Experimental Aerodynamics

Lecture 6:
Slender Body Aerodynamics

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Slender bodies

• Wings are only one of the types of body that can be tested in a wind tunnel.
• Although wings play a crucial role in aeronautical applications (as well as some non-aeronautical applications), other bodies play equally crucial roles.
• One example is slender bodies:
  – Fuselages
  – Engine nacelles
  – External stores
• Such bodies are generally not designed to produce lift although they can do
• Their main aerodynamic contribution is drag.
Slender body examples

- Engine nacelle
- Nacelle with tail boom
- External stores
Non-aeronautical slender bodies

Street luminaires

Anemometers

Wind turbine nacelles

Experimental Aerodynamics
Drag of slender bodies

• There are no simple but accurate methods for estimating the aerodynamic forces acting on slender bodies.
• Slender bodies are usually designed for operation at minimum drag and zero lift.
• The main consideration then, is the estimation of the drag of such bodies.
• Nevertheless, they can generate significant amounts of lift in off-design conditions.
Drag estimation

• The best approach for estimating the drag of slender bodies is to carry out wind tunnel experiments
• There are some simple methods that can be used in the design stage. However, these can prove to be highly inaccurate.
• Such methods are usually applied in the conceptual design stage for aircraft. The method described here comes from Torenbeek.
Drag breakdown

• As usual, there are many sources of drag:
  – Skin friction
  – Profile
  – Induced
  – Interference
  – Compressibility

• In this case, we will assume that the main drag sources are skin friction and profile.

• Furthermore, it will be assumed that the flow is mostly attached, therefore the profile drag is lower than the skin friction drag.

• Interference and compressibility will be ignored
Nomenclature

- Slender body dimensions

Front view

\[ h \]

\[ b \]

Side view

\[ l \]

- \( l \): length
- \( b \): width
- \( h \): height
Flat plate analogy

- The drag of fuselages, tail booms and other slender bodies can be estimated using the flat plate analogy.
- The skin friction drag of the body is approximated by that of a flat plate with the same wetted area.
- The flow regime (laminar or turbulent) over the flat plate must be representative of the real flow.
- A shape correction is applied in order to model the profile drag. This shape correction compares the shape of the body to that of a cylindrical ‘cigar’.
Flat plate analogy (2)

• The profile drag of the body is then given by

\[ C_D S = C_F (1 + \phi) S_{wet} \]  

(1)

• Where \( C_D \) is the drag coefficient, \( S \) is a reference area, \( S_{wet} \) is the body’s wetted area and \( \phi \) is the shape correction factor.

• Notice that \( C_D S = \frac{D}{1/2 \rho V_\infty^2} \)
Skin friction coefficient as function of Reynolds number for different flow regimes
Skin friction flat plate solution

- For laminar flow, the skin friction coefficient of a flat plate is given by
  \[ C_F = \frac{1.328}{\sqrt{\text{Re}}} \]  
  (2a)
  - Where \( \text{Re} \) is the Reynolds number based on the length of the slender body.
  - For turbulent flow, it can be approximated as
    \[ C_F = \frac{0.455}{\log(\text{Re})^{2.58}} \]  
    (2b)
  - Or, more simply, as
    \[ C_F = \frac{0.074}{\text{Re}^{0.2}} \]  
    (2c)
Laminar and fully turbulent

Comparison of $C_F$ values for laminar and fully turbulent flows, using the two approximations:

- Laminar: $0.455/\log_{10}(Re)^{2.5}$
- $0.074/Re^{0.2}$

![Graph showing the comparison of $C_F$ values for laminar and fully turbulent flows.](image-url)
Remarks

• If the flow is not fully turbulent, it will start off as laminar and undergo turbulent transition over the plate. Then the skin friction coefficient will depend on the location of the transition point.

• For high $Re$ it is simpler to assume that the flow is fully turbulent. For lower $Re$ values, both the laminar and turbulent drag can be calculated. Then the actual drag will lie between these two values.

• The skin friction coefficient will also be affected by compressibility effects.

• Assume that the flow is incompressible.
Slenderness ratio

- Forebody and afterbody:

- Slenderness ratio:
  \[ \lambda_{\text{eff}} = \left\{ \begin{array}{cl}
  \frac{l}{\sqrt{\frac{4}{\pi} A_c}} & \text{whichever is less}
  \\
  \frac{l_N + l_A}{\sqrt{\frac{4}{\pi} A_c}} + 2
  \end{array} \right. \]  
  \( A_c = \text{cross-sectional area} \)
Shape factor

• Then the shape factor for bodies with pointed tail sections is given by

\[ \phi = \frac{2.2}{\lambda_{eff}^{1.5}} + \frac{3.8}{\lambda_{eff}^{3}} \]  (4)

• with the condition that

\[ \frac{l_A}{\sqrt{\frac{4}{\pi} A_c}} \geq 2 \]

• Then, the profile drag of the body is obtained from equation 1 using equations 2-4.
The shape factor usually takes values between 0 and 0.5.

The curves shown in this figure assume an axisymmetric shape. Swept up tail section increase the drag.
Blunt afterbodies

- For bodies with blunt or short afterbodies, calculate the basic drag from equation 1 using

\[
\lambda_{\text{eff}} = \begin{cases} 
\frac{l_N + l_C}{\sqrt{\frac{4}{\pi} A_c}} + 2 \\
4 + \frac{l_N}{\sqrt{\frac{4}{\pi} A_c}}
\end{cases}
\]

whichever is less
Blunt afterbody correction

- Then, the total drag is the basic drag plus a correction, i.e.

\[ C_D S = C_F (1 + \phi) S_{wet} + \left( C_{D_b} \right)_{ref} \frac{\Delta C_{DA}}{C_{D_b}} A_C \]

- Where

\[
\left( C_{D_b} \right)_{ref} = 0.015 \sqrt{\frac{4}{\pi}} \sqrt{\frac{A_C}{C_F \left( l_N + l_C \right)}}
\]

- And \( \frac{\Delta C_{DA}}{\left( C_{D_b} \right)_{ref}} \) can be read from the figure overleaf.
Afterbody drag correction

This figure was obtained using statistical data on slender bodies of different shapes.

Where $D_f=b$
Slender body at an angle of attack

Fuselage at an angle of attack.
Crossflow correction

• If the angle of attack of the slender body is not zero, there is an additional drag contribution due to this crossflow, given by

\[ \Delta(C_{DS}) = \int_{0}^{l} \sin^{3}(\alpha_f - \beta) c_{dc} \frac{b}{\cos \beta} dx \]

• Where \( c_{dc} = 1 \) for a cylindrical cross-section and \( c_{dc} = 1.5-2 \) for a rectangular cross-section with rounded edges.

• The integral is usually calculated numerically.
Axisymmetric slender bodies

- For axisymmetric slender bodies, there exists a potential flow solution, as described by Katz and Plotkin.
- This solution can yield the values of the lift, drag and sideforce, given potential flow assumptions.
- This means that skin friction and separation are ignored.
Potential flow solution

- The three forces acting on the body are given by

\[ F_x = \int_{0}^{1} \int_{0}^{2\pi} R'(x)R(x)p(x,\theta)\,d\theta\,dx \]

\[ F_y = -\int_{0}^{1} \int_{0}^{2\pi} R(x)p(x,\theta)\cos\theta\,d\theta\,dx \]

\[ F_z = -\int_{0}^{1} \int_{0}^{2\pi} R(x)p(x,\theta)\sin\theta\,d\theta\,dx \]

- Where \( F_x \) is the drag, \( F_y \) the sideforce and \( F_z \) the lift.
- \( R \) is the local radius of the body at \( x \) and \( R' \) is its first derivative.
Pressure distribution

- The pressure distribution on the surface of the body is given by

\[ p(x, \theta) = \frac{1}{2} \rho V_\infty^2 C_p(x, \theta) + p_\infty \]

- And the pressure coefficient is given by

\[ C_p(x, \theta) = -\frac{2q_{xA}}{V_\infty} - (R')^2 - 4\alpha_f R' \sin \theta + \alpha_f^2 (1 - 4 \cos \theta) \]

- With

\[ q_{xA} = \frac{V_\infty}{2\pi} S''(x) \ln \frac{R}{2} + \frac{V_\infty}{4\pi} \int S'''(x_0) \ln |x - x_0| \, dx_0 \]

- \( S \) is the cross-sectional area of the body, as a function of \( x \).
Practical session

- You are given a fuselage to test in the wind tunnel.
- Take measurements of your fuselage
- Install the fuselage in the wind tunnel’s aerodynamic balance and carry out tests to measure its drag, lift and sideforce under the following conditions:
  - 0-10 degrees angle of attack
  - 0-10 degrees angle of yaw
- Repeat the tests after re-installing the fuselage back to front (the front becomes the rear)
- Calculate theoretical estimates for the drag and compare with your measurements.