Rotorcraft Aeromechanics

WAYNE JOHNSON

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Wayne Johnson
NASA Ames Research Center

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Preface

Rotorcraft is a class of aircraft that uses large-diameter rotating wings to accomplish efficient vertical takeoff and landing. The class thus encompasses helicopters of numerous configurations, tilting proprotor aircraft, compound helicopters, and many other innovative concepts.

Defining "aeromechanics" is more difficult. Today's dictionaries do not capture what the term means for the rotorcraft community. The definitions are not broad enough, and they do not reflect the multidisciplinary facet of the word as applied to rotorcraft. In my 2010 Nikolsky Lecture for the American Helicopter Society, I proposed the following definition:

> Aeromechanics: The branch of aeronautical engineering and science dealing with equilibrium, motion, and control of elastic rotorcraft in air.

Aeromechanics covers much of what the rotorcraft engineer needs: performance, loads, vibration, stability, flight dynamics, and noise. These topics cover many of the key performance attributes and many of the often encountered problems in rotorcraft designs.

As with my previous book *Helicopter Theory* (written in 1976, published in 1980 by Princeton University Press, republished in 1994 by Dover Publications), this text is focused on analysis, with only occasional reference to test data to develop arguments or support results, and with nothing at all regarding the techniques of testing in wind tunnels or flight. Calculated results are presented to illustrate analysis characteristics and rotor behavior. Generally these results were obtained using computer programs that I have developed: the rotorcraft comprehensive analysis CAMRAD II and the sizing code NDARC.

I aim to be comprehensive in coverage, presenting in as much depth as possible what engineers need to know about modeling rotorcraft aeromechanics. Although connections to *Helicopter Theory* are apparent throughout this text, many significant advances in the theory have occurred since 1976. I assume the reader has a general knowledge of aeromechanics fields, such as classical dynamics, beam theory, lifting-line theory, and two-dimensional airfoils. I do provide introductory material where needed as a foundation for rotary-wing developments. Unlike *Helicopter Theory*, no attempt is made to be comprehensive in the bibliography. Sources are cited where considered historically important or the development is associated with a specific

work and also to direct the reader to expanded coverage of a subject. Several topics conclude with an outline of the history of their theoretical development.

The scope of this text is still a subset of rotorcraft aeromechanics. A shaft-driven helicopter is the primary focus, but other rotorcraft configurations are discussed, and most of the analysis is relevant to all configurations. Based mainly on my experience and interests, important areas such as structures, materials, and propulsion are not covered. The topic of flight dynamics here encompasses the aircraft behavior, but not handling qualities, which would require treatment of the control system and the pilot. Computational fluid dynamics is covered with an emphasis on identifying the unique aspects of the methods as applied to rotary wings. The equations are developed with an emphasis on rotating wings, but nothing is presented regarding solution procedures.

Chapter 1 describes the helicopter rotor and helicopter configurations. Design trends are shown to illustrate the aircraft characteristics. A brief history of helicopter invention is presented. Chapter 2 summarizes the notation used in this book, providing an important overview of the description of a rotor for analysis.

Chapters 3 to 8 constitute an introduction to rotorcraft aerodynamics and performance. Chapters 9 to 14 cover advanced aerodynamic topics, and Chapters 15 to 20 cover advanced topics in dynamics.

Chapter 3 begins the analysis of aeromechanics by considering hover, which is the key to helicopter effectiveness; it presents the first description of momentum theory, blade element theory, and vortex theory. Chapter 4 extends the analysis to vertical flight, both climb and descent. Chapter 5 examines the wake in forward flight in terms of momentum and vortex theories. Aerodynamic interference is covered, including rotor-to-airframe and rotor-to-tail effects. Chapter 6 on the edgewise flight of a rotor is the longest chapter in the book, dealing with blade element theory calculation of rotor forces and power and beginning the analysis of blade motion, particularly flapping. Chapter 7 summarizes performance analysis for the isolated rotor and for the complete aircraft. Chapter 8 discusses rotor and rotorcraft configurations further, as well as special topics related to design.

Chapter 9 deals with wings and wakes, as the start of advanced aerodynamics. Lifting-line theory and nonuniform inflow from a vortex wake are covered, including free wake geometry. Chapter 10 presents unsteady aerodynamic theory, beginning with the classical two-dimensional analysis, and covers special models and problems for the rotary wing. Chapter 11 is on actuator disk models, concluding with dynamic inflow theory. Chapter 12 describes dynamic stall of airfoils, stall of rotor blades, and stall effects on rotor performance and loads. Chapter 13 on computational aerodynamics focuses on the unique aspects of applications to rotorcraft. Chapter 14 deals with the theory of rotor-generated noise.

Chapter 15 introduces advanced dynamics by describing the mathematics of rotating wings, including multiblade coordinates and Floquet theory, and the solution of equations of motion. Chapter 16 on blade motion is a long chapter that derives the equations of motion for blade flap, lag, and pitch degrees of freedom, including hub reactions and shaft motion, and the aerodynamic loads. Solutions of these equations are found in subsequent chapters. Chapter 17 derives linear and nonlinear beam theory for rotor blades. Chapter 18 on rotor dynamics covers blade frequencies, structural loads, vibration, and higher harmonic control. Chapter 19 is on the stability and response of the blade flap motion, which is fundamental to the behavior of helicopter rotors. Chapter 20 solves the equations of motion for several stability

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problems, including pitch-flap flutter, flap-lag dynamics, ground resonance, and whirl flutter.

Chapter 21 analyzes rotorcraft flight dynamics, including hover and forward flight operation, single main rotor and multi-rotor configurations, control gyros, and flying qualities specifications.

Chapter 22 concludes the book with a discussion of rotorcraft comprehensive analyses.

My thanks go to my wife Juliet for her support. The time I spent on this book was as much hers as mine. I am indebted to Michael P. Scully, William Warmbrodt, Gloria K. Yamauchi, Franklin D. Harris, Anubhav Datta, Christopher Silva, and Gareth D. Padfield for reviewing the draft manuscript. Their numerous suggestions have resulted in a much improved work.

I got into helicopter research through some interesting thesis topics at the Massachusetts Institute of Technology. I stay in the field because I like the multidisciplinary part of aeromechanics and because we have not run out of problems to solve. Since graduating from MIT, I have been associated with NASA and the U.S. Army at Ames Research Center, even during the 12 years I spent working alone as Johnson Aeronautics. My first assignment at Ames was with the 40- by 80-Foot Wind Tunnel branch and the latest is with the Aeromechanics Branch, always doing rotorcraft research. I have enjoyed collaboration with many capable people, both at Ames and around the world. I am fortunate that they are good friends as well as good engineers.

Wayne Johnson
Palo Alto, California
August 2012

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1 Introduction

1.1 The Helicopter

The helicopter is an aircraft that uses rotating wings to provide lift, propulsion, and control. Figure 1.1 shows the principal helicopter configurations. The rotor blades rotate about a vertical axis, describing a disk in a horizontal or nearly horizontal plane. Aerodynamic forces are generated by the relative motion of a wing surface with respect to the air. The helicopter with its rotary wings can generate these forces even when the velocity of the vehicle is zero, in contrast to fixed-wing aircraft, which require a translational velocity to sustain flight. The helicopter therefore has the capability of vertical flight, including vertical take-off and landing. The efficient accomplishment of heavier-than-air hover and vertical flight is the fundamental characteristic of the helicopter rotor.

The rotor must supply a thrust force to support the helicopter weight. Efficient vertical flight means a high power loading (ratio of rotor thrust to rotor power required, T/P), because the installed power and fuel consumption of the aircraft are proportional to the power required. For a rotary wing, low disk loading (the ratio of rotor thrust to rotor disk area, T/A) is the key to a high power loading. Conservation of momentum requires that the rotor lift be obtained by accelerating air downward, because corresponding to the lift is an equal and opposite reaction of the rotating wings against the air. Thus the air left in the wake of the rotor possesses kinetic energy that must be supplied by a power source in the aircraft if level flight is to be sustained. This is the induced power, a property of both fixed and rotating wings that constitutes the absolute minimum power required for equilibrium flight. For the rotary wing in hover, the induced power loading is inversely proportional to the square root of the rotor disk loading ($P/T \propto \sqrt{T/A}$). Hence the efficiency of rotor thrust generation increases as the disk loading decreases.

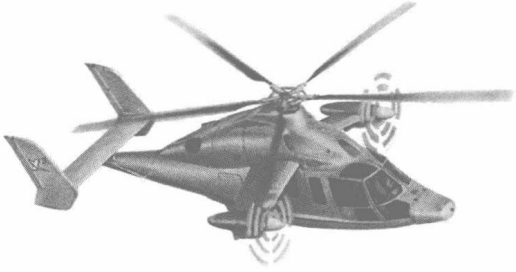
For a given gross weight the induced power is inversely proportional to the rotor radius, and therefore the helicopter is characterized by large diameter rotors. The disk loading characteristic of helicopters is in the range of 5 to 15 lb/ft^2. The small diameter rotating wings found in aeronautics, including propellers and turbofan engines, are used mainly for aircraft propulsion. For such applications a high disk loading is appropriate, since the rotor is operating at high axial velocity (which reduces the induced power) and at a thrust equal to only a fraction of the gross weight. However, the use of high disk loading rotors for direct lift severely compromises the

single main rotor helicopter (UH-1)

single main rotor helicopter (SH-60)

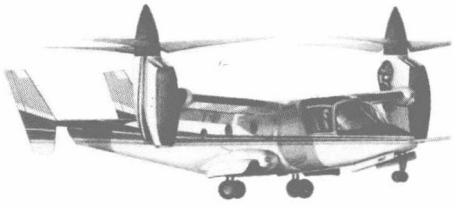
single main rotor helicopter (Bo-105)

tandem helicopter (CH-47D)

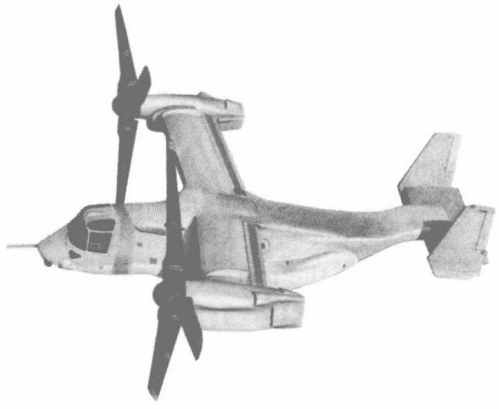


compound helicopter (EC X^3)

coaxial helicopter (Ka-32)



tiltrotor (XV-15)



tiltrotor (V-22)

Figure 1.1. Rotorcraft configurations; drawings by Eduardo Solis.

vertical flight capability in terms of greater installed power and much reduced hover endurance. The helicopter uses the lowest disk loading of all VTOL (vertical takeoff and landing) aircraft designs and hence has the most efficient vertical flight capability. The helicopter can be defined as an aircraft using large diameter, low disk loading rotary wings to provide the lift for flight.

Because the helicopter must also be capable of translational flight, a means is required to produce a propulsive force to oppose the aircraft drag and rotor drag in forward flight. For low speeds at least, this propulsive force is obtained from the rotor, by tilting the thrust vector forward. The rotor is also the source of the forces and moments on the aircraft that control its position, attitude, and velocity. In a fixed-wing aircraft, the lift, propulsion, and control forces are provided by largely separate aerodynamic surfaces. In the helicopter, all three are provided by the rotor.

Vertical flight capability is not achieved without a cost, which must be weighed against the value of VTOL capability in the desired applications of the aircraft. The task of the engineer is to design an aircraft that accomplishes the required operations in the most effective manner. The price of vertical flight includes a higher power requirement than for fixed-wing aircraft, a factor that influences the purchase price and operating cost. For most configurations, a large transmission is required to deliver the power to the rotor at low speed and high torque. The fact that the rotor is a mechanically complex system increases purchase price and maintenance costs. The rotor is a source of vibration, requiring a vibration alleviation system to avoid increased maintenance costs, passenger discomfort, and pilot fatigue. There are high alternating loads on the rotor, reducing the structural component life and in general resulting in increased maintenance cost. Aircraft noise is an important factor in air transportation, as the primary form of interaction of the aircraft with a large part of society. The helicopter is among the quietest of aircraft (or at least can be), but utilization of VTOL capability often involves operation close to urban areas, leading to stricter noise requirements. All these factors can be overcome to design a highly successful aircraft. The engineering analysis required for that task is the subject of this book.

1.1.1 The Helicopter Rotor

The conventional helicopter rotor consists of two or more identical, equally spaced blades attached to a central hub. The blades are maintained in uniform rotational motion, usually by a shaft torque from the engine. The lift and drag forces on these rotating wings produce the torque, thrust, and other forces and moments of the rotor. The large diameter rotor required for efficient vertical flight and the high aspect ratio blades required for good aerodynamic efficiency of the rotating wing result in blades that are considerably more flexible than high disk loading rotors such as propellers. Consequently, there is substantial elastic motion of the rotor blades in response to the aerodynamic forces in the rotary-wing environment. This motion can produce high stresses in the blades or large moments at the root, which are transmitted through the hub to the helicopter. Attention must therefore be given in the design of the helicopter rotor blades and hub to keeping these loads small. The centrifugal stiffening of the rotating blade results in the motion being predominantly about the blade root. Hence the design task focuses on the configuration of the rotor hub. Figure 1.2 shows some typical helicopter rotor hubs.

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