Outline

- Forces and Torques
- Drag of Spheres
- Drag of Cylinders
- Drag Coefficient for 2D Objects
- Drag Coefficient for 3D Objects
- Lift Force for an Airfoil
Drag Coefficient

\[
C_D = \frac{\text{Drag Force}}{\frac{1}{2} \rho V^2 A}
\]

\[C_D = C_D(\text{Re})\]

\[\text{Re} = \frac{VL}{v}\]

\[C_D = C_{D,\text{Press}} + C_{D,\text{Fric}}\]

Drag Reduction

\[
C_D = \frac{F_D}{\frac{1}{2} \rho V^2 LD}
\]

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Karman Vortices

Flow Past Circular Cylinders

Flows Around a Circular Cylinder
Drag Coefficients

- Cylinder: $C_D = 1.0$
- Sphere: $C_D = 0.4$
- Parallel disc: $C_D = 1.2$
- Body: $A = \text{friction area}$

Two-Dimensional Bodies

- Upright: $A = 5.5 \text{ ft}^2$, $C_D = 1.1$
- Racing: $A = 3.9 \text{ ft}^2$, $C_D = 0.9$
- With faying: $A = 4.6 \text{ ft}^2$, $C_D = 0.12$
- Passenger car or sport car: $C_D = 0.3$

Drag Coefficients for 3D Bodies at Low Reynolds Number

- Sphere: $C_D = 3$
- Hemisphere: $C_D = 0.7$
- Normal disc: $C_D = 8$
- Parallel disc: $C_D = 3$

Viscous drag coefficients for low Reynolds number flow (valid for $Re < 1$).

<table>
<thead>
<tr>
<th>Shape</th>
<th>Reference Length</th>
<th>$C_D$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sphere</td>
<td>$D$</td>
<td>$3\pi$</td>
</tr>
<tr>
<td>Hemisphere</td>
<td>$D$</td>
<td>$0.7$</td>
</tr>
<tr>
<td>Normal disc</td>
<td>$D$</td>
<td>$8$</td>
</tr>
<tr>
<td>Parallel disc</td>
<td>$D$</td>
<td>$3$</td>
</tr>
<tr>
<td>Normal rod</td>
<td>$L$</td>
<td>$\frac{4\pi}{\ln(2D/L) + 0.5}$</td>
</tr>
<tr>
<td>Parallel rod</td>
<td>$L$</td>
<td>$\frac{2\pi}{\ln(2D/L) + 0.72}$</td>
</tr>
</tbody>
</table>

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Drag Coefficients

Three-Dimensional Bodies

Drag Force for a Sphere

Drag Coefficient for a Sphere

Drag Coefficients for Cars

Drag Coefficients for Trucks

Experiment

Oseen

Stokes

Eq. (5)

Re

Drag Coefficient for a Sphere

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**Drag Reduction**

- Shape Variation for Drag Reduction
- Leaf Curls with Wind Speed

**Drag Control**

- Start-Up
- Separation/Vortex Formation
- Vortex is Shed
- Full Lift

**Flow over an Airfoil**

- Kutta Condition
Flow over an Airfoil

Flow Visualization

Small Angle of Attack

High Angle of Attack

Lift and Drag

Lift and Drag Coefficients

Lift and Drag Coefficients
Concluding Remarks

- Forces and Toques
- Drag of Spheres
- Drag of Cylinders
- Drag Coefficient for 2D Objects
- Drag Coefficient for 3D Objects
- Lift Force for an Airfoil