3.6.4 Takeoff-Weight Sizing

In the early stages of conceptual design, it's worthwhile to have a healthy skepticism for the accuracy of your own numbers. The straight lines of Figure 3.1 might lull you into the belief that there is an exact relationship between aircraft empty weight and takeoff weight. The lines are based on a statistical analysis of data for existing aircraft, and in reality there is a fairly wide dispersion of empty weights, so it's unfortunate that the actual data points are not shown on the figure. In Roskam Part 1 (Ref. 3.6.4.1), Figures 2.3 - 2.14, the data points are shown, and looking at the trends for military patrol, bombers and transport airplanes, it appears that there is a dispersion in empty weights of about 2,500 lb for a airplane in the W_0 ~ 50,000 lb class. Data points are also shown in Schaufele (Ref 3.6.4.2) Figures 3-19 - 3-24. Weight growth factors are discussed below, and Raymer shows in Section 3.6 that the weight growth factor for the example ASW aircraft is about 2. That means that an increase in 2,500 lb in empty weight would result in an increase in 5,000 lb in takeoff gross weight. In the calculations in Box 3.1, there is therefore nothing to be gained in performing the W_0 iteration when the guessed and calculated weights agree to within 5,000 lb, or if we are really confident about the accuracy of the empty weight values, to within about 2,500 lb. The last two iterations at the bottom of the box are therefore superfluous. More importantly, calculating the value of W_0 to the nearest 2 lb might make you believe that the result is accurate to within 2 lb. Sadly, it isn't. The same can be said for the iterations in the following examples in this Chapter.

As described in the Annotation to Section 3.3 Empty Weight Estimation, if the relationship between empty weight, W_e, and takeoff gross weight, W_0, is assumed to be linear and in the form

$$W_e = K + G W_0 \tag{3.6.4.1}$$

(K is not the same as the induced drag factor) then a non-iterative approach can be derived using the procedure from Gundlach (Ref. 3.6.4.3), starting from Raymer Eq. (3.2). This works well over a fairly wide band of takeoff gross weights:

$$W_0 = W_c + W_p + \left(\frac{W_f}{W_0}\right) W_0 + \left(\frac{W_e}{W_0}\right) W_0$$

$$W_0 = W_c + W_p + \left(\frac{W_f}{W_0}\right) W_0 + \left(\frac{K}{W_0} + G\right) W_0$$

Divide by W_0

$$1 = \frac{W_c + W_p}{W_0} + \frac{W_f}{W_0} + \frac{K}{W_0} + G$$

Collect terms

$$\left(1 - \frac{W_f}{W_0} - G\right) = \frac{K + W_c + W_p}{W_0}$$

$$W_0 = \frac{K + W_p + W_c}{1 - \frac{W_f}{W_0} - G} \qquad (3.6.4.2)$$

W_p = payload
W_c = crew weight
W_f/W_0 = fuel fraction, which is constant for a given mission

For example, the equation for military cargo/bombers in exponential form in Raymer Table 3.2 can be approximated in a linear form with a constant K = 1800 lb, and gradient G = 0.4. In the Raymer example in Box 3.1 ASW Sizing Calculations

W_p = 10,000 lb
W_c = 800 lb
W_f/W_0 = 0.3773

This gives the result W_0 = 56,578 lb, which matches the iterative solution very closely. It might well be asked why this method isn't used instead of the iterative method. The answer is that the linear relationship of empty weight to TOGW doesn't match the exponential relationship quite as well if the TOGW is below 30,000 lb. For other classes of aircraft it can be seen the linear relationship does not fit the empty weight data points outside the takeoff gross weight range of interest. At the same time, it can be questioned how well the exponential form of the relationship matches real-world data.

References

3.6.4.1 Roskam, J., "Airplane Design, Part 1 Preliminary Sizing of Airplane", Roskam Aviation and Engineering Corp., 1985

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

3.6.4.3 Gundlach, J., "Designing Unmanned Aircraft Systems", AIAA, 2012