

# **Fundamentals of Aerodynamics 6th Edition**

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$$\begin{aligned}
A' &= \int_{LE}^{TE} (-p_u \sin\theta + \tau_u \cos\theta) ds_u \\
&\quad + \int_{LE}^{TE} (p_\ell \sin\theta + \tau_\ell \cos\theta) ds_\ell \qquad (1.8)
\end{aligned}$$

$$A' = \int_{LE}^{TE} (p_u - p_\ell) dy + \int_{LE}^{TE} (\tau_u + \tau_\ell) dx$$

$$A' = \int_{LE}^{TE} [(p_u - p_\infty) - (p_\ell - p_\infty)] dy + \int_0^c (\tau_u + \tau_\ell) dx$$

$$\frac{A'}{q_\infty c} = \frac{1}{c} \int_{LE}^{TE} \left[ \left( \frac{p_u - p_\infty}{q_\infty} \right) - \left( \frac{p_\ell - p_\infty}{q_\infty} \right) \right] dy + \frac{1}{c} \int_0^c \left( \frac{\tau_u}{q_\infty} + \frac{\tau_\ell}{q_\infty} \right) dx$$

$$\boxed{c_a = \frac{1}{c} \int_{LE}^{TE} (c_{p_u} - c_{p_\ell}) dy + \frac{1}{c} \int_0^c (c_{\tau_u} - c_{\tau_\ell}) dx}$$

This is Eq. (1.16).

$$\begin{aligned}
M'_{LE} &= \int_{LE}^{TE} [(p_u \cos\theta + \tau_u \sin\theta)x - (p_u \sin\theta - \tau_u \cos\theta)y] ds_u \\
&\quad + \int_{LE}^{TE} [-p_\ell \cos\theta + \tau_\ell \sin\theta)x + (p_\ell \sin\theta + \tau_\ell \cos\theta)y] ds_\ell
\end{aligned}$$

$$\begin{aligned}
M'_{LE} &= \int_{LE}^{TE} [p_u - p_\ell] x dx - \int_{LE}^{TE} (\tau_u + \tau_\ell) x dy \\
&\quad + \int_{LE}^{TE} [p_u - p_\ell] y dy + \int_{LE}^{TE} (\tau_u + \tau_\ell) y dx
\end{aligned}$$

$$\begin{aligned}
M'_{LE} &= \int_{LE}^{TE} [(p_u - p_\infty) - (p_\ell - p_\infty)] x dx - \int_{LE}^{TE} (\tau_u + \tau_\ell) x dy \\
&\quad + \int_{LE}^{TE} [p_u - p_\infty) - (p_\ell - p_\infty)] y dy + \int_{LE}^{TE} (\tau_u + \tau_\ell) y dx
\end{aligned}$$

Divide by  $q_\infty c^2$ :

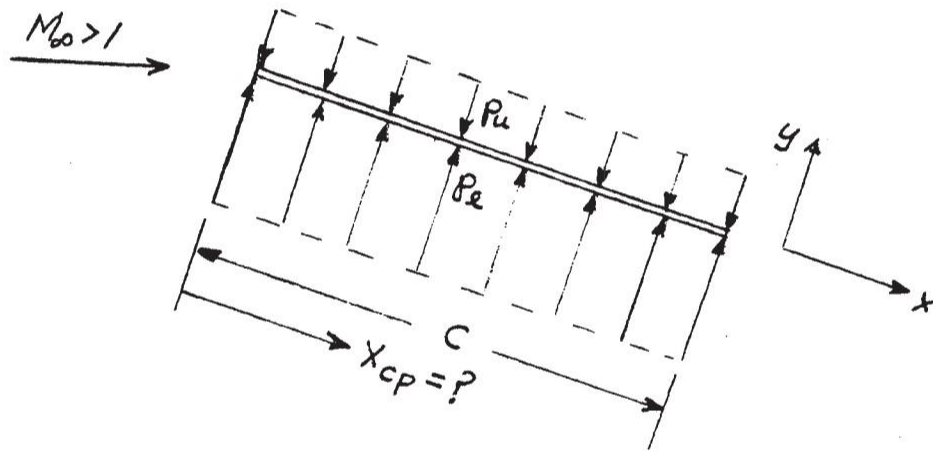
$$\frac{M'_{LE}}{q_\infty c^2} = \frac{1}{c^2} \int_{LE}^{TE} \left[ \left( \frac{p_u - p_\infty}{q_\infty} \right) - \left( \frac{p_\ell - p_\infty}{q_\infty} \right) \right] x dx - \frac{1}{c^2} \int_{LE}^{TE} \left( \frac{\tau_u}{q_\infty} + \frac{\tau_\ell}{q_\infty} \right) x dy$$

$$+ \frac{1}{c^2} \int_{LE}^{TE} \left[ \left( \frac{p_u - p_\infty}{q_\infty} \right) - \left( \frac{p_\ell - p_\infty}{q_\infty} \right) \right] y \, dy + \frac{1}{c^2} \int_{LE}^{TE} \left( \frac{\tau_u}{q_\infty} + \frac{\tau_\ell}{q_\infty} \right) y \, dx$$

$$c_{m_{ic}} = \frac{1}{c^2} \left[ \int_0^c (C_{p_u} - C_{p_\ell}) x \, dx - \int_{LE}^{TE} (C_{f_u} + C_{f_\ell}) x \, dy \right. \\ \left. + \int_{LE}^{TE} (C_{p_u} - C_{p_\ell}) y \, dy + \int_0^c (C_{f_u} + C_{f_\ell}) y \, dx \right]$$

This is Eq. (1.17).

1.3



$$M'_{LE} = - \int_0^c (p_\ell - p_u) (dx) (1) x - (p_\ell - p_u) \int_0^c x \, dx$$

$$M'_{LE} = - (p_\ell - p_u) \frac{c^2}{2}$$

$$N' = \int_0^c (p_\ell - p_u) \, dx = (p_\ell - p_u) c$$

$$x_{cp} = -\frac{M'_{LE}}{N'} = -\frac{\left[ -(p_\ell - p_u) \frac{c^2}{2} \right]}{(p_\ell - p_u) c}$$

$$\boxed{x_{cp} = c/2}$$

1.3 For a flat plate,  $\theta = 0$  in Eqs. (1.7) – (1.11). Hence,

$$N' = \int_0^c (p_\ell - p_u) dx = \int_0^1 [-2 \times 10^4 (x-1)^2 + 1.19 \times 10^5] dx$$

$$N' = -2 \times 10^4 \left[ \frac{x^3}{3} - x^2 + x \right]_0^1 + [1.19 \times 10^5 x]_0^1 = \boxed{1.12 \times 10^5 \text{ N}}$$

$$A' = \int_0^c (\tau_\ell - \tau_u) dx = \int_0^1 (731 x^{-0.2} + 288 x^{-0.2}) dx$$

$$A' = [1274 x^{0.8}]_0^1 = \boxed{1274 \text{ N}}$$

$$L' = N' \cos \alpha - A' \sin \alpha = 1.12 \times 10^5 \cos 10^\circ - 1274 \sin 10^\circ$$

$$= \boxed{1.105 \times 10^5 \text{ N}}$$

$$D' = N' \sin \alpha + A' \cos \alpha = 1.12 \times 10^5 \sin 10^\circ + 1274 \cos \alpha$$

$$= \boxed{2.07 \times 10^4 \text{ N}}$$

$$M'_{LE} = \int_0^c [p_u - p_\ell] x dx = \int_0^1 [2 \times 10^4 (x-1)^2 - 1.19 \times 10^5] x dx$$

$$+ 2 \times 10^4 \left[ \frac{x^4}{4} - \frac{2x^3}{3} + \frac{x^2}{2} \right]_0^1 - [0.595 \times 10^5 x^2]_0^1 = \boxed{-5.78 \times 10^4 \text{ Nm}}$$

$$M'_{c/4} = M'_{LE} + L' (c/4) = -5.78 \times 10^4 + 1.105 \times 10^5 (0.25)$$

$$= \boxed{-3.02 \times 10^4 \text{ N/m}}$$

$$x_{cp} = -\frac{M'_{LE}}{N'} = -\frac{(-5.78 \times 10^4)}{1.12 \times 10^5} = \boxed{0.516 \text{ m}}$$

1.5

$$c = c_n \cos\alpha - c_a \sin\alpha$$

$$= (1.2) \cos 12^\circ - (0.3) \sin\alpha = \boxed{1.18}$$

$$c_d = c_n \sin\alpha + c_a \cos\alpha$$

$$= (1.2) \sin 12^\circ + (0.3) \cos\alpha = \boxed{0.279}$$

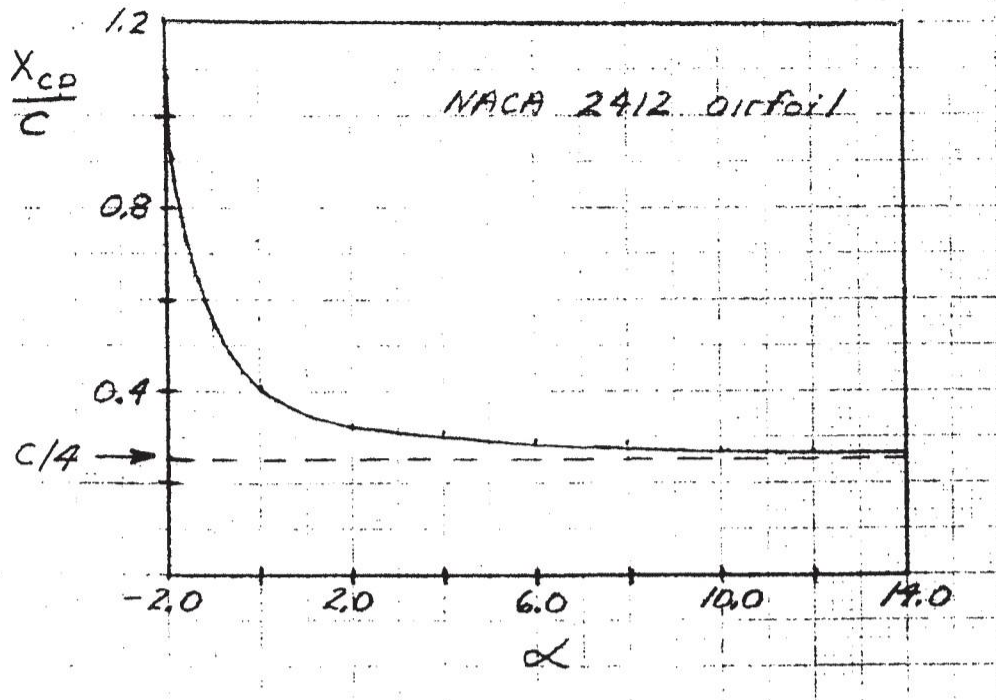
1.6  $c_n = c_r \cos\alpha + c_d \sin\alpha$

Also, using the more accurate  $N'$  rather than  $L'$  in Eq. (1.22), we have

$$x_{cp} = \frac{c}{4} - \frac{M'_{c/4}}{N'} = \frac{c}{4} - c \left( \frac{c_{m_{c/4}}}{c_n} \right)$$

Hence:

<u><math>\alpha(^{\circ})</math></u>	<u><math>c_n</math></u>	<u><math>x_{cp}/c</math></u>
-2.0	0.0498	1.09
0	0.25	0.41
2.0	0.44	0.336
4.0	0.639	0.306
6.0	0.846	0.293
8.0	1.07	0.284
10.0	1.243	0.277
12.0	1.402	0.271
14.0	1.52	0.266



Note that  $x_{cp}$  moves forward as  $\alpha$  is increased, and that it closely approaches the quarter-chord point in the range of  $\alpha$  of  $10^\circ$  to  $14^\circ$ . At higher angles-of-attack, beyond the stall ( $\alpha > 16^\circ$ ),  $x_{cp}$  will reverse its movement and move rearward as  $\alpha$  continues to increase. Compare the above variation with the center-of-pressure measurements of the Wright Brothers on one of their airfoils, shown in Fig. 1.28.

1.7  $K = 3$  (mass, length, and time)

$$f_1(D, \rho_\infty, V_\infty, c, g) = 0 \quad \text{Hence } N = 5$$

We can write this expression in terms of  $N - K = 5 - 3 = 2$  dimensionless Pi products:

$$f_2(\Pi_1, \Pi_2)$$

where

$$\Pi_1 = f_3(\rho_\infty, V_\infty, c, D)$$

$$\Pi_2 = f_4(\rho_\infty, V_\infty, c, g)$$

$$\text{Let } \Pi_1 = \rho_\infty^a V_\infty^b c^d D$$

$$1 = (m \ell^{-3})^a (\ell t^{-1})^b \ell^c (m \ell t^{-2}) = 0$$

$$\text{mass: } a + 1 = 0$$

$$\text{length: } -3a + b + c + 1 = 0$$

$$\text{time: } -b - 2 = 0$$



$$a = -1$$

$$b = -2$$

$$c = -2$$

Hence:

$$\Pi_1 = \frac{D}{\rho_\infty V_\infty^2 c^2}, \text{ or } \Pi_1 = \frac{D}{\frac{1}{2} \rho_\infty V_\infty^2 c^2}$$

$$\Pi_1 = \frac{D}{q_\infty c^2}$$

Let  $\Pi_2 = \rho_\infty^2 V_\infty c^b g^d$

$$1 = (m \ell^{-3})^a (\ell t^{-1})^b (\ell t^{-2})^d = 0$$

$$\text{mass: } a = 0$$

$$a = 0$$

$$\text{length: } -3a + 1 + b + d = 0$$

$$d = -1/2$$

$$\text{time: } -1 - 2d = 0$$

$$b = -1/2$$

Hence:

$$\Pi_2 = \frac{V_\infty}{\sqrt{cg}}$$

Thus:

$$f_2(\Pi_1, \Pi_2) = f_2\left(\frac{D}{q_\infty c^2}, \frac{V_\infty}{\sqrt{cg}}\right) = 0$$

or:

$$\boxed{C_D = f(F_r)}$$

1.8  $D_w = f_1(\rho_\infty, V_\infty, c, a_\infty, c_p, c_v)$

$K = 4$  (mass, length, time, degrees)

$$f_2(D_w, \rho_\infty, V_\infty, c, a_\infty, c_p, c_v) = 0$$

Hence,  $N = 7$ . This can be written as a function of  $N - K = 7 - 4 = 3$  pi products:

$$f_3(\Pi_1, \Pi_2, \Pi_3) = 0$$

where:

$$\Pi_1 = f_4(\rho_\infty, V_\infty, c, c_p, D)$$

$$\Pi_2 = f_5(\rho_\infty, V_\infty, c, c_p, a_\infty)$$

$$\Pi_3 = f_6(\rho_\infty, V_\infty, c, c_p, c_v)$$

The dimensions of  $c_p$  and  $c_v$  are

$$[c_p] = \frac{\text{energy}}{\text{mass}(\text{°})} = \frac{(\text{force})(\text{distance})}{\text{mass}(\text{°})} = \frac{(\text{m}\ell\text{t}^{-2})(\ell)}{\text{m}(\text{°})}$$

$$[c_p] = \ell^2 \text{t}^{-2} (\text{°})^{-1} \text{ where } (\text{°}) \text{ degrees.}$$

For  $\Pi_1$ :

$$\rho_\infty^i V_\infty^j c^k c_p^n D = \Pi_1$$

$$(\text{m } \ell^{-3})^i (\ell \text{ t}^{-1})^j (\ell)^k (\ell^2 \text{t}^{-2})^n (\text{°})^{-n} (\text{m } \ell \text{ t}^{-2}) = 1$$

$$\text{mass: } i + 1 = 0 \qquad i = -1$$

$$\text{length: } -3i + j + k + 2n + 1 = 0 \qquad n = 0$$

$$\text{time: } -j - 2n - 2 = 0 \qquad j = -2$$

$$\text{degrees: } -n = 0 \qquad k = -2$$

Hence:

$$\Pi_1 = \frac{D}{\rho_\infty V_\infty^2 c^2}, \text{ or } \Pi_1 = \frac{D}{q_\infty c}$$

For  $\Pi_2$ :

$$\Pi_2 = \rho_\infty^i V_\infty^j c^k a_\infty^n$$



$$1 = (m \ell^{-3})^i (\ell \text{ t}^{-1})^j (\ell^2 \text{ t}^{-2})^k (\text{t}^0)^{-k} (\ell \text{ t}^{-1})^n$$

$$\left. \begin{array}{l} \text{mass: } i = 0 \\ \text{length: } -3i + 1 + j + 2k + n = 0 \\ \text{time: } -1 - 2k - n = 0 \\ \text{degrees: } -k = 0 \end{array} \right\} \begin{array}{l} i = 0 \\ k = 0 \\ n = -1 \\ j = 0 \end{array}$$

Hence:

$$\Pi_2 = \frac{V_\infty}{a_\infty}$$

For  $\Pi_3$ :

$$\Pi_3 = \rho_\infty^i V_\infty^j c^k c_p^n c_v$$

$$1 = (m \ell^{-3})^i (\ell \text{ t}^{-1})^j \ell^k (\ell^2 \text{ t}^{-2})^n (\text{t}^0)^{-n} (\ell \text{ t}^{-2}) (\text{t}^0)^{-1}$$

$$\left. \begin{array}{l} \text{mass: } i = 0 \\ \text{length: } -3i + j + k + 2n + 2 = 0 \\ \text{time: } -j - 2n - 2 = 0 \\ \text{degrees: } -n - 1 = 0 \end{array} \right\} \begin{array}{l} i = 0 \\ n = -1 \\ j = 0 \\ k = 0 \end{array}$$

Hence:

$$\Pi_3 = \frac{c_v}{c_p}. \text{ We can take the reciprocal, and still have a dimensionless product.}$$

Hence,

$$\Pi_3 = \frac{c_v}{c_p} = \gamma$$

Thus,

$$f_3 \left( \frac{D}{q_\infty S}, \frac{V_\infty}{a_\infty}, \frac{c_p}{c_v} \right)$$

or,

$$C_D = f(M_\infty, \gamma)$$

---

$$1.9 \quad \frac{M_1}{M_2} = \frac{V_1 a_2}{V_2 a_1} = \frac{V_1}{V_2} \sqrt{\frac{T_2}{T_1}} = \frac{100}{200} \sqrt{\frac{800}{200}} = 1$$

Hence, the Mach numbers of the two flows are the same.

$$\frac{Re_1}{Re_2} = \frac{\rho_1 V_1 c_1}{\rho V_2 c_2} \left( \frac{\mu_2}{\mu_1} \right) = \frac{\rho_1 V_1 c_1}{\rho V_2 c_2} \sqrt{\frac{T_2}{T_1}} = \left( \frac{1.23}{1.739} \right) \left( \frac{100}{200} \right) \left( \frac{1}{2} \right) \sqrt{\frac{800}{200}} = 0.354$$

The Reynold's numbers are different. Hence, the two flows are not dynamically similar.

---

1.10 Denote free flight by subscript 1, and the wind tunnel by subscript 2. For the lift and drag coefficients to be the same in both cases, the flows must be dynamically similar. Hence

$$M_1 = M_2$$

and

$$Re_1 = Re_2$$

For Mach number:

$$\frac{V_1}{a_1} = \frac{V_2}{a_2}$$

Since  $a \propto \sqrt{T}$ , we have

$$\frac{V_2}{\sqrt{T_2}} = \frac{V_1}{\sqrt{T_1}} = \frac{250}{\sqrt{223}} = 16.7 \quad (1)$$

For Reynolds number:  $\frac{\rho_1 V_1 c_1}{\mu_1} = \frac{\rho_2 V_2 c}{\mu_2}$

Assume, as before, that  $\mu \propto \sqrt{T}$ . Hence

$$\frac{\rho_2 V_2 c_2}{\sqrt{T_2}} = \frac{\rho_1 V_1 c_1}{\sqrt{T_1}}$$

---

or,

$$\frac{\rho_2 V_2}{\sqrt{T_1}} = \frac{\rho_1 V_1}{\sqrt{T_1}} \left( \frac{c_1}{c_2} \right) = \frac{(0.414)(250)}{223} \left( \frac{5}{1} \right)$$

or,

$$\frac{\rho_2 V_2}{\sqrt{T_2}} = 34.65 \quad (2)$$

Finally, from the equation of state:

$$\rho_2 T_2 = \frac{p_2}{R} = \frac{1.01 \times 10^5}{287} = 351.9 \quad (3)$$

Eqs. (1) – (3) represent three equations for the three unknowns,  $\rho_2$ ,  $V_2$ , and  $T_2$ . They are summarized below:

$$\frac{V_2}{\sqrt{T_2}} = 1.67 \quad (1)$$

$$\frac{\rho_2 V_2}{\sqrt{T_2}} = 34.65 \quad (2)$$

$$\rho_2 T_2 = 351.9 \quad (3)$$

From Eq. (3):

$$\rho_2 = 351.9/T_2 \quad (4)$$

Subst. (4) into (2):

$$\frac{351.9}{T_2} \left( \frac{V_2}{\sqrt{T_2}} \right) = 34.65 \quad (5)$$

Subst. (1) into (5):  $\frac{351.9}{T_2} (16.7) = 34.65$

Hence,

$$T_2 = \frac{(351.9)(16.7)}{(34.65)} = \boxed{169.6^\circ\text{K}}$$

$$\text{From Eq. (1): } V_2 = 16.7 \sqrt{T_2} = 16.7 \sqrt{169.6} = \boxed{217.5 \frac{\text{m}}{\text{sec}}}$$

$$\text{From Eq. (3): } \rho_2 = \frac{351.9}{T_2} = \frac{351.9}{169.6} = \boxed{2.07 \frac{\text{kg}}{\text{m}^3}}$$

$$1.11 \quad p_b = p_a - \rho g \Delta h$$

$$= 1.01 \times 10^5 - (1.36 \times 10^4)(9.8)(0.2)$$

$$p_b = \boxed{7.43 \times 10^4 \text{ N/m}^2}$$

1.12 Weight = Buoyancy force + lift

$$W = B + L$$

$$B = \underbrace{(15,000)}_{\text{volume (m}^3\text{)}} \underbrace{(1.1117)}_{\text{air density at 1000m (kg/m}^3\text{)}} \underbrace{(9.8)}_{\text{acceleration of gravity (m/sec}^2\text{)}} = 1.634 \times 10^5 \text{ N}$$

$$q_\infty = \frac{1}{2} \rho_\infty V_\infty^2 = \frac{1}{2} (1.1117) (30)^2 = 500 \text{ N/m}^2$$

$$S = \pi d^2/4 = \pi(14)^2/4 = 153.9 \text{ m}^2$$

$$L = q_\infty S C_L = (500)(153.9)(0.05) = 3487 \text{ N}$$

Hence:

$$W = 1.634 \times 10^5 + 3487 = \boxed{1.67 \times 10^5 \text{ N}}$$

1.13 Let us use the formalism surrounding Eq. (1.16) in the text. In this case,  $c_d = c_a$ , and from Eq. (1.16), neglecting skin friction

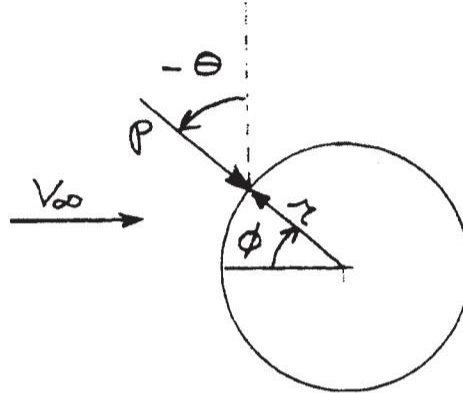
$$c_d = \frac{1}{c} \int_{LE}^{TE} (C_{p_u} - C_{p_t}) dy \quad (1)$$

From Eq. (1.13) in the text, Eq. (1) above can be written as

$$c_d = \frac{1}{c} \int_{LE}^{TE} (C_{p_u} - C_{p_t}) (-\sin \theta ds) \quad (2)$$

Draw a picture:

Following our sign convention, note that  $\theta$  is drawn counterclockwise in this sketch, hence it is a negative angle,  $-\theta$ .



From the geometry:

$$-\theta = \pi - \phi$$

Hence,  $\sin(-\theta) = -\sin \theta = \sin(\pi - \theta) = \cos \phi$

Substitute this into Eq. (2), noting also that  $ds = r d\phi$  and the chord  $c$  is twice the radius,  $c = 2r$ . From Eq. (2),

$$c_d = \frac{1}{2r} \int_{LE}^{TE} (C_{p_u} - C_{p_t}) \cos \phi r d\phi$$

$$c_d = \frac{1}{2} \int_{LE}^{TE} (C_{p_u} - C_{p_t}) \cos \phi d\phi$$

$$c_d = \frac{1}{2} \int_{LE}^{TE} C_{p_u} \cos \phi d\phi - \frac{1}{2} \int_{LE}^{TE} C_{p_t} \cos \phi d\phi \quad (3)$$

Consider the limits of integration for the above integrals. The first integral is evaluated from the leading edge to the trailing edge along the upper surface. Hence,  $\phi = 0$  at LE and  $\pi$  at TE.

The second integral is evaluated from the leading edge to the trailing edge along the bottom surface. Hence,  $\phi = 2\pi$  at LE and  $\pi$  at the TE. Thus, Eq. (3) becomes

$$c_d = \frac{1}{2} \int_0^\pi C_{p_u} \cos \phi \, d\phi - \frac{1}{2} \int_{2\pi}^\pi C_{p_t} \cos \phi \, d\phi \quad (4)$$

In Eq. (4),

$$C_{p_u} = 2 \cos^2 \phi \quad \text{for } 0 \leq \phi \leq \pi/2$$

$$C_{p_u} = 0 \quad \text{for } \frac{\pi}{2} \leq \phi \leq \pi$$

$$C_{p_t} = 2 \cos^2 \phi \quad \text{for } \frac{3\pi}{2} \leq \phi \leq 2\pi$$

$$C_{p_t} = 0 \quad \text{for } \pi \leq \phi \leq \frac{3\pi}{2}$$

Thus, Eq. (4) becomes

$$c_d = \int_0^{\pi/2} \cos^3 \phi \, d\phi - \int_{2\pi}^{3\pi/2} \cos^3 \phi \, d\phi$$

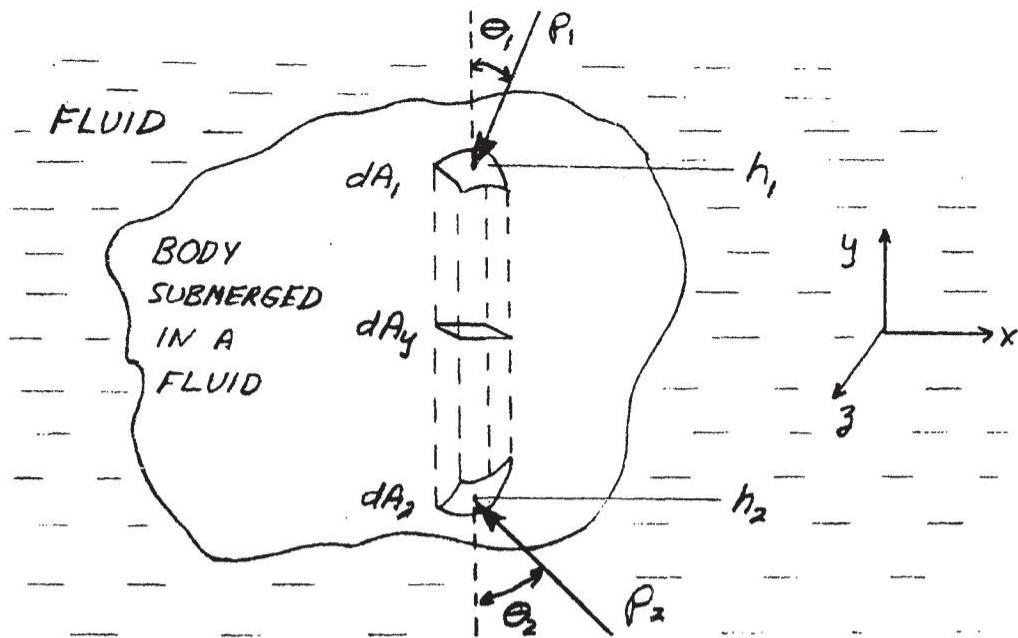
Since  $\cos^3 \phi \, d\phi = (\frac{1}{3} \sin\phi)(\cos^2 \phi + 2)$ , Eq. (5) becomes

$$c_d = \left[ \left( \frac{1}{3} \sin\phi \right) (\cos^2 \phi + 2) \right]_0^{\pi/2} - \left[ \left( \frac{1}{3} \sin\phi \right) (\cos^2 \phi + 2) \right]_{2\pi}^{3\pi/2}$$

$$c_d = \left( \frac{1}{3} \right) (1)(2) - \left( \frac{1}{3} \right) (-1)(2)$$

$$\boxed{c_d = 4/3}$$

1.14



Consider the arbitrary body sketched above. Consider also the vertical cylinder element inside the body which intercepts the surface area  $dA_1$  near the top of the body, and  $dA_2$  near the bottom of the body. The pressures on  $dA_1$  and  $dA_2$  are  $p_1$  and  $p_2$  respectively, and makes angles  $\theta_1$  and  $\theta_2$  respectively with respect to the vertical line through the middle of  $dA_1$  and  $dA_2$ . The net pressure force in the y-direction on this cylinder is:

$$dF_y = -p_1 \cos \theta_1 dA_1 + p_2 \cos \theta_2 dA_2 \quad (1)$$

Let  $dA_y$  be the projection of  $dA_1$  and  $dA_2$  on a plane perpendicular to the y axis.

$$dA_y = \cos \theta_1 dA_1 = \cos \theta_2 dA_2$$

Thus, Eq. (1) becomes

$$dF_y = (p_2 - p_1) dA_y \quad (2)$$

From the hydrostatic equation

$$p_2 - p_1 = \int_{h_1}^{h_2} \rho g dy \quad (3)$$

Combining Eqs. (2) and (3),

$$dF_y = \int_{h_1}^{h_2} \rho g dy dA_y \quad (4)$$

However,  $dy dA_y = dV =$  element of volume of the body. Thus, the total force in the y direction,  $F_y$ , is given by Eq. (4) integrated over the volume of the body

$$F_y = \underbrace{\iiint_V \rho g dV}$$

Force on body      Weight of fluid displaced by body.

---

1.15 From Eq. (1.45)

$$C_L = \frac{L}{q_\infty S} = \frac{2W}{\rho_\infty V_\infty^2 S} = \frac{2(2950)}{(0.002377)V_\infty^2 (174)}$$

$$C_L = \frac{14265}{V_\infty^2} \quad (1)$$

Also,

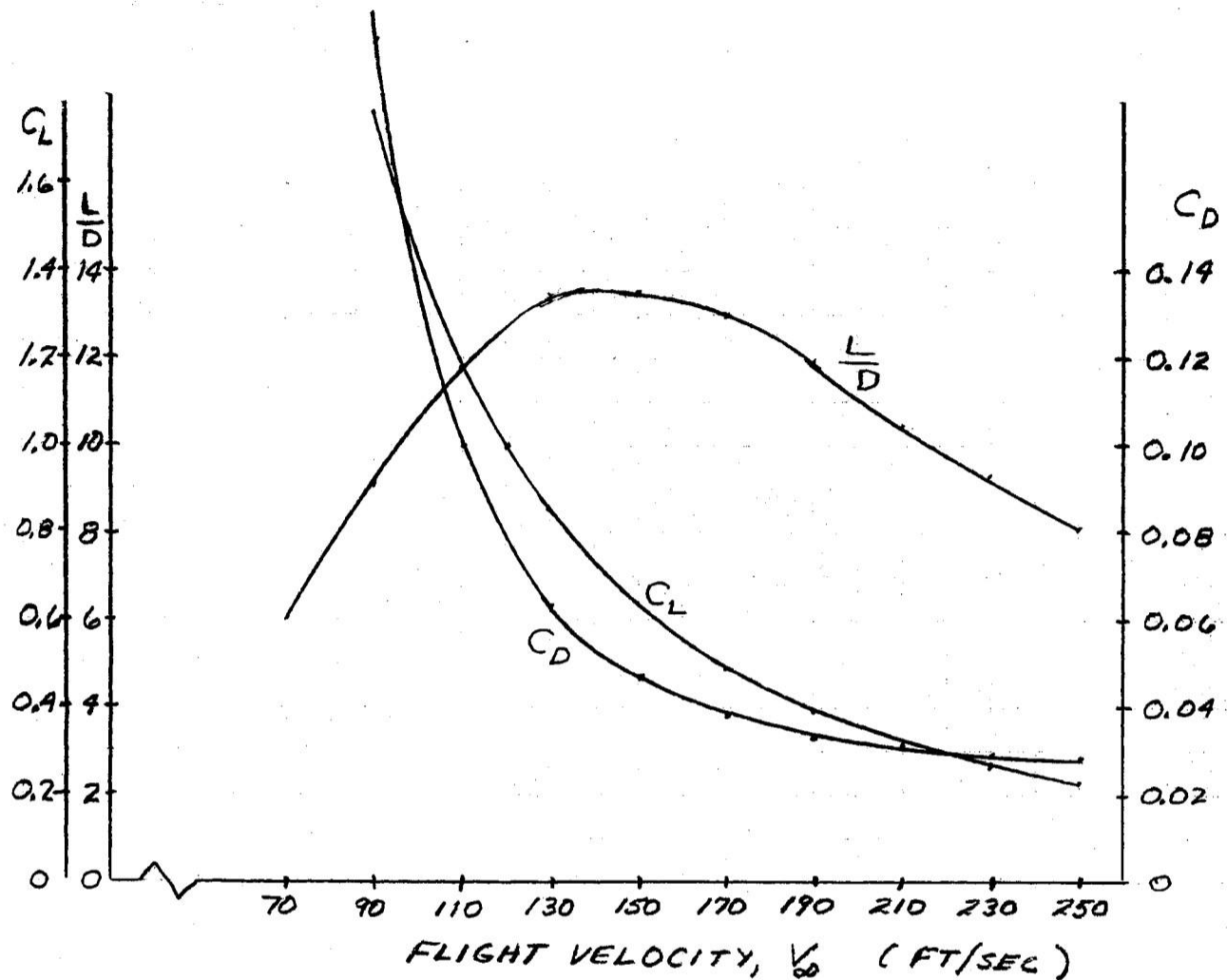
$$C_D = 0.025 + 0.054 C_L^2 \quad (2)$$

Tabulate Eqs. (1) and (2) versus velocity.

$V_\infty$ (ft/sec)	$C_L$	$C_D$	$\frac{L}{D} = \frac{C_L}{C_D}$
70	2.911	0.483	6.03
90	1.761	0.192	9.17
110	1.179	0.100	11.79
130	0.844	0.063	13.40
150	0.634	0.047	13.49
170	0.494	0.038	13.0
190	0.395	0.033	11.97
210	0.323	0.031	10.42
230	0.270	0.029	9.31
250	0.228	0.028	8.14

These results are plotted on the next page.





Examining this graph, we note, for steady, level flight:

1. The lift coefficient decreases as  $V_\infty$  increases.
2. At lower velocity range, the drag coefficient decreases even faster than the lift coefficient with velocity. (Note that on the graph the scale for  $C_D$  is one-tenth that for  $C_L$ .)
3. As a result, the lift-to-drag ratio first increases, goes through a maximum, and then gradually decreases as velocity increases.

It can be shown that the maximum velocity for this airplane is about 265 ft/sec at sea level. As seen in the graph, the maximum value of  $L/D$  occurs around  $V_\infty = 140$  ft/sec, which is much lower than the maximum velocity. However, at higher velocity the value of  $L/D$  decreases only gradually as  $V_\infty$  increases. This has the practical implication that at higher speeds, even though the value of  $L/D$  is less than its maximum, it is still a reasonably high value. The range of the aircraft is proportional to  $L/D$  (see for example, Anderson, Aircraft Performance and Design, McGraw-Hill, 1999, or Anderson, Introduction to Flight, 4<sup>th</sup> ed.,

McGraw-Hill, 2000). To obtain maximum range, the airplane should fly at the velocity for maximum  $L/D$ , which for this case is 140 ft/sec. However, one reason to fly in an airplane is to get from one place to another in a reasonably short time. By flying at the low velocity of  $V_{\infty} = 140$  ft/sec, the flight time may be unacceptably long. By cruising at a higher speed, say 200 ft/sec, the flight time will be cut by 30%, with only an 18% decrease in  $L/D$ .

1.16 From Eq. (1.59), in the text,

$$\tau_w = \mu \left( \frac{dV}{dy} \right)_{y=0}$$

or,

$$\left( \frac{dV}{dy} \right)_{y=0} = \frac{\tau_w}{\mu}$$

As given in Section 1.11,  $\mu$  at standard sea level temperature is

$$\mu = 1.7894 \times 10^{-5} \text{ kg/(m)(s)}$$

Thus,

$$\left( \frac{dV}{dy} \right)_{y=0} = \frac{\tau_w}{\mu} = \frac{282}{1.7894 \times 10^{-5}} = \boxed{1.576 \times 10^7 \text{ sec}^{-1}}$$

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1.17 From Eq. (1.60)

$$\left( \frac{dT}{dy} \right)_{y=0} = -\frac{\dot{q}_w}{k}$$

The heat transfer into the surface is  $-0.03 \text{ MW/m}^2$ , and from Section 1.11, the thermal conductivity at standard sea level temperature is

$$k = 2.53 \times 10^{-2} \text{ J/(m)(s)(K)}$$

$$\dot{q}_w = -0.03 \text{ MW/m}^2 = -0.03 \times 10^6 \text{ W/m}^2$$

$$\left(\frac{dT}{dy}\right)_{y=0} = \frac{0.03 \times 10^6}{2.53 \times 10^{-2}} = \boxed{1.186 \times 10^6 \frac{K}{m}}$$

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1.18 (a) At standard sea level, from Appendix E,  $\rho_\infty = 0.002377 \text{ slug/(ft}^3\text{)}$ . Also, from Section 1.11,  $\mu_\infty = 3.7373 \times 10^{-7} \text{ slug/(ft)(s)}$ . Putting the velocity in consistent units,

$$V_\infty = (200) \frac{88}{60} = 293.3 \text{ ft/sec}$$

Thus,

$$\text{Re} = \frac{\rho_\infty V_\infty c}{\mu_\infty} = \frac{(0.002377)(293.3)(14.25)}{3.7373 \times 10^{-7}}$$

$$\boxed{\text{Re} = 2.66 \times 10^7}$$

$$(b) \quad \text{Re} = \frac{\rho_\infty V_\infty c}{\mu_\infty} = \frac{(0.002377)(1340)(21.5)}{3.7373 \times 10^{-7}}$$

$$\boxed{\text{Re} = 1.83 \times 10^8}$$

1.19 From Figure 1.65, we have the normal and tangential force coefficients at 3-degree angle of attack given as 0.546 and 0 respectively. From Eqs. (1.1) and (1.2), written in terms of force coefficients, and using Lilienthal's nomenclature:

$$C_L = \eta \cos \alpha - \theta \sin \alpha$$

$$C_D = \eta \sin \alpha + \theta \cos \alpha$$

The ratio of lift-to-drag is

$$\frac{L}{D} = \frac{C_L}{C_D} = \frac{\eta \cos \alpha - \theta \sin \alpha}{\eta \sin \alpha + \theta \cos \alpha}$$

$$\frac{L}{D} = \frac{0.546 \cos 3^\circ - 0}{0.546 \sin 3^\circ + 0} = \cot 3^\circ = \boxed{19.08}$$

At  $\alpha=2^\circ$ , from the Lilienthal Table,  $\eta = 0.489$  and  $\theta = 0.008$

$$\frac{L}{D} = \frac{0.489 \cos 2^\circ - 0.008 \sin 2^\circ}{0.489 \sin 2^\circ + 0.008 \cos 2^\circ} = \frac{0.4887 - 2.79 \times 10^{-4}}{0.0171 + 8 \times 10^{-3}}$$

$$\frac{L}{D} = \frac{0.488}{0.0251} = 19.44$$

At  $\alpha=1^\circ$ ,  $\eta = 0.434$  and  $\theta = 0.016$

$$\frac{L}{D} = \frac{0.434 \cos 1^\circ - 0.016 \sin 1^\circ}{0.434 \sin 1^\circ + 0.016 \cos 1^\circ}$$

$$\frac{L}{D} = \frac{0.4339 - 2.792 \times 10^{-4}}{7.574 \times 10^{-3} + 0.01599} = \frac{0.4336}{0.023356} = 18.56$$

$\underline{At\alpha=4^\circ}$ ,  $\eta = 0.6$  and  $\theta = 0.007$

$$\frac{L}{D} = \frac{0.6 \cos 4^\circ + 0.007 \sin 4^\circ}{0.6 \sin 4^\circ + 0.007 \cos 4^\circ} = \frac{0.5985 + 4.883 \times 10^{-4}}{0.04185 - 6.9829 \times 10^{-3}}$$

$$\frac{L}{D} = \frac{0.59899}{0.03487} = 17.18$$

So we have the following tabulation:

<u><math>\alpha</math>-degrees</u>	<u>L/D</u>
1°	18.56
2°	19.44
3°	19.08
4°	17.18

The Wright brothers chose a three-degree angle of attack for their design point because, from the Lilienthal Table, it corresponded very nearly to the maximum, L/D.