Towards Wake-Resistant Aircraft through LiDAR-Based Wake Impact Alleviation

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Outline

• Introduction

• Wake impact alleviation concept
  • Online wake identification
  • Wake impact alleviation control command generation

• Setup of sensitivity analysis

• Results

• Conclusions
Wake impact alleviation control system can be used to reduce wake-induced aircraft reaction
- Safety increase
- Reduce risk of injuries
- Reduced separation minima possible with same safety standards ➔ capacity gain

Information of forward-looking Doppler LiDAR sensor used to generate alleviating control commands

Alleviation performance strongly dependent on quality of LiDAR measurement

Challenges:
- Many design parameters of LiDAR sensor influence overall performance in complex way
- Sensor characteristics not defined yet

Parameter study to identify role of each parameter and adequate parameter combinations
Remote LiDAR (Light Detection and Ranging) sensor measures line-of-sight components of wind velocities in front of aircraft.

Online Wake Identification (OWI) estimates parameters of wake vortex model on basis of LiDAR measurement.

Wake Impact Alleviation Control (WIAC) determines wake-induced disturbance moments resulting from detected wake vortex model and commands control surface deflections which compensate for this disturbance.
Purpose of Online Wake Identification

- Due to line-of-sight measurement most information about wake vortex velocities is lost.
- Wake identification algorithm is used to reconstruct the missing information about the disturbance (based on DLR Patent EP 2 340 438 B1).
- Maximum likelihood problem: minimization of error between line-of-sight wind velocities measured by LiDAR and reconstructed by wake vortex model with estimated parameters.

Output of online wake identification module:
parameters of wake vortex model
Online Wake Identification

![Diagram showing the process of online wake identification.](chart.png)
Online Wake Identification

- the vortex circulation (i.e. vortex strength) $\Gamma$
- the distance between the two vortex cores $b'$
- four geometry parameters specifying location and orientation of the wake vortex relative to the aircraft
Online Wake Identification

[Diagram with a flowchart showing the process of online wake identification, involving MP position, wake vortex model, LiDAR sensor model, and optimization stages to determine wake impact alleviation.]

- **ADS-B** input is processed through a decision flowchart:
  - From scratch (A, B) to last OWI result, initializing wake parameters.
  - MP position and wake vortex model are considered for LiDAR sensor model analysis.
  - Optimization for final wake parameters.
  - Cost function determined.
  - Activation check: if STD > Ref?, pass with V_{Los}; if not, stop.
  - Plausibility check: if pass, continue; if fail, stop.

- **WIAC:** Wake Impact Alleviation Control
  - Measurement buffer with point-to-point update rates at 5 Hz and 100 Hz.
  - Control surface commands adjusted accordingly.

[Source: DLR.de • Chart 8 • Jana Ehlers • Towards Wake-Resistant Aircraft through LiDAR-Based Wake Impact Alleviation > 22 April 2015]
Online Wake Identification

![Diagram of wake identification process](chart_9)

- **MP position**
- **Wake vortex model**
- **LiDAR sensor model**
- **ADS-B**
- **Initialization**
- **Last OWI result**
- **from scratch A B**
- **Standard deviation of V\textsubscript{LoS} [m/s]**

### Chart

- Current STD
- STD when buffer is filled
- 120\% STD when buffer is filled

### Flowchart

1. **STOP**
2. **Activation**
   - STD > Ref?
   - Yes
3. **V\textsubscript{LoS}**
4. **Measurement buffer**
5. **WiAC: Wake Impact Alleviation Control**
6. **Control surface commands**

### Parameters

- **@ 5 Hz**
- **@ 100 Hz**
- Sensor Point-to-Point Update Rate [Hz]
Online Wake Identification

Diagram showing the process of online wake identification, including ADS-B data, wake vortex model, LiDAR sensor model, optimizer, and control surface commands.
Online Wake Identification

Evaluate if reasonable limits are satisfied for:

- **Vortex strength**
- **Distance between vortex cores**
- **Wake elevation**
- **Wake azimuth** compared to ADS-B generator track
- **Position of vortex centerline** with respect to LiDAR measurements in data buffer
Online Wake Identification

- ADS-B
- LiDAR sensor model
- Optimization
- Wake vortex model
- last OWI result

Activation:
- STD > Ref?
- Plausibility check?

WIAC: Wake Impact Alleviation Control

@ sensor point-to-point update rate [Hz]

@ 5 Hz
@ 100 Hz

△ control surface commands
Wake Impact Alleviation Control Command Generation

Wind Field (possibly containing a wake vortex) → LiDAR Sensor → OWI: Online Wake Identification → WIAC: Wake Impact Alleviation Control → Δ Control Commands

OWIDIA: Online Wake Identification and Impact Alleviation
Wake Impact Alleviation Control Command Generation

**From OWI:**
Wake Parameters

- Prediction of strip positions at time “now + total time delay”
- Wind velocity at future strip positions (Burnham-Hallock)

**Aerodynamic Interaction Model**
- Force and moment contribution of each strip
- Total induced forces and moments

**From AC Air Data and Inertial Reference Systems**

- Roll and yaw allocation
- Pitch allocation
- Control allocation

Delta Control surface commands

1. @ 100 Hz
2. @ 5 Hz
3. Buffer
Exemplary Simulation of Wake Impact Alleviation

A320 encountering wake of A340, encounter angle: 10° lateral, 0° vertical
LiDAR Sensor

- Measurement quality strongly influences quality of identification result → wake impact alleviation performance

- No off-the-shelf sensor available → characteristics not defined yet
  
  - Large number of parameters whose effects are not independent from each other and strongly nonlinear

What are the optimal parameter combinations? What are the minimum requirements for the LiDAR settings?
Setup of Sensitivity Study

• **Goal:** Identification of possible interesting sensor characteristics (not yet thorough assessment of a given system configuration)

• Encounter scenario: A320 encountering wake of A340 during approach
  wake vortex 2 m above aircraft
  0° vertical encounter angle,
  lateral encounter angle $\Delta \Psi_{WV} = 5^\circ, 10^\circ, 15^\circ, 30^\circ$
  no pilot inputs, autopilot not engaged
### LiDAR Parameters of Sensitivity Study

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range of values</th>
</tr>
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<tbody>
<tr>
<td>minimum measurement range [m]</td>
<td>60; 90; 120; (150)</td>
</tr>
<tr>
<td># MP along measurement axis, $N_a$</td>
<td>1; 3; 5</td>
</tr>
<tr>
<td># horizontal MP axes, $N_h$</td>
<td>3; 5; 7; 9</td>
</tr>
<tr>
<td># vertical MP axes, $N_v$</td>
<td>3</td>
</tr>
<tr>
<td>lateral scan angle range $\psi_{\text{scan}}$ [°]</td>
<td>+/-16; +/-30; +/-40</td>
</tr>
<tr>
<td>vertical scan angle range $\theta_{\text{scan}}$ [°]</td>
<td>+/-10</td>
</tr>
<tr>
<td>blur depth [m]</td>
<td>15; 30</td>
</tr>
<tr>
<td>full screen update rate [Hz]</td>
<td>5; 10</td>
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</tbody>
</table>

**Parameters have different influences on measurement noise and spatial resolution**

- range $\uparrow$ $\rightarrow$ noise $\uparrow$ & spatial resolution $\downarrow$
- blur depth $\uparrow$ $\rightarrow$ noise $\downarrow$ & spatial resolution $\downarrow$
- axis update rate $\uparrow$ $\rightarrow$ noise $\uparrow$ & spatial resolution $\uparrow$
- field of view $\uparrow$ $\rightarrow$ noise $\approx$ & spatial resolution $\downarrow$
- # MP along axis $\uparrow$ $\rightarrow$ noise $\uparrow$ & spatial resolution $\uparrow$
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- Ranges of parameter values assumed to be technically feasible for future sensors

Example of LiDAR parameters from EU Project „Green-Wake“

Range: 50 … 200 m  
# MP axes: 100  
# MP along measurement axis: 2  
Full screen update rate: 2.5 Hz  
Field of view: 120 x 50 m  
(e.g. 200 m range, \(\Psi_{\text{scan}} = +/-16°\), \(\Theta_{\text{scan}} = +/- 7°\))
Availability of Wake Identification Result

- Wake identification algorithm requires minimum SNR to find valid solution
- Two reasons why no OWI result is provided

- Only encounters with active OWIDIA will be considered here
Results of Sensitivity Study

- Only cases considered with at least one valid wake identification result
- Maximum bank angle during encounter for different sensor settings

\[ \Psi_{wv} = 5^\circ \] without wake impact alleviation
\[ \Psi_{wv} = 15^\circ \] without wake impact alleviation
\[ \Psi_{wv} = 30^\circ \] without wake impact alleviation

\[ \Psi_{scan} = +/-16^\circ \]
\[ \Psi_{scan} = +/-30^\circ \]
\[ \Psi_{scan} = +/-40^\circ \]
Results of Sensitivity Study

- Only cases considered with at least one valid wake identification result
- Maximum bank angle during encounter for different sensor settings

- Systematic graphical representation required to identify adequate parameters
  - $\Delta \Psi_{WV} = 30^\circ$ (small absolute bank angles) and 120 m range (high noise) excluded for improved visibility
Relative Reduction of Maximum Bank Angle

Encounter angle

# horizontal MP
x # MP per axis

field of view

Improvement on $\Delta \Phi$ max
Range min 60 m

Improvement on $\Delta \Phi$ max
Range min 90 m

blur depth and full scan update rate:
+ 15 m and 5 Hz
+ 15 m and 10 Hz
+ 30 m and 5 Hz
+ 30 m and 10 Hz

each cross = 1 simulation

2 range cases

60 m

90 m
Relative Reduction of Maximum Bank Angle

Encounter angle

# horizontal MP x # MP per axis

field of view

one color for each letter = one LiDAR setting for all 3 encounter scenarios

blur depth and full scan update rate:

+ 15 m and 5 Hz
+ 15 m and 10 Hz
+ 30 m and 5 Hz
+ 30 m and 10 Hz
Relative Reduction of Maximum Bank Angle

blur depth and full scan update rate:
+ 15 m and 5 Hz
+ 15 m and 10 Hz
+ 30 m and 5 Hz
+ 30 m and 10 Hz

improvement

improvement

improvement
General Findings of Sensitivity Study

• On average 60 m range provides significantly better results than 90 m

• Good compromise required between spatial resolution and measurement noise
  • too few MP: bad spatial resolution → bad results
  • too many MP: noise too high → few valid, relatively bad results
Main Findings of Sensitivity Study

- On average 60 m range provides significantly better results than 90 m
- Good compromise required between spatial resolution and measurement noise
- Best and most robust (against blur depth, update rate) performance for

7 horizontal MP axes, 1 MP per axis
60 m range
Ψ_{\text{scan}} = +/-30°, \Theta_{\text{scan}} = +/-10°
Main Findings of Sensitivity Study

- Very good performance with low requirements for sensor parameters
  - 3 horizontal MP x 3 vertical MP x 1 MP along axis → 9 MP in total
  - 60 m range
  - 15 m blur depth
  - 10 Hz full screen update rate
  - $\Psi_{\text{scan}} = +/-16^\circ$, $\Theta_{\text{scan}} = +/-10^\circ$

- 70% bank angle reduction thanks to the OWIDIA system
Conclusions

- Complex cross-dependencies between the modules (sensor, OWI, WIAC) of wake impact alleviation control system
- First insights into the domains of adequate parameter combinations
  - most robust performances with parameter combinations leading to a good compromise between measurement noise and spatial resolution
  - minimum sensor requirements (allowing 70% bank angle reduction)
    - 9 measurement points (3 x 3 x 1), 60 m range, \( \Theta_{\text{scan}} = +/-10^\circ \), \( \Psi_{\text{scan}} = +/-16^\circ \), 15 m blur depth, 10 Hz full screen update rate
- Some parameter combinations lead to increase of bank angle
  - expected because wide range of LiDAR parameters were considered
  - sensor with these parameters are not adequate for application with OWIDIA

**BUT**: many parameter sets allow good wake impact alleviation performance *for all considered encounters*

Wake alleviation performance of about 60% (bank angle reduction) seems achievable with the proposed system and various sets of a priori realistic sensor characteristics
Thank you for your attention!

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Reference: