Experimental Aerodynamics

Lecture 5:

Basic wind tunnel measurements and corrections

G. Dimitriadis
Some testing procedures

• There are hundreds of different testing procedures that can be employed in a wind tunnel.
• The choice of procedure depends on the test objectives, the model, the wind tunnel, the instrumentation etc.
• In this lecture, several additional procedures will be introduced:
  – Lift from pressure distributions
  – Drag from a wake survey
  – Vortex shedding frequency measurements
A pressure distribution is the variation of static pressure on the surface of a body.

As lift is caused by a pressure difference on the upper and lower surfaces of a body, pressure distributions can be used to calculate lift.

Pressure distributions are measured using pressure tappings leading to pressure transducers.
Pressure tappings

• A pressure tapping is simply a hole perpendicular to the surface of a body.
• The hole is connected to a tube that goes to a pressure sensing device.
• The pressure sensing device in the past used to be a multi-tube manometer.
• These days it’s a piezo-electric pressure sensor.
Example of tapping placement
Interior arrangement

Pressure tappings inside wing connected to tubes

Pressure tappings linked to pressure sensors
Complete setup

Closed up wing

Cables from sensors to data acquisition device
Pressure sensor connections

- There are two options for connecting pressure sensors to pressure tappings:
  - Very short connection tubes leading from the tappings to sensors inside the model. The sensors are connected to a data acquisition device via long electric cables.
  - Long connection tubes leading from the tappings to sensors outside the wind tunnel.
- Option 1 is necessary for unsteady pressure measurements. Long tubes can set up acoustic resonances.
- Option 2 is necessary for small models that cannot accommodate pressure sensors.
Pressure sensors

Multi-tube manometer

Piezo-electric pressure transducer

To pressure tapping

Sensing surface

Cap

Transducer

Glue
Pressure distribution

The top-bottom pressure difference causes a normal aerodynamic force, $N$.

The front-back pressure difference causes a tangential force, $T$. 
Pressure integrals

• The normal aerodynamic force is given by:

\[ N = \int p \, dx = \int_0^c \Delta p(x) \, dx \]

• Where \( \Delta p(x) \) is the pressure difference between top and bottom surface at the same chordwise position.

• The tangential aerodynamic force is given by

\[ T = \int p \, dy = \int_{-t/2}^{t/2} \Delta p^*(y) \, dy \]

• Where \( \Delta p^*(y) \) is the pressure difference between front and back surface at the same height position.
Lift and drag

- Once the normal and tangential forces have been calculated, the lift and drag can be obtained.

\[ L = N \cos \alpha - T \sin \alpha \]
\[ D = N \sin \alpha + T \cos \alpha \]

The lift and drag are always parallel and perpendicular to the free stream.
Aerodynamic Moment

• The aerodynamic moment around the leading edge can also be calculated from the pressure distribution:

\[ M = -\int p x \, dx = \int_0^c \Delta p(x) x \, dx \]
Comments on pressure distributions

- The quality of the lift and drag will be as good as that of the pressure measurements.
- Pressure tappings must cover the entire airfoil surface but should be denser near the leading and trailing edge.
- The drag value is not complete because it does not contain skin friction.
- The calculated lift, drag and moment must be corrected for wind tunnel effects.
Use a circle-based scheme for pressure tapping placement, to ensure that the tappings are denser near the leading and trailing edge.
3D pressure distributions

- Pressure distributions can also be measured on 3D wings.
- The pressure distribution is measured at several spanwise stations.
- Many pressure tappings!
Wake survey

• It has already been mentioned that there is a momentum deficit in the wake.
• In other words, the total pressure inside the wake is less than the total pressure in the free stream.
• This total pressure difference can be exploited in order to estimate the drag force acting on a wing section.
The variation of local airspeed in the wake can be measured using a total head rake. It can also be measured using a single pitot-static tube that can travel across the wake.
Profile drag

• The part of the air that passes over the airfoil loses momentum. This loss is equal to the profile drag of the airfoil.

\[ dd = dm(V_\infty - V(y)) \]

• Where \( dm \) is a small amount of mass flow rate. Integrating,

\[ d = \int_{-Y}^{Y} \rho V(V_\infty - V)dy \]

• Or, in coefficient form

\[ c_{d0} = \frac{2}{c} \int_{-Y}^{Y} \left( \sqrt{\frac{q}{q_\infty}} - \frac{q}{q_\infty} \right)dy \]
Wake survey details

- The wake survey is usually carried out far enough behind the wing to ensure that there are not static pressure variations across the wake. A sample distance is $0.7c$.
- Wake surveys fail when the flow over the wing is separated.
- They also fail when the wake contains a vortex street.
- Wake surveys can be repeated at several spanwise stations. However, it can be found that the profile drag varies with span, even for 2D experiments.
Vortex street measurements

• When the wake contains a vortex street, the wake survey method fails.
• The profile drag is no longer a constant. In fact, all aerodynamic forces become functions of time.
• The frequency of the vortex shedding determines the frequency of the aerodynamic forces.
• It is important to measure this frequency
Vortex streets

Von Karman vortex street behind a rectangle

Von Karman vortex street behind the Juan Fernandez Islands in Chile.
Vortex shedding frequency

A shed vortex travels at the free stream airspeed. Therefore, the spatial distribution and temporal frequency, \( n \), of the vortex street are related.

\[
n = \frac{U}{x_v}
\]

A non-dimensional estimate of the frequency of vortex shedding is the Strouhal number, \( \text{Str} \):

\[
\text{Str} = \frac{d}{x_v} = \frac{nd}{U}
\]
Aerodynamic forces due to vortex shedding

- Vortex shedding introduces a periodicity in the flow. This will lead to a periodic variation of the aerodynamic forces and moments.
- The forces and moments in 2D can be written as
  
  \[
  L = \frac{1}{2} \rho V^2 \bar{c} \bar{l} \sin(2\pi n t + \phi_l)
  \]
  
  \[
  D = \frac{1}{2} \rho V^2 \bar{c} \bar{d} \sin(2\pi n t + \phi_d)
  \]
  
  \[
  M = \frac{1}{2} \rho V^2 \bar{c} \bar{m} \sin(2\pi n t + \phi_m)
  \]

- Where barred quantities denote mean lift, drag etc coefficients that depend on the particular cross-section shape.
Measuring Str

• The Strouhal number can be measured in two ways:
  – Direct measurements measure the wake itself. This can be achieved by:
    • Flow visualization (e.g. PIV)
    • Hot wire measurements in the wake near the model
  – Indirect measurements measure the effect of the vortex shedding on the model.
    • Strain gauge balances can be used to measure the unsteady forces.
    • Accelerometers can be used to measure the model’s vibrations.
    • The best estimates of the shedding frequency are obtained when maximum aerodynamic force (or vibration) amplitudes are observed, i.e. when the structure resonates.
Remarks on vortex shedding

• Bodies do not shed periodic vortices at all conditions. Even bluff bodies.
• The shedding of periodic vortices depends on the flow Reynolds number.
• However, even in cases where non-periodic vortices are shed (turbulent wake), there can be a dominant frequency.
Vortex shedding behind a circular cylinder

It is clear that only the case $30 < \text{Re} < 5000$ leads to a Von Karman vortex street. However, the turbulent wake can also have a dominant frequency and, hence, Strouhal number.
Wind tunnel corrections

- Wind tunnels cannot recreate flowfields identical to the original.
- Wind tunnel flows are different to the original due to several factors.
- These differences necessitate corrections to be applied to measurements obtained in wind tunnels.
- The type and number of corrections depends on whether the simulated flow is 2D or 3D.
2D Wind tunnel corrections

• In 2D experiments, the model is constrained between flat plates or walls to force the flowfield to be nearly 2D.
• There are several sources of inaccuracy for 2D experiments in wind tunnels.
• The most important are:
  – Buoyancy
  – Solid blockage
  – Wake blockage
  – Streamline curvature
Buoyancy

- Wind tunnel buoyancy is caused by the fact that the boundary layer grows on the walls of the working section.
- Boundary layer growth is equivalent to a contraction of the working section area.
- The flow is accelerated, causing a drop in static pressure.
- Therefore, models with a big frontal area are pushed backwards.
- Buoyancy artificially increases the drag.
Longitudinal pressure gradient

- The longitudinal pressure drop is nearly linear.
- The longitudinal pressure gradient is given by:
  \[ \frac{dp}{dl} = -k \frac{\rho V^2}{2h} \]
- Where \( k = 0.016-0.040 \) is a factor that must be measured for a given wind tunnel.
- \( h \) is the height of the working section.
Buoyancy correction

- The buoyancy correction depends on the longitudinal pressure gradient and the volume of the body, i.e.

\[ \Delta D_B = \frac{dp}{dl} V_B \]

- Where \( \Delta D_B \) is the correction to be applied to the measured drag force and \( V_B \) the body volume.
- More accurate corrections have been estimated for airfoils, Rankine ovals, ellipses and other simple shapes.
Solid blockage

- The presence of a model in the working section reduces the area through which the air can flow.
- The air velocity is increased over the model.
- This effect is called solid blockage.
- The effect can be corrected by increasing the effective wind tunnel airspeed.
Solid blockage correction

• The correction to the airspeed for a circular cylinder is given by:

$$\Delta V = \varepsilon_{sb} V_u$$

• Where $V_u$ is the uncorrected airspeed and $\varepsilon_{sb}$ is given by:

$$\varepsilon_{sb} = \frac{\pi^2 R^2}{3 h^2}$$

• For a more general shape,

$$\varepsilon_{sb} = \frac{K_1 V_B}{S^{3/2}}$$

• Where $K_1=0.74$ for a horizontal model and 0.52 for a vertical model. $S$ is the working section area.
The airspeed in the wake must be lower than $V$. In a closed duct this means that the airspeed outside the wake must be larger than $V$ for a constant mass flow rate.

The wake blockage effect can also be corrected using an increment in the effective airspeed.
Wake blockage correction

• The airspeed correction is given by
  \[ \Delta V = \varepsilon_{wb} V_u \]

• Where \( \varepsilon_{wb} \) is given by:
  \[ \varepsilon_{wb} = \frac{c}{2h} c_{du} \]

• Where \( c \) is the model’s length (or wing chord) and \( c_{du} \) is the uncorrected 2D drag coefficient.
Streamline curvature

• The wind tunnel ceiling and floor artificially straighten the curvature of the flow streamlines around the model.

• The model appears to have more camber than it really has, i.e. it has too much lift.

• This effect requires corrections to angle of attack, lift coefficient and moment coefficient
Demonstration

- Idealize the airfoil by a single vortex
- Add mirror images to model tunnel walls

\[ V \xrightarrow{\Gamma} \]

\[ w \]

\[ u \]

\[ h \]

\[ x \]

\[ h \]
Induced airspeeds

• The first pair of mirror images induces zero horizontal airspeed but non-zero vertical airspeed.

• Therefore, assuming that $h \gg x$:

\[
\begin{align*}
    u &= 0 \\
    w &= \frac{\Gamma}{2\pi} \frac{x}{h^2 + x^2}
\end{align*}
\]
Total flowfield

- The variation of $w$ with chord gives the following result:

- This is equivalent to an effective camber that is induced by the straightening of the streamlines
Streamline curvature corrections

- The angle of attack becomes:
  \[ \alpha = \alpha_u + \frac{57.3\sigma}{2\pi} \left( c_{l_0} + 4c_{m1/2_u} \right) \]
- The lift coefficient becomes:
  \[ c_l = c_{l_u} \left( 1 - \sigma - 2\varepsilon \right) \]
- The moment coefficient around the half chord becomes:
  \[ c_{m1/2} = c_{m1/2_u} \left( 1 - 2\varepsilon \right) + \frac{\sigma c_l}{4} \]
- Where \( \varepsilon = \varepsilon_{sb} + \varepsilon_{wb} \) and

\[
\sigma = \frac{\pi^2}{48} \left( \frac{c}{h} \right)^2
\]
Total corrections

- The total corrected airspeed is:
  \[ V = V_u (1 + \varepsilon) \]

- The total corrected dynamic pressure:
  \[ q = q_u (1 + 2\varepsilon) \]

- The total corrected Reynolds number:
  \[ Re = Re_u (1 + \varepsilon) \]

- The total corrected drag (zero-lift):
  \[ c_{d0} = c_{d0u} \left( 1 - 3\varepsilon_{sb} - 2\varepsilon_{wb} \right) \]
3D Corrections

• In cases where the flow around the model is expected to have a 3D form, we apply 3D corrections.

• 3D corrections include all 2D corrections plus downwash corrections:
  – Buoyancy
  – Solid blockage
  – Wake blockage
  – Streamline curvature
  – Downwash corrections
Simple approximation

• A simple approximation for the total solid blockage and wake blockage corrections in 3D is given by:

\[ \varepsilon_t = \frac{1}{4} \frac{\text{Model frontal area}}{\text{Test section frontal area}} \]

• The ratio Model/Test section area should probably not exceed 7.5%.
Downwash corrections

- 3D wings and other lifting bodies generate a downwash, i.e. push air downwards.
- The downwash is constrained by the tunnel walls. Therefore, corrections must be applied.
- The downwash corrections depend on the shape of the wind tunnel, e.g. rectangular, octagonal, circular etc.
Practice Session

- The wind tunnel contains a rectangular wing, attached to the 3-component aerodynamic balance.
- The hot wire anemometer is mounted behind the wind tunnel
  - Measure the aerodynamic forces acting on the wing at two angles of attack and apply the necessary wind tunnel corrections
  - Vary the position of the hot wire until you locate the wake. Measure the momentum deficit at several heights in the wake and calculate the profile drag.
  - Compare the profile drag to the total drag and discuss