Aircraft Performance

An Engineering Approach

Mohammad H. Sadraey

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Engineering – Mechanical

Aircraft Performance: An Engineering Approach introduces flight performance analysis techniques that enable readers to determine performance and flight capabilities for prop-driven and jet aircraft, and their design implications. The text uses a consistent student-oriented learning approach, supported by examples, problems, color illustrations, and MATLAB® routines.

Features:

- Introduces flight performance analysis techniques for fixed-wing air vehicles, both jet and propeller-driven
- Includes new and emerging topics, such as range and insurance for electric engine aircraft
- Demonstrates techniques for determining aircraft zero-lift drag coefficients
- Includes MATLAB routines to demonstrate the role of computer analysis in aerospace engineering
- Analyzes modern aircraft designs through the use of real aircraft data
- Includes a Solutions Manual and figure slides for qualified instructors adopting the text

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An Engineering Approach

To Fatemeh Zafarani, Ahmad, and Atieh for all their love and understanding

Preface

Flight is the process in which a vehicle moves through the air without any direct mechanical support from the ground. In physics, the science of the action of forces on material bodies is referred to as mechanics. Mechanics is basically divided into two branches: (1) dynamics and (2) statics. The branch of mechanics that deals with the motion of objects in relation to force, mass, momentum, and energy is referred to as dynamics. Flight mechanics (or flight dynamics) is the study of the motion of flying objects (e.g., aircraft, missile) through air. It covers two main areas:

1. Flight performance
2. Flight stability and control

As aircraft do not usually have a static motion (except for VTOL aircraft), we mostly deal with flight dynamics. On the other hand, there are two types of aircraft motions: (1) steady-state motion and (2) perturbed-state motion. It is customary that steady-state motion be studied in a course called flight dynamics I and that perturbed-state motion be studied in flight dynamics II. In some institutions, flight mechanics is referred to as flight dynamics I, and flight stability and control is referred to as flight dynamics II.

The first topic (flight dynamics I) includes subjects such as maximum speed, absolute ceiling, rate of climb, range, endurance, turn performance, and takeoff run. The second topic (flight dynamics II) is mainly to examine such subjects as aircraft trim, control, stability, maneuverability, and flying qualities. The subject of aircraft performance mainly deals with the forces applied to the aircraft, but the subject of flight dynamics concentrates on various moments (either aerodynamic or non-aerodynamic) that determine the trajectory. Time span in aircraft performance is mostly in the range of hours, but time span in flight dynamics is primarily in the range of seconds.

The objective of this book is to introduce flight performance analysis techniques of fixed-wing air vehicles, particularly heavier-than-air craft. This subject will be interesting for aeronautical/mechanical engineers, aircraft designers, pilots, aircraft manufacturing companies, airlines, air forces, and primarily students of the field of aeronautical/aerospace engineering.

This group of people often face the following questions:

1. How fast can this airplane fly in a cruising flight?
2. How high can this airplane fly?
3. How far can this airplane fly?
4. How long must be the runway for takeoff?
5. How long can this airplane be airborne?
6. How fast can this airplane climb to a certain altitude?
7. How fast can this airplane turn?
8. How tight can this airplane turn?

9. How capable is this aircraft in a maneuver?
10. What are the limits of this airplane in flight?
11. How much does it cost for this airplane to fly over a certain distance?

And, in one sentence, what is the performance of this airplane?

If one has access to a manufactured airplane, the answers to all these questions can be found through flight tests. However, the primary objective of this book is to enable the reader to answer these questions without having access to the aircraft itself. Therefore, an aircraft designer can predict the performance of an airplane during the design process, before manufacturing it. In addition, an aircraft buyer can calculate and evaluate the performance of an aircraft prior to its purchase. In this way, the buyer can compare the performances of different aircraft and choose the most suitable one.

The performance of a military airplane is of high importance, since in an aerial mission, the fighter aircraft that has a high performance will always fulfill the mission's purpose. The result of an air fight depends not only on aircraft weight, configuration, cost, pilot experience, and so on, but also on its capabilities, that is, flight performance. This book presents techniques and methods that enable the reader to analyze the performance and flight capabilities of an aircraft by utilizing only aircraft weight data, geometry, and engine characteristics.

Chapter 1 is devoted to the atmosphere as the flight condition. The methods to calculate atmospheric variables such as pressure, temperature, and air density as a function of altitude are presented. In Chapter 2, the equations of motion and of an air vehicle are presented, and its steady-state version is derived. The four major forces acting on an aircraft are weight, engine thrust, lift, and drag (i.e., aerodynamic forces). Drag and engine thrust need detailed considerations, so the techniques to calculate these forces are offered in Chapters 3 and 4.

Chapters 5 through 9 cover all aspects of flight performance analysis for propeller-driven and jet aircraft. Both constant-speed flight and accelerated flight are covered. In every case, we start with a mathematical equation which governs that specific flight condition. Then an applicable algebraic equation is derived in order to perform the analysis of various flight performance areas such as maximum speed, maximum range, maximum ceiling, maximum rate of climb, and maximum endurance. Takeoff and landing performance is addressed in Chapter 8. In Chapter 9, turn performance and related topics such as pull-up are covered. The technique to plot the flight envelope (i.e., *V-n* diagram) in order to find the maximum g-load on an air vehicle is presented in this chapter. In addition, advanced materials in flight mechanics such as fastest turn, tightest turn, and flight maneuvers are investigated.

There are complex performance cases and flight missions where analysis requires a long and complex mathematical solution. A popular and powerful technique for such cases are numerical methods. Chapter 10 is devoted to the performance analysis of aircraft using numerical methods, mainly using the MATLAB® software package (i.e., MATLAB code).

The appendices are devoted to real statistics of current aircraft and flight records throughout the history of flight. This information gives the readers an insight and a criterion to compare their calculated and achieved results. The book is prepared such that it can be covered as an undergraduate course in aerospace engineering or aeronautical engineering programs at the junior level. A Solutions Manual and figure slides are available for qualified instructors adopting the text.

Currently, the International System of Units (SI), metric units (Newton, kilogram, meter, second, Kelvin), is the standard system of units used in most parts of the world. However, the English Engineering System, British Units (pounds, slug, feet, second, Rankine), is still the primary system of units in the United States. In addition, many Federal Aviation Regulations (e.g., stall speed) are written using British units. This situation is gradually changing, particularly in the aerospace community. Nevertheless, a familiarity with both systems of units is still necessary for engineers and engineering students. Current engineering students should be familiar and be able to work professionally with both systems. For this reason, both unit systems are employed in worked examples and end-of-chapter problems in this book. The readers are encouraged to familiarize themselves with both unit systems. Readers are expected to have basic knowledge of dynamics, calculus, and aerodynamics.

I am enormously grateful to the Almighty for the opportunity to serve the aerospace community by writing this book. I acknowledge the many contributors and photographers who contributed to this book. I am especially grateful to those who provided great aircraft photos to this text: Alex Snow (Russia); Ryosuke Ishikawa (Japan); Kas van Zonneveld (the Netherlands); Daniel Mysak (Austria); Gustavo Corujo (Canada); Steve Dreier (United Kingdom); Jan Selig (Germany); Georgi Petkov (Bulgaria); Maurice Kockro (Germany); Fabian Dirscherl; Capenti Fabrizio (Italy); and Weimeng (China); and www.airliners.net. In addition, my effort was helped immeasurably by the many insights and constructive suggestions provided by students and instructors in the past 21 years. Unattributed figures are held in the public domain and are from either the U.S. government departments and agencies or Wikipedia.

Putting a book together requires the talents of many people, and talented people abound at Taylor & Francis Group/CRC Press. My sincere gratitude goes to Jonathan W. Plant, Executive Editor for Mechanical, Aerospace & Nuclear Engineering, for coordinating the whole publication process. I especially owe a large debt of gratitude to the reviewers of this text. Their ideas, suggestions, and criticisms have helped me to write more clearly and accurately and have influenced markedly the evolution of this book.

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March 1, 2016

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Dr. Mohammad H. Sadraey is an associate professor in the Engineering School at Southern New Hampshire University (SNHU), Manchester, New Hampshire. Dr. Sadraey's main research interests are in aircraft design techniques, aircraft performance, flight dynamics, and design and automatic control of unmanned aircraft. He earned his MSc in aerospace engineering in 1995 from RMIT, Melbourne, Australia, and his PhD in aerospace engineering from the University of Kansas, Kansas, in 2006. Dr. Sadraey is a senior member of the American Institute of Aeronautics and Astronautics (AIAA), Sigma Gamma Tau, and the American Society for Engineering Education (ASEE). He is also listed in *Who's Who in America*. He has more than 20 years of professional experience in academia and industry. Dr. Sadraey is the author of three other books, including *Aircraft Design: A Systems Engineering Approach* published by Wiley publications in 2012.

List of symbols

Symbols	Names	Units
a	Speed of sound	m/s, ft/s
a	Acceleration	m/s^2, ft/s^2
a	Lift curve slope	1/rad
ac	Aerodynamic center	—
a_c	Centripetal acceleration	m/s^2, ft/s^2
AR	Aspect ratio	—
b	Wing span	m, ft
C	Specific fuel consumption	N/h kW, lb/h hp
C	Mean aerodynamic chord	m, ft
C_D	Drag coefficient	—
C_{D_o}	Zero-lift drag coefficient	—
C_{D_i}	Induced drag coefficient	—
C_{D_w}	Wave drag coefficient	—
C_f	Skin friction coefficient	—
C_L	Lift coefficient	—
$C_{L_{max}}$	Maximum lift coefficient	—
cp	Center of pressure	—
D	Drag force, drag	N, lb
E	Endurance	hour, second
e	Oswald span efficiency factor	—
F	Force, friction force	N, lb
FAA	Federal Aviation Administration	
FAR	Federal Aviation Regulations	
F_C	Centrifugal force	N, lb
g	Gravity constant	9.81 m/s^2, 32.2 ft/s^2
G	Fuel weight fraction	—
GA	General Aviation	—
h	Altitude	m, ft
i_t	Tail incidence	deg, rad
i_T	Engine incidence	deg, rad
I	Moment of inertia	kg m^2, slug ft^2
ISA	International Standard Atmosphere	—

(*Continued*)

Symbols	Names	Units
K	Induced drag factor	—
KEAS	Knot Equivalent Airspeed	knot
KTAS	Knot True Airspeed	knot
knot	Nautical mile per hour	nmi/h
L	Fuselage length	m, ft
L	Lift force, lift	N, lb
L	Lapse rate	0.0065°C/m, 0.002°C/ft
$(L/D)_{max}$	Maximum lift-to-drag ratio	—
M	Mach number	—
m_f	Fuel mass	kg, slug
m_{TO}	Takeoff mass	kg, slug
$MTOW$	Maximum takeoff weight	N, lb
MAC	Mean aerodynamic chord	m, ft
n	Load factor	—
ω	Turn rate	rad/s, deg/s
P	Pressure	N/m^2, Pa, lb/in.^{2}, psi
P	Power	kW, hp
P_{req}	Required power	kW, hp
P_{av}	Available power	kW, hp
P_{exc}	Excess power	kW, hp
q	Dynamic pressure	N/m^2, Pa, lb/in^2, psi
Q	Fuel flow rate	kg/s, lb/s
R	Range	m, km, ft, mile, mi
R	Turn radius	m, ft
R	Air gas constant	287.26 J/kg K
R	Radius of action	km, ft
Re	Reynolds number	—
ROC	Rate of climb	m/s, ft/min, fpm
ROD	Rate of descent	m/s, ft/s
rpm	Revolutions per minute	Rev/min
S	Gross wing area	m^2, ft^2
S_{exp}	Exposed wing area	m^2, ft^2
S_{ref}	Reference wing area	m^2, ft^2
S_t	Tail area	m^2, ft^2
S_w	Wing area	m^2, ft^2
S_{wet}	Wetted area	m^2, ft^2
S_{TO}	Takeoff run	m, ft
S_G	Ground roll	m, ft
S_A	Airborne section of the takeoff run	m, ft
SFC	Specific fuel consumption	N/h kW, lb/hr·hp, lb/hr/lb
t	Time	second
T	Engine thrust	N, lb
T	Temperature	°C, °R, K, °R
T_{req}	Required thrust	N, lb
T_{av}	Available thrust	N, lb
V^*	Corner speed	knot, m/s, ft/s
V	Velocity, speed, airspeed	m/s, ft/s, km/h, mi/h, knot
V_A	Maneuver speed	m/s, ft/s, km/h, mi/h, knot
V_D	Dive speed	m/s, ft/s, km/h, mi/h, knot

(Continued)