



**Egbert Torenbeek**

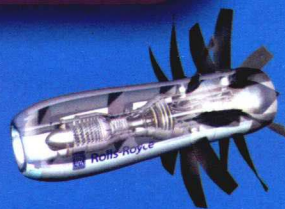
# Advanced Aircraft Design

**Conceptual Design, Analysis and  
Optimization of Subsonic Civil Airplanes**

**Aerospace Series**

Editors Peter Belobaba, Jonathan Cooper,  
Roy Langton and Allan Seabridge

 **WILEY**



# ADVANCED AIRCRAFT DESIGN

## CONCEPTUAL DESIGN, ANALYSIS AND OPTIMIZATION OF SUBSONIC CIVIL AIRPLANES

**Egbert Torenbeek**

*Delft University of Technology, The Netherlands*



 **WILEY**

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# Foreword

Aircraft design is a very fascinating and motivating topic for pupils, students and young researchers. They are interested in the engineering subject, knowing that this is a complex subject with the aerodynamics to make the aircraft fly, with the structural layout to accommodate some sort of payload and keep the integrity of the vehicle, and with the aspects of flight mechanics to stabilize and control the aircraft, just to mention the basic aspects. In the scientific world, the faculties of aerospace engineering follow this principle and consider the basic disciplines such as aerodynamics, lightweight structures, flight mechanics and space technologies as the fundamentals to provide the envelope for aeronautics and space for the engineering students. Aircraft design is normally not considered a specific discipline worthy of inaugurating a specific chair. Some exceptions, however, do exist. The Delft University of Technology was one of the first Technical Universities in Europe to inaugurate a specific chair for aircraft design, and with the nomination of Egbert Torenbeek in 1980 they found a very strong personality who has further developed the scientific approach and methodology for preliminary aircraft design. The Technical University of München (TUM) in 1995 established a new chair for aeronautical engineering with the specific focus on aircraft design and I was nominated for this chair. This shows that the focus of integrated aircraft design has only slowly found its role in the scientific world.

A similar view can also be seen in industry. During my time at Airbus, the Technical management was not fully convinced that the aircraft design had the same importance and role as the big engineering departments like aerodynamics, structures, systems, propulsion and cabin. On the other hand, Airbus suddenly discovered about some ten years ago with some urgency that they did not have enough engineers with sufficient global knowledge to understand the total aircraft as a complex system. A huge push was then started to develop within the company 'aircraft architects' and 'aircraft integrators', also highlighting, that the discipline 'aircraft design' with its specific knowledge and experience is of prime importance.

There is, however, a huge discrepancy between industry and research centres or universities with regard to integrated aircraft design. Industry claims and wishes that universities as well as research centres should not look too closely at aircraft integration; this is seen as the unique role of industry. Industry claims to be the only partner, who knows the market demand and who has to consider the right design approach with respect to time, cost, quality and risk before deciding on a new product and its introduction onto the market. Industry therefore would like to keep the universities out of the domain of aircraft design, and do not want to give too many details to the scientific community, on how to prepare an innovative aircraft design. On the other hand, students and young engineers have to be trained and have to learn

and understand the basic features of aircraft design at university during their studies. Students are primarily not so much fascinated by details of low speed aerodynamics or the detailed design of a fuselage frame compared to designing an aircraft. They are motivated to develop aircraft models, sailplanes and want to know how to design this sort of flying vehicles and what is the approach to defining the size of the wing, tailplane and engines. The scientific approach to aircraft design is therefore a major topic for the universities and has to be part of the aeronautical engineering curriculum.

There are several good books on the market, one of the best in my view written by Egbert Torenbeek. But these books were written mainly in the years 1980 to 1990 and have established a lot of design data, collected from aircraft designs of the 1960s to the 1980s. Also at that time the focus was on the preliminary aircraft design, starting from the weight breakdown, defining wing and tailplane areas and checking stability and controllability.

Over the past twenty years, computer capabilities have improved considerably and a lot of aircraft design software programs are distributed on the market with some quite good success and good results as long as the aircraft design follows the classical design features. The new dimension which has been added to the aircraft design process is called multidisciplinary optimization (MDO) methodologies. The continuous increase in computer speed and capacity has first allowed FEM methods for all sort of structural layout and CFD methods for the aerodynamic design of aircraft components and the total aircraft to be developed. The next steps were then multidisciplinary tools, first, to integrate the different design boundaries such as high-speed and low-speed aerodynamics, and in a next step, today the multidisciplinary methods permit an aircraft to be designed by using the integration of aerodynamic, structural and flight mechanics design constraints and by using multidisciplinary optimization methodologies. MDO is the new design methodology for all aircraft design features and nearly all papers in aircraft design are now using some sort of multidisciplinary optimization approach.

I remember that some five years ago – sitting on the Wolga beach in Samara (Russia) during a seminar for aircraft design professors – we had some lively discussions on some aircraft optimization problems. We also learned that Egbert Torenbeek was working on a new book about advanced aircraft design. However, he had some doubts whether there were still enough people interested in learning about the complex aspects of advanced aircraft design, while all institutions are just working with big and complex software tools. He was not sure whether the aircraft community would like to see such a book. We encouraged him very much to continue. Egbert Torenbeek has a very high reputation among the aircraft design professors and I am very happy to see that he finally managed to finish his book. Having read several chapters, I really believe that his way of addressing a quasi-analytical approach to aircraft design is very valuable and an excellent complementary way to the common normal approach of computerized analysis.

In the next decades, the aeronautical industry will be faced with considerable new environmental challenges. The past success of air transport will be confronted with new questions like ‘Which optimal flight altitude will have minimum impact on the atmosphere?’ or ‘How can new aircraft concepts with new engine options like Open Rotors improve fuel efficiency and also the environmental footprint for a given mission?’ I am convinced that new aircraft concepts for the future will be required to cope better with the increasing environmental restrictions which air transport will have to face. This book will be of great help and interest for these sorts of questions where the impact of new boundary conditions will have to be analyzed and investigated and where the large industrial computer software is not yet properly

validated and verified. The physics-based approach of this book will help to better qualify the dominant parameters for different new and unconventional aircraft concepts and also help the reader to understand the assessment of benefits and risks of these concepts.

I wish this book a lot of success and hope that my colleagues from industry and the scientific community and especially the young scientists will appreciate this book as well.

Prof.h.c. Dr.-Ing. Dr.h.c. Dieter Schmitt  
*Aeronautical consultant. Former Head of Future Projects at Airbus SAS  
Former Professor at TU München, Institute of Aeronautical Engineering  
Blagnac, 25th November 2012*

# Series Preface

The Aerospace Series covers a wide range of aerospace vehicles and their systems, comprehensively covering aspects of structural and system design in theoretical and practical terms. This book complements the others in the Series by looking at the concept phase of design of the aircraft.

Aircraft Design is an early stage of activity in the evolution of an aircraft project starting at the concept and enduring until the preliminary design. It is time for broad thinkers, for people prepared to take risks and to understand the big picture. At this stage of an aircraft project the important issues are the shape of the aircraft, its fuel and load carrying capability and its mass leading to an assessment of its suitability to perform a mission. From ideas generated during this process will gradually emerge a solution that can be committed to design and manufacture.

The author introduces the topic with an overview of the advanced design process, considering design requirements and methodologies, considerations driving a design, followed by an example of early design mass prediction. The next stage deals with the selection of the aircraft general arrangement, an essential but complex issue which concerns new technology applications and operational properties. Decisions made at this stage involve and affect many disciplines in a project – many of those dealt with in other books in the Series. This is the challenging stage of integration and the role of the Chief Designer. Then an approach to explicit optimization by means of quasi-analytic relations is developed and the book concludes with analytical examples that are essential to advanced design in general and optimization in particular.

This is performed in a clear and concise manner to make the book a comprehensive treatise on the subject of advanced design of subsonic civil aircraft from initial sizing through to final drag calculations. There are lessons to be learned here also for military aircraft designers. It will be of great use to undergraduate and postgraduate students as well as to practitioners in the field of aircraft design and scientists in aerospace research and development. The author has given his work authority by basing it on many years of research at the Delft University of Technology where this subject is taught under the auspices of a Chair in the subject.

Peter Belobaba, Jonathan Cooper and Allan Seabridge

# Preface

I don't know why people are frightened by new ideas.  
It's the old ones that frighten me.

—John Cage, American composer

Advanced Design (AD) is the name for the activity of a team of engineers and analysts during the early stages of an aircraft design and development process. The point of departure is a set of top level requirements specifying payload/range capabilities, cabin accommodation, flight performance, operational, and environmental characteristics. The first design activity generates a conceptual baseline configuration defined by (electronic) drawings of its layout, a database specifying the physical characteristics and the essential technological assumptions, and an assessment of the feasibility of complying with the requirements. Designers may propose one or several concepts which are subsequently refined and compared during the second advanced design stage called the preliminary design. Conceptual design and preliminary design are crucial phases in the development process during which creativity and ingenuity are of paramount importance to support the far-reaching decisions that can make or break the programme as a whole.

Since the 1970s, aircraft design has become the subject of academic education and research at an increasing number of academic institutions which have an aerospace curriculum. Many topics typical of aircraft design projects are nowadays covered in academic courses, and educational handbooks, and an abundance of software tools have become available to support students in their design exercises. Although many academic courses pay modest attention to aircraft design, a design-oriented approach to the traditional aeronautical disciplines can contribute to an improved understanding of aeronautical science as a whole. However, design handbooks are essentially based on existing or even obsolete technology and may produce unrealistic results when applied to future advanced aircraft design projects. And design technologies are becoming more complicated due to the introduction of integrated product design technology and multidisciplinary design optimization, subjects not covered in most handbooks.

In writing this book it has been the author's aim to contribute to the advancement of aircraft design (teaching) by emphasizing clear design thinking rather than sophisticated computation or using a huge collection of statistical information. Another orientation came from industrial design staff and academic teachers who indicated that they would be particularly interested in assessments of unusual aircraft concepts and examples of practical optimization in the early design stage. It was decided to focus on subsonic transports and executive (business) aircraft. The present text combines the author's academic teaching approach with numerous results



from in-depth investigations on advanced technologies and innovative aircraft configurations reported since the 1970s. Particular attention is paid to research by staff of the aircraft design chair at Delft University of Technology between 1980 and 2000. Although some information about design methodologies and statistical data of recent airplane models are included, the result is not intended to be used as a handbook in the first place. Most of the material presented is readily understood by those who have previous experience with airplane design. The niche market for this book is formed by MSc and PhD students doing design-oriented research, academic staff teaching design, advanced airplane designers and applied scientists at aeronautical research laboratories.

The contents of this book can be subdivided into the following groups of chapters.

1. Chapters 1 and 2 offer an overview of the advanced design process, design requirements and methodologies, considerations driving a design, and an example of early design weight prediction by applying the unity equation. Chapter 3 is a summary of modern gas turbine engine technology and configurations, defining characteristics such as overall efficiency and thrust lapse rates to be used in subsequent chapters. Chapter 4 introduces the reader to different methods of decomposing and predicting aerodynamic drag and to technologies for drag reduction. Many of these topics are familiar to experienced designers; some of them may be eye-openers to students or researchers.
2. Chapters 5 and 6 focus on the choice of the aircraft's general arrangement. This is an essential but complex issue since numerous decisions with respect to (new) technology applications and operational properties are involved and many of these decisions have a highly interdisciplinary sphere of influence. Chapter 5 deals with the basic question of how to allocate the useful load inside a generic combination of a wing and a fuselage body. In the past, this question gave rise to a discussion between analysts, some in favour of and some against the flying wing. However, the optimum configuration is not necessarily an all-wing aircraft or a traditional tube and wing (TAW). For instance, the blended wing body could become a viable alternative. Chapter 6 deals with clean-sheet design of aircraft which do not have a payload inside the wing. A qualitative assessment is made of several unusual concepts such as canard and three-surface configurations, highly non-linear lifting systems, the joined wing, twin-fuselage and hydrogen-propelled aircraft. An unusual configuration may be the best solution in the case of a dominant performance requirement or geometric constraint.
3. Chapters 7 to 10 are intended to develop an approach to explicit optimization by means of quasi-analytic relations between figures of merit – such as the maximum take-off weight or energy efficiency – and primary selection variables. Chapter 7 offers an overview of the general optimization problem, terminology and strategies to identify a feasible solution. Chapter 8 is primarily devoted to weight engineering, an essential discipline of aircraft design. Design-sensitive expressions are derived for the gross weight and its components. These are intended to show how a baseline design may be modified to improve different figures of merit, disregarding design constraints. Chapter 9 deals with matching the engines to the airframe by incorporating constraints on the installed engine power or thrust derived from high- and low-speed performance requirements. Chapter 10 derives analytical criteria for optimum wing planform area, aspect ratio, sweep angle and thickness ratio. Results are illustrated for a subsonic freighter and a transonic jetliner, both with a classical general arrangement.

4. The last chapters deal with subjects with a predominantly analytical character that are essential to advanced design in general and optimization in particular. Chapter 11 presents the derivation of a wing structure weight prediction methodology which satisfies most of the requirements for application to conceptual optimization. Chapter 12 explains why traditional criteria for optimum cruising flight cannot be applied to high-speed airplanes. The theory is unified for (optimum) cruise performance analysis of propeller- as well as jet-powered aircraft and includes a simplified estimation of mission and reserve fuel.

The quasi-analytical character of the present approach to conceptual design optimization cannot replace rigorous numerical methods. Intended primarily to support advanced designers and researchers and help them to understand the complex relationships between the effects on airplane characteristics of varying design parameters, the results may also be useful to validate complex design sizing and optimization programs. Moreover, the simplicity of the analytical criteria is useful to quickly estimate the effects of introducing alternative technologies for propulsion and airframe design. If used judiciously, quasi-analytical relationships can be sufficiently accurate to successfully answer ‘what-if’ questions and make trade-off studies such as weight growth problems, specification changes and considering derivative aircraft. From this perspective, the present book can be seen as a tribute to prominent scientists and designers from the past – such as I.H. Ashkenas, R.T. Jones, D. Küchemann, and G.H. Lee – who pioneered this approach during the era when computer-based aircraft design technology did not yet exist. The author hopes that this effort will contribute to the way of thinking of those who consider conceptual design as an art rather than a science: the art of conceiving and building well-tempered aircraft.

# Acknowledgements

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This book would never have been realized without the support of my wife. Dear Nellie Volker, considering my weakness to find a proper balance between the dedication you deserve and my insatiable fascination for aeronautical engineering, I am eternally grateful that you tolerated my periods of distraction and continued to respect me during the more than 10 years of writing this book.

E. Torenbeek

*Delft University of Technology, The Netherlands, April 2013*

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