Impact of Turbulence and Ground on Wake Vortex Evolution - Towing Tank Studies

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Wake Vortices in Real Life: Exemplar Contrail of an Airliner

Condensation behind engines
(view from window of a Boeing 747, tail plane to the upper right)

Roll-in of condensate into wake vortices

Natural decay of wake vortices (Crow-instability)
Experimental Study on Wake Vortices: Measurements in a Water Towing Tank

Object:
Wake (2-vortex-system) of a F-13 model in the water towing tank Göttingen („Wasserschleppkanal Göttingen“, WSG)

Methods:
- Time-resolved stereo Particle Image Velocimetry (PIV)
- Time-resolved vortex core visualization
- Turbulence generation: Pilot carriage with grid, selectable velocity / delay

Configurations:
- Wake with / without turbulent environment
- Wake close to ground surface with / without ground obstacles
Experimental Study on Wake Vortices: The Model

F-13 Model for Generation of Wake Vortices:

- Span: 175 mm
- Chord: 35 mm
- Angle-of-attack: 10° (adjustable)
- Option: Tail wing for 4-vortex-systems (not used here)
- Initial vortex core distance: $b_0 = 153$ mm
Experimental Study on Wake Vortices: The Model

Visualization of Vortex Cores:
- Outlets at wing tips
- Contrast agent fed from vessel 0.5 m above water surface
- Gravity-driven flow without additional forcing
- Contrast agent (high concentration):
  a) Polyamide particles in water (scattering), side illumination
  b) Ink (absorbing), back-illuminated
Turbulence Generation: Pilot Carriage

- Pilot carriage with independent drive
- Grating square profiles: (20 mm)$^2$
- Grating spacing: 200 mm
- Velocity: Up to 1 m/s
- Turbulence field with temporal decay
Turbulence Generation: Characterization

- Grating velocity: 1 m/s
- Stereo PIV measurement
- PIV correlation window size:
  - 3.2 mm @ field of view 190 x 130 mm²
  - 1.6 mm @ field of view 100 x 70 mm²
**Stereo PIV: Setup**

- Laser: Lee LDP 200-MQG @ 1 kHz, 25 mJ / pulse
- Cameras: Photron APX-RS @ 1kHz, 1 mega pixel
- Lenses: Nikkor 1.8/50 @ F# 5.6, Distagon 2.8/21 @ F# 8
- Imaging: Scheimpflug-condition, prisms optimize interface to water
- Camera system on vertical translation stages, selectable velocity
**Stereo PIV: Calibration and Evaluation**

### Calibration:
- Light sheet perpendicular to flight direction
- Cameras on both sides of light sheet
- Transparent calibration grid on glass carrier
- Grid spacing: 10 mm
- Disparity correction based on particle images

### PIV Evaluation:
- Multigrid cross correlation evaluation, image deformation
- Correlation window size 24 * 24 pixels
- PIV delay 2 – 20 ms, automatic adaptation according to outlier rate (< 0.5%)
- Time resolution 50 ms
Wake Vortices Impacted by Turbulence: Properties

**Requirements / Features:**

- Undisturbed vortex pair descents with approximately constant velocity and constant core distance
- Vortices impacted by turbulence change velocity / direction in non-predictable way
- Field of view should capture vortices as long as possible

**Measurement:**

- Translation stages move cameras with descent rate of undisturbed vortices
- Field of view: 340 x 190 mm²
- Correlation window size: 4.8 mm (24 pixels)

Reference time: \( t_0 = \frac{b_0}{w_0} \)

Vortex age: \( \tau = \frac{t}{t_0} \)

\( (b_0: \) vortex core distance, \( w_0: \) descent rate)
Wake Vortices Impacted by Turbulence: PIV Measurement Sequence

**Measurement Sequence:**
- Settling time for turbulence inside tank > 20 minutes
- Start of pilot carriage with grid, velocity 1 m/s
- Time at rest, duration defined by delay between grid and model
- Start of model carriage
- Model carriage passing PIV plane triggers measurement sequence:
  - Cameras start recording
  - Translation stages follow vortex descent
- Both carriages transported back to start position
- Transfer of image data from cameras to computer
# Wake Vortices Impacted by Turbulence: Configurations

<table>
<thead>
<tr>
<th>Configuration</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
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<tbody>
<tr>
<td>Time after grid passing [s]</td>
<td>without grid</td>
<td>without grid</td>
<td>80</td>
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<tr>
<td>Turb. RMS [mm/s]</td>
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<td>0</td>
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<tr>
<td>Model velocity [m/s]</td>
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<td>2.44</td>
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<td>2.44</td>
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<td>Reynolds number:</td>
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<td>85000</td>
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<tr>
<td></td>
<td>Circulation based</td>
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<td>52000</td>
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<tr>
<td>Initial circulation [m²/s]</td>
<td>0.017</td>
<td>0.052</td>
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<tr>
<td>Descent rate [mm/s]</td>
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<td>44</td>
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<tr>
<td>Reference time $t_0$ [s]</td>
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<td>3.5</td>
<td>8.5</td>
<td>3.5</td>
<td>8.5</td>
<td>3.5</td>
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</table>
Wake Vortices Impacted by Turbulence: PIV Results

Parameters:
- Model velocity: 2.44 m/s
- Moving coordinate system: 44 mm/s descent rate
- Time delay grid – model: 80 s (turb. RMS: 5 mm/s)
- Circulation: 0.052 m²/s
- Here in display: 10 s ($\tau = t / t_0 = 2.9$ resp. $159 b_0$)
Vortex Core Visualization: Setup

- Three cameras (PCO.4000, 11 mega pixel) in linear arrangement under towing tank
- Lenses: Distagon 2.8/21, Nikkor 2.8/28 @ F# 8
- Side cameras under Scheimpflug-condition
- Recording rate: 2 frames / s
- Captured volume: min. 700 * 360 * 600 mm³
- Background above tank darkened by black fabric
- Illumination by xenon flash lamps (Rapp OptoElectronic NGW10) on both sides of tank
- Release of polyamide particles from wing tips into vortex cores
- Recording of flash illuminated particles
Vortex Core Visualization: Results (Qualitative)

Parameters:
- Model velocity: 2.44 m/s
- Time delay grid – model: 80 s (turb. RMS: 5 mm/s)
- Recording rate: 2 frames / s
- Here in display: 15 s (τ = 4.3 resp. 239 b₀)

Low turbulence  
With grid turbulence (example)
Wake Vortices in Proximity to Surfaces: Properties

Parameters:
- Model at constant distance $h$ above flat ground
- Optional 2D obstacles perpendicular to flight direction on ground in front of / behind measurement plane:
  - Square profiles with side length $a = 10$ mm, 20 mm, 30 mm
  - Sine wave, height $a = 40$ mm, wave length $l = 1300$ mm
- Ground and obstacles made from PMMA (acrylic glass, „Perspex“)
Wake Vortices in Proximity to Surfaces: Properties

Requirements / Features:
- Wake vortices decelerated by ground
- Wake vortex path diverted sideways by ground
- Ground topology influences vortices

Measurement:
- Flat intermediate ground installed in towing tank
- Model distance to ground adjustable by translation stage
- Field of view covers complete vortex path of one side
- Video visualization for qualitative analysis

Towing tank with installed intermediate ground

Light sheet enters tank from the side

Visualization of wake vortices
Wake Vortices in Proximity to Surfaces: Visualization

**Parameters:**
- Model velocity: 2.44 m/s
- Distance to ground: 80 mm ($0.5 \, b_0$)
- Here in display: 5 s ($\tau = 1.4$ resp. 80 $b_0$)

Flat ground

Ground with 2 square profiles ($30 \, \text{mm})^2$ perpendicular to flight direction
Wake Vortices in Proximity to Surfaces: PIV Results

Parameters:
- Model velocity: 2.44 m/s
- Distance to ground: 80 mm ($0.5 b_0$)
- Option: Profile perpendicular to flight direction on ground in front of and behind PIV plane
- Field of view: 400 x 240 mm²
- Correlation window size: 6.4 mm (32 pixels)
- Here in display: 15 s ($\tau = 4.3$ resp. 239 $b_0$)

Flat ground

Ground with square profile (30 mm)$^2$
in front of and behind PIV plane at $X = +/- 550$ mm
Wake Vortices in Proximity to Surfaces: Visualization

Parameters:
- Model velocity: 2.44 m/s
- Distance to ground: 80 mm (0.5 \( b_0 \))
- Here in display: 5 s (\( \tau = 1.4 \) resp. 80 \( b_0 \))
Wake Vortices in Proximity to Surfaces: PIV Results

Ground with square profile (30 mm)$^2$
in front of PIV plane $X = 550$ mm

Ground with sine wave ($2\pi$),
maximum (4 cm) at $X = 650$ mm

Parameters:
- Model velocity: 2.44 m/s
- Distance to ground: 80 mm (0.5 $b_0$)
- Profiles perpendicular to flight direction in front of PIV plane
- Field of view: 400 x 240 mm$^2$
- Correlation window size: 6.4 mm (32 pixels)
- Here in display: 15 s ($\tau = 4.3$ resp. 239 $b_0$)
Wake Vortices in Proximity to Surfaces: PIV Results — Vortex Position

Parameters:
- Model velocity: 2.44 m/s
- Distance to ground: 80 mm (0.5 b₀)
- Profile perpendicular to flight direction in front of PIV plane
- Disturbance propagates in flight direction
Wake Vortices in Proximity to Surfaces: PIV Results — Circulation

Parameters:
- Model velocity: 2.44 m/s
- Distance to ground: 80 mm (0.5 \( b_0 \))
- Profile perpendicular to flight direction in front of PIV plane
- Disturbance propagates in flight direction
Conclusions / Outlook:

Conclusions:
- Investigation of wake vortices from F-13 Model in the water towing tank Göttingen (WSG) with
  - time-resolved stereo PIV
  - time-resolved vortex core visualization
- Wake vortices in turbulent environment
- Wake vortices in proximity to (ground) surfaces
- Influence of selected 2D ground obstacles
- Data base for numeric vortex models

Future Work:
- Quantitative evaluation of visualizations
- Evaluation / analysis of vortex bending
- Investigation of additional ground topologies (3D topologies)
- 3-dimensional (tomographic) PIV measurement of vortex development at ground obstacles