Lesson Plan

Lesson: **PRELIMINARY WEIGHT SIZING OF AIRPLANES**

Timeframe: 2 x 75-minute class meetings

Materials needed:
- Projection system for presenting powerpoint slides.
- Access to computers with AAA program
- Airplane Design textbook by Jan Roskam, volume 1.
- Article by Riboldi & Gualdoni

Learning Objectives:

- Estimate the required gross takeoff weight (W_{TO}) of an airplane to carry out a specified mission.
    - Differentiate between gas-powered airplanes and electric airplanes (i.e. be able to use an appropriate method to size each of these two distinct types of airplanes).
        - Use the fuel-fraction method to size a gas-powered airplane.
        - Use the Riboldi & Gualdoni method to size an electric airplane.
    - Select an appropriate data base of similar airplanes to use as a reference for making assumptions about important airplane performance parameters [e.g. maximum lift coefficient (C_{Lmax}), lift-to-drag ratio (L/D), specific fuel consumption (sfc), propeller efficiency (η_p), battery energy density (W/kg), etc.].
    - Estimate the empty weight of the airplane (W_E) making appropriate assumptions for the use of advanced materials.
    - Estimate the fuel weight (W_F, for gas-powered aircraft) or the battery weight (W_B for electric/hybrid aircraft) necessary to carry out the mission.
    - Make reasonable assumptions regarding important airplane performance parameters [e.g. maximum lift coefficient (C_{Lmax}), lift-to-drag ratio (L/D), specific fuel consumption (sfc), propeller efficiency (η_p), battery energy density (W/kg), etc.].
    - Make reasonable projections for these parameters, taking into consideration technological advancements in the future.
- Predict the takeoff weight sensitivities to (a) payload weight, (b) empty weight, (c) range, (d) cruise speed, (e) specific fuel consumption, (f) propeller efficiency, and for electric/hybrid aircraft in addition to the aforementioned parameters to (g) battery energy density (h) battery specific power, and (i) motor efficiency.

Background

The preliminary design of an airplane begins with preliminary sizing. This involves the estimation of the required takeoff weight, power/thrust, and wing area necessary to carry out the mission. This is a very important, interesting, and critical part of the preliminary design process, as we attempt to nail the airplane weight, the power (for propeller-driven airplanes) or thrust (for jet-driven airplanes) and the wing area required before we even have an idea of what the airplane will look like. These numbers are needed because they will drive one way or another the design of the entire airplane (fuselage, wing and high-lift system, propulsion system integration, landing gear, empennage, weight & balance, stability & control, etc.). The methods used are obviously empirical and rely on a large database of airplanes already built. Having said this, it immediately becomes clear that if we are to propose a drastically new concept (e.g. an electric general aviation aircraft), we will not have a database to rely on for making reasonable assumptions about the various design parameters. Rather, we will have to rely on new technologies that will make this new design concept possible. Hence, we will need to educate ourselves about both the current state-of-the-art in each and every one of these critical technologies (e.g. batteries, electric motors) as well as predictions as to where this state-of-the-art might be five or ten years down the road when this new airplane will be built.

Introduction to Lesson

Students will read chapters 1 & 2 of the textbook (Roskam, 1985) and the article by Riboldi & Gualdoni (2016).

An iterative method is used to determine the takeoff weight of their airplane.

A. Gas-powered aircraft (Roskam, 1985)

The takeoff weight is broken down as:

$W_{TO} = W_{PL} + W_E + W_F$

where W_{PL} is the payload weight, W_E is the empty weight of the airplane – including the crew and the engines – and W_F the fuel weight required for the mission. The payload is easily calculated from the mission specification of the airplane. The iterative process begins by guessing the takeoff weight by comparison to aircraft with similar mission specification. The fuel is then determined using the fuel fraction method and the empty weight follows from the equation above. The relationship between takeoff weight and the (allowable) empty weight, however, is a technological barrier and is unique to each particular class of airplanes (e.g. general aviation, jet transports, turboprop commuter airplanes, etc.). This relationship is expressed with a straight line in a log-log plot. The resulting empty weight calculated from the guessed takeoff weight using the fuel fraction method is compared to the allowable empty weight based on this relationship. If the two values are more than 5% apart, a new takeoff weight is assumed and the process repeated until the empty weight of the airplane converges to within 5%.

B. Electric aircraft (Riboldi & Gualdoni, 2016)

The takeoff weight is broken down as:

$W_{TO} = W_{PL} + W_E + W_{bat} + W_{mot}$

where W_{PL} is the payload weight, W_E is the empty weight of the airplane – including the crew but not the engines – W_{bat} is the weight of the batteries required for the mission, and W_{mot} is the weight of the electric motors. Before we can estimate the weight of the batteries and the motors needed to fulfill the mission, the required power must first be estimated.

For climb: $P_{req-climb} = W_{TO}(RC) + \frac{1}{2}\rho_{climb}C_{D-climb}SV_{climb}^3$

For cruise: $P_{req-cruise} = \frac{1}{2}\rho_{cruise} C_{D-cruise} S V_{cruise}^3$
For loiter: $P_{req-loiter} = \frac{1}{2}\rho_{loiter} C_{D-loiter} S V_{loiter}^3$

where the drag coefficient for each configuration (climb, cruise, and loiter) is estimated from the corresponding airplane drag polar:

$$C_{D,climb} = C_{D0} + KC_{L,climb}^2$$

$$C_{D,cruise} = C_{D0} + KC_{L,cruise}^2$$

$$C_{D,loiter} = C_{D0} + KC_{L,loiter}^2$$

Here only the lift coefficient is assumed different for each configuration; the zero-lift drag coefficient is assumed to be that of the clean aircraft for all three cases. The same assumption (i.e. constant value) is made for K:

$$K = \frac{1}{\pi A e}$$

The lift coefficient will, of course, be different for each configuration and can be estimated from:

$$C_L = \frac{2W_{TO}}{\rho V^2 S}$$

The weight of the batteries is determined from:

$$W_{bat} = \frac{g}{\eta_p} max \left\{ \frac{E_{Climb} + E_{Cruise} + E_{Loiter}}{e}, \frac{max\left[P_{req.climb}, P_{req.cruise,} P_{req.loiter} x \frac{W_{TO}}{\left(W_{TO}/_{P}\right)}\right]}{p} \right\}$$

where:
η_p is the propeller efficiency
e is the specific energy of the battery (Wh/kg)
p is the specific power of the battery (W/kg)

while the weight of the electric motors is determined from:

$$log W_{mot} = C + DP_{mot}$$

where C and D are regression coefficients in the motor weight vs. power relationship for existing electric aircraft and depend on the database of electric aircraft used in this relationship.

Procedure [Time needed, include additional steps if needed]:

Pre-Class Individual Space Activities and Resources:

Steps	**Purpose**	**Estimated Time**	**Learning Objective**
Step 1: Read Roskam vol.1, chapter 2, sections 2.1 – 2.5	Become familiar with preliminary weight sizing method for gas-powered aircraft.	1 hr	Estimate the required gross takeoff weight (W_{TO}) of a gas-powered airplane to carry out a specified mission.
Step 2: Read Roskam vol.1, chapter 2, section 2.6 (examples)	Become familiar with preliminary weight sizing method for gas-powered aircraft.	30 min	Estimate the required gross takeoff weight (W_{TO}) of a gas-powered airplane to carry out a specified mission.
Step 3: Read article by Riboldi & Gualdoni (pages 1 – 5) on the weight sizing of electric aircraft.	Become familiar with preliminary weight sizing method for electric aircraft.	1 hr	Estimate the required gross takeoff weight (W_{TO}) of an electric airplane to carry out a specified mission.
Step 4: Carry out examples 1, 2, and 3 in Roskam 2.6.1, 2.6.2, and 2.6.3 in the Advanced Aircraft Analysis (AAA) Program installed in the computers in AE MMCL (Engr.164)	Become familiar with the Advanced Aircraft Analysis (AAA) Program.	30 min	Estimate the required gross takeoff weight (W_{TO}) of a gas-powered airplane to carry out a specified mission.
Step 5: Carry out the examples discussed in Riboldi & Gualdoni (pp. 8-16) in the Advanced Aircraft Analysis (AAA) Program installed in the computers in AE MMCL (Engr.164)	Become familiar with the Advanced Aircraft Analysis (AAA) Program.	30 min	Estimate the required gross takeoff weight (W_{TO}) of an electric airplane to carry out a specified mission.

In-Class Group Space Activities and Resources:

Steps	**Purpose**	**Estimated Time**	**Learning Objective**
Step 1: Individual quiz on preliminary weigh sizing concepts.	Accountability for individual space activities.	10 min	Make reasonable assumptions regarding important airplane performance parameters [e.g. maximum lift coefficient (C_{Lmax}), lift-to-drag ratio (L/D), specific fuel consumption (sfc), propeller efficiency (η_p), battery energy density (Wh/kg), etc.].

Step 2: Outline weight sizing method for gas-powered and electric aircraft.	Review material read during individual space activities; answer questions	10 min	Estimate the required gross takeoff weight (W_{TO}) of an airplane to carry out a specified mission. Differentiate between gas-powered airplanes and electric airplanes (i.e. be able to use an appropriate method to size each of these two distinct types of airplanes).
Step 3: Students estimate the fuel weight or the battery weight based on the selected mission specification of their airplane. 3.1 Determine the mission payload (W_{PL}) 3.2 Guess a likely value of the takeoff weight ($W_{TO,guess}$) 3.3 Determine the mission fuel weight (W_{ff}) 3.4 Find the allowable value of the empty weight (W_E) from stats of similar airplanes	Carry out step 2 of the preliminary design sequence for their selected airplane mission.	20 min	Estimate the fuel weight (gas-powered) or the battery weight (electric) necessary to carry out the mission
Step 4: Students estimate the required gross takeoff weight based on the selected mission specification of their airplane.		10 min	Estimate the required gross takeoff weight (W_{TO}) of a gas-powered or an electric airplane to carry out a specified mission.
Step 5: Students are called to share the results of their preliminary weight sizing.	Students receive feedback on their results from peers and instructor.	15 min	All.
Closing Minutes	Summarize, synthesize, solicit questions	10 min	All

Closure / Evaluation:
Selected Type of Activity: ***PBL***

Why is this activity well suited to the concept / topic?
Students will engage, as it is relevant to their particular airplane design project, on which lies their entire course grade.

How will you know that students have mastered the CLO as a result of this activity?
(a) From their answers on the quiz and (b) from the results of their preliminary design.

Analysis:

This is a graduate GWAR course and students are required to do individual projects, so they can write individual reports to ensure that each and every student improves their writing skills. Hence, unlike other design courses in which each team has one project, in AE271 each student designs his/her own airplane and write their own report. Teamwork is still used, however, in ways that allows students to compare notes on their projects, check and comment on each other's work, and provide feedback to each other.

In the past many students had difficulty with various parts of the project and never came for help outside of class. The in-class group space activities require all students to work on critical parts of their design projects when I am available to answer questions and coach each student according to their individual needs. This is especially important for preliminary design as students struggle to make various assumptions about key parameters, which have a major impact on their design.

Post-Class Individual Space Activities:

Students will start writing Chapter 2 of their aircraft design report – preliminary weight sizing – following the outline below:

Title (e.g. Four Seat General Aviation Electric Aircraft)

List of Symbols (update to include all new parameters introduced in chapter 2)

Chapter 2 – Weight Sizing & Weight Sensitivities

(What follows is a specification for the minimum required content of chapter 2 of your aircraft design report. You may within each section add subsections, if you so desire. You may also add appendices.)

Introduction

The purpose of this chapter is to…

Mission Weight Estimates

2.1 Data Base for Takeoff Weights and Empty Weights of Similar Airplanes

Include at least 10 airplanes in this data base.
Tabulate the weight data, airplane types and data source.

2.2 Determination of Regression Coefficients A and B

Include a log-log plot of your weight data.
Compare your results with those in Roskam or in other references, as appropriate.
You must use the regression coefficients that you determined for the calculation of your takeoff weight.

2.3 Determination of Mission Weights

2.3.1 Manual Calculation of Mission Weights

You must perform and document at least one hand calculation to demonstrate an understanding of the procedure.

2.3.2 Calculation of Mission Weights using the AAA Program

Include the appropriate screendump(s) to document your work.

Takeoff Weight Sensitivities

3.1. Manual Calculation of Takeoff Weight Sensitivities

Perform and document at least one hand calculation for each sensitivity to demonstrate an understanding of the procedure.

3.2 Calculation of Takeoff Weight Sensitivities using the AAA Program

Study the sensitivity of your W_{TO} with respect to as many of the following parameters as appropriate for your airplane:

- payload weight W_{PL}
- empty weight W_E
- range R
- endurance E
- lift-to-drag ratio L/D
- specific fuel consumption (sfc)
- propeller efficiency η_p
- battery energy density
- motor efficiency

…and calculate the corresponding growth factors.
Include the appropriate screendump(s) to document your work.

3.3 Trade Studies

Perform trade studies of W_{TO} vs. critical parameters in your mission (e.g. L/D, sfc, battery energy density, etc.)
In particular, do a trade study between range and payload as follows:

Keep W_{TO} constant and trade R for W_{PL} or vice versa. Show the results on a W_{PL} vs. R graph (you may also want to set an upper limit for W_{PL} based on fuselage volume constraints and/or load bearing limits).

The results of all the trade studies should be presented in graphs.
Use the trade studies you performed to find the best design point relating to the mission of your airplane.

4. Discussion

Discuss the results of your weight calculations.
Discuss the significance of the W_{TO} sensitivities and compare them against your trade studies results.

5. Conclusions and Recommendations

5.1 Conclusions

5.2 Recommendations

References

Connections to Future Lesson Plan(s):

The next topics within Step 2 of the preliminary design sequence involve:

A. Calculating takeoff weight sensitivities to (a) payload weight, (b) empty weight, (c) range, (d) cruise speed, (e) specific fuel consumption, (f) propeller efficiency, and for electric/hybrid aircraft in addition to the aforementioned parameters to (g) battery energy density (h) motor efficiency.
B. Performing trade studies.

You will then complete Chapter 2 of your design report with the addition of the subsections highlighted in red above.

References

Bradley, M.K. & Droney, C.K. (2012, May). Subsonic ultra green aircraft research phase II: N+4 advanced concept development. NASA/CR-2012-217556.

Bradley, M.K. & Droney, C.K. (2015, April). Subsonic ultra-green aircraft research phase II: Hybrid electric design exploration. NASA/CR–2015-218704/Volume II.

Bradley, M.K., Allen, T.J. & Droney, C.K. (2014, April). Subsonic ultra-green aircraft research phase II: Truss braced wing aeroelastic test report. NASA/CR–2015-218704/Volume III.

Riboldi, C.E.D. & Gualdoni, F. (2016). An integrated approach to the preliminary weight sizing of small electric aircraft. *Aerospace Science and Technology,* 58, 134–149.

Roskam, J. (1985). Airplane design, Part 1: Preliminary sizing of airplanes. Roskam Aviation and Engineering Corporation Rt4, Box 274, Ottawa, Kansas 66067, USA.