comparison more convenient. Recall that each horse power (hp) is equivalent to 550 lb.ft/sec. An example application is presented in Section 4.4.

If instead of the maximum speed, the cruising speed is given as a design requirement, assume that the maximum speed is about 20 to 30 percent greater than cruise speed.

$$V_{\max} = 1.2V_C \quad to \quad 1.3V_C \tag{4.58}$$

This is due to the fact that cruise speeds for prop-driven aircraft are usually calculated at 75 to 80 percent power.

4.3.3.2. Aircraft C_{Do} Estimation

An important aircraft parameter that must be known and is necessary in constructing the matching plot is the aircraft zero-lift drag coefficient (C_{Do}). Although the aircraft is not aerodynamically designed yet at this phase of design, but there is a reliable way to estimate this parameter. The technique is primarily based on a statistics. However, in most references; such as Ref. 1; the aircraft C_{Do} is not given, but it can be readily determined based on aircraft performance which is often given.

Consider a jet aircraft that is flying with its maximum speed at a specified altitude. The governing trim equations are introduced in Section 4.3.3.1 and the relationships are expanded until we obtained the following equation:

$$\left(\frac{T_{SL}}{W}\right) = \rho_o V_{\max}^2 C_{D_o} \frac{1}{2\left(\frac{W}{S}\right)} + \frac{2K}{\rho \sigma V_{\max}^2}\left(\frac{W}{S}\right) \tag{4.47}$$

The aircraft C_{Do} can be obtained from this equation as follows:

$$\left(\frac{T_{SL}}{W}\right) - \frac{2KW}{\rho\sigma V_{\max}^2 S} = \rho_o V_{\max}^2 C_{D_o} \frac{S}{2W} \Rightarrow C_{D_o} = \frac{\frac{T_{SL}}{W} - \frac{2KW}{\rho\sigma V_{\max}^2 S}}{\rho_o V_{\max}^2 \frac{S}{2W}} \tag{4.59}$$

or

$$C_{D_o} = \frac{2T_{SL_{\max}} - \frac{4KW^2}{\rho\sigma V_{\max}^2 S}}{\rho_o V_{\max}^2 S} \tag{4.60}$$

If the aircraft is prop-driven, the engine thrust is a function of engine power, airspeed, and propeller efficiency (η_P), so:

$$T_{max} = \frac{P_{max} \cdot \eta_P}{V_{max}} \tag{4.61}$$

where prop efficiency is about 0.7 to 0.85 when an aircraft is cruising with its maximum speed.

No	Aircraft type	C_{Do}
1	Jet transport	0.015 − 0.02
2	Turboprop transport	0.018 − 0.024
3	Twin-engine piton prop	0.022 − 0.028
4	Small GA with retractable landing gear	0.02 − 0.03
5	Small GA with fixed landing gear	0.025 − 0.04
6	Agricultural	0.04 − 0.07
7	Sailplane/Glider	0.012 − 0.015
8	Supersonic fighter	0.018 − 0.035
9	Homebuilt	0.025 − 0.04
10	Microlight	0.02 − 0.035

Table 4.12. Typical values of C_{Do} for different types of aircraft

The equation 4.61 can be substituted into the equation 4.60:

$$C_{D_o} = \frac{2\frac{P_{SL_{max}} \cdot \eta_P}{V_{max}} - \frac{4KW^2}{\rho\sigma V_{max}^2 S}}{\rho_o V_{max}^2 S} \tag{4.62}$$

The equations 4.60 and 4.62 are employed to determine the aircraft C_{Do} for jet and prop-driven aircraft respectively. In these equations, $T_{SL_{max}}$ is the maximum engine thrust at sea level, and $P_{SL_{max}}$ is the maximum engine power at sea level, ρ is the air density at flight altitude, and σ is the relative air density at flight altitude. Make sure to use a consistent unit for all parameters (either in metric unit or British unit).

In order to estimate the C_{Do} for the aircraft which is under preliminary design, calculate the C_{Do} of several aircraft which have similar performance characteristics and similar configuration. Then fine the average C_{Do} of those aircraft. If you have selected five similar aircraft, then the C_{Do} of the aircraft under preliminary design is determined as follows:

$$C_{D_o} = \frac{C_{D_{o1}} + C_{D_{o2}} + C_{D_{o3}} + C_{D_{o4}} + C_{D_{o5}}}{5} \tag{4.63}$$

where $C_{D_{oi}}$ is the C_{Do} of ith aircraft. Table 4.12 presents typical values of C_{Do} for different types of aircraft. References 5 and 8 present details of the technique to calculate complete C_{Do} of an aircraft.

Example 4.1. C_{Do} Calculation

Determine the zero-lift drag coefficient (C_{Do}) of the fighter aircraft F/A-18 Hornet which is flying with a maximum speed of Mach 1.8 at 30,000 ft. This fighter has the following characteristics:

T_{SLmax} = 2 × 71,170 N, m_{TO} = 16,651 kg, S = 37.16 m^2, AR = 3.5, e = 0.7

Solution:

We need to first find out maximum speed in terms of m/sec. The air density at 30,000 ft is 0.000892 slug/ft^3 or 0.46 kg/m^3, and the air temperature is 229 K. From Physics, we know that speed of sound in a function of air temperature. Thus:

$$a = \sqrt{\gamma R T} = \sqrt{1.4 \times 287 \times 229} = 303.3 \ \frac{m}{\sec} \tag{4.64}$$

From Aerodynamics, we know that Mach number is the ratio between airspeed to the speed of sound. Hence, the aircraft maximum speed is:

$$M = \frac{V}{a} \Rightarrow V_{maax} = M_{\max} \cdot a = 1.8 \times 303.3 = 546 \ \frac{m}{\sec} \tag{4.65}$$

The maximum engine thrust at 30,000 ft is:

$$K = \frac{1}{\pi \cdot e \cdot AR} = \frac{1}{3.14 \times 0.7 \times 3.5} \Rightarrow K = 0.13 \tag{4.41}$$

Then:

$$C_{D_o} = \frac{2T_{SL_{\max}} - \frac{4KW^2}{\rho\sigma V_{\max}^2 S}}{\rho_o V_{\max}^2 S} = \frac{2 \times 2 \times 71{,}170 - \frac{4 \times 0.13 \times (16{,}651 \times 9.81)}{0.46 \times \left(\frac{0.46}{1.225}\right) \times (546)^2 \times (37.16^2)}}{1.225 \times (546)^2 \times (37.16^2)} = 0.02 \tag{4.60}$$

Thus, the zero-lift drag coefficient (C_{Do}) of the fighter aircraft F/A-18 Hornet at 30,000 ft is 0.02.

Example 4.2. C_{Do} Estimation

You are a member of a team that is designing a transport aircraft which is required to carry 45 passengers with the following performance features:

1. Max speed: at least 300 knots at sea level
2. Max range: at least 1,500 km
3. Max rate of climb: at least 2,500 fpm

4. Absolute ceiling: at least 28,000 ft
5. Take-off run: less than 4,000 ft

In the preliminary design phase, you are required to estimate the zero-lift drag coefficient (C_{Do}) of such aircraft. Identify five current similar aircraft and based on their statistics, estimate the C_{Do} of the aircraft being designed.

Solution:

Ref. 1 is a reliable source to look for similar aircraft in terms of performance characteristics. Shown below is Table 4.13 illustrating five aircraft with similar performance requirements as the aircraft that is being designed. There are 3 turboprops and 2 jets, so either engine configuration may be satisfactory. All of them are twin engines, and have retractable gear. There are no mid-wing aircraft listed here. The wing areas are very similar, ranging from 450 ft^2 - 605 ft^2. Except for the Bombardier Challenger 604 which can carry 19 passengers (the minimum requirement for the aircraft being designed) the other four listed aircraft can accommodate approximately 50 passengers. The weights of the aircraft vary, with the Challenger 800 weighing the most. The power of the prop-driven aircraft are all around 2000 hp/engine, and then thrust for the jet aircraft is around 8000 lb/engine.

In order to calculate the C_{Do} of each aircraft, equation 4.60 is employed for the jet aircraft and equation 4.62 is used for the prop-driven aircraft.

No	Name	Pax	V_{max} (knot)	Range (km)	ROC (fpm)	S_{TO} (ft)	Ceiling (ft)
1	DHC-8 Dash 8-300B	50	287	1,711	1,800	3,600	25,000
2	Antonov 140	46	310 @ 23,620 ft	1,721	1,345	2,890	25,000
3	Embraer 145MP	50	410@ 37,000 ft	3,000	1,750	6,465	37,000
4	Bombardier Challenger 604	19	471 @ 17,000 ft	4,274	3,395	2,910	41,000
5	Saab 340	35	280 @ 20,000 ft	1,750	2,000	4,325	25,000

Table 4.13. Characteristics of five aircraft with similar performance

$$C_{D_o} = \frac{2T_{SL_{max}} - \dfrac{4KW^2}{\rho\sigma V_{max}^2 S}}{\rho_o V_{max}^2 S} \tag{4.60}$$

$$C_{D_o} = \frac{2\dfrac{P_{SL_{max}} \cdot \eta_P}{V_{max}} - \dfrac{4KW^2}{\rho\sigma V_{max}^2 S}}{\rho_o V_{max}^2 S} \tag{4.62}$$

The Oswald span efficiency factor was assumed to be 0.85, and the prop efficiencies for the propeller aircraft were assumed to be 0.82. Example 4.1 shows the application of the equation

4.60 for a jet aircraft, the following is the application of equation 4.62 for Saab 340, a turboprop-driven airliner. The cruise altitude for Saab 340 is 20,000 ft, so the air density at 20,000 ft is 0.001267 slug/ft^3 and the relative air density at 20,000 ft is 0.533.

No	Aircraft	Type	W_o (lb)	P (hp)/T (lb)	S (ft^2)	AR	C_{Do}
1	DHC-8 Dash 8-300B	Twin-turboprop	41,100	2×2500 hp	605	13.4	0.02
2	Antonov An-140	Twin-turboprop	42,220	2×2,466 hp	549	11.5	0.016
3	Embraer EMB-145	Regional jet	42,328	2×7040 lb	551	7.9	0.034
4	Bombardier Challenger 604	Business jet	47,600	2×9,220 lb	520	8	0.042
5	Saab 340	Twin-turboprop	29,000	2×1750 hp	450	11	0.021

Table 4.14. C_{Do} of five similar aircraft

$$K = \frac{1}{\pi \cdot e \cdot AR} = \frac{1}{3.14 \times 0.85 \times 11} = 0.034 \tag{4.41}$$

$$C_{D_o} = \frac{2\frac{2 \times 1750 \times 550 \times 0.82}{280 \times 1.688} - \frac{4 \times 0.034 \times (29{,}000)^2}{0.001267 \times 0.533 \times (280 \times 1.688)^2 \times 450}}{0.002378 \times (280 \times 1.688)^2 \times 450} \Rightarrow C_{D_o} = 0.021 \tag{4.62}$$

where 1 knot is equivalent to 1.688 ft/sec and 1 hp is equivalent with 550 lb.ft/sec.

The aircraft geometries, engine powers, and C_{Do} and also the results of the calculation are shown in Table 4.14. The zero lift drag coefficient for two turboprop aircraft is very similar, 0.02 or 0.021 and one is only 0.016. This coefficient for jet aircraft is higher, 0.034 and 0.042. It seems these three numbers (0.016, 0.034, and 0.042) are unrealistic; therefore, some of the published data are not reliable. The estimation of C_{Do} of the aircraft being design is determined by taking the average of five C_{Do}.

$$C_{D_o} = \frac{C_{D_{o1}} + C_{D_{o2}} + C_{D_{o3}} + C_{D_{o4}} + C_{D_{o5}}}{5} = \frac{0.02 + 0.016 + 0.034 + 0.042 + 0.021}{5} \tag{4.63}$$

$$\Rightarrow C_{D_o} = 0.027$$

Therefore, the C_{Do} for the aircraft under preliminary design will be assumed to be 0.027.

4.3.4. Take-Off Run

The take-off run (S_{TO}) is another significant factor in aircraft performance and will be employed in constructing matching chart to determine wing area and engine thrust (or power). The take-off requirements are frequently spelled out in terms of minimum ground run requirements, since