## 3.5 Takeoff-Weight Calculation

Raymer Section 3.5 describes a method for calculating the takeoff gross weight (TOGW) for an aircraft that is required to perform a given mission. It reduces to the iterative solution of Eq. (3.11), which contains both the fuel fraction required to perform the mission, and the empty weight fraction based on historical data for aircraft in that class. This method works, but it is not entirely intuitive as to what is going on.

An alternative method of calculating TOGW (as used by Nicolai) is to match the empty weight from historical data (called "empty weight required") to the empty weight after calculating the fuel required to perform the mission (as described in Raymer Section 3.4), called "empty weight available". Using Raymer Eq. 3.1, empty weight available is defined as

$$W_{empty_{available}} = W_0 - W_{fuel} - \left(W_{crew} + W_{payload}\right) \tag{3.5.1}$$

For an assumed TOGW, fuel weight ($W_{fuel}$) is calculated using Raymer Eq. (3.11), and crew and payload weights are fixed, enabling empty weight available to be calculated.

The estimate of empty weight required is based on historical data for other airplanes in that class (e.g. flying boat, jet fighter, jet trainer, etc.). The limitations of this method will become apparent shortly.

In the annotation to Section 3.3 it was shown that the empty weight can be expressed as the sum of a fixed weight that is independent of takeoff gross weight, and a variable weight that is proportional to takeoff gross weight, as shown in Fig. 3.5.1. Expressing the relationship in this format is somewhat more descriptive than Raymer's Fig. 3.1.

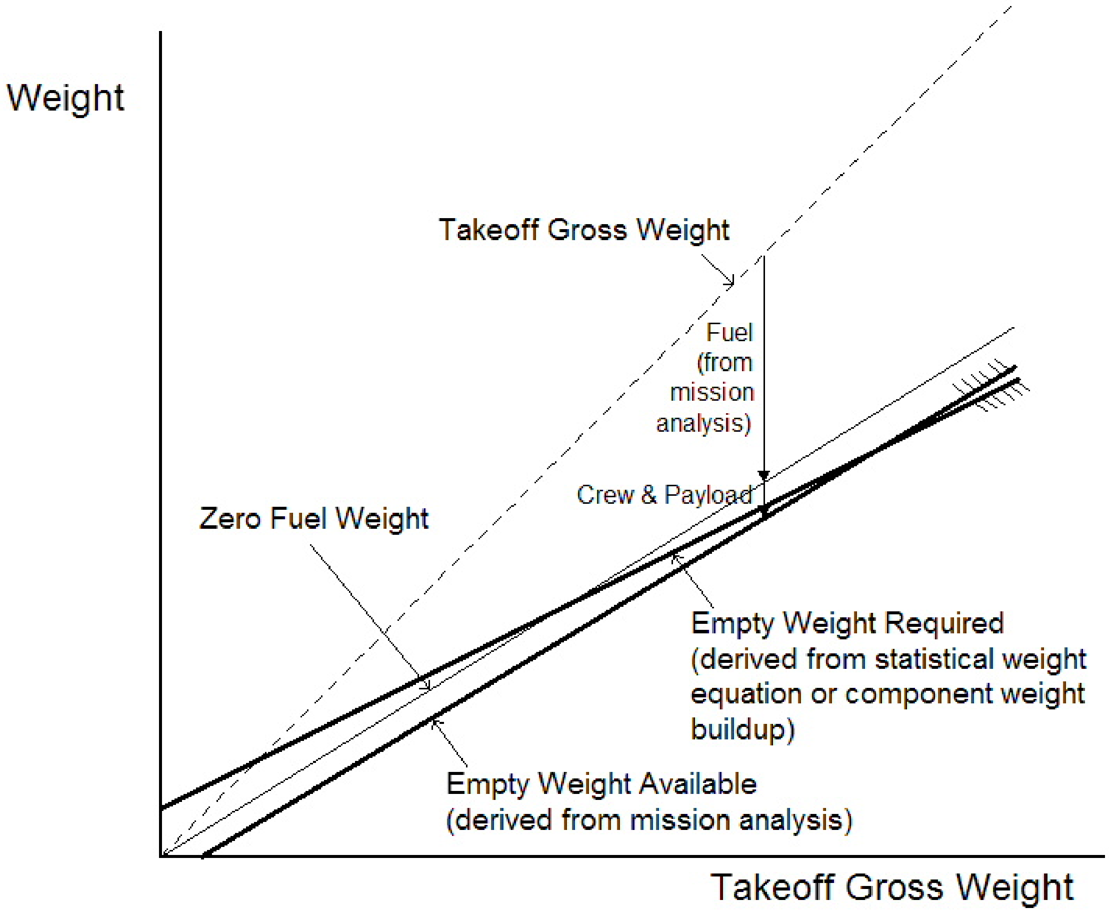

Fig 3.5.1 Matching Empty Weight Required to Empty Weight Available

Nicolai's process is also illustrated in Fig. 3.5.1. As with the method described in Raymer Section 3.5, the process requires iterating for different values of TOGW, but in this case the process continues until empty weight available (from flying the mission) matches empty weight required (based on historical data). The figure provides some useful insights into the sensitivity of TOGW to fixed weights such as crew and payload. If the crew and payload were removed (but leaving the rest of the aircraft unchanged), the aircraft would resize to the intersection of the zero fuel weight line and the empty weight required line. This reduction in TOGW is greater than the reduction in crew and payload weight by a factor as high as 4, as illustrated in an algebraic approach to weight sensitivity described in the annotation to Section 3.6. More often the sensitivity factor is somewhat less, between 2 and 3.

It should be noted that in this section crew weight is considered separately from empty weight, and this is common practice for fighters. For transport airplanes, the weight of flight deck crew and their flight bags is considered part of the empty weight, which is more properly called operating empty weight. This is the case in the annotations to Section 3.6.

You should also remember that in this initial analysis, the line for empty weight required is based on a best fit line for a set of data of empty weight versus TOGW for aircraft in the same class, and there is a fair amount of variation in these data values. Depending on your design assumptions, your aircraft may have an empty weight that is lighter (or heavier) than similar aircraft in its class. For example, if you select a higher aspect ratio than other aircraft in its class, you will show a higher value of cruise *L/D* and lower fuel fraction, but the higher aspect ratio will not be reflected in the empty weight required. You will therefore calculate a lower TOGW than the airplane should have, but this will not become apparent until you calculate empty weight using component buildup. For this reason, calculating TOGW using this method is often skipped in the conceptual design process. For a commercial airplane that replaces an older design with a similar mission, the designer may well start with that older design as a baseline. The design analyst will generate the first estimate of TOGW using a component weight buildup, using equations such as those in Raymer Chapter 15.

If the payload is small, and the portion of empty weight that is independent of TOGW is also small, then the lines for empty weight required and empty weight available will be almost parallel. Small changes in any design or engine performance assumptions can have a very large impact on TOGW. An example is the National AeroSpace Plane (NASP), a scramjet-powered vehicle designed for single stage to orbit carrying a small payload. At hypersonic speeds engine net thrust was only about 10% of gross thrust, the difference being engine ram drag. So a 1% change in nozzle efficiency made a 10% change in net thrust. The equivalent of the Breguet range equation for an accelerating vehicle (Raymer Eq. 19.8) involves a term $\frac{V}{T}(T-D)$, so that if thrust is not much greater than drag, then there is even further sensitivity of the ratio TOGW/EW (i.e., the gradient of the empty weight available line) to nozzle efficiency. Since nozzle efficiency at hypersonic speeds was not known with any level of confidence, then it was impossible to determine the TOGW within an order of magnitude.

Another insight that can be gleaned from Fig. 3.5.1 is that if the fuel consumption is very high or the mission is very long so that the gradient of the zero fuel weight line is less than the gradient of the empty weight required line, then the design weight will not converge for any value of TOGW. Early turbojets were gas-guzzlers, and commercial jets could barely make it from London to New York (2,145 nmi). Non-stop transpacific flights were impossible. With greatly improved engine fuel consumption, reduced empty weight and slightly improved L/D, aircraft can be designed for much longer routes. Qantas is seriously considering flying London to Sydney non-stop (9,188 nmi) using a Boeing 777-200LR.

If the mission is short (so that the fuel fraction is small), the empty weight available line becomes steeper so that the sensitivity of TOGW to changes in empty weight becomes less. Technology that may be justified for a long-range airplane may not be cost effective for a short-range airplane. Long-range airplanes also benefit more from eliminating every last pound of unnecessary empty weight.

The same basic procedures, as described above, are used in all mission sizing programs in industry. Weight equations, especially for wing weight, may be treated as company proprietary. Industrial-grade programs will typically have additional capabilities such as the ability to:

- define the mission in great detail, including the ability to drop weapons, or to land, offload cargo, takeoff and return to the original airfield without refueling,
- calculate *L/D* over a wide range of operating conditions,
- define weights with detailed weight equations,
- include detailed engine thrust and fuel flow data for all possible speeds and altitudes,
- calculate manufacturing and operating costs (and thus return on investment),
- calculate community noise (as defined in FAR Part 36, or other noise definitions),
- perform parametric analysis on almost design variable, and generate plots such as shown in Raymer Fig. 19.4,
- optimize the design using multi-variable optimization procedures.