Helicopter Test
and Evaluation
HELICOPTER TEST
AND EVALUATION

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Blackwell Science
QinetiQ
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Preface

The authors of this book have been employed at the Empire Test Pilots’ School (ETPS), part of QinetiQ, for the past ten years instructing student test pilots and flight test engineers on helicopter testing. Alastair Cooke has a masters degree in flight dynamics from Cranfield University and graduated as a flight test engineer from ETPS in 1989. Eric Fitzpatrick is a former military helicopter pilot and instructor who graduated as a test pilot from ETPS in 1986.

This book has been produced using the experience of the authors in flight test and flight test training gained over a combined period of 25 years in the field. Much of the material has its origin in the training notes produced by ETPS. These have been developed over a period of over forty years since the start of specific training for helicopter test pilots. The book has been designed to appeal to professionals working in the area of rotorcraft test and evaluation but it is hoped that it will also prove useful to a wider audience. In our experience, we have found that helicopter pilots are generally not well informed about the process that has led to their aircraft entering service, nor about why it has certain limitations imposed on it. We hope this book will provide pilots with this information as well as being a useful text for practising engineers and technologists. The rotor theory presented is more extensive than is found in most aeronautical degree courses and so the book should prove useful to graduates specializing in rotorcraft technology. Perhaps uniquely, this work approaches this important subject from both the theoretical and practical viewpoints.

For each topic the theory is explained briefly and is then followed by details of the practical aspects of testing a helicopter. These details include the safety considerations related to the anticipated tests, planning the tests themselves, and, where appropriate, the most efficient way to conduct individual flights. Following a description of each type of test, typical results are examined and an explanation given as to why they would be important to the clearance process. Whenever possible examples of actual test results have been presented and used in the subsequent discussion. The book is split into four main sections:

- Introduction: covering a methodology for testing and general aspects of test programmes.
- Performance: in this section level flight, vertical and climb/descent performance is addressed. The planning of performance trials is covered together with the methods for airborne data gathering and analysis of results.
- Handling qualities: this is a major section and covers the basics of helicopter stability and control testing. Also included are frequency domain methods and the use of mission task elements.
- Systems: in this section the major systems required to enable a helicopter to fly are
covered. This includes assessment of the cockpit, air data systems, engine control systems, and automatic flight control systems. Also addressed in this section is the testing of system failures.

Although highly specialized, the topic of helicopter testing is still vast and no single text could hope to cover everything. The authors have attempted, therefore, to concentrate on the most important aspects using their own knowledge of the subject as a guide. Inevitably, a number of important areas have not been covered; for example, it has not been possible to include information on specialist areas such as underslung load trials, deck operation trials or armament testing. The amount of information on systems testing to include in the book was a difficult decision due to the plethora of systems that can be fitted to a modern rotorcraft. Consequently, it was decided to detail the general methodology used in this type of testing and then to concentrate on systems which are intrinsic to the operation of all helicopters. Thus, it has not been possible to include the testing of hydraulics, electrics and lubrication systems. Similarly the testing of a number of cockpit systems such as piloting vision aids, navigation systems, weapons, and mission displays were considered to be beyond the scope of this book. Finally, it was not possible to include some types of testing which often play a large part in the life of a test pilot such as environmental trials, notably cold weather and icing. Despite these omissions, it is believed that the book covers all the essential areas of rotorcraft testing and will prove useful to a large part of the helicopter community. As the authors’ background has been in military test and evaluation this has clearly influenced the subject matter that has been presented. However, most of the information given in the book can be applied, with only minor modification, to the testing of civil rotorcraft.

Before closing we would like to acknowledge the help of Mr Mike Cook of Cranfield University, Mr Mark Roots of QinetiQ Ltd and Miss Julia Burden of Blackwell Publishing in helping us develop our manuscript for publication.

Alastair Cooke and Eric Fitzpatrick
ETPS, QinetiQ Ltd
MOD Boscombe Down

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The example helicopter

On several occasions throughout this book quantitative calculations have been made to support the theoretical trends being discussed. Where possible the calculations have been made using the same baseline data, referred to as the example helicopter. The
details of this helicopter, which is loosely based on the Westland Lynx, are summarized below:

### Main rotor
- **Radius**: 6.5 m
- **Blade chord**: 0.4 m
- **Standard rotor speed**: 35 rad/s
- **Number of blades**: 4
- **Lift curve slope**: 0.1/°
- **Twist**: 10°
- **Profile drag coefficient**: 0.008 or 0.01

### Tail rotor
- **Tail arm**: 7.5 m
- **Radius**: 1.1 m
- **Blade chord**: 0.2 m
- **Standard rotor speed**: 165 rad/s
- **Number of blades**: 4
- **Profile drag coefficient**: 0.010
- **Fuselage frontal drag area**: 2 m²
- **Fuselage vertical drag area**: 8 m²
- **Mass (unless otherwise indicated)**: 5000 kg
## Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA</td>
<td>aircraft allowance</td>
</tr>
<tr>
<td>ACAH</td>
<td>attitude command/attitude hold</td>
</tr>
<tr>
<td>ACT</td>
<td>active control technology</td>
</tr>
<tr>
<td>ADI</td>
<td>attitude direction indicator</td>
</tr>
<tr>
<td>ADS</td>
<td>Aeronautical Design Standard</td>
</tr>
<tr>
<td>AFCS</td>
<td>automatic flight control system</td>
</tr>
<tr>
<td>AGL</td>
<td>above ground level</td>
</tr>
<tr>
<td>AI</td>
<td>attitude indicator</td>
</tr>
<tr>
<td>AltR</td>
<td>altimeter reading</td>
</tr>
<tr>
<td>AOA, AoA</td>
<td>angle of attack</td>
</tr>
<tr>
<td>AOB, AoB</td>
<td>angle of bank</td>
</tr>
<tr>
<td>APU</td>
<td>auxiliary power unit</td>
</tr>
<tr>
<td>ASE</td>
<td>automatic stabilization equipment</td>
</tr>
<tr>
<td>ASI</td>
<td>airspeed indicator</td>
</tr>
<tr>
<td>ASIR</td>
<td>airspeed indicator reading</td>
</tr>
<tr>
<td>ASW</td>
<td>anti-submarine warfare</td>
</tr>
<tr>
<td>AUM</td>
<td>all-up-mass</td>
</tr>
<tr>
<td>BCV</td>
<td>bleed control valve</td>
</tr>
<tr>
<td>CAA</td>
<td>Civil Aviation Authority</td>
</tr>
<tr>
<td>CAS</td>
<td>calibrated airspeed</td>
</tr>
<tr>
<td>CBEM</td>
<td>combined blade element and momentum (theory)</td>
</tr>
<tr>
<td>CFSS</td>
<td>collective fixed static stability</td>
</tr>
<tr>
<td>CG</td>
<td>centre of gravity</td>
</tr>
<tr>
<td>CP</td>
<td>collective pitch</td>
</tr>
<tr>
<td>CR Point</td>
<td>control reference point</td>
</tr>
<tr>
<td>CR Posn</td>
<td>control reference position</td>
</tr>
<tr>
<td>CWP</td>
<td>centralized warning panel</td>
</tr>
<tr>
<td>DA</td>
<td>density altitude</td>
</tr>
<tr>
<td>DEP</td>
<td>design eye position</td>
</tr>
<tr>
<td>DH</td>
<td>decision height</td>
</tr>
<tr>
<td>DVE</td>
<td>degraded visual environment</td>
</tr>
<tr>
<td>EAS</td>
<td>equivalent airspeed</td>
</tr>
<tr>
<td>ECS</td>
<td>engine control system</td>
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<tr>
<td>EFIS</td>
<td>electronic flight information system</td>
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<tr>
<td>EGT</td>
<td>exhaust gas temperature</td>
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<tr>
<td>EOL</td>
<td>engine-off landing</td>
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<td>ERGA</td>
<td>engine and rotor governing assessment</td>
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<tr>
<td>ETPS</td>
<td>Empire Test Pilots’ School</td>
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<tr>
<td>FADEC</td>
<td>full authority digital engine control</td>
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<tr>
<td>FAR</td>
<td>Federal Aviation Regulations</td>
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<tr>
<td>FBW</td>
<td>fly-by-wire</td>
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<tr>
<td>FCMC</td>
<td>flight control mechanical characteristics</td>
</tr>
<tr>
<td>FCS</td>
<td>flight control system</td>
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<tr>
<td>FFR</td>
<td>fuel flow rate</td>
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<tr>
<td>FIG</td>
<td>flight idle glide</td>
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<td>FLIR</td>
<td>forward looking infra-red</td>
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<tr>
<td>FMECA</td>
<td>failure modes effect and criticality analysis</td>
</tr>
</tbody>
</table>
Abbreviations

FOD foreign object debris
FOR field of regard
FOV field of view
FPT free power turbine
FTE flight test engineer
FW fixed wing
GCA ground controlled approach
GPS global positioning system
GSDI groundspeed and drift indicator
GVE good visual environment
GW gross weight
HDD head down display
HIGE inside ground effect hover
HMD helmet mounted display
HOGE outside ground effect hover
HQR handling qualities rating
HSI horizontal situation indicator
HTA helicopter type allowance
HUD head-up display
IAS indicated airspeed
IAT indicated air temperature
ICAO International Civil Aviation Organization
IFR instrument flight rules
IGE inside ground effect
IGV inlet guide vanes
ILS instrument landing system
IMC instrument meteorological conditions
INS inertial navigation system
IRE identified risk element
ISA ICAO standard atmosphere
JAR Joint Airworthiness Regulations
KCAS knots calibrated airspeed
KEAS knots equivalent airspeed
KIAS knots indicated airspeed
KTAS knots true airspeed
LCD liquid crystal display
LDO lateral/directional oscillation
LDP landing decision point
LED light-emitting diode
M Mach number
MAR military aircraft release
MAUM maximum all-up-mass
MAUW maximum all-up-weight
MFD multi-function display
MPOG minimum pitch on ground
MPV maximum power vertical
MSL mean sea level
MTBF mean time between failures
NDB non-directional beacon
NOE nap of the earth
NTPS National Test Pilots’ School
Abbreviations

NVG  night vision goggles
OAT  outside air temperature
ODM  operating data manual
OEI  one engine inoperative
OFE  operational flight envelope
OGE  outside ground effect
PE   pressure error
PEC  pressure error correction
PFL  practice forced landing
PFLF power for level flight
PH   (hover) position hold
PIO  pilot-induced oscillation
PTIT power turbine inlet temperature
PUPO pull-up/push-over
RAD ALT radar altimeter
RCAH rate command/attitude hold
RCDH rate command/direction hold
RCDI rate of climb and descent indicator
RCHH rate command/height hold
REP  reference eye position
RH   relative humidity
ROC, RoC rate of climb
ROD, RoD rate of descent
RPM revolutions per minute
RPV reduced power vertical
RRM  risk reduction measure
RRPM rotor revolutions per minute
RVR  runway visual range
RW   rotary wing
SAR  search and rescue; specific air range
SAS  stability augmentation system
SFC  specific fuel consumption
SHSS steady heading sideslip
SSC  side stick controller
TAS  true airspeed
TCDB trim control displacement band
TCWP trim changes with power
TDP  take-off decision point
TE   tip effects
TFCP trimmed flight control position
TGT  turbine gas temperature
TI   trials instruction
TO1C turn on one control
TPS  trailing pitot-static
VFR visual flight rules
VMC  visual meteorological conditions
VNE  maximum never to exceed speed
VNO  maximum normal operational speed
VOR VHF omnidirectional range
VSI  vertical speed indicator
VSS  variable stability system
Notation

Arabic symbols

\( A \) disk area
\( a \) lift curve slope
\( A_l \) lateral cyclic pitch
\( a_l \) longitudinal cyclic flap
\( A_R \) aspect ratio
\( B \) tip loss factor
\( b \) number of blades in main rotor or tail rotor
\( B_l \) longitudinal cyclic pitch
\( b_l \) lateral cyclic flap
\( c \) rotor blade chord
\( C_D \) drag coefficient
\( C_L \) lift coefficient
\( C_{L_{\text{max}}} \) maximum mean lift coefficient
\( C_{L_{\text{nom}}} \) nominal mean lift coefficient
\( C_p \) power coefficient
\( C_Q \) torque coefficient
\( C_T \) thrust coefficient
\( D \) drag; rotor diameter
\( f \) drag area
\( g \) acceleration due to gravity
\( H_D \) density altitude
\( H_{P}, h_P \) pressure altitude
\( L \) lift
\( l_{TR} \) tail rotor moment arm
\( m \) mass
\( N \) engine RPM
\( N_c \) compressor RPM
\( N_f \) free turbine RPM
\( N_G \) gas generator RPM
\( N_h \) high speed spool RPM
\( N_l \) low speed spool RPM
\( N_R \) rotor speed RPM
\( P, P_t \) static pressure
\( p \) change in roll rate from trim
\( P_i \) induced power
\( P_P \) total or pitot pressure
\( P_{par} \) parasite power
\( P_{pr} \) profile power
\( P_{\infty} \) ambient pressure
\( q \) change in pitch rate from trim
\( Q_{MR} \) main rotor torque
\( R \) rotor radius
\( r \) change in yaw rate from trim
Notation

\( s \)     solidity
\( S, S_f, S_v \)     blade area, frontal drag area, vertical drag area
\( T \)     thrust; engine temperature
\( T_2, T_{1/2} \)     time to double or half bank angle
\( u \)     change in speed along \( X \)-axis
\( V \)     true airspeed
\( v \)     change in speed along \( Y \)-axis
\( V_c \)     calibrated airspeed; climb speed
\( V_i \)     equivalent airspeed
\( V_i \), \( V_v \)     forward (horizontal) velocity component
\( V_{t} \)     maximum speed in level flight
\( V_{imp} \)     indicated airspeed corrected for instrument error, induced velocity
\( V_{ME} \)     indicated minimum power speed
\( V_{MP} \)     maximum endurance airspeed
\( V_{MP} \)     minimum power airspeed
\( V_{MR} \)     maximum range airspeed
\( V_{toss} \)     take-off safety speed
\( V_{t} \)     tip speed
\( v_t \)     vertical velocity component
\( V_{Y}, v_y \)     speed for maximum rate of climb
\( W \)     weight
\( w \)     change in speed along \( Z \)-axis
\( Z \)     tapeline height

Greek symbols

\( \alpha \)     angle of attack
\( \beta \)     sideslip angle; flap angle
\( \gamma \)     Lock number; flight path angle; disk tilt
\( \delta \)     relative pressure; angle between rotor blade hinge lines
\( \varepsilon \)     rotor frequency parameter
\( \zeta \)     relative damping
\( \eta \)     vertical velocity ratio (\( V_i/v_{ih} \)); efficiency
\( \theta \)     relative temperature; pitch attitude; rotor feather angle
\( \theta_0, \theta_1 \)     collective pitch and twist
\( \theta_{TR} \)     tail rotor pitch
\( \kappa \)     non-uniform inflow factor
\( \lambda \)     inflow ratio
\( \mu \)     advance ratio (\( V/V_T \)); forward velocity ratio (\( V/v_{ih} \))
\( \nu \)     induced velocity ratio (\( v/v_{ih} \))
\( \xi \)     lead/lag angle
\( \rho \)     air density
\( \sigma \)     relative density
\( \tau \)     time constant
\( \phi \)     bank angle; inflow angle
\( \chi \)     rotor wake skew angle
\( \psi \)     azimuth angle; yaw angle
\( \Omega, \omega \)     rotor speed; angular velocity; frequency
Chapter 1
The Flight Test Process

1.1 INTRODUCTION

Flight test is an expensive activity, which by its very nature attracts levels of risk higher than normal operations. To ensure that all trials are conducted as efficiently and safely as possible, a flight test process has been developed over the years. This process is used, with only minor variations, in nearly all test organisations throughout the world whether they be military, civilian or based at a manufacturing facility. Many of the steps in this process have evolved as the result of painful lessons and, therefore, the authors consider them vital to the overall test activity.

It is perhaps true to say that at the beginning of their careers, flight test personnel show greater interest in the test methods that they need to apply than in the overall system used to approve, authorize and regulate test flying. Consequently it was decided to make the test process the first chapter of this book to demonstrate the importance that the authors attach to this subject. It is our belief that without an understanding of the process the knowledge contained within the rest of the book cannot be applied effectively.

Brief details of the flight test process are given below. For more details the reader is referred to the AGARD flight test techniques and instrumentation series [1.1 and 1.2]. Generally the flight test process can be broken down into three major areas:

- Flight test planning.
- Conducting the test.
- Post-test actions.

1.2 FLIGHT TEST PLANNING

Thorough planning is vital for all flight trials to ensure that they are conducted safely, efficiently and that the trials objective is met. When a trial is first proposed to a test establishment a management plan is produced which includes a work breakdown structure defining the individual elements of the trial. For each element the department or departments which are to undertake the work are determined together with costs and timescales. Part of the management plan is to define the exact project technical objectives and it is at this level that this book will examine the planning process.

1.2.1 Technical objectives

To define the project technical objectives the exact requirements of the customer calling for the trial have to be understood clearly. Once this has been done then the