Mass analysis by D.P. Raymer: Aircraft Design, A conceptual Approach, AIAA Series

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	Crew
Exhaust system	Fuel-usable
Cooling provisions	-trapped
Engine controls	Oil
Starting system	Passengers
Fuel system/tanks	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 groups given to mass analysis

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.

Masses of basic elements of an aircraft

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 $W_{missile}$
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 $N_{pass}^{1.33}$
Short range aircraft	0.31 $N_{pass}^{1.33}$
Business/executive aircraft	3.90 $N_{pass}^{1.33}$
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_{wing}

Miscellaneous masses

Fighter/Attack Weights

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

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

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

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

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

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

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

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

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

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

where K_d and L_s are from Fig. 15.2.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Formulas to compute masses of combat aircraft

Cargo/Transport Weights

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

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

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

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

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

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

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

(includes air induction)

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Formulas to compute masses of transport aircraft

General-Aviation Weights

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

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

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

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

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

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

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

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

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

$$W_{\text{hydraulics}} = 0.001\ W_{\text{dg}}$$

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

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

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

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

Formulas to compute masses in „General aviation" group

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

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

Mass correction for non-typical materials

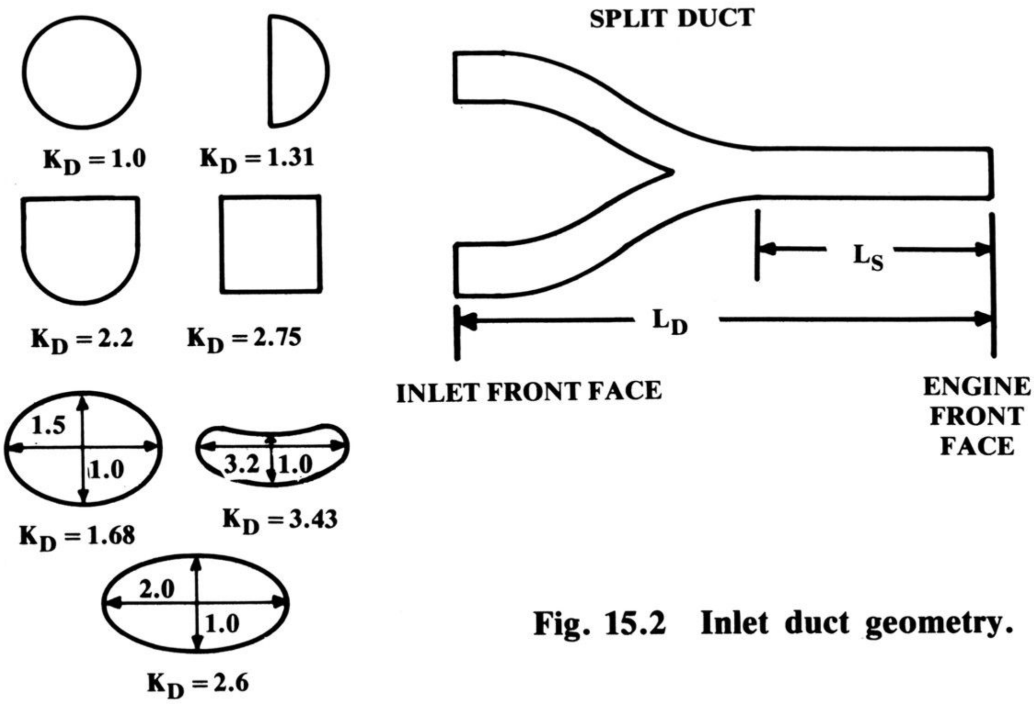

Fig. 15.2 Inlet duct geometry.

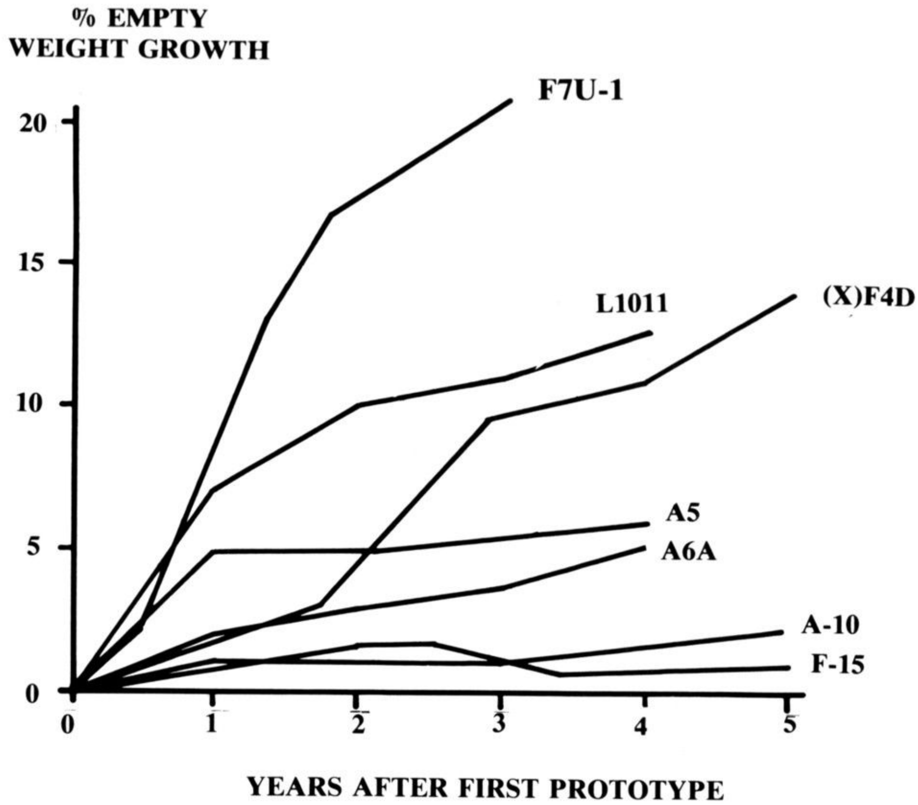

Fig. 15.3 Aircraft weight growth.