Automatic Differentiation for the Optimization of a Ship Propulsion and Steering System

Quellen: Voith AG, Heidenheim & Ralf Leidenberger

Automatic Differentiation for the Optimization of a Ship Propulsion and Steering System

A joint work with Karsten Urban
Problem
Voith-Schneider-Propeller (VSP) Optimization

Application in 2D
Configuration
Results

Application in 3D
Configuration
Results

Conclusion & Outlook
Problem

Voith-Schneider-Propeller (VSP) Optimization

Application in 2D
Configuration
Results

Application in 3D
Configuration
Results

Conclusion & Outlook
Functionality of the VSP

- different angles of attack during one rotation

Source: Voith AG, Heidenheim
Functionality of the VSP

- different angles of attack during one rotation
- driving power is resulting force

Source: Voith AG, Heidenheim
Functionality of the VSP

- different angles of attack during one rotation
- driving power is resulting force
- enables resulting force in each direction

Source: Voith AG, Heidenheim
Functionality of the VSP

Source: Voith AG, Heidenheim

Functionality
- different angles of attack during one rotation
- driving power is resulting force
- enables resulting force in each direction

Efficiency of the VSP

\[ \vec{F} = \int p\vec{v}dS \quad \vec{F} = (F_x, M)^T \]
Functionality of the VSP

- different angles of attack during one rotation
- driving power is resulting force
- enables resulting force in each direction

Source: Voith AG, Heidenheim

Efficiency of the VSP

\[ \vec{F} = \int p \vec{v} dS \quad \vec{F} = (F_x, M)^T \]
\[ F_m = \frac{n_f}{2\pi} \int_0^{2\pi} F_x \ d\Theta \quad \text{(thrust)} \]
\[ M_m = \frac{n_f}{2\pi} \int_0^{2\pi} M \ d\Theta \quad \text{(driving torque)} \]
Functionality of the VSP

- different angles of attack during one rotation
- driving power is resulting force
- enables resulting force in each direction

Source: Voith AG, Heidenheim

Efficiency of the VSP

\[
\vec{F} = \int p \vec{v} dS \\
F_m = \frac{n_f}{2\pi} \int_0^{2\pi} F_x \, d\Theta \\
M_m = \frac{n_f}{2\pi} \int_0^{2\pi} M \, d\Theta
\]

\[
\vec{F} = (F_x, M)^T \\
J = \frac{U_\infty}{nD} , \quad U_\infty \text{ flow rate, } D \text{ diameter, } n \# \text{ revolutions}
\]
Functionality of the VSP

▶ different angles of attack during one rotation
▶ driving power is resulting force
▶ enables resulting force in each direction

Efficiency of the VSP

\[
\vec{F} = \int p \vec{v} dS \\
F_m = \frac{n_f}{2\pi} \int_0^{2\pi} F_x \, d\Theta \\
M_m = \frac{n_f}{2\pi} \int_0^{2\pi} M \, d\Theta \\
F = (F_x, M)^T \\
J = \frac{U_\infty}{nD}, \ U_\infty \text{ flow rate, } D \text{ diameter, } n \# \text{ revolutions} \\
k_t \text{ dimensionless value of } F_m \\
k_q \text{ dimensionless value of } M_m
\]
Functionality of the VSP

- different angles of attack during one rotation
- driving power is resulting force
- enables resulting force in each direction

Source: Voith AG, Heidenheim

Efficiency of the VSP

\[
\begin{align*}
\vec{F} &= \int p \vec{v} dS \\
F_m &= \frac{n_f}{2\pi} \int_0^{2\pi} F_x \ d\Theta \\
M_m &= \frac{n_f}{2\pi} \int_0^{2\pi} M \ d\Theta
\end{align*}
\]

\[
\vec{F} = (F_x, M)^T
\]

\[
J = \frac{U_\infty}{nD} , \ U_\infty \text{ flow rate, } D \text{ diameter, } n \# \text{ revolutions}
\]

\[
k_t \text{ dimensionless value of } F_m
\]

\[
k_q \text{ dimensionless value of } M_m
\]

\[
\eta := \frac{k_t \ J}{k_q 2\pi}
\]
Problem
Voith-Schneider-Propeller (VSP) Optimization

Application in 2D
Configuration
Results

Application in 3D
Configuration
Results

Conclusion & Outlook
Optimization Aim

Optimization Targets

- optimize blade angle curve (Sebastian Singer)
- optimize blade profile (Robert Deininger)
- optimize VSP & boat together (Michael Hopfensitz, Juan Matutat)
Optimization Aim

Optimization Targets

▶ optimize blade angle curve  (Sebastian Singer)
▶ optimize blade profile  (Robert Deininger)
▶ optimize VSP & boat together  (Michael Hopfensitz, Juan Matutat)

Optimization Approaches

▶ derivative free methods
▶ derivative based methods, compute derivatives with AD
Optimization Aim

Optimization Targets

▶ optimize blade angle curve (Sebastian Singer)
▶ optimize blade profile (Robert Deininger)
▶ optimize VSP & boat together (Michael Hopfensitz, Juan Matutat)

Optimization Approaches

▶ derivative free methods
▶ derivative based methods, compute derivatives with AD

Model Problem

▶ single blade
▶ variable angle of attack
▶ instead of $\eta$ consider forces in $y$-direction
Problem
Voith-Schneider-Propeller (VSP)
Optimization

Application in 2D
Configuration
Results

Application in 3D
Configuration
Results

Conclusion & Outlook
Problem
Voith-Schneider-Propeller (VSP)
Optimization

Application in 2D
Configuration
Results

Application in 3D
Configuration
Results

Conclusion & Outlook
Geometry & Optimization Problem

Configuration

▶ solver: caffa

1 Computer Aided Fluid Flow Analysis from Ferziger & Peric
Geometry & Optimization Problem

Configuration

- solver: caffa\(^1\)
- angle of attack: \(\alpha\)

\[^1\text{Computer Aided Fluid Flow Analysis from Ferziger & Peric}\]
Geometry & Optimization Problem

Configuration

- solver: caffa
- angle of attack: $\alpha$
- surface forces: $f(\alpha) = \left(f_x(\alpha), f_y(\alpha)\right)^T$

$\begin{align*}
\alpha &= 0 \\
\alpha &= -\frac{\pi}{6} \\
\alpha &= -\frac{\pi}{3} \\
\alpha &= -\frac{\pi}{2}
\end{align*}$
Geometry & Optimization Problem

Configuration

► solver: caffa\(^1\)
► angle of attack: \(\alpha\)
► surface forces: \(f(\alpha) = (f_x(\alpha), f_y(\alpha))^T\)

Optimization Problem

► \(\max_{\alpha \in (0, \alpha_{\text{max}})} \{f_y(\alpha)\}\)

\(^1\)Computer Aided Fluid Flow Analysis from Ferziger & Peric
Geometry & Optimization Problem

Configuration

- solver: caffa
- angle of attack: $\alpha$
- surface forces: $f(\alpha) = \left(f_x(\alpha), f_y(\alpha)\right)^T$

Optimization Problem

- $\max_{\alpha \in (0, \alpha_{\text{max}})} \{f_y(\alpha)\}$
- from experiments is known that $f_y(\alpha) \forall \alpha \in (0, \alpha_{\text{max}})$ is concave

---

$\alpha = 0$  $\alpha = -\frac{\pi}{6}$  $\alpha = -\frac{\pi}{3}$  $\alpha = -\frac{\pi}{2}$

---

$^1$Computer Aided Fluid Flow Analysis from Ferziger & Peric
Geometry & Optimization Problem

Configuration

- solver: caffa
- angle of attack: $\alpha$
- surface forces: $f(\alpha) = (f_x(\alpha), f_y(\alpha))^T$

Optimization Problem

- $\max_{\alpha \in (0, \alpha_{\text{max}})} \{ f_y(\alpha) \}$
- from experiments is known that $f_y(\alpha) \ \forall \ \alpha \in (0, \alpha_{\text{max}})$ is concave
- $\arg \left\{ \max_{\alpha \in (0, \alpha_{\text{max}})} \{ f_y(\alpha) \} \right\} \Leftrightarrow \arg \{ f'_y(\alpha) = 0 \}$

---

1 Computer Aided Fluid Flow Analysis from Ferziger & Peric
Geometry & Optimization Problem

Configuration

- solver: caffa
- angle of attack: $\alpha$
- surface forces: $f(\alpha) = (f_x(\alpha), f_y(\alpha))^T$

Optimization Problem

- $\max_{\alpha \in (0, \alpha_{\text{max}})} \{ f_y(\alpha) \}$
- from experiments is known that $f_y(\alpha) \forall \alpha \in (0, \alpha_{\text{max}})$ is concave
- $\arg \{ \max_{\alpha \in (0, \alpha_{\text{max}})} \{ f_y(\alpha) \} \} \iff \arg \{ f'_y(\alpha) = 0 \}$
- Newton-Fixpoint-Iteration: $\Phi_{f_y}(\alpha_k) = \alpha_{k-1} - \frac{f'_y(\alpha_{k-1})}{f''_y(\alpha_{k-1})}$

$^1$Computer Aided Fluid Flow Analysis from Ferziger & Peric
Problem
Voith-Schneider-Propeller (VSP)
Optimization

Application in 2D
Configuration
Results

Application in 3D
Configuration
Results

Conclusion & Outlook
Regularization Effect

Forces: $f_{[y]}(\alpha) \forall \alpha \in (0, -0.7)$
Regularization Effect

Finite Differences (FD): 

\[ f'_{[y],FD}(\alpha) = \frac{f[y](\alpha+h) - f[y](\alpha-h)}{2h} \]

Forces: 

\[ f[y](\alpha) \]
Regularization Effect

Automatic Differentiation (AD): $f'_{[y], AD}(\alpha)$

Forces: $f_{[y]}(\alpha)$
Regularization Effect

2nd FD: \( f''_{[y],FD,FD}(\alpha) = \frac{f_{[y]}(\alpha+h)-2f_{[y]}(\alpha)+f_{[y]}(\alpha-h)}{h^2} \)
Regularization Effect

FD of $f'_{[y], AD}$: $f''_{[y], AD, FD}(\alpha) = \frac{f'_{[y], AD}(\alpha+h) - f'_{[y], AD}(\alpha-h)}{2h}$

Application in 2D

Forces: $f_{[y]}(\alpha)$

2. finite differences forces y
finite differences of derivative forces y

2. derivative forces y

Finite Differences (FD):

Automatic Differentiation (AD):

Comments
Regularization Effect

2nd AD: $f''_{[y],AD,AD}(\alpha)$

Forces: $f_{[y]}(\alpha)$

Application in 2D

Finite differences of derivative forces $y$

Finite differences forces $y$

2. derivative forces $y$

2. finite differences forces $y$
Regularization Effect

\[ f''_{[\gamma], FD, FD}, f''_{[\gamma], FD, AD} \& f''_{[\gamma], AD, AD} \]

\[ f'_{[\gamma], FD(\alpha)} \& f'_{[\gamma], AD(\alpha)} \]

Forces: \( f_{[\gamma]}(\alpha) \)

Comments

- Justify the application of AD in 2D flow simulation
Regularization Effect

\[ f''_{[y]} , FD, FD , f''_{[y]} , FD, AD \ & \ f''_{[y]} , AD, AD \]

**Comments**

- Justify the application of AD in 2D flow simulation
- Regularization effect grows from \( f'_{[y]} (\alpha) \) to \( f''_{[y]} (\alpha) \)
Newton-Fixpoint-Iteration

Angle of attack (AOA) of the profil

Remark

- starting point: \( \alpha_0 = -0.03 \)
- maximum change rate of \( \alpha \):
  \[ \alpha_{\Delta, \text{max}} = 0.1 \text{ [radian]} \]

Force: \( f_{[y]}(\alpha_k) \)

Newton-Iterations

| Lt. | AOA: \( \alpha \) | \( f'_{[y]}(\alpha) \) |
Newton-Fixpoint-Iteration

Angle of attack (AOA) of the profil

- starting point: $\alpha_0 = -0.03$
- maximum change rate of $\alpha$: $\alpha_{\Delta, max} = 0.1$ [radian]

Force: $f_{[y]}(\alpha_k)$

Newton-Iterations

<table>
<thead>
<tr>
<th>It.</th>
<th>AOA: $\alpha$</th>
<th>$f'_{[y]}(\alpha)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-0.03000000</td>
<td>-0.01327457810</td>
</tr>
</tbody>
</table>
Newton-Fixpoint-Iteration

Remark

- starting point: $\alpha_0 = -0.03$
- maximum change rate of $\alpha$:
  $\alpha_{\Delta,max} = 0.1$ [radian]

Newton-Iterations

<table>
<thead>
<tr>
<th>It.</th>
<th>AOA: $\alpha$</th>
<th>$f'_{y\alpha}(\alpha)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.</td>
<td>-0.03000000</td>
<td>-0.01327457810</td>
</tr>
<tr>
<td>1.</td>
<td>-0.13000000</td>
<td>-0.01114433244</td>
</tr>
</tbody>
</table>
Newton-Fixpoint-Iteration

Angle of attack (AOA) of the profil

Remark

- starting point: $\alpha_0 = -0.03$
- maximum change rate of $\alpha$:
  $\alpha_{\Delta, max} = 0.1$ [radian]

Newton-Iterations

<table>
<thead>
<tr>
<th>It.</th>
<th>AOA: $\alpha$</th>
<th>$f_y'(\alpha)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>-0.03000000</td>
<td>-0.01327457810</td>
</tr>
<tr>
<td>1.0</td>
<td>-0.13000000</td>
<td>-0.01114433244</td>
</tr>
<tr>
<td>2.0</td>
<td>-0.23000000</td>
<td>-0.00603337754</td>
</tr>
</tbody>
</table>

Force: $f_y(\alpha_k)$
Newton-Fixpoint-Iteration

Angle of attack (AOA) of the profil

Remark

- starting point: \(\alpha_0 = -0.03\)
- maximum change rate of \(\alpha\):
  \[\alpha_{\Delta,max} = 0.1 \text{ [radian]}\]

Force: \(f_{[y]}(\alpha_k)\)

Newton-Iterations

<table>
<thead>
<tr>
<th>It.</th>
<th>AOA: (\alpha)</th>
<th>(f'_{[y]}(\alpha))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-0.03000000</td>
<td>-0.01327457810</td>
</tr>
<tr>
<td>1</td>
<td>-0.13000000</td>
<td>-0.01114433244</td>
</tr>
<tr>
<td>2</td>
<td>-0.23000000</td>
<td>-0.00603337754</td>
</tr>
<tr>
<td>3</td>
<td>-0.33000000</td>
<td>+0.00048255801</td>
</tr>
</tbody>
</table>
Newton-Fixpoint-Iteration

Angle of attack (AOA) of the profil

Remark

- starting point: $\alpha_0 = -0.03$
- maximum change rate of $\alpha$:
  \[ \alpha_{\Delta, \text{max}} = 0.1 \text{ [radian]} \]

Newton-Iterations

<table>
<thead>
<tr>
<th>Iteration</th>
<th>AOA: $\alpha$</th>
<th>$f'_{[y]}(\alpha)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>-0.03000000</td>
<td>-0.01327457810</td>
</tr>
<tr>
<td>1.0</td>
<td>-0.13000000</td>
<td>-0.01114433244</td>
</tr>
<tr>
<td>2.0</td>
<td>-0.23000000</td>
<td>-0.00603337754</td>
</tr>
<tr>
<td>3.0</td>
<td>-0.33000000</td>
<td>+0.00048255801</td>
</tr>
<tr>
<td>4.0</td>
<td>-0.32140508</td>
<td>-0.00000113055</td>
</tr>
</tbody>
</table>

Force: $f_{[y]}(\alpha_k)$
Newton-Fixpoint-Iteration

Angle of attack (AOA) of the profil

Remark

- starting point: $\alpha_0 = -0.03$
- maximum change rate of $\alpha$:
  $\alpha_{\Delta, max} = 0.1$ [radian]

Force: $f_{[y]}(\alpha_k)$

Newton-Iterations

<table>
<thead>
<tr>
<th>It.</th>
<th>AOA: $\alpha$</th>
<th>$f'_{[y]}(\alpha)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-0.03000000</td>
<td>-0.01327457810</td>
</tr>
<tr>
<td>1</td>
<td>-0.13000000</td>
<td>-0.01114433244</td>
</tr>
<tr>
<td>2</td>
<td>-0.23000000</td>
<td>-0.00603337754</td>
</tr>
<tr>
<td>3</td>
<td>-0.33000000</td>
<td>+0.00048255801</td>
</tr>
<tr>
<td>4</td>
<td>-0.32140508</td>
<td>-0.00000113055</td>
</tr>
<tr>
<td>5</td>
<td>-0.32142512</td>
<td>+0.00000008440</td>
</tr>
</tbody>
</table>
Newton-Fixpoint-Iteration

Angle of attack (AOA) of the profil

Remark
- starting point: $\alpha_0 = -0.03$
- maximum change rate of $\alpha$:

$$\alpha_{\Delta, \text{max}} = 0.1 \text{ [radian]}$$

Newton-Iterations

<table>
<thead>
<tr>
<th>It.</th>
<th>AOA: $\alpha$</th>
<th>$f'_{[y]}(\alpha)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-0.03000000</td>
<td>-0.01327457810</td>
</tr>
<tr>
<td>1</td>
<td>-0.13000000</td>
<td>-0.01114433244</td>
</tr>
<tr>
<td>2</td>
<td>-0.23000000</td>
<td>-0.00603337754</td>
</tr>
<tr>
<td>3</td>
<td>-0.33000000</td>
<td>+0.00048255801</td>
</tr>
<tr>
<td>4</td>
<td>-0.32140508</td>
<td>-0.00000113055</td>
</tr>
<tr>
<td>5</td>
<td>-0.32142512</td>
<td>+0.00000008440</td>
</tr>
<tr>
<td>6</td>
<td>-0.32142362</td>
<td>+0.00000007550</td>
</tr>
</tbody>
</table>
Problem
Voith-Schneider-Propeller (VSP) Optimization

Application in 2D
Configuration
Results

Application in 3D
Configuration
Results

Conclusion & Outlook
Problem
Voith-Schneider-Propeller (VSP)
Optimization

Application in 2D
Configuration
Results

Application in 3D
Configuration
Results

Conclusion & Outlook
Geometry & Simulation Parameters

Boundary-Conditions

- Red: Inflow
- Green: Outflow
- Blue: Non-reflection
- Yellow: Wall

Simulation Parameters

- solver: Comet\(^2\)

\(^2\)is a commercial software from CD-adapco
Geometry & Simulation Parameters

Boundary-Conditions
- Red: Inflow
- Green: Outflow
- Blue: Non-reflection
- Yellow: Wall

Simulation Parameters
- solver: Comet²
- no moving grid - grid moving realized with script language

²is a commercial software from CD-adapco
Geometry & Simulation Parameters

Boundary-Conditions
- Red: Inflow
- Green: Outflow
- Blue: Non-reflection
- Yellow: Wall

Simulation Parameters
- solver: Comet\(^2\)
- no moving grid - grid moving realized with script language
- Idea: variable inflow direction

\(^2\)is a commercial software from CD-adapco
Problem
Voith-Schneider-Propeller (VSP)
Optimization

Application in 2D
Configuration
Results

Application in 3D
Configuration
Results

Conclusion & Outlook
Regularization Effect

Forces: \( f_y(\alpha) \)

Comments

- smooth forces curve
Regularization Effect

FD: $f'_{[y],FD}(\alpha) = \frac{f_{[y]}(\alpha+h) - f_{[y]}(\alpha-h)}{2h}$

Forces:

- **Comments**
  - smooth forces curve
  - FD: strong, many outliers
Regularization Effect

$\text{AD: } f'_{[y], AD}(\alpha)$

Forces: $f_{[y]}(\alpha)$

- smooth forces curve
- FD: strong, many outliers
- AD: good regularization effect
Regularization Effect

FD \( f'_{[y],FD}(\alpha) \) & AD \( f'_{[y],AD}(\alpha) \)

Forces: \( f_{[y]}(\alpha) \)

Comments

▶ smooth forces curve
▶ FD: strong, many outliers
▶ AD: good regularization effect
▶ justify the application of AD 3D flow simulations
Problem
Voith-Schneider-Propeller (VSP)
Optimization

Application in 2D
Configuration
Results

Application in 3D
Configuration
Results

Conclusion & Outlook
Conclusion & Outlook

Conclusion

- justify the application of AD in 2D & 3D flow simulation
- regularisation effect of AD in 2D & 3D flow simulation
- many *handwork* until a AD simulation runs

Outlook

- more complex geometries
- moving grids in 3D (Comet)
- optimization of a full VSP
- more flexible approach of AD
Conclusion & Outlook

**Conclusion**
- justify the application of AD in 2D & 3D flow simulation
- regularisation effect of AD in 2D & 3D flow simulation
- many *handwork* until a AD simulation runs

**Outlook**
- more complex geometries
- moving grids in 3D (Comet)
- optimization of a full VSP
- more flexible approach of AD
Literature

R. Leidenberger

Automatic differentiation in flow simulation.
Literature

R. Leidenberger

*Automatic differentiation in flow simulation.*

Contact

Ralf Leidenberger
Ralf.Leidenberger@uni-ulm.de

DFG Research Training Group 1100,
Institute for Numerical Mathematics,
Ulm University
Literature

R. Leidenberger

*Automatic differentiation in flow simulation.*

Contact

Ralf Leidenberger

Ralf.Leidenberger@uni-ulm.de

DFG Research Training Group 1100,
Institute for Numerical Mathematics,
Ulm University

Thank you for your attention.