

MechaTwing

TWINNING FOR EXCELLENCE IN MORPHING AND AERO-MECHATRONIC WING
CONTROL: A LEAP TOWARDS ECO-SMART AVIATION (101159722)

CTU Summer School
14 – 18 September 2026

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Modeling of Aerodynamic forces

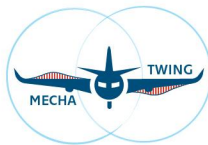
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Aerodynamic and Structural Methods for Loads



- In aircraft design, aerodynamic methods are required for different kinds of analyses
 - estimation of the overall performance (e.g. lift over drag ratio L/D)
 - calculation of stability derivatives (for handling qualities (HQ), flight control systems (FCS), etc.)
 - calculation of loads (steady/unsteady, components, for detailed design, etc.)
- Depending on the type of analysis to be performed, the aerodynamic methods can be classified as follows:
 - Steady / Unsteady
 - Viscous effects considered
 - Compressible effects considered
 - Thickness effects considered
 - Unsteady methods: Time or frequency domain solution
- For loads analyses – especially for jet transport aircraft – several simplifying assumptions can be made
 - drag forces are typically more than one order of magnitude lower than lift forces along the wing, their impact on structural sizing is rather low, thus they can be omitted for most configurations
 - Reynolds numbers are high, roughly between 10 millions and 70 millions, thus viscous effects can be omitted
 - geometrical simplifications can be made (e.g. thin airfoils or wings can be represented by lifting surfaces)
 - It is important that the aerodynamic method gives “distributed” aerodynamic forces



CFD Methods (Euler, Navier-Stokes)

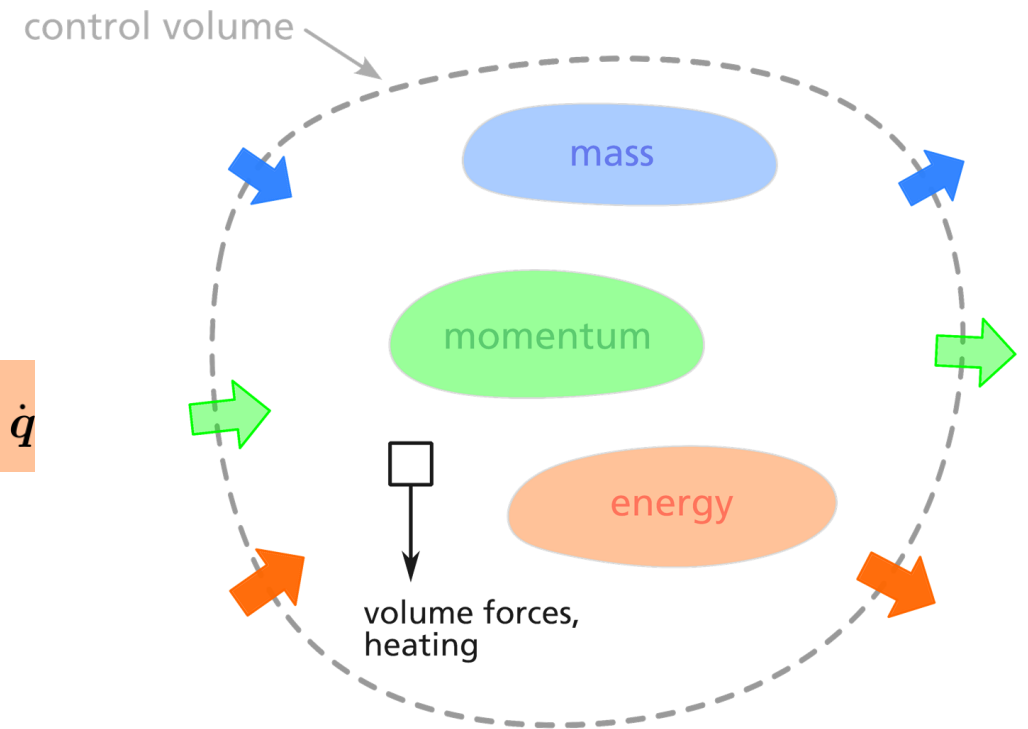
- Consider a typical CFD (volume grid) approach
- Compressible governing equations (Navier-Stokes) are discretized (e.g. by Finite-Volume approach) together with the fluid domain and solved iteratively

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{V}) = 0$$

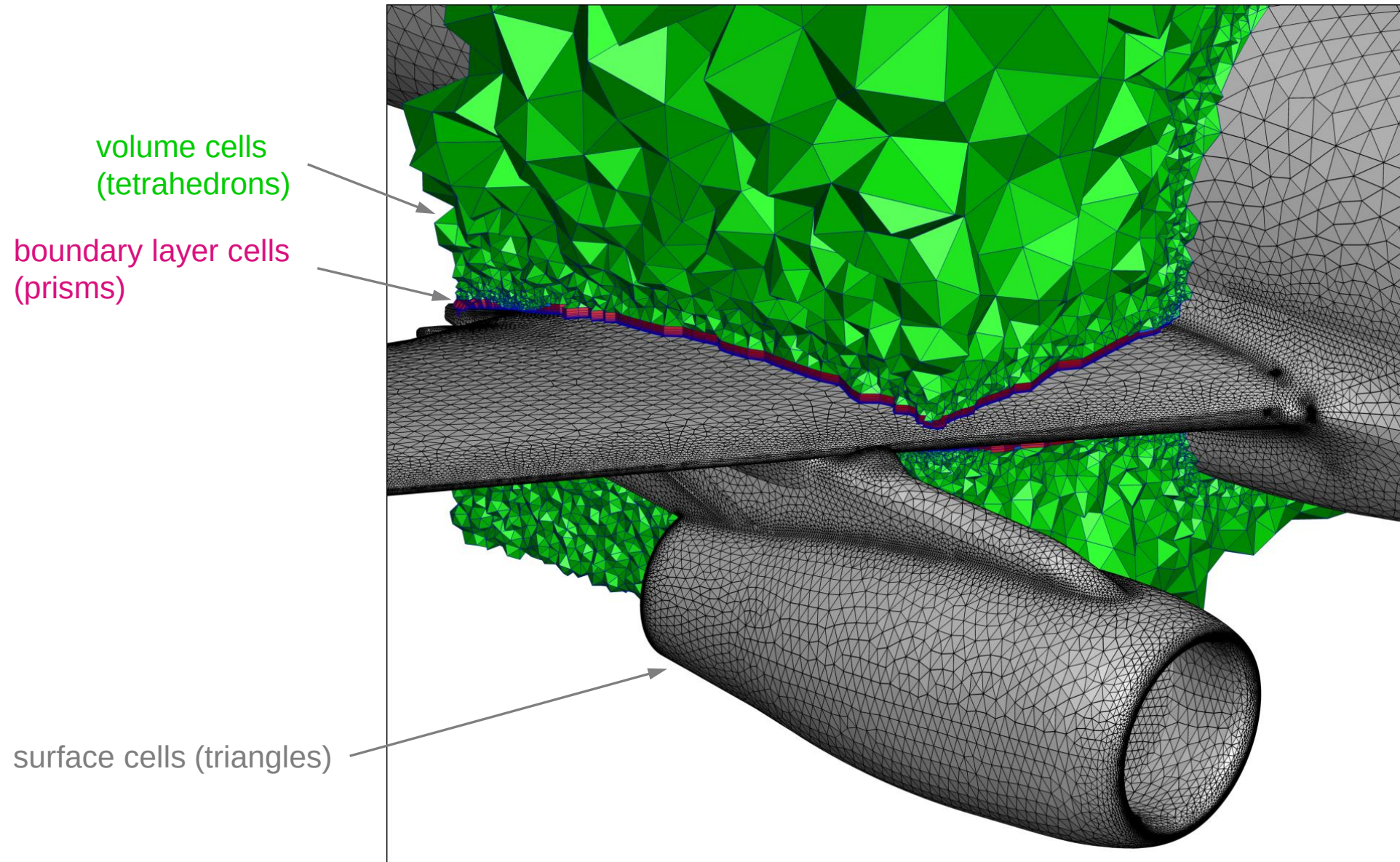
$$\frac{\partial (\rho \mathbf{V})}{\partial t} + \nabla \cdot (\rho \mathbf{V} \mathbf{V}^T) = \rho \mathbf{f} - \nabla p + \nabla \cdot \bar{\bar{\tau}}$$

$$\frac{\partial (\rho h_0 - p)}{\partial t} + \nabla \cdot (\rho \mathbf{V} h_0) = \dot{q}_v + \rho \mathbf{f} \cdot \mathbf{V} + \nabla \cdot (\bar{\bar{\tau}} \cdot \mathbf{V}) - \nabla \cdot \dot{\mathbf{q}}$$

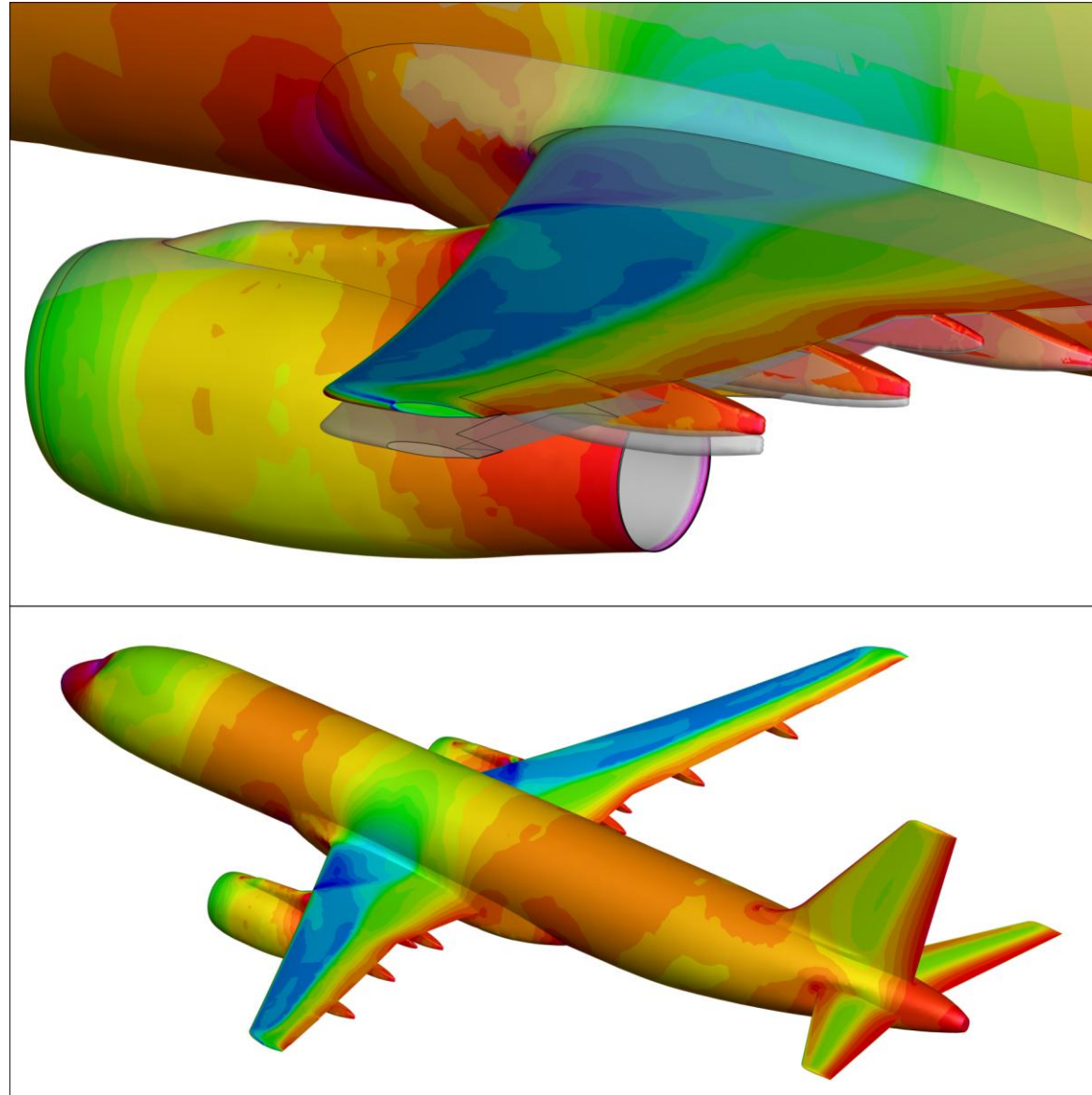
- Equations are highly nonlinear
- They account for compressibility, viscous effects, heat exchange
- At least five unknowns: density, 3 x velocity, enthalpy
- More e.g. for turbulence equations



CFD Methods (Navier-Stokes)



CFD Methods (Navier-Stokes)

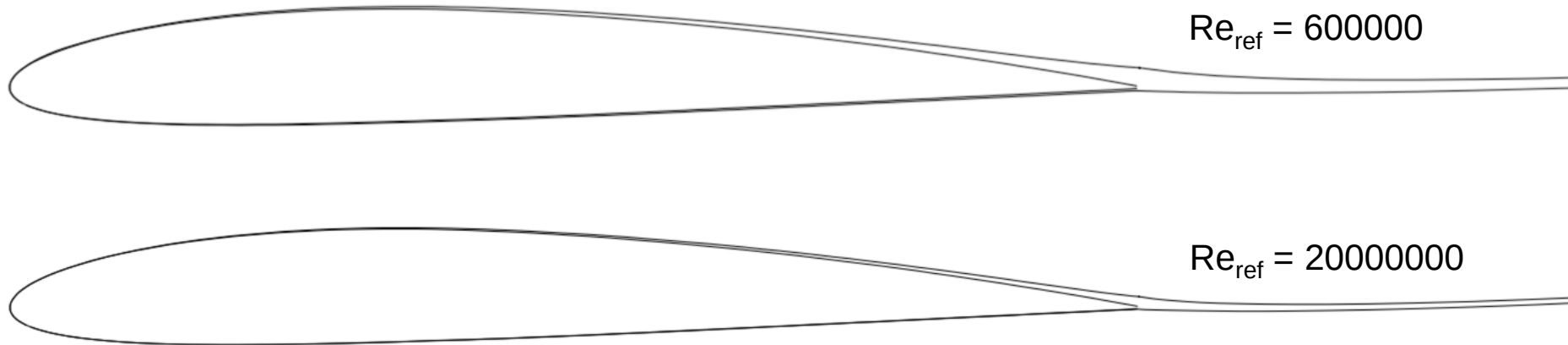


Simplifications of the Fluid Governing Equations

- The Euler or Navier-Stokes governing equations can be simplified if particular assumptions regarding the flow field are accepted
- 1st assumption: Attached flow at high Reynolds number, “few” viscous effects

$$\bar{\rho} \frac{\partial(\bar{\mathbf{V}})}{\partial t} + \bar{\rho} \bar{\mathbf{V}} \cdot \bar{\nabla} \bar{\mathbf{V}} = -\bar{\nabla} \bar{p} + \frac{1}{Re_{ref}} \bar{\nabla} \cdot \bar{\bar{\tau}} \quad Re = \frac{V c}{\nu} = \frac{\rho V c}{\mu}$$

- Viscous term scales with 1/Re and is omitted
- Regions with vorticity are restricted to (thin) boundary layers (but they won't be neglected → wake)
- The outer flow is effectively inviscid



Simplifications of the Fluid Governing Equations



- 2nd assumption: Irrotational flow

$$\nabla \times \mathbf{V} = \mathbf{0}$$

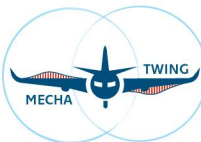
- No production of vorticity e.g. at shocks
- The flow field (velocity) can then be described by the gradient of a scalar function, the velocity potential, ϕ

$$\mathbf{V} = \nabla \phi \quad \mathbf{V} = [u \ v \ w]^T \quad u = \frac{\partial \phi}{\partial x} \quad v = \frac{\partial \phi}{\partial y} \quad w = \frac{\partial \phi}{\partial z}$$

- 3rd assumption: Incompressible flow
- For adiabatic flows, density variations $\frac{\Delta \rho}{\rho}$ scale as M^2 , for low speed flow cases this implies an almost constant density equal to the freestream value

$$\nabla \cdot \mathbf{V} = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$$

- Continuity equation reduces to a divergence-free flow field
- Energy and state equations decouple and are not needed



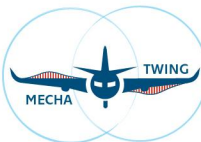
Laplace's Equation



- Combining the assumptions yields

$$\nabla \cdot \mathbf{V} = \nabla \cdot \nabla \phi = \Delta \phi = 0$$

- Laplace's equation for incompressible and irrotational flow:
 - Linear, elliptic, second-order PDE
 - no time-dependent term, i.e. the system can be steady or unsteady (depends on boundary conditions)
- Now there's only one variable to solve for, the velocity potential ϕ
- For incompressible flows, pressure is a kinematic magnitude resulting from the velocity field (via the incompressible Bernoulli equation, which can be obtained from the momentum equation)
- Although the governing (Laplace) equation describes an incompressible flow, we can retrieve compressibility for steady and harmonic flows (at subsonic speeds) by a simple transformation (Göthert-Transformation) later on
- We now have to seek for suitable solutions of Laplace's equation $\Delta \phi = 0$
- A bulk of functions will actually (mathematically) fulfill this equation
- A "general" methodology is given by the application of Green's theorem, which yields source and doublet distributions
- Another approach for solving Laplace's equation is to focus on flow physics rather than mathematics, i.e. we decide how to model our system with "elements" that provide e.g. displacement and lifting effects

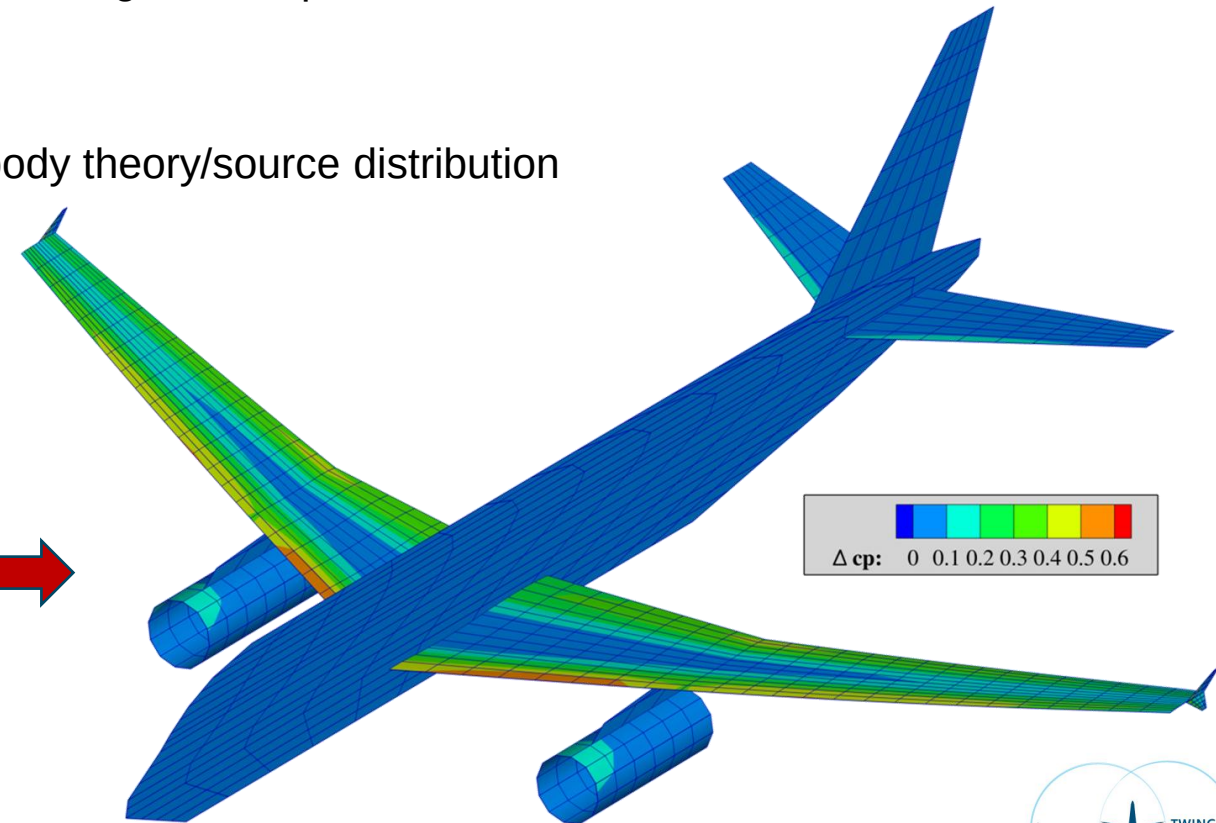


Aerodynamic Methods based on Potential Theory: VLM

- For aerodynamic applications, displacement and lifting effects are needed
- Displacement effects are modelled by source distributions, lift is linked to (bound) vorticity
- A mid-fidelity tool based on aerodynamic potential theory is the Vortex-Lattice Method (VLM), a general method for the numerical solution of the 3D lifting surface problem
- Key features:
 - lifting (camber) surface representation of geometry
 - thus no displacement effects (can be added by slender body theory/source distribution on fuselage)
 - variation of circulation in span- and chordwise direction by discretization of the lifting segments into (flat) panels
 - **Boundary layer and displacement effects “cancel”**

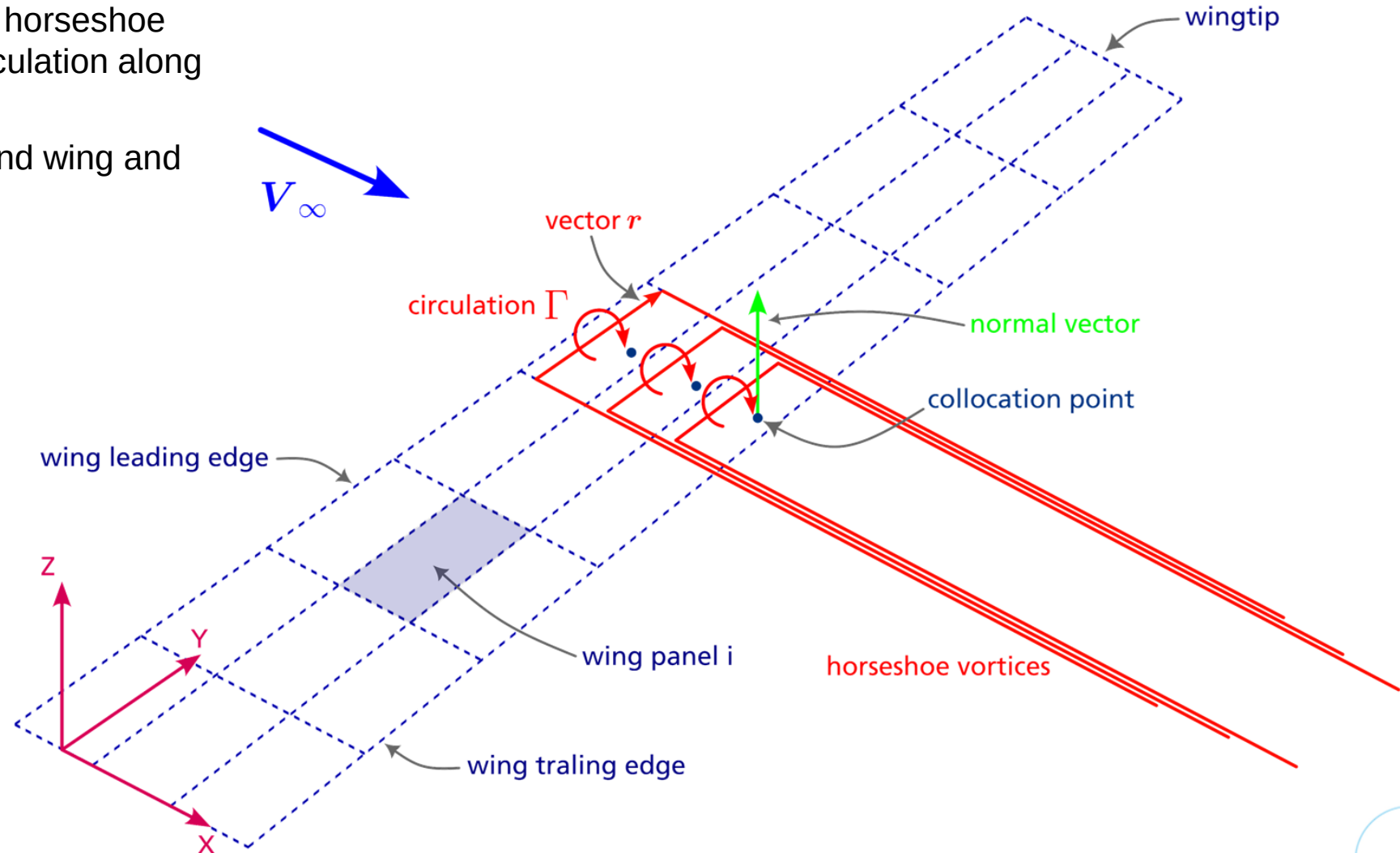


geometrical simplification
and discretization



Aerodynamic Methods based on Potential Theory: VLM

- Original formulation uses horseshoe vortices with constant circulation along bound and trailing legs
- Starting vortex is far behind wing and its influence is neglected

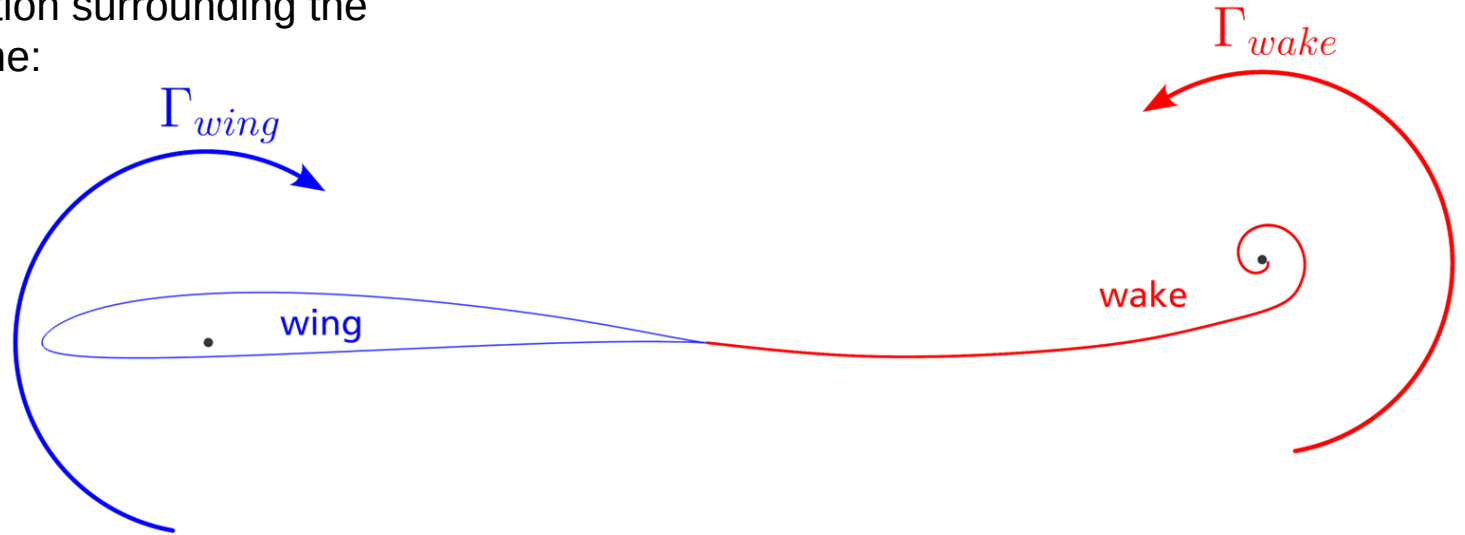


Aerodynamic Methods based on Potential Theory: UVLM

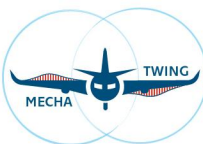


- Unsteady flows are treated by unsteady boundary conditions and the application of Kelvin's theorem (conservation of angular momentum)
- Kelvin's theorem states that the total circulation surrounding the wing and the wake does not change with time:

$$\frac{D}{Dt}(\Gamma_{wing} + \Gamma_{wake}) = 0$$

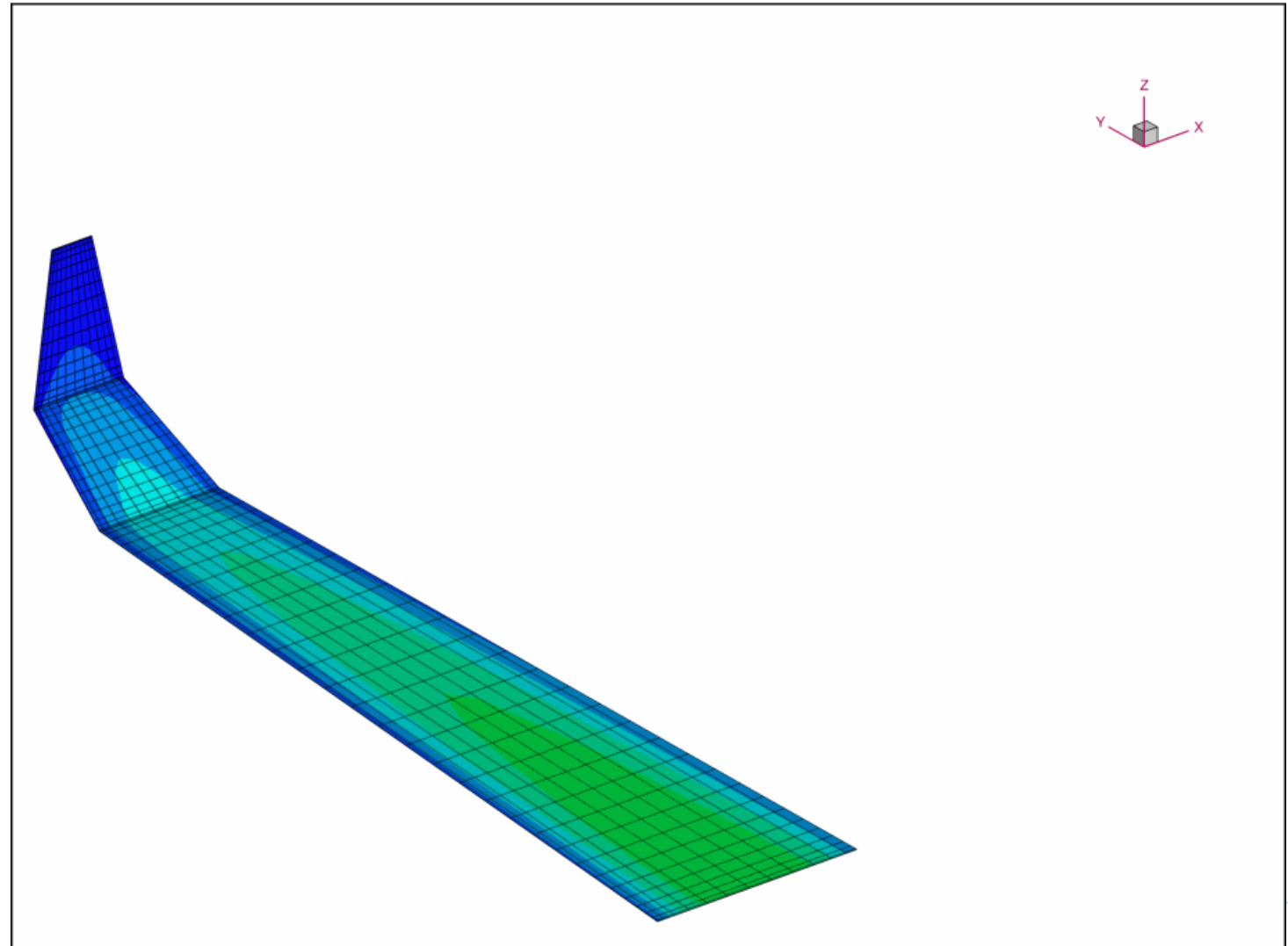


- Each time-dependent change of the circulation of the wing is associated with a change in the circulation of the wake
- This explains the appearance of a starting vortex as the wing is set into motion
- It is "hard" to implement this requirement in a continuous-time methodology
- The easiest way for the VLM is the wake-shedding approach



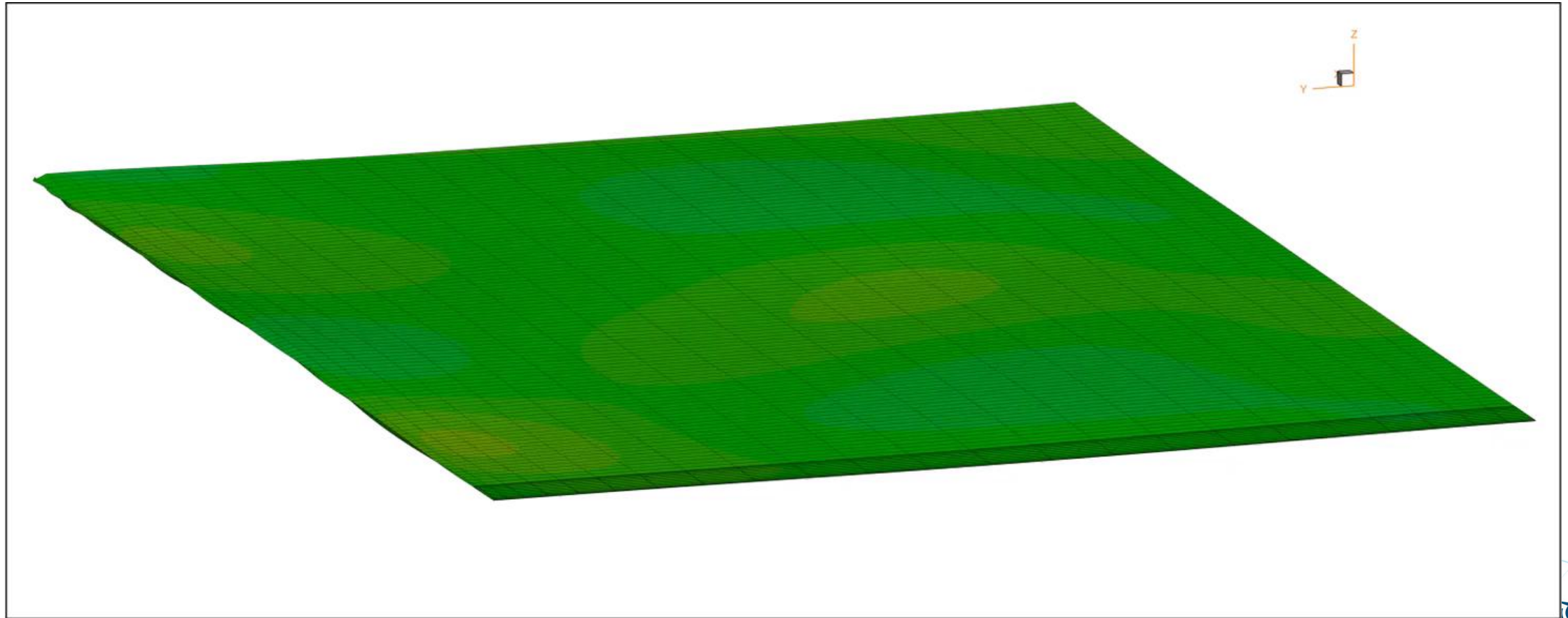
Aerodynamic Methods based on Potential Theory: UVLM

- The unsteady Vortex-Lattice Method (UVLM)
- The wing is suddenly set into motion (Wagner's function)
- Wake relaxation is physically more accurate since the wake carries no loads (it becomes a stream surface)



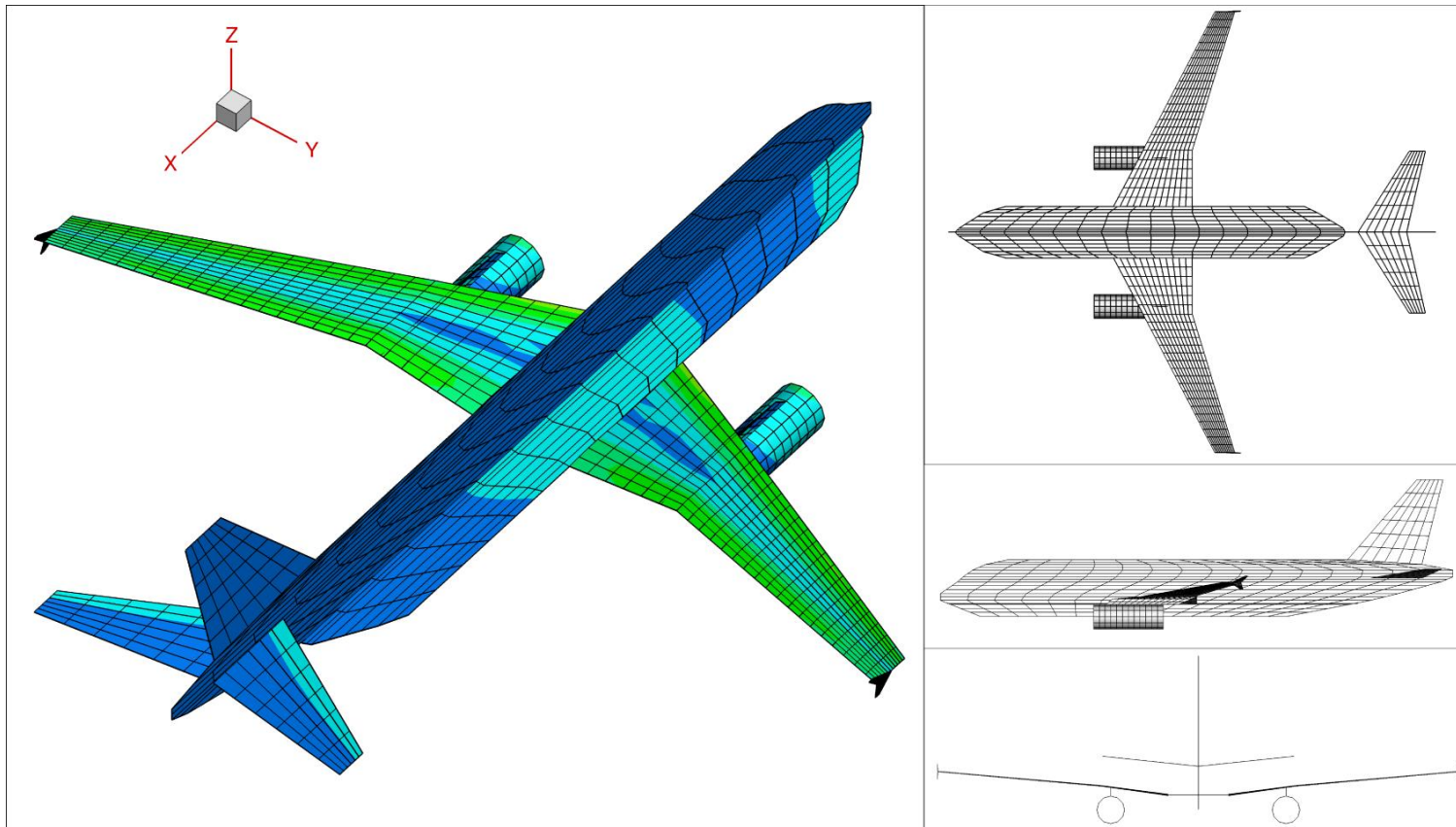
Aerodynamic Methods based on Potential Theory: UVLM

- The unsteady Vortex-Lattice Method (UVLM)
- Time-domain flutter simulation of a slender high aspect ratio wing structure
- Vorticity is shed from the trailing edge into the wake



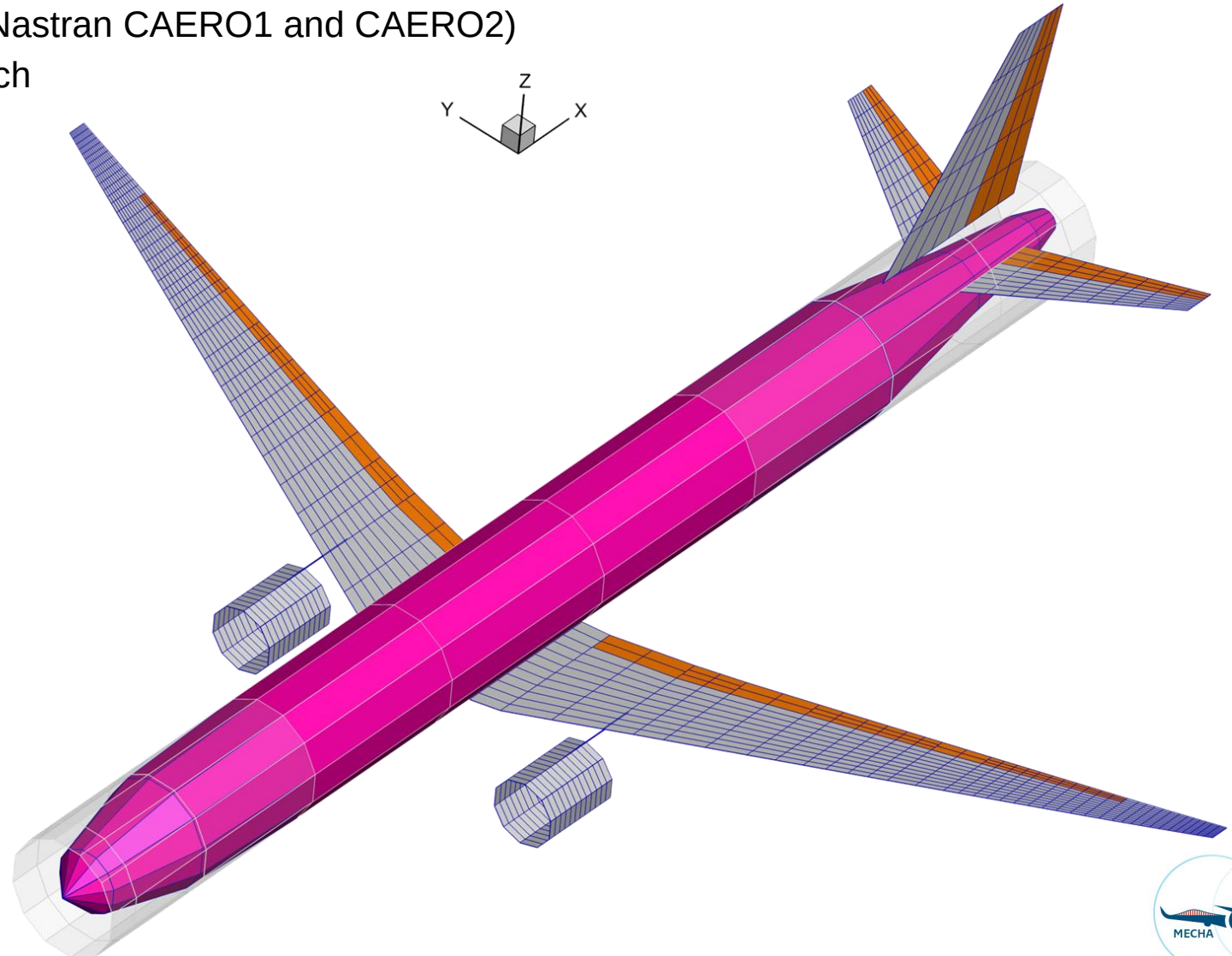
Aerodynamic Methods based on Potential Theory: VLM

- As mentioned in the introduction, a number of several hundred or thousand load cases must be considered in a reasonable time for a typical aircraft loads process
- To this end, potential methods are heavily favored over CFD methods for loads analysis, especially in an industrial context
- Example: VLM/DLM-grid and solution of Airbus A320 configuration



Aerodynamic Methods based on Potential Theory: VLM

- Mid range jet transport aero model (MSC Nastran CAERO1 and CAERO2)
- fuselage modeled by slender body approach
- Engines/nacelles as through-flow surfaces



Pros and Cons VLM/UVLM

Pro	Remark
easy model/grid generation	lifting surface representation (no thickness effects)
low computational costs	simulation time can be significant for particular unsteady problems
geometrically nonlinear	spatial linearization (wake, downwash) easy
comparatively high accuracy	regarding the level of complexity
induced drag calculation	using streamwise segments of wake vortex rings or Trefftz plane analysis for steady case
viscous drag estimation	based on airfoil polar
well suited for aeroelastic applications	due to good geometry representation, unsteady formulation
state-space formulation	nonlinear or linearized (frozen wake, small disturbances)

Con	Remark
no "general" compressible unsteady formulation	compressible formulation based on velocity potential and harmonic motions/solutions possible (see work of Geissler, AE)
wake handling can be cumbersome	finite-core option or vortex-particle method can be applied
no displacements effects	interaction between slender bodies (fuselage) and lifting surfaces (wing) difficult to model