5.4 Selection of Thrust to Weight and Wing Loading

Chapter 5 contains enough information to make a pretty good first estimate of the required values of *T/W* and *W/S*. Construction of a performance constraint plot is described in more detail in Chapter 19 (see for example Figs. 19.3 and 19.4), and much of the rest of Raymer's book is a refinement of the material in this chapter and in Chapter 6.

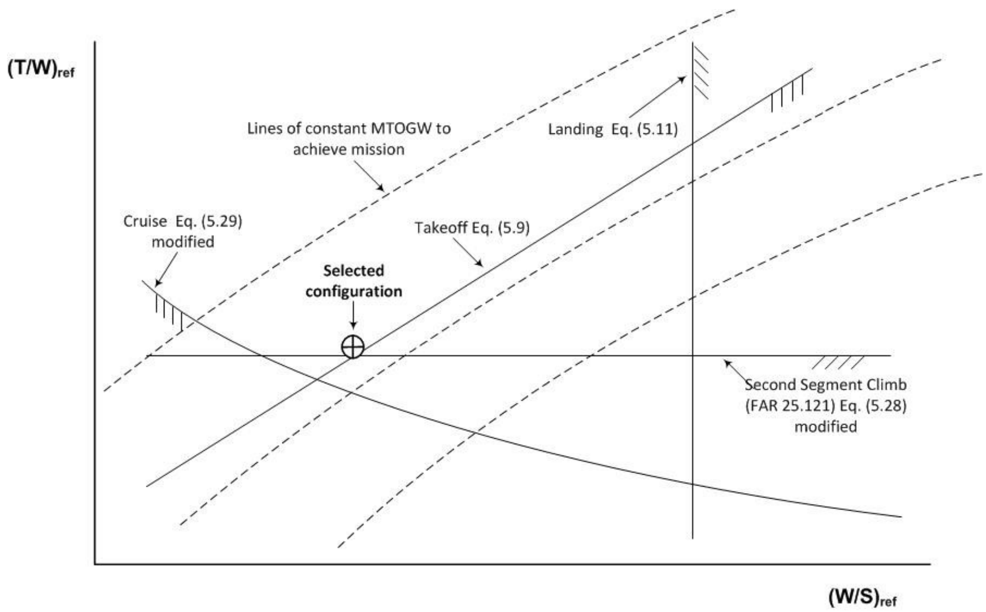

Figure 5.4.1 Performance Constraint Plot for Commercial Aircraft

The performance constraint plot is the single most important tool for the manual optimization and sensitivity analysis of a configuration, and it is widely used in the aerospace industry. It is also useful for students in understanding the effect of the various performance constraints on the design of an aircraft.

Figure 5.4.1 shows a performance constraint plot for a commercial aircraft. The axes are reference values of Thrust/Weight (*T/W*) and Wing Loading (*W/S*). What constitutes "reference" may vary slightly from company to company and even within a company for certain projects, but the usual reference values are:

- Thrust (*T*) – Standard day, sea level, static (i.e., the airplane is stationary) installed thrust at maximum takeoff rating with all engines operating
- Weight (*W*) – Maximum design takeoff gross weight at brake release
- Wing Area (*S*) – Reference trapezoidal wing area.

Boeing may use the engine thrust at 0.7 V_{LO} (where V_{LO} is liftoff speed); this thrust value is more representative of average takeoff thrust. Boeing also uses 'Wimpress area' to define the reference wing area; this area includes partial area of the 'yehudi'(in Boeing parlance), or 'batt' (in Lockheed parlance), plus additional leading edge area. Airbus uses a different definition from either Boeing or Lockheed. The batt adds wing area to the trailing edge for a variety of reasons, including accommodation for the main landing gear and flaps.

Many performance constraints are for flight conditions for which the engine thrust and airplane weight are very different from the reference values, so the values of *T/W* and *W/S* must be factored by the appropriate ratio of the thrust or weight at that flight condition to the reference thrust or weight.

For example, to plot the required reference values of *T/W* as a function of *W/S* in a sustained turn (Raymer Eq. (5.24)), the value of $(W/S)_{ref}$ must first be converted into the value of *W/S* at that flight condition:

$$\left(\frac{W}{S}\right) = \left(\frac{W}{S}\right)_{ref}\left(\frac{W}{W_{ref}}\right) \tag{5.4.1}$$

The value of *T/W* at that flight condition can then be calculated. Finally, the value of *T/W* must be converted into the value of $(T/W)_{ref}$:

$$\left(\frac{T}{W}\right)_{ref} = \left(\frac{T}{W}\right)\left(\frac{T_{ref}}{T}\right)\left(\frac{W}{W_{ref}}\right) \tag{5.4.2}$$

These corrections must be performed for all performance constraint plots. In technical reports, the "ref" subscript is often omitted in figures, but implied. This sometimes results in these important corrections being forgotten.

The solid lines in the figure represent performance constraints. These may be either requirements that are set by the specification, in which case they may not be absolutely hard and fast (in which case they may be called 'desirements'), or set by FARs, or other fixed requirements.

The dashed lines represent contours of equal takeoff gross weight required to perform the specified mission. These contours are generated completely independently of the constraint lines, and their method of generation is described in Raymer Section 19.4.

To meet takeoff requirements, you can either select small engines and a big wing (bottom left quadrant of the graph) so that the airplane accelerates slowly and lifts off at a very low speed, or big engines and small wing (top right quadrant of the graph) so that the airplane accelerates fast and lifts off at a high speed, so the takeoff field length line goes from bottom left to top right.

For commercial airplanes, the constraint for start of cruise (or top of climb) is a U-shape curve that has a minimum value of *T/W* at a value of *W/S* that is normally outside the area of interest on the figure. The annotation for Section 5.3.11 describes a modification of Eq. (5.29) that will enable you to plot constraint lines for cruise (as shown here) or climb at a specified dynamic pressure, q. The FAR 2^{nd} segment climb constraint is a special case in which the climb speed varies with wing loading, resulting in a constraint that is a function of *T/W* only. This is described in the annotations to Section 17.3, but the result is similar in principle to the subsection titled 'Minimum Value of T/W' in Section 5.3.11.

The equations referenced in Fig 5.4.1 must be rearranged to the form $(T/W)_{ref} = f\,(W/S)_{\rm ref}$ so that they can be plotted using Excel or Matlab.

Raymer defines the wing loading for maximum range in Eq. 5.14. This is not a constraint because other wing loadings will also work, but at a higher takeoff gross weight to meet a given range. For most subsonic commercial aircraft this wing loading is higher than that imposed by other constraints, such as the takeoff or landing constraint.

In many cases the contours of constant TOGW to perform the mission are roughly parallel to the takeoff field length constraint. In this case there is some flexibility as to whether to choose smaller engines and bigger wing, or bigger engines and smaller wing. It's always better to choose a smaller engines and bigger wing, if such a choice is available, and the selected configuration is identified in Fig. 5.4.1. If the engine manufacturer offers an engine with a higher rated thrust at some time in the future, then the designer can increase the takeoff gross weight of the airplane and still meet all the performance constraints. If the wing is sized for the landing constraint, then the designer is stuck, and the only way to increase the takeoff gross weight is to either increase the wing area or redesign the high-lift system in order to meet the landing constraint.

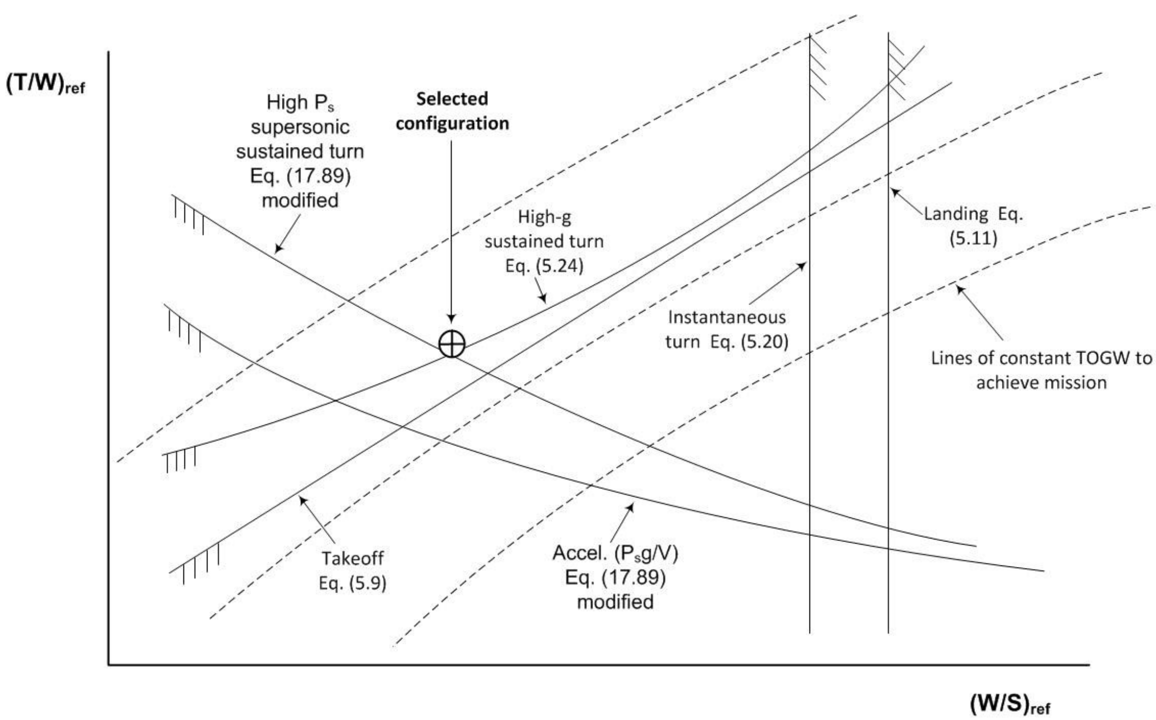

Fig. 5.4.3 Performance Constraint Plot for Combat Aircraft

For a combat aircraft there are usually many performance requirements associated with aerial maneuvering, as illustrated in Fig. 5.4.3. Some of these requirements, such as for a defined specific excess power (P_s) at certain maneuver conditions, are not addressed until

Raymer Chapter 17, so it is more difficult to estimate the required values of *T/W* and *W/S* at this point in the design process. Nearly all the aerial maneuver requirements are defined by one equation, as described in the annotation to Section 17.6.

Note that constraints involving P_s, which imply climb or acceleration capability, usually have a minimum *T/W* at a high value of *W/S*, whereas a high-*g* turn has a minimum *T/W* at a low value of *W/S*. A large wing is not required for climb or acceleration, but a large wing is required for high-*g* turn. A more detailed explanation of these requirements is given in the annotation to Section 17.6.

References

5.4.1 Schaufele, R.D., "The Elements of Aircraft Preliminary Design", Aries Publications, 2007.