Project Assignment #1
Aerodynamic Analysis of the BWB Wind Tunnel Model
Due: September 21 at the end of lab

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1 Objective

The objective of this project assignment is to estimate the lift, drag, and pitching moment coefficients for the BWB wind tunnel which we will test this semester in the Wright Brothers' Wind Tunnel.

2 Data

Table 1 contains geometric data for the full-scale BWB. Table 2 contains data for the wind tunnel. For now, assume that the air is at standard sea level conditions (i.e. the temperature, density, pressure, and viscosity) in the wind tunnel test section. This is a reasonable first guess since the test section is essentially open to the atmosphere.

Symbol	Parameter	Value
S_{ref}	Reference Area (trapezoidal wing)	7,840 ft^2
S_{wet}	Wetted Area	31,324 ft^2
b	Wing span	280 ft
c_{mac}	Mean aerodynamic chord	30.75 ft

Table 1: Geometric data for full-scale BWB

Symbol	Parameter	Value
	Model scale	1/47
U_∞	freestream velocity	50 and 100 mph

Table 2: Wind tunnel data

3 Aerodynamic Model

To estimate the aerodynamic forces and moment on the BWB in the tunnel, you will combine a vortex lattice calculation with a semi-empirical estimate of the skin friction and pressure drag (C_{Df}

and C_{Dp}, respectively). The vortex lattice calculation will provide you with an estimate for the lift coefficient (C_L), the induced drag coefficient (C_{Di}), and the pitching moment coefficient about the aircraft nose (C_{M0}). The total drag will be the sum of the three drag estimates,

$$C_D = C_{Di} + C_{Df} + C_{Dp}.$$

Note, since the wind tunnel test is at subsonic conditions, wave drag is not expected to occur.

4   Notes on Moments, x_{cp}, and x_{ac}
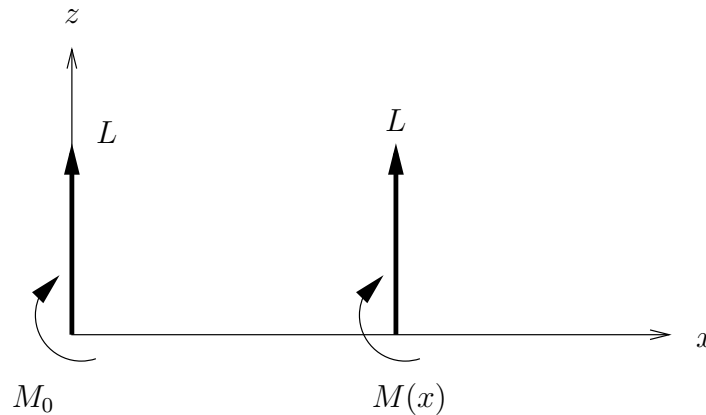

Figure 1: Lift force and pitching moment translation

The coordinate system used in the vortex lattice software (AVL) is: x downstream, y out the right wing, and z is up. With this convention, the pitching moment (which is the moment about the y axis) will be positive when it is nose up. Throughout this project, we will need to determine various aerodynamic quantities (e.g. the center of pressure, the aerodynamic center, the moment at the aerodynamic center, etc) related to the pitching moment. To calculate these quantities, we need to relate the pitching moment at one location to the pitching moment at another location. As illustrated in Figure 1, the moment at any x location can be related to the moment at the origin (i.e. $x = 0$) through,

$$M(x) = M_0 + Lx. \tag{1}$$

The location of the center of pressure (x_{cp}) is defined as the location at which the aerodynamic moments are zero. Thus,

$$
\begin{aligned}
M(x_{\mathrm{cp}}) &= 0 \\
&= M_0 + Lx_{\mathrm{cp}} \\
\Rightarrow x_{\mathrm{cp}} &= -\frac{M_0}{L}.
\end{aligned}
\tag{2}
$$

The location of the aerodynamic center (x_{ac}) is defined as the location at which the pitching moment does not change with a change in the lift. Thus,

$$\frac{dM(x_{\mathrm{ac}})}{dL} = 0$$

2

$$= \frac{d}{dL}(M_0 + Lx_{ac})$$

$$\Rightarrow x_{ac} = -\frac{dM_0}{dL}. \tag{3}$$

Usually, we will work with the forces and moments in non-dimensional form. Specifically:

$$C_D \equiv \frac{D}{q_\infty S_{ref}}, \tag{4}$$

$$C_L \equiv \frac{L}{q_\infty S_{ref}}, \tag{5}$$

$$C_M \equiv \frac{M}{q_\infty S_{ref} c_{mac}}, \tag{6}$$

where $q_\infty \equiv \frac{1}{2}\rho_\infty U_\infty^2$ is the freestream dynamic pressure. Note that the normalization of the pitching moment requires an extra length scale for which the mean aerodynamic chord is typically used (i.e. c_{mac}). Then, in non-dimensional form, Equations (1)-(3) can be written,

$$C_M\left(\frac{x}{c_{mac}}\right) = C_{M0} + C_L \frac{x}{c_{mac}}, \tag{7}$$

$$\frac{x_{cp}}{c_{mac}} = -\frac{C_{M0}}{C_L}, \tag{8}$$

$$\frac{x_{ac}}{c_{mac}} = -\frac{dC_{M0}}{dC_L}. \tag{9}$$

Usually, the aerodynamic center of an aircraft moves very little with changes in angle of attack for low angles of attack because the moment and the lift tend to vary linearly with angle of attack for low angles. The center of pressure, however, usually moves significantly at low angles. This can be seen by considering the limiting behavior of x_{cp} at $C_L \to 0$. First, we note that regardless of location, the moment is constant at $C_L = 0$ (this is because no force exists to create an additional moment through a moment arm). This leads to the result that,

$$C_{M0} = C_M(x_{cp}/c_{mac}) = C_M(x_{ac}/c_{mac}) \text{ when } C_L = 0.$$

If the moment at zero lift is finite (i.e. $C_M \neq 0$ when $C_L = 0$) then the center of pressure will move to either $\pm\infty$ depending on the sign of C_M in this limit.

5 Required Tasks

5.1 Mach and Reynolds Number for Wind Tunnel Tests

Calculate the Mach and Reynolds number for the BWB model in the wind tunnel at the different windspeeds.

5.2 Description of Friction and Pressure Drag Estimation

Using the Lift & Drag Primer available on the 16.100 website, develop a simple skin friction and pressure drag estimate. Assume that the flow in the boundary layer will be fully turbulent when estimating the skin friction drag (we will check the validity of this assumption in the wind tunnel later). Provide a brief, though complete, description of the model.

5.3   Plots

From the wind tunnel, data will be collected for wind speeds of 50 and 100 mph, with angles of attack varying from about -3 to 15 degrees. For both the 50 and 100 mph wind speeds, perform the following plots:

1. The coefficient of lift, C_L, versus angle of attack (in degrees)

2. C_L versus the coefficient of drag, C_D

3. The pitching moment coefficient about the aerodynamic center, C_{Mac} versus C_L. Note, in this plot, fix the location of the aerodynamic center as the aerodynamic center of the BWB at zero lift.

4. The distance of the aerodynamic center, x_{ac}, and the center of pressure, x_{cp}, from the nose of the BWB versus C_L (note: plot both x_{ac} and x_{cp} on the same graph and normalize them by c_{mac}.

5.4   Questions

1. How did the change in velocity impact the force and moment coefficients?

2. Given the response to the previous question, what will the impact of the changing the velocity by a factor of two have on the force and moments (i.e. not the force and moment coefficients)?