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THIRD EDITION

Flight Dynamics PRINCIPLES

A LINEAR SYSTEMS APPROACH TO AIRCRAFT STABILITY AND CONTROL

MICHAEL V. COOK

MATLAB® examples

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Flight Dynamics Principles

A Linear Systems Approach to Aircraft Stability and Control

Third Edition

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LONGITUDINAL EQUATIONS OF MOTION – BRITISH NOTATION

Referred to aircraft body axes

$$m\dot{u} - X_{\dot{w}}\dot{w} = X_u u + X_w w + \left(X_q - mW_e\right)q - mg\theta\cos\theta_e + X_\eta \eta + X_\tau \tau$$

$$m\dot{w} - Z_{\dot{w}}\dot{w} = Z_u u + Z_w w + \left(Z_q + mU_e\right)q - mg\theta\sin\theta_e + Z_\eta \eta + Z_\tau \tau$$

$$I_y\dot{q} - M_{\dot{w}}\dot{w} = M_u u + M_w w + M_q q + M_\eta \eta + M_\tau \tau$$

Stability and control derivatives

Dimensionless	Multiplier	Dimensional		Dimensionless	Multiplier	Dimensional
X_u	$\frac{1}{2}\rho V_0 S$	X_u		$Z_{\dot{w}}$	$\frac{1}{2}\rho S\bar{\bar{c}}$	$Z_{\dot{w}}$
X_w	$\frac{1}{2}\rho V_0 S$	X_w		Z_q	$\frac{1}{2}\rho V_0 S\bar{\bar{c}}$	Z_q
$X_{\dot{w}}$	$\frac{1}{2}\rho S\bar{\bar{c}}$	$X_{\dot{w}}$		M_u	$\frac{1}{2}\rho V_0 S\bar{\bar{c}}$	M_u
X_q	$\frac{1}{2}\rho V_0 S\bar{\bar{c}}$	X_q		M_w	$\frac{1}{2}\rho V_0 S\bar{\bar{c}}$	M_w
Z_u	$\frac{1}{2}\rho V_0 S$	Z_u		$M_{\dot{w}}$	$\frac{1}{2}\rho S\bar{\bar{c}}^2$	$M_{\dot{w}}$
Z_w	$\frac{1}{2}\rho V_0 S$	Z_w		M_q	$\frac{1}{2}\rho V_0 S\bar{\bar{c}}^2$	M_q
X_η	$\frac{1}{2}\rho V_0^2 S$	X_η		X_τ	1	X_τ
Z_η	$\frac{1}{2}\rho V_0^2 S$	Z_η		Z_τ	1	Z_τ
M_η	$\frac{1}{2}\rho V_0^2 S\bar{\bar{c}}$	M_η		M_τ	$\bar{\bar{c}}$	M_τ

LONGITUDINAL EQUATIONS OF MOTION – AMERICAN NOTATION

Referred to aircraft body axes

$$\dot{u} = \mathrm{X}_u u + \mathrm{X}_w w + \mathrm{X}_{\dot{w}}\dot{w} + \left(\mathrm{X}_q - W_e\right)q - g\theta\cos\theta_e + \mathrm{X}_{\delta_s}\delta_s + \mathrm{X}_{\delta_{th}}\delta_{th}$$

$$\dot{w} = \mathrm{Z}_u u + \mathrm{Z}_w w + \mathrm{Z}_{\dot{w}}\dot{w} + \left(\mathrm{Z}_q + U_e\right)q - g\theta\sin\theta_e + \mathrm{Z}_{\delta_s}\delta_s + \mathrm{Z}_{\delta_{th}}\delta_{th}$$

$$\dot{q} = \mathrm{M}_u u + \mathrm{M}_w w + \mathrm{M}_{\dot{w}}\dot{w} + \mathrm{M}_q q + \mathrm{M}_{\delta_s}\delta_s + \mathrm{M}_{\delta_{th}}\delta_{th}$$

Stability and control derivatives

Dimensionless coefficient	Multiplier	Dimensional normalised		Dimensionless coefficient	Multiplier	Dimensional normalised
C_{x_u}	$\rho V_0 S/2m$	X_u		C_{z_w}	$\rho V_0 S/2m$	Z_w
$C^*_{x_u}$	$\rho V_0 S/2m$	X^*_u		C_{z_q}	$\rho V_0 S\bar{\bar{c}}/4m$	Z_q
$C_{x_{\dot{w}}} = C_{x_{\dot{\alpha}}}$	$\rho S\bar{\bar{c}}/4m$	$\mathrm{X}_{\dot{w}}$		C_{z_δ}	$\rho V_0^2 S/2m$	Z_δ
C_{x_w}	$\rho V_0 S/2m$	X_w		C_{m_u}	$\rho V_0 S\bar{\bar{c}}/2I_y$	M_u
C_{x_q}	$\rho V_0 S\bar{\bar{c}}/4m$	X_q		$C^*_{m_u}$	$\rho V_0 S\bar{\bar{c}}/2I_y$	M^*_u
C_{x_δ}	$\rho V_0^2 S/2m$	X_δ		$C_{m_{\dot{w}}} = C_{m_{\dot{\alpha}}}$	$\rho S\bar{\bar{c}}^2/4I_y$	$\mathrm{M}_{\dot{w}}$
C_{z_u}	$\rho V_0 S/2m$	Z_u		$C_{m_w} = C_{m_\alpha}$	$\rho V_0 S\bar{\bar{c}}/2I_y$	M_w
$C^*_{z_u}$	$\rho V_0 S/2m$	Z^*_u		C_{m_q}	$\rho V_0 S\bar{\bar{c}}^2/4I_y$	M_q
$C_{z_{\dot{w}}} = C_{z_{\dot{\alpha}}}$	$\rho S\bar{\bar{c}}/4m$	$\mathrm{Z}_{\dot{w}}$		C_{m_δ}	$\rho V_0^2 S\bar{\bar{c}}/2I_y$	M_δ

Common auxiliary equations

$U_e = V_0\cos\theta_e$ $\quad W_e = V_0\sin\theta_e$ $\quad \dot{\theta} = q$ $\quad w = V_0\tan\alpha$ $\quad \dot{h} = -w\cos\theta_e + u\sin\theta_e + \theta V_0$ $\quad \gamma_e = \theta_e - \alpha_e$ $\quad n_z = -\dfrac{a_z}{g}$ $\quad a_{z_{cg}} = \dot{w} - qU_e$ $\quad a_{z_p} = \dot{w} - qU_e - \dot{q}x_p$

American-British dimensionless derivative equivalents

American	British		American	British		American	British		American	British		American	British		American	British
C_{x_u}			C_{x_α}	X_w		C_{z_u}			C_{z_α}	Z_w		C_{m_u}			C_{m_α}	M_w
$C^*_{x_u}$	X_u		C_{x_q}	$2X_q$		$C^*_{z_u}$	Z_u		C_{z_q}	$2Z_q$		$C^*_{m_u}$	M_u		C_{m_q}	$2M_q$
$C_{x_{\dot{\alpha}}}$	$2X_{\dot{w}}$		C_{x_δ}	$X_{\eta,\tau}$		$C_{z_{\dot{\alpha}}}$	$2Z_{\dot{w}}$		C_{z_δ}	$Z_{\eta,\tau}$		$C_{m_{\dot{\alpha}}}$	$2M_{\dot{w}}$		C_{m_δ}	$M_{\eta,\tau}$

State space matrix notation

$\mathbf{M}\dot{\mathbf{x}} = \mathbf{A}'\mathbf{x} + \mathbf{B}'\mathbf{u}$ $\quad \dot{\mathbf{x}} = \mathbf{M}^{-1}\mathbf{A}'\mathbf{x} + \mathbf{M}^{-1}\mathbf{B}'\mathbf{u}$ $\quad \dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u}$ $\quad \mathbf{x}^T = [u \;\; w \;\; q \;\; \theta]$ $\quad \mathbf{u}^T = [\eta \;\; \tau]$ $\quad \mathbf{u}^T = [\delta_s \;\; \delta_{th}]$

Common format of the aircraft state equation in terms of concise derivatives

$$\begin{bmatrix}\dot{u}\\ \dot{w}\\ \dot{q}\\ \dot{\theta}\end{bmatrix} = \begin{bmatrix} x_u & x_w & x_q & x_\theta\\ z_u & z_w & z_q & z_\theta\\ m_u & m_w & m_q & m_\theta\\ 0 & 0 & 1 & 0\end{bmatrix}\begin{bmatrix}u\\ w\\ q\\ \theta\end{bmatrix} + \begin{bmatrix} x_\eta & x_\tau\\ z_\eta & z_\tau\\ m_\eta & m_\tau\\ 0 & 0\end{bmatrix}\begin{bmatrix}\eta\\ \tau\end{bmatrix}$$

or

$$\begin{bmatrix}\dot{u}\\ \dot{\alpha}\\ \dot{q}\\ \dot{\theta}\end{bmatrix} = \begin{bmatrix} x_u & x_\alpha & x_q & x_\theta\\ z_u & z_\alpha & z_q & z_\theta\\ m_u & m_\alpha & m_q & m_\theta\\ 0 & 0 & 1 & 0\end{bmatrix}\begin{bmatrix}u\\ \alpha\\ q\\ \theta\end{bmatrix} + \begin{bmatrix} x_{\delta_s} & x_{\delta_{th}}\\ z_{\delta_s} & z_{\delta_{th}}\\ m_{\delta_s} & m_{\delta_{th}}\\ 0 & 0\end{bmatrix}\begin{bmatrix}\delta_s\\ \delta_{th}\end{bmatrix}$$

Flight Dynamics Principles

A Linear Systems Approach to Aircraft Stability and Control

Preface

It seems that, in the five years since its publication, the second edition of *Flight Dynamics Principles* has continued to enjoy modest success in the undergraduate marketplace, and there is some limited evidence of its increasing adoption by university courses in North America. So it was not surprising that Elsevier proposed a third edition with the principal objective of enhancing the book's appeal to the American undergraduate market. Central to the objective is the requirement to achieve direct compatibility with American math notation and to link the embedded computational examples with the use of MATLAB or equivalent software tools. In coming to a conclusion about how the book might be developed, Elsevier conducted a review with a fair few universities where relevant courses are taught. Needless to say, every reviewer had a different subjective opinion on the content, structure, and presentation of a text on flight dynamics. However, in general most of the reviews were positive and provided helpful suggestions as to how a third edition might be developed. All of the reviews were carefully analysed, and common areas for attention were identified.

Analysis of the reviews revealed a number of areas for potential improvement, including the substantial addition of new material, the development of existing material, greater emphasis on American notation, and explicit use of MATLAB examples. The most commonly requested addition was more on design of flight control systems. This is a very large subject area indeed, much of which falls outside the scope and intent of this book with the exception of stability augmentation, which has been included from the outset. However, in deference to the requests new material on command augmentation has been added. Some reviewers expressed dissatisfaction with the treatment of some topics in the second edition, and it was agreed that these could be improved. Accordingly, the topics in question have been reorganised and further developed; also, in some instances additional worked examples have been introduced to further enhance the material. The question of the differences between British and American math notations remains a distinguishing feature of all publications on flight dynamics intended for global consumption. Sections explaining the parallel development of the equivalent American notation were introduced in considerable detail in the second edition, and this remains more or less unchanged. Improvements to raise the emphasis, including additional worked examples, have been added where appropriate.

The inclusion of MATLAB examples showing command line entries or passages of programme code have been strenuously avoided. The reason for this is that software tools evolve rather more rapidly than books; in the author's experience most students come to the subject already proficient in the use of MATLAB, and equally capable alternative software tools are available and in use. At least one of the reviewers endorsed this opinion. The solution to this is to set out worked examples in sufficient detail, and in a step-by-step fashion, sufficient to enable direct transfer to the MATLAB environment or to any other similar software environment.

The most important changes introduced in the third edition are summarised as follows. The chapter on longitudinal and lateral-directional static stability has been completely overhauled and revised, mainly to enhance the presentation of the material on lateral-directional static stability. Worked examples have been added to the material on the development of the equations of motion to illustrate the application of American notation. The chapter on manoeuvrability has been expanded to include new material and worked examples on calculation of the manoeuvring control characteristics of aircraft with stability augmentation. The chapter on design of stability augmentation systems has been expanded to include new material and examples on the design of command augmentation systems for the enhancement of handling qualities. The chapter on aerodynamic stability and control derivatives has been expanded to include a substantial worked example to illustrate estimation of real aircraft derivative data. Chapter 14 is an entirely new chapter that summarises the effect of flight in a nonsteady atmosphere, and is based on the application and interpretation of British and American military flying qualities requirements documents. Finally, a new coursework example is added to Chapter 15 which involves the design of a basic flight control system architecture for an unmanned air vehicle of unconventional layout.

It is proposed that purchasers of this third edition of *Flight Dynamics Principles* will be able to download a computer programme called FDA-CAD, "Flight Dynamics Analysis—Control Augmentation Design," from the Elsevier website in due course. This is a MATLAB programme developed over a number of years for use by the author's students. Simple to use, it is based on a graphical user interface and is capable of undertaking all computations and transformations associated with the equations of motion, solution of the equations of motion, control-response plotting, design of simple feedback loops for stability augmentation, and design of command path augmentation for handling qualities enhancement. It is hoped that this software will be available soon after this edition has been launched. Please visit booksite.elsevier.com/9780080982427 for access to the companion software. For instructors using the text as part of their course, additional instructor support material is available by registering at www.textbooks.elsevier.com.

As for the book's previous editions, it is appropriate to reiterate that *Flight Dynamics Principles* is introductory in its scope and is intended for those coming to the subject for the first time. The intended audience remains unchanged and includes undergraduate and postgraduate students studying aeronautical subjects, avionics, systems engineering, control engineering, mathematics, and so forth. It is also appropriate to include young engineers working in the aerospace industry who are involved in flight dynamics, flight control, and related activities. Most important, in an increasingly automated world the principal objective of the book remains to provide a secure foundation from which to move on to nonlinear flight dynamics, simulation, and advanced flight control system design.

Michael V. Cook
Frinton-on-Sea, Essex
June 2012

Preface to the second edition

It is almost exactly ten years since *Flight Dynamics Principles* was first published, and during that time there has been a modest but steady demand for it. It is apparent that during this period there has been a growing recognition in academic circles that it is more appropriate to teach "aircraft stability and control" in a systems context rather than in the traditional aerodynamic context—a view which is endorsed by industry. This is no doubt due to the considerable increase in application of automatic flight control to all types of aircraft and to the ready availability of excellent computer tools for handling the otherwise complex calculations. Thus the relevance of the book is justified, and this has been supported by positive feedback from readers all over the world.

The publisher was clearly of the same opinion, and a second edition was proposed. It was evident that the first edition had become required reading for many undergraduate courses, but that its original structure was not ideal for the teaching environment. In particular, the lack of examples for students to work was regarded as an omission too far. Consequently, the primary aim of the second edition is to support more generally the requirement of the average undergraduate course, and so it is hoped that it will appeal more widely to students undertaking courses in aeronautical engineering and aeronautical systems engineering at all levels.

The original concept for the book seems to have worked well, so the changes are few. Readers familiar with the book will be aware of rather too many minor errors in the first edition, arising mainly from editing problems in the production process. These have been purged from the second edition, and it is hoped that not so many new errors have been introduced. Apart from editing here and there, the most obvious additions are a versatile computer programme for calculating aircraft trim, introduction of material dealing with the interchangeability of North American notation, new material on lateral-directional control derivatives, and examples for students at the end of most chapters. Once again, the planned chapter on atmospheric disturbance modelling has been omitted because of time constraints. However, an entirely new chapter on coursework studies for students has been added.

It is the opinion of the author that, at the postgraduate level in particular, the assessment of students by means of written examinations tends to trivialise the subject by reducing problems to exercises which can be solved in a few minutes—the real world is not often like that. Consequently, traditional examining was abandoned sometime ago in favour of more realistic, and hence protracted, coursework studies. Each exercise is carefully structured to take the student step by step through the solution of an expansive flight dynamics problem, usually based on real aircraft data. Thus, instead of the short sharp memory test, student assessment becomes an extension and consolidation of the learning process, and equips students with the essential enabling skills appreciated by industry. Feedback from students is generally very positive and it appears that they genuinely enjoy a realistic challenge.

For those who are examined by traditional methods, examples are included at the end of most chapters. These are taken from earlier Cranfield University exam papers set by the author and from more recent exam papers set and kindly provided by Dr Peter Render of Loughborough University. The reader should not assume that chapters without such examples are not examinable. Ready-made questions were simply not available in the very tight time scale applying.

In the last ten years there has been an explosive growth in unmanned air vehicle (UAV) technology, and vehicles of every type, size, and configuration have made headlines on a regular basis. At the simplest level of involvement, many university courses now focus on experimental flight dynamics based on low-cost radio-controlled model technology. The theoretical principles governing the flight dynamics of such vehicles remains unchanged and the content of this book is equally applicable to all UAVs. The only irrelevant material is that concerning piloted aircraft handling qualities since UAVs are, by definition, pilotless. However, the flying qualities of UAVs are just as important as they are for piloted aircraft; although envelope boundaries may not be quite the same, they will be equally demanding. Thus the theory, tools, and techniques described in this book may be applied without modification for analysing the linear flight dynamics of UAVs.

The intended audience for *Flight Dynamics Principles* remains unchanged—that is, undergraduate and postgraduate students studying aeronautical subjects and those students studying avionics, systems engineering, control engineering, mathematics, and the like, with aeronautical application in mind. In view of the take-up by the aerospace industry, it is perhaps appropriate to add young engineers involved in flight dynamics and flight control to the potential readership. It is also appropriate to reiterate that the book is introductory in its scope and is intended for those coming to the subject for the first time. Most important, in an increasingly automated world the principal objective of the book remains to provide a secure foundation from which to move on to nonlinear flight dynamics, simulation, and advanced flight control.

Michael V. Cook
School of Engineering, Cranfield University
May 2007

Preface to the first edition

When I joined the staff of the College of Aeronautics some years ago, I was presented with a well-worn collection of lecture notes and invited to teach a course on aircraft stability and control to postgraduate students. Inspection of the notes revealed the unmistakable signs that their roots reached back to the work of W. J. Duncan, which is perhaps not surprising since Duncan was the first professor of aerodynamics at Cranfield some 50 years ago. It was undoubtedly a privilege and, at first, very daunting to be given the opportunity to follow in the footsteps of such a distinguished academic. From that humble beginning my interpretation of the subject has continuously evolved to its present form, which has provided the basis for this book.

The classical linearised theory of the stability and control of aircraft is timeless, it is brilliant in its relative simplicity, and it is very securely anchored in the domain of the aerodynamicist. What is new? The short answer is, not a great deal. However, today the material is used and applied in ways that have changed considerably, largely because of the advent of the digital computer. The computer is used as the principal tool for analysis and design, and it is also the essential component of the modern flight control system on which all advanced-technology aeroplanes depend. It is the latter development in particular which has had, and continues to have, a major influence on the way in which the material of the subject is now used. It is no longer possible to guarantee good flying and handling qualities simply by tailoring the stability and control characteristics of an advanced-technology aeroplane through aerodynamic design alone. Flight control systems now play an equally important part in determining the flying and handling qualities of an aeroplane by augmenting the stability and control characteristics of the airframe in a beneficial way. Therefore, the subject has had to evolve in order to facilitate integration with flight control, and today the integrated subject is much broader in scope and is more frequently referred to as *flight dynamics*.

The treatment of the material in this book reflects my personal experience of using, applying, and teaching it over a period of many years. My formative experience was gained as a systems engineer in the avionics industry, where the emphasis was on the design of flight control systems. In more recent years, in addition to teaching a formal course in the subject, I have been privileged to have spent many hours teaching the classical material in the College of Aeronautics airborne laboratory aircraft. This experience has enabled me to develop the material from the classical treatment introduced by Duncan in the earliest days of the College of Aeronautics to the present treatment, which is biased towards modern systems applications. However, the vitally important aerodynamic origins of the material remain clear, for which I can take no credit.

Modern flight dynamics tends be concerned with the wider issues of flying and handling qualities rather than with the traditional, and more limited, issues of stability and control. The former is, of course, largely shaped by the latter, and for this reason the emphasis is on dynamics and their importance to flying and handling qualities. The material is developed using dimensional or normalised dimensional forms of the aircraft equations of motion only. These formulations are in common use, with minor differences, on both sides of the North Atlantic. Understanding of the dimensionless equations of motion has too often been a major stumbling block for many students, and I have never found it necessary, or even preferable, to work with the classical dimensionless equations of motion. These are a creation of the aerodynamicist and are referred to only insofar as is necessary to explain the origins and interpretation of the dimensionless aerodynamic stability and control derivatives. However, it remains most appropriate to use dimensionless derivatives to describe the aerodynamic properties of an airframe.

It is essential that the modern flight dynamicist have not only a thorough understanding of the classical theory of aircraft stability and control but also some knowledge of the role and structure of flight control systems. Consequently, a basic understanding of the theory of control systems is necessary, and then it becomes obvious that the aircraft may be treated as a *system* that may be manipulated and analysed using the tools of the control engineer. As a result, it is common to find control engineers looking to modern aircraft as an interesting challenge for the application of their skills. Unfortunately, it is also too common to find control engineers who have little or no understanding of the dynamics of their *plant*, which, in my opinion, is unacceptable. It has been my intention to address this problem by developing the classical theory of the stability and control of aircraft in a systems context in order that it become equally accessible to both the aeronautical engineer and the control engineer. This book, then, is an aeronautical text which borrows from the control engineer rather than a control text which borrows from the aeronautical engineer.

Flight Dynamics Principles is primarily intended for undergraduate and postgraduate students studying aeronautical subjects and those studying avionics, systems engineering, control engineering, mathematics, and so forth, who wish to include some flight dynamics in their studies. Of necessity the book's scope is limited to linearised small-perturbation aircraft models since the material is intended for those coming to the subject for the first time. However, a good understanding of the material should give the reader the basic skills and confidence to analyse and evaluate aircraft flying qualities and to initiate preliminary augmentation system design. It should also provide a secure foundation from which to move on to nonlinear flight dynamics, simulation, and advanced flight control.

Michael V. Cook
College of Aeronautics, Cranfield University
January 1997

Acknowledgements

Over the years I have been fortunate to have worked with a number of very able people from whom I have learned a great deal. My own understanding and interpretation of the subject of flight dynamics has benefited enormously from that contact, and it is appropriate to acknowledge the contributions of these individuals.

My own formal education was founded on the text by W.J. Duncan and later on the first text by A. W. Babister. As a result, the structure of the third edition of *Flight Dynamics Principles* has many similarities to those earlier texts. This, I think, is inevitable because the treatment and presentation of the subject have not really been bettered in the intervening years, although the way in which the material is handled today is significantly different.

During my formative years at GEC-Marconi Avionics Ltd (now BAE Systems), I worked with David Sweeting, John Corney, and Richard Smith on various flight control system design projects. This activity also brought me into contact with Brian Gee, John Gibson, and Arthur Barnes at British Aerospace (Military Aircraft Division), all of whom are now retired. Of the many people with whom I worked, these individuals in particular were, in some way, instrumental in helping me to develop a greater understanding of flight dynamics in its widest modern context.

During my early years at Cranfield, my colleagues Angus Boyd, Harry Ratcliffe, Dr Peter Christopher, and Dr Martin Eshelby were especially helpful with advice and guidance at a time when I was establishing my teaching activities. I also consider myself extremely fortunate to have spent hundreds of hours flying with a small but distinguished group of test pilots—Angus McVitie, Ron Wingrove, and Roger Bailey—as we endeavoured to teach and demonstrate the rudiments of flight mechanics to generations of students. My involvement with the experimental flying programme was an invaluable experience which has enhanced my understanding of the subtleties of aircraft behaviour considerably. Later, the development of the postgraduate course in flight dynamics brought me into contact with colleagues Peter Thomasson, Jim Lipscombe, John Lewis, and Dr Sandra Fairs, with all of whom it was a delight to work. Their cooperative interest, and indeed their forbearance during the long preparation of the first edition of this book, provided much appreciated encouragement. In particular, the knowledgeable advice and guidance so freely given by Jim Lipscombe and Peter Thomasson, both now retired, is gratefully acknowledged as it was certainly influential in my development of the material. On a practical note, I am indebted to Chris Daggett, who obtained for me the experimental flight data which has been used to illustrate the examples based on the College of Aeronautics Jetstream aircraft.

After the publication of the first edition of *Flight Dynamics Principles*, a steady stream of constructive comments was received from a very wide audience and all of these were noted in the preparation of the second edition. However, a number of individuals were especially supportive, including Dr David Birdsall of Bristol University, who wrote a very complimentary review shortly after publication; Dr Peter Render of Loughborough University, an enthusiastic user of the book who very kindly provided a selection of his past examination papers for inclusion in the second edition; and my good friend Chris Fielding of BAE Systems, who was particularly helpful by providing continuous industrial liaison and by helping to focus the second edition on industrial applications. I am also most grateful to Dr Stephen Carnduff, also of BAE Systems, who provided considerable help at the last minute by preparing the solutions manual for the end-of-chapter problems.

In the preparation of the third edition, I am once again indebted to my colleagues at Cranfield, Dr James Whidborne and Dr Alastair Cooke, and to my retired colleague and friend Peter Thomasson, for the opportunity to discuss ideas for development with them and for their helpful comments and suggestions. Once again, I am also especially indebted to my friend and colleague Chris Fielding, recently retired from BAE Systems, for his continuing total support for the book and for his considerable help in developing the new Chapter 14 to better reflect industrial practice.

I am very pleased that Elsevier agreed to retain the second edition front cover photograph for the third edition. I remain indebted to BAE Systems, which kindly provided the photograph, and especially to communications manager Andy Bunce, who arranged permission for it to be reproduced. The splendid photograph shows a Eurofighter Typhoon IPA1, captured by Ray Troll, photographic services manager, just after take-off from Warton for its first flight in the production colour scheme.

The numerous bright young people who have been my students have unwittingly contributed to the material content of *Flight Dynamics Principles* by providing all important "customer feedback". Since my students represent a large part of the audience to which the work is directed, it is fitting that what has probably been the most important contribution to its continuing development be gratefully acknowledged.

Finally, I am indebted to Joe Hayton of Elsevier, whose belief in the future potential of the book as an undergraduate text convinced me that the time was right for a third edition. I am also grateful to Fiona Geraghty, Heather Tighe, and their colleagues at Elsevier for their help in the production process, and for maintaining the gentle pressure to ensure that I delivered on time.

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Nomenclature

Of the very large number of symbols required by the subject, many have more than one meaning. Usually the meaning is clear from the context in which the symbol is used.

a	Wing or wing-body lift curve slope: Acceleration: Local speed of sound
a'	Inertial or absolute acceleration
a_0	Speed of sound at sea level: Tailplane zero-incidence lift coefficient
a_1	Tailplane lift curve slope
a_{1_f}	Canard foreplane lift curve slope
a_{1_F}	Fin lift curve slope
a_2	Elevator lift curve slope
a_{2_A}	Aileron lift curve slope
a_{2_R}	Rudder lift curve slope
a_3	Elevator tab lift curve slope
a_∞	Lift curve slope of infinite-span wing
a_h	Local lift curve slope at coordinate h
a_y	Local lift curve slope at spanwise coordinate y
$a_{z_{cg}}$	Normal acceleration at the cg
a_{z_p}	Normal acceleration at the pilot
ac	Aerodynamic centre
A	Aspect ratio
A_F	Effective aspect ratio of fin
A_T	Effective aspect ratio of tailplane
$\mathbf{A}$	State matrix
b	Wing span
b_1	Elevator hinge moment derivative with respect to α_T
b_2	Elevator hinge moment derivative with respect to η
b_3	Elevator hinge moment derivative with respect to β_η
b_T	Tailplane span
$\mathbf{B}$	Input matrix
c	Chord: Viscous damping coefficient: Command input
$\bar{c}$	Standard mean chord (*smc*)
$\bar{\bar{c}}$	Mean aerodynamic chord (*mac*)
$\bar{\bar{c}}_\eta$	Mean elevator chord aft of hinge line
c_h	Local chord at coordinate h
c_r	Root chord

c_t	Tip chord
c_y	Local chord at spanwise coordinate y
cg	Centre of gravity
cp	Centre of pressure
C	Command path transfer function
$\mathbf{C}$	Output matrix
C_D	Drag coefficient
C_{D_0}	Zero-lift drag coefficient
C_l	Rolling moment coefficient
C_L	Lift coefficient
C_{L_w}	Wing or wing-body lift coefficient
C_{L_T}	Tailplane lift coefficient
C_H	Elevator hinge moment coefficient
C_m	Pitching moment coefficient
C_{m_0}	Pitching moment coefficient about aerodynamic centre of wing or wing-body
C_{m_α}	Slope of C_m-α plot
C_n	Yawing moment coefficient
C_x	Axial force coefficient
C_y	Lateral force coefficient
C_z	Normal force coefficient
C_τ	Thrust coefficient
d	Maximum body width; gust length
D	Drag
D'	Drag in a lateral-directional perturbation
$\mathbf{D}$	Direction cosine matrix; direct matrix
D_c	Drag due to camber
D_α	Drag due to incidence
e	Exponential function
e	Oswald efficiency factor
E	Input matrix of gust and turbulence terms
f	Cyclic frequency (Hz)
F	Aerodynamic force: Feed-forward path transfer function: ESDU empirical factor
F	Direct matrix of gust and turbulence terms
F_c	Aerodynamic force due to camber
F_W	ESDU empirical correction factor
F_α	Aerodynamic force due to incidence
F_η	Elevator control force

g	Acceleration due to gravity
g_η	Elevator stick to surface mechanical gearing constant
G	Controlled system transfer function: ESDU empirical factor: Transfer function gain
G_f	Filter transfer function
h	Height; centre of gravity position on reference chord: Spanwise coordinate along wing sweep line; body height
h_0	Aerodynamic centre position on reference chord
h_F	Fin height coordinate above roll axis
h_m	Controls-fixed manoeuvre point position on reference chord
h'_m	Controls-free manoeuvre point position on reference chord
h_n	Controls-fixed neutral point position on reference chord
h'_n	Controls-free neutral point position on reference chord
H	Elevator hinge moment: Feedback path transfer function
H_F	Fin span measured perpendicular to roll axis
H_m	Controls-fixed manoeuvre margin
H'_m	Controls-free manoeuvre margin
i_x	Dimensionless moment of inertia in roll
i_y	Dimensionless moment of inertia in pitch
i_z	Dimensionless moment of inertia in yaw
i_{xz}	Dimensionless product of inertia about ox and oz axes
I'	Normalised inertia
I_x	Moment of inertia in roll
I_y	Moment of inertia in pitch
I_z	Moment of inertia in yaw
$\mathbf{I}$	Identity matrix
I_{xy}	Product of inertia about ox and oy axes
I_{xz}	Product of inertia about ox and oz axes
I_{yz}	Product of inertia about oy and oz axes
j	Complex variable $(\sqrt{-1})$
J	ESDU empirical sideforce correction factor
k	General constant; spring stiffness coefficient
k_q	Pitch rate transfer function gain constant
k_u	Axial velocity transfer function gain constant
k_w	Normal velocity transfer function gain constant
k_θ	Pitch attitude transfer function gain constant
k_τ	Turbo-jet engine gain constant
K	Feedback gain: Constant in drag polar: Gust filter gain constant

$\mathbf{K}$	Feedback gain matrix
K_f	Feel system spring constant
K_n	Controls-fixed static stability margin
K'_n	Controls-free static stability margin
l_f	Fin arm measured between wing and fin quarter-chord points
l_t	Tail arm measured between wing and tailplane quarter-chord points
l_F	Fin arm measured between *cg* and fin quarter-chord point
l_T	Tail arm measured between *cg* and tailplane quarter-chord points
L	Lift; rolling moment
L'	Lift in lateral-directional perturbation
L_c	Lift due to camber
L_w	Wing or wing-body lift
L_F	Fin lift
L_T	Tailplane lift
L_α	Lift due to incidence
L	Gust and turbulence scale length
m	Mass
m'	Normalised mass
m_F	ESDU fin moment arm about *cg*
M	Local Mach number
M_0	Free stream Mach number
M_{crit}	Critical Mach number
M	Pitching moment
$\mathbf{M}$	"Mass" matrix
M_0	Wing-body pitching moment about wing aerodynamic centre
M_T	Tailplane pitching moment about tailplane aerodynamic centre
n	Total normal load factor
n_α	Normal load factor per unit angle of attack
n'	Inertial normal load factor
n_z	Normal load factor
N	Yawing moment; white noise
o	Origin of axes
p	Roll rate perturbation: Trim reference point; system pole
q	Pitch rate perturbation
Q	Dynamic pressure
r	Yaw rate perturbation: General response variable
R	Radius of turn