In Eq. (14.63) we have found the inverse of the reduced k matrix. By substituting the actual values of the loadings P we determine the deflections as provided in Eq. (14.64). We can then use the deflections of the nodes to solve for the strain and stress, as follows:

$$\epsilon_1 = (0.093 - 0.077)/12 = 0.0013 \tag{14.65}$$

$$\epsilon_2 = (0.077 - 0)/14 = 0.0055 \tag{14.66}$$

$$\sigma_1 = 14{,}267 \text{ psi} \tag{14.67}$$

$$\sigma_2 = 58{,}850 \text{ psi} \tag{14.68}$$

This 1-D example does not illustrate the complications caused by 3-D geometry. For this simple example the deflections at the nodes produce identical changes in the length of the bars. Were the bars connected at some angle, the identical nodal deflections would produce different changes in bar lengths. Matrix direction-cosine terms must be used to keep track of these 3-D effects.

Most finite-element analyses use surface elements rather than simple bar elements. The triangle element shown in Fig. 14.45 is typical, and allows a complicated structure to be broken into numerous connected elements. These elements are assumed to be connected at the nodes (corners) where the deflections are identical.

Equations are prepared in matrix form describing how each element responds to loadings at its nodes. The element stiffness matrices are combined using appropriate direction cosine terms to account for 3-D geometry, and the combined matrix is inverted to solve for the deflections for a given loading.

For dynamic analysis, mass and damping terms are developed using matrix methods. These greatly increase the number of inputs required for the analysis.

Fortunately, working structural engineers do not need to develop their own FEM program every time they wish to analyze a structure. There are numerous "canned" FEM programs available, ranging from simple personal-computer ones to million-line programs.

The industry-standard FEM program is the "NASTRAN (NAsa STRuctural ANalysis)" program, developed years ago for NASA and continuously enhanced both by NASA and various private companies. NASTRAN handles virtually everything, but requires substantial experience to insure that the results are meaningful. However, for complex structural analysis, some variant of NASTRAN will probably be in use for many years to come.

15 WEIGHTS

15.1 INTRODUCTION

The estimation of the weight of a conceptual aircraft is a critical part of the design process. The weights engineer interfaces with all other engineering groups, and serves as the "referee" during the design evolution.

Weights analysis per se does not form part of the aerospace engineering curriculum at most universities. It requires a broad background in aerospace structures, mechanical engineering, statistics, and other engineering disciplines.

There are many levels of weights analysis. Previous chapters have presented crude statistical techniques for estimating the empty weight for a given takeoff weight. These techniques estimate the empty weight directly and are only suitable for "first-pass" analysis.

More sophisticated weights methods estimate the weight of the various components of the aircraft and then sum for the total empty weight. In this chapter, two levels of component weights analysis will be presented.

The first is a crude component buildup based upon planform areas, wetted areas, and percents of gross weight. This technique is useful for initial balance calculations and can be used to check the results of the more detailed statistical methods.

The second uses detailed statistical equations for the various components. This technique is sufficiently detailed to provide a credible estimate of the weights of the major component groups. Those weights are usually reported in groupings as defined by MIL-STD-1374, or some similar groupings defined by company practice. MIL-STD-1374 goes into exhaustive detail (taxi lights, for example!), but at the conceptual level the weights are reported via a "Summary Group Weight Statement." A typical summary format appears as Table 15.1, where the empty weight groups are further classified into three major groupings (structure, propulsion, and equipment).

The structures group consists of the load-carrying components of the aircraft. Note that it includes the inlet (air-induction-system) weight, as well as the nacelle (engine-section) weight including motor mounts and firewall provisions—despite their obvious relationship to the engine. The propulsion group contains only the engine-related equipment such as starters, exhaust, etc. The as-installed engine includes the propeller, if any.

Armament is broken down into fixed items, which are in the equipment groups, and expendable items, which are in the useful load. Sometimes a judgement call is required. For example, a gun may be considered to be fixed equipment, or it may be viewed as readily removable and unimportant to flight and therefore a part of the useful load.

The takeoff gross weight—the sum of the empty weight and the useful load—reflects the weight at takeoff for the normal design mission. The flight design gross weight represents the aircraft weight at which the structure will withstand the design load factors. Usually this is the same as the takeoff weight, but some aircraft are designed assuming that maximum loads will not be reached until the aircraft has taken off and climbed to altitude, burning off some fuel in the process.

"DCPR" stands for "Defense Contractors Planning Report." The DCPR weight is important for cost estimation, and can be viewed as the

Table 15.1 Group weight format

Group	Group
STRUCTURES GROUP	EQUIPMENT GROUP
Wing	Flight controls
Tail-horizontal/canard	APU
vertical	Instruments
ventral	Hydraulic
Body	Pneumatic
Alighting gear-main	Electrical
auxiliary	Avionics
arresting gear	Armament
catapult gear	Furnishings
Nacelle/engine section	Air conditioning/ECS
Air induction system	Anti-icing
	Photographic
	Load and handling
PROPULSION GROUP	TOTAL WEIGHT EMPTY
Engine—as installed	USEFUL LOAD GROUP
Accessory gearbox and drive	
Exhaust system	Crew
Cooling provisions	Fuel-usable
Engine controls	-trapped
Starting system	Oil
Fuel system/tanks	Passengers
	Cargo/baggage
	Guns
	Ammunition
	Pylons and racks
	Expendable weapons
	Flares/chaff
	TAKEOFF GROSS WEIGHT
	Flight design gross weight
	Landing design gross weight
	DCPR weight

weight of the parts of the aircraft that the manufacturer makes, as opposed to buys and installs. DCPR weight equals the empty weight less the weights of the wheels, brakes, tires, engines, starters, cooling fluids, fuel bladders, instruments, batteries, electrical power supplies/converters, avionics, armament, fire-control systems, air conditioning, and auxiliary power unit. DCPR weight is also referred to as "AMPR" weight (Aeronautical Manufacturers Planning Report).

In a Group Weight Statement, the distance to the weight datum (arbitrary reference point) is included, and the resulting moment is calculated. These are summed and divided by the total weight to determine the actual center-of-gravity (c.g.) location. The c.g. varies during flight as fuel is burned off and weapons expended.

To determine if the c.g. remains within the limits established by an aircraft stability and control analysis, a "c.g.-envelope" plot is prepared (Fig. 15.1).

The c.g. must remain within the specified limits as fuel is burned, and whether or not the weapons are expended. It is permissible to "sequence" the fuel tanks, selecting to burn fuel from different tanks at different times to keep the c.g. within limits. However, an automated fuel-management system must be used, and that imposes additional cost and complexity.

Note that the allowable limits on the c.g. vary with Mach number. At supersonic speeds the aerodynamic center moves rearward, so the forward-c.g. limit may have to move rearward to allow longitudinal trim at supersonic speeds. However, the aft-c.g. limit is often established by the size of the vertical tail, which loses effectiveness at supersonic speeds. This prevents moving the aft limit rearwards at supersonic speeds, forcing a very narrow band of allowable limits.

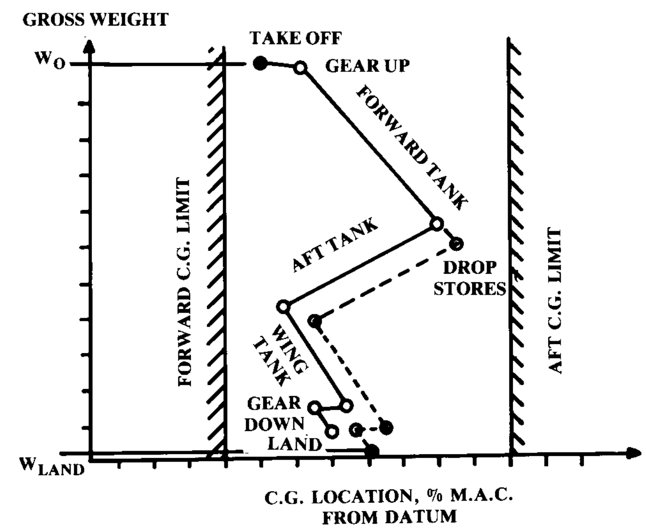

Fig. 15.1 C.G. envelope diagram.

Table 15.2 Approximate empty weight buildup

Item	Fighters	Transports and bombers	General aviation	Multiplier[a]	Approximate location
Wing	9.0	10.0	2.5	$S_{\text{exposed planform}}$ ft^2	40% MAC
Horizontal tail	4.0	5.5	2.0	$S_{\text{exposed planform}}$ ft^2	40% MAC
Vertical tail	5.3	5.5	2.0	$S_{\text{exposed planform}}$ ft^2	40% MAC
Fuselage	4.8	5.0	1.4	$S_{\text{wetted area}}$ ft^2	40–50% length
Landing gear[b]	.033 .045 Navy	.043	.057	TOGW (lb)	—
Installed engine	1.3	1.3	1.4	Engine weight (lb)	—
"All-else empty"	.17	.17	.10	TOGW (lb)	40–50% length

[a]Results are in pounds.
[b]15% to nose gear; 85% to main gear.

15.2 APPROXIMATE GROUP WEIGHTS METHOD

Early in design it is desirable to do a rough c.g. estimate. Otherwise, substantial rework may be required after the c.g. is properly estimated. A rough c.g. estimate can be done with a crude statistical approach as provided in Table 15.2.

The wing and tail weights are determined from historical values for the weight per square foot of exposed planform area. The fuselage is similarly based upon its wetted area. The landing gear is estimated as a fraction of the takeoff gross weight. The installed engine weight is a multiple of the uninstalled engine weight. Finally, a catch-all weight for the remaining items of the empty weight is estimated as a fraction of the takeoff gross weight.

This technique also applies the approximate locations of the component c.g. as given in Table 15.2. The resulting c.g. estimate can then be compared to the desired c.g. location with respect to the wing aerodynamic center. Also, these approximate component weights can be used as a check of the more detailed statistical equations provided below.

15.3 STATISTICAL GROUP WEIGHTS METHOD

A more refined estimate of the group weights applies statistical equations based upon sophisticated regression analysis. Development of these equations represents a major effort, and each company develops its own equations.

To acquire a statistical database for these equations, weights engineers must obtain group-weight statements and detailed aircraft drawings for as many current aircraft as possible. This sometimes requires weights engineers to trade group-weight statements much like baseball cards ("I'll trade you a T-45 for an F-16 and a C-5B"!)

The equations presented below typify those used in conceptual design by the major airframe companies, and cover fighter/attack, transport, and general-aviation aircraft. They have been taken from Refs. 62–64 and other sources. Definitions of the terms follow the equations.

It should be understood that there are no "right" answers in weights estimation until the first aircraft flies. However, these equations should provide a reasonable estimate of the group weights. Other, similar weights equations may be found in Refs. 10, 11, and 23. It's a good idea to calculate the weight of each component using several different equations and then select an average, reasonable result.

Reference 11 tabulates group-weight statements for a number of aircraft. These can also be used to help select a reasonable weight estimate for the components by comparing the component weights as a fraction of the empty weight for a similar aircraft.

Table 15.3 tabulates various miscellaneous weights.

When the component weights are estimated using these or similar methods, they are tabulated in a format similar to that of Table 15.1 and are summed to determine the empty weight. Since the payload and crew weights are known, the fuel weight must be adjusted to yield the as-drawn takeoff weight that is the sum of the empty, payload, crew, and fuel weights. If the empty weight is higher than expected, there may be insufficient fuel to

Table 15.3 Miscellaneous weights (approximate)

Missiles	
Harpoon (AGM-84 A)	1200 lb
Phoenix (AIM-54 A)	1000 lb
Sparrow (AIM-7)	500 lb
Sidewinder (AIM-9)	200 lb
Pylon and launcher	$.12\ W_{\text{missile}}$
M61 Gun	
Gun	250 lb
940 rds ammunition	550 lb
Seats	
Flight deck	60 lb
Passenger	32 lb
Troop	11 lb
Instruments	
Altimeter, airspeed, accelerometer, rate of climb, clock, compass, turn & bank, Mach, tachometer, manifold pressure, etc.	1-2 lb each
Gyro horizon, directional gyro	4-6 lb each
Heads-up display	40 lb
Lavatories	
Long range aircraft	$1.11\ N_{\text{pass}}^{1.33}$
Short range aircraft	$0.31\ N_{\text{pass}}^{1.33}$
Business/executive aircraft	$3.90\ N_{\text{pass}}^{1.33}$
Arresting gear	
Air Force-type	$.002\ W_{dg}$
Navy-type	$.008\ W_{dg}$
Catapult gear	
Navy carrier-based	$.003\ W_{dg}$
Folding Wing	
Navy carrier based	$.06\ W_{\text{wing}}$

complete the design mission. This must be corrected by resizing and optimizing the aircraft as described in Chapter 19, *not* by simply increasing fuel weight for the as-drawn aircraft (which would invalidate the component weight predictions that were based on the as-drawn takeoff weight).

Fighter/Attack Weights

$$W_{\text{wing}} = 0.0103 K_{\text{dw}} K_{\text{vs}} (W_{\text{dg}} N_z)^{0.5} S_w^{0.622} A^{0.785} (t/c)_{\text{root}}^{-0.4} \times (1+\lambda)^{0.05} (\cos\Lambda)^{-1.0} S_{\text{csw}}^{0.04} \tag{15.1}$$

$$W_{\text{horizontal tail}} = 3.316 \left(1 + \frac{F_w}{B_h}\right)^{-2.0} \left(\frac{W_{\text{dg}} N_z}{1000}\right)^{0.260} S_{\text{ht}}^{0.806} \tag{15.2}$$

$$W_{\text{vertical tail}} = 0.452 K_{\text{rht}} (1 + H_t/H_v)^{0.5} (W_{\text{dg}} N_z)^{0.488} S_{\text{vt}}^{0.718} M^{0.341} \times L_t^{-1.0} (1 + S_r/S_{\text{vt}})^{0.348} A_{\text{vt}}^{0.223} (1+\lambda)^{0.25} (\cos\Lambda_{\text{vt}})^{-0.323} \tag{15.3}$$

$$W_{\text{fuselage}} = 0.499 K_{\text{dwf}} W_{\text{dg}}^{0.35} N_z^{0.25} L^{0.5} D^{0.849} W^{0.685} \tag{15.4}$$

$$W_{\substack{\text{main landing}\\ \text{gear}}} = K_{\text{cb}} K_{\text{tpg}} (W_l N_l)^{0.25} L_m^{0.973} \tag{15.5}$$

$$W_{\substack{\text{nose landing}\\ \text{gear}}} = (W_l N_l)^{0.290} L_n^{0.5} N_{\text{nw}}^{0.525} \tag{15.6}$$

$$W_{\substack{\text{engine}\\ \text{mounts}}} = 0.013 N_{\text{en}}^{0.795} T^{0.579} N_z \tag{15.7}$$

$$W_{\text{firewall}} = 1.13 S_{\text{fw}} \tag{15.8}$$

$$W_{\substack{\text{engine}\\ \text{section}}} = 0.01 W_{\text{en}}^{0.717} N_{\text{en}} N_z \tag{15.9}$$

$$W_{\substack{\text{air induction}\\ \text{system}}} = 13.29 K_{\text{vg}} L_d^{0.643} K_d^{0.182} N_{\text{en}}^{1.498} (L_s/L_d)^{-0.373} D_e \tag{15.10}$$

where K_d and L_s are from Fig. 15.2.

$$W_{\text{tailpipe}} = 3.5 D_e L_{\text{tp}} N_{\text{en}} \tag{15.11}$$

$$W_{\substack{\text{engine}\\ \text{cooling}}} = 4.55 D_e L_{\text{sh}} N_{\text{en}} \tag{15.12}$$

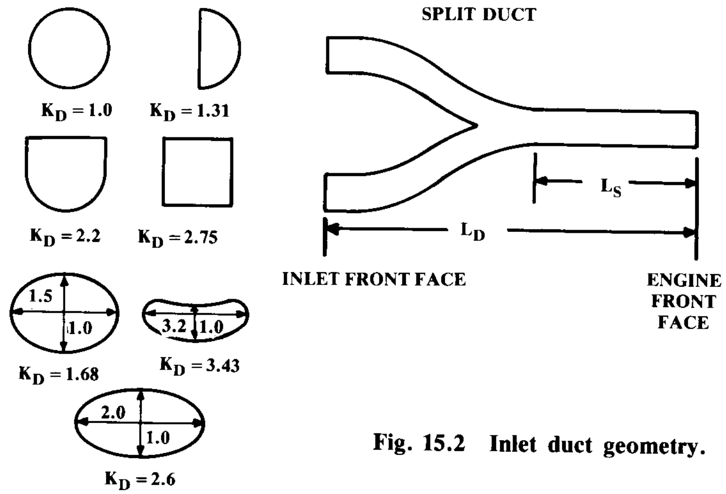

Fig. 15.2 Inlet duct geometry.

$$W_{\text{oil cooling}} = 37.82 N_{\text{en}}^{1.023} \tag{15.13}$$

$$W_{\substack{\text{engine}\\\text{controls}}} = 10.5 N_{\text{en}}^{1.008} L_{\text{ec}}^{0.222} \tag{15.14}$$

$$W_{\substack{\text{starter}\\\text{(pneumatic)}}} = 0.025\, T_e^{0.760} N_{\text{en}}^{0.72} \tag{15.15}$$

$$W_{\substack{\text{fuel system}\\\text{and tanks}}} = 7.45\, V_t^{0.47}\left(1 + \frac{V_i}{V_t}\right)^{-0.095}\left(1 + \frac{V_p}{V_t}\right) N_t^{0.066} N_{\text{en}}^{0.052}\left(\frac{T \cdot \text{SFC}}{1000}\right)^{0.249} \tag{15.16}$$

$$W_{\substack{\text{flight}\\\text{controls}}} = 36.28 M^{0.003} S_{\text{cs}}^{0.489} N_s^{0.484} N_c^{0.127} \tag{15.17}$$

$$W_{\text{instruments}} = 8.0 + 36.37 N_{\text{en}}^{0.676} N_t^{0.237} + 26.4(1 + N_{ci})^{1.356} \tag{15.18}$$

$$W_{\text{hydraulics}} = 37.23 K_{\text{vsh}} N_u^{0.664} \tag{15.19}$$

$$W_{\text{electrical}} = 172.2 K_{mc} R_{\text{kva}}^{0.152} N_c^{0.10} L_a^{0.10} N_{\text{gen}}^{0.091} \tag{15.20}$$

$$W_{\text{avionics}} = 2.117\, W_{\text{uav}}^{0.933} \tag{15.21}$$

$$W_{\text{furnishings}} = 217.6 N_c \tag{15.22}$$

$$W_{\substack{\text{air conditioning}\\\text{and anti-ice}}} = 201.6[(W_{\text{uav}} + 200\, N_c)/1000]^{0.735} \tag{15.23}$$

$$W_{\substack{\text{handling}\\\text{gear}}} = 3.2 \times 10^{-4}\, W_{\text{dg}} \tag{15.24}$$

Cargo/Transport Weights

$$W_{\text{wing}} = 0.0051\,(W_{\text{dg}} N_z)^{0.557} S_w^{0.649} A^{0.5} (t/c)_{\text{root}}^{-0.4}\,(1 + \lambda)^{0.1} \times (\cos\Lambda)^{-1.0} S_{\text{csw}}^{0.1} \tag{15.25}$$

$$W_{\substack{\text{horizontal}\\\text{tail}}} = 0.0379 K_{\text{uht}} (1 + F_w/B_h)^{-0.25} W_{\text{dg}}^{0.639} N_z^{0.10} S_{\text{ht}}^{0.75} L_t^{-1.0} \times K_y^{0.704} (\cos\Lambda_{\text{ht}})^{-1.0} A_h^{0.166}\,(1 + S_e/S_{\text{ht}})^{0.1} \tag{15.26}$$

$$W_{\substack{\text{vertical}\\\text{tail}}} = 0.0026(1 + H_t/H_v)^{0.225} W_{\text{dg}}^{0.556} N_z^{0.536} L_t^{-0.5} S_{\text{vt}}^{0.5} K_z^{0.875} \times (\cos\Lambda_{\text{vt}})^{-1} A_v^{0.35} (t/c)_{\text{root}}^{-0.5} \tag{15.27}$$

$$W_{\text{fuselage}} = 0.3280 K_{\text{door}} K_{\text{Lg}} (W_{\text{dg}} N_z)^{0.5} L^{0.25} S_f^{0.302} (1 + K_{\text{ws}})^{0.04} (L/D)^{0.10} \tag{15.28}$$

$$W_{\substack{\text{main landing}\\\text{gear}}} = 0.0106 K_{\text{mp}} W_l^{0.888} N_l^{0.25} L_m^{0.4} N_{\text{mw}}^{0.321} N_{\text{mss}}^{-0.5} V_{\text{stall}}^{0.1} \tag{15.29}$$

$$W_{\substack{\text{nose landing}\\\text{gear}}} = 0.032 K_{np} W_l^{0.646} N_l^{0.2} L_n^{0.5} N_{nw}^{0.45} \tag{15.30}$$

$$W_{\substack{\text{nacelle}\\\text{group}}} = 0.6724 K_{ng} N_{Lt}^{0.10} N_w^{0.294} N_z^{0.119} W_{\text{ec}}^{0.611} N_{\text{en}}^{0.984} S_n^{0.224} \tag{15.31}$$

(includes air induction)

$$W_{\substack{\text{engine}\\\text{controls}}} = 5.0 N_{\text{en}} + 0.80 L_{\text{ec}} \tag{15.32}$$

$$W_{\substack{\text{starter}\\\text{(pneumatic)}}} = 49.19\left(\frac{N_{\text{en}} W_{\text{en}}}{1000}\right)^{0.541} \tag{15.33}$$

$$W_{\substack{\text{fuel}\\\text{system}}} = 2.405\, V_t^{0.606} (1 + V_i/V_t)^{-1.0} (1 + V_p/V_t) N_t^{0.5} \tag{15.34}$$

$$W_{\substack{\text{flight}\\ \text{controls}}} = 145.9 N_f^{0.554} (1 + N_m/N_f)^{-1.0} S_{cs}^{0.20} (I_y \times 10^{-6})^{0.07} \tag{15.35}$$

$$W_{\substack{\text{APU}\\ \text{installed}}} = 2.2\, W_{\substack{\text{APU}\\ \text{uninstalled}}} \tag{15.36}$$

$$W_{\text{instruments}} = 4.509 K_r K_{tp} N_c^{0.541} N_{en} (L_f + B_w)^{0.5} \tag{15.37}$$

$$W_{\text{hydraulics}} = 0.2673 N_f (L_f + B_w)^{0.937} \tag{15.38}$$

$$W_{\text{electrical}} = 7.291 R_{kva}^{0.782} L_a^{0.346} N_{gen}^{0.10} \tag{15.39}$$

$$W_{\text{avionics}} = 1.73\, W_{uav}^{0.983} \tag{15.40}$$

$$W_{\text{furnishings}} = 0.0577 N_c^{0.1} W_c^{0.393} S_f^{0.75} \tag{15.41}$$

$$W_{\substack{\text{air}\\ \text{conditioning}}} = 62.36 N_p^{0.25} (V_{pr}/1000)^{0.604} W_{uav}^{0.10} \tag{15.42}$$

$$W_{\text{anti-ice}} = 0.002\, W_{dg} \tag{15.43}$$

$$W_{\substack{\text{handling}\\ \text{gear}}} = 3.0 \times 10^{-4}\, W_{dg} \tag{15.44}$$

$$W_{\substack{\text{military cargo}\\ \text{handling system}}} = 2.4 \times (\text{cargo floor area, ft}^2) \tag{15.45}$$

General-Aviation Weights

$$W_{\text{wing}} = 0.036 S_w^{0.758} W_{fw}^{0.0035} \left(\frac{A}{\cos^2\Lambda}\right)^{0.6} q^{0.006} \lambda^{0.04} \left(\frac{100\, t/c}{\cos\Lambda}\right)^{-0.3} (N_z W_{dg})^{0.49} \tag{15.46}$$

$$W_{\substack{\text{horizontal}\\ \text{tail}}} = 0.016 (N_z W_{dg})^{0.414} q^{0.168} S_{ht}^{0.896} \left(\frac{100\, t/c}{\cos\Lambda}\right)^{-0.12} \times \left(\frac{A}{\cos^2\Lambda_{ht}}\right)^{0.043} \lambda_h^{-0.02} \tag{15.47}$$

$$W_{\substack{\text{vertical}\\ \text{tail}}} = 0.073\left(1 + 0.2\frac{H_t}{H_v}\right)(N_z W_{dg})^{0.376} q^{0.122} S_{vt}^{0.873} \left(\frac{100\, t/c}{\cos\Lambda_{vt}}\right)^{-0.49} \times \left(\frac{A}{\cos^2\Lambda_{vt}}\right)^{0.357} \lambda_{vt}^{0.039} \tag{15.48}$$

$$W_{\text{fuselage}} = 0.052\, S_f^{1.086} (N_z W_{dg})^{0.177} L_t^{-0.051} (L/D)^{-0.072} q^{0.241} + W_{\text{press}} \tag{15.49}$$

$$W_{\substack{\text{main landing}\\ \text{gear}}} = 0.095 (N_l W_l)^{0.768} (L_m/12)^{0.409} \tag{15.50}$$

$$W_{\substack{\text{nose landing}\\ \text{gear}}} = 0.125 (N_l W_l)^{0.566} (L_n/12)^{0.845} \tag{15.51}$$

$$W_{\substack{\text{installed engine}\\ \text{(total)}}} = 2.575\, W_{en}^{0.922} N_{en} \tag{15.52}$$

$$W_{\text{fuel system}} = 2.49\, V_t^{0.726} \left(\frac{1}{1 + V_i/V_t}\right)^{0.363} N_t^{0.242} N_{en}^{0.157} \tag{15.53}$$

$$W_{\substack{\text{flight}\\ \text{controls}}} = 0.053 L^{1.536} B_w^{0.371} (N_z W_{dg} \times 10^{-4})^{0.80} \tag{15.54}$$

$$W_{\text{hydraulics}} = 0.001\, W_{dg} \tag{15.55}$$

$$W_{\text{electrical}} = 12.57 (W_{\text{fuel system}} + W_{\text{avionics}})^{0.51} \tag{15.56}$$

$$W_{\text{avionics}} = 2.117\, W_{uav}^{0.933} \tag{15.57}$$

$$W_{\substack{\text{air conditioning}\\ \text{and anti-ice}}} = 0.265\, W_{dg}^{0.52} N_p^{0.68} W_{\text{avionics}}^{0.17} M^{0.08} \tag{15.58}$$

$$W_{\text{furnishings}} = 0.0582\, W_{dg} - 65 \tag{15.59}$$

Weights Equations Terminology

- A = aspect ratio
- B_h = horizontal tail span, ft
- B_w = wing span, ft
- D = fuselage structural depth, ft
- D_e = engine diameter, ft
- F_w = fuselage width at horizontal tail intersection, ft
- H_t = horizontal tail height above fuselage, ft
- H_t/H_v = 0.0 for conventional tail; 1.0 for "T" tail
- H_v = vertical tail height above fuselage, ft
- I_y = yawing moment of inertia, lb-ft^2 (see Chap. 16)

K_{cb} = 2.25 for cross-beam (F-111) gear; = 1.0 otherwise
K_d = duct constant (see Fig. 15.2)
K_{door} = 1.0 if no cargo door; = 1.06 if one side cargo door; = 1.12 if two side cargo doors; = 1.12 if aft clamshell door; = 1.25 if two side cargo doors and aft clamshell door
K_{dw} = 0.768 for delta wing; = 1.0 otherwise
K_{dwf} = 0.774 for delta wing aircraft; = 1.0 otherwise
K_{Lg} = 1.12 if fuselage-mounted main landing gear; = 1.0 otherwise
K_{mc} = 1.45 if mission completion required after failure; = 1.0 otherwise
K_{mp} = 1.126 for kneeling gear; = 1.0 otherwise
K_{ng} = 1.017 for pylon-mounted nacelle; = 1.0 otherwise
K_{np} = 1.15 for kneeling gear; = 1.0 otherwise
K_p = 1.4 for engine with propeller or 1.0 otherwise
K_r = 1.133 if reciprocating engine; = 1.0 otherwise
K_{rht} = 1.047 for rolling tail; = 1.0 otherwise
K_{tp} = 0.793 if turboprop; = 1.0 otherwise
K_{tpg} = 0.826 for tripod (A-7) gear; = 1.0 otherwise
K_{tr} = 1.18 for jet with thrust reverser or 1.0 otherwise
K_{uht} = 1.143 for unit (all-moving) horizontal tail; = 1.0 otherwise
K_{vg} = 1.62 for variable geometry; = 1.0 otherwise
K_{vs} = 1.19 for variable sweep wing; = 1.0 otherwise
K_{vsh} = 1.425 if variable sweep wing; = 1.0 otherwise
K_{ws} = $0.75[1 + 2\lambda)/(1 + \lambda)]\ (B_w \tan\Lambda/L)$
K_y = aircraft pitching radius of gyration, ft ($\cong 0.3L_t$)
K_z = aircraft yawing radius of gyration, ft ($\cong L_t$)
L = fuselage structural length, ft (excludes radome, tail cap)
L_a = electrical routing distance, generators to avionics to cockpit, ft
L_d = duct length, ft
L_{ec} = length from engine front to cockpit—total if multiengine, ft
L_f = total fuselage length
L_m = length of main landing gear, in.
L_n = nose gear length, in.
L_s = single duct length (see Fig. 15.2)
L_{sh} = length of engine shroud, ft
L_t = tail length; wing quarter-MAC to tail quarter-MAC, ft
L_{tp} = length of tailpipe, ft
M = Mach number
N_c = number of crew
N_{ci} = 1.0 if single pilot; = 1.2 if pilot plus backseater; = 2.0 pilot and copassenger
N_{en} = number of engines
N_f = number of functions performed by controls (typically 4–7)
N_{gen} = number of generators (typically = N_{en})
N_l = ultimate landing load factor; = $N_{gear} \times 1.5$
N_{Lt} = nacelle length, ft
N_m = number of mechanical functions (typically 0–2)
N_{mss} = number of main gear shock struts
N_{mw} = number of main wheels
N_{nw} = number of nose wheels

N_p = number of personnel onboard (crew and passengers)
N_s = number of flight control systems
N_t = number of fuel tanks
N_u = number of hydraulic utility functions (typically 5–15)
N_w = nacelle width, ft
N_z = ultimate load factor; = 1.5 × limit load factor
q = dynamic pressure at cruise, lb/ft^2
R_{kva} = system electrical rating, kv · A (typically 40–60 for transports, 110–160 for fighters & bombers)
S_{cs} = total area of control surfaces, ft^2
S_{csw} = control surface area (wing-mounted), ft^2
S_e = elevator area, ft
S_f = fuselage wetted area, ft^2
S_{fw} = firewall surface area, ft^2
S_{ht} = horizontal tail area
S_n = nacelle wetted area, ft^2
S_r = rudder area, ft^2
S_{vt} = vertical tail area, ft^2
S_w = trapezoidal wing area, ft^2
SFC = engine specific fuel consumption—maximum thrust
T = total engine thrust, lb
T_e = thrust per engine, lb
V_i = integral tanks volume, gal
V_p = self-sealing "protected" tanks volume, gal
V_{pr} = volume of pressurized section, ft^3
V_t = total fuel volume, gal
W = fuselage structural width, ft
W_c = maximum cargo weight, lb
W_{dg} = design gross weight, lb
W_{ec} = weight of engine and contents, lb (per nacelle), $\cong 2.331\ W_{engine}^{0.901}\ K_p K_{tr}$
W_{en} = engine weight, each, lb
W_{fw} = weight of fuel in wing, lb
W_l = landing design gross weight, lb
W_{press} = weight penalty due to pressurization, $= 11.9 + (V_{pr}P_{delta})^{0.271}$, where P_{delta} = cabin pressure differential, psi (typically 8 psi)
W_{uav} = uninstalled avionics weight, lb (typically = 800–1400 lb)
Λ = wing sweep at 25% MAC

15.4 ADDITIONAL CONSIDERATIONS IN WEIGHTS ESTIMATION

These statistical equations are based upon a database of existing aircraft. They work well for a "normal" aircraft similar to the various aircraft in the database. However, use of a novel configuration (canard pusher) or an advanced technology (composite structure) will result in a poor weights estimate when using these or similar equations. To allow for this, weights engineers adjust the statistical-equation results using "fudge factors" (defined as the variable constant that you multiply your answer by to get the right answer!)

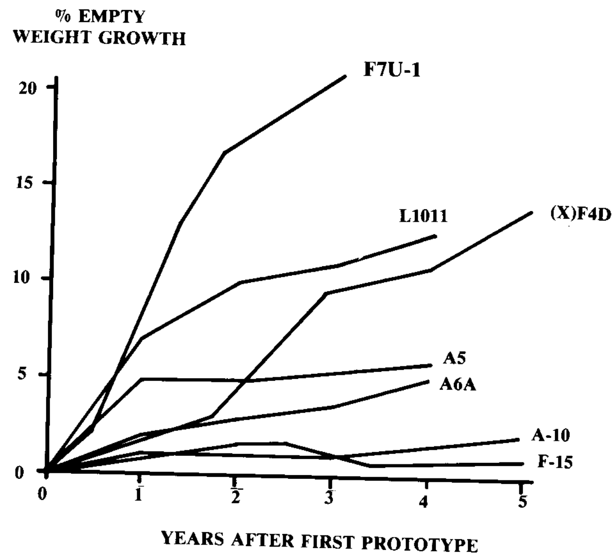

Fig. 15.3 Aircraft weight growth.

Table 15.4 Weights estimation "fudge factors"

Category	Weight group	Fudge factor (multiplier)
Advanced composites	Wing	0.85
	Tails	0.83
	Fuselage/nacelle	0.90
	Landing gear	0.95
	Air induction system	0.85
Braced wing	Wing	0.82
Wood fuselage	Fuselage	1.60
Steel tube fuselage	Fuselage	1.80
Flying boat hull	Fuselage	1.25

Fudge factors are also required to estimate the weight of a class of aircraft for which no statistical equations are available. For example, there have been too few Mach 3 aircraft to develop a good statistical database. Weights for a new Mach 3 design can be estimated by selecting the closest available equations (probably the fighter/attack equations) and determining a "fudge factor" for each type of component.

This is done using data for an existing aircraft similar to the new one (such as the XB-70 for a Mach 3 design) and calculating its component weights using the selected statistical equations. Fudge factors are then determined by dividing the actual component weights for that aircraft by the calculated component weights.

To estimate the component weights for the new design, these fudge factors are multiplied by the component weights as calculated using the selected statistical equations.

Fudge factors for composite-structure, wood or steel-tube fuselages, braced wings, and flying-boat hulls are provided in Table 15.4. These should be viewed as rough approximations only and subject to heated debate. For example, there are those who claim that a properly-designed steel-tube fuselage can be lighter than an aluminum fuselage.

One final consideration in aircraft-weights estimation is the weight growth that most aircraft experience in the first few years of production. This growth in empty weight is due to several factors, such as increased avionics capabilities, structural fixes (such as replacing an aluminum fitting with steel to prevent cracking), and additional weapons pylons.

Figure 15.3 shows the empty-weight growth of a number of aircraft. In the past, a weight growth of 5% in the first year was common. Today's better design techniques and analytical methods have reduced that to less than 2% in the first year. Still, some allowance for weight growth should be made in the conceptual-design weight estimation.