3.6 Design Example: ASW Aircraft

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 Vol 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. 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.

Trade Studies

In the conceptual or preliminary design phases of an aircraft, a fixed weight added to the airplane does not simply add the same value of the weight to the maximum takeoff gross weight (MTOGW) in order to achieve the same payload and range. The whole aircraft (wing, landing gear, empennage, etc.) must increase in size and weight. The ratio of the increase in MTOGW to the unit increase in fixed weight is the aircraft weight growth factor, and depends on the mission flown.

In this section Raymer determines the growth factor iteratively, but it can also be done without iteration, as the following example shows for a commercial aircraft.

For commercial aircraft MTOGW can be broken down into five categories:

$$W_{E_{Variable}} = Empty\ weight\ proportional\ to\ MTOGW\left(eg,\ landing\ gear,\ wing,\ etc\right)$$
$$W_{E_{Payload}} = Empty\ weight\ proportional\ to\ payload\ \left(eg,\ cabin\ crew,\ seats,\ toilets\right)$$
$$W_{E_{Fixed}} = Fixed\ weight\ \left(Flight\ deck\ crew,\ flight\ deck,\ avionics\right)$$
$$W_{Payload} = Payload\ weight$$
$$W_{Fuel} = Fuel\ weight$$

E.g. for a Boeing 707-320B (weights are in lb and are approximate)

$$\begin{aligned} W_{TO} &= W_{E_{Variable}} + W_{E_{Payload}} + W_{E_{Fixed}} + W_{Payload} + W_{Fuel} \\ &= 98K + 7K + 43K + 35K + 153K \\ &= 336K \end{aligned} \quad (3.6.1)$$

From the Breguet range equation we know that for a constant range

$$\ln\left(\frac{W_{TO}}{W_{LDG}}\right) = constant \quad \text{so} \quad \frac{W_{TO}}{W_{LDG}} = constant \quad (3.6.2)$$

$$\text{So} \quad \left(\frac{W_{TO}}{W_{TO} - W_{Fuel}}\right) = \left(\frac{1}{1 - \frac{W_{Fuel}}{W_{TO}}}\right) = constant \quad (3.6.3)$$

$$\text{So} \quad \frac{W_{Fuel}}{W_{TO}} = constant \quad (3.6.4)$$

If we designate the original MTOGW with the suffix 1 and the MTOGW of the configuration with the extra weight, W_x, with the suffix 2, then

$$W_{TO_!} = W_{E_{Variable}} + W_{E_{Payload}} + W_{E_{Fixed}} + W_{Payload} + W_{Fuel} \quad (3.6.5)$$

$$W_{TO_2} = W_{E_{Variable}}\left(\frac{W_{TO_2}}{W_{TO_1}}\right) + W_{E_{Payload}} + W_{E_{Fixed}} + W_{Payload} + W_{Fuel}\left(\frac{W_{TO_2}}{W_{TO_1}}\right) + W_x \quad (3.6.6)$$

We define the total growth in MTOGW as $\Delta W_{TO} = W_{TO_2} - W_{TO_1}$ (3.6.7)

Subtracting Eq. (3.6.6) from Eq. (3.6.5) we get

$$\begin{aligned} \Delta W_{TO} &= W_{E_{Variable}}\left(\frac{W_{TO_2}}{W_{TO_1}} - 1\right) + W_{Fuel}\left(\frac{W_{TO_2}}{W_{TO_1}} - 1\right) + W_x \\ &= W_{E_{Variable}}\left(\frac{\Delta W_{TO}}{W_{TO_1}}\right) + W_{Fuel}\left(\frac{\Delta W_{TO}}{W_{TO_1}}\right) + W_x \end{aligned} \quad (3.6.8)$$

Rearranging terms we get

$$\Delta W_{TO}\left(1 - \frac{W_{E_{Variable}}}{W_{TO_1}} - \frac{W_{Fuel}}{W_{TO_1}}\right) = W_x \quad (3.6.9)$$

By definition the growth factor is

$$\frac{\Delta W_{TO}}{W_x} = \frac{1}{1 - \frac{W_{E_{Variable}}}{W_{TO_1}} - \frac{W_{Fuel}}{W_{TO_1}}} \quad (3.6.10)$$

Plugging in the numbers for the example Boeing 707 we get

$$Growth\,factor = \frac{1}{1 - \frac{98K}{336K} - \frac{153K}{336k}} = 4.0 \qquad (3.6.11)$$

Note that the smaller the fuel fraction, $\frac{W_{Fuel}}{W_{TO}}$, the smaller the growth factor. This suggests that for short range airplanes the application of advanced weight-saving technology does not offer such a large payoff as for long range airplanes.

For aircraft with very small payload and crew fractions and large fuel fractions (such as the National AeroSpace Plane), the denominator tends towards zero and the growth factor becomes very large. Very small changes in structural fraction or fuel fraction have an enormous effect on TOGW. Variables such as specific impulse (the inverse of specific fuel consumption) is almost impossible to predict at Mach numbers above 10, so it was almost impossible to estimate TOGW.