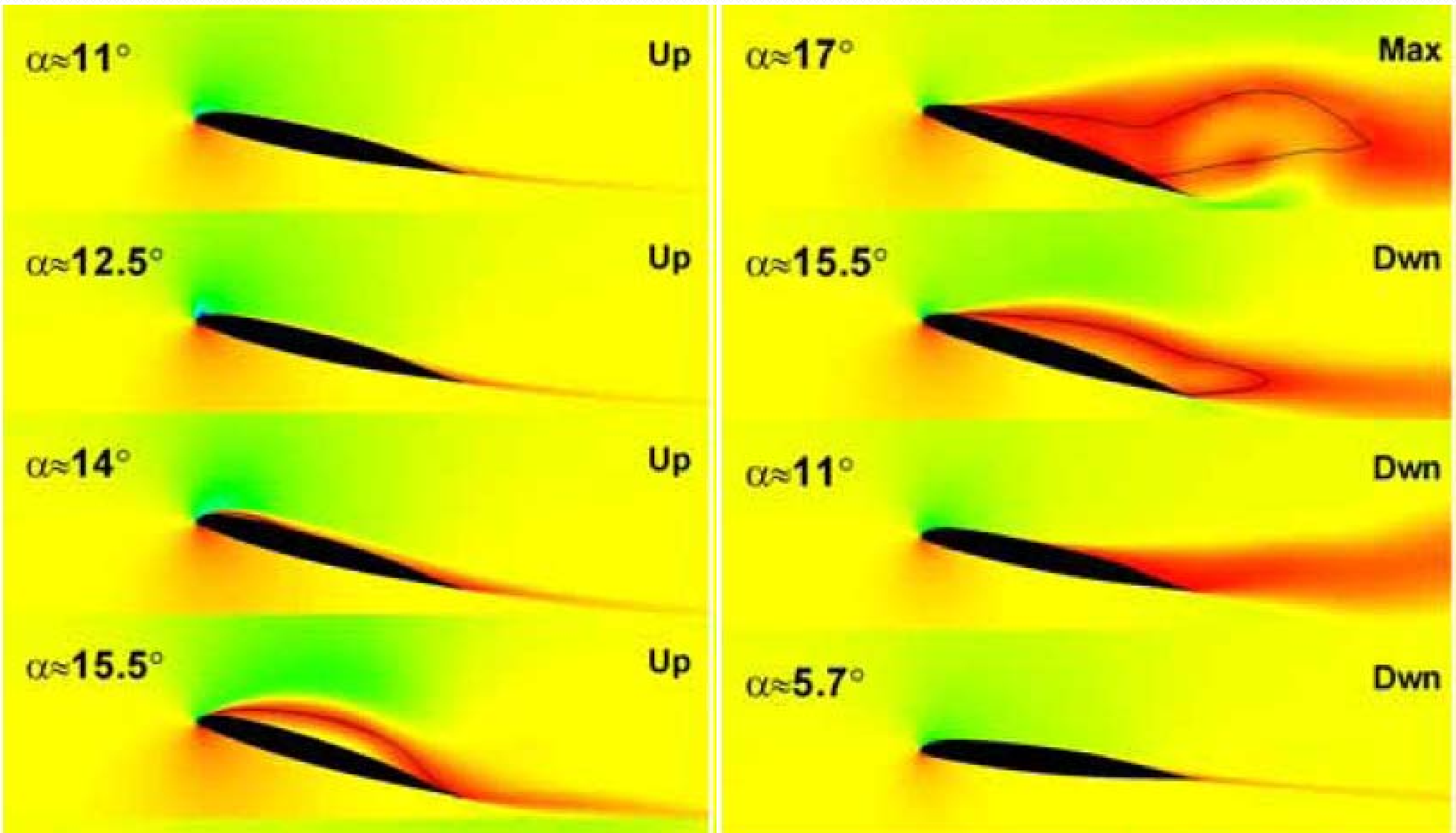


Dynamic Stall

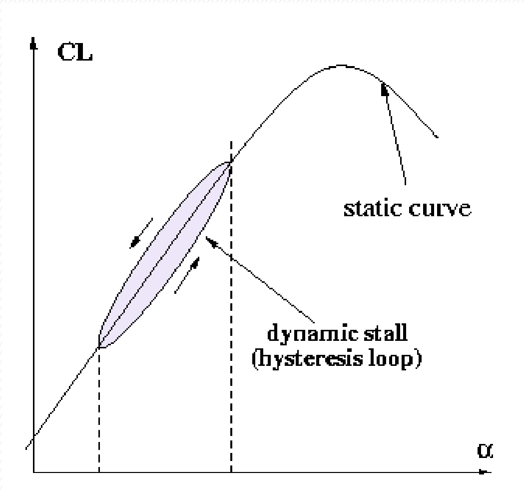
Unsteady flow around rotor make it susceptible to dynamic stall

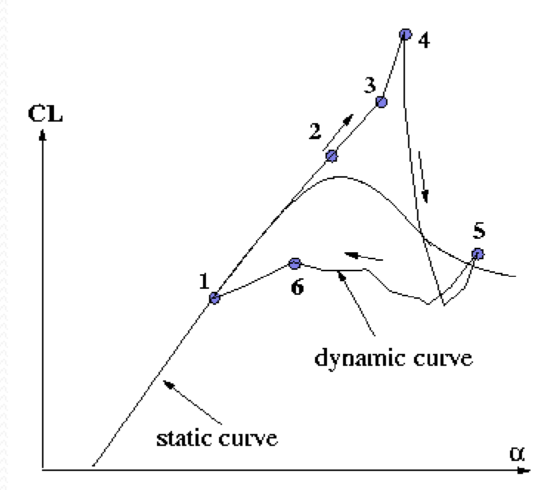
- Dynamic lift follows static lift curve as angle of attack increases
- Static angle of attack limit exceeded – flow reversals take place near surface
- Flow separation moves upstream to leading edge – formation of vortex
- Vortex convects downstream (augmentation of lift, moment stall)
- Vortex is shed off at the trailing edge (drastic drop in lift), fully separated flow over upper surface
- As angle of attack reduces, flow reattaches

Dynamic Stall



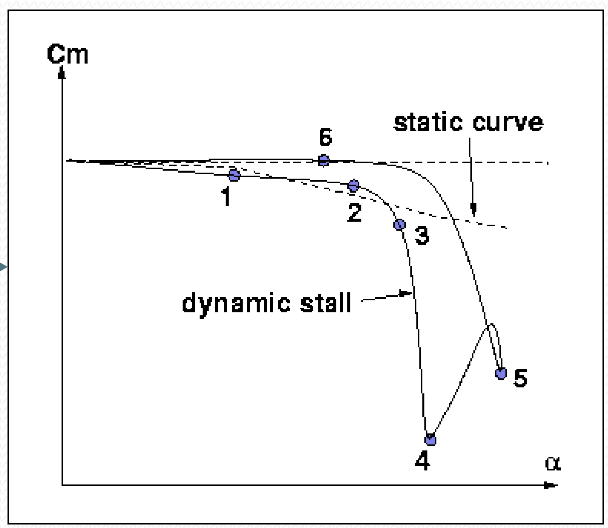
Dynamic Stall (Continued)



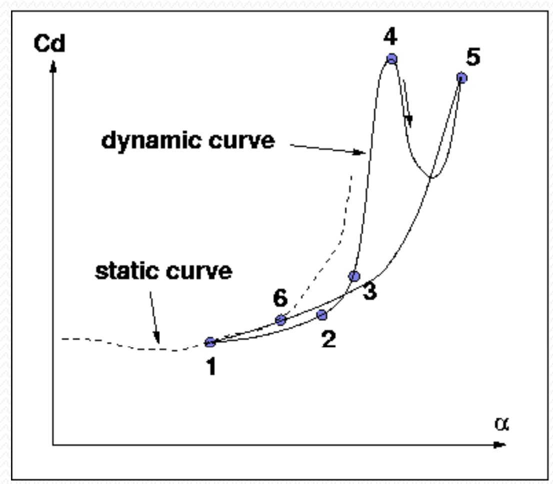


Lift

Moment



Drag



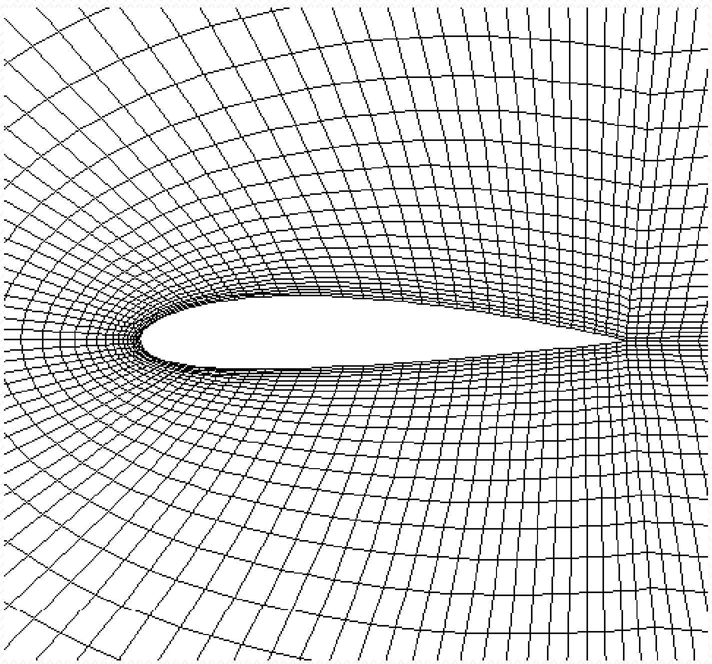
Governing Equations

- **Euler Equations:** Describes compressible inviscid fluid dynamics
- **Navier Stokes Equations:** governing equations for a viscous, compressible flow
- Consists of
  - Conservation of mass
  - Conservation of momentum
  - Conservation of energy

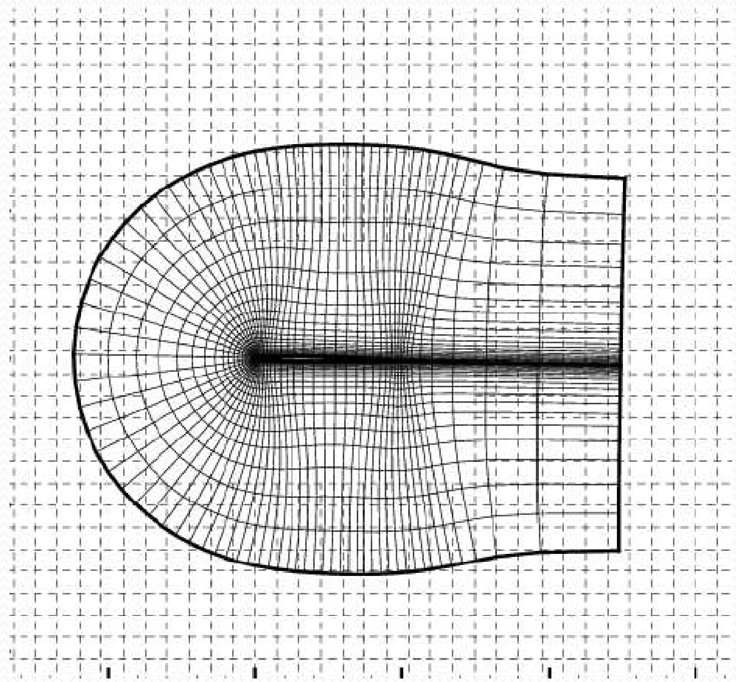
  (For a given fluid element in the domain)
- Expressed in point form or integral form
- Form a mixed system of PDEs with a hyperbolic flux function and dissipative source term
- Need for a **turbulence model.**

Mesh Generation

- Domain is an airfoil in free-stream – C-type structured mesh
- Simulation of airfoil in wind tunnel: use of overset grids



C-type mesh around an airfoil



Overset Mesh

Numerical Scheme

- Conservative form of the **2D Euler Equations**

$$\frac{\partial \mathbf{u}}{\partial t} + \nabla . \mathcal{F} = 0$$

$$\mathbf{u} = \begin{bmatrix} \rho \\ \rho u \\ \rho v \\ E \end{bmatrix}, \ \mathbf{f}(\mathbf{u}) = \begin{bmatrix} \rho u \\ \rho u^2 + P \\ \rho u v \\ (E+P)u \end{bmatrix}, \ \mathbf{g}(\mathbf{u}) = \begin{bmatrix} \rho v \\ \rho u v \\ \rho v^2 + P \\ (E+P)v \end{bmatrix}$$

- **Navier Stokes Equations:** additional dissipative source term to the conservative form
- Finite volume (FV) formulation:

$$\frac{d\mathbf{u_{ij}}}{dt} V_{ij} + \sum_{faces} \mathbf{F}.\hat{\mathbf{n}} dS = 0 \Rightarrow \frac{d\mathbf{u_{ij}}}{dt} = \mathbf{Res}(i,j)$$

Numerical Scheme (Continued)

- FV formulation: handles non-Cartesian meshes without using transformation metrics
- Computation of the hyperbolic flux term
  - Characteristic decomposition normal to cell interface (mimic the wave nature of the solution)
  - Four eigenvalues and complete set of eigenvectors (two acoustic and two entropy waves)
  - Upwinded reconstruction based on eigenvalue sign
- Dissipative source term computed through a high order central differencing

Numerical Scheme (Continued)

- Numerical Flux computed through the Essentially Non-Oscillatory (ENO) and Weighted Essentially Non-Oscillatory (WENO) class of schemes
  - Adaptive stenciling to avoid discontinuities
  - Achieves high order accuracy in smooth regions of the solution
  - No oscillations around discontinuities
- ENO/WENO reconstruction applied to each characteristic field for the system of PDEs
- Time Marching through a multi-stage Runge-Kutta ODE solver

Validation

- Validation of inviscid Euler code:
  - Cartesian meshes – 2D Riemann problems, Shock Wave reflection problem, Blast Wave problem
  - Non – Cartesian meshes – Compression Ramp, Cylindrical blunt body problem, steady flow over airfoil

Validation (Continued)

- Validation of Navier Stokes code:
  - Steady test cases: flow over airfoils (NACA 0012 and 0015) and prediction of lift, drag and moment coefficients (experimental and computational results available)
  - Unsteady test cases, including dynamic stall: for NACA 0012, 0015 airfoils as well as airfoils optimized for rotors
    - Wind tunnel results available
    - Validation against TURNS results (Navier Stokes code)

End