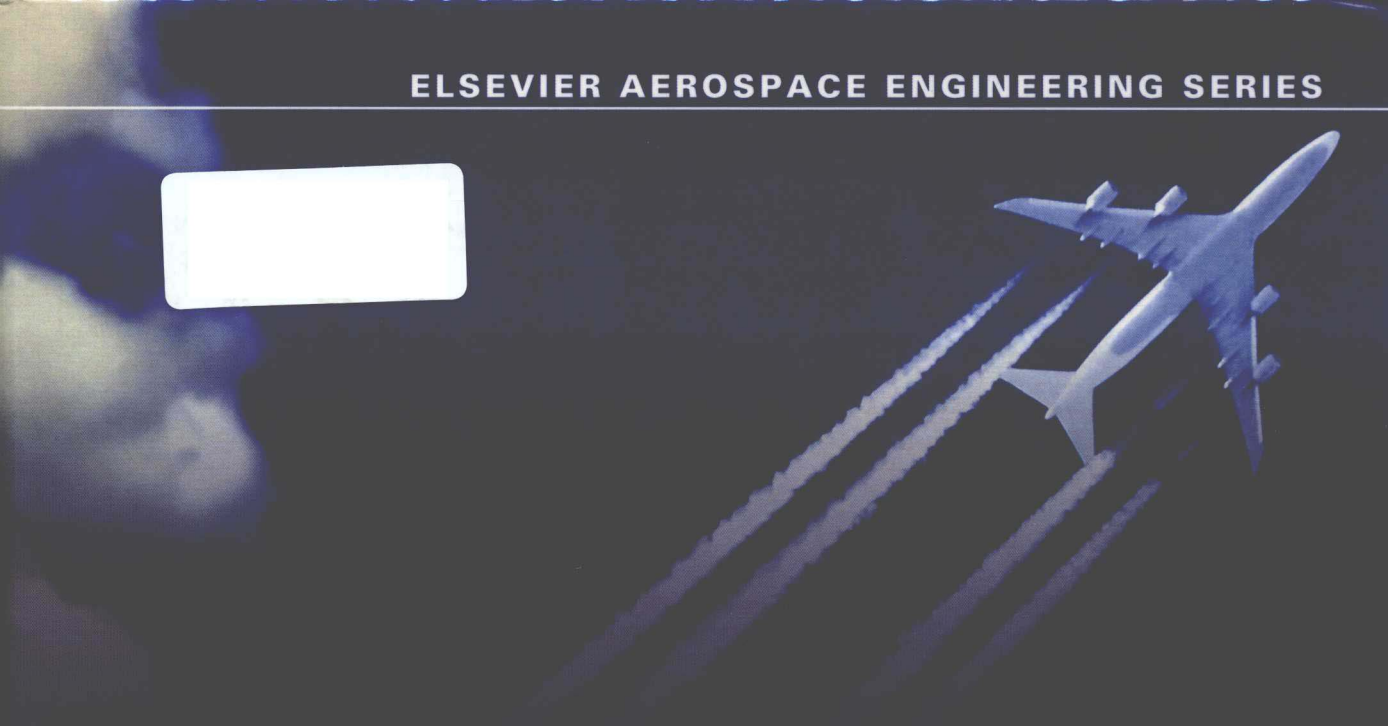
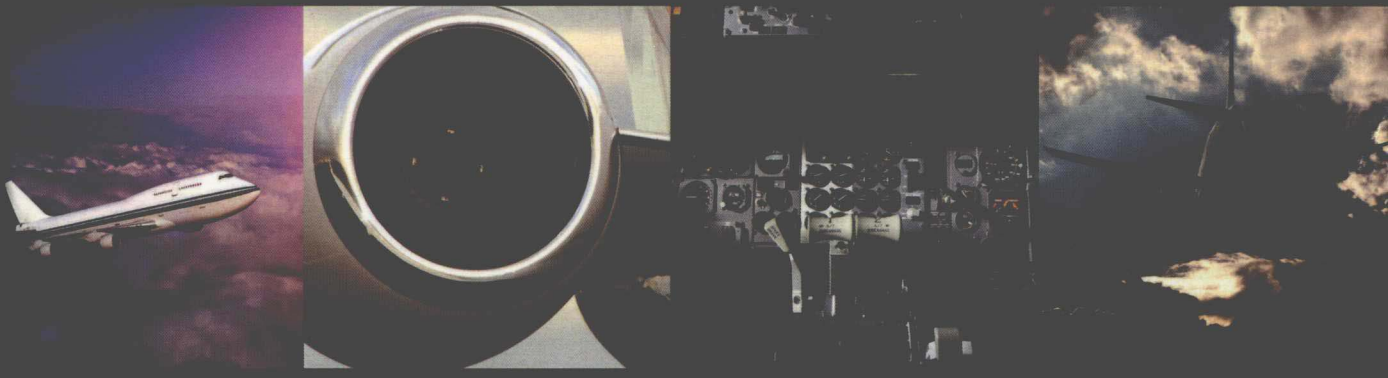
ELSEVIER AEROSPACE ENGINEERING SERIES



Commercial Airplane Design Principles



Pasquale M. Sforza

B/H

Commercial Airplane Design Principles

Pasquale M. Sforza
University of Florida

ELSEVIER

AMSTERDAM • BOSTON • HEIDELBERG • LONDON
NEW YORK • OXFORD • PARIS • SAN DIEGO
SAN FRANCISCO • SINGAPORE • SYDNEY • TOKYO

Butterworth-Heinemann is an imprint of Elsevier

Butterworth-Heinemann is an imprint of Elsevier
The Boulevard, Langford Lane, Kidlington, Oxford OX5 1GB, UK
225 Wyman Street, Waltham, MA 02451, USA

First edition 2014

Notice

No responsibility is assumed by the publisher for any injury and/or damage to persons or property as a matter of products liability, negligence or otherwise, or from any use or operation of any methods, products, instructions or ideas contained in the material herein. Because of rapid advances in the medical sciences, in particular, independent verification of diagnoses and drug dosages should be made.

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library

Library of Congress Cataloging-in-Publication Data
A catalog record for this book is available from the Library of Congress

ISBN: 978-0-12-419953-8

Preface

This book grew out of a handbook originally prepared to support a one-semester senior undergraduate course devoted to airplane design. It is intended primarily to involve students in the preliminary design of a modern commercial turbofan or turboprop transport. The technical content is arranged to illustrate how the material covered in aerospace engineering analysis courses is used to aid in the design of a complex system. In addition, the format of the book is aimed at being amenable to self-education in the topic and to distance-learning online applications.

Commercial aircraft design is a relatively mature field and sufficient reference material is available to provide a secure mooring for student research and study. An industrial approach is taken in order to help instill the spirit of the design process, which is that of making informed choices from an array of competing options and developing the confidence to do so. In the classroom setting this design effort culminates in the preparation of a professional quality design report and an oral presentation describing the design process and the resulting aircraft. This report and presentation provides evidence of both the design and communication skills of the author(s) and can be of significant value in job interviews as well as in the developing report-writing skills for graduate theses.

The book is arranged in a manner that facilitates team effort, the usual course of action, but also provides sufficient guidance to permit individual students to carry out a creditable design as part of independent study. Emphasis is placed on the use of standard, empirical, and classical methods in support of the design process in order to enhance understanding of basic concepts and to gain some familiarity with employing such approaches which are often encountered in practice. Though some popular computational methods are described, none are specifically used in this book. Students may choose to use available codes for particular applications, and have done so, with varying degrees of success. Spreadsheet skills are generally sufficient to support the preliminary design process and such skills are quite valuable to those setting out on industrial careers. Because CAD courses are generally required in engineering programs, their use in preparing drawings is encouraged.

My experience in teaching design over the years has led me to embrace the use of basic analyses and reliable empiricisms so that students have the opportunity to learn some of those applied aeronautical engineering skills that have been edged out of modern curricula by reductions in the total credit hours required as well as the perceived need for broadening skills in other areas. Indeed, it is often the case that many students studying aerospace engineering have only a passing acquaintance with the airplane as a system that integrates many of the individual technologies they have been studying in analysis courses. Class meetings in a university setting rarely provide more than 40 contact hours for explaining the design process and for conferring with the instructor. Thus there must be a substantial amount of time spent outside class in preparing the aircraft design.

This book represents cumulative efforts of the author over a number of years of offering this course at the University of Florida, and before that, at the Polytechnic Institute of New York University in Brooklyn. Because of the wide diversity of material and techniques employed, errors are bound to appear. The responsibility for such errors is mine and I would appreciate learning of any so they may be corrected.

I would like to acknowledge the contributions to these notes over the years made by the late Professors A.R. Krenkel, B. Erickson, and G. Strom and to the students who have participated in my course over the years and often provided suggestions and corrections that proved to be of great value. Finally, I am delighted to once again thank my wife, Anne, for her continuing encouragement and support for my efforts in writing yet another book.

Pasquale M. Sforza
Highland Beach, FL
September 2, 2013

Introduction and Outline of an Airplane Design Report

Preliminary design

The preliminary design of a commercial aircraft is a feasibility study aimed at determining whether or not a conceptual aircraft is worthy of detailed design study. Only six statements are needed to define the mission specification and initiate a preliminary design study for a civil aircraft: type (private, business, or commercial), powerplant (reciprocating, turboprop, or turbofan), passenger capacity, cruise speed, cruise altitude, and maximum range in cruise. The information sought in a preliminary design study is described in the following list:

1. market survey: an assessment of the competing aircraft that have characteristics similar to those of the concept aircraft,
2. initial sizing and weight estimate: development of preliminary weight information based on range requirements and empirical data,
3. fuselage design: development of cabin design layout based on mission specification,
4. engine selection: terminal operations and cruise requirements set the range of engine possibilities and the wing size,
5. wing design: wing planform and airfoil selection, high lift devices, maximum lift capability, cruise drag including compressibility effects,
6. tail design: tail surface planform and airfoil selection, longitudinal and lateral static stability considerations
7. landing gear design: loads on landing gear, clearance issues, shock absorbers, tires and wheels, braking systems,
8. refined weight estimate: center of gravity location, control surface sizing, final layout of aircraft with all components properly placed,
9. drag estimation: careful analysis and accounting of the drag contribution of all components throughout the contemplated speed and altitude envelope
10. performance analyses: take-off, climb, cruise, descent, and landing performance of the final configuration,
11. economic analysis: capital cost of the airframe and engines, direct operating cost, and revenue generation,
12. final report and presentation: synthesis of the preliminary design in a report suitable for management, customers, and technical staff, version for oral presentation.

Final design

The tasks for final design are much more detailed and involve many more engineers than those for preliminary design. The more important areas of interest for final design are described in the following list:

1. detailed aerodynamic studies: computational fluid dynamics (CFD) analyses of the aircraft configuration, wind tunnel tests for verification of CFD studies and to assess particular aerodynamic issues, performance analyses throughout the flight range, preparation of aerodynamic models for stability and control analyses, handling qualities studies and simulations,
2. detailed structural design: detailed layout of structural components of the airframe, computational assessment of structural integrity, detailed weight estimation,
3. loads and dynamics: determination of aerodynamic, inertial, and other loads imposed upon the aircraft in all flight and ground operations, determination of the natural frequencies of the airframe and all important modes under excitation from engines, control surfaces, and other aerodynamics forcing functions, determination of unsteady loads and flutter effects,
4. design of subsystems: electrical, hydraulic, auxiliary power, avionics (guidance, navigation, and control), cockpit layout and human factors engineering, selection of equipment and vendors,
5. manufacturing considerations: detailed CAD drawings of all manufactured parts, assembly drawings, installation drawings, component interference evaluation, design of manufacturing tools, dies, and jigs, and assembly line design and preparation,
6. economics and sales studies: marketability analyses, customer feedback, cash flow analysis, capitalization,
7. prototype model: construction of demonstrator aircraft for ground, flight, and structural tests.

Preparation of technical reports

One of the most important tasks facing every engineer is the preparation of a technical report. This may be a document like a proposal, which seeks to engage the interest of a sponsor to financially support the technical task proposed, or one describing the work that has been carried out in completing a technical task. Typically, engineers enjoy performing the technical work required to solve the particular problem at hand, but often dread the planning, writing, and preparation of the technical document that describes the work.

A report is intended to present information clearly, and in a manner that is both self-contained and interesting. Conceptually, report preparation is rather simple, being in essence an edited log of the work that has been, or is proposed to be, performed.

Thus, it is convenient to keep a good journal of the work done along with the relevant background and illustrative material used. Though the technical work done may be well understood and appreciated by the engineer who carried it out day by day, this is not necessarily the case for other people who also need to know about that work. If the reader finds the report difficult to understand because the presentation is poor, then the engineer has wasted all the technical work done because the information cannot get beyond the person who actually did the work. So it is important to be sure that some basic requirements are met by the design report, such as the following: the reader should not have to search for important facts, the technical content should not be obscured by poor writing, and ambiguity should be avoided.

There is always some concern about the perspective of the report, that is, who is the reader? For design reports there are generally three classes of readers: business and sales executives, technical managers, and technical staff engineers. To satisfy this broad group with one report, it is common to include an executive summary, a main text, and detailed appendices. Executives generally read the brief executive summary to clearly understand the general approach and results of the study. Technical management personnel read the executive summary and the main text so as to be able to guide the executive group as necessary. The technical staff needs all three sections since they may be called upon to review detailed questions from the other two groups who are involved in making major business decisions.

Outline of the design report

Aircraft companies have standard formats for reports used both within and outside the company. Though the details may vary from company to company, there is a general outline that tends to be followed. The particular format to be followed here is shown in outline form as follows:

Chapter Number	Chapter Heading
	Title page
	Executive Summary
	Table of contents
1	Introduction and Market Survey
2	Preliminary Weight Estimate
3	Fuselage Design
4	Engine Selection
5	Wing Design
6	Tail Design
7	Landing Gear Design
8	Refined Weight Estimate
9	Drag Estimation
10	Performance Analysis

Chapter Number	Chapter Heading
11	Airplane Pricing and Economics
12	Conclusions and Recommendations
	References
	Appendices

The report should be prepared using a computer for word processing, for production of graphs, and for production of drawings using CAD systems, like Pro/Engineer. It is likely that a well-prepared and -presented report will be of great value in preparing similar reports and in improving one's design and communication capabilities.

Title page, executive summary, and table of contents

The title or cover page should be informative and attractive to the prospective reader. Therefore it should be laid out in a logical and interesting fashion and should give the title of the report, the author, the organization issuing the report, the name of the organization for which the report was prepared, and the date of issue of the report.

The executive summary of the report is a brief, but complete, narrative description of the report. Its length will vary, depending upon the size and complexity of the report, but in most cases should be kept to one or two pages. This summary, as its name implies, is intended for a prospective reader in the executive ranks of a corporation or government agency, one who needs to know the nature and outcome of the report but cannot devote the time to read through the whole report. In this sense it is perhaps the most important section of the report since it will be read by executives who can say "yes" to a proposal of this sort. Though many echelons of industrial personnel may say "no," the approval of a major decision-maker will make these technical critics pay close attention to the details within the body of the report before bringing a "no" to the upper levels. Therefore it is important to make the best possible case for your proposed design and to include some of the most interesting and compelling results the report contains. Remember that the objective of writing the report is to communicate your ideas to others and to persuade them of the value of your work to them. In the particular instance of design reports, the author is actually carrying out part of a sales activity, where the author is trying to get the reader, or reader's organization, to financially support the proposed design.

The table of contents provides still more information to the reader by laying out the chapter headings, subsection headings, etc. and their page numbers in the report. One may learn more about the details of the format requirements described here by studying the textbook reference materials, and other publications. There are generally accepted norms for the layout of technical reports and one should keep an observant eye on how this is done by others in the field.

Main text

The main text of the design report parallels the outline of this book. Chapter 1 is the introduction to the design case studied and describes the mission profile in detail. The market survey portrays details of the competing aircraft that most closely meet the specified mission requirements. The preliminary weight estimate is covered in Chapter 2 and illustrates how the aircraft is sized as to total weight, empty weight, fuel weight, etc. Analytical techniques and historical correlations are used to generate the weight make-up of the proposed aircraft that will be used to carry the design along through more detail. Fuselage design comes next in Chapter 3 and planning and sizing the overall configuration culminates in the generation of three-view drawings providing the outline of the proposed aircraft. Using the gross size and weight characteristics from the previous chapters permits the selection of appropriate engines for the proposed aircraft and this comprises the content of Chapter 4. The take-off, landing, and cruise constraints on the design are applied to narrow the choice of engines among those that are currently available. Chapter 5 addresses the design of the wing by utilizing methods that form an industry-wide standard basis for comparative aerodynamics and stability and control evaluations. After the design is taken this far, the stability and control surfaces of the proposed aircraft, i.e., the horizontal and vertical tails, are sized and positioned on the aircraft in Chapter 6. The requirements for the size and location of the landing gear and the associated ground handling characteristics of the aircraft are developed in Chapter 7. Then, having determined the size and placement of all the major components of the aircraft in the previous chapters, a refined weight estimate and center of gravity location are carried out in Chapter 8. In Chapter 9, a careful drag estimate is carried out, again using common industrial approaches. Chapter 10 presents an analysis of the performance potential of the aircraft in all aspects of its mission profile, as carried out using standard techniques. An assessment of the cost of producing and operating the proposed aircraft is carried out in Chapter 11 using a variety of techniques developed by government agencies and industry associations. Finally, there should be a Chapter 12 which presents the conclusions and recommendations arrived at in carrying out the design of the proposed aircraft for the specified mission. Following that would be a list of the references quoted and the appendices that may have been cited within the main text.

Suggestions for report preparation

Report preparation should proceed in a timely manner; in a university setting this should be carried out regularly during the course presentation and not be delayed to the end of the semester. The reports should be prepared on a word processor and attention should be paid to regularly backing up files. Drawings are to be made on any CAD system available. Again it is important to remember to back up all files. The report should be submitted as a spiral bound or stapled document printed on standard white 8.5×11 inch paper. The pages must be numbered consecutively using

a standard system throughout the report and should be consistent with the table of contents.

It may be useful to review some of the common errors in report preparation which are listed as follows:

1. Title page omitted or incomplete.
2. Table of contents omitted or paginated incorrectly.
3. An important section of the report, like the executive summary or a main test chapter, is omitted.
4. References enumerated properly at the end of chapters, but not cited in the text of the chapter, or vice versa.
5. Figures captioned properly as they appear, but not cited in the text, or vice versa.
6. Pages are not numbered sequentially, or are omitted entirely.
7. Three-view drawings of the aircraft, and similar supporting drawings are omitted or are of poor quality.
8. Printing is of poor quality or non-standard font employed.
9. Spelling, grammar, and punctuation are poor.
10. Material presented indicates that the author(s) poorly understands it.
11. Extensive quoting, or even plagiarizing, of previously published material.
12. Improper use of appendices; repetitive material, tables, etc. are to be incorporated into appendices so as to keep the flow of ideas smooth in the main text.
13. Improper inclusion of calculations in the main text; there should be sufficient information, such as equations, in the report to permit another engineer trained in the art to reproduce the results shown, but no actual incorporation of numbers therein.
14. Uneven emphasis among chapters, usually indicating varying degrees of effort among contributors.
15. Too much repetition or discussion of irrelevant material.
16. The conclusions reached by carrying out the work are not clearly stated.

Suggestions for preparing graphs and other figures are as follows:

1. Figures should be introduced as part of the text, with appropriate numbering and captioning.
2. The figures should be placed near to where they are described, so that they can be easily found.
3. Figures should be self-contained so that, with the descriptive caption, their content can be easily grasped.
4. The ordinate and abscissa of a graph must be clearly labeled, including units and scale divisions; a somewhat heavier line width may be used for the axes.
5. Scales must be chosen appropriately so that the behavior being described in the text is apparent; auto-scale features of graphing packages must be scrutinized in this regard.
6. Analytic results should be indicated by lines that are distinguishable without color since reports are often Xeroxed or faxed without benefit of color; different line styles, such as dotted, dot-dash, etc. may be employed.

7. Experimental data should be represented by discrete symbols; again avoid using symbols of different color.
8. Maintain some degree of uniformity among the symbols and lines used on graphs dealing with essentially the same subject for ease of interpretation.
9. Extrapolations and interpolations should be indicated by a change in the line style, such as changing from solid to dotted lines.
10. Major grid lines in both coordinate directions should be shown.

Contents