Schaufele Annotations

Chapter 8 Engine Sizing and Arrangement

In conceptual design analysis, it is important to think (and analyze) in terms of T/W and W/S, rather than thrust and wing area. All aircraft with a similar design requirement will have similar values of T/W and W/S, so it becomes very easy to perform a quick sanity check as to the validity of any analysis.

Engine Size for Takeoff Field Length

The procedure in this section is to find the required engine size to meet a given takeoff field length (TOFL) requirement. Often this will be defined in terms of $(T/W)_{ref} = T_{static}/W$, where T_{static} is installed sea level static (SLS) thrust with all engines operating, and W is TOGW. From Schaufele Figure 8-4, for a given TOFL the required Takeoff Parameter (TOP) can be determined.

The Takeoff Parameter in this figure is defined as:

$$TOP = \frac{W^2}{\sigma S\, T\, C_{L_{max_{TO}}}}$$

where T is thrust at $0.7\ V_{TO}$.

Rearrange this equation as

$$\left(\frac{T}{W}\right)_{0.7\,V_{TO}} = \frac{W}{S}\,\frac{1}{TOP\ \sigma\ C_{L_{max_{TO}}}}$$

You can solve this equation for known values of TOP (determined from the figure), $\frac{W}{S}$, σ and $C_{L_{max_{TO}}}$.

In this exercise, obtain W from Chapter 3, S from Chapter 4,
$C_{L_{max_{TO}}}$ from Fig 4-4 and σ from the required conditions.

However, reference thrust is for installed SLS conditions, so a correction is required.

Find $\frac{T_{0.7\,V_{TO}}}{T_{static}}$ for a given bypass ratio using Fig 8-5

$$C_{L_{max_{TO}}} = \frac{L}{\frac{1}{2}\rho V_{stall_{TO}}^2 S}$$

so $$V_{stall_{TO}} = \sqrt{\frac{2}{\rho C_{L_{max_{TO}}}}\frac{W}{S}}$$

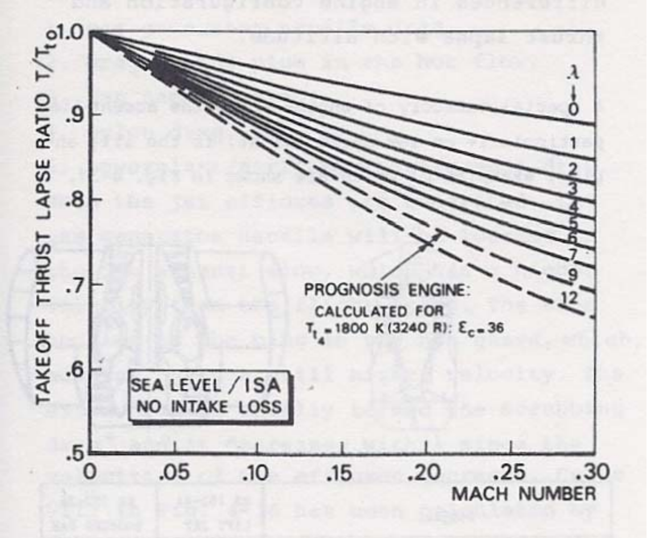
Now $$V_{TO} = 1.2\ V_{stall_{TO}} = 1.2\sqrt{\frac{2}{\rho C_{L_{max_{TO}}}}\frac{W}{S}}$$

so $$0.7\ V_{TO} = 0.84\sqrt{\frac{2}{\rho C_{L_{max_{TO}}}}\frac{W}{S}}$$

The speed of sound can be found from Figure 1-9 and hence the appropriate value of M to enter Fig 8-5 from which you can find $\frac{T_{0.7\,V_{TO}}}{T_{static}}$

Then $$\left(\frac{T}{W}\right)_{ref} = \left(\frac{T}{W}\right)_{0.7\,V_{TO}}\frac{T_{static}}{T_{0.7\,V_{TO}}}$$

Schaufele Fig 8-6 shows that when the Mach number is zero the value of Thrust/T_{static} is about 97%. That suggests that the static thrust as defined in this figure is the uninstalled static thrust. The value of reference thrust in all calculations in this book is installed static thrust. All curves in the figure should have a value of 1.0 when the Mach number is zero. Figure 8.1 is a better representation of thrust as a function of Mach number and bypass ratio (λ in this figure) for which the reference thrust is the installed static thrust. Fortunately for a BPR = 6 and M = 0.2 (which is a typical value for 0.7 V_{TO}) Schaufele Fig. 8-5 and the figure below match reasonably closely.



Source: Torenbeek

Figure 8.1 Takeoff Thrust Ratio

Engine Size for Operational Rate of Climb

Schaufele assumes that at the top of climb the aircraft is flying at its cruise speed, and cruise L/D. In equations (8-6) and (8-10), use the cruise L/D that you have estimated (using Fig. 3-8, 3-9 or other method). It must be assumed that values of cruise L/D in Fig. 3-8 and 3-9 are at $(M*L/D)_{max}$ in which case you can use these values directly. If you have a drag polar, you can find the value of $(L/D)_{max}$ and assume that:

$$\left(\frac{L}{D}\right)_{cruise} = 0.866\left(\frac{L}{D}\right)_{max}$$

Equation (8-6) may be written as

$$\left(\frac{T}{W}\right)_{max\,climb} = \frac{R/C_{MIN\ REQ'D}}{V \times K.E.\ Factor} + \frac{1}{\left(\frac{L}{D}\right)_{cruise}}$$

As stated in the text, the value of $R/C_{MIN\ REQ'D}$ is usually 300 ft/min (or 50 ft/sec), V is the cruise speed in ft/sec and the appropriate K.E. Factor is obtained from Fig. 8-6. Note that the K.E. Factor for climb at constant Mach number applies only below 36,089 ft. Above that altitude the speed of sound is constant with altitude, and the K.E. Factor is unity. As stated on page 189, for conservatism the weight at top of climb is taken as the TOGW.

As in the previous section, the value of $(T/W)_{\text{max climb}}$ must be converted to the sea level static thrust condition. This is done in a two-step procedure. First, find the value of $(T_{\text{max climb}}/T_{\text{max cruise}})$ from Schaufele Fig 8-8, then find the value of $(T_{\text{max cruise}}/T_{SLST})$ from Figs. 8-9 to 8-11. Modifying Schaufele Eq. (8-7), we can write:

$$\left(\frac{T}{W}\right)_{ref} = \left(\frac{T}{W}\right)_{maxclimb} \text{x} \frac{T_{maxcruise}}{T_{maxclimb}} \text{x} \frac{T_{SLST}}{T_{maxcruise}} = \left(\frac{T}{W}\right)_{maxclimb} \text{x} \frac{1}{\left(T_{maxclimb}/T_{maxcruise}\right)} \text{x} \frac{1}{\left(T_{maxcruise}/T_{SLST}\right)}$$

Selection of Thrust/Weight Ratio

Select the greater of the values of thrust/weight for the three conditions:

- Takeoff Field Length
- Operational Rate of Climb
- Initial Cruise

Typical values of $(T/W)_{SLS}$ are

- Four engines: 0.20 - 0.28
- Three engines: 0.24 - 0.32
- Twin engines: 0.28 - 0.40 (lower value for large twins, higher value for bizjets)

If the thrust requirement is determined by the TOFL, then a shorter TOFL will require a higher $(T/W)_{SLS}$, and vice versa. A twin engine transport with a long TOFL may have lower $(T/W)_{SLS}$ than described above (such as the B.787). Other exceptions may occur if the engine is flat-rated (i.e., thrust limited) at the static condition.

Thrust is the thrust of all engines at sea level static condition, installed, and weight is the maximum takeoff gross weight. There are also exceptions to this rule: some Boeing programs have used the reference thrust at 0.7 V_{TO}, as is used in Fig. 8-4. The definition of TOGW is usually ramp weight, but may be at brake release. The difference is small, but some fuel is consumed between the ramp and the start of takeoff roll.

Engine Placement

Smaller transport airplanes (below about 150 passengers) may operate into airports without an enclosed jetway (or at least these gates are reserved for larger aircraft), so there is a requirement for airstairs (passenger boarding stairs carried by the aircraft). Engines are usually mounted on the aft fuselage and the shorter landing gear results in airstairs of a manageable length. Increased structural weight due to loss of wing root bending relief has to be accepted. Business jets have a similar requirement, and almost all (except for the Honda Jet) have engines mounted on the rear fuselage.

Transport airplanes above 150 passengers almost always operate into gates with jetways, and engines are mounted on the wing.

Advantages and disadvantages of rear-fuselage-mounted engines may be summarized as follows:

Advantages:

- Shorter (and thus lighter) landing gear which takes up less space in the fuselage.
- Passenger door is closer to the ground. Can use airstairs.
- Easier loading of cargo.
- Easier service of galleys and lavatories.
- Quieter forward (i.e., first class) cabin.
- Smaller engine-out yawing moments (but this benefit is offset by reduced moment arm of vertical stabilizer).
- Clean wing with continuous trailing edge flaps and slats, resulting in higher $C_{L_{max}}$ on approach.
- Slightly reduced probability of foreign object ingestion because inlet is further from the ground.

Disadvantages:

- More difficult to balance the airplane. C.g. moves forward as passengers and cargo are loaded.
- Heavier wing structure. No wing root bending relief.
- Heavier fuselage. Additional bending moment on fuselage forward and aft of the wing intersection.
- Must use T-tail (or cruciform tail). Heavier vertical stabilizer and unfavorable longitudinal stability characteristics.
- Increased probability of structural damage from uncontained engine failure.