Principles of Helicopter Aerodynamics

Second Edition

The helicopter is truly a unique form of aircraft and a mastery of modern aeronautical engineering that fulfills a variety of civilian and military roles. The usefulness of the helicopter lies in its unique ability to take off and land vertically on almost any terrain, to hover stationary relative to the ground, and to fly forward, backward, or sideways. These unique flying characteristics, however, come at a price, including complex aerodynamic problems, significant vibrations, high levels of noise, and relatively large power requirements compared to a fixed-wing aircraft of the same weight.

This book, written by an internationally recognized teacher and researcher in the field, provides a thorough, modern treatment of the aerodynamic principles of helicopters and other rotating-wing vertical lift aircraft such as tilt-rotors and autogiros. The first part of the text begins with a unique technical history of helicopter flight and then covers basic methods of rotor aerodynamic analysis and related issues associated with the performance of the helicopter and its aerodynamic design. The second part is devoted to more advanced topics in helicopter aerodynamics, including airfoil flows, unsteady aerodynamics, dynamic stall, rotor wakes and rotor–airframe aerodynamic interactions. The third part of the book contains chapters on autogiros and advanced methods of helicopter aerodynamic analysis. A companion chapter on the aerodynamics of wind turbines recognizes both the commonalities and differences with the aerodynamic problems found on helicopters. Every chapter is extensively illustrated and concludes with a comprehensive bibliography and a set of homework problems.

Advanced undergraduate and graduate students, as well as practicing engineers and researchers, will welcome this thorough and up-to-date text on the principles of helicopter and rotating-wing aerodynamics.

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Second Edition

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TO MY STUDENTS

in appreciation of all they have taught me

Contents

Preface to the Second Edition

The reader will see many changes to this second and much enlarged edition of *Principles of Helicopter Aerodynamics*. However, the goal in writing the book remains the same, to give a reasonably adequate description of background theory and present an up-to-date treatment of the subject of helicopter aerodynamics, or at least as up to date as it can be. With the life span of a modern engineering textbook being measured in a few years, it seemed appropriate to regularly update the book with both revised and new material that, in part, reflect both current areas of topical interest as well as areas of ongoing fundamental research. The revised text will continue to appeal both to those learning the field anew and to those who are practicing engineers. The text requires some familiarity with basic aerodynamics and mathematical concepts, although no prior background in rotating-wing aerodynamics is assumed. Both new and updated questions at the end of each chapter will satisfy instructors who have used the first edition of the book in the classroom and have found the solutions manual useful in their teaching.

Work on revising the first edition and compiling the second edition started early in 2003, although planning, gathering materials, and writing started well before then. The new material was finally defined late in 2003 and some of it was taught in my "Helicopter Aerodynamics II" class during the spring of 2004. In this second edition I have taken the opportunity to thoroughly revise the original text for content and clarity, as well as to finally weed out the remaining evasive typographical errors that made it into the third printing of the first edition. Any errors that do remain are entirely of my own doing. Many revisions to the text have been made based on my own rereading during the last five years, as well as on the feedback and suggestions received from many readers, a lot of them students. In the first instance, I have put back some important parts of the original manuscript that were edited out of the first published edition. This by itself has provided much better detail and continuity between sections and chapters, as well as giving a fresh new look to the book. A few original sections have been deemed duplicative or redundant with the addition of the new chapters and so have been edited out completely. Other parts of the text have been moved to the new chapters. Most of the original figures have been revised or updated, or have been reordered in a more logical sequence.

The introductory chapter on the development of the helicopter has been completely revised. I have taken the opportunity to thoroughly check historical events, dates, and other details, which are often conflicting between different publications. Tracing original documents back over ninety years in some cases has proved challenging, but I have been helped in this task by many willing individuals. I am particularly grateful to Roger Connor of the National Air and Space Museum for sharing his extensive knowledge of helicopters and VTOL aircraft. I have also added new material to this chapter that has strengthened the description of the technological advances needed for vertical flight. The addition of new material on engines has helped put the development of the helicopter into a better perspective when compared to the development of other aircraft. Chapters 2 and 3 describe the fundamental aerodynamic characteristics of helicopter rotors, and these two chapters have seen the fewest changes in the second edition. Even here, however, several additions have been made to better introduce the fundamentals of helicopter flight and to provide an essential primer for the more advanced materials contained in the subsequent chapters of the book. Chapter 4 on rotating blade motion has seen the addition of sections on teetering and semi-rigid rotors to complement the discussion on the articulated form of rotor. A discussion of pitch–flap coupling and an introductory section on ground resonance helps round out the revised chapter. Finally, the discussion on the methods of solving for rotor trim has expanded to complete this chapter. Chapter 5 is on helicopter performance. Initially I focused on a better description of the international standard atmosphere and why it is used in performance work. The addition of a section on compressibility losses on the rotor operating at higher forward speeds helps better explain the impact of this deleterious effect on helicopter performance. A new section on engines and the issues of specific fuel consumption connect better to a revised section on flight range and endurance. There is also a new section on maximum altitude (ceiling) performance. Performance issues in rapidly descending flight have received some recent attention and this seems to be a topic that is very poorly understood from a fundamental standpoint. To this end, revised and expanded sections on autorotational flight and the vortex ring state should help cover the field. Finally, a section on maneuvering flight performance helps round out Chapter 5.

The first part of the book concludes with Chapter 6, which addresses helicopter aerodynamic design issues. This chapter has seen an expanded consideration of airframe download and other performance penalties. A new section on the use of wind tunnel testing in the evaluation of rotor air loads and helicopter performance helps put the difficulties of accurate flight performance estimation into proper perspective. The issues of maneuvering flight are considered again through a discussion of precessional stall effects, both on the main rotor and the tail rotor. Four new sections have been added to Chapter 6. The first is on "smart" rotor systems, which may be one approach whereby the performance of the helicopter could be significantly improved. It remains to be seen, however, if the practical issues in building and certifying a cost-competitive smart rotor system can be overcome. Second, the ideas of a human-powered helicopter are introduced. This is a problem that continues to interest generation after generation of students, although, as the discussion shows, the physiological limits of humans severely limit the possibilities of ever achieving successful human-powered vertical flight. Nevertheless, it remains a problem that will continue to hold great fascination and it is worthy of consideration from both an aerodynamics and a vehicle design perspective. Third, there is a new section on micro air vehicles (MAVs). The flight of MAVs involves low Reynolds number issues for which there is little existing knowledge of their aerodynamics, and so they require special considerations in their performance estimation. Fourth, a brief section on performance degradation issues associated with rotor and airframe icing completes this chapter.

The second part of the book starts in Chapter 7 with a revised discussion on airfoil sections used for helicopter applications. The chapter is enhanced by a more thorough and up-to-date discussion on advanced airfoil design. The addition of a section on circulation controlled airfoils reflects renewed interest in this concept for alternative rotorcraft concepts. A short section on very low Reynolds number airfoil characteristics complements the discussion on MAVs found in Chapter 6. Finally, a section on the aerodynamic degradation of helicopter rotor airfoils from ballistic damage completes this chapter. Chapter 8 is a fairly large chapter on unsteady aerodynamics, and the existing material has seen several changes. A new section on the unsteady aerodynamics of airfoils with trailing edge flaps recognizes their use on modern rotors for vibration and noise reduction and perhaps as a primary means of rotor control by replacing the swashplate. The addition of a new section on rotor aeroacoustics in this chapter helps make the connection between unsteady aerodynamic forces and the often obtrusive noise that seems to plague the modern helicopter. This section also provides a primer for students and aerodynamicists learning the field of acoustics anew, as well as lending a bridge to practicing acousticians who need greater than superficial knowledge about helicopter related acoustic problems. Chapter 10 on rotor wakes has seen the addition of new material throughout. This includes a fresh discussion on tip vortex modeling, including the effects of turbulence within the vortex core. The understanding of helicopters in maneuvering flight has received much recent attention by the technical community, so a section on time-accurate wake modeling seemed a natural addition to the book.

Chapters 11 through 14 are all new chapters. Chapter 11 is on rotor–airframe interactional aerodynamics that contains material left over from the draft of the first edition. Because the helicopter as a system must function properly and predictably throughout its operational flight envelope, an understanding of component-interaction aerodynamics is essential to the successful design of the modern helicopter. Several sections on this topic from the original text have now been parsed out and integrated with the new material that forms this chapter. Chapter 12 describes the technological development of autogiros and gyroplanes, and recognizes the fundamental role that the autogiro played in the development of the helicopter. This chapter also contains the essential aerodynamic theory of the autogiro. The need for this chapter also reflects a renaissance of interest in the commercialization of a modern gyroplane, for which new engineers must be suitably knowledgeable.

Chapter 13 is on the aerodynamics of wind turbines. It may seem surprising to some to find a chapter on wind turbines in a book on helicopters, but the aerodynamics of wind turbines have many similarities to the aerodynamics of helicopters, yet also with important differences. There are so relatively few books on wind turbines and those describing the aerodynamics are frequently out of print. Environmental concerns about global warming and the storage of waste from nuclear power plants has seen an increased emphasis on the use of wind energy, which is likely to see much more rapid and expansive use in years to come. The performance of wind turbines can be analyzed by many of the same methods used for helicopters, and the cross fertilization of expertise in the two areas will hopefully help foster a new understanding of both fields.

Finally, Chapter 14 explains the basis of modern computational methods for rotor and helicopter analysis, and these are put into context with the capabilities classical methods and modern engineering approaches. Dr. Richard Brown of Imperial College at the University of London contributed heavily the writing of this chapter. To some, the development of the field of computational fluid dynamics (CFD) by itself is held out to be the "Holy Grail" for the helicopter aerodynamicist. But this is a very misleading perspective because CFD does not, by itself, hold the answer to all of the various problems found on helicopters. The answer lies more in the successful integration of advanced forms of aerodynamic analysis into other disciplines of analysis. It is also unwise for other approaches to be abandoned in the shorter term while CFD matures to an accepted level of capability, given that this could still be decades off, despite more optimistic claims. These CFD models require continuous and careful validation, both against more complete solutions and/or analytical results and against detailed experimental measurements. This is one reason why wind tunnel testing of helicopters and subsystems will continue to be essential to better understand and predict the capabilities of the helicopter in response to specific aerodynamic phenomena. The future offers many opportunities for new research focused toward the development of more innovative computational models with greater predictive capabilities for helicopter applications. Only then can the problems that limit the performance and capabilities of the helicopter be understood and mitigated.

Preface to the First Edition

This book is a college-level analytical and applied level exposition of the aerodynamic principles of helicopters and other rotating-wing vertical lift aircraft. It is written for students who have no background in rotating-wing aerodynamics but have had at least two semesters of basic aerodynamics at the undergraduate level and possibly one course at graduate level. The material covered has grown mainly out of two graduate-level courses in "Helicopter Aerodynamics" that I have taught at the University of Maryland since 1988. I have also taught a somewhat more general senior-level undergraduate course in "Helicopter Theory" about every other year, which is centered around the first half of this book. These courses have been offered as part of the formal curriculum in the Center for Rotorcraft Education and Research, which was originally founded in 1982, partly through the efforts of Professor Alfred Gessow. It is now nearly fifty years since Alfred Gessow and Gary Myers' well-known book *The Aerodynamics of the Helicopter* was first published. I am pleased to record in the preface to this book that in his status as Professor Emeritus, Alfred Gessow continues to be active in activities at the University of Maryland and also within government and professional organizations. As a testimony to his life-long dedication to education and research in helicopter technology, the Rotorcraft Center at the University of Maryland has been recently named in his honor.

In the institutions where formal courses in helicopter technology have been taught, either at the undergraduate or graduate level, my experience is that they have been well received and very popular with the students. What is often most attractive to students is the highly multidisciplinary nature of helicopter engineering problems. Therefore, an introductory course in helicopters provides a good capstone to the aerospace engineering curriculum. Another factor for most students who have taken a helicopter course is the realization that so much more remains to be learned about fundamental aerodynamics, especially as it applies to rotating-wing aircraft. This is reflected in the experience levels in predicting the aerodynamics and overall behavior of helicopters before their first flight, which are less than desirable. Consequently, it is fair to say that the various aerodynamic problems associated with helicopters and other new forms of rotary-wing aircraft probably provide the scientists and engineers of the future with some of the most outstanding research challenges to be found in the field of theoretical and applied aerodynamics.

Serious work on this book project started about three years ago and was motivated primarily by my students. It has grown out of a relatively informal collection of classroom notes and research papers and an overwhelming need to synthesize both older and newer information on the subject of helicopter aerodynamics into one coherent volume. With the ever increasing content of new research material on helicopters and the increasing proportion of recent research material being included in the course, especially in the second semester, the development of a formal textbook was really a logical step. Even since 1980, when Wayne Johnson's excellent book *Helicopter Theory* was published, progress in understanding helicopter aerodynamics and other related fields has been remarkable. A glance at the content of recent proceedings of the Annual Forum of the American Helicopter Society or the European Rotorcraft Forum shows the scope and depth of new work being conducted today, which continues despite tightly controlled budgets. This has been fueled, in part, by the great advances in computer technology, which has fostered ambitious new analytical and numerical approaches to solving helicopter technology problems. Some of these approaches now come under the banner of computational fluid dynamics (CFD) using numerical solutions to the Euler and Navier–Stokes equations. While these techniques are not yet mature, CFD methods have begun to provide new insight into the complicated aerodynamic problems associated with helicopters that were previously intractable with existing mathematical methods or were limited by available experimental techniques. As these new numerical methods continue to mature and become better validated, the first decade of the twenty-first century will see an increasing use of CFD tools in the design of new and improved helicopters. The past twenty years has also marked a revolution in the experimental studies of helicopter aerodynamics, where advances in flow diagnostic and other instrumentation has allowed measurements on rotors to be made with a fidelity that was considered impossible just a few years ago. The complex nature of the problems found on helicopters means that both experiment and theory must continue to go hand in hand to forge a better understanding of the whole. This will result in the development of new rotating-wing aircraft with better performance, lower vibration, better reliability and maintainability, and with lower direct and operational costs. The modern spirit of international cooperation in research and development makes the years ahead in the twenty-first century very exciting.

As I have already mentioned, a significant part of the content of this book has been focused toward students at the graduate level who are learning the principles of helicopter aerodynamics and are exploring the tools available to approach the vigorous, multidisciplinary research and development of the modern helicopter. In planning the content of this book, I have organized the material in two main parts. The first part will be appropriate for a one-semester course in helicopter aerodynamics for senior undergraduate and first-year graduate students. This material essentially represents a thorough introduction to fundamental helicopter problems, basic methods of rotor analysis, issues associated with helicopter performance, and conceptual design issues. I have attempted to follow the spirit of Gessow & Myers's book, where theory is supported throughout by liberal references to experimental observations and measurements. In this regard, rediscovering the less well-known early NACA and RAE technical literature on the subject of helicopter aerodynamics proved to be one of the most satisfying aspects of writing this book. The rapid progress made in understanding the problems of the helicopter during the period between 1930 and 1950, and the ingenuity shown in both the experimental and analytical work, are quite remarkable.

The second part of the book gives a more advanced treatment of more detailed aspects of helicopter aerodynamics, again with emphasis on physical concepts and basic methods of analysis. This part will appeal more to those students who plan to conduct research in helicopter aerodynamics and related fields or who are already practicing engineers in industry and government laboratories. However, I do hope that practicing engineers will relish in the opportunity to revisit the first part of the book to review the basics and also to review the inherent assumptions and limitations of the fundamental concepts and methods. These are so often taken for granted, but they form the backbone of many modern forms of helicopter analysis. Because I have always found a need to bring "industrial practice" into the classroom, I have tried to incorporate engineering practice as well as some of my own industrial experience into the second part of the book. For this, I thank my former colleagues at Westland Helicopters for sharing their knowledge with me.

Like most textbooks, the final product has turned out to be not exactly what was originally planned. Along the way, topics have been added, parts of the text rearranged, and some other topics deleted. Also, in light of the reviews of the preliminary manuscript, new figures have been added, many were modified, and others deleted. While more than 400 figures were originally prepared, less than 275 finally made it to the finished book. In the interests of space and publication costs, two chapters have been left out completely. These were "Interactional Aerodynamics" and "Advanced Computational Aerodynamic Techniques." Both topics are referred to, albeit briefly, throughout the book, but to include them would have made the final size of the book prohibitively long. There have also been such rapid recent advances in these areas in the past few years that they are best left for a second edition. The list of key references for each chapter is extensive but by no means complete, and the reader is encouraged to follow through with the references contained in each publication, as required. Problems are provided at the end of each chapter and have been drawn on time-proven homework and examination questions. Solutions have been provided in a companion instructors' solution manual.

Chapter 1 introduces the helicopter through its technical history. This chapter grew out of my personal research into the Berliner helicopter experiments that were conducted during the early 1920s at the College Park Airport, which is close to the University of Maryland. Whereas in the technical development of fixed-wing aircraft it is possible to point to several key historical events, it becomes quickly apparent that things are much less clear in the development of the helicopter. There are already many authoritative publications that detail the historical development of the helicopter, so I have tried to approach the discussion on more of a technical theme and to put the background and difficulties in understanding the aerodynamics of vertical flight into broader perspective. This introduction is followed in Chapter 2 by an analysis of hovering and axial flight using the Rankine–Froude momentum theory. The basic momentum theory concept was extended to forward flight by Glauert and others from the RAE at Farnborough, inspired not by the helicopter, but by the success of Cierva's Autogiro. It is shown that many of the important performance and operational characteristics of the helicopter can be deduced from Glauert's extension of the basic momentum theory. The blade element and combined blade-element momentum theory is discussed in Chapter 3. These ideas were developed in the 1940s and provide the foundation for a more modern treatment of the aerodynamics of rotors. On the basis of certain assumptions, important information on blade design, such as optimum or ideal shapes for the blade planform and blade twist, can be deduced from the combined blade element momentum theory. Because helicopter blades have articulation, in that they can flap and lag about hinges located near the root of each blade, it is not possible to understand the behavior of the helicopter solely from an aerodynamics perspective. Therefore, in Chapter 4 a discussion of rigid blade motion leads naturally into an understanding of the issues associated with rotor response to the changing aerodynamic loads and also to rotor control. Also introduced here are the ideas of rotor trim; that is, the pilot's control inputs required to enable equilibrium flight of the helicopter. Chapter 5 gives an introduction to helicopter performance and operational issues such as climbing and descending flight, including the autorotative state and flight near the ground. The first part of the book concludes in Chapter 6, which reviews issues associated with the conceptual aerodynamic design of helicopters, including the main rotor, the fuselage and empennage, and the tail rotor. Although it might have been more appropriate to place this chapter at the end of the book, it provides a good bridge between the fundamentals and results to many problems that are still more of a research nature for which experimental research is incomplete and predictive capabilities are not yet mature.

Chapter 7 starts the second part of the book with an important practical review of basic airfoil aerodynamics, including boundary layer and viscous aerodynamics, and the role of compressibility. This is followed by applications of these concepts to understanding some of the special requirements and characteristics of rotor airfoils. Again, liberal reference to experimental measurements makes the present treatment relatively unique amongst textbooks on helicopters. Chapters 8 and 9 comprise a comprehensive discussion on unsteady aerodynamics, with emphasis on the relevance to helicopter problems. Classical techniques of unsteady aerodynamics, including Theodorsen's theory and Loewy's theory, the indicial response method, and dynamic inflow, are reviewed in Chapter 8. Extensions of some of these methods to the compressible flow problems found on helicopters are described, with validation with experimental measurements where possible. Indicial methods are treated in some detail because they form the foundation for many modern methods of helicopter analysis and are not covered in any previous helicopter text. Chapter 9 discusses the problem of dynamic stall, which is known to be a barrier to attaining high speed forward flight with a conventional helicopter. Engineering methods of dynamic stall prediction are also reviewed, along with some examples of the general predictive capability to be found with these models. The physical nature of helicopter rotor wakes, both in hovering and forward flight, are discussed in Chapter 10. Nearly all of what we know about rotor wakes comes from empirical observations, and this has led to the development of well-validated mathematical models of the rotor wake using vortex techniques. Chapter 10 concludes with a brief discussion on interactional aerodynamics. Although many the problems of rotor aerodynamics can be studied by considering the rotor in isolation to the fuselage, tail rotor and empennage, aerodynamic interactions between the components lead to many problems that are not yet fully understood.

A word about systems of units is in order. In the preparation of this book, I have found it necessary to use both the British (Imperial) and metric (SI) systems. Any preference for one over the other is done simply for the sake of convenience, and I think there is really little reason to change units for the sake of standardization in the text. As aerospace engineers, and particularly helicopter engineers, we are used to working with both systems and even with mixed units in the same breath, and so most readers will have no problems with this approach. For the foreseeable future, students will have to learn to become fully conversant in both systems. Where I have felt it would be helpful, units in both systems are stated. For convenience, a table of conversion factors is also included in the appendix.

Having said all this and made my excuses, I hope this edition of the book will be judged, especially by the practicing engineer, on what it contains and not on what else could potentially have been included. Like everything in aviation, the final product is always a compromise and is always under a continuous state of revision, development, and improvement. As a final comment, it seems appropriate to quote Igor Sikorsky who has said: "At that time [1908] aeronautics was neither an industry nor even a science . . . it was an art, I might say, a passion. Indeed at that time it was a miracle." As we stand now at the turn of the new millennium, I'm sure that if he was alive Igor Sikorsky would have agreed that the past century has indeed seen many miracles, both in aeronautics and in helicopter technology. The new century will almost certainly see more.

Acknowledgments

This book is the product of an opportunity afforded to me by the University of Maryland. The research and writing of the first edition of this book was unique experience and has led to many lessons. It was gratifying to see how well the first edition was received, with feedback being received from the four corners of the world. The first edition took the best part of 2,500 desk hours, mainly during evenings and weekends and spread over three years. In this regard, I am forever grateful to my wife, Alice Marie Leishman, for her love and understanding, and for providing me continuous support where writing, proofreading, drawing figures, and plotting graphs meant many long nights and all too short weekends. Preparing this second edition required about 1,300 desk hours, spread over about eighteen months, but ultimately even with the benefit of experience and hindsight, it proved to be no lesser a task than the first edition.

Special acknowledgment is due to a great many people, both on and off the University of Maryland campus. I am most grateful for the council of my colleagues at the University of Maryland, Professors Alfred Gessow (now deceased), Inderjit Chopra, Roberto Celi, James Baeder, Christopher Cadou, and Dr. Vengalattore Nagaraj. Professor Gessow had read substantial parts of the first edition and offered many useful suggestions for improvement. Before he passed away in May of 2002, Alfred Gessow and I had many significant discussions about the autogiro and the role it played in the fundamental development of the helicopter, from the point of view of both engineering theory and practice. Chapter 12 in this second edition reflects the spirit of our discussions, and I dedicate this chapter to his memory. Al Gessow's knowledge and first-hand experience working at NACA Langley during the 1940s and 1950s in the technical development of early helicopters was also invaluable to me. Professors Inderjit Chopra and Roberto Celi provided good suggestions for Chapter 4 and kindly allowed me to use some of their own course material on blade motion and rotor trim. Professor James Baeder read Chapter 8 on unsteady aerodynamics and Chapter 14 on computational methods for helicopter applications, and I am grateful to him and his students for their willingness to help me with figure preparation. Dr. Chris Cadou read the revised parts of Chapter 1, and I enjoyed our engaging conversations on early engine development and the history of aircraft technology in general. Dr. Nagaraj read the revised Chapters 5 and 6 and offered more good suggestions on helicopter design issues.

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List of Main Symbols

Listed below alphabetically are the main symbols used in this book. Note that more than one meaning may be assigned to a symbol. Other symbols are defined internally within each chapter.

a	sonic velocity
a	wake induction factor (for a wind turbine)
A	rotor disk area, πR^2
A	axial (chord) force
A_b	blade area, σA
A_{ov}	rotor overlap area
B	tip-loss factor
B	temperature lapse rate
c	blade chord
C	Theodorsen's function
C'	Loewy's function
C_d	section drag coefficient
C_{d_0}	section zero-lift drag coefficient
C_{D_f}	fuselage drag coefficient
C_{D_v}	fuselage vertical drag coefficient
c_f	local skin friction coefficient, $\tau_w/\frac{1}{2}\rho V_\infty^2$
C_H	H-force coefficient, $H/\rho A(\Omega R)^2$
C_l	section lift coefficient, $L/\frac{1}{2}\rho U^2 c$
$C_{l_{\max}}$	maximum lift coefficient
C_{l_α}	section lift-curve slope
$\bar{C}_L$	rotor mean lift coefficient, $6(C_T/\sigma)$
C_m	airfoil pitching moment coefficient, $M/\frac{1}{2}\rho U^2 c^2$
$C_{m_{1/4}}$	airfoil pitching moment coefficient about 1/4-chord, $M_{1/4}/\frac{1}{2}\rho U^2 c^2$
$C_{m_{0.25}}$	airfoil pitching moment coefficient about 1/4-chord, $M_{0.25}/\frac{1}{2}\rho U^2 c^2$
$C_{m_{ac}}$	airfoil pitching moment coefficient about aerodynamic center, $M_{ac}/\frac{1}{2}\rho U^2 c^2$
C_{M_x}	rolling moment coefficient, $M_x/\rho A R(\Omega R)^2$
C_{M_y}	pitching moment coefficient, $M_y/\rho A R(\Omega R)^2$
C_n	normal force coefficient, $N/\frac{1}{2}\rho U^2 c$
C_{n_α}	slope of normal force coefficient versus α curve
C_p	specific heat at a constant pressure
C_p	pressure coefficient, $(p - p_\infty)/0.5\rho V_\infty^2$
C_p'	pressure coefficient, $100(p - p_\infty)/0.5\rho \Omega^2 R^2$
C_P	rotor power coefficient, $P/\rho A(\Omega R)^3$
C_{P_c}	climb power coefficient, $P_c/\rho A(\Omega R)^3$
C_{P_i}	induced power coefficient, $P_i/\rho A(\Omega R)^3$

C_{P_0}	profile power coefficient, $P_0/\rho A(\Omega R)^3$
C_{P_p}	parasitic power coefficient, $P_p/\rho A(\Omega R)^3$
C_R	resultant force coefficient, $R/\frac{1}{2}\rho V_\infty^2 c$
C_Q	rotor torque coefficient, $Q/\rho A(\Omega R)^2 R$
C_T	rotor thrust coefficient, $T/\rho A(\Omega R)^2$
C_T/σ	blade loading coefficient
C_W	weight coefficient, $W/\rho A(\Omega R)^2$
C_W	work coefficient or torsional damping factor, $\oint C_m d\alpha$
C_X	X-force (longitudinal-force) coefficient, $X/\rho A(\Omega R)^2$
C_Y	Y-force (side-force) coefficient, $Y/\rho A(\Omega R)^2$
C_μ	jet momentum coefficient, $\dot{m}V_j/\frac{1}{2}\rho V_\infty^2 c$
D	drag force
DL	rotor disk loading, T/A
$D.F.$	torsional damping factor, $\oint C_m d\alpha$
e	flapping hinge offset as a fraction of rotor radius
f	equivalent flat plate area of fuselage, etc., $D/\frac{1}{2}\rho V_\infty^2$
f	effective flow separation point as a fraction of chord
F	Prandtl's tip-loss function
FM	figure of merit, $C_T^{3/2}/(\sqrt{2}C_P)$
F_x	aerodynamic force parallel to disk plane
F_z	aerodynamic force normal to disk plane
h	altitude or elevation (height)
h	plunge displacement
h	perpendicular distance from vortex to evaluation point
h_p	pressure altitude
h_ρ	density altitude
H	rotor drag force
H	Hankel function
i	blade control point index
$I_{b_{i,j}}$	influence coefficient
I_b	blade mass moment of inertia
I_β	blade mass moment of inertia about the flapping hinge
I_ζ	blade mass moment of inertia about the lagging hinge
$\Im$	imaginary or out-of-phase part
J	Bessel function of the first kind
k	reduced frequency, $\omega c/2V_\infty$
k_g	gust reduced frequency, $\omega_g c/2V_\infty$
k_x, k_y	longitudinal and lateral inflow gradients, respectively
KE	kinetic energy
l	length of influencing vortex filament
L	section lift force per unit span
m	mass per unit length of rotor blade
m	maximum camber
m	tandem rotor overlap fraction
$\dot{m}$	mass flow rate
M	Mach number or local free-stream Mach number, U/a
M^*	critical Mach number
M	mass

M	moment per unit span
M_∞	free-stream Mach number, V_∞/a
M_{dd}	drag divergence Mach number
M_{tip}	rotor hover tip Mach number, $\Omega R/a$
M_x	rotor rolling moment, positive to right (starboard)
M_y	rotor pitching moment, positive nose-up
M_β	aerodynamic flapping moment
N	normal force
N_b	number of rotor blades
p	pressure
p	roll rate about the x axis
p	point of maximum camber
$\bar{p}$	nondimensional roll rate, p/Ω
p	Laplace variable
P	rotor power
PL	rotor power loading, T/P
q	airfoil nondimensional pitch rate, $\dot{\alpha}c/V$
q	dynamic pressure
q	roll rate about the y axis
q_∞	free-stream dynamic pressure, $\frac{1}{2}\rho V_\infty$
$\bar{q}$	nondimensional pitch rate, q/Ω
Q	rotor torque
r	nondimensional radial distance
r_0	blade root cut out
r_c	vortex core radius
r_v	vortex release point along blade span
$\vec{r}$	position vector of a point in space
$\bar{r}$	nondimensional radial coordinate, r/r_c
R	blade radius
R	gas constant
Re	Reynolds number based on chord, $\rho V c/\mu$
Re_x	Reynolds number based on distance x, $\rho V x/\mu$
$\Re$	real part
Ri	Richardson's number
s	relative distance traveled by airfoil in semi chords, $2Vt/c$
S	Sears's function, referenced with respect to airfoil midchord
S	reference area or surface area
S_{ref}	reference area
S'	Sears's function, referenced with respect to airfoil leading edge
SFC	specific fuel consumption
t	time
t	maximum airfoil thickness
T	temperature
T	rotor thrust
T/A	rotor disk loading
U	resultant velocity at blade element, $\sqrt{U_P^2 + U_T^2}$
U_P	out-of-plane velocity normal to rotor disk plane
U_R	radial velocity along blade at disk plane

U_T	in-plane velocity parallel to rotor disk plane
v_h	hover induced velocity, $\sqrt{T/2\rho A}$
V_r, V_θ, V_z	radial, tangential, axial velocity components, respectively
V	velocity
$V_{\Omega R}$	hover tip speed
$\vec{V}$	velocity vector
V_∞	magnitude of free-stream velocity
$\vec{V}_\infty$	free-stream velocity vector
V_c	climb velocity
V_g	gust convection velocity
V_j	jet velocity
V_{mp}	speed to fly for minimum power
V_{mr}	speed to fly for maximum range
w	slipstream velocity
w	velocity normal to chord
w_g	upwash or gust velocity normal to chord
W	weight
W	work done on fluid
W_f	weight of fuel
x, y, z	Cartesian coordinate system
$\bar{x}$	nondimensional distance along airfoil chord, x/c
X	rotor longitudinal force, positive aft
X_n, Y_n	recurrence functions
X_{TSR}	wind turbine tip speed ratio, $\Omega R/V_\infty$
Y	rotor side force, positive right (starboard)
Y	Bessel function of the second kind
α	blade section angle of attack
α	rotor disk angle of attack
α_0	zero-lift angle of attack
α_e	effective angle of attack
α_{ind}	induced angle of attack
α_{TPP}	rotor tip-path-plane angle of attack, positive tilted forward
β	Glauert's compressibility factor, $\sqrt{1-M^2}$
β	blade flapping angle, positive up
β_0	blade coning angle, positive up
β_{1c}	longitudinal flapping angle
β_{1s}	lateral flapping angle
γ	ratio of specific heats
γ	blade Lock number, $\rho C_{l_\alpha} c R^4/I_b$
γ_b	bound vortex sheet strength
γ_w	vortex sheet strength in wake
Γ_b	bound vortex strength
Γ_v	vortex circulation strength
$\hat{\Gamma}$	nondimensional circulation strength, $\Gamma/(\Omega R C)$
δ	boundary layer thickness
δ	effective viscosity coefficient multiplier
ζ	blade lag angle, positive aft
η	efficiency factor

η	flap deflection angle
θ	blade pitch angle
θ_0	blade collective pitch
θ_{1c}	lateral cyclic pitch
θ_{1s}	longitudinal cyclic pitch
θ_{tip}	geometric pitch at blade tip
θ_{tw}	linear blade twist rate
$\theta_{0.75}, \theta_{75}$	pitch angle at 75% radius
κ	induced power factor
κ_{int}	induced power factor from rotor-on-rotor interference
λ	rotor inflow ratio, positive downward through disk
λ	gust speed ratio, $V/(V + V_g)$
λ_c	climb inflow ratio
λ_g	wavelength of sinusoidal gust
λ_i	rotor induced inflow ratio, $v_i/\Omega R$
Λ	local sweep or yaw angle, $\tan^{-1}(U_R/U_T)$
μ	rotor advance ratio, $V_\infty \cos\alpha/\Omega R$
μ	dynamic viscosity
μ_x	rotor advance ratio parallel to disk, $V_\infty \cos\alpha/\Omega R$
μ_z	rotor advance ratio perpendicular to disk, $V_\infty \sin\alpha/\Omega R$
ν	kinematic viscosity coefficient
ν_β	blade rotating flap frequency (nondimensional)
ν_ζ	blade rotating lag frequency (nondimensional)
ρ	density of air
σ	rotor solidity, $N_b c/\pi R$
σ_e	equivalent rotor solidity
τ	time constant
τ_w	wall shear stress
ϕ	inflow angle of attack, $\tan^{-1}(U_P/U_T)$
ϕ	general indicial response function
ϕ_W	Wagner indicial response function
ψ	azimuth angle
ψ	Küssner sharp-edged gust function
ψ_b	blade azimuth angle
ψ_w	wake age
ω	angular velocity (circular frequency)
ω_g	gust frequency
Ω	rotational frequency of rotor
χ	wake skew angle

Subscripts and Superscripts

∞	free-stream conditions
0	profile part
$1c$	first harmonic cosine component
$1s$	first harmonic sine component
1/4	quarter chord
3/4	three-quarter chord
ac	aerodynamic center