Boat-tail effect on the wake of the Ahmed body: from symmetry-breaking modes to periodic vortex-shedding

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Outline

1 Introduction: symmetry-breaking modes of the wake of the Ahmed body

2 Experimental setup and definitions

3 Results: from symmetry-breaking modes to periodic vortex-shedding
   - Squareback geometry
   - Cases $\theta_B = 5^\circ$
   - Cases $\theta_B = 10^\circ$
   - Boat-tail effect on drag: a good idea?

4 Conclusion
Introduction: symmetry-breaking modes of the wake of the Ahmed body

Experimental setup and definitions

Results: from symmetry-breaking modes to periodic vortex-shedding

Conclusion
Introduction: wake of the Ahmed body

Ahmed body (W=97mm, H=76mm)

- Symmetric wake up to \( Re_H = 250 \)
- Static bifurcation due to static modes...
- ... leading to symmetry-breaking modes at high \( Re \)

(Grandemange et al. (2015). A study of wake effects on the drag of Ahmed’s squareback model at the industrial scale. JWEIA, 145)
Introduction: wake of the Ahmed body

- Goal: drag reduction
- 1/3 of the total drag generated at the base of the body
- Boat-tail effect successfully tested on box-shaped vehicles (Peterson, Littlewood) and on the Ahmed body (Grandemange)
- Possible explanation: reduction of bluffness (Roshko)

(Peterson (1981). Drag reduction obtained by the addition of a boat-tail to a box shaped vehicle. NASA Contractor Report, 163113)
(Grandemange et al. (2015). A study of wake effects on the drag of Ahmed’s squareback model at the industrial scale. JWEIA, 145)

(Roshko (1993). Perspectives on bluff body aerodynamics. JWEIA, 49)
We know that the wake of the Ahmed body is governed by symmetry-breaking modes ...
Introduction: wake of the Ahmed body

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We know that the wake of the Ahmed body is governed by symmetry-breaking modes . . .

- What is the effect of a boat-tailed geometry on the symmetry-breaking modes?
- Is the strength any wake structure modified?
- Can symmetry-breaking modes be controlled or suppressed with boat-tails?
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Experimental setup

- Model-scale wind tunnel of the GIE-S2A (Montigny-le-Bretonneux, France)
- Instantaneous aerodynamic load measurements (3-axes balance) at 10 Hz
- Base pressure measurements at 100 Hz (Scanivalve ZOC33):
  \[ c_p(x^*, y^*, z^*, t^*) = \frac{p(x^*, y^*, z^*, t^*) - p_{\infty}}{\frac{1}{2} \rho U_{\infty}^2} \]
- Free-stream velocity: \( U_\infty = 20 \text{ m.s}^{-1} \)
- \( \text{Re}_H \approx 4.4 \times 10^5 \)
Experimental setup

- Square-back Ahmed body aligned with the incoming flow ($\alpha = 0^\circ$, $\beta = 0^\circ$): height $H = 0.298$ m, width-to-height ratio of the body $W/H = 1.174$

- Ground clearance $c^* = c/H = 0.168 > c_c^*$: SB modes (Cadot, 2015)

- Rear blocks of length $l_B$ can be modified

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Experimental setup

Boat-tail geometry on the Ahmed body

\[ \theta_i \]

\[ l_B \]

\[ i \in \{T,B\} \]

(a) \[ \theta_B = 0^\circ, \theta_T = 0^\circ \]

(b) \begin{align*}
\theta_B &= 5^\circ, \theta_T = 0^\circ \\
\theta_B &= 5^\circ, \theta_T = 7.5^\circ \\
\theta_B &= 5^\circ, \theta_T = 12.5^\circ \\
\theta_B &= 10^\circ, \theta_T = 0^\circ \\
\theta_B &= 10^\circ, \theta_T = 7.5^\circ \\
\theta_B &= 10^\circ, \theta_T = 12.5^\circ
\end{align*}

(c)
Experimental setup
Pressure taps location and base pressure gradients

- Horizontal and vertical base pressure gradients: $G_y^*, \ G_z^*$
- Complex base pressure gradient $\hat{G} = G_y^* + iG_z^*$
- **Polar description** $\Rightarrow \hat{G} = g \times \exp(i\phi)$ with $g > 0$
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Conclusion
Squareback case: $\theta_T = 0^\circ$, $\theta_B = 0^\circ$

$\rightarrow$ Modulus $g \approx 0.23$: saturated Symmetry-Breaking mode

$\rightarrow$ Two peaks of the phase ($\phi = 0$ and $\phi = \pi$) corresponding to SB modes

$\Rightarrow$ How are the phase and the modulus modified by boat-tails?
Pressure distribution on the rear part of the body

Squareback case: $\theta_T = 0^\circ$, $\theta_B = 0^\circ$

What is the effect of boat-tails on the pressure distribution?
Cases $\theta_B = 5^\circ$:

$\rightarrow$ Modulus $g \approx 0.15$: attenuated Symmetry-Breaking mode. . .

$\rightarrow$ . . . but a vertical mode (either $\phi = \pi/2$ either $\phi = -\pi/2$) is selected
Cases $\theta_B = 5^\circ$:

$\Rightarrow$ Wake rotation: phase-locking at $\phi = \pi/2$ or $\phi = -\pi/2$

$\Rightarrow$ Similar effect as underbody disturbances (Barros, 2017)

Squareback case: $\theta_T = 0^\circ$, $\theta_B = 0^\circ$

Case $\theta_B = 5^\circ$ with $\theta_T = 0^\circ$ (left) and $\theta_T = 12.5^\circ$ (right)
Squareback case: $\theta_T = 0^\circ$, $\theta_B = 0^\circ$

Optimal case: $\theta_T = 7.5^\circ$, $\theta_B = 5^\circ$
Cases $\theta_B = 10^\circ$: 

$-$ Larger modulus attenuation for $\theta_T = 12.5^\circ$ . . .
$-$ . . . and two-peaks PDF of the phase: a new instability?
Cases $\theta_B = 10^\circ$:

- Base pressure almost not affected by boat-tails
- Low pressure on the boat-tailed parts
Cases $\theta_B = 10^\circ$:

$\Rightarrow$ For $\theta_B = 10^\circ$, $\theta_T = 12.5^\circ$, periodic mode: vortex-shedding!
Squareback case: $\theta_T = 0^\circ$, $\theta_B = 0^\circ$

Case: $\theta_B = 10^\circ$, $\theta_T = 12.5^\circ$ (instantaneous fields)
Boat-tail effect on drag: a good idea?

Mean aerodynamic drag coefficient:  \( C_x = \frac{F_x}{\frac{1}{2} \cdot \rho \cdot S \cdot U_{\infty}^2} \)

Mean base pressure coefficient: \( C_b = -\int c_{p,\text{base}} \)

<table>
<thead>
<tr>
<th>( \theta_B )</th>
<th>( \theta_T )</th>
<th>0°</th>
<th>7.5°</th>
<th>12.5°</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>0.177</td>
<td>0.281</td>
<td>-5.6%</td>
<td>-0.7%</td>
</tr>
<tr>
<td>5°</td>
<td>+2.8%</td>
<td>+3.9%</td>
<td>-24.3%</td>
<td>-6.8%</td>
</tr>
<tr>
<td>10°</td>
<td>+7.3%</td>
<td>+12.8%</td>
<td>-23.7%</td>
<td>-1.8%</td>
</tr>
</tbody>
</table>

→ Increase of base pressure except for bottom only (ground influence)
→ Only one boat-tail ⇒ Strong asymmetry: drag increase
→ Large angles ⇒ Periodic mode: drag increase
→ Moderate and "equal" angles ⇒ Reduced SB mode: drag decrease

⇒ The drag generated on the boat-tail may increase the total drag by up to 12.8%... but clever use of boat-tails may lead to 6.8% drag reduction!
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Conclusion

Boat-tailed rear-end geometries for the Ahmed body lead to:

- Loss of strength of the symmetry-breaking modes.
- But no wake symmetrization nor wake modes removal.
- Slight base pressure recovery in most cases (except lower boat-tail only).
- But large low-pressure areas on the boat-tails.
- Changes in wake topology: bi-stability ($\phi_0$ and $\phi_{\pi}$) or phase selection ($\phi_{\pi/2}$ and $\phi_{3\pi/2}$).
- Domination of a periodic mode (vortex shedding) instead of the static asymmetric modes when the imposed geometrical constraint becomes impossible to satisfy.
Conclusion

Boat-tailed rear-end geometries for the Ahmed body lead to:

- Loss of strength of the symmetry-breaking modes...

Changes in wake topology: bi-stability ($\phi_0$ and $\phi_{\pi}$) or phase selection ($\phi_{\pi} \{2 \text{ and } \phi_{\pi} \{2 \}$)

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- … but large low-pressure areas on the boat-tails
- Changes in wake topology: bi-stability ($\phi = 0$ and $\phi = \pi$) or phase selection ($\phi = -\pi/2$ and $\phi = \pi/2$)
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Drag reduction can be performed by controlling the symmetry-breaking modes...
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... and not necessarily by removing it!
Conclusion

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- Asymmetry has a negative impact on drag.
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Drag reduction can be performed by controlling the symmetry-breaking modes...  

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Asymmetry has a negative impact on drag.

Optimization process on angles and shapes ⇒ beneficial base pressure recovery not overwhelmed by the drag generated on boat-tailed geometries.
Thank you for your attention!

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