Pressure and Friction Drag I

Hydromechanics VVR090

Fluid Flow About Immersed Objects

Flow about an object may induce:

• drag forces
• lift forces
• vortex motion

Asymmetric flow field generates a net force

Drag forces arise from pressure differences over the body (due to its shape) and frictional forces along the surface (in the boundary layer)
D’Alembert’s Paradox

No net force on an object submerged in a flowing fluid.
Ideal fluid $\rightarrow$ no viscosity (implies not friction, no separation)

Jean d’Alembert
(1717-1783)

Drag and Lift on an Immersed Body

Early studies in naval architecture and aerodynamics.
More recent work in structural engineering (e.g., houses, bridges) and vehicle design (e.g., cars, trains).
Drag and Lift on an Immersed Body II

Drag and Lift on an Immersed Body

Drag and lift on a small element:

\[ dD = pdA \sin \theta + \tau_o dA \cos \theta \]

\[ dL = -pdA \cos \theta + \tau_o dA \sin \theta \]
Total drag and lift force on the body:

\[ D = \int_A dD = \int_A p \sin \theta dA + \int_A \tau_o \cos \theta dA \]

\[ L = \int_A dL = -\int_A p \cos \theta dA + \int_A \tau_o \sin \theta dA \]

Effects of the shear stress on lift negligible:

\[ L = -\int_A p \cos \theta dA \]

Drag force:

\[ D = \int_A p \sin \theta dA + \int_A \tau_o \cos \theta dA \]

Pressure drag \((D_p)\)  Frictional drag \((D_f)\)
(form drag)

Pressure drag function of the body shape and flow separation

Frictional drag function of the boundary layer properties (surface roughness etc)
Examples of Flow around Bodies I

\[ \sin \theta = 0, \quad \cos \theta = 1 \]

\[ D_p = 0, \quad D_f = \int_A \tau \, dA \]

\( \rightarrow \) No pressure drag

\[ \sin \theta = 1, \quad \cos \theta = 0 \]

\[ D_p = \int_A p \, dA, \quad D_f = 0 \]

\( \rightarrow \) No frictional drag

Examples of Flow around Bodies II

1. \( D_p > D_f \)

2. \( D_p \approx D_f \)

3. \( D_p << D_f \)

\( D_1 > D_2 > D_3 \)
Dimensional Analysis of Drag and Lift

**Assumed relationships:**

\[ D = f_1 \{ A, \rho, \mu, V_o, E \} \]

\[ L = f_2 \{ A, \rho, \mu, V_o, E \} \]

**Derived \( \Pi \)-terms:**

\[ \Pi_1 = \frac{\rho \sqrt{AV_o}}{\mu} = \text{Re} \]

\[ \Pi_2 = \frac{\rho V_o^2}{E} = \frac{V_o^2}{a^2} = \text{M}^2 \]

\[ \Pi_3 = \frac{D}{A \rho V_o^2} \quad \text{(drag)} \]

\[ \Pi_3 = \frac{L}{A \rho V_o^2} \quad \text{(lift)} \]
Results of Dimensional Analysis

Total drag force:

\[ D = f_3(Re, M) \frac{1}{2} \rho AV_o^2 = C_D \frac{1}{2} \rho AV_o^2 \]

\[ C_D = f_3(Re, M) \]

Total lift force:

\[ L = f_4(Re, M) \frac{1}{2} \rho AV_o^2 = C_L \frac{1}{2} \rho AV_o^2 \]

\[ C_L = f_4(Re, M) \]

Properties of \( C_D \) and \( C_L \)

Bodies of same shape and alignment with the flow have the same \( C_D \) and \( C_L \), if \( Re \) and \( M \) are the same.

\( Re \) describes the ratio between inertia forces and viscous forces

\( M \) describes the ratio between inertia forces and elastic forces

\( \rightarrow M \) only important at high flow velocities (e.g. supersonic flows)
Drag Coefficient for Various Bodies

Drag Coefficient for a Sphere

Mach number effects

Ernst Mach (1838-1916)
Drag Coefficient at Sound Barrier

$C_D$ as a function of $M$

Example I: Drag Force on an Antenna Stand

What is the total drag force on the stand and moment at the base?

30 m wind
35 m/s

0.3 m

Standard atmosphere
(101 kPa, 20 deg)
Example II: Sphere Dropped from an Airplane

Plastic sphere falling in air – what is the terminal speed?

Relative density of sphere \( S = 1.3 \)

Standard atmosphere
(101 kPa, 20 deg)

Flow around an airfoil

small angle of attack
(drag from frictional losses)  
large angle of attack
(drag from pressure losses)
Flow Separation

cylinder
airfoil

contraction expansion