2.2 Viscous Resistance
Flow around a ship hull
2.2 Viscous Resistance
Flow around a ship hull
(G. Kuiper: Resistance and Propulsion of Ships)

- Main features:
  - High Reynolds number flow.
  - Boundary-layer developing from the bow to the stern.
  - Initial part of the boundary-layer is laminar. Transition to turbulent regime depends on Reynolds number and hull shape (pressure gradient imposed to the boundary-layer).
  - At full scale (real ship), transition is located close to the bow.
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Flow around a ship hull
G. Kuiper: Resistance and Propulsion of Ships

• Main features:
  – At the bow, the pressure gradient is usually favourable.
  
  – At the stern, the longitudinal pressure gradient is adverse. This leads to a rapid increase of the thickness of the viscous region of the flow (region with non negligible viscous stresses), which can no longer be assumed to be a “thin-layer”, i.e. significantly smaller than the typical dimensions of the ship.
  
  – The boundary-layer is three-dimensional.
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Three-dimensional (3D) boundary-layer

- $x$ axis aligned with the external flow (outside the boundary-layer). $z$ axis perpendicular to the wall.

- No slip and impermeability conditions lead to zero velocity on the surface.
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Three-dimensional (3D) boundary-layer

- Velocity profile with two components:
  1. Streamwise velocity
  2. Crosswise velocity.

- Cross-flow angle
  \[ \tan \beta = \frac{v(z)}{u(z)} \]

- Limiting streamline
  \[ \tan \beta_w = \lim_{z \to 0} \frac{v(z)}{u(z)} = \frac{(\partial v/\partial z)_w}{(\partial u/\partial z)_w} = \frac{\tau_{wy}}{\tau_{wx}} \]
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Separation of three-dimensional boundary-layers
Streamwise flow separation

- Separation line transversal to the streamlines of the external flow (main flow direction).
- Flow reversal downstream of the separation line.
- In the vicinity of point S, flow is similar to two-dimensional separation.
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Separation of three-dimensional boundary-layers
Streamwise flow separation

- Separated flow region similar to a separation bubble, with a recirculating region in its interior.

- Drastic increase of the “displacement thickness” imposed by the viscous flow region. This leads to a significant increase of the pressure resistance coefficient (form drag).
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Separation of three-dimensional boundary-layers

Streamwise flow separation
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Separation of three-dimensional boundary-layers
Converging limiting streamlines

- $x$ axis aligned with the external flow (outside the boundary-layer). $y$ axis perpendicular to the wall.
- Limiting streamlines are converging on the surface ($\Delta z \to 0$).
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Separation of three-dimensional boundary-layers
Converging limiting streamlines

• Outer streamlines increase distance to the wall, i.e. thickness of stream tube grows.

• Mass conservation implies that flow moves away (separates) from the surface.
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Separation of three-dimensional boundary-layers
Converging limiting streamlines

• Separation line aligned longitudinally with the external flow.

• Streamlines converge tangentially to the separation line.

• Flow moves away (separates) from the wall.
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Separation of three-dimensional boundary-layers
Converging limiting streamlines

- No streamwise flow reversal in the vicinity of the separation line.

- Separated surface contains vorticity that tends to roll-up into a vortex. The formation of this vortex corresponds to a loss of energy to the wake and consequently to an increase of pressure resistance.
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Wake of simple ship shapes
U sections

- Velocity of the external potential flow (outside the boundary-layer) at the lateral part of the ship is higher than at the bottom.

- Pressure on the lateral surface is smaller than on the bottom.
2.2 Viscous Resistance
Wake of simple ship shapes
U sections

- Inside the boundary-layer, the fluid flows from the bottom to the side of the ship.

- This cross-flow originates a bilge vortex with negative circulation (clockwise). Vortex visualized in the wake by a tuft test.
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Wake of simple ship shapes
Pram sections

- Velocity of the external potential flow (outside the boundary-layer) is higher at the bottom than at the lateral part of the ship.

- Pressure on the bottom is smaller than on the lateral surface.
2.2 Viscous Resistance
Wake of simple ship shapes
Pram sections

- Inside the boundary-layer, the fluid flows from the side of the ship to the bottom.

- Cross-flow generates a counter-clockwise vortex visualized at the wake by a tuft test.
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Wake flow of simple shapes
Combintion of U and Pram sections

- No vortices in the wake.
- No flow separation.
- Small cross-flow velocities in the wake.
- Smaller viscous resistance than in the previous shapes.
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Wake flow of simple shapes
Effect of bilge vortices in the resistance of a ship
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Flow around a ship hull
Flow visualization

- Tuft test.
- Flexible yarn at the tip of supporting wires.
- Direction of the flow is easy to identify. Streamwise flow separation is easy to detect.
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Flow around a ship hull
Flow visualization

• Paint test.

• Ink of appropriate viscosity applied for strips on the ship surface.

• Shear-stress at the wall drives the ink flow that visualizes the limiting streamlines.

• Example: Flow on a bulbous bow.
2.2 Viscous Resistance
Flow around a ship hull
Flow visualization

- Paint test.
- Ink of appropriate viscosity applied on strips of the ship surface.
- Shear-stress at the wall drives the ink flow that visualizes the limiting streamlines.
- Example: Flow on the stern of a fast ship.
2.2 Viscous Resistance
Velocity in the propeller plane

- The velocity distribution of the wake flow at the propeller plane is a key feature for the performance of the propeller.

- The knowledge of the velocity distribution at the propeller plane is fundamental for the project of the propulsor.

- The velocity distribution at the propeller plane obtained without the propeller is the nominal wake velocity, or simply, the nominal wake.
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Velocity in the propeller plane

• The nominal wake is usually determined experimentally from measurements of the three velocity components at the propeller plane (pitot tube, LDV, PIV). Nowadays it is also possible to determine numerically the nominal wake.

• Experiments have a large amount of accumulated knowledge. However, they are time-consuming, expensive and we have to take into account scale effects. Accuracy of the acquired data depends on the selected technology and quality of the experimental facilities.
2.2 Viscous Resistance  
Velocity in the propeller plane

• The nominal wake is usually determined experimentally from measurements of the three velocity components at the propeller plane (pitot tube, LDV, PIV). Nowadays it is also possible to determine numerically the nominal wake.

• Numerical predictions must rely on a proper mathematical model able to deal with turbulent flows at high Reynolds numbers. Accuracy of the predictions (numerical and modelling) is still questionable for most of the available methods.

• Present trend is to combine both approaches.
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Velocity in the propeller plane
Measurements with 5-hole pitot tube

- Pressure difference between the five holes is measured to determine the velocity magnitude and the flow direction in two perpendicular planes.

- Calibration curves convert the measured pressure differences in to the three velocity components.
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Nominal wake

- Velocity components
  - Axial velocity
    \( v_a / V \)
  - Radial velocity
    \( v_r / V \)
  - Tangential velocity
    \( v_t / V \)
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Nominal wake

- Velocity components using the wake fraction
  - Wake fraction
    \[ w_n = \frac{V - v_a}{V} = 1 - \frac{v_a}{V} \]
  - Radial velocity
    \[ v_r / V \]
  - Tangential velocity
    \[ v_t / V \]
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Nominal wake

- Nominal wake coefficient (volumetric averaging)

\[ \bar{v}_a = \frac{1}{\pi R^2} \int_0^R \int_0^{2\pi} v_a(r, \theta) r \, d\theta \, dr \]

\[ \bar{w}_n = \frac{V - \bar{v}_a}{V} = 1 - \frac{\bar{v}_a}{V} \]
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Nominal wake

\[ \frac{V_a}{V} \]
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Nominal wake
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Nominal wake

Experimental result
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Nominal wake

Numerical prediction
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Influence of the ship shape in the nominal wake

Figure 4.17: Hullform Variations
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Influence of the ship shape in the nominal wake