

Teaching Aircraft Conceptual Design at the Undergraduate and Graduate Levels

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Abstract: *Overview of syllabus for teaching a class in aircraft conceptual design at the fourth year undergraduate or graduate level*

1 INTRODUCTION

This paper provides a brief overview of a syllabus for teaching aircraft conceptual design based on the author's experience working in the advanced design department of a major US aircraft manufacturer, and teaching in several US and foreign universities.

The syllabus in any course is strongly affected by the textbook selected by the instructor, and several English-language books are available [1,2,3,4]. Raymer [1] is used in many design courses in the US. The course concentrates on those aspects of conceptual design that are the responsibility of designers and analysts in the conceptual/preliminary design department. The course is also useful to engineers in other technical disciplines who contribute to conceptual or preliminary design, and help them understand their contributions and the necessary trades that must be made between different technologies.

One of the goals of the course is to teach students the procedures for aircraft conceptual design. But progress is only achieved by adopting new ideas and concepts, and another goal should be to encourage students to innovate. Unfortunately a one-semester course may not provide sufficient time to quantify the benefits of new ideas. For example, conceptual design weight estimation methods are based on analyses of weights of past and current airplanes, so it is difficult to estimate the weight reduction from a strut-braced wing from either Raymer's [1] or Nicolai's [3] weight equations (although this can be estimated from Torenbeek's or Cessna's methods reproduced in Roskam's text [4]). It may be very difficult to estimate the empty weight of a truly novel concept.

Even so, it is worth introducing students to unique and innovative concepts at the start of the course. Examples of these are described in Raymer, Ch. 22. Many more can be found online. Discussion of what the designers were trying to achieve, and why they designed certain configurations, is a useful introduction to the design process, and helps to explain why airplanes for a given mission often look similar. Canard aircraft deserve special attention for comparison with conventional configurations.

Class notes, presentations, sample spreadsheets, descriptive bibliography, and related notes pertaining to Raymer [1] and Schaufele [2] may be found at the website shown at the top of this page.

2 DESIGN REQUIREMENTS

Establishing military design requirements may take ten years or more to develop, with requirements changing over time as a result of evolving threats, available technologies, or shifting politics. For commercial airliners, requirements are usually defined by a team comprising the manufacturer and one or more airlines who will be initial operators, and this process may take only a couple of years. The requirements team must agree on the technology readiness level (TRL) of the technologies that will be employed in the design. For commercial aircraft, this should be TRL 7 or greater, but for military applications the value will typically be lower. For this course the requirements document is usually provided by the instructor, or the students compete in an AIAA student design competition for which requirements may be military, commercial, or general aviation. Students should also be introduced to the relevant Federal Aviation Regulations (FARs), especially Parts 1, 23, 25, 36, 91 and 121.

An important part of the requirements document is the mission profile, which for business jets should be defined by the National Business Aircraft Association (NBAA) rules, or for larger passenger-carrying aircraft by FAR 121.639 (US domestic operations), or FAR 121.645 (international operations).

3 THE ATMOSPHERE AND AIRSPEEDS

In many textbooks (including Raymer and Nicolai & Carichner), the characteristics of the standard atmosphere and the definitions of various airspeeds are relegated to appendices. Schaufele introduces these in the first chapters, and this is the preferred approach. It is particularly important for the student to understand the difference between true airspeed (TAS), equivalent airspeed (EAS), and indicated airspeed (IAS).

4 INITIAL ESTIMATE OF TAKEOFF GROSS WEIGHT

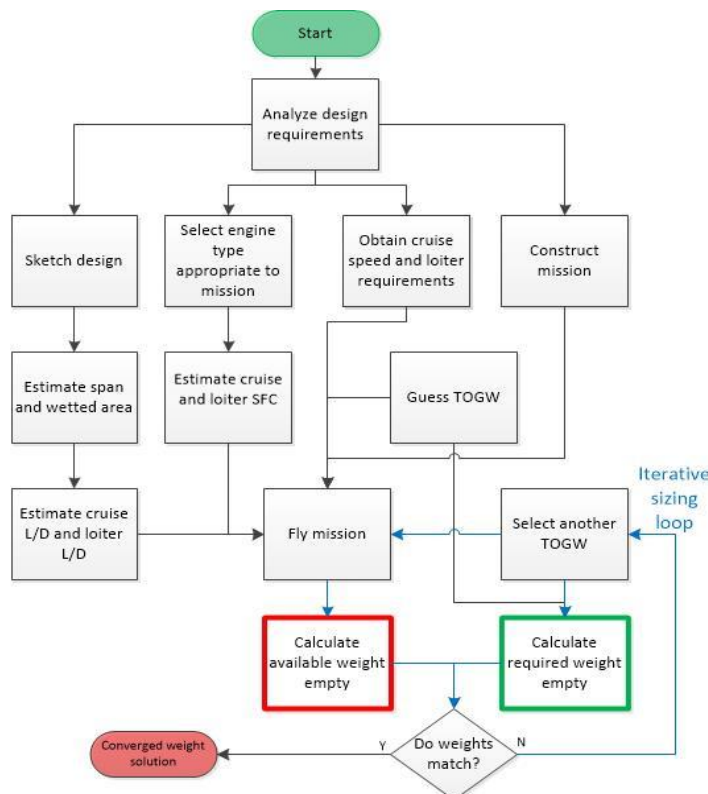


Figure 1 Flowchart for Initial Sizing

In industry, preferably two or more design concepts are developed through the conceptual (and possibly preliminary) design process, with downselect by an integrated product team (IPT) which includes various technical disciplines. Raymer's book describes one such development. An initial 'sketch' is drawn (but more realistically a three-view drawing) for which takeoff gross weight (TOGW), thrust/weight (T/W) and wing loading (W/S) have not yet been calculated. One of the first analytical tasks is to estimate the TOGW required to perform the design mission (Fig. 1).

If the relationship between empty weight required (using Nicolai’s terminology) and TOGW is non-linear, based on statistical relationships of similar aircraft (e.g., single aisle, twin-engine airliners), or component weight buildup, then “empty weight matching” is the preferred method, i.e., matching empty weight required with the empty weight available, based on analytically flying the aircraft on the design mission, and subtracting fuel, crew, and payload weight from the assumed value of TOGW (Fig. 2). This is an iterative process, and may be solved manually, graphically using the Solver add-in to MS Excel, or other computer software. Fig. 2 shows empty weight required as a linear function, in which case iteration would not be required, but in practice it is not quite linear.

If the takeoff gross weight is expressed as:

$$W_0 = W_{crew} + W_{payload} + W_f + W_e \tag{1}$$

- where W_0 = takeoff gross weight
- W_{crew} = crew weight
- $W_{payload}$ = payload weight
- W_f = mission fuel weight, including reserves
- W_e = empty weight required

then
$$W_0 = \frac{W_{crew} + W_{payload}}{1 - (\frac{W_f}{W_0} + \frac{W_e}{W_0})} \tag{2}$$

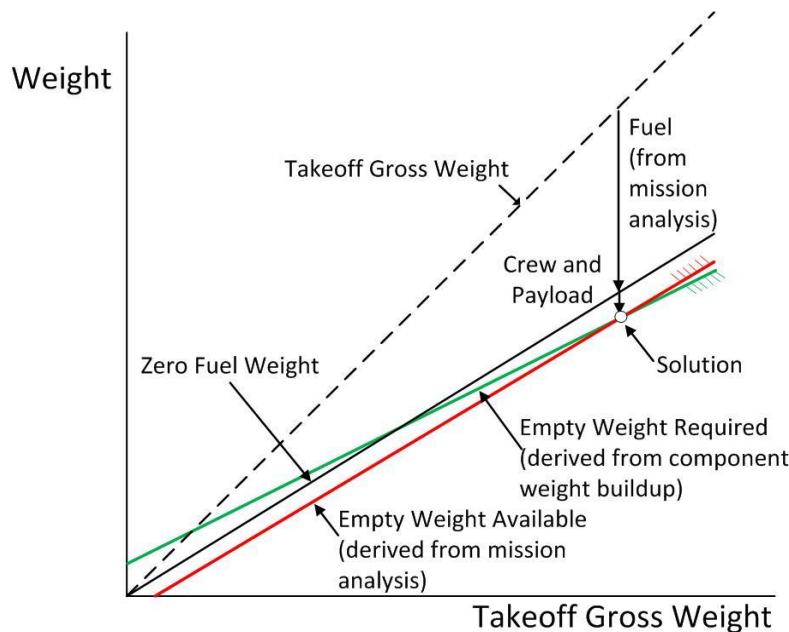


Figure 2 Illustration of Empty Weight Matching

The fuel fraction is determined using the Breguet range equation, plus estimates of fuel burned in takeoff and landing. Eq. (2) and Fig. 2 reveal an inherent difficulty with estimating takeoff gross weight. If the crew plus payload weight is small as a fraction of takeoff gross weight, then the fuel plus empty weight fraction approaches unity. This makes the denominator of the equation very small,

and very sensitive to either fuel fraction or empty weight required fraction. Both of these values are rather rough estimates. In the Breguet range equation, both lift/drag ratio (L/D) and specific fuel consumption (sfc) are estimates, and the empty weight required ratio is based on the class of aircraft, and not related to the drawing. The reality is that in industry, this step may be skipped entirely, and the initial value of TOGW is simply based on that of a competitive aircraft; detailed sizing is done with an “industrial-grade” program which contains more detailed methods for estimating performance variables and weights.

Nevertheless, it is worth introducing the process of empty weight matching early in the design process. It is the process used in industrial-grade sizing programs, using more accurate methods for calculating L/D, sfc, mission definition, and empty weight required. These will be introduced to the students later on in the course.

If MS Excel (with Solver installed) or MATLAB code has been written to size the aircraft, then it is easy to do an initial sensitivity analysis (Table 1) to give students a good idea of the sensitivity of assumptions to TOGW.

Configuration	(L/D) _{max}	Cruise sfc	Empty weight reduction factor	Empty weight	TOGW
Baseline	18.0	0.50	1	???	???
L/D improvement	19.8	0.50	1.0	???	???
SFC improvement	18.0	0.45	1.0	???	???
Empty weight reduction	18.0	0.50	0.9	???	???
All technologies applied	19.8	0.45	0.0	???	???

Table 1 Example of Initial Sensitivity Analysis

5 THRUST/WEIGHT AND WING LOADING

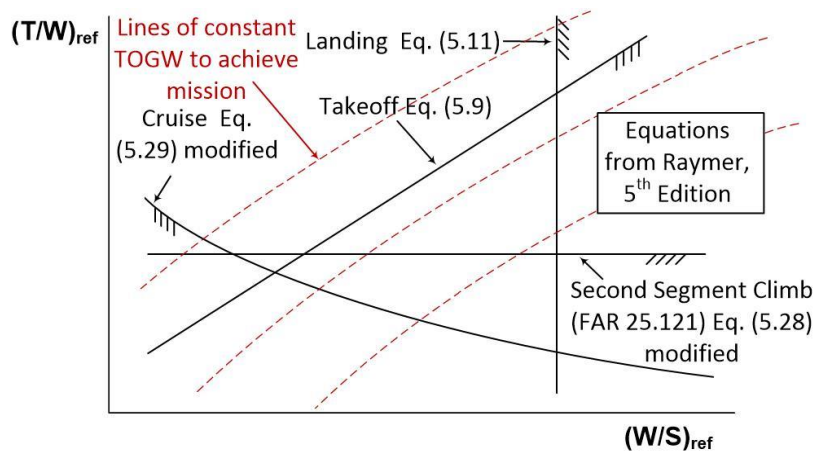


Figure 3 T/W vs. W/S Plot for Commercial Aircraft
 $(W/S)_{ref}$, and how they constrain the design. Roskam [5, Vol I] introduces this constraint plot early in the design process, and this is the preferred approach. Using Raymer, it is possible to generate a slightly simplified plot using equations in Chapter 5, with some minor modifications, as shown in Fig. 3.

Note that the values of T/W and W/S are reference values, usually defined by:

T_{ref} = Installed thrust at sea level static, standard day conditions, all engines operating

W_{ref} = Maximum takeoff gross weight (usually ramp weight)

S_{ref} = Reference wing area (usually trapezoidal, but Boeing and Airbus use different definitions).

Often the suffix _{ref} is implied, but it is important to ratio the values, calculated at the appropriate point in the mission, to the reference values. Takeoff gross weight is a useful proxy for aircraft operating cost, because the two are closely related, so minimizing takeoff gross weight is a good first-order goal. Contours of takeoff gross weight to perform a subsonic commercial airliner mission are superimposed on the figure. Those of a military aircraft are often similar (see Raymer Fig. 19.3), but those of a supersonic airliner or UAV may be very different. Generating these contours

In both Raymer's, and Nicolai & Carichner's, textbooks the concept of the thrust/weight $(T/W)_{ref}$ and wing loading $(W/S)_{ref}$ constraint plot is not introduced to students until quite late in the book. This leaves students wondering what the relationships are between $(T/W)_{ref}$ and

requires more information than is available to the students at this point in the design process, but the contours illustrate that for a subsonic airliner a constrained minimum gross weight configuration lies somewhere along the takeoff constraint line. Values of $(T/W)_{\text{ref}}$ and $(W/S)_{\text{ref}}$ should be selected that are far from the landing constraint line to provide for future growth in TOGW without exceeding the landing constraint.

The location of the takeoff and landing constraint lines are a function of the design takeoff and landing lift coefficients. A higher takeoff lift coefficient may result in a lower value of $(T/W)_{\text{ref}}$. Quantifying this trade (higher wing weight vs. reduced engine weight) is beyond the capabilities of the student at this time. Values of lift coefficient for takeoff and landing should be selected that are based on comparable aircraft. An industrial-grade sizing and performance program will generate plots similar to Fig. 3.

6 LAYOUT AND LOFT

Student teams of four or five students should have at least one member who is proficient in computer-aided design (CAD). However, hand-drawn drawings are preferable to crude CAD drawings. Vehicle Sketch Pad (www.openvsp.com) may be used to generate the outer mold line (OML). When the design is reasonably firm, the designer should also generate a model of the primary load-carrying structure (“bones drawing”) and also show where the major components, such as cockpit, passenger cabin (or other payload bays), fuel tanks, landing gear, avionics bay, environmental control system, radar, and other systems are located. For passenger aircraft, attention must be paid to both regular exits and emergency exits defined by FAR 25.807. For military airlifters, the ability to load bulky cargo (if required in the request for proposal), such as large vehicles or weapons, must also be demonstrated.

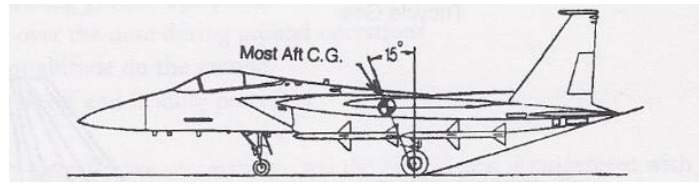
Students should examine cutaway drawings of similar aircraft, of which many can probably be found on the internet. Why are commercial airplanes and military airlifters so different structurally from fighters? What are the primary loads, both point loads (such as landing loads), and distributed (such as lift), and how are these loads carried through the structure? Students must get a good feel for these load paths, even though they may not have enough time for quantitative evaluation. Students should also understand why components, such as the auxiliary power unit (APU) are usually placed in a certain position. For military aircraft design, a qualitative discussion of stealth characteristics is required.

Wing design is a separate technical discipline, and in a design office the designer will work closely with aerodynamicists, structural engineers, stability and control engineers, and others, to optimize the wing. Airfoil section properties as a function of spanwise location are mostly the responsibility of the aerodynamics group, but overall characteristics (aspect ratio, sweep, thickness/chord, taper ratio) are joint responsibilities. Optimization may be either graphical or using multidisciplinary optimization (MDO) software. In the student environment, there is usually insufficient time for this, and students may have to select values based on competitive aircraft.

7 LANDING GEAR AND SUBSYSTEMS

Particular attention must be paid to landing gear location and retraction. An initial assumption must be made of the forward and aft center of gravity (c.g.) locations. Based on data in Torenbeek [5], for commercial designs or airlifters, a range of 15% to 35% of the mean aerodynamic chord (MAC) is reasonable, with a nominal value of 25% MAC. For fighters a nominal range of 20% to 40% can be assumed.

For conceptual design a 15° angle between the aft center of gravity and main landing gear trunnion (Fig. 4) is usually acceptable, although additional design analysis may show that this angle can be decreased by a few degrees for an unswept wing, and must be increased for a highly swept wing.



Source: Schaufele

Figure 4 Location of MLG Relative to Aft c.g.

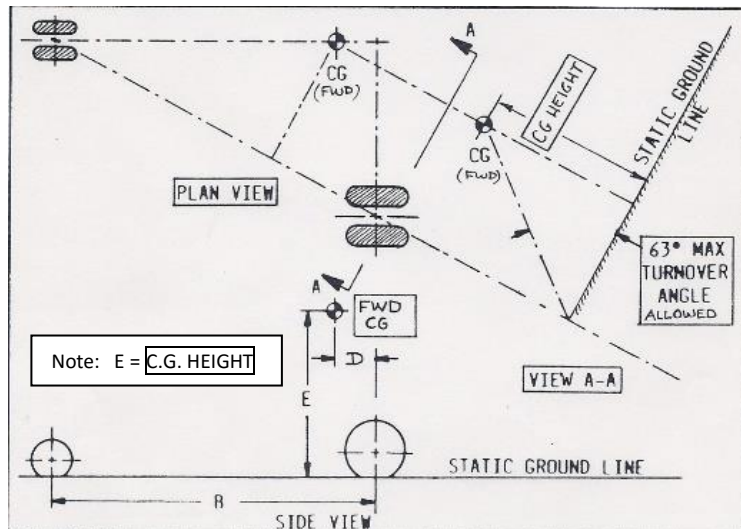


Figure 5 Calculation of Lateral Tip-over Angle

Students often have difficulty generating the scrap view, shown as VIEW A-A in Fig. 5 to illustrate compliance with the 63° maximum angle for lateral tipover. The scrap view is a view looking along the axis parallel to the line between the center of the nose landing gear trunnion (projected vertically on to the ground) and the center of the main landing gear trunnion, similarly projected. The value of 63°

represents a one-half g lateral turn on a taxiway. This requirement can usually be met quite easily for an aircraft with wing-mounted main landing gear, but more difficult to meet for fuselage-mounted gear. For carrier-based aircraft, the value is usually 54° .

7 PROPULSION SYSTEM SELECTION AND LOCATION

For students, selecting an engine with characteristics that best match the mission requirements is difficult, and at the most simple level may be based on an engine with static thrust that most closely meets that required by performance analysis, and has a bypass ratio that is similar to that of competitive aircraft.

Selecting the wrong engine location for an aircraft type has doomed some aircraft programs, and it is worth discussing the various trades involved. For commercial aircraft, they usually involve many aircraft characteristics, such as maximum lift coefficient ($C_{L_{max}}$), minimum control speed (V_{MC}), longitudinal stability, empty weight fraction, maintainability, passenger and cargo loading, and interior noise.

8 AERODYNAMICS

Generating C_L vs. α plots is described in a fairly straightforward manner in most textbooks. Raymer and Nicolai & Carichner reference α values to the wing reference plane, rather than the fuselage reference plane as used in Schaufele and Torenbeek, the latter which is standard for commercial aircraft. The difference between the two planes is selected by the designer, and is a function of the desired fuselage attitude during cruise.

Calculating zero-lift drag is also straightforward, and almost all textbooks use the same procedure, although few present the calculations in a tabular format that is suitable for spreadsheet analysis. Estimation of incompressible drag due to lift (universally, but incorrectly, referred to as ‘induced’ drag) is also fairly straightforward. Using the methods of Shevell [6], Schaufele provides a method for calculating the effect of the fuselage on drag due to lift.

Estimating the effect of compressibility on drag due to lift is difficult, in part because of disagreement about definitions. The Boeing definition of drag divergence Mach number (M_{DD}) is the Mach number at which the drag is 20 counts (or $\Delta C_D = 0.0020$) above the incompressible value. The Douglas definition (also used by the US Air Force and by other researchers in this area) is the Mach number at which $dC_D/dM = 0.10$. In general, the Douglas definition is preferred. Raymer also states that the Douglas value of M_{DD} is about 0.06 above the Boeing value. In practice, this difference can vary considerably, and sometimes the Douglas definition produces a value that is less than that of the Boeing definition. This is due to large differences in the shape of the drag rise for different airfoil sections. This can be seen in the numerous drag plots (i.e. sets of curves of C_D as a function of M for different values of C_L) in Obert [7]. A notional plot is shown in Fig. 6. The best that can be done is to admit that whatever results are generated can only be approximate.

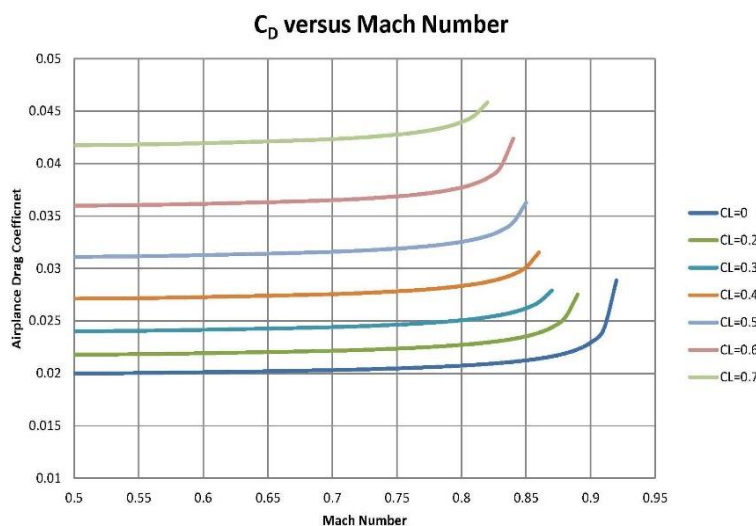


Figure 6 Spreadsheet-generated Notional Drag Plot

The drag plot does not appear in Raymer or Nicolai & Carichner, although it is probably the single most useful way to compare the aerodynamic efficiency of high-speed subsonic aircraft. Two additional plots are derived from the drag plot: a plot of L/D vs. C_L , and a plot of ML/D vs. C_L , both for different values of Mach number. The latter plot provides confirmation for selection of the cruise Mach number. A procedure for generating these plots is described in Schaufele. The critical issue is the method for estimating M_{DD} . Options are to use one of the following: 1) the chart in Raymer, 2) the chart in Schaufele showing M_{DD} as a function of average t/c , C_L and wing sweep, 3) the Korn equation ([8], Section 9.15), or 4) DATCOM [9]. Schaufele’s chart ([2], Fig. 4.8), or the Korn equation, are the preferred methods for generating an equation for M_{DD} as a function of wing geometry to insert in a spreadsheet. The Korn equation contains a constant (κ) which allows more advanced wing technology to be assumed.

Supersonic zero-lift drag and drag due to lift can only be approximated without using methods beyond those available to students. These approximate methods are described in Raymer and Nicolai & Carichner. An explanation of the significance of area ruling provides an example of a major breakthrough in aerodynamics.

A qualitative explanation of winglets, vortex generators, and other flow modification methods should also be discussed.

9 STRUCTURES AND LOADS

Students should be able to generate the maneuver V - n diagram and estimate the gust V - n diagram (the exact diagram requires detailed computational analysis). They should also understand the relative benefits of different structural layouts and materials. Simple loads analysis is usually left to a two-semester course.

10 WEIGHT ESTIMATION

Most textbook weight equations only apply to the most common configurations, and it is difficult, for example, to do a trade study on transport aircraft engine location, because the weight equations for both wing and fuselage may not include that variable. Torenbeek's methods include wing weight reduction for engines mounted on the wing although they not consider spanwise location. Nor do they include the additional fuselage bending weight penalty from having engine mounted on the rear fuselage. Just about all weight equation systems do allow parametric evaluation of aspect ratio, sweep and t/c , but the location of the optimum configuration is strongly dependent on the equations themselves, which do not consider every design feature. So the benefit of doing such a trade study is questionable. Roskam's Airplane Design, Part V [5] probably has the most comprehensive set of weight equations, and includes those of Cessna, USAF, and Torenbeek.

11 STABILITY AND CONTROL

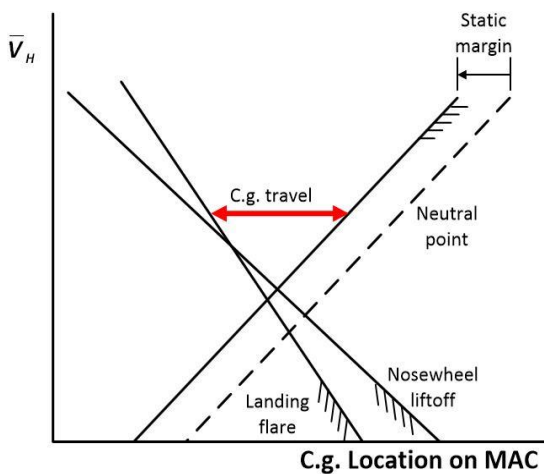
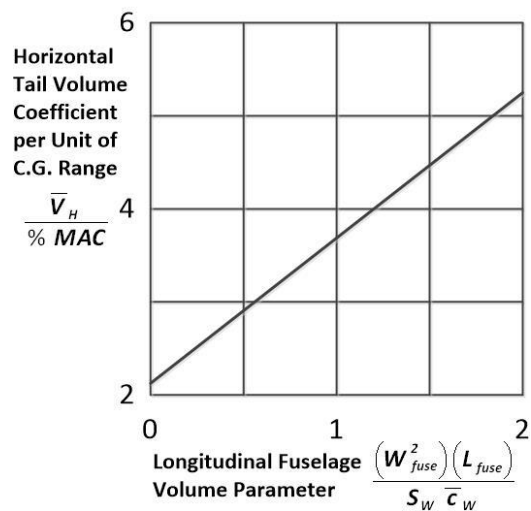


Figure 7 Notch Chart to Calculate \bar{V}_H

To calculate the horizontal tail volume coefficient (\bar{V}_H) the method used in industry is to plot a “notch” chart (using the Lockheed term), or “scissors” plot (using Douglas terminology), (Fig. 7). Generation of the notch chart requires fairly detailed knowledge of aircraft geometry and associated aerodynamic forces, and cannot be expected of students in a one-semester course.

For commercial airplane designer, one of the most important stability requirements is that for the most critical c.g. location the aircraft must have a positive static margin, as required by FAR 25.175. Students must appreciate the importance of getting the c.g. travel forward of the neutral point. For a fighter the static margin may be negative, and adequate longitudinal stability achieved artificially.



Source: data from Schaufele

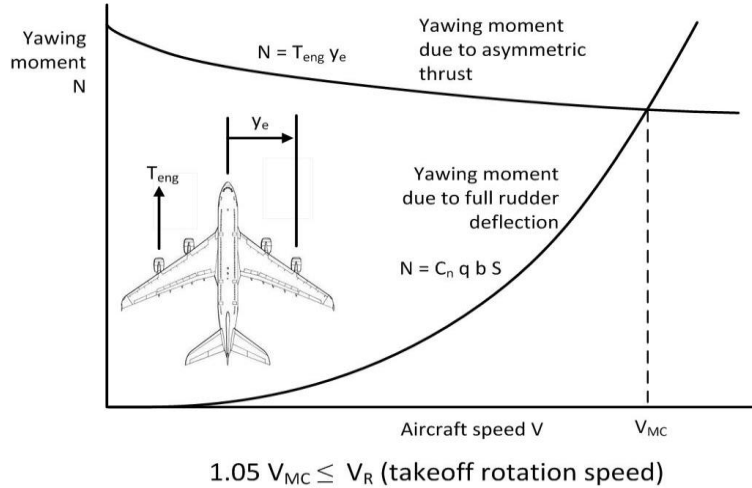
Figure 8 Estimation of \bar{V}_H

For horizontal tail sizing, the simplest method is to select a horizontal tail volume coefficient that is comparable with other aircraft in the same class.

A slightly more accurate method is to use the correlation between horizontal tail volume coefficient per unit of c.g. travel ($\frac{\bar{V}_H}{\%MAC}$) and the longitudinal fuselage volume

parameter $\left(\frac{W_{fus}^2 L_{fuse}}{S_W \bar{c}_W}\right)$ (Fig. 8), where W_{fus} is fuselage width, L_{fus} is fuselage length, S_W is reference wing area and \bar{c}_W is the MAC. The correlation exists, but cause and effect is not obvious.

There is a similar hierarchy of methods for estimating the vertical tail volume coefficient (\bar{V}_V).



$$1.05 V_{MC} \leq V_R \text{ (takeoff rotation speed)}$$

Figure 9 Calculation of V_{MC}

For a commercial aircraft the tail is often sized for meeting the FAR requirements for takeoff minimum control speed (V_{MC}) (Fig. 9). Students can check that $V_{MC} \leq 1.13 V_{SR}$ (stall speed in the takeoff condition) (FAR 25.149(c)).

Detailed aileron sizing is usually left to a two- or three-semester course.

12 PERFORMANCE

A single equation relates required (T/W) vs. (W/S) , at a given point in the mission, for level flight, climb, acceleration, or sustained turn.

$$\frac{T}{W} = q \frac{C_{D0}}{\left(\frac{W}{S}\right)} + \left[\left(\psi \frac{V}{g} \right)^2 + 1 \right] \frac{K}{q} \left(\frac{W}{S} \right) + \frac{P_S}{V} \quad (3)$$

where q is dynamic pressure, C_{D0} is zero-lift drag, ψ is sustained turn rate, V is true airspeed, K is induced drag factor, and P_S is required specific excess power. This equation is needed to add constraint curves to the constraint plot for military aircraft. Students must remember (but often forget) to factor input values of (W/S) from reference values, and factor output values of (T/W) to reference values. A separate equation is required for instantaneous turn rate.

Although of more interest to glider pilots, students should be aware of differences in speeds for gliding at the minimum sink rate and minimum sink angle.

For takeoff and landing, Schaufele provides the best procedure for detailed calculation of balanced field length, all-engine takeoff field length (and hence FAR field length), and landing field length for commercial aircraft. Raymer provides an empirical equation, taken from Torenbeek, to estimate balanced field length which usually also defines FAR field length. These methods provide a more accurate estimate than methods used in initial constraint analysis.

13 COSTS

For military aircraft life cycle cost (LFC) is the preferred method for comparing aircraft costs, and this is treated adequately in Raymer. For commercial aircraft, direct operating cost (DOC) is the preferred method. Through the 1970s and '80s a standardized method of calculating DOC, the Air Transportation Association 1967 (ATA '67) method, was used by both industry and airlines, but when its limitations (such as omission of capital costs) became increasing apparent, several different methods emerged, many of them proprietary. No standardized method has emerged.

An estimation method known as DOC+I (Direct Operating Cost plus Interest) is based on the work of Liebeck [10], who drew upon the operating costs of McDonnell Douglas airplanes in commercial service up until 1993, using data which reflect costs in a deregulated environment. The DOC+I method takes into account the following operating expenditures: fuel, flight crew, airframe maintenance, engine maintenance, landing fees, navigation fee (for international flights), depreciation, interest, and insurance. The equations can be adjusted to account for inflation. Students should be familiar with this or similar methods, but it is unlikely that time can be found to make use of it in a one-semester course.

14 CONCLUSIONS

A one-semester course in aircraft conceptual design can provide only a quick overview of the design process. Students will learn how each technical discipline contributes to the design, and how these technologies must be traded. Time constraints prevent detailed trade studies, but these studies are an important part of the design process. Design analysis is only one part of aircraft design. The design of an aerodynamically, structurally and operationally efficient aircraft is equally important.

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