FLOW SEPARATION

Aerodynamics
Bridge-Pier Design
Combustion Chambers
Human Blood Flow
Building Design Etc.

(Form Drag, Pressure Distribution, Forces and Moments, Heat And Mass Transfer, Vortex Shedding)
Separation and Drag

Total drag = friction drag + form drag

No separation, then friction drag dominates, with separation form drag dominates.

boundary layer separation results in a large increase in the drag on the body because of increased form drag.
Why does separation increase the drag?

Start from D’Alambert’s paradox

Applying Bernoulli’s equation to the streamline around the cylinder we find that the pressure distribution is symmetrical also so that the total pressure force on the upstream side of the cylinder is exactly equal to the pressure on the downwind side. So net force on the cylinder is zero.

If the flow of a viscous fluid about a body is such that the boundary layer remains attached, then we have almost the same result—we'll just have a small drag due to the skin friction.

However, if the boundary layer separates and the coefficient of drag is 1.2, much larger than the coefficient of drag due to skin friction 0.01.
Some interesting drag facts

\[
D \sim \rho U^2 A/2
\]

\[
P = DU = \rho U^3 A/2
\]

increases with the \textit{cube} of the speed.
What it means is It's going to take you 8 times the power to ride a bicycle at 30 mph than riding it at 15 mph.

a dimpled golf ball has one-fifth the drag of a smooth golf ball of the same size. Why?
3D Separation classification by Skin-friction Topology

Open and Closed type separation

Open - Flow upstream of separation enters separation region. Separation occurs along a dividing streamline.

Closed – Flow upstream of separation does not enter the separation region (bubble). Flow separates from a saddle point of separation.
saddle point

dividing streamline

closed

Open
Classification based on shear layer reattachment

• Separation without reattachment
  Interactions between opposite signed vortices shed from separation points
  (e.g. Flow past cylinders, spheres, normal flat plates etc)

• Separation with reattachment
  Interaction between vortices and the solid surface
  (e.g. Flow past leading edge blunt cylinders, backward facing steps etc)
Distinguishing features between the two kinds of classification

- Open and closed should not be confused with reattaching and non-reattaching
- All open separation is non-reattaching, but, closed separation can either be non-reattaching or reattaching, (i.e.) the separation bubble may shed or attach to the body
- Also, open and closed terminology is mainly used only for 3D separation as saddles and nodes cannot be accurately defined in 2D separation. Non-reattaching or reattaching terminology is more general in that sense.
Main instabilities in separated flows

1. Initial instability
   Kelvin Helmholtz instability
   (Both non-reattaching and reattaching)
   vortex formation due to roll up of shear layer
Main instabilities in separated flows

2. Karman instability
   Non-reattaching
   opposite signed vortices interaction
   (asymmetric vortex shedding)
   Reattaching
   vortex and image interaction
   (symmetric vortex shedding)
Initial instability causes KH vortices

KH vortices amalgamate to form large scale vortices

Large scale vortices impinge on body

Karman type shedding (symmetric mode - interaction with mirror vortex)
Main instabilities in separated flows

3. Low frequency modulation

**Non reattaching** - vortex dislocations in flow past cylinders

**Reattaching** - flapping instability
(enlarging and shrinking of separation bubble)
Main instabilities in separated flows

Horse shoe vortices:

Occurs when a boundary layer encounters an obstacle attached to the surface. Presence of the obstacle causes adverse pressure gradient in the boundary layer flow, leading to three dimensional separations, i.e., horseshoe vortices that wrap around the obstacle.
Main instabilities in separated flows

Helical Vortices

Boundary layer separation from the sharp leading edged of the delta wing forms three-dimensional shear layer that roll into a core of rotating vortex.

The shear layer exhibits Kelvin-Helmholtz type instability giving rise to vortical sub-structures which wrap around the leading-edge jet-like vortex core.

At a sufficiently high angle of attack jet-like vortex undergo a sudden expansion to a wake-like vortex.

This process is called vortex breakdown.
The Strouhal Number

The **Strouhal Number** is a dimensionless value useful for analyzing oscillating, unsteady fluid flow dynamics problems. The Strouhal Number can be expressed as:

\[ St = \frac{\omega l}{v} \]

where
- \( St \) = Strouhal Number
- \( \omega \) = oscillation frequency
- \( l \) = relevant length scale
- \( v \) = relevant velocity scale
where $Sr$ is the General Strouhal number, $f$ is the frequency of vortex shedding, $D$ is the hydraulic diameter or length of the object in the fluid flow and $V$ is the velocity of the fluid

Buffer the body, lower the general Strouhal number
Relevant scales for Strouhal number

• KH instability for viscous flow

KH instability is mainly a inviscid phenomenon where vortex sheet strength (tangential velocity jump across the vortex sheet) determines the instability frequency.

Related term in viscous flows is the momentum thickness which involves $\tau_w = \mu \frac{\partial u}{\partial y}$, velocity difference across the shear layer.

Relevant velocity scaling would be the shear layer velocity.

$St_\theta = f_{KH} \frac{\theta}{U_S}$ is observed to be constant throughout a range of $Re$, but changes with geometry.
Relevant scales for Strouhal number

- Karman instability. 
  Due to interaction between two oppositely signed vortices.
So, Relevant length scale would then be distance between the two separated shear layers.
And, velocity scaling is shear layer velocity

$$St_U = f_{KH} h/ U_S = 0.08$$, found to be constant through both Re and geometry, thus termed universal Strouhal number
Relevant scales for Strouhal number

- Flapping instability
  - change in reattachment length.
  So, relevant length scale would then be mean reattachment length
  And, velocity scaling is shear layer velocity

*Frequency scales with flow velocity and reattachment length* \((St_R = f_{KH} \frac{X_R}{U})\)
Relevant scales for Strouhal number

Horse shoe vortices:
L = Thickness of the body
V = Boundary layer velocity
F = largest frequency

Helical vortices:
Frequency x distance from vortex break down = constant
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<th>Re-attaching flows</th>
<th>Parameters</th>
<th>Regime</th>
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<th>High frequency (Korvin Helmholtz instability; Scales with ( \delta ))</th>
<th>Medium frequency (vortex shedding, scales with ( H ))</th>
<th>Low frequency (Flapping scales with reattachment length ( X_a ))</th>
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<td>Geometry</td>
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<td>General St. No. ( \frac{St}{H-U} )</td>
<td>General St. No. ( \frac{St}{H-U} )</td>
<td>General St. No. ( \frac{St}{H-U} )</td>
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<tr>
<td>2H Blunt cylinder</td>
<td>Re= 22000</td>
<td>Turbulent</td>
<td>Separated and reattaching (vortex shedding due to amalgamation of shear layer vortices, shedding due to interaction with mirror vortex)</td>
<td>20.6</td>
<td>0.065 *</td>
<td>0.07–0.09</td>
<td>0.025 *</td>
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<td>Simpson (1995)</td>
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<td></td>
<td>Kiya and Sasaki (1985)</td>
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<td>Backward facing step</td>
<td>Re=33000</td>
<td>Turbulent</td>
<td>Separated and reattaching (vortex shedding due to amalgamation of shear layer vortices, shedding due to interaction with mirror vortex)</td>
<td>0.022</td>
<td>0.063</td>
<td>&lt; 0.063</td>
<td>0.02</td>
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<tr>
<td>Leading edge separation bubble of foils</td>
<td>Laminary</td>
<td>Separated and reattaching</td>
<td>-</td>
<td>0.0068</td>
<td>-</td>
<td>-</td>
<td>0.01358</td>
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<td>Roos and Keegelman (1986)</td>
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</table>

\( \delta \) = half wakes thickness as per Rossby's hodograph theory

\( U_c \) = shear layer velocity at separation = \( U_{\infty} (1-C) \)

\( U_c \) = center of shear layer = average separated shear layer velocity approximately 0.5 \( U_{\infty} \)

\( \theta \) = momentum thickness of shear layer at separation

\( H \), = projected length scale to flow normal direction

\* = estimated from experiments.
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<th>Non-Reattaching flows</th>
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<td><strong>Circular cylinder</strong></td>
<td>Re ~ 29 to 140-194</td>
<td>Laminar</td>
<td>Non-reattaching, Only streamwise vortices</td>
<td>Vortex dislocation, low frequency due to transition from mode a to b</td>
<td>0.19, 0.08</td>
<td>St. No. / St.</td>
<td>Williamson (1990)</td>
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<td></td>
<td>190~260</td>
<td>Laminar</td>
<td>Spanwise / streamwise vortices</td>
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<td></td>
<td>1000 to 20000</td>
<td>Transition, Turbulent</td>
<td>Increase in formation length</td>
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<td></td>
<td>10000000</td>
<td>Turbulent</td>
<td>Turbulent boundary layer separation, Sheddind still observed</td>
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<tr>
<td><strong>Sphere</strong></td>
<td>Re ~ 300 to 800</td>
<td>Laminar</td>
<td>Non reattaching, helical/homogenous vortex</td>
<td>low frequency modulation 3 to 4</td>
<td>-0.2, -0.08</td>
<td></td>
<td>Sakamoto and Hasegawa (1990)</td>
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<td></td>
<td>800 ~ Re &lt; 60000</td>
<td>Transition/Turbulent</td>
<td>Vortex tube formation due to small scale instability of separating shear layer</td>
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<td><strong>Inclined flat plate with bevel</strong></td>
<td>Re = 300000 α = 30</td>
<td>Turbulent</td>
<td>Non reattaching</td>
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<td>Chen et al (1996)</td>
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<td></td>
<td>Re = 20000 α = 60</td>
<td>Turbulent</td>
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<td><strong>Rectangular plate normal to flow</strong></td>
<td>Re = 20000</td>
<td>Turbulent</td>
<td>Non reattaching elliptic wake with bimodal vortices</td>
<td>Low frequency due to axis switching</td>
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<td>Kiya and Abe (1989)</td>
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<td><strong>Circular disk normal to flow</strong></td>
<td>Re = 300</td>
<td>Laminar</td>
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<td>Huang and Liu (1998)</td>
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<td>Re = 1100</td>
<td>Laminar</td>
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<td>Function of aspect ratio</td>
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<td></td>
<td>Re = 1.5 x 10^6</td>
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<td>Low frequency 1/3 vortex shedding frequency pumping vortex</td>
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</tbody>
</table>

References:
- Williamson (1990)
- Sakamoto and Hasegawa (1990)
- Kiy (2000)
- Chen et al (1996)
- Kiya and Abe (1989)
- Huang and Liu (1998)
- Kiya (2000)
Surface Piercing NACA 0024
Athena, \( Fr = 0.25 \)

Figure 3: Isosurfaces of \( Q_3 \) (=300) showing vortex shedding from appendages for model-scale AH simulation using DES. Three different types (A, B and C) of juncture vortices are marked and associated dominant frequency modes are shown. Contours are of the absolute pressure with levels from -0.5 to 0.1 at an interval of 0.02.
Transom Flow Vortical Structures Instability Analysis
Karman-like shedding

Figure: Phases of transom vortex shedding is shown for full-scale fully appended Athena, fixed sinkage and trim without propeller simulation at cross-section close to the symmetry plane $Y=0.01$. Contours are of the absolute pressure with levels from -0.2 to 0.1 at an interval of 0.006.
Figure: Phases of hull-strut juncture vortex shedding due to shear-layer instability is shown for full-scale, fixed motions without propeller simulation at cross-section \( Y=0.0524 \) for full-scale fully appended Athena simulations.
Figure: Flapping-like instability ($\tau=0.16$) for DES for model-scale Athena bare hull. The vortical structures are shown by the isosurfaces of $Q_3 (=300)$ and colored by absolute pressure with levels from -0.5 to 0.1 at an interval of 0.02.
KVLCC2 drift angle 30° (vortex system, limiting streamlines)
- The sonar dome (SD_{TV}) and bilge keel (BK_{TV}) vortices exhibits helical instability breakdown.
- Shear-layer instabilities: port bow (B_{SL1}, B_{SL2}) and fore-body keel (K_{SL}).
- Karman-like instabilities on port side bow (B_{K})
- Wave breaking vortices on port (FS_{BW1}) and starboard (FS_{BW2}). Latter exhibits horse shoe type instability.