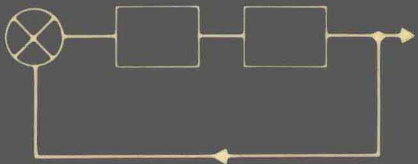

PRENTICE HALL INTERNATIONAL
SERIES IN SYSTEMS AND
CONTROL ENGINEERING
SERIES EDITOR: M. J. GRIMBLE

Automatic Flight Control Systems

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Automatic Flight Control Systems

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PRENTICE HALL

New York · London · Toronto · Sydney · Tokyo · Singapore

First published 1990 by
Prentice Hall International (UK) Ltd
66 Wood Lane End, Hemel Hempstead
Hertfordshire HP2 4RG
A division of
Simon & Schuster International Group

Typeset in 10/12 pt Times
by Columns of Reading
Printed and bound in Great Britain at the
University Press, Cambridge

Library of Congress Cataloging-in-Publication Data

McLean, Donald. 1936–
Automatic flight control systems / by Donald McLean.
p. cm.
Bibliography: p.
Includes index.
ISBN 0–13–054008–0: $60.00
1. Flight control. I. Title.
TL589.4.M45 1990
629.132'6 – – dc20 89–22857
CIP

British Library Cataloguing in Publication Data

McLean, D. (Donald, 1936–)
Automatic flight control systems.
1. Aircraft. Automatic flight control systems
I. Title
629.135'2
ISBN 0–13–054008–0

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2 3 4 5 94 93 92

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Prentice Hall International
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Preface

This is an introductory textbook on automatic flight control systems (AFCSs) for undergraduate aeronautical engineers. It is hoped that the material and the manner of its presentation will increase the student's understanding of the basic problems of controlling an aircraft's flight, and enhance his ability to assess the solutions to the problems which are generally proposed. Not every method or theory of control which can be used for designing a flight controller is dealt with in this book; however, if a reader should find that some favourite technique or approach has been omitted, the fault lies entirely with the author upon whose judgement the selection depended. The method is not being impugned by its omission.

Before understanding how an aircraft may be controlled automatically in flight it is essential to know how any aircraft will respond dynamically to a deliberate movement of its control surfaces, or to an encounter with unexpected and random disturbances of the air through which it is flying. A sound knowledge of an aircraft's dynamic response is necessary for the succesful design of any AFCS, but that knowledge is not sufficient. A knowledge of the quality of aircraft response, which can result in the aircraft's being considered by a pilot as satisfactory to fly, is also important. In this book the first six chapters are wholly concerned with material relevant to such important matters.

There are now so many methods of designing control systems that it would require another book to deal with them alone. Instead, Chapters 7 and 8 have been included to provide a reasonably self-contained account of the most significant methods of designing linear control systems which find universal use in AFCSs. Emphasis has been placed upon what are spoken of as modern methods of control (to distinguish them from the classical methods): it is most unlikely that today's students would not consider the use of a computer in arriving at the required solution. Being firmly based upon time-domain methods, modern control theory, particularly the use of state equations, is a natural and effective technique for use with computer aided engineering and harmonizes with the mathematical description of the aircraft dynamics which are most completely, and conveniently, expressed in terms of a state and an output equation. The form involved leads naturally to the use of eigenvalues and eigenvectors which make consideration of the stability properties of the aircraft simple and straightforward. Since computers are to be used, the need for normalizing the dynamic equations can be dispensed with and the differential equations can be solved to find the aircraft's motion in real time. The slight cost to be borne for this convenience is that the stability derivatives of the aircraft which are used in the analysis are dimensional;

however, since the aircraft dynamics are in real time, the dynamics of the flight controller, the control surface actuators, and the motion sensors can also be dealt with in real time, thereby avoiding the need for cumbersome and unnecessary transformations. Since dimensional stability derivatives were to be used, the American system of notation for the aircraft equations of motions was adopted: most papers and most data throughout the world now use this system.

Chapters 9 to 11 relate to particular modes of an AFCS, being concerned with stability augmentation systems, attitude and path control systems. A particular AFCS may have some, or all, of these modes involved in its operation, some being active at all times in the flight, and others being switched in by the pilot only when required for a particular phase of flight. Although helicopter flight control systems do not differ in principle from those used with fixed wing aircraft, they are fitted for different purposes. Furthermore, both the dynamics and the means of controlling a helicopter's flight are radically different from fixed wing aircraft. Consequently, helicopter AFCSs are dealt with wholly in Chapter 13 to emphasize the distinctive stability and handling problems that their use is intended to overcome.

Active control systems are dealt with in Chapter 12 and only a brief treatment is given to indicate how structural motion can be controlled simultaneously, for example, with controlling the aircraft's rigid body motion. Ride control and fuselage pointing are flight control modes dealt with in this chapter.

In the thousands of commercial airliners, the tens of thousands of military aircraft, and the hundreds of thousands of general aviation aircraft which are flying throughout the world today, examples of the types of AFCS discussed in this book can easily be found. But most modern AFCSs are digital, and to account for this trend Chapter 14 has been added to deal solely with digital control methods. The consequences for the dynamic response of the closed-loop system of implementing a continuous control law in a digital fashion is emphasized. Results complementary to those in Chapters 9 to 11, obtained using wholly digital system analysis, are also shown.

The final chapter deals briefly with the subject of adaptive flight control systems, and three appendices provide a summary of information relating to actuators, sensors, aircraft stability data, and human operators.

In writing a textbook, ideas and techniques which have been used effectively and easily by the author over the years are discussed and presented, but the original source is often forgotten. If others find their work used here but unacknowledged, please be assured that it was unintentional and has occurred mostly as a result of a middle-aged memory rather than malice, for I am conscious of having had many masters in this subject. At the risk of offending many mentors, I wish to acknowledge here only the special help of three people, for the list of acknowledgements would be impossibly long otherwise. Two are American scholars: Professors Jack d'Azzo and Dino Houpis, of the United States Air Force Institute of Technology, in Dayton, Ohio. They are nonpareil as teachers of control and taught me in a too-short association the importance of the student and his needs. The other is my secretary, Liz Tedder, who now knows, to her lasting regret, more about automatic flight control systems than she ever wished to know.

D. McLEAN
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flight control system (AFCS). In aircraft, such AFCSs employ feedback control to achieve the following benefits:

1. The speed of response is better than from the aircraft without closed loop control.
2. The accuracy in following commands is better.
3. The system is capable of suppressing, to some degree, unwanted effects which have arisen as a result of disturbances affecting the aircraft's flight.

However, under certain conditions such feedback control systems have a tendency to oscillate; the AFCS then has poor stability. Although the use of high values of gain in the feedback loops can assist in the achievement of fast and accurate dynamic response, their use is invariably inimical to good stability. Hence, designers of AFCSs are obliged to strike an acceptable, but delicate, balance between the requirements for stability and for control.

The early aeronautical experimenters hoped to make flying easier by providing 'inherent' stability in their flying machines. What they tried to provide was a basic, self-restoring property of the airframe without the active use of any feedback. A number of them, such as Cayley, Langley and Lilienthal, discovered how to achieve longitudinal static stability with respect to the relative wind, e.g. by setting the incidence of the tailplane at some appropriate value. Those experimenters also discovered how to use wing dihedral to achieve lateral static stability. However, as aviation has developed, it has become increasingly evident that the motion of an aircraft designed to be inherently very stable, is particularly susceptible to being affected by atmospheric turbulence. This characteristic is less acceptable to pilots than poor static stability.

It was the great achievement of the Wright brothers that they ignored the attainment of inherent stability in their aircraft, but concentrated instead on making it controllable in moderate weather conditions with average flying skill. So far in this introduction, the terms dynamic and static stability have been used without definition, their imprecise sense being left to the reader to determine from the text. There is, however, only one dynamic property – stability – which can be established by any of the theories of stability appropriate to the differential equations being considered. However, in aeronautical engineering, the two terms are still commonly used; they are given separate specifications for the flying qualities to be attained by any particular aircraft. When the term static stability is used, what is meant is that if a disturbance to an aircraft causes the resulting forces and moments acting on the aircraft to tend initially to return the aircraft to the kind of flight path for which its controls are set, the aircraft can be said to be statically stable. Some modern aircraft are not capable of stable equilibrium – they are statically unstable. Essentially, the function of static stability is to recover the original speed of equilibrium flight. This does not mean that the initial flight path is resumed, nor is the new direction of motion necessarily the same as the old. If, as a result of a disturbance, the resulting forces and moments do not tend initially to restore the aircraft to its former equilibrium flight path, but leave it in its disturbed state, the aircraft is neutrally stable. If it tends initially to deviate further from its equilibrium flight path, it is statically unstable. When an aircraft is put in a state of equilibrium by the action of the pilot adjusting the controls, it is said to be trimmed. If, as a result of a disturbance, the aircraft tends to return eventually to its equilibrium flight path, and remains at that position, for some time, the aircraft is said to be dynamically stable. Thus, dynamic stability governs how an aircraft recovers its equilibrium after a disturbance. It will be seen later how some aircraft may be statically stable, but are dynamically unstable, although aircraft which are statically unstable will be dynamically unstable.

1.2 CONTROL SURFACES

Every aeronautical student knows that if a body is to be changed from its present state of motion then external forces, or moments, or both, must be applied to the body, and the resulting acceleration vector can be determined by applying Newton's Second Law of Motion. Every aircraft has control surfaces or other means which are used to generate the forces and moments required to produce the accelerations which cause the aircraft to be steered along its three-dimensional flight path to its specified destination.

A conventional aircraft is represented in Figure 1.1. It is shown with the usual control surfaces, namely elevator, ailerons, and rudder. Such conventional aircraft have a fourth control, the change in thrust, which can be obtained from the engines. Many modern aircraft, particularly combat aircraft, have considerably more control surfaces, which produce additional control forces or moments. Some of these additional surfaces and motivators include horizontal and vertical canards, spoilers, variable cambered wings, reaction jets, differentially operating horizontal tails and movable fins. One characteristic of flight control is that the required motion often needs a number of control surfaces to be used simultaneously. It is shown later in this book that the use of a single control surface always produces other motion as well as the intended motion. When more than one control surface is deployed simultaneously, there often results

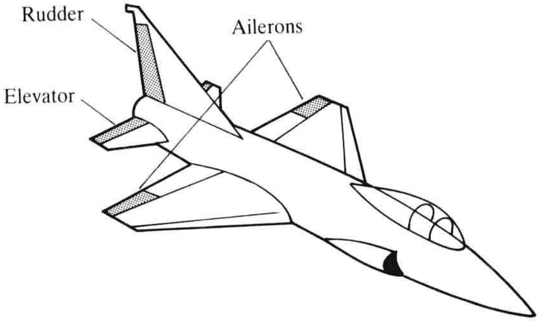

Figure 1.1 Conventional aircraft.

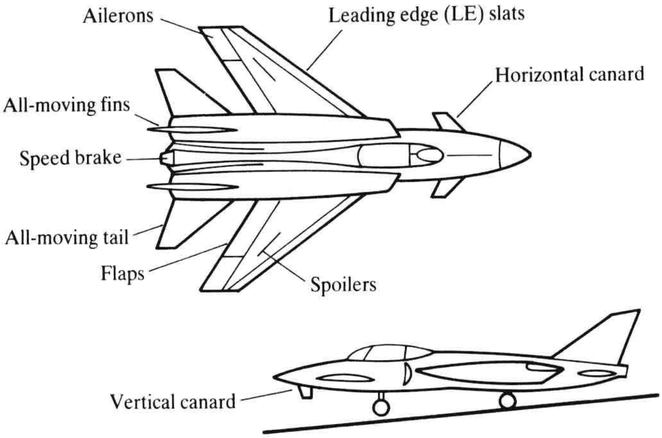

Figure 1.2 A proposed control configured vehicle.

considerable coupling and interaction between motion variables. It is this physical situation which makes AFCS design both fascinating and difficult. When these extra surfaces are added to the aircraft configuration to achieve particular flight control functions, the aircraft is described as a 'control configured vehicle' (CCV). A sketch of a proposed CCV is illustrated in Figure 1.2 in which there are shown a number of extra and unconventional control surfaces. When such extra controls are provided it is not to be supposed that the pilot in the cockpit will have an equal number of extra levers, wheels, pedals, or whatever, to provide the appropriate commands. In a CCV such commands are obtained directly from an AFCS and the pilot has no direct control over the deployment of each individual surface. The AFCS involved in this activity are said to be *active control technology* systems. The surfaces are moved by actuators which are signalled electrically (fly-by-wire) or by means of fibre optic paths (fly-by-light). But, in a conventional aircraft, the pilot has direct mechanical links to the surfaces, and how he commands the deflections, or changes, he requires from the controls is by means of what are called the *primary flying controls*.

1.3 PRIMARY FLYING CONTROLS

In the UK, it is considered that what constitutes a flight control system is an arrangment of all those control elements which enable controlling forces and moments to be applied to the aircraft. These elements are considered to belong to three groups: pilot input elements, system output elements and intervening linkages and elements.

The primary flying controls are part of the flight control system and are defined as the input elements moved directly by a human pilot to cause an