John Seddon and Simon Newman

Basic Helicopter Aerodynamics

Third Edition

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

WILEY

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BASIC HELICOPTER AERODYNAMICS

Third Edition

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WILEY
A John Wiley & Sons, Ltd., Publication

Registered office

John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, United Kingdom

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Library of Congress Cataloging-in-Publication Data

Seddon, John M.

Basic helicopter aerodynamics / John Seddon, Simon Newman. – 3rd ed.

p. cm.

Includes bibliographical references and index.

ISBN 978-0-470-66501-5 (hardback)

1. Helicopters–Aerodynamics. I. Newman, Simon, 1947- II. Title.

TL716.S43 2011

629.133'352-dc22

2011010960

A catalogue record for this book is available from the British Library.

Print ISBN: 9780470665015

ePDF ISBN: 9781119994107

oBook ISBN: 9781119994114

ePub ISBN: 9781119972723

Mobi ISBN: 9781119972730

To Stella, for everything

About the Authors

The late **John Seddon** was a research scientist at the Royal Aircraft Establishment and then Director-General in the UK Ministry of Defence. He later became a consultant to Westland Helicopters.

Simon Newman attended Grammar School in Farnborough near the site of the Royal Aircraft Establishment. He then read mathematics at the University of Southampton, graduating in 1970. Continuing the aircraft theme, he then began a career in helicopter aerodynamics, dynamics and design for the next 41 years. Starting at Westland Helicopters, at Yeovil, Somerset, in 1970 he worked in the Aerodynamics Research Department on rotors systems, performance and aeromechanics. After a year back at Southampton in 1974, where he obtained an MSc in Aeronautics, he returned to Yeovil to work in the Aerodynamics and Dynamics Departments on rotor aerodynamics, blade behaviour and shipborne operations. He was in the Technical Office during the Falklands War, contributing to the technical backup. In 1985 he returned to Southampton as a member of academic staff, reaching the grade of Reader in 2007. His research interests have concentrated on shipborne operations, blade sailing in particular, for which he obtained his doctorate in 1995. Other research has focused on the vortex ring state and the tumble behaviour of microlight aircraft. He has several hobbies, principally photography and golf. Apart from his academic duties, he is also an Esquire Bedell of the University, carrying the mace at graduation ceremonies.

Series Preface

The field of aerospace is wide ranging and multi-disciplinary, covering a large variety of products, disciplines and domains, not merely in engineering but in many related supporting activities. These combine to enable the aerospace industry to produce exciting and technologically advanced products. The wealth of knowledge and experience that has been gained by expert practitioners in the various aerospace fields needs to be passed onto others working in the industry, including those just entering from University.

The *Aerospace Series* aims to be practical and topical series of books aimed at engineering professionals, operators, users and allied professions such as commercial and legal executives in the aerospace industry. The range of topics is intended to be wide ranging, covering design and development, manufacture, operation and support of aircraft as well as topics such as infrastructure operations and developments in research and technology. The intention is to provide a source of relevant information that will be of interest and benefit to all those people working in aerospace.

Helicopters are able to perform a wide range of roles that are not possible with conventional fixed wing aircraft, particularly due to their capability to hover, and to take-off and land vertically. There are a number of technical difficulties that have presented helicopter designers with many challenges over the years, including the aerodynamics of flexible rotors that not only provide lift, but also enable the helicopter to move forward in the desired direction.

This book, *Basic Helicopter Aerodynamics*, is the third edition of the original version that was written by the late

John Seddon. Simon Newman has maintained the ethos of the first book, producing a further revision of this introductory text aimed at undergraduates and engineers new to the field that illustrates the fundamental features of rotor aerodynamics and helicopter design. Importantly, the book also maintains the balance of not delving into too much technical detail, whilst avoiding gross simplification of key important features and physical explanations. There is much to be commended in this latest expanded edition which contains a number of valuable additions to the material.

Peter Belobaba, Jonathan Cooper, Roy Langton and Allan Seabridge

Preface to First Edition

During the past decade and a half, several noteworthy textbooks have been published in the previously neglected field of helicopter aerodynamics, spurred no doubt by a growing acceptance world-wide of the importance of the helicopter in modern society. One may cite in this context Bramwell's *Helicopter Dynamics* (1976), Johnson's *Helicopter Theory* (1980) and *Rotary Wing Aerodynamics* (1984) by Stepniewski and Keys. The appearance now of another book on the subject requires some explanation, therefore. I have three specific reasons for writing it.

The first reason is one of brevity. Bramwell's book runs to 400 pages, that of Stepniewski and Keys to 600 and Johnson's extremely comprehensive treatment to over 1000. The users I have principally in mind are University or Polytechnic students taking a short course of lectures – say one year – in the subject, probably as an ‘optional’ or ‘elective’ in the final undergraduate or early post-graduate year. The object in that time is to provide them with a grounding while hopefully stimulating an interest which may carry them further in the subject at a later date. The amount of teaching material required for this purpose is only a fraction of that contained in the standard textbooks and a monograph of around 150 pages is more than sufficient to contain what is needed and hopefully may be produced at a price not beyond the individual student's pocket.

My second reason, which links with the first, concerns the type of approach. This book does not aim at a comprehensive treatment but neither is it content to consign problems to the digital computer at the earliest opportunity. In between lies an analytical route to solutions, taken far enough to produce results of usable accuracy for many practical purposes, while at the same time providing a physical understanding of the phenomena involved, which rapid recourse to the computer often fails to do. It is this route that the book attempts to follow. The analytical approach is usually terminated when it is thought to have gone far enough to serve the stated purpose, the reader being left with a reference to one of the standard textbooks in case he should wish to pursue the topic further.

The third reason is one of content. Despite the need for brevity, I have thought it worthwhile to include, in addition to treatments of the standard topics – momentum theory, blade element theory, basic performance, stability and control – a strong flavour of research and development activity (Chapter 6) and of forward-looking, if speculative, calculations (Chapter 7). It might be considered that these items are of such a transitory nature as not to be suitable for a textbook, but my criterion of stimulating the student's interest is what has determined their inclusion. Certainly they have proved to be interesting in classroom presentation and there seems no reason why that should not be so for the written word.

In addition to meeting the needs of students, to whom it is primarily addressed, the book should have an appeal as background material to short courses held in or on behalf of industry: such courses are increasing in popularity. Companies and research establishments may also find it useful for new entrants and for more established workers requiring a ‘refresher’ text.

Reverting to the matter of brevity, the recent publication *Helicopter Aerodynamics* by Prouty is a most admirable short exposition, well worth studying as an adjunct to any other textbook: however it shuns the mathematics completely and therefore will not suffice alone for the present purposes. Saunders' *Dynamics of*

Helicopter Flight is not greatly beyond the target length but as the title implies it is concerned more with flight dynamics than with aerodynamics and is adapted more to the needs of pilots than to those of engineering students already equipped with a general aerodynamic background.

I have taken it as a starting point that my readers have a knowledge of the aerodynamics of lifting wings as they exist in fixed-wing aircraft. A helicopter rotor blade performs the same function as a lifting wing but in a very different environment; and to note the similarities on the one hand and the distinctions on the other can be a considerable fillip to the learner's interest, one which I have tried to nurture by frequent references back to fixed-wing situations. This again is a somewhat non-standard approach.

Substantial omissions from the book are not hard to find. A historical survey might have been included in Chapter 1 but was thought not necessary despite its undoubted interest. To judge by the work effort it attracts, wake analysis (‘Vortex theory’) deserves a more extensive treatment than it gets (Chapters 2 and 5) but here it was necessary to refrain from opening a Pandora's box of different approaches. Among topics which could have been included in Chapter 5 are autorotation in forward flight, pitch-flap coupling and blade flexibility but these were seen as marginally ‘second-line’ topics. The forward look in Chapter 6 might have contained a discussion of the potential of circulation control, the only system which is capable of attacking all the three non-uniformities of rotor blade flow, chordwise, spanwise and azimuthal; but the subject is too big and too distinct from the main line of treatment. The reference to autostabilization in Chapter 8 is brief in the extreme but again the choice was between this and a much lengthier

exposition in which aerodynamics would have been largely submerged beneath system mechanics and electronics.

In compiling the book I have been greatly helped by discussions with Mr D.E.H. (‘Dave’) Balmford, Head of Advanced Engineering at Westland Helicopters, to whom my thanks are expressed. Other Westland staff members whose assistance I wish to acknowledge in specific contexts are Dr M.V. Lowson (now Professor of Aerospace Engineering at Bristol University) for Section 7.10, Mr F.J. Perry for Section 6.6, Mr R.V. Smith for Section 7.11 and Mr B. Pitkin for Chapter 8. Naturally the standard textbooks, particularly those mentioned earlier, have been invaluable in places and I trust that this fact is duly recognized in the text and diagrams.

Formal acknowledgement is made to Westland Helicopters for permission to reproduce the photographs at Figures 2.11, 4.10, 4.11, 7.6 and 7.7; to Edward Arnold, Publishers, for the use of Figures 2.10, 2.13, 5.1, 5.3, 6.3, 8.5 and 8.6 from A.R.S. Bramwell's book *Helicopter Dynamics* (1976); to Mr P.G. Wilby of the Royal Aircraft Establishment for Figures 6.2 and 6.5, which are reproduced with the permission of the Controller of Her Majesty's Stationery Office; and to Dr J.P. Jones for the use of Figures 2.12, 4.2 and 4.4.

My thanks are due to Molly Gibbs of Bristol University who copy-typed the manuscript and to my grandson Daniel Cowley who drew the figures.

J. Seddon

Preface to Second Edition

The original *Basic Helicopter Aerodynamics* was conceived and written by Dr John Seddon. It found a respected place in the subject of rotary wing aircraft and has informed many. Sadly John Seddon has since passed away and I was very flattered to be asked to revise his manuscript for a second edition. This brought an immediate problem. Do I strip the work down to nuts and bolts or do I revise it as it stands but add my own contributions? Since the book is now under joint authorship, it would have been unfeeling to have pursued the former option since the original concept of John Seddon would have disappeared. For that reason I decided to pursue the latter option of revising the text and adding to it – particularly in the field of illustrations. The design, manufacture and operation of the helicopter rotor tend to be rather esoteric for the newcomer and long textual descriptions can be dry and not helpful. I have added, therefore, a substantial number of images to illustrate and clarify the discussions.

The original diagrams were created by hand, which did not altogether succeed. Since that time, computer technology has improved greatly and the book's graphics have been updated accordingly. The book's size has increased to allow for the additions but I have been mindful of the need to retain the compactness of the original work.

Helicopter rotor aerodynamics continues to be investigated. It is essential to introduce recent developments to the student and I intend to maintain this book in a form that will introduce the latest developments. While an introductory text cannot hope to describe new techniques in detail it must be capable of establishing the correct thoughts in the reader's mind, thus preparing them for more intensive study.

The revisions have been aimed at illustrating, more fully, the various features of rotor aerodynamics and helicopter design. The helicopter is unique in its linking of the aerodynamic and mechanical features and a full appreciation of these air vehicles can only be achieved by understanding these interactions. Many of the extra figures illustrate the diversity in the design and operation of a helicopter and these differences are highlighted in the text.

As with all things aeronautical, a team effort is always needed, and the assembly of this book is no exception. A picture says a thousand words so I have called upon the skills of many people to provide as many photographs as possible to amplify and, hopefully, clarify the explanations. While I have been able to supply a number of these photographs personally, a considerable number have been kindly supplied and I would like to sincerely thank the following people for their generosity. Denny Lombard of Lockheed Martin, Alan Vincent, Alan Brocklehurst and Alan Jeffrey of GKN Westland Helicopters, Harry Parkinson of Advanced Technologies Incorporated, Stewart Penney, Guy Gratton, David Long of Kaman and Steve Shrimpton.

While I am quite pleased with my own photographic attempts, I am mindful that the pictures were taken on the ground, usually on a pleasant warm day with plenty of time to press the shutter release. In contrast, the above mentioned people have obtained better quality results while often hanging out of an aircraft in very difficult situations. This marks the difference between the amateur and the true professional.

I would also like to thank my colleagues and researchers who have provided much thought provoking discussion, which I hope, is reflected in the book. I am very grateful to David Balmford for his suggestions in correcting the text. I also would like to express my thanks to Ian Simons for his constant advice on all matters aeronautical. I offer many thanks to Julia Burden at Blackwell Science for her forbearance. The manuscript was late and she stuck with it, probably biting her lip but giving me valuable support. She offered me the task of revising the book and I hope she is not disappointed.

Finally I would like to thank my wife, Stella, for putting up with my constant whizzing around putting the final touches to this work, snatching a cup of coffee as I speed by.

Simon Newman
Winchester
January 2001

Preface to Third Edition

The first edition of *Basic Helicopter Aerodynamics* was written by John Seddon and quickly found a place in educating new helicopter engineers and technologists in addition to undergraduates and postgraduates. Very sadly his early demise prevented him from seeing his creation develop. The publishers kindly approached me to conduct the first revision of the book and it was completed nearly a decade ago. It was a real pleasure to provide my own input to the book's evolution; it was certainly daunting but I believe it still has a firm place in the helicopter world. This same daunting feeling returned about two years ago when the present publishers asked me to prepare a third edition. It is imperative in an introductory text, as this book is, not to take the reader too far into the fine details of the subject; however, it is being unfair to lightly touch on the subject and gloss over important factors which link the various theories and analyses together.

The linking of technical methods is particularly relevant in the helicopter since it is not possible to isolate the aerodynamics of the rotor and overall aircraft from the dynamic responses of the blades themselves. Each influences the other and the complete problem has to be solved.

In 1970, after graduating in mathematics, I arrived at Westland Helicopters in Yeovil to begin my career. I walked into a subject in which I had the mathematical skills but very soon became aware that I needed to learn how to apply that mathematical knowledge. I also soon realized that I was working with some very sharp minds and, with their help, encouragement and a wealth of experience became a colleague. It is due to their dedication and generosity that I came to build a career in helicopter aeromechanics – for which I will always be

grateful. I was well schooled in the intricacies of helicopter rotors, initially by Geoff Byham, Ian Simons and Bob Hansford. As my career developed I enjoyed the company of colleagues Alan Vincent, Steve King, Tom Beddoes and John Perry.

I have had many interactions with other academics, researchers, those in the armed forces and a whole host of flyers, and they too have my gratitude. In academia I learnt a great deal from Geoffrey Lilley, Ian Cheeseman, Roddy Galbraith, Roy Bradley, Gordon Leishman, Gareth Padfield and Richard Brown. Working in the helicopter industry allows contact with experts in their field, such as the late Peter Wilby of the RAE, Tim Cansdale of dstl and David Lee of the Empire Test Pilots' School. One of the great pleasures of working in a university is seeing young minds develop and I was lucky enough to see Ajay Modha, Malcolm Wallace, Mark Jones, Peter Knight and Matthew Orchard through their earliest days in helicopter research and into the aerospace industry. I sometimes felt a twinge of envy when, perhaps with another start, I could have made a greater contribution. However, they are the young minds that will define the future and I will leave it in their capable hands.

To create a book, you need help and contributions and I would like to detail them now. If we start with the text, then the staff of the university must be acknowledged. I am very grateful to my Head of School, Mark Spearing, for encouraging me to undertake this task. I am in debt to my colleagues, Scott Walker and Hazel Paul, who have been instrumental in keeping me on the rails. Their contribution was to get a set of chapters assembled, in a sensible time, and which read well. This is vital for an introductory text. I owe them some favours. I was very fortunate to have David Lee of the Empire Test Pilot's School check Chapter 8 and make valuable suggestions to help its readability. The book contains many images and while I was able to produce some myself, I needed to ask for the generosity of many skilful photographers to fill in the many gaps. David Gibbings of Agusta Westland has been very generous with his time in providing images and technical support. In digging around on the Web I encountered high-quality photographic work from Ashai Bagai, Steve Rod, Markus Herzig, John Olafson and Stewart Penney who kindly let me make use of their hard work. John Piasecki of the Piasecki Corporation was very supportive by providing two images of its compound helicopter designs. Christina Gotzhein of Eurocopter was very helpful in supplying two images of its helicopters either in the Himalayas or with their latest design – only just past its first flight! Paul Oelkrug of the McDermott Library at the University of Texas provided the image of the XC 142 and I am grateful for all of his efforts.

Finally, I would like to express my sincere appreciation of the US Navy and Air Force websites which contain a gallery of really outstanding images and which are placed in the public domain. They have made a significant contribution to the content of this book.

I would like to thank Debbie Cox and Eric Willner of John Wiley & Sons, Ltd for their encouragement and willingness to grease the works, which relieves me of many factors required to get a book onto the bookshelves.

I would also like to record my gratitude to one of their colleagues, Nicky Skinner. Nicky provided my main interface with John Wiley & Sons, Ltd and helped me enormously with the nuts and bolts that authors all too easily forget. She also lit the odd fire under me when my mind drifted onto other things and deadlines were approaching at an alarming rate. I was looking forward to seeing it through with her and only recently we met to go for the final push to the book hitting the shelves. She was young, bright and delightful and knew her job inside out, so it was with great sadness I learned that she had passed away, suddenly and all too early. In a fairer world she had her life before her and many authors to encourage and help over the finish line. It is a great shame that this can no longer happen and I would like to acknowledge the many, and valued, contributions she made to the genesis of this book. I will miss her charm and above all her smile. The task of getting the book from computer to the page requires a considerable effort from the production staff and I am very grateful to Genna Manaog for helping the book through its final run in to the printing press. The difference between what you want to say and what you actually say is always a problem. It takes a good copy editor to straighten out the words and I am indebted to Neville Hankins for his contributions.

I have one final acknowledgement to make. My wife Stella has provided me with considerable support over my working life but due to a severe illness has not been able to take part in putting this book together in the normal way. However, I have had her spirit with me throughout and I would hope that she would, under normal circumstances, have approved of the final result. I would like to dedicate this book to her.

In looking at the final version of this book, I am reminded of the long road I have travelled. I started working on helicopters because, quite honestly, I had but one job offer after graduation and that was in the Aerodynamics Research Department at Westland Helicopters. So on 2 September 1970, wearing a brand new suit from Dunn and Co., and on a sunny morning in Somerset, I plunged headlong into the subject. So writing this on 18 February 2011, there are 41 years gone by; sometimes it feels like 141 years and sometimes like 41 days. In either case it has been interesting, difficult, frustrating, maddening but ultimately worthwhile, enlightening, humbling and fun. I have said earlier that I have had support from many colleagues and I consider that I have been lucky indeed. I hope there are still more hurdles to clamber over and while there is a neuron or two left I will keep at it. To you the reader, there is still much to do and I wish you well. I sincerely hope that, in reading this book, you will be encouraged and stimulated. It will never be easy but then, if it was, there would be no satisfaction. If you keep at it there will be the occasional Eureka moment and those are the times when you will feel fulfilled.

Bon voyage.

Simon Newman
Winchester
March 2011

Notation

General

a lift curve slope $dC_L/d\alpha$

a_0 first term in Fourier expansion of β

a_1 coefficient of second term in Fourier expansion of β

a_2 coefficient of fourth term in Fourier expansion of β

A area of rotor disc

A_b total blade area (N blades)

A_1 coefficient of second term in Fourier expansion of β

A_2 coefficient of fourth term in Fourier expansion of β

A_p projected frontal area of rotor head (Chapter 6)

A_s flow spoiling factor (Chapter 6)

A_z boundary layer shielding factor (Chapter 6)

b_1 coefficient of third term in Fourier expansion of β

b_2 coefficient of fifth term in Fourier expansion of β

B tip loss factor in $r = BR$

B_1 coefficient of third term in Fourier expansion of β

B_2 coefficient of fifth term in Fourier expansion of β

c blade chord

C_D drag coefficient

C_L lift coefficient

C_H H-force coefficient

C_P power coefficient

C_Q torque coefficient

C_T thrust coefficient

d differential operator

D aerodynamic drag

e hinge offset ratio

f equivalent flat-plate area

H H-force

I moment of inertia

k empirical constant in expression for profile power

K empirical constant in Glauert expression for induced velocity

l moment arm of tail rotor thrust about main shaft

L aerodynamic lift

m blade mass per unit span

M figure of merit

M Mach number

M moment (Figures 8.4 and 8.5)

M_T aerodynamic moment about flapping axis

n inertia number (Chapter 8)

N number of blades

p static pressure

P power

q dynamic pressure, $½\rho V^2$

q torque coefficient (Bramwell definition)

Q torque

R blade radius

S stiffness number

t_c thrust coefficient (Bramwell definition)

T thrust

u component velocity (non-dimensional, $U/\Omega R$)

U component velocity (dimensional)

v induced velocity

V hypothetical velocity in Glauert formula for forward flight

V_c climbing speed

V_i stream velocity (flight speed)

w disc loading, T/A

W aircraft weight

x fraction of blade span from axis ($=r/R$)

y distance along blade span from axis

z height of rotor plane above ground

Greek

α incidence (angle of attack) of blade, positive nose-up

α incidence of fuselage (Chapter 6), positive nose-up

α_r angle of attack of tip path plane to flight direction, positive nose-down

β compressibility factor (Chapter 6)

β flapping angle (blade span to reference plane)

γ Lock number

δ relative density of air, ρ/ρ_0

Δ prefix denoting increment, thus Δ*P*
ζ lag angle
θ blade pitch angle
κ empirical constant in expression for induced power
λ blade natural flapping frequency (Chapters 8)
λ inflow factor (non-dimensional induced velocity)
μ advance ratio, *V*/Ω*R*
π pi
ρ absolute density of air
σ blade solidity factor
ϕ angle of resultant velocity at blade to reference plane
χ sweep angle
ψ angle of azimuth in blade rotation
Ω blade rotational speed, radians per second

Suffixes

av available
b blade
c suffix for thrust coefficient (Bramwell definition)
C in climb
D drag
D descent
h hover value
H *H*-force
i induced
L lift
Max maximum
o basic or constant value
p parasite
P power
Q torque
req required
t blade tip
tw blade twist
T thrust
∞ conditions ‘at infinity’, that is where flow is undisturbed
0 hover value