CHAPTER

# Introduction

# 1

## 1.1 Overview

This book is primarily concerned with the provision of good flying and handling qualities in conventional piloted aircraft, although the material is equally applicable to *uninhabited air vehicles* (UAV). Consequently, it is also very much concerned with the stability, control, and dynamic characteristics which are fundamental to the determination of those qualities. Since flying and handling qualities are of critical importance to safety and to the piloting task, it is essential that their origins are properly understood. Here, then, the intention is to set out the basic principles of the subject at an introductory level and to illustrate the application of those principles by means of worked examples.

Following the first flights made by the Wright brothers in December 1903, the pace of aeronautical development quickened and the progress made in the following decade or so was dramatic. However, the stability and control problems that faced early aviators were sometimes considerable since the flying qualities of their aircraft were often less than satisfactory. Many investigators were studying the problems of stability and control at the time, although it is the published works of Bryan (1911) and Lanchester (1908) which are usually credited with laying the first really secure foundations for the subject. By conducting many experiments with flying models, Lanchester was able to observe and successfully describe mathematically some dynamic characteristics of aircraft. The beauty of Lanchester's work was its practicality and theoretical simplicity, which facilitates easy application and interpretation. Bryan, on the other hand, was a mathematician who chose to apply his energies, with the assistance of a Mr. Harper, to the problems of aircraft stability and control. He developed the general equations of motion of a rigid body with six degrees of freedom to successfully describe aircraft motion. His treatment, with very few changes, is still in everyday use. What has changed is the way in which the material is now used, due largely to the advent of the digital computer as an analysis tool. Together, the stability and control of aircraft is a subject which has its origins in aerodynamics, and the classical theory of the subject is traditionally expressed in the language of the aerodynamicist. However, most advanced-technology aircraft may be described as an *integrated system* comprising airframe, propulsion, flight controls, and so on. It is therefore convenient and efficient to utilise powerful computational systems engineering tools to analyse and describe the system's flight dynamics. Thus, the objective of the present work is to revisit the development of the classical theory and to express it in the language of the systems engineer where it is more appropriate to do so.

The subject of *flight dynamics* is concerned with the relatively short-term motion of aircraft in response to controls or to external disturbances such as atmospheric turbulence. The motion of interest can vary from small excursions about trim to very-large-amplitude manoeuvring when normal aerodynamic behaviour may well become very non-linear. Since the treatment of the subject is introductory, a discussion of large-amplitude dynamics is beyond the scope of the present work.

The dynamic behaviour of an aircraft is shaped significantly by its stability and control properties, which in turn have their roots in the aerodynamics of the airframe. Previously the achievement of aircraft with good stability characteristics usually ensured good flying qualities, all of which depended only on good aerodynamic design. Expanding flight envelopes and the increasing dependence on an *automatic flight control system* (AFCS) for stability augmentation means that good flying qualities are no longer a guaranteed product of good aerodynamic design and good stability-characteristics. The reasons for this apparent inconsistency are now reasonably well understood and, put very simply, result from the addition of flight control system dynamics to those of the airframe. Flight control system dynamics are of course a necessary, but not always desirable, by-product of command and stability augmentation.

Modern flight dynamics is concerned not only with the dynamics, stability, and control of the basic airframe but also with the sometimes complex interaction between the airframe and flight control system. Since the flight control system comprises motion sensors, a control computer, control actuators, and other essential items of control hardware, a study of the subject becomes a multidisciplinary activity. Therefore, it is essential that the modern flight dynamicist has not only a thorough understanding of the classical stability and control theory of aircraft but also a working knowledge of control theory and of the use of computers in *flight-critical* applications. Modern aircraft comprise the airframe together with the flight control equipment and may be treated as a whole *system* using the traditional tools of the aerodynamicist and the analytical tools of the control engineer.

Thus in a modern approach to the analysis of stability and control, it is convenient to treat the airframe as a system component. This leads to the derivation of mathematical models which describe aircraft in terms of aerodynamic *transfer functions*. Described in this way, the stability, control, and dynamic characteristics of aircraft are readily interpreted with the aid of very powerful computational systems engineering tools. It follows that the mathematical model of the aircraft is immediately compatible with, and provides the foundation for integration with, flight control system studies. This is an ideal state of affairs since today it is commonplace to undertake stability and control investigations as a precursor to flight control system development.

The modern flight dynamicist tends to 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 are, of course, largely determined by the latter. The present treatment of the material is shaped by answering the following questions which a newcomer to the subject might be tempted to ask:

> *How are the stability and control characteristics of aircraft determined, and how do they influence flying qualities?*

The answer to this question involves the establishment of a suitable mathematical framework for the problem, the development of the equations of motion and their solution, investigation of response to controls, and the general interpretation of dynamic behaviour.

> *What are acceptable flying qualities; how are the requirements defined, interpreted, and applied; and how do they limit flight characteristics?*

The answer to this question involves a review of contemporary flying qualities requirements and their evaluation and interpretation in the context of stability and control characteristics.

> *When an aircraft has unacceptable flying qualities, how may its dynamic characteristics be improved?*

The answer to this question involves an introduction to the rudiments of feedback control as the means of augmenting the stability of the basic airframe.

## 1.2 Flying and handling qualities

The flying and handling qualities of an aircraft are those properties which describe the ease and effectiveness with which the aircraft responds to pilot commands in the execution of a flight task, or *mission task element* (MTE). In the first instance, therefore, flying and handling qualities are described qualitatively and are formulated in terms of *pilot opinion*; consequently, they tend to be rather subjective. The process involved in pilot perception of flying and handling qualities may be interpreted in the form of a signal flow diagram, as shown in Fig. 1.1. The solid lines represent physical, mechanical or electrical signal flow paths; the dashed lines represent sensory feedback information to the pilot. The author's interpretation distinguishes between *flying qualities* and *handling qualities* as indicated. The pilot's perception of flying qualities is considered to be a qualitative description of how well the aeroplane carries out the commanded task. On the other hand, the pilot's perception of handling qualities is considered to be a qualitative description of the adequacy of the short-term dynamic response to controls in the execution of the flight task. The two *qualities* are therefore very much interdependent and in practice are probably inseparable. To summarise, then, flying qualities may be regarded as being task-related whereas the handling qualities may be regarded as being response-related. When the airframe characteristics are augmented by a flight control system, the way in which that system may influence the flying and handling qualities is clearly shown in Fig. 1.1.

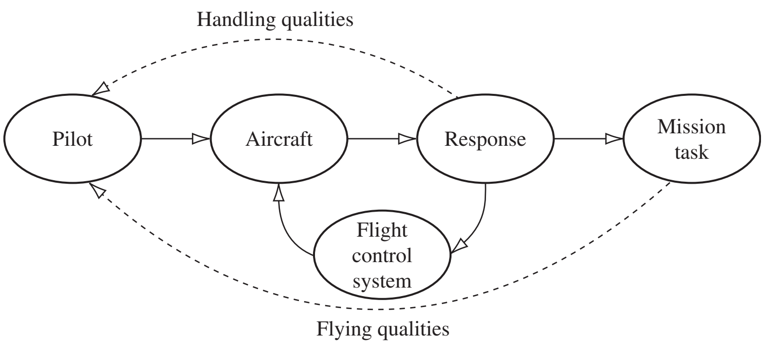


**FIGURE 1.1 Flying and handling qualities of conventional aircraft.**

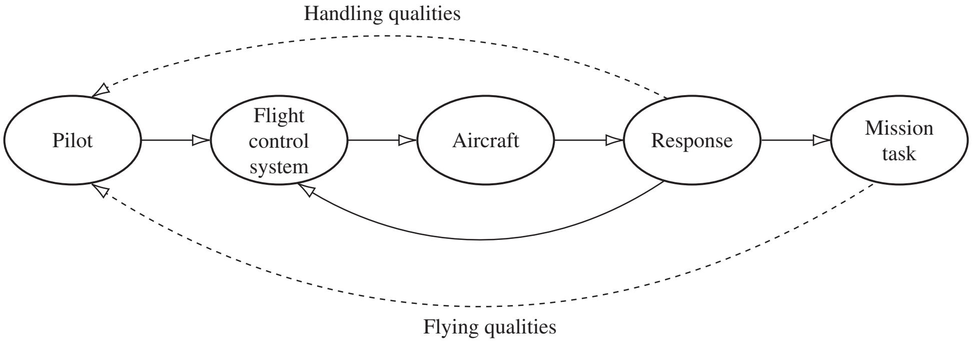


**FIGURE 1.2 Flying and handling qualities of FBW aircraft.**

Most advanced modern aeroplanes employ *fly-by-wire* (FBW) primary flight controls, and these are usually integrated with the stability augmentation system. In this case, the interpretation of flying and handling qualities is modified to that shown in Fig. 1.2. Here the flight control system becomes an integral part of the primary signal flow path, and the influence of its dynamic characteristics on flying and handling qualities is of critical importance. The need for very careful consideration of the influence of the flight control system in this context cannot be over-emphasised.

The pilot's perception of the flying and handling qualities of an aircraft will be influenced by many factors, among them stability, control, and dynamic characteristics of the airframe; flight control system dynamics; response to atmospheric disturbances; and the less tangible effects of cockpit design. This last factor includes considerations such as control inceptor design, instrument displays, and field of view. Not surprisingly, the quantification of flying qualities is difficult. However, there is an overwhelming necessity for some sort of numerical description of flying and handling qualities for use in engineering design and evaluation. It is well established that the flying and handling qualities of an aircraft are intimately dependent on the stability and control characteristics of the airframe, including the flight control system if one is installed. Since stability and control parameters are readily quantified, these are usually used as indicators and measures of the likely flying qualities of the aeroplane. Therefore, the prerequisite for almost any study of flying and handling qualities is a descriptive mathematical model of the aeroplane which is capable of providing an adequate quantitative indication of its stability, control, and dynamic properties.

## 1.3 General considerations

In a systematic study of the principles governing the flight dynamics of aircraft, it is convenient to break the problem down into manageable descriptive elements. Thus before attempting to answer the questions posed in Section 1.1, it is useful to consider and define a suitable framework in which the essential mathematical development may take place.

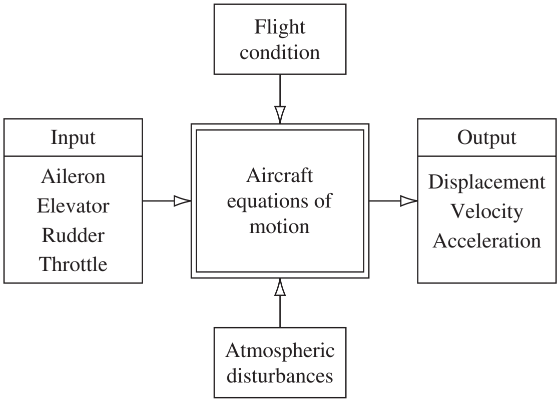


**FIGURE 1.3 Basic control-response relationships.**

### 1.3.1 Basic control-response relationships

A description of the basic input-output relationships on which the flying and handling qualities of unaugmented aircraft depend is essential. These relationships are described by the aerodynamic transfer functions which provide the simplest and most fundamental description of airframe dynamics. They describe the control-response relationship as a function of flight condition and may include the influence of atmospheric disturbances when appropriate. These basic relationships are illustrated in Fig. 1.3.

Central to this framework is a mathematical model of the aircraft, usually referred to as *the equations of motion*. The equations of motion provide a complete description of response to controls, subject only to modelling limitations defined at the outset, which is measured in terms of displacement, velocity, and acceleration variables. The flight condition describes the conditions under which the observations are made and includes parameters such as Mach number, altitude, aircraft geometry, mass, and trim state. When the airframe is augmented with a flight control system, the equations of motion are modified to model this configuration. The response transfer functions, derived from the mathematical solution of the equations of motion, are then no longer the basic aerodynamic transfer functions but are obviously the transfer functions of the augmented aeroplane.

### 1.3.2 Mathematical models

From the foregoing, it is apparent that it is necessary to derive mathematical models to describe the aircraft, its control systems, atmospheric disturbances, and so on. The success of any flight dynamics analysis hinges on the suitability of the models to the problem at hand. Often the temptation is to attempt to derive the most accurate model possible. High-fidelity models are capable of reproducing aircraft dynamics accurately, but they are seldom simple. Their main drawback is the lack of *functional visibility*. In very complex aircraft and system models, it may be difficult, or even impossible, to relate response to the simple physical aerodynamic properties of the airframe or to the properties of the control system components. For the investigation of flying and handling qualities, it is frequently adequate to use simple approximate models, which have the advantage of maximising functional visibility and thereby drawing attention to the dominant characteristics. Such models have the potential to enhance the visibility of the physical principles involved, greatly facilitating the interpretation of flying and handling qualities. Often the deterioration in fidelity of the response resulting from the use of approximate models may be relatively insignificant. For a given problem, it is necessary to develop a model which balances the desire for response fidelity against the requirement to maintain functional visibility. As is so often the case in many fields of engineering, simplicity is a most desirable virtue.

### 1.3.3 Stability and control

Flying and handling qualities are substantially dependent on, and are usually described in terms of, the stability and control characteristics of an aircraft. It is therefore essential to be able to completely describe and quantify stability and control parameters. Analysis may then be performed using the stability parameters. Static stability analysis enables the *control displacement* and *control force* characteristics to be determined for both steady and manoeuvring flight conditions. Dynamic stability analysis enables the temporal *response to controls* and reponse to atmospheric disturbances to be determined for various flight conditions.

### 1.3.4 Stability and control augmentation

When an aircraft has flying and handling deficiencies it becomes necessary to correct, or *augment*, the aerodynamic characteristics which give rise to them. To a limited extent, this could be achieved by modification of the aerodynamic design of the aircraft. In this event, it is absolutely essential to understand the relationship between the aerodynamics of the airframe and controls and the stability and control characteristics of that airframe. However, many aircraft today are designed with their aerodynamics optimised for performance over a very large flight envelope, and a consequence of this is that their flying qualities are often deficient. The intent at the outset is to rectify those deficiencies with a stability augmentation system. Therefore, the alternative to aerodynamic design modification is the introduction of a flight control system. In this case it becomes essential to understand how feedback control techniques may be used to artificially modify the apparent aerodynamic characteristics of the airframe. So once again, but for different reasons, it is absolutely essential to understand the relationship between the aerodynamics of the airframe and its stability and control characteristics. Further, it becomes very important to appreciate the effectiveness of servo-systems for autostabilisation whilst acknowledging the attendant advantages, disadvantages, and limitations introduced by the system hardware. At this stage of consideration it is beginning to become obvious why flight dynamics is now a complex multidisciplinary subject. However, since this work is introductory, the subject of stability augmentation is treated only at the most elementary level.

## 1.4 Aircraft equations of motion

The equations of motion of an aeroplane are the foundation on which the framework for flight dynamics studies is built; they provide the key to a proper understanding of flying and handling qualities. At their simplest, the equations of motion can describe small-perturbation motion about trim only. At their most complex, they can be completely descriptive, simultaneously embodying static stability, dynamic stability, aero-elastic effects, atmospheric disturbances, and control system dynamics for a given aeroplane configuration. The equations of motion enable the rather intangible description of flying and handling qualities to be related to quantifiable stability and control parameters, which in turn may be related to identifiable aerodynamic characteristics of the airframe. For initial studies the theory of small perturbations is applied to the equations to facilitate their analytical solution and to enhance their functional visibility. However, for more advanced applications, which are beyond the scope of the present work, the fully descriptive non-linear form of the equations might be retained. In this case the equations are difficult to solve analytically and computer simulation techniques become necessary to obtain a numerical solution.

## 1.5 Aerodynamics

The aerodynamics of the airframe and its controls make a fundamental contribution to the stability and control characteristics of the aircraft. It is usual to incorporate aerodynamic descriptions in the equations of motion in the form of *aerodynamic stability and control derivatives*. Since it is necessary to constrain the motion to well-defined limits to obtain the derivatives, the scope of the resulting aircraft model is similarly constrained in its application. However, it is quite common to find aircraft models constrained in this way being used to predict flying and handling qualities at conditions well beyond the imposed limits. This is not recommended practice! An important aspect of flight dynamics concerns the proper definition of aerodynamic derivatives as functions of common aerodynamic parameters. It is also most important that the values of the derivatives are compatible with the scope of the problem to which the model is to be applied. The processes involved in the estimation or measurement of aerodynamic derivatives provide an essential contribution to a complete understanding of aircraft behaviour.

### 1.5.1 Small perturbations

The aerodynamic properties of an aircraft vary considerably over the flight envelope, and their mathematical descriptions are approximations at best. The limit of the approximations is determined either by the ability of mathematics to describe the physical phenomena involved or by the acceptable complexity of the description. The aim is to obtain the simplest approximation consistent with adequate physical representation. In the first instance this aim is best met when the motion of interest is constrained to *small perturbations* about a steady flight condition, which is usually, but not necessarily, trimmed equilibrium. This means that the aerodynamic characteristics can be approximated by *linearising* about the chosen flight condition. Simple approximate mathematical descriptions of aerodynamic stability and control derivatives then follow relatively easily. This is the approach pioneered by Bryan (1911), and it usually works extremely well provided the limitations of the model are recognised from the outset.

## 1.6 Computers

No discussion of flight dynamics would be complete without mention of the very important role played by the computer in all aspects of the subject. It is probably true to say that the development of today's very advanced aircraft would not have been possible without parallel developments in computer technology. In fact, there is ample evidence to suggest that the demands of aeronautics have forced the pace of computer development. Computers are used for two main functions: as a general-purpose tool for design and analysis and to provide "intelligence" in flight control systems.

### 1.6.1 Analytical computers

In the past, all electronic computation, whether for analysis, simulation, or airborne flight control, would have been analogue. Analogue computer technology developed rapidly during and immediately after World War II and by the late 1960s had reached its highest level of development following the introduction of the electronic integrated operational amplifier. The principal role of the analogue computer was that of simulation, and its main advantages were its ability to run in real time, its continuous electrical signals, and its high level of functional visibility. Its main disadvantage was that the electronic hardware required was directly proportional to the functional complexity of the problem to be simulated. This meant that complex aircraft models with complex flight control systems required physically large and very costly hardware. During the 1960s and 1970s electronic digital computing technology advanced rapidly and soon displaced the analogue computer as the primary tool for design and analysis. However, it took somewhat longer before the digital computer acquired the capacity and speed necessary to meet the demands of simulation. Today most of the computational requirements for design, analysis, and simulation can be provided by a modest personal computer.

### 1.6.2 Flight control computers

In the present context, flight control is taken to mean *flight-critical stability augmentation*, where a computer malfunction or failure might hazard the continued safe operation of the aircraft. In the case of a FBW computer, a total failure would mean total loss of control. Therefore, hardware integrity is a very serious issue in flight control computer design. The modern aircraft may also have an autopilot computer, air data computer, navigation computer, energy management computer, weapon systems computer, and more. Many of these additional computers may be capable of exercising some degree of control over the aircraft, but none is quite as critical as the stability augmentation computer in the event of a malfunction.

For the last 70 years or more, computers have been used in aircraft for flight control. For much of that time the dedicated analogue electronic computer was unchallenged because of its relative simplicity, its easy interface engineering with mechanical flying controls, and its excellent safety record. Toward the end of the 1970s the digital computer had reached the stage of development where its use in flight-critical applications became a viable proposition, with the promise of vastly expanded control capability. The pursuit of increasingly sophisticated performance goals led to an increase in complexity of the aerodynamic design of aircraft. This in turn placed greater demands on the flight control system for the maintenance of good flying and handling qualities. The attraction of the digital computer for flight control is its capability for handling very complex control functions easily. The disadvantage is its lack of functional visibility and the consequent difficulty of ensuring safe trouble-free operation. Nevertheless, the digital flight-critical computer is here to stay and is now used in all advanced-technology aircraft. Research continues to improve hardware, software, and applications. Confidence in digital flight control systems is now such that applications include full-FBW civil transport aeroplanes.

Functionally complex flight control systems have given the modern aeroplane hitherto unobtainable performance benefits. But nothing is free! The consequence of using such systems is the unavoidable introduction of unwanted control system dynamics. These usually manifest themselves as control phase lag and can intrude on the piloting task in an unacceptable way, resulting in an aircraft with poor flying and handling qualities. This problem is still a subject of research and is very much beyond the scope of this book. However, the essential foundation material on which such studies are built is set out in the following chapters.

### 1.6.3 Computer software tools

Many computer software tools are now available which are suitable for flight dynamics analysis. Most packages are intended for control systems applications, but they are ideal for handling aeronautical system problems and may be installed on a modest PC. Software tools used regularly by the author are listed here, but it must be appreciated that the list is by no means exhaustive, nor is it implied that the programs listed are the best or necessarily the most appropriate.

#### *Matlab*

Matlab is a very powerful control system design and analysis tool which is intended for systems configured in state-space format. As a result, all computation is handled in matrix format. Matlab's screen graphics are good. All of the examples and problems in this book can be solved with the aid of Matlab.

#### *Simulink*

Simulink is a continuous simulation supplementary addition to Matlab, on which it depends for its mathematical modelling. It is also a powerful tool and is easy to apply using a block diagram format for model building. Simulink is not strictly necessary for application to the material in this book, although it can be used with advantage for some examples. Its main disadvantage is its limited functional visibility since models are built using interconnecting blocks whose functions are not always immediately obvious to the user. Nevertheless, Simulink enjoys widespread use throughout industry and academia.

#### *Matlab and Simulink, Student Version Release 14*

Matlab *and* Simulink, Student Version Release 14 is a combined package available to registered students at low cost.

#### *Program CC, Version 5*

Program CC, Version 5 is also a very powerful control system design and analysis tool. It is capable of handling classical control problems in transfer function format as well as modern state-space control problems in matrix format. The current version is very similar in use to Matlab to the extent that many procedures are identical. This is not entirely surprising since the source of the underlying mathematical routines is the same for both programs. An advantage of Program CC is that it was written by flight dynamicists for flight dynamicists; as a result, its use is intuitive once the commands have been learned. The screen graphics are good and have some flexibility of presentation. A downloadable low-cost student version is available which is suitable for solving all examples and problems in this book.

### *Mathcad*

Mathcad Prime 2 is a very powerful general-purpose tool for mathematical problem solving. It is useful for repetitive calculations, but it comes into its own for solving difficult non-linear equations. It is also capable of undertaking complex algebraic computations. The screen graphics are generally very good and are very flexible. In particular, Mathcad is a valuable tool for aircraft trim and performance computations where the requirement is to solve simultaneous non-linear algebraic equations. Its use in this role is illustrated in Chapter 3. A low-cost student version of this software is available to registered students.

### *20-sim*

20-sim is a modern version of the traditional simulation language and has been written to capitalise on the functionality of the PC. Models can be built up from the equations of motion, from the equivalent matrix equations, or from both. Common modules can be assigned icons of the user's design, and the simulation can then be constructed in a manner similar to the block diagram format of Simulink. The versatility of 20-sim is enhanced by its direct compatibility with MATLAB. Significant advantages are excellent functional visibility, model-building flexibility, and the infinitely variable control of the model structure. The screen graphics are excellent, and there is the additional facility for direct visualisation of the modelled system in real time. At the time of writing, the main disadvantage of 20-sim is the lack of a library of aerospace simulation components; however, this will no doubt be addressed as the language matures.

## 1.7 Summary

An attempt has been made in this chapter to provide a broad appreciation of what flight dynamics is all about. To produce a comprehensive text on the subject would require many volumes, assuming that it were even possible. The present intention is therefore to set out fundamental principles only. However, where appropriate, comments are included in the text to indicate the direction in which the material in question might be developed for more advanced studies.

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