Preliminary Design of a Business Jet Aircraft

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Type: Design Project
Student Time: One semester (actual class time approximately 10-12 one hour
                    lessons)
Location: In class and take home

Summary

This project requires students to complete the preliminary design of a business jet aircraft. The aircraft parameters which must be estimated or determined are the: payload weight, fuel weight, gross take-off weight, wing planform dimensions, size and location of the horizontal and vertical tail (or canard), cruise lift and drag, engine size and location, and fuselage size. In addition, the mission specifications of range, cruise speed, and time of flight must be determined by each student team. The students complete the design process as a series of structured homework assignments. The final design project report is a compendium of the homework assignments and any additional material the students wish to include in it.

This project is intended to motivate students by providing them a realistic design project in the Freshman Year. However, it does require that the instructor understand aircraft performance and be able to lead students through the empirical process used to arrive at the aircraft parameters.

ABET Descriptors

Engr Sci Content: First Year Engineering
Type: System
Elements: Establish specifications, synthesis, analysis, evaluation
Features: Creativity, open-ended, design theory and methods, formulate
                    specifications, alternative solutions, feasibility, design description
Constraints: Economic, safety, aesthetics, regulations, performance
Effort: Team

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Your team is to design a business jet capable of being flown by a pilot and a co-pilot and carrying from four(4) to twelve(12) passengers and their baggage. Assume that the weight allowance for each crew member and passenger is 200 pounds. During the design process, your team will be required to determine the following:
  1) Weights -- payload weight, gross design take-off weight, and fuel weight
  2) Wing, vertical tail, and horizontal tail or canard {if included} dimensions -- airfoil section, root chord, tip chord, span, aspect ratio, taper ratio, and quarter chord sweep angle
  3) Wing, vertical tail, and horizontal tail or canard {if included} locations
  4) Fuselage size and shape.

During the course of the semester these parameters will be determined in a series of homework problems. At the end of the semester the team will submit a *Design Project Package* in the following format.

Contents and Required Order of the *Design Project Package*

1. A cover sheet in the format provided in the Sample Handout, including team member's full names AND signatures.   [handwritten on 8 1/2 x 11 white paper is OK]

2. A Specification Sheet properly filled out either in ink or typewritten.

3. A two-view drawing properly dimensioned and in the format provided in the Sample Handout. Dimension in inches.   [on 8 1/2 x 11 white paper]

4. A wing panel drawing properly dimensioned and in the format provided in the Sample Handout. Eliminate the labels except for the MAC and the AFT C.G. and enter all dimensions in inches.   [on 8 1/2 x 11 white paper]

5. A top view of the cabin section showing seat and door locations (include the galley and/or lavatory if present in your airplane). Dimension in inches.
                                                                [on 8 1/2 x 11 white paper]

6. The supporting calculations for your design:
  a) neatly handwritten (pencil OK) if the calculations are done by hand
  b) a copy of the input and output from a software package **and** a copy of the equations from the package if the calculations are done on a computer
      1) copy of the equations means either
              (i) copy of the equations in the cells of a spreadsheet such as Excel, or
              (ii) source listing of the program if you wrote a package in BASIC, FORTRAN, etc.

The above are the required items which **must** be included in the *Design Project Package*. Your team may include any other drawings or information related to the design project you would like to include.

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Engineering Notes: The following are descriptions of the process, assumptions, and empirical and theoretical equations used in completing this design. Each "step" is in the format of the homework assignment and then the information required to complete the homework assignment. No drawing formats have been included in this project description.

HW#1. Determine the payload and gross take-off weight of the business jet.
    a. Determine the A/C payload weight

        $W_{payload} = n (170 + W_{baggage\ allowance}) + W_{cargo}$

        $W_{payload}$ = weight of people, baggage and cargo to be carried

            n = total number of people on board (crew + passengers)

          170 = weight of one person specified in the FARs in pounds

        $W_{baggage\ allowance}$ = baggage allowance, typically 25 - 40 pounds/person

        W_{cargo} = weight of additional payload in pounds force

           Use a baggage allowance of 30 lb_f per person

        so that the total weight per person will be 200 lb_f per person

    b. Determine the Gross Take-off Weight, W_{TO}

        W_{TO} = 10 x $W_{payload}$ {*empirical relationship*}

        Where did   10   come from?

        Data fit using EXCEL spreadsheet and aircraft data for Business/Executive Jets in Aviation Week & Space Technology Source Book issue, Jan. 1997

        Results (W_{TO}/ $W_{payload}$):

           for all these aircraft   average = 10.2   std. dev. = 2.6

        for all aircraft < 16 passengers   average =   9.9   std. dev. = 2.9

        for all aircraft ≤ 12 passengers   average = 10.2   std. dev. = 2.7

        Therefore, ten (10) is a reasonable "empirical" based multiple to use to "ESTIMATE" the aircraft "gross weight" from the "payload weight" ASSUMING - number of passengers includes crew members AND each passenger + baggage weighs 200 lbs.   AND no cargo OR cargo weight is offset by reducing the number of passengers

HW#2. Determine the wing planform area(S) required to meet the desired landing speed.
    a. Lift (L) generated by the aircraft is calculated using the Lift Equation:

           $L = 1/2 \ \rho \ V^2 \ S \ C_L$

    b. Definition: Wing planform area (S) equals the area of the shadow of the wing cast on the tarmac by a point source of light at an infinite distance directly above the aircraft. It DOES NOT end at the fuselage and is always measured from the wing tip to the center line of the aircraft.

    c. Rearranging the Lift Equation

          $\underline{\quad\quad L \quad\quad}$

$$S \quad = \quad 1/2 \; \rho \; V^2 \; C_L$$

and recognizing that in flight $L \sim W$

and $\rho = \rho_o$ = standard air density at sea level = 2.3769×10^{-3} slugs/ft^3

and from FARs $V_{landing} = 1.1 \; V_{stall}$, but V is
usually expressed in knots (nautical miles/hour) need to convert to ft/sec
using conversion factor # knots $\times$ 1.6890 = # ft/sec for correct units

d. C_L ranges from 0.1 to close to 2.2 for supercritical airfoils, BUT flap systems
increase C_L and for landing we are interested in C_{LMAX} which is where stall
occurs - for complex flap and leading edge systems C_{LMAX} can be as high
as 3.4

Reasonable value for business jets is C_{LMAX} of approximately 1.8 - 2.2

e. Resulting in:

$$S \quad = \quad \frac{W_{gross}}{1/2 \; \rho_O \; (V_{stall})^2 \; C_{LMAX}} .$$

CHECK the units

S will be in ft^2 IF: W_{gross} in lb$_f$, V_{stall} in ft/sec, and ρ_O in slugs/ft^3

*HW#3. Estimate the wing span (b), root chord (C_r), tip chord (C_t), quarter chord
sweep angle and complete the drawing of the starboard wing semi-span.*

a. Students need to select the following parameters: aspect ratio(AR), taper
ratio(λ), and sweep angle of the 1/4 chord line($\Lambda_{C/4}$). Again Jane's or
other references can be helpful or student's can satisfy their artistic sense.
From these the remaining geometric parameters of span (b) and tip and
root chords (C_t & C_r) are calculated using b = { AR S }$^{1/2}$, $C_t = \lambda \; C_r$
AND

$$C_r \quad = \quad \frac{2 \; S}{b \, (1 + \lambda)} .$$

b. The mean geometric chord (MGC) is assumed to be equal to the mean
aerodynamic chord and the student's are taught a geometric construction
using the wing semi-span drawing to determine the MGC.   The
aerodynamic center (a.c.) is then located as the C/4 point on the MGC.

c. The aircraft "most aft" center of gravity (c.g.) is ASSUMED to be located at a
point 10% forward of the a.c. on the MGC. This is the point used to locate
and size the vertical and horizontal tail locations. The actual c.g. is not
calculated.

*HW#4. Determine the vertical and horizontal tail {and canard if applicable} areas (S_{HT},
S_{VT}, S_C). Then chose AR, $\bf{1}$, and $\bf{L}_{C/4}$ for all these control surfaces and then determine b,
C_r , and C_t for both these control surfaces using the same process as for the wing. Draw
separate planforms for each of the control surfaces, labeling the aerodynamic centers on
each. Draw two views of the location of the control surfaces with respect to the wing.*

*a) top view -- Draw the entire wing planform (both panels) and the entire
horizontal tail planform (both panels) {and canard if applicable}. Be sure to
include the most aft c.g. location and the a.c. location on the wing and the*

a.c. of the horizontal tail {or canard} and the distance between the aft c.g. location and the horizontal tail {or canard} a.c. location.

b) *side view -- Draw a M.G.C. wing airfoil section and a "planview" of the vertical tail. Again be sure to include the location of the aft c.g. and the a.c.'s of the wing and the vertical tail and the distance between the aft c.g. location and the vertical tail a.c. location.*

c) *For both views, label the moment arms to the control surface from the most aft c.g. location, that is l_{tHT} in the top view and l_{tVT} in the side view.*

a. In sizing the horizontal and vertical tail surfaces use the following "rules of thumb" or empirical relationships

- $S_{HT} = 0.30\ S_{wing}$ and $S_{VT} = 0.20\ S_{wing}$

b. To determine the position of the tail aft of the wing for proper stability and control characteristics, the a.c. of the tail surfaces should be at least 2.5 times the M.G.C. of the wing behind the most aft c.g. location.

HW#5. Select your aircraft cruise altitude and cruise speed and then determine for cruise conditions the Reynold's Number (R_e); lift coefficient (C_L); parasite (C_{Do}), induced (C_{Di}), and total drag (C_D) coefficients; and the total drag (D).

a. C_{Do} can be estimated from:

$$C_{Do} = 1.02 \frac{0.455}{(\log R_e)^{2.58}} \left(\frac{S_{wetted}}{S} \right) \quad \textbf{\{empirical relationship\}}$$

where 1.02, 0.455, and 2.58 are pure numbers

$$R_e\ (\text{Reynold's number}) = \frac{\rho\, V\, \overline{c}}{\mu} = \frac{V\, \overline{c}}{\nu}$$

where ρ is the air density ***at altitude*** in slugs/ft^3
   $\underline{V}$ is the true airspeed of the aircraft in ft/sec
   c is the mean aerodynamic (geometric) chord of the wing in ft
   μ is the air viscosity ***at altitude*** in lb sec/ft^2
   S_{wetted} = total exposed surface area of the aircraft, and
   S = wing planform area (the ratio
      of $S_{wetted} / S \simeq 4$, typically)   **\{empirical relationship\}**

b. Therefore, having selected an altitude and Mach number for cruise, the student can then compute the velocity and Reynold's Number and estimate S_{wetted} to determine the parasite drag coefficient.

c. Will also need to "estimate" the "induced" drag caused by producing lift

from $$C_{Di} = \frac{C_L{}^2}{\pi\, e\, AR}$$

where: C_L = lift coefficient
      π = 3.14159......
      e = Oswald's efficiency factor (0.70 to 0.90)
      AR = previously "estimated" wing aspect ratio

In order to determine the lift coefficient, assume that $L = W$ in level, unaccelerated flight and that the weight in cruise equals the gross take-off weight.

d. Then the "estimated" cruise $$C_L = \frac{2\,W_{gross}}{\rho_o\,\sigma\,V^2\,S}$$

where ρ = air density at cruise altitude = $\rho_o\,\sigma$ (slugs/ft^3)

V = true airspeed (ft/sec)

S = wing planform area (ft^2)

e. Therefore, the "induced" drag caused by producing lift is:

$$C_{D_i} = \frac{C_L{}^2}{\pi\,e\,AR}$$

f. The "total" drag coefficient is $C_D = C_{Do} + C_{Di}$ and

the total drag is $$D = \frac{1}{2}\,\rho\,V^2\,S\,C_D$$

HW#6. Select the cruise range and engine for your aircraft. Include the data source for your engine, the number of engines, and the following engine data: model number and/or designation, manufacturer, maximum thrust at Sea Level, TSFC at Maximum Power. Calculate the fuel loads for the cruise phase, the required reserve fuel, and the total fuel load. Also, calculate the aircraft fuel fraction.

a. Selection of an appropriate Jet Engine

For level, unaccelerated flight $T = D$ at the aircraft flight altitude, BUT most engine manufacturers rate their engines in a test stand at sea level conditions AND publish the data as Maximum Thrust generated at ZERO airspeed at Standard Sea Level atmospheric conditions.

Also, the throttle setting (engine rpm) is NOT maximum in cruise AND thrust decreases with increasing altitude (due to pressure drop).

b. Therefore, to account for the difference between the way manufacturers rate their engines and the way the aircraft is actually operated in cruise flight, use the empirical relationship

$(T_{MAX})_{SLS} = T / 0.35 = D / 0.35$

where $(T_{MAX})_{SLS}$ is the MAXIMUM Sea Level STATIC thrust

T is the thrust available from the engine at cruise altitude and rpm

AND T is approximately = the Drag of the aircraft in cruise

c. $(T_{MAX})_{SLS}$ is the TOTAL thrust required, so if designing a multi-engined aircraft (many business jets have two engines) then the Maximum Sea Level Static thrust per engine is determined from

$(T_{MAX})_{SLS}$ per engine = $(T_{MAX})_{SLS}$ / # of engines

d. The cruise fuel load can be estimated by the following:

$(W_{fuel})_{cr} = T\ (TSFC)\ t_{cr}$

where T = the required thrust at altitude (= D),

TSFC = the Thrust Specific Fuel Consumption, and

t_{cr} = the amount of time the aircraft is in the cruise phase

    e. Determine the cruise time (in hours) by "selecting" a range for the aircraft - previously selected cruise speed (or M) when estimating drag (D) AND

$$t_{cr} = X_{cr} / V \quad \text{where } X_{cr} = \text{cruise range (usually in nautical miles) and}$$
$$V = \text{cruise speed (usually in knots nm/hr)}$$

    f. TSFC is a "fuel economy" rating of jet engines that is used to compare engines of different thrust levels, because it is "thrust specific" , that is

"Fuel Consumption(FC)" = weight of fuel consumed per unit time (lbs/hr)
"Thrust Specific(TS)" = unit of thrust (lb)

However, common units used for TSFC are (1/hr), that is (per hour)

    g. So if we

      1) multiply the TSFC by the thrust (T) produced by the aircraft engine(s), then know the fuel consumption in lbs / hour, AND THEN

      2) multiply the fuel consumption by the time the engine(s) burn the fuel, then know the "fuel load" used in cruise in (lbs).

However, the FAA specifies "reserve fuel" requirements for operating aircraft and the normal IFR requirement is for a "reserve" which allows 45 minutes flight time beyond the planned destination airport, therefore the "reserve fuel" load is given by

      3) $\qquad\qquad\qquad (W_{fuel})_{res} = T \ (TSFC) \ (\ 0.75 \ \text{hour} \ )$

      4) Then the total fuel load can be estimated from

$$W_{fuel} = (W_{fuel})_{cr} + (W_{fuel})_{res} = T \ (TSFC) \ (\ t_{cr} + 0.75 \ \text{hrs} \ )$$

    h. **NOTE** that the T in the fuel load calculations is the TOTAL thrust developed by the engine (s) in cruise, <u>NOT</u> the amount of thrust per engine. There is NO NEED to multiply TSFC by the number of engines being flown.

    i. The engine must be capable of generating the thrust needed to overcome drag.

      1) Look for engines with the per engine $(T_{MAX})_{SLS}$ in the range of

$(T_{MAX})_{SLS}$ required $\leq$ T of engine $\leq$ $(T_{MAX})_{SLS}$ required + 200 lbs

      2) Select the engine in the group of engines generated in 1) the has the LOWEST TSFC to minimize the fuel load.

    j. As a rough check on the consistency of the design parameters, compute the aircraft $\qquad$ Fuel Fraction $= W_{fuel} \ / \ W_{gross}$

The aircraft fuel fraction should be approximately 20-25 % for a primarily aluminum structured aircraft.

There are no further homework assignments; however, there are additional configuration and layout features which must be decided upon. The following are covered in the "Final Workshop" usually conducted two weeks prior to the due date of the final **Design Project Package**.

I. Fuselage sizing and Airframe Configuration

    a. To size the cabin (or passenger compartment) assume that seating is arranged as 2 side-by-side with an aisle between seats: 1) divide the # of passengers by 2 and if the result is an integer, then that is the # of rows required, if result is an integer + 1/2, then take the next highest integer as the # of rows. 2) multiply the # of rows by 40" (the "seat pitch", or the fore-to-aft spacing allotted for passengers,

including leg room {this value is normally only used for First Class seating}. The result is the length of cabin required for seating of passengers. If you want to include a galley, assume that it is the same size as one seat position. The same is true for a lavatory.

b. Then establish the fuselage diameter. Actual diameters range from approx. 68" for the Rockwell Sabreliner to approx. 84" for the Gulfstream American G-III. The Sabreliner carries 4 to 6 passengers while the G-III can carry up to 20. The walking headroom in the aisle is directly related to the fuselage diameter and the location of the floor.

c. After establishing the cabin length and diameter, the students still need to add a cockpit and nose cone and a tail cone to the main cabin.

d. A useful source of data on cabin layout and fuselage sizing is Jan Roskam's Volume III (the Yellow one) of his series <u>Airplane Design</u>, pp. 85-107.

II.   After deciding on fuselage configuration, the students need to determine wing positioning relative to the fuselage, that is "high", "low", or "mid-wing." The advantages and disadvantages of the following five factors are discussed: interference drag, lateral stability, field of view from the cockpit, landing gear weight (assuming the gear is wing mounted), and the wing structural carry-through (required to transmit the forces on the wing to the fuselage).

III. Finally, the students need to decide on engine location. The advantages and disadvantages of the four (4) most common engine locations are discussed: under wing, over wing, aft fuselage, and at the wing root (or "buried"). However, the students need to be warned that the engine inlet's should "see" clean, undisturbed air for best performance, and the horizontal tail should be out of the "jet wash" (or engine exhaust).

Objectives/Comments:

The objective of this design project is to motivate students by provided them a realistic design project in the Freshman Year. Over the past four years of using this project in the Freshman "Introduction to Aerospace Engineering" course it has proven to be very motivational for students at Embry-Riddle Aeronautical University; however, these students have a very, very high interest in aviation and airplanes. The course is two semester hours and meets for one hour twice a week. Many other topics are included in the course content.

This design project also requires the students to use library and Internet resources to obtain information on aircraft and jet engines. The students are encouraged to find aircraft similar to theirs and use these data to select the design parameters for their aircraft. Students quickly learn to use Internet and library resources to obtain more information.

The design project is taught as a series of "workshops" for the student design teams rather than in a lecture format. During the first two workshops, the aircraft design process as outlined in <u>Airplane Design</u> by Jan Roskam and in <u>Aircraft Design</u> by Dan Raymer is discussed and explained. The iterative nature of design in general is discussed and the students are permitted to change parameters and "iterate" the design of their

aircraft during the course of the semester long project. A team of four students seems to work the best for this project. The student teams are allowed two weeks to complete each homework assignment.

Outcome: The student teams are expected to complete the preliminary design of a business jet aircraft with a payload and all mission parameters of their choice. During the project they learn the aircraft design process and iterate their design in an attempt to optimize their aircraft. The students learn to use library and Internet resources to find information related to their aircraft and jet engines.

Discussion/Follow-up: The project also serves as a method to introduce the students to the courses they will take prior to the senior capstone aircraft design courses. Thus, it provides a method of outlining the topics and knowledge required to complete more detailed and complicated aircraft design projects. It also provides a means to discuss economic, human factors, safety, regulatory, and other issues which are important considerations in the design, manufacture, and operations of aircraft.