Aerodynamics of Sails

P13 -

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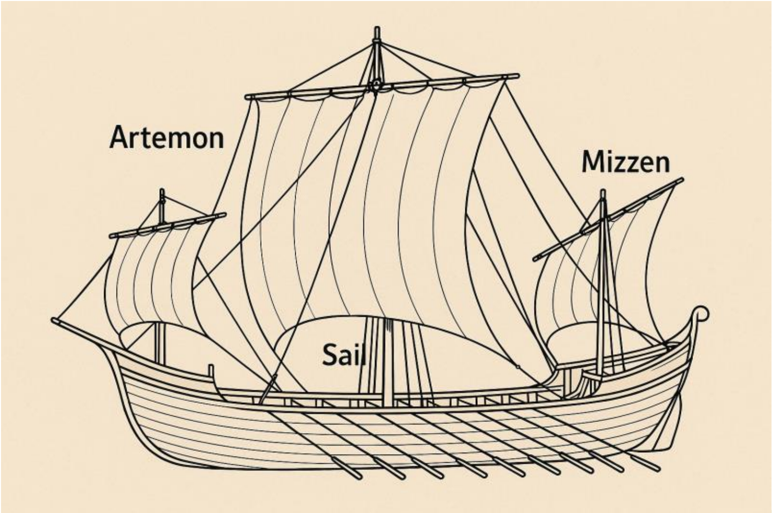
Objective

- To explore the aerodynamic principles governing sail performance and their influence on sailing efficiency and control.
- To analyse the **historical evolution of sail rigs**, emphasizing how sail design adapted to enhance propulsion and stability.
- To investigate the formation and role of **Leading-Edge Vortices (LEV)** in downwind sails such as spinnakers.
- To demonstrate the use of **Computational Fluid Dynamics (CFD)** in modern sail optimization and the impact of parameters like curvature and angle of attack on lift generation.
- To understand how **biomimicry and fluid dynamics** intersect in the evolution and function of sails.

Background Information

History of Sails boats -

- This sail rig was **in continuous use for over 1,500 years**, evolving but not being replaced, even as new technologies emerged.
- It facilitated the transition from **oar-based propulsion to pure sailing vessels**, leading to larger, more efficient cargo ships, reduced crew needs, and extended range .
- Archaeological finds (e.g., brail rings, pulley sheaves) across **Etruscan, Egyptian, Roman, and Hellenistic sites** affirm its widespread adoption, suggesting a **shared Mediterranean maritime culture**
- As sailors began venturing into **more windward courses**, the traditional square sail was adapted with **additional sails** like the *artemon* (a small foresail) and later the *mizzen*.
- Evidence from ports like **Myos Hormos** and **Berenike** in the Red Sea shows that the Mediterranean square sail was **exported beyond the Mediterranean**, reaching parts of the **western Indian Ocean** during the early 1st millennium AD.



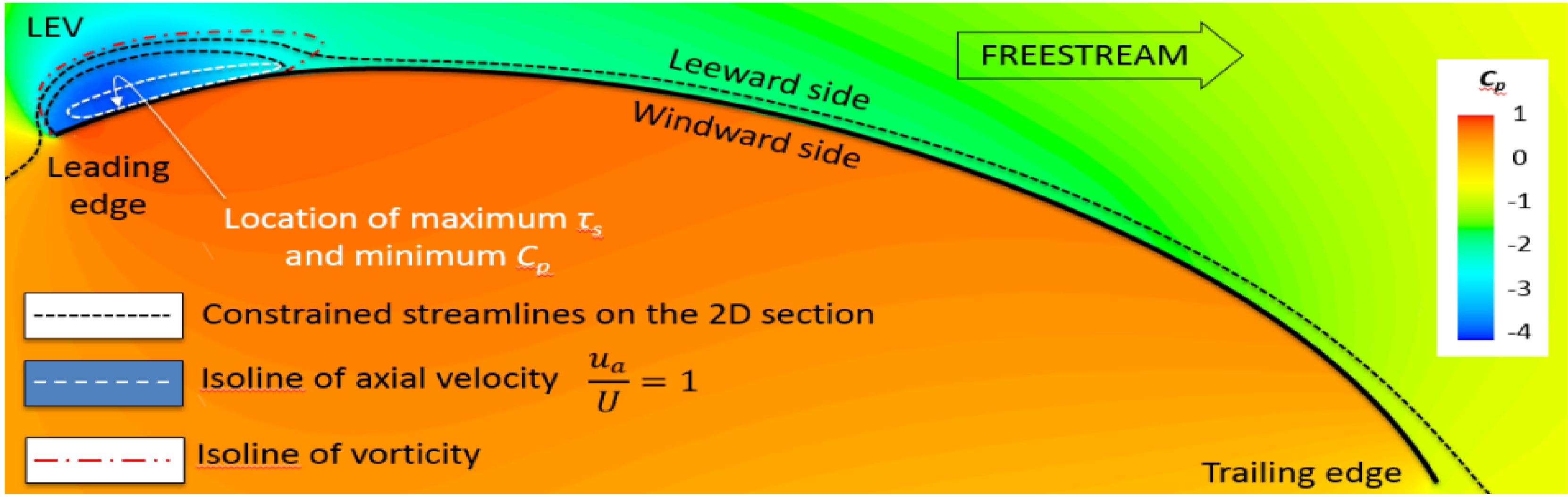
Downwind Aerodynamics of sails

Leading-Edge Vortex (LEV)

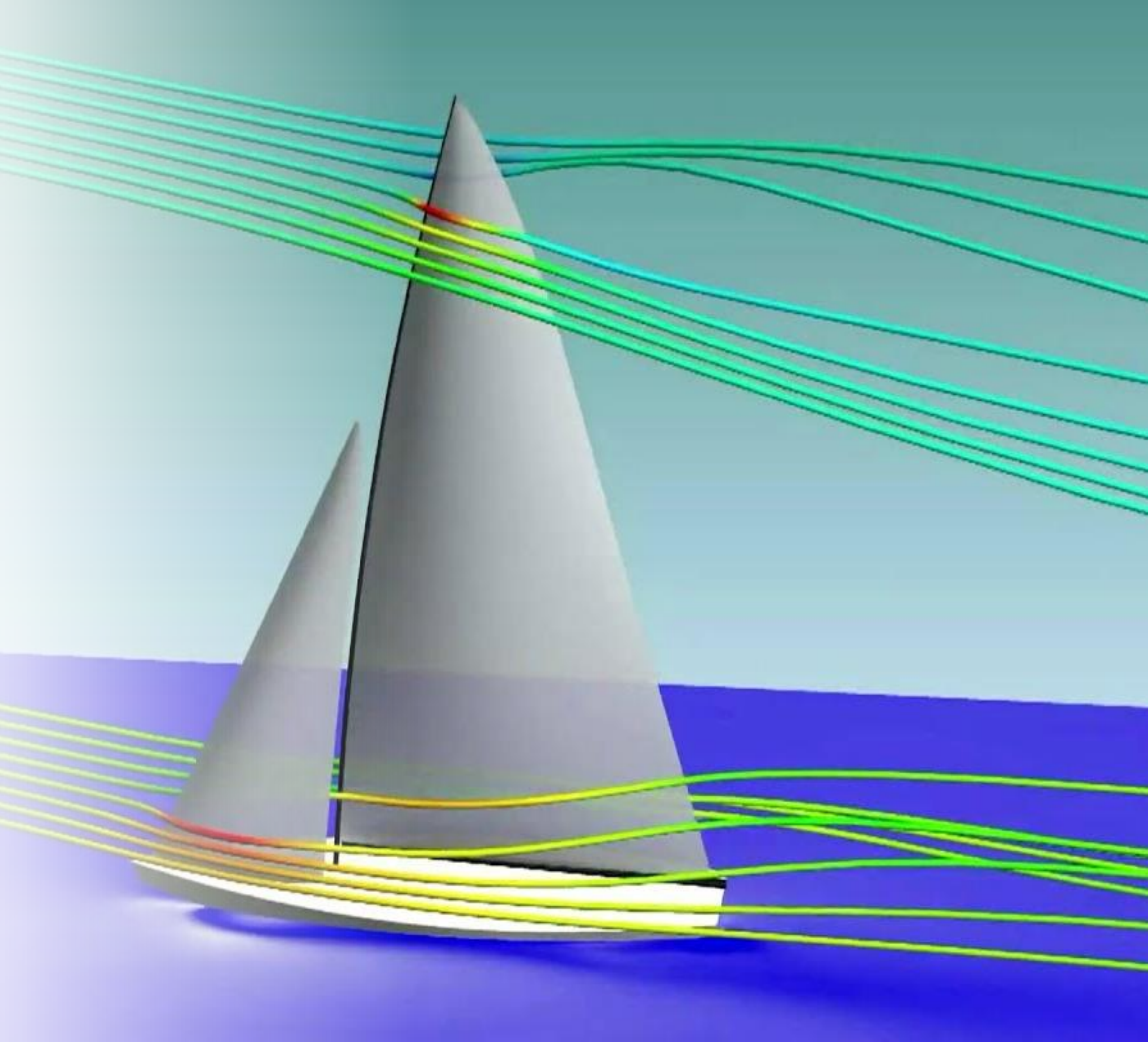
What is LEV?

The **Leading-Edge Vortex (LEV)** is a rotating mass of air that forms at the **sharp leading edge** of asymmetric downwind sails (spinnakers) when sailing at high apparent wind angles. It rolls up due to flow separation and remains near the sail surface due to suction and spanwise pressure gradients.

- **Why is it important?**
  - **Lift Generation**: The LEV contributes **~25% of the sectional lift** in the upper half of the spinnaker (confirmed experimentally via PIV in a flume) .
  - **Drive Force Boost**: Because the LEV is located forward on the sail, it increases **forward thrust (drive force)** even more than it does vertical lift.
  - **Biological Analogy**: This vortex mechanism is comparable to what occurs on **bird wings** and **delta wings**, where vortex lift enables high lift at large angles of attack.



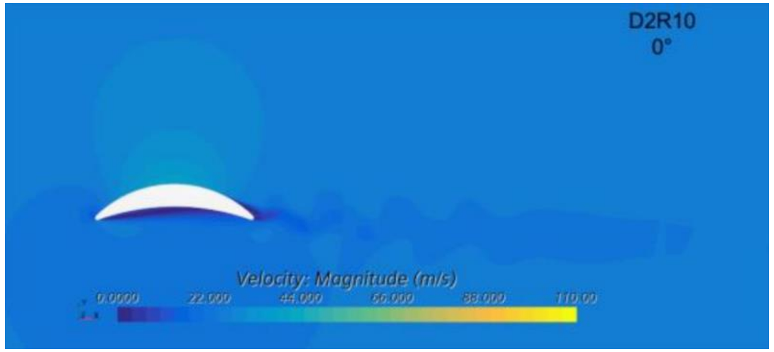
Computational Methods in Sail Design (CFD)



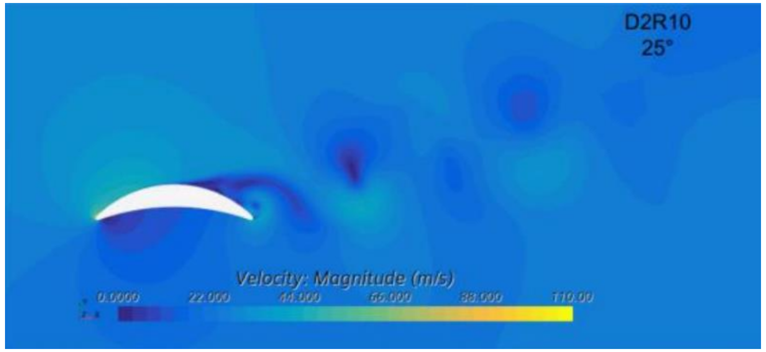
- CFD is a numerical method used to simulate fluid flow around objects by solving the governing equations of fluid dynamics (Navier–Stokes equations).
- CFD is used extensively to analyze aerodynamic performance without physical prototypes.
- CFD proves to be an effective tool in sail design and optimization, enabling performance evaluation of innovative profiles
- A study was conducted which showed some of the key variables in sail performance where Angle of Attack, Curvature and Thickness.

Outcome of the study

Parameter	C_L	C_D
Increase in AoA	Increases (till ~20˚)	Increases
Reduction in thickness	Increases	Increases Slightly
Higher Curvature	Increases	Increases Significantly



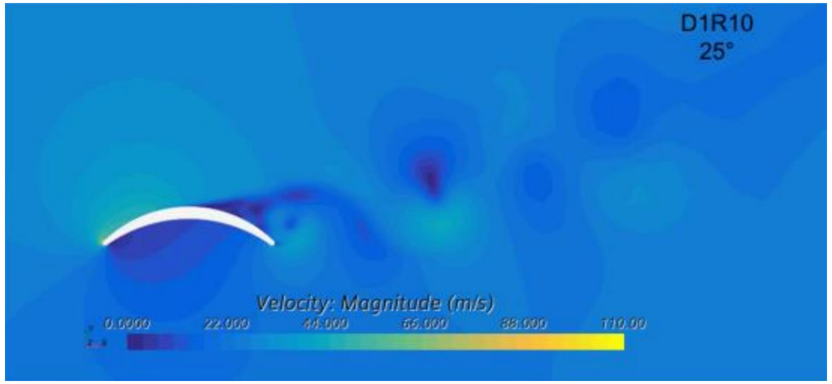
At zero angle of attack



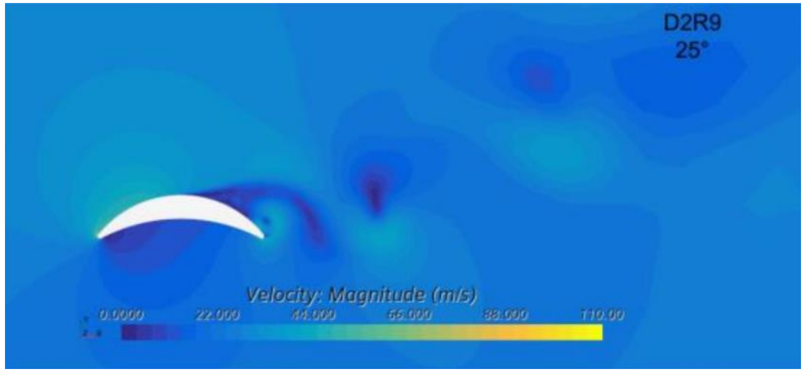
At 25 degree angle of attack

Trends in C_L and C_D:

- D2R10 at 0°: $C_L \approx 0.97$, $C_D \approx 0.048$
- D2R10 at 20°: $C_L \approx 2.38$, $C_D \approx 0.212$
- D2R10 at 25°: $C_L \approx 2.41$, $C_D \approx 0.334$
- D2R9 (more curved) at 20° : $C_L \approx 2.53$, CD ≈ 0.268
- D1R10 (lower diameter) at 20°: $C_L \approx 2.62$, $C_D \approx 0.22$



At half the diameter of sail



At higher curvature of sail

Thank you

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