The DRA research Lynx ALYCAT (Aeromechanics LYnx Control and Agility Testbed)
shown flying by the large motion system of the DRA advanced flight simulator
(Photograph courtesy of Simon Pighills)

1 Introduction

The underlying premise of this book is that flight dynamics and control is a central discipline, at the heart of aeronautics, linking the aerodynamic and structural sciences with the applied technologies of systems and avionics and, above all, with the pilot. Flight dynamics engineers need to have breadth and depth in their domain of interest, and often hold a special responsibility in design and research departments. It is asserted that more than any other aerospace discipline, flight dynamics offers a viewpoint on, and is connected to, the key rotorcraft attributes and technologies – from the detailed fluid dynamics associated with the interaction of the main rotor wake with the empennage, to the servo-aeroelastic couplings between the rotor and control system, through to the evaluation of enhanced safety, operational advantage, and mission effectiveness of good flying qualities. It is further asserted that the multidisciplinary nature of rotorcraft flight dynamics places it in a unique position to hold the key to concurrency in requirements capture and design, i.e. the ability to optimise under the influence of multiple constraints.

In the author's view, the role of the practising flight dynamics engineer is therefore an important one, and there is a need for guidebooks and practitioner's manuals on the subject to assist in the development of the required skills and knowledge. This book is an attempt at such a manual, and it discusses flight dynamics under two main headings – simulation modelling and flying qualities. The importance of good simulation fidelity and robust flying qualities criteria in the requirements capture and design phases of a new project cannot be overstated, and this theme will be expanded on later in this chapter and throughout the book. Together, these attributes underpin confidence in decision-making during the high-risk early design phase and are directed toward the twin goals of achieving super-safe flying qualities and getting designs right, first time. These goals have motivated much of the research conducted in government research laboratories, industry, and universities for several decades.

In this short general Introduction, the aim is to give the reader a qualitative appreciation of the two main subjects – simulation modelling and flying qualities. The topics that come within the scope of flight dynamics are also addressed briefly but are not covered in the book for various reasons. Finally, a brief roadmap to the nine technical chapters is presented.

1.1 Simulation Modelling

It is beyond dispute that the observed behaviour of aircraft is so complex and puzzling that, without a well-developed theory, the subject could not be treated intelligently.

We use this quotation from Duncan (Ref. 1.1) in expanded form as a guiding light at the beginning of Chapter 3, the discourse on building simulation models. Duncan wrote these words in relation to fixed-wing aircraft many decades ago and they still hold a profound truth today. However, while it may be 'beyond dispute' that well-developed theories of flight are vital, a measure of the development level at any one time can be gauged by the ability of Industry to predict behaviour correctly before first flight, and rotorcraft experience to date is not good. In the 1989 American Helicopter Society (AHS) Nikolsky Lecture (Ref. 1.2), Crawford promotes a back-to-basics approach to improving rotorcraft modelling to avoid major redesign effort resulting from poor predictive capability. Crawford cites examples of the redesign required to improve, or simply

Helicopter Flight Dynamics: Including a Treatment of Tiltrotor Aircraft, Third Edition. Gareth D. Padfield.

put right, flight performance, vibration levels, and flying qualities for several contemporary US military helicopters. A similar story could be told for European helicopters. In Ref. 1.3, the author presents data on the percentage of development test flying devoted to handling and control, with values between 25% and 50% being quite typical. The message is that helicopters take a considerable length of time to qualify to operational standard, usually much longer than originally planned, and a principal reason lies with the deficiencies in analytical design methods. Highlighting this aspect further, Dunford discusses the evolution of the V-22 Osprey in Ref. 1.4 citing the immaturity of aeromechanics prediction as a contributor to the 18-year-long development phase. In this third edition of the book, tiltrotor aircraft feature as a topic in Chapter 10.

Underlying the failure to model flight behaviour adequately are three aspects. First, there is no escaping that the rotorcraft is an extremely complex dynamic system and the modelling task requires extensive skill and effort. Second, such complexity needs significant investment in analytical methods and specialist modelling skills, and the recognition by programme managers that these are most effectively applied in the formative stages of design. The channelling of these investments towards the critically deficient areas is also clearly very important. Third, there is still a serious shortage of high-quality, validation test data, both at model scale and from full-scale flight test. There is an adage in the world of flight dynamics relating to the merits of test versus theory, which goes something like – ‘everyone believes the test results, except the person who made the measurements, and nobody believes the theoretical results, except the person who calculated them’. This stems from the knowledge that it is easier, for example, to program the computer to output rotor blade incidence at 3/4 radius on the retreating side of the disc than it is to measure this incidence. What are required, in the author’s opinion, are research and development programmes that integrate the test and modelling activities so that the requirements for the one drive the other.

There are some signs that the importance of modelling and modelling skills is recognised at the right levels, but the problem will require constant attention to guard against the attitude that ‘big’ resources should be reserved for production, when the user and manufacturer, in theory, receive their greatest rewards. Chapters 3–5 of this book are concerned with modelling conventional helicopters, but we shall not dwell on the deficiencies of the acquisition process, but rather on where the modelling deficiencies lie. Chapter 10 addresses modelling and simulation of tiltrotors. The author has taken the opportunity in this Introduction to reinforce the philosophy promoted in Crawford’s Nikolsky Lecture with the thought that the reader may well be concerned as much with the engineering ‘values’ as with the technical detail.

No matter how good the modelling capability, without criteria as a guide, helicopter designers cannot even start on the optimization process; with respect to flying qualities, a completely new approach has been developed, and forms a significant content of this book.

1.2 Flying Qualities

> *Experience has shown that a large percentage, perhaps as much as 65%, of the lifecycle cost of an aircraft is committed during the early design and definition phases of a new development program. It is clear, furthermore, that the handling qualities of military helicopters are also largely committed in these early definition phases and, with them, much of the mission capability of the vehicle. For these reasons, sound design standards are of paramount importance both in achieving desired performance and avoiding unnecessary program cost.*

This quotation, extracted from Ref. 1.5, states the underlying motivation for the development of flying qualities criteria – they give the best chance of having mission performance designed in, whether through safety and economics with civil helicopters or through military effectiveness. But flying quality is an elusive topic and it has two equally important facets that can easily get mixed up – the objective and the subjective. Only recently has enough effort been directed towards establishing a valid set of flying qualities criteria and test techniques for rotorcraft that has enabled both the subjective and objective aspects to be addressed in a complementary way. That effort has been orchestrated under the auspices of several different collaborative programmes to harness the use of flight and ground-based simulation facilities and key skills in North America and Europe. The result was Aeronautical Design Standard (ADS)-33, which has changed the way the helicopter community thinks, discusses, and acts about flying quality. Although the primary target for ADS-33 was the Light Helicopter Experimental (LHX), and later the RAH-66 Comanche programme, other nations have used or developed the standard to meet their own needs for requirements capture and design. Chapters 6–8 of this book will refer extensively to ADS-33, with the aim of giving the reader some insight into its development. The reader should note, however, that these chapters, like ADS-33 itself, address how a helicopter with good flying qualities should behave, rather than how to construct a helicopter with good flying qualities. In this third edition, the author looks back before ADS-33 and, in the new Chapter 9, explores the origins of rotorcraft flying qualities, and builds on the 'story of an idea' that quality can be quantified.

In search of the meaning of *flying quality*, the author has come across many different interpretations, from Pirsig's somewhat abstract but appealing, 'at the moment of pure quality, subject and object are identical' (Ref. 1.6), to a point of view put forward by one flight dynamics engineer: 'flying qualities are what you get when you've done all the other things'. Unfortunately, the second interpretation has a certain ring of truth because, until ADS-33, there was very little coherent guidance on what constituted good flying qualities. The first breakthrough for the flying qualities discipline came with the recognition that criteria needed to be related to task. The subjective rating scale, developed by Cooper and Harper (Ref. 1.7) in the late 1960s, was already task and mission oriented. In the conduct of a handling qualities experiment, the Cooper–Harper approach forces the engineer to define a task with performance standards and to agree with the pilot on what constitutes minimal or extensive levels of compensation. But the objective criteria at that time were more oriented to the stability and control characteristics of aircraft than to their ability to perform tasks well. The relationship is clearly important but the lack of task-oriented test data meant that early attempts to define criteria boundaries involved a large degree of guesswork and hypothesis. Once the two ingredients essential for success in the development of new criteria, task-orientation and test data, were recognised and resources were channelled effectively, the combined expertise of several agencies focused their efforts, and during the 1980s and 1990s, a completely new approach was developed. With the advent of digital flight control systems, which provide the capability to confer different mission flying qualities in the same aircraft, this new approach can be exploited to the full.

One of the aspects of the new approach is the relationship between the internal attributes of the air-vehicle and the external influences. The same aircraft might have perfectly good handling qualities for nap-of-the-earth operations in the day environment, but degrade severely at night; obviously, the visual cues available to the pilot play a fundamental role in the perception of flying qualities. This is a fact of operational life, but the emphasis on the relationship between the internal attributes and the external influences encourages design teams to think more synergistically, e.g. the quality of the vision aids, and what the symbology should do, becomes part of the same flying qualities problem as what goes into the control system, and, more importantly, the issues need to be integrated in the same solution. We try to emphasise the importance of this synergy first in Chapter 2, then later in Chapters 6 and 7.

The point is made on several occasions in this book, for emphasis, that good flying qualities make for safe and effective operations; all else being equal, less accidents will occur with an aircraft with good handling qualities compared with an aircraft with merely acceptable handling, and operations will be more productive. This statement may be intuitive, but there is very little supporting data to quantify this, although the compelling evidence is growing. Later, in Chapter 7, the potential benefits of handling to flight safety and effectiveness through a probabilistic analysis are examined, considering the pilot as a component with failure characteristics like any other critical aircraft component. The results may appear controversial and they are certainly tentative, but they point to one way in which the question 'How valuable are flying qualities?' may be answered. This theme is continued in Chapter 8, where the author presents an analysis of the effects of degraded handling qualities on safety and operations, looking in detail at the impact of degraded visual conditions, flight system failures, and strong atmospheric disturbances. Chapter 10 addresses the flying qualities of tiltrotors.

1.3 Missing Topics

It seems to be a common feature of book writing that the end product turns out quite different than originally intended, and *Helicopter Flight Dynamics* is no exception. It was planned to be much shorter and to cover a wider range of subjects! In hindsight, the initial plan was perhaps too ambitious, although the extent of the final product, cut back considerably in scope, has surprised even the author.

There are three major topic areas, originally intended as separate chapters, that have virtually disappeared – stability and control augmentation (including active control), design for flying qualities, and simulation validation (including system identification tools). All three are referred to as required, usually briefly, throughout the book, but there have been such advances in recent years that to give these topics appropriate coverage would have extended the book considerably. They remain topics for future treatment, particularly the progress with digital flight control and the use of simulators in design, development, and certification. In the context of both these topics, we appear to be in an era of rapid development, suggesting that a better time to document the state of the art may well be some years from now. The absence of a chapter or section on simulation model validation techniques may appear to be particularly surprising, but is compensated for by the availability of the AGARD (Advisory Report on Rotorcraft System Identification), which gave a detailed coverage of the state of the art in this subject up to the early 1990s (Ref. 1.8).

Since the publication of the first and second editions, significant strides have been made in the development of simulation models for use in design and training simulators. Refs. 1.9 and 1.10 review some of these developments but we are somewhat in mid-stream with this new push to quantify and increase fidelity and the author has resisted the temptation to bring this topic into the second or third editions. Chapter 3 does briefly discuss some of the latest developments, however.

The book says very little about the internal hardware of flight dynamics – the pilot's controls and the mechanical components of the control system including the hydraulic actuators. The pilot's displays and instruments and their importance for flight in poor visibility are briefly treated in Chapter 7 and the associated perceptual issues are treated in some depth in Chapter 8, but the author is conscious of the many missing elements here. In Chapter 3, the emphasis has been on modelling the main rotor, and many other elements, such as the engine and transmission systems, are given limited coverage.

It is hoped that the book will be judged more on what it contains than on what it doesn't.

1.4 Simple Guide to the Book

Following this Introduction, the book contains nine technical chapters. For an overview of the subject of helicopter flight dynamics, the reader is referred to the Introductory Tour in Chapter 2. Engineers familiar with flight dynamics, but new to rotorcraft, may find this a useful starting point for developing an understanding of how and why helicopters work. Chapters 3–5 are a self-contained group concerned with modelling helicopter flight dynamics. To derive benefit from these chapters requires a working knowledge of the mathematical analysis tools of dynamic systems. Chapter 3 aims to provide sufficient knowledge and understanding to enable a basic flight simulation of a helicopter to be created.

Chapter 4 discusses the problems of trim and stability, providing a range of analytical tools necessary to work at these two facets of helicopter flight mechanics. Chapter 5 extends the analysis of stability to considerations of constrained motion and completes the 'working with models' theme of Chapters 4 and 5 with a discussion on helicopter response characteristics. In Chapters 4 and 5, flight test data from the Royal Aircraft Establishment's (RAE's) research Puma and Lynx and the Deutsche Forschungs- und Versuchsantalt fuer Luft- und Raumfahrt (DLR's) Bo105 are used extensively to provide a measure of validation to the modelling. In Chapter 5 of the third edition, the author has included a detailed analysis of two accidents using the approximation theory from Chapter 4. This piece shows how both rotary and fixed-wing aircraft can suffer the same adverse aircraft-pilot-coupling during low speed flight. Chapters 6 and 7 deal with helicopter flying qualities from objective and subjective standpoints respectively, although Chapter 7 also covers several 'other topics', including agility and flight in degraded visual conditions. Chapters 6 and 7 are also self-contained and do not require the same background mathematical knowledge as that required for the modelling chapters. A unified framework for discussing the response characteristics of flying qualities is laid out in Chapter 6, where each of the four 'control' axes are discussed in turn. Quality criteria are described, drawing heavily on ADS-33 and the associated publications in the open literature. Chapter 8 was new in the second edition and contains a detailed treatment of the sources of degraded flying qualities, particularly flight in degraded visual conditions, the effects of failures in flight system functions, and the impact of severe atmospheric disturbances. These subjects are also discussed within the framework of quantitative handling qualities engineering, linking with ADS-33, where appropriate. The idea here is that degraded flying qualities should be taken into consideration in design with appropriate mitigation technologies.

Two new chapters have been written for the third edition. Chapter 9 documents the historical developments of rotorcraft flying qualities, placing the advances reported in Chapters 6 and 7 in context. Chapter 10 presents an extensive coverage of the flight dynamics of tiltrotor aircraft.

Chapters 3 and 4 are complemented and supported by appendices. Herein lie the tables of configuration data and stability and control derivative charts and tables for the three case study aircraft. Chapter 10 is similarly complemented with its own appendices, featuring data on the tiltrotor case study aircraft, the Bell/NASA/Army XV-15.

The author has found it convenient to use both metric and British systems of units as appropriate throughout the book, although with a preference for metric where an option was available. Although the metric system is strictly the primary world system of units of measurements, many helicopters are designed to the older British system. Publications, particularly those from the United States, often contain data and charts using the British system, and it has seemed inappropriate to change units for the sake of unification. This does not apply, of course, to cases where data from different sources are compared. Helicopter engineers are used to working in mixed units; for example, it is not uncommon to find, in the same paper, references to height in feet, distance in metres and speed in knots – such is the rich variety of the world of the helicopter engineer.

A final point before launching into Chapter 2: The author discusses in Chapter 3 and elsewhere how mathematical models are useful for predicting behaviour and how they can help engineers understand behavioural causes and effects. Finding analytical approximations to complex behaviour is often the best pathway to understanding causal relationships, and the reader should find examples of this throughout the book. In Chapters 5 and 10, analytic models offer explanations for root causes of accidents and represent classic examples of the power of analytics. More generally, approximations to flying qualities parameters can build the bridge between design criteria and engineering configuration. It is hoped that the book will encourage the reader to develop skills in analytic modelling to strengthen this bridge and advance the knowledge base of rotorcraft flight dynamics.