Classical Aircraft Sizing II

W. H. Mason

Advanced Concepts from NASA TM-1998-207644
Previously (Sizing I)

• Mission definition
• Basic Sizing to Estimate TOGW
• Examples

Now: More Details and Picking W/S and T/W

• Federal Air Regulations (FARs) and MIL STD Requirements
• Basic Considerations for Wing Size
• Sizing Theory: Getting a Little More Precise
• Tradeoffs, Parametric Studies and Carpet Plots
The Conceptual Design Team: A Suggested Organization

1. Leader (the keeper of the notebook)
2. Configuration Designer
3. Weights (rock eater) also balance/inertia
4. Vehicle Performance and Mission Analysis
5. Aero Configuration (drag buster)
6. Flight Controls (mechanical as well as handling qualities)
7. Propulsion & Propulsion System Integration
8. Structures/Materials
9. Aircraft Systems
10. Cost and Manufacturing — last but not least!
FAR and MIL STD Requirements

Gov’t requirements dictate some of the design requirements
• interest is safety, not economic performance
• examples:
  – engine out minimum performance,
    » the second segment climb requirement
  – reserve fuel requirements
  – emergency exits on transport aircraft
  – deicing procedures
• Raymer, App. F
• Roskam: Part VII is entirely devoted to stability and control
  and performance FAR and MIL requirements
• Key parts for us: Pt 25 (Transport Airplanes), Pt 36 (Noise), Pt 121 (Operations)
• See web charts for definitions for classifying a/c

see the class web page for a link to the FARs
## Takeoff Requirements

<table>
<thead>
<tr>
<th>Item</th>
<th>MIL-C5011A</th>
<th>FAR Part 23</th>
<th>FAR Part 25</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity</td>
<td>$V_{TO} \geq 1.1 \ V_S$</td>
<td>$V_{TO} \geq 1.1 \ V_S$</td>
<td>$V_{TO} \geq 1.1 \ V_S$</td>
</tr>
<tr>
<td></td>
<td>$V_{CL} \geq 1.2 \ V_S$</td>
<td>$V_{CL} \geq 1.1 \ V_S$</td>
<td>$V_{CL} \geq 1.2 \ V_S$</td>
</tr>
<tr>
<td>Climb</td>
<td>Gear up:</td>
<td>Gear up:</td>
<td>Gear down:</td>
</tr>
<tr>
<td>Gradient</td>
<td>500 fpm @ SL</td>
<td>300 fpm @ SL (AEO)</td>
<td>1/2% @ $V_{TO}$ (AEO)</td>
</tr>
<tr>
<td>Gear up:</td>
<td>100 fpm @ SL (OEI)</td>
<td></td>
<td>3% @ $V_{CL}$ (OEI)</td>
</tr>
<tr>
<td>Field-length</td>
<td>Takeoff distance over 50-ft obstacle</td>
<td>Takeoff distance over 50-ft obstacle</td>
<td>115% of takeoff distance with AEO over 35 ft or balanced field length*</td>
</tr>
<tr>
<td>definition</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rolling coefficient</td>
<td>$\mu = 0.025$</td>
<td>not specified</td>
<td>not specified</td>
</tr>
</tbody>
</table>

* see discussion on next slide

AEO: all engines operating, OEI: one engine inoperative

from Nicolai, *Fundamentals of Aircraft Design*, , 1975
See Raymer, App. F,
Balanced Field Length (Takeoff)  
(Critical Field Length for Military Aircraft)

Following engine failure, at decision speed $V_1 \ (1.1V_{Stall})$ either:

a) continue takeoff (including obstacle clearance)

or

b) stop

- if $V > V_1$ - takeoff
- if $V < V_1$ - stop

• $V_1$ chosen such that distance for both is equal

• details require precise takeoff speed definitions:
  
  see Sean Lynn’s Report, “Aircraft Takeoff Analysis in the Preliminary Design Phase,” on our web page or the FARs

• assume smooth, hard, dry runway

• for early design studies this is usually determined without allowing for a stopway past end of runway
# 2nd Segment Climb Requirement

at $V_2$, from 35ft to 400 ft above ground level:
for engine failure, flaps in takeoff position, landing gear retracted:

<table>
<thead>
<tr>
<th># of engines</th>
<th>climb gradient (CGR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>3.0%</td>
</tr>
<tr>
<td>3</td>
<td>2.7%</td>
</tr>
<tr>
<td>2</td>
<td>2.4%</td>
</tr>
</tbody>
</table>

$V_2$: airspeed obtained at the 35ft height point

$V_2 > 1.2V_{stall}$ in TO Config or $V_2 > 1.1V_{mc}$

$V_{mc}$ is minimum control speed in the engine out condition

see FAR Part 25 for more complete requirements or Raymer, App. F
### CTOL Landing Requirements

<table>
<thead>
<tr>
<th>Item</th>
<th>MIL-C5011A (Military)</th>
<th>FAR Part 23 (Civil)</th>
<th>FAR Part 25 (Commercial)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity</td>
<td>$V_A &gt; 1.2 \ V_S$</td>
<td>$V_A &gt; 1.3 \ V_S$</td>
<td>$V_A &gt; 1.3 \ V_S$</td>
</tr>
<tr>
<td></td>
<td>$V_{TD} &gt; 1.1 \ V_S$</td>
<td>$V_{TD} &gt; 1.15 \ V_S$</td>
<td>$V_{TD} &gt; 1.15 \ V_S$</td>
</tr>
<tr>
<td>Field-length definition</td>
<td>Landing Distance over 50-ft obstacle</td>
<td>Landing Distance over 50-ft obstacle</td>
<td>Landing Distance over 50-ft obstacle divided by 0.6</td>
</tr>
<tr>
<td>Braking coefficient</td>
<td>$\mu = 0.30$</td>
<td>not specified</td>
<td>not specified</td>
</tr>
</tbody>
</table>

see Raymer, App. F,
Missed Approach Requirement

One engine out at landing weight,
- in the approach configuration and landing gear retracted

<table>
<thead>
<tr>
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<th>climb gradient (CGR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>2.7%</td>
</tr>
<tr>
<td>3</td>
<td>2.4%</td>
</tr>
<tr>
<td>2</td>
<td>2.1%</td>
</tr>
</tbody>
</table>

see FAR Part 25 for more complete requirements
[also Raymer, App. F,
Reserve Fuel Requirements

• FAR Part 121 and ATA standards (more stringent than Pt 121)

Domestic Operations
- fly 1 hr at end of cruise fuel flow for 99% max range
- execute missed approach, climb out and fly to alternate airport 200nm away

International Operations
- fly 10% of trip time at normal cruise altitude at fuel flow for 99% max range
- execute a missed approach, climbout and fly to alternate airport 200nm away

Flight to Alternate Airport
- cruise thrust for 99% max range, then hold at greater of max endurance or min speed for comfortable handling
- cruise at BCA unless greater than climb/descent distance

Approximation often used in very early stages of design studies:
- add 400 to 600 nm to design range
Stability and Control

- FAR requirements are qualitative only
- MIL STD 1797A (was MIL SPEC 8785) is used to establish quantitative guidelines for control power requirements and handling qualities
- Good flying qualities depend on good nonlinear aerodynamics (stall characteristics):
  - in early design, before wind tunnel and flight test, draw on lessons from the past (Stinton’s *Flying Qualities* book is one good place to start)
  - expect a lot of effort to go into getting this right
Basic Considerations for Wing Size

• Wing weight is important
• Integrate Aerodynamics and Structures for minimum weight design
• Wing loading is an important design parameter
  - driven by two opposing requirements
• Can define problem reasonably well
Wing Weight equation for Fighters (from Nicolai):

\[ W_{WNG} = 3.08 K_T \left( \frac{K_{PIV} N W_{TO}}{(t / c)} \left[ 1 + \tan^2 \Lambda_{c/2} \right]^2 \times 10^{-6} \right)^{0.593} \]

\[ \times \left[ (1 + \lambda) AR \right]^{0.89} S_W^{0.741} \]

- \( K_T \) – technology factor
- \( K_{PIV} \) – variable sweep factor = 1.175 (1 for fixed geometry)
- \( W_{TO} \) – TOGW
- \( N \) – ultimate load factor (\( = 11 \) for fighters, \( 1.5 \times 7.33 \))

+ standard variables - \( t/c, \Lambda, \lambda, AR, S \)
Regrouping the Weight Equation:

\[ W_{WING} = 3.08K_T \left( \frac{K_{PIVNW_{TO}}}{(t/c)} \left[ 1 + \tan^2 \Lambda_{c/2} \right]^2 \times 10^{-6} \right)^{0.593} (1 + \lambda)^{0.89} b^{1.78} S_W^{-0.149} \]

Drivers:
- thickness, \( t/c \)
- span, \( b \)
- sweep, \( \Lambda \)
- Wing area, \( S \) (different for fixed \( AR \) or \( b \))
- taper, \( \lambda \)
- TOGW \( (W_{TO}) \)

for low wing weight:
- thick wings (\( t/c \) large)
- low span (\( b \) low)
- high taper (\( \lambda \) small)
- low sweep (\( \Lambda \) small)
Wing Size and Wing Loading Issues
Consider Wing Loading to Find Wing Area

- Specific Range (sr), best range formula, drag rise neglected

\[ best \ sr = \frac{1.07}{sfc} \left\{ \frac{(W / S)}{\rho} \right\}^{1/2} \frac{1}{\left\{ \frac{AR \cdot E}{C_{D_0}} \right\}^{3/4} \frac{1}{W}} \]

Increase: \( W/S, \) altitude (decreases \( \rho \)), \( AR, E \) (L/D)

Decrease: zero lift drag, weight (W), sfc

Here: HIGH W/S is good
Wing Loading Considerations (Cont’d)

Sustained Maneuvering

\[ n = \frac{q}{(W / S)} \sqrt{\pi \text{ARE} \left( \frac{T}{qS} - C_{D_0} \right)} \]

Takeoff

\[ l_t = 37.7 \cdot \text{TOP}, \quad \text{TOP} = \frac{(W / S)}{\sigma \cdot C_{L_{\text{max}}} (T / W)} \]

Landing

\[ V_{\text{APP}} = 17.15 \sqrt{\frac{W / S}{\sigma \cdot C_{L_{\text{APP}}}}} \], \quad (\text{knots})

Here: LOW W/S is good
Sizing Theory: Getting a Little More Precise

- Can use simple representation of technologies and do some decent analysis
- Several possibilities:
  - rubber airplane and engine
  - rubber airplane and specified engine
  - new wing on existing airplane
  - etc.
Thrust to Weight and Wing Loading

*Engine size (or thrust to weight, T/W)*
• based on sizing the engine to meet constraints
typically established by the Specs we’ve discussed

*Wing size (or wing loading, W/S)*
• also based on meeting key requirements

*T/W - W/S charts are typically used*
• putting all the constraints on the plot lets
you select the best combination

*Often the wing is allowed to be bigger,*
- to allow for future growth

*Prop Airplanes use Power Loading, W/P in place of T/W*

see L.K. Loftin, Jr., “Subsonic Aircraft: Evolution and theMatching of Size to Performance,” NASA RP 1060, Aug. 1980,
- available as a pdf file from http://ntrs.larc.nasa.gov/
(see pages 358-360, for examples for prop airplanes).
Thrust Loading and Wing Loading Matching

![Diagram showing the relationship between Thrust Loading (T/W) and Wing Loading (W/S), highlighting the feasible solution space, landing field length, take-off field length, cruise, second-segment climb gradient, match point, and missed approach.]

Tradeoffs and Parametric Studies

- Pervasive in design: establish a basis for design decisions
- Graphical representation required, two approaches
  - the Thumbprint plot
  - the Carpet plot
- Need a picture to get insight
Thumbprint Plot for an HSCT

Contours of constant aircraft weight are drawn on the $T/W - W/S$ chart, which also contains the constraints. The “Best Design” can be picked.

from NASA TM 4058:

note decreasing scale for $W/S$ in this example
Example of Constraint Lines
(approximate examples, be able to derive your own)

Takeoff: \( \frac{T}{W} \approx \frac{37.7 \cdot W/S}{\sigma \cdot C_{L_{\text{max} \ TO}} \cdot s_{\text{TOFL}}} \)

Landing: \( W/S \approx 2.8 \rho \cdot C_{L_{\text{max} \ Ldg}} \cdot s_{\text{ldgfl}} \)

Cruise (\( T = D \)): \( \frac{T}{W} = q \frac{C_{D_0}}{(W/S)_{\text{cruise}}} + \frac{(W/S)_{\text{cruise}}}{q\pi ARE} \)

Climb gradient requirements:

\( \frac{T}{W} = \left( \frac{N}{N - 1} \right) \left( CGR + \frac{1}{L/D} \right) \)

where, \( \sigma = \frac{\rho}{\rho_{\text{sea level}}} \)

Note: convert \( T/W \) to \( M=0, h=0 \) values, \( W/S \) to takeoff values, \( N \) is the number of engines, where we assume one engine out is the critical case, CGR is the climb gradient, \( q \) implies best altitude, Mach, and \( L/D \) should be for correct flight condition.
Carpet Plots

- Simple Parametric Plots can be confusing
- Shifting the plot axis provides a better way to understand parametric studies
- Resulting plot is called a carpet plot
- Particularly good for examination of the effects of constraints

See also the writeup on carpet plots from Sid Powers that is also available with these charts.
How to Construct a Carpet Plot

Step 1: plot weights for various $T/W$, W/S held at constant 1

Step 2: shift scale, plot weights for various $T/W$, W/S held at constant 2

Step 3: complete the baseline carpet, and delete the abscissa and the plot lines

Step 4: add constraints

Based on Nicolai, *Fundamentals of Aircraft Design*, METS, Inc., 1975
An Example Using Carpet Plots

Examine:

- $W/S$ - the Wing Loading
- $T/W$ - the Thrust Loading

Understand $W/S$ and $T/W$ Sensitivity and the impact of constraints:

- Weight to meet mission requirements
- Effect of M0.9, 30K Sustained Maneuver Req’t.
- Accel: M0.9 to M1.6 at 30K
- Field Performance (landing and takeoff)
- All constraints included on the same plot

Impact of Improved Maneuvering Technology
The Example Design: A Supersonic Fighter

Note: Aircraft Designed by Nathan Kirschbaum

Basic Carpet
(each point is a solution for the given mission)

The baseline chart, ready to add the constraints

- $\Lambda_{LE}^{57}$°
- t/c 0.045

FIXED TURBOJET

TOGW ~ LB

T/W 0.8

W/S 50 PSF

1.3
1.2
1.1
1.0
0.9

20,000
22,000
24,000
26,000
28,000
30,000
32,000
34,000
Carpet with Transonic Maneuver Constraints

Constraints for g’s at M.9/30K ft added

Note large weight increase required to pull more g’s
Carpet with Accel Constraints

Accel constraints added for accel times from M0.9 to M1.6 at 30k ft. alt.
Carpet with Field Performance Constraints

Takeoff and landing constraints added
Sea level, std. day, vectoring and reversing
Carpet with All Constraints Included

Sustained g’s: M0.9/30k ft
Accel time: M0.9 to 1.6 at 30k ft
TO/LDG: s.l., std day, thrust reversing
Example: Using a Carpet Plot to Assess How to Use Advanced Technology to Improve Maneuver Performance: SC3

Transport Constraints

There is another important constraint for transports:
The airplane must meet the initial cruise altitude requirement
  - at the initial cruise altitude (about 98% of TOGW), the so-called “top of climb”, airplane must still have a specified rate of climb (500 or 300 ft/min)

According to the book by Jenkinson, Simpkin and Rhodes, *Civil Jet Aircraft Design*,
- Twin-engine aircraft are likely to be second-segment climb critical
- Four-engine aircraft are likely to be climb critical (top of climb performance)
To Conclude:

• You are now equipped to *think* about aircraft design

• We’ve covered the basic physics dictating selection of aircraft weight, wing and engine size

• We’ve explained the basic carpet and thumbprint methods to understand effects of constraints, comparison of concepts, and design tradeoffs

• Even major aircraft companies have problems doing the tradeoffs scientifically: lots of bias and prejudice (they wouldn’t admit it - but that’s part of the reason for the evolutionary aircraft development we see)

• The next step: How to get your ideas on paper, and done so you can tell if they make sense
**Wing Planform/Tail Location Are Not Arbitrary**

**Pitch-Up Limits Planform Selection**

*Pitching moment characteristics as separation occurs must be controllable. Requires careful aero design.*

*Horizontal tail location is critical*

historical trends from early wind tunnel data

![Graph showing relationship between aspect ratio and quarter chord sweep with fighters and transports labeled as probably pitchup prone and probably OK.](image)

Note: DATCOM has a more detailed chart