CHAPTER

Flying and Handling Qualities

10

10.1 Introduction

Some general concepts describing the meaning of *flying and handling qualities* were introduced in Chapter 1 and so are not repeated in full here. However, it is useful to recall that flying and handling qualities are those properties which govern the ease and precision with which the aeroplane responds to pilot commands in the execution of the flight task. Although these rather intangible properties are described qualitatively and are formulated in terms of *pilot opinion*, it becomes necessary to find alternative quantitative descriptions for more formal analyses. As described previously, flying and handling qualities of an aeroplane are, in part, intimately dependent on its stability and control characteristics, including the effects of a flight control system if one is installed. It was shown in previous chapters how the stability and control properties of an aeroplane may be quantified, and these are commonly used as indicators and measures of flying and handling qualities. The object here, then, is to introduce, at an introductory level, the way in which stability and control parameters are used to quantify those qualities.

10.1.1 Stability

A stable aeroplane is an aeroplane which can be established in an equilibrium flight condition where it will remain, showing no tendency to diverge. Therefore, a stable aeroplane is in general a safe aeroplane. However, it has already been established that too much stability can be as hazardous as too little stability. The degree of stability determines the magnitude of the control action, measured in terms of control displacement and force, required to manoeuvre about a given flight path. Thus *controllability* is concerned with the correct *harmonisation* of control power with the degrees of static, manoeuvre, and dynamic stability of the airframe. Because of the interdependence of the various aspects of stability and control, the provision of well-harmonised control characteristics by entirely aerodynamic means over the entire flight envelope may well be difficult, if not impossible, to achieve. This is especially so in many modern aeroplanes which are required to operate over extended flight envelopes and in aerodynamically difficult flight regimes. The solution to this problem is found in the installation of a *control and stability augmentation system* (CSAS), where the object is to restore good flying qualities by *artificial* non-aerodynamic means.

Aircraft handling is generally concerned with two relatively distinct aspects of response to controls, the short term, or transient, response and the rather longer-term response. Short term handling is very much concerned with the short-period dynamic modes and their critical influence on manoeuvrability. The ability of a pilot to handle the short term dynamics satisfactorily is critically dependent on the speed and stability of response. In other words, the bandwidth of the human pilot and the control bandwidth of the aeroplane must be compatible, and the stability margins of the dynamic modes must be adequate. An aeroplane with poor, or inadequate, short term dynamic stability and control characteristics is simply not acceptable. Thus, the provision of good short term handling tends to be the main consideration in flying and handling qualities studies.

Longer term handling is concerned with the establishment and maintenance of a steady flight condition, or trimmed equilibrium, which is determined by static stability in particular and is influenced by the long-period dynamic modes. The dynamic modes associated with long term handling tend to be slow, and the frequencies involved are relatively low. Thus their control is well within the bandwidth and capabilities of the average pilot, even when the modes are marginally unstable. As a result, the requirements for the stability of low frequency dynamics are more relaxed. However, those aspects of control which are dependent on static and manoeuvre stability parameters are very important and result in well defined boundaries for the static and manoeuvre margins.

10.2 Short term dynamic models

As explained previously, the critical aspects of aircraft handling qualities are concerned mainly with the dynamics of the initial, or transient, response to controls. Thus since the short term dynamics are of greatest interest, it is common practice to conduct handling qualities studies using reduced order dynamic models derived from the full order equations of motion. The advantage of this approach is that it gives maximum *functional visibility* to the motion drivers of greatest significance. It is therefore easier to interpret and understand the role of the fundamental aerodynamic and dynamic properties of the aeroplane in the determination of its handling qualities. It also goes without saying that the reduced order models are much easier to work with because they are algebraically simpler.

10.2.1 Controlled motion and motion cues

Reduced to the simplest interpretation, when a pilot applies a control input to the aeroplane, he is simply commanding a change in flight path. The change might be temporary, such as manoeuvring about the flight path to return to the original flight path on completion of the manoeuvre. Alternatively, the change might be permanent, such as manoeuvring to effect a change in trim state involving a change in flight path direction. Whatever the ultimate objective, the method of control is much the same. Normal manoeuvring involves rotating the airframe in roll, pitch, and yaw to point the lift vector in the desired direction; by operating the pitch control, the pilot adjusts the angle of attack to produce the lift force required to generate the acceleration to manoeuvre. Thus the pilot's perception of the handling qualities of the aeroplane is concerned with the precise way in which it responds to commands, sensed predominantly as the change in normal acceleration. Indeed, the pilot is extremely sensitive to even the smallest changes in acceleration in all three axes. Clearly, then, short term normal acceleration dynamics provide a vitally important cue in considerations of aircraft handling qualities and are most easily modelled with the reduced order equations of motion. Obviously, other motion cues are equally important to the pilot, such as attitude, angular rate, and angular acceleration, although these variables were not, in the past, regarded with the same level of importance as normal acceleration. Thus, in the analysis of aircraft handling qualities, by far the greatest emphasis is on the longitudinal short term dynamic response to controls.

10.2.2 The longitudinal reduced order model

The reduced order longitudinal state equation describing short term dynamics only is given by equation (6.1) in terms of concise derivatives and may be written as

$$\begin{bmatrix} \dot{\alpha} \\ \dot{q} \end{bmatrix} = \begin{bmatrix} z_w & 1 \\ m_w & m_q \end{bmatrix} \begin{bmatrix} \alpha \\ q \end{bmatrix} + \begin{bmatrix} \dfrac{z_\eta}{U_e} \\ m_\eta \end{bmatrix} \eta \tag{10.1}$$

since $z_q \cong U_e$ and w is replaced by α. Solution of equation (10.1) gives the two short term response transfer functions

$$\frac{\alpha(s)}{\eta(s)} = \frac{\dfrac{z_\eta}{U_e}\left(s + U_e \dfrac{m_\eta}{z_\eta}\right)}{(s^2 - (m_q + z_w)s + (m_q z_w - m_w U_e))} \equiv \frac{k_\alpha\left(s + 1/T_\alpha\right)}{(s^2 + 2\zeta_s \omega_s s + \omega_s^2)} \tag{10.2}$$

$$\frac{q(s)}{\eta(s)} = \frac{m_\eta(s - z_w)}{(s^2 - (m_q + z_w)s + (m_q z_w - m_w U_e))} \equiv \frac{k_q\left(s + 1/T_{\theta_2}\right)}{(s^2 + 2\zeta_s \omega_s s + \omega_s^2)} \tag{10.3}$$

Equations (10.2) and (10.3) compare directly with equations (6.17) and (6.18), respectively. The short term response transfer function describing pitch attitude response to elevator follows directly from equation (10.3):

$$\frac{\theta(s)}{\eta(s)} = \frac{k_q\left(s + 1/T_{\theta_2}\right)}{s(s^2 + 2\zeta_s \omega_s s + \omega_s^2)} \tag{10.4}$$

With reference to Section 5.5, the short term response transfer function describing, approximately, the normal acceleration response to elevator may be derived from equations (10.2) and (10.3):

$$\frac{a_z(s)}{\eta(s)} = \frac{m_\eta z_w U_e}{(s^2 - (m_q + z_w)s + (m_q z_w - m_w U_e))} \equiv \frac{k_{a_z}}{(s^2 + 2\zeta_s \omega_s s + \omega_s^2)} \tag{10.5}$$

In the derivation it is assumed that z_η / U_e is insignificantly small. With reference to Section 5.7.3, the short-term response transfer function describing flight path angle response to elevator is also readily derived from equations (10.2) and (10.4):

$$\frac{\gamma(s)}{\eta(s)} = \frac{-m_\eta z_w}{s(s^2 - (m_q + z_w)s + (m_q z_w - m_w U_e))} \equiv \frac{k_\gamma}{s(s^2 + 2\zeta_s \omega_s s + \omega_s^2)} \tag{10.6}$$

and, again, it is assumed that z_η / U_e is insignificantly small. By dividing equation (10.6) by equation (10.4), it may be shown that

$$\frac{\gamma(s)}{\theta(s)} = \frac{1}{(1 + sT_{\theta_2})} \tag{10.7}$$

which gives the important result that, in the short term, flight path angle response lags pitch attitude response by T_{θ_2}, sometimes referred to as *incidence lag*.

For the purpose of longitudinal short term handling analysis, the responsiveness or manoeuvrability of the aeroplane is quantified by the derivative parameter *normal load factor per unit angle of attack*, denoted n_α. Since this parameter relates to the aerodynamic lift generated per unit angle of attack at a given flight condition, it is proportional to the lift curve slope and the square of the velocity. An expression for n_α is easily derived from the previous short term transfer functions. Assuming a unit step input to elevator such that $\eta(s) = 1/s$, the Laplace transform of the incidence response follows from equation (10.2):

$$\alpha(s) = \frac{\dfrac{z_\eta}{U_e}\left(s + U_e\dfrac{m_\eta}{z_\eta}\right)}{(s^2 - (m_q + z_w)s + (m_q z_w - m_w U_e))}\frac{1}{s} \tag{10.8}$$

Applying the final value theorem, equation (5.33), to equation (10.8), the resultant steady value of incidence may be obtained:

$$\alpha(t)\Big|_{ss} = \frac{m_\eta}{(m_q z_w - m_w U_e)} \tag{10.9}$$

In a similar way the corresponding resultant steady value of normal acceleration may be derived from equation (10.5):

$$a_z(t)\Big|_{ss} = \frac{m_\eta z_w U_e}{(m_q z_w - m_w U_e)} \tag{10.10}$$

Now the normal load factor per unit angle of attack is given by

$$n_\alpha = \frac{n_z(t)}{\alpha(t)}\Bigg|_{ss} \equiv -\frac{1}{g}\frac{a_z(t)}{\alpha(t)}\Bigg|_{ss} \tag{10.11}$$

Thus, substituting equations (10.9) and (10.10) into equation (10.11), the important result is obtained:

$$n_\alpha = -\frac{z_w U_e}{g} \equiv \frac{U_e}{gT_{\theta_2}} \tag{10.12}$$

since, approximately, $T_{\theta_2} = -1/z_w$.

The transfer functions given by equations (10.2) through (10.7) describe the classical longitudinal short term response to elevator and represent the foundation on which most modern ideas of handling qualities are based; see, for example, Gibson (1995). For the classical aeroplane the response characteristics are determined by the aerodynamic properties of the airframe, which are usually linear, bounded, and predictable. It is also clear that the short term dynamics are those of a linear second order system, and aeroplanes which possess similar dynamic behaviour are said to have *second order like* response characteristics. The response properties of all real aeroplanes diverge to some extent from these very simple and rather idealised models. Actual response is coloured by longer term dynamics, non-linear aerodynamic airframe characteristics, and, of course, the influence of a stability augmentation system when fitted. However, whatever the degree of complexity of the aeroplane and its operating conditions, a sound design objective is to achieve second order like dynamic response properties.

EXAMPLE 10.1

The classical second order like response characteristics are most easily seen in simple light aircraft having a limited subsonic flight envelope and flying qualities which are determined entirely by aerodynamic design. Such an aeroplane is the Navion Aircraft Corporation, Navion/H, for which the equations of motion were obtained from Teper (1969). The flight condition corresponds with a cruising speed of 176 ft/s at sea level. The longitudinal reduced order state equation is

$$\begin{bmatrix} \dot{\alpha} \\ \dot{q} \end{bmatrix} = \begin{bmatrix} -0.0115 & 1 \\ -0.0395 & -2.9857 \end{bmatrix} \begin{bmatrix} \alpha \\ q \end{bmatrix} + \begin{bmatrix} -0.1601 \\ -11.0437 \end{bmatrix} \eta \tag{10.13}$$

and the reduced order longitudinal response transfer functions are

$$\frac{\alpha(s)}{\eta(s)} = \frac{-0.1601(s + 71.9844)}{(s^2 + 5.0101s + 12.9988)} \tag{10.14}$$

$$\frac{q(s)}{\eta(s)} = \frac{-11.0437(s + 1.9236)}{(s^2 + 5.0101s + 12.9988)} \quad 1/\mathrm{s} \tag{10.15}$$

$$\frac{\theta(s)}{\eta(s)} = \frac{-11.0437(s + 1.9236)}{s(s^2 + 5.0101s + 12.9988)} \tag{10.16}$$

$$\frac{a_z(s)}{\eta(s)} = \frac{-28.1700(s - 10.1241)(s + 13.1099)}{(s^2 + 5.0101s + 12.9988)} \quad \mathrm{ft/s^2/rad} \tag{10.17}$$

$$\frac{\gamma(s)}{\eta(s)} = \frac{0.1601(s - 10.1241)(s + 13.1099)}{s(s^2 + 5.0101s + 12.9988)} \tag{10.18}$$

The first 5 s of the longitudinal response of the Navion to a 1 degree elevator step input, as defined by equations (10.14) through (10.18), is shown in Fig. 10.1. The response plots in the figure are absolutely typical of the second order like characteristics of a classical aeroplane.

The key parameters defining the general response shapes are

Short-period undamped natural frequency $\omega_s = 3.61$ rad/s
Short-period damping ratio $\zeta_s = 0.7$
Incidence lag $T_{\theta_2} = \dfrac{1}{1.9236} = 0.52$ s

These parameters may be obtained directly from inspection of the appropriate transfer functions given above.

It will be observed that the normal acceleration response transfer functions given by equations (10.5) and (10.17) have different numerators; the same is true for the flight path angle response transfer functions given by equations (10.6) and (10.18). This is due to the fact that the algebraic forms are based on a number of simplifying approximations, whereas the numerical forms were obtained from an exact solution of the state equation (10.8) without approximation. However, with reference to Fig. 10.1, both equation (10.17) and equation (10.18) may be approximated by

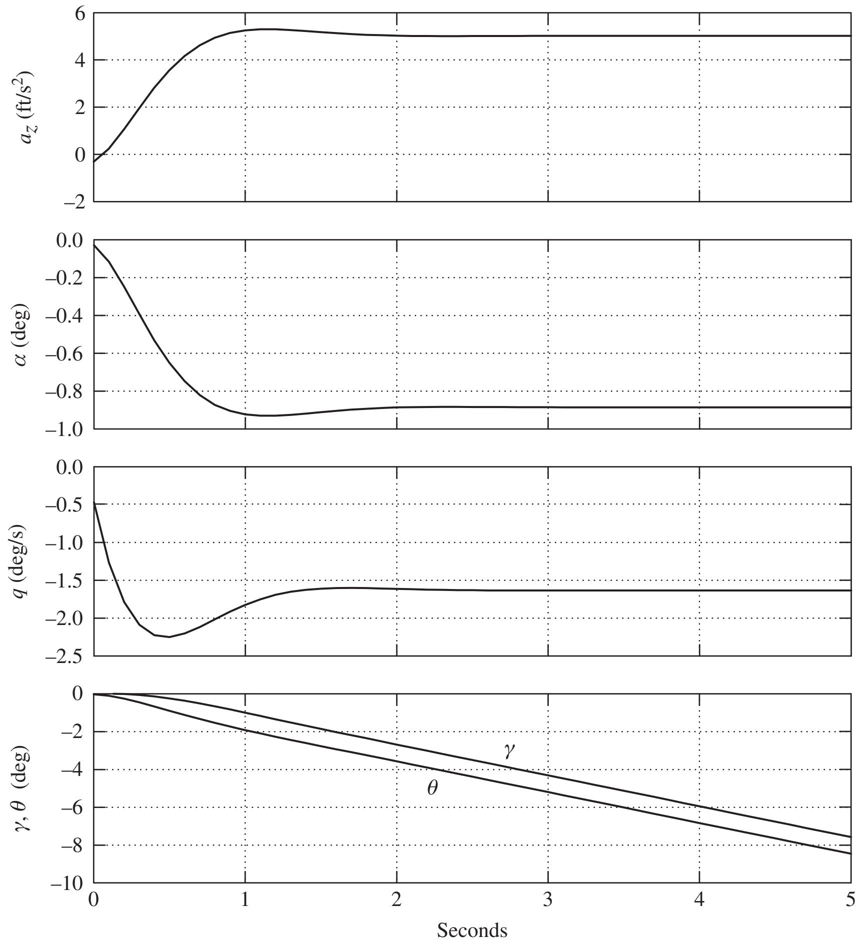

FIGURE 10.1 Longitudinal short term response to elevator step input.

transfer functions having constant numerators in the style of equations (10.5) and (10.6), respectively, and in both cases the response shapes are essentially identical. Equations (10.17) and (10.18) may be approximated by

$$\frac{a_z(s)}{\eta(s)} = \frac{3738.89}{(s^2 + 5.0101s + 12.9988)} \quad \text{ft/s}^2/\text{rad} \tag{10.19}$$

$$\frac{\gamma(s)}{\eta(s)} = \frac{-1.6347}{s(s^2 + 5.0101s + 12.9988)} \tag{10.20}$$

With reference to Fig. 10.1, it is clear that following a steady elevator step input the short term response, after the short-period transient has damped out, results in steady normal acceleration a_z, steady incidence α, and steady pitch rate q. The corresponding pitch attitude θ and flight path angle γ responses increase linearly with time, the aeroplane behaving like a simple integrator in this respect. It is evident from the latter response plots that flight path angle γ lags pitch attitude θ by about 0.5 s (see equation (10.7)), which corresponds very well with the exact value of T_{θ_2}. These response characteristics are quite typical and do not change significantly with flight condition since the Navion has a very limited flight envelope.

Operation of the elevator causes tailplane camber change, which results in instantaneous change in tailplane lift. This in turn generates a pitching moment causing the aeroplane to respond in pitch. Thus, as a result of his control action, the pilot sees a change in pitch attitude as the primary response. Or, for a steady step input, the response is a steady pitch rate, at least for the first few seconds. For this reason, the nature of control is referred to as a *rate command* characteristic, which is typical of all three control axes because the aerodynamic mechanism of control is similar. With reference to Fig. 10.1, the pitch rate response couples with forward speed to produce the incidence response, which in turn results in the normal acceleration response. This explains why a steady pitch rate is accompanied by steady incidence and normal acceleration responses.

In an actual aeroplane these simple relationships are modified by the influence of the longer term phugoid dynamics. In particular, the pitch rate and normal acceleration response tend to decay with the damped phugoid motion. However, incidence tends to remain more nearly constant at its trim value throughout. Thus, viewed more broadly, the nature of longitudinal control is sometimes referred to alternatively as an *incidence command* characteristic. These ideas may be more easily appreciated by referring to Examples 6.1 and 6.2.

Since the traditional longitudinal motion cue has always focused on normal acceleration, and since in the short term approximation this is represented by a transfer function with a constant numerator, equation (10.19), the only parameters defining the response shape are the short-period mode damping ratio and undamped natural frequency. Similarly, it is evident that incidence dynamics are governed by the same parameters. Pitch rate response is similar in shape to both normal acceleration and incidence responses with the exception of the peak overshoot, which is governed by the value of the numerator term $1/T_{\theta_2}$. However, T_{θ_2} is determined largely by the value of the wing lift curve slope which, for a simple aeroplane like the Navion, is essentially constant throughout the flight envelope. So for a classical aeroplane with second order like response characteristics it is concluded that the short term dynamics are predictable and that the transient is governed predominantly by short-period mode dynamics. Thus it is not surprising that the main emphasis in the specification of aeroplane flying qualities has been on the correct design of the damping and frequency of the short term stability modes, in particular the longitudinal short-period mode.

10.2.3 The "thumb print" criterion

For the reasons outlined, the traditional indicators of the short term longitudinal handling qualities of an aeroplane were securely linked to the damping ratio and undamped natural frequency of the short-period mode. As experience grew over the years of evolutionary development of aeroplanes, the short-period dynamics which resulted in good handling characteristics became established fact. A tradition of experimental flight tests using variable stability aeroplanes was established in the early years after the Second World War specifically for investigating flying and handling qualities. In particular, much of this early experimental work was concerned with longitudinal short term handling qualities. This research has enabled the definition of many *handling qualities criteria* and the production of *flying qualities specification* documents. The tradition of experimental flight tests for handling qualities research is still continued today, mainly in the United States.

One of the earliest flying qualities criteria, the so-called longitudinal short-period *thumb print* criterion, became an established tool in the 1950s; see, for example, Chalk (1958). The thumb print criterion provides guidance for aeroplane designers and evaluators concerning the best combinations of longitudinal short-period mode damping and frequency to give good handling qualities. However, it must be remembered that the information provided is empirical and based entirely on pilot opinion. The common form of presentation of the criterion is shown in Fig. 10.2, and the example shown relates to typical classical aeroplanes in which the undamped short-period mode frequency is around 3 rad/s.

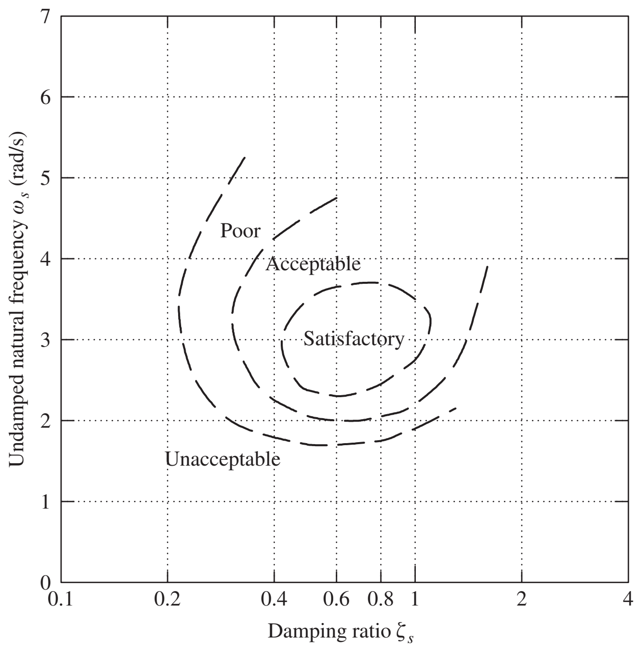

FIGURE 10.2 Longitudinal short-period pilot opinion contours: The thumb print criterion.

Although the criterion is still most applicable to the modern aeroplane, as has been suggested, the achievement of excellent short-period mode dynamics does not necessarily guarantee excellent longitudinal handling qualities. Indeed, many other factors play an important part, and some of these are discussed in the following paragraphs.

10.2.4 Incidence lag

The incidence lag T_{θ_2} is critically important in the determination of the longitudinal handling characteristics of an aeroplane. For classical subsonic aeroplanes, T_{θ_2} remains near constant over the flight envelope and, consequently, the short term pitch dynamics also remain near constant for a given short-period mode damping and frequency. Therefore, the overall longitudinal handling qualities tend to remain nicely consistent over the flight envelope. For this reason incidence lag was not accorded a great deal of attention in the past. However, as aeroplanes have become larger and their operating altitude and Mach number envelopes have been greatly extended, the variation in lift curve slope has become significant. The result of this is that the variation in T_{θ_2} over the flight envelope of typical modern high performance aeroplanes can no longer be ignored. Incidence lag has therefore become as important as short-period mode damping and frequency in the determination of longitudinal short term handling.

Gibson (1995) suggests that, typically, T_{θ_2} may vary from less than 0.5 s at high speed at sea level to greater than 4.0 s at low speed at high altitude. Other significant changes might be introduced by camber control or by direct lift control, as frequently found in advanced modern aircraft of all types. To illustrate the effect of incidence lag on short term pitch response, consider the following transfer functions, which are based nominally on those of Example 10.1:

$$\begin{aligned}\frac{q(s)}{\eta(s)} &= \frac{-13(1+0.5s)}{(s^2+5s+13)} \quad 1/\mathrm{s}\\ \frac{\theta(s)}{\eta(s)} &= \frac{-13(1+0.5s)}{s(s^2+5s+13)}\end{aligned} \tag{10.21}$$

and, clearly, $\omega_s = 3.6$ rad/s, $\zeta_s = 0.69$, and $T_{\theta_2} = 0.5$ s.

The response to a stick pull, equivalent to a 1 degree elevator step input, is shown in Fig. 10.3. Also shown are the responses for an incidence lag of 1, 2, and 4 seconds, the short-period mode parameters being held constant throughout. In accordance with the models given by equations (10.2), (10.5), and (10.6), the corresponding incidence, normal acceleration, and flight path angle responses remain unchanged. However, the pitch motion cue to the pilot may well suggest a reduction in damping in view of the significant increase in pitch rate overshoot at larger values of T_{θ_2}. This is of course not the case since the short-period mode damping ratio is 0.69 throughout. The pilot also becomes aware of the increase in lag between the pitch attitude response and acquisition of the desired flight path.

10.3 Flying qualities requirements

Most countries involved in aviation have national agencies to oversee aeronautical activity in their territories. In the United Kingdom the Civil Aviation Authority (CAA) regulates all non-military

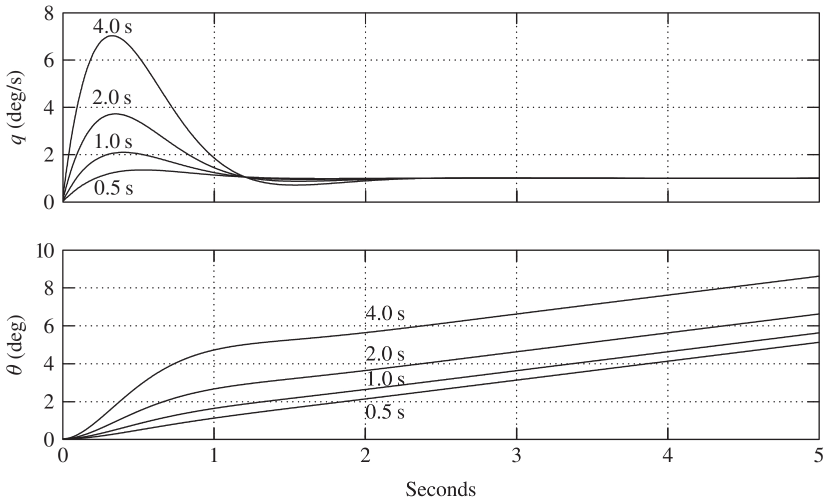

FIGURE 10.3 Effect of variation in incidence lag on pitch response.

aviation and the Ministry of Defence (MoD) oversees all military aeronautical activity. Additionally, a group of European countries have agreed to cooperate in the development of Joint Aviation Requirements (JARs) and, where relevant, these requirements supersede the British Civil Airworthiness Requirements (BCARs). The Joint Aviation Authority which administers this activity comprises the aviation authorities from the participating countries. Thus, for example, in the United Kingdom the JAR documents are issued by the CAA. In the United States the corresponding agencies are the Federal Aviation Administration (FAA) and the Department of Defense (DoD), respectively. All of these agencies issue extensive documentation specifying the minimum acceptable standards for construction, performance, operation, and safety of all air vehicles operated under their jurisdiction. In more recent years the emphasis has been on the adoption of common standards, for obvious reasons. In the absence of their own standards, many countries adopt those of the American, British, or joint European agencies, which is obviously constructive in achieving very high standards of aviation safety worldwide.

All of the above mentioned agencies issue documents which specify the minimum acceptable standard of flying qualities in some detail, more commonly known as *flying qualities requirements*. Some of the relevant documents are listed in the references at the end of this chapter. In very general terms, the flying qualities requirements for civil aircraft issued by the CAA and FAA are primarily concerned with safety; specific requirements relating to stability, control, and handling are relatively relaxed. On the other hand, the flying qualities requirements issued by the MoD and DoD are specified in much greater detail in every respect. It is the responsibility of the aircraft manufacturer, or supplier, to demonstrate that its aircraft *complies* with the appropriate specification prior to acceptance by the operator. Thus *demonstration of compliance* with the specification is the principal interest of the regulating agencies.

Since the military flying qualities requirements in particular are relatively complex, their correct interpretation may not always be obvious. To alleviate this difficulty the documents also include advisory information on *acceptable means of compliance* to help the manufacturer or supplier apply the requirements to his particular aeroplane. The extensive programme of flight tests which most new aeroplanes undergo prior to service are, in part, used to demonstrate compliance with the flying qualities requirements. However, it is unlikely that an aeroplane will satisfy the requirements completely unless it has been designed to do so from the outset. Therefore, the flying qualities requirements documents are also vitally important to the aircraft designer and to the flight control system designer. In this context, the specifications define the *rules* by which stability, control and handling must be designed and evaluated.

The formal specification of flying and handling qualities is intended to assure flying qualities that provide adequate mission performance and flight safety. Since the most comprehensive, and hence demanding, requirements are included in the military documents, it is these on which the material in the following paragraphs is based. As the military use all kinds of aeroplanes, including small light trainers, large transports, and high performance combat aircraft, flying qualities requirements applicable to all types are quantified in the specification documents. Further, an aeroplane designed to meet military flying and handling qualities requirements undoubtedly also meets civil requirements. Since most of the requirements are quantified in terms of stability and control parameters, they are most readily applied in the current analytical context

The object here is to provide an overview of the flying qualities requirements as set out in the military specification documents. Liberal reference has been made to the British Defence Standard DEF-STAN 00-970 and to the American Military Specification MIL-F-8785C, which are very similar in style and convey much the same information. This is not surprising since the former was deliberately modelled on the latter in the interests of uniformity. Using an amalgam of material from both sources, no attempt is made to reproduce the requirements with great accuracy or in great detail (for a complete appreciation the reader should consult the references). Rather, the emphasis is on a limited review of the material relevant to the fundamental stability and control properties of the aeroplane as described in earlier chapters.

It is important to appreciate that the requirements in both DEF-STAN 00-970 and MIL-F-8785C are based on the dynamics of classical aeroplanes whose short term response is essentially second order like. This is simply due to the fact that the requirements are empirical and have evolved to capitalise on many years of accumulated experience and pilot opinion. Although attempts have been made to revise the requirements to allow for aeroplanes with stability augmentation, this has had only limited success. Aeroplanes with simple stability augmentation which behave essentially like classical unaugmented aeroplanes are generally adequately dealt with. However, in recent years it has become increasingly obvious that the requirements in both DEF-STAN 00-970 and MIL-F-8785C are unable to cope with aeroplanes whose flying qualities are substantially dependent on a flight control system. For example, there is evidence that some advanced technology aeroplanes have been designed to meet the flying qualities requirements very well, only to attract adverse pilot opinion concerning their handling qualities. With the advent of the fly-by-wire (FBW) aeroplane, it became necessary to seek additional or alternative methods for quantifying and specifying flying qualities requirements.

The obvious deficiencies of the earlier flying qualities requirements for dealing with highly augmented aeroplanes spawned considerable research activity from the late 1960s onward. As a result, all kinds of criteria have emerged, a few of which have enjoyed enduring, but limited, success. Nevertheless, understanding has improved considerably, and the first serious attempt at producing a flying qualities requirements document suitable for application to highly augmented aeroplanes resulted in the proposal reported by Hoh et al. (1982). This report eventually evolved into the formal American Military Standard MIL-STD-1797A. However, the report by Hoh et al. (1982) is a useful alternative to the Military Standard since it contains some supporting explanatory material. These newer flying qualities requirements still include much of the classical material derived from the earlier specifications, but with the addition of material relating to the influence of command and stability augmentation systems on aircraft handling qualities. Although Hoh et al. (1982) and MIL-STD-1797A provide a very useful progression from DEF-STAN 00-970 and MIL-F-8785C, the material relating to highly augmented aeroplanes takes the subject well beyond the scope of the present book. The interested reader will find an excellent overview of the ideas relating to the handling qualities of advanced technology aeroplanes in Gibson (1995).

10.4 Aircraft role

It is essential that the characteristics of any dynamic system which is subject to direct human control are bounded. Outside these bounds the system would not be capable of human control. However, the human is particularly adaptable such that the variation in acceptable dynamic characteristics within the performance boundary of the system is considerable. In terms of aeroplane dynamics, this means that wide variation in stability and control characteristics can be tolerated within the bounds of acceptable flying qualities. However, it is important that the flying qualities be appropriate to the type of aeroplane in question and to the task the aeroplane is carrying out. For example, the dynamic handling qualities appropriate to a fighter aircraft in an air combat situation are quite inappropriate to a large civil transport aircraft on final approach. Thus it is easy to appreciate that the stability and control characteristics which comprise flying qualities requirements are bounded by the limitations of the human pilot; within those bounds, however, the characteristics are defined in a way which is most appropriate to the prevailing flight condition.

Thus flying qualities requirements are formulated to allow for the type, or *class*, of aeroplane and for the flight task, or *flight phase*, in question. Further, the degree of excellence of flying qualities is described as the *level of flying qualities*. Thus prior to referring to the appropriate flying qualities requirements the aeroplane must be classified and its flight phase defined. A designer would then design to achieve the highest level of flying qualities whereas, an evaluator would seek to establish that the aeroplane achieved the highest level of flying qualities in all normal operating states.

10.4.1 Aircraft classification

Aeroplane types are classified broadly according to size and weight as follows:

Class I: small, light
Class II: medium weight, low to medium manoeuvrability
Class III: large, heavy, low to medium manoeuvrability
Class IV: high manoeuvrability

10.4.2 Flight phase

A sortie or mission may be completely defined as a sequence of piloting tasks. Alternatively, a mission may be described as a succession of flight phases. Flight phases are grouped into three *categories*, and each category comprises a variety of tasks requiring similar flying qualities for successful execution. The tasks are separately defined in terms of *flight envelopes*. The flight phase categories are defined as follows:

Category A: non-terminal flight phases that require rapid manoeuvring, precision tracking, or precise flight path control
Category B: non-terminal flight phases that require gradual manoeuvring, less precise tracking, and accurate flight path control
Category C: terminal flight phases that require gradual manoeuvring and precision flight path control

10.4.3 Levels of flying qualities

The levels of flying qualities quantify the degree of acceptability of an aeroplane in terms of its ability to complete the mission for which it is designed. The three levels of flying qualities seek to indicate the severity of the *pilot workload* in the execution of a mission flight phase and are defined as follows:

Level 1: flying qualities clearly adequate for the mission flight phase
Level 2: flying qualities adequate to accomplish the mission flight phase but with an increase in pilot workload and/or degradation in mission effectiveness
Level 3: degraded flying qualities but such that the aeroplane can be controlled, inadequate mission effectiveness, and high, or limiting, pilot workload

Level 1 flying qualities imply a fully functional aeroplane which is 100% capable of achieving its mission with acceptable pilot workload at all times. It follows, then, that any fault or failure occurring in airframe, engines, or systems may well degrade the level of flying qualities. Consequently, the *probability* of such a situation arising during a mission becomes an important issue. This means that the levels of flying qualities are very much dependent on the *aircraft failure state*, which in turn is dependent on the reliability of the critical functional components of the aeroplane. The development of this aspect of flying qualities assessment is a subject in its own right and is beyond the scope of the present book.

10.4.4 Flight envelopes

The operating boundaries of altitude, Mach number, and normal load factor define the *flight envelope* for an aeroplane. Flight envelopes describe the absolute "never exceed" limits of the airframe and define the operating limits required for a particular mission or flight phase.

Permissible flight envelope

The permissable flight envelope describes the limiting flight condition boundaries within which an aeroplane may be flown and safely recovered without exceptional pilot skill.

Table 10.1 Operational Flight Envelopes

Flight Phase Category	Flight Phase
A	Air-to-air combat Ground attack Weapon delivery/launch Reconnaissance In-flight refuel (receiver) Terrain following Maritime search Aerobatics Close formation flying
B	Climb Cruise Loiter In-flight refuel (tanker) Descent Aerial delivery
C	Take-off Approach Overshoot Landing

Service flight envelope

The service flight envelope defines the boundaries of altitude, Mach number, and normal load factor pertaining to all operational mission requirements. It denotes the limits to which an aeroplane may normally be flown without risk of exceeding those limits.

Operational flight envelope

The operational flight envelope lies within the service flight envelope and defines the boundaries of altitude, Mach number, and normal load factor for each flight phase. It is a requirement that the aeroplane be capable of operation up to those boundaries. The operational flight envelopes defined in DEF-STAN 00-970 are listed in Table 10.1.

When assessing the flying qualities of an aeroplane, Table 10.1 may be used to determine which flight phase category is appropriate for the flight condition in question.

EXAMPLE 10.2

To illustrate the altitude–Mach number flight envelope, consider the McDonnell-Douglas A4-D Skyhawk and its possible deployment in a *ground attack* role. The service flight envelope for the

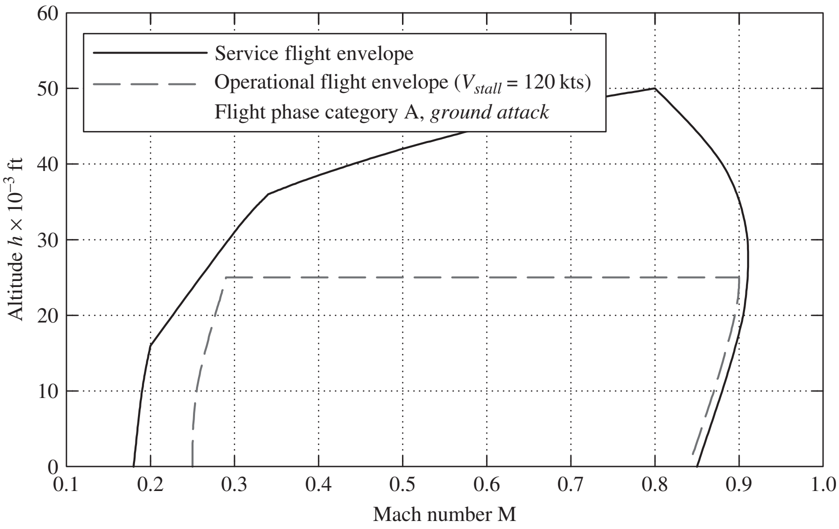

FIGURE 10.4 Flight envelopes for the McDonnell-Douglas A4-D Skyhawk.

aircraft was obtained from Teper (1969) and is shown in Fig. 10.4. Assuming that this aircraft is to be procured by the Royal Air Force, it must meet the operational flight envelope requirement for the ground attack role as defined in DEF-STAN 00-970. The altitude-speed requirements for this role are given as follows:

Minimum operational speed: $V_{0_{\min}} = 1.4V_{stall}$
Maximum operational speed: $V_{0_{\max}} = V_{MAT}$
Minimum operational altitude: $h_{0_{\min}}$ = Mean sea level (MSL)
Maximum operational altitude: $h_{0_{\max}} = 25000\text{ft}$

where V_{MAT} is the maximum speed at *maximum augmented thrust* in level flight. The operational flight envelope for the ground attack role is superimposed on the service flight envelope for the aircraft as shown in Fig. 10.4; the implications of these limits are self-evident for the role in question.

EXAMPLE 10.3

To illustrate the normal load factor–speed flight envelope, consider the Morane Saulnier MS-760 Paris aircraft as registered by the CAA for operation in the United Kingdom. The Paris is a small four seat twin jet fast liaison aircraft which first flew in the late 1950s. It is a classical "aerodynamic" aircraft, with an unswept wing and a T-tail, and is typical of the small jet

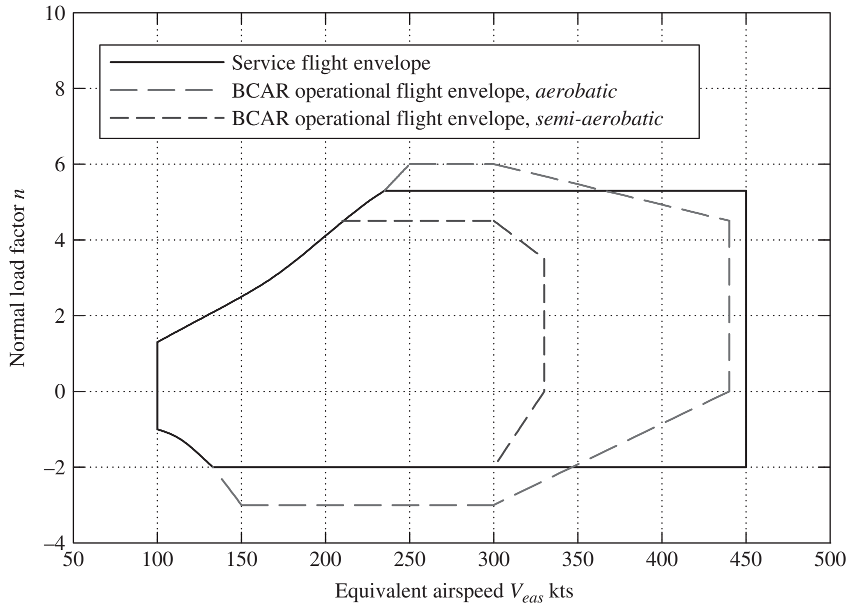

FIGURE 10.5 Flight envelopes for the Morane-Saulnier MS-760 Paris.

trainers of the period. The manoeuvring flight envelopes for this aircraft were obtained from "Notes for Technical Observers" (College of Aeronautics, 1965) and are reproduced in Fig. 10.5. Clearly the service flight envelope fully embraces the BCAR operational flight envelope for *semi-aerobatic* aircraft, whereas some parts of the BCAR operational flight envelope for *fully aerobatic* aircraft are excluded. Consequently, the aircraft is registered in the semi-aerobatic category and certain aerobatic manoeuvres are prohibited. It is clear from Fig. 10.5 that the Paris was designed with structural normal load factor limits of $+5.2g$, $-2g$ which are inadequate for fully aerobatic manoeuvring.

10.5 Pilot opinion rating

Pilot opinion rating scales have been in use for a considerable time and provide a formal procedure for the qualitative assessment of aircraft flying qualities by experimental means. Since qualitative assessment is very subjective, the development of a formal method for the interpretation of pilot opinion has turned a rather "imprecise art" into a useful tool which is routinely used in flight test programmes. The current pilot opinion rating scale was developed by Cooper and Harper (1969) and is universally known as the *Cooper-Harper rating scale*.

Table 10.2 The Cooper-Harper Handling Qualities Rating Scale

Adequacy for Selected Task	Aircraft Characteristic	Demands on Pilot (workload)	Pilot Rating
Satisfactory	Excellent	Very low	1
Satisfactory	Good	Low	2
Satisfactory	Fair	Minimal pilot compensation required	3
Unsatisfactory—warrants improvements	Minor deficiencies	Moderate pilot compensation required	4
Unsatisfactory—warrants improvements	Moderate deficiencies	Considerable pilot compensation required	5
Unsatisfactory—warrants improvements	Tolerable deficiencies	Extensive pilot compensation required	6
Unacceptable—requires improvements	Major deficiencies	Adequate performance not attainable	7
Unacceptable—requires improvements	Major deficiencies	Considerable pilot compensation required for control	8
Unacceptable—requires improvements	Major deficiencies	Intense pilot compensation required for control	9
Catastrophic—improvement mandatory	Major deficiencies	Loss of control likely	10

Table 10.3 Equivalence of Cooper-Harper Rating Scale with Levels of Flying Qualities

Level of Flying Qualities	Level 1	Level 2	Level 3	Below Level 3
Cooper-Harper rating scale	1 2 3	4 5 6	7 8 9	10

The Cooper-Harper rating scale is used to assess the flying qualities or, more specifically, the handling qualities of an aeroplane in a given flight phase. The procedure for conducting the flight test evaluation and the method for post-flight reduction and interpretation of pilot comments are defined. The result of the assessment is a *pilot rating* between 1 and 10. A rating of 1 suggests excellent handling qualities and low pilot workload, whereas a rating of 10 suggests an aircraft with many handling deficiencies. The adoption of a common procedure for rating handling qualities enables pilots to clearly state their assessment without ambiguity or the use of misleading terminology. A summary of the Cooper-Harper handling qualities rating scale is shown in Table 10.2.

It is usual and convenient to define an equivalence between the qualitative Cooper-Harper rating scale and quantitative Level of flying qualities. This permits easy and meaningful interpretation of flying qualities between the piloting and analytical domains. The equivalence is summarised in Table 10.3.

10.6 Longitudinal flying qualities requirements

10.6.1 Longitudinal static stability

It was shown in Chapter 3 that longitudinal static stability determines pitch control displacement and force to trim. Clearly this must be of the correct magnitude if effective control of the aeroplane is to be maintained at all flight conditions. For this to be so, the controls-fixed and controls-free static margins must not be too large or too small.

In piloting terms, a change of trim is seen as a change in airspeed, or Mach number, and involves a forward stick push to increase speed and an aft stick pull to decrease speed when the aeroplane possesses a normal level of static stability. The requirement states that variation in pitch control position and force with speed is to be smooth and the gradients at the nominal trim speed are to be stable or, at worst, neutrally stable. In other words, the static margins are to be greater than or equal to zero. The maximum acceptable degree of static stability is not specified, but it is limited by the available control power and the need to be able to lift the nose wheel at rotation for take-off at a reasonable airspeed. Abrupt changes in gradient with airspeed are not acceptable. Typical stable gradients are shown in Fig. 10.6, where it is indicated that the control characteristics do not have to be linear but changes in gradient must be smooth. The minimum acceptable control characteristics obviously correspond with neutral static stability.

In the transonic flight regime in particular, the static stability margins can change significantly such that the aeroplane may become unstable for some part of its speed envelope. The requirements recognise such conditions and permit mildly unstable pitch control force gradients in transonic flight provided that the flight condition is transitory. Maximum allowable unstable gradients are quantified, and a typical boundary is indicated in Fig. 10.6. Aeroplanes which may be required to

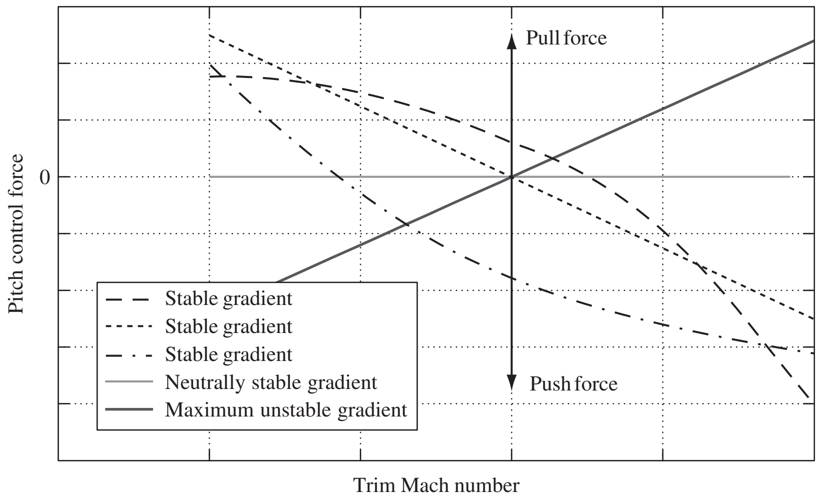

FIGURE 10.6 Typical pitch control force gradients.

operate for prolonged periods in transonic flight conditions are not permitted to have unstable control force gradients.

10.6.2 Longitudinal dynamic stability

Short-period pitching oscillation

For the reasons explained in Section 10.2, the very important normal acceleration motion cue and the short-period dynamics are totally interdependent. The controls-fixed manoeuvre margin H_m and the short-period frequency ω_s are also interdependent, as explained in Chapter 8 (Section 8.5). The requirements for short-period mode frequency reflect these relationships and are relatively complex. A typical illustration is shown in Fig. 10.7.

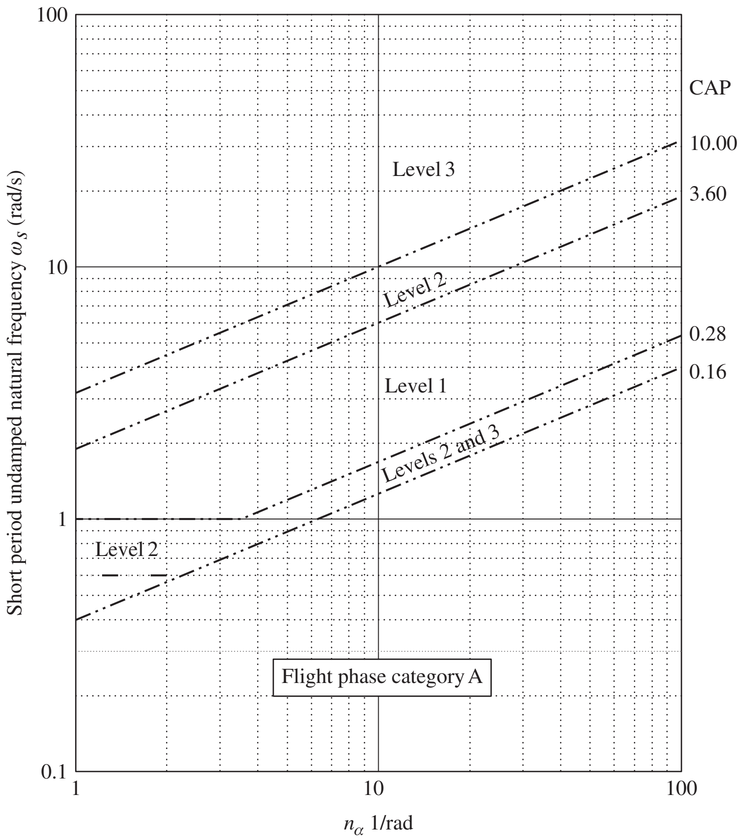

FIGURE 10.7 Typical short-period mode frequency requirements.

Three similar charts are given, one for each flight phase category, That for category A is presented in Fig. 10.7. The boundaries shown are equivalent to lines of constant *control anticipation parameter* (CAP), which is proportional to the controls-fixed manoeuvre margin. The boundaries therefore implicitly specify the constraint on manoeuvrability, quantified in terms of short-period mode undamped natural frequency. The meaning of CAP is explained in Section 10.7.

Now, the derivative parameter n_α quantifies the normal load factor per unit angle of attack, or incidence, as defined by equation (10.11). As its value increases with speed, the lower values of n_α correlate with the lower speed characteristics of the aeroplane and vice versa. As speed increases the aerodynamic pitch stiffness of the aeroplane also increases, which in turn results in an increase in short-period mode frequency. This natural phenomenon is reflected in the requirements, as the boundaries allow for increasing frequency with increasing n_α.

Acceptable limits on the stability of the short-period mode are quantified in terms of maximum and minimum values of the damping ratio as a function of flight phase category and Level of flying qualities, as set out in Table 10.4.

The maximum values of short-period mode damping ratio obviously imply that a stable nonoscillatory mode is acceptable.

Table 10.4 Short-Period Mode Damping

Flight Phase	**Level 1**		**Level 2**		**Level 3**
	ζ_s ***min***	ζ_s ***max***	ζ_s ***min***	ζ_s ***max***	ζ_s ***min***
CAT A	0.35	1.30	0.25	2.00	0.10
CAT B	0.30	2.00	0.20	2.00	0.10
CAT C	0.50	1.30	0.35	2.00	0.25

Phugoid

Upper and lower values for phugoid frequency are not quantified. However, it is recommended that the phugoid and short-period mode frequencies be well separated. Also, it is suggested that handling difficulties may become obtrusive if the frequency ratio of the modes $\omega_p/\omega_s \leq 0.1$. Generally the phugoid dynamics are acceptable provided the mode is stable and damping ratio limits are quantified as shown in Table 10.5.

Table 10.5 Phugoid Damping Ratio

Level of Flying Qualities	**Minimum** ζ_p
1	0.04
2	0
3	Unstable, period $T_p > 55$ s

10.6.3 Longitudinal manoeuvrability

The requirements for longitudinal manoeuvrability are largely concerned with manoeuvring control force, or *stick force per g*. It is important that the value of this control characteristic is not too large or too small. In other words, the controls-free manoeuvre margin must be constrained to an acceptable and appropriate range. If the control force is too *light*, there is a danger that the pilot may inadvertently apply too much normal acceleration to the aircraft with the consequent possibility of structural failure. On the other hand, if the control force is too *heavy*, the pilot may not be strong enough to fully utilise the manoeuvring flight envelope of the aircraft.

Thus the requirements define the permitted upper and lower limits for controls-free manoeuvre margin expressed in terms of the pitch control manoeuvring force gradient because this is the quantifiable parameter seen by the pilot. Further, the limits are functions of the type of control inceptor, a single stick or wheel type, and the limiting normal load factor appropriate to the airframe in question. The rather complex requirements are tabulated, and their interpretation for an aircraft with a single stick controller and a limiting normal load factor of $n_L = 7.0$ is shown in Fig. 10.8. Again, the limits on stick force per g are expressed as a function of the flight condition parameter n_α.

10.7 Control anticipation parameter

It has been reported by Bihrle (1966) that, *in order to make precise adjustments to the flight path, the pilot must be able to anticipate the ultimate response of the airplane, and that angular pitching acceleration is used for this purpose*. Aeroplanes which have good second order like short term longitudinal response properties generally provide the pilot with good anticipatory handling cues. Clearly, this depends on the damping and frequency of the short-period pitching mode in particular. However, Bihrle (1966) reports pilot observation that, *for airplanes having high inertia or low static stability, the angular pitching acceleration accompanying small adjustments to flight path may fall below the threshold of perception*. In other words, the anticipatory nature of the response cues may become insignificant, thereby giving rise to poor handling qualities. To deal with such cases Birhle defines a quantifiable measure of the anticipatory nature of the response which he calls *control anticipation parameter* (CAP). The formal definition of CAP is, *the amount of instantaneous angular pitching acceleration per unit of steady-state normal acceleration*.

The steady normal acceleration response to a pitch control input is determined by the aerodynamic properties of the aeroplane, the wing and tailplane in particular. However, the transient peak magnitude of angular pitching acceleration immediately following the control input is largely determined by the short-period dynamics, which in turn are dependent on the longitudinal static stability and moment of inertia in pitch. Thus CAP effectively quantifies acceptable short-period mode characteristics appropriate to the aerodynamic properties and operating condition of the aeroplane.

A simple expression for CAP is easily derived from the longitudinal short-term transfer functions described in Section 10.2.2.

The angular pitch acceleration transfer function is obtained from equation (10.3):

$$\frac{\dot{q}(s)}{\eta(s)} = \frac{m_\eta s(s - z_w)}{(s^2 - (m_q + z_w)s + (m_q z_w - m_w U_e))} \tag{10.22}$$

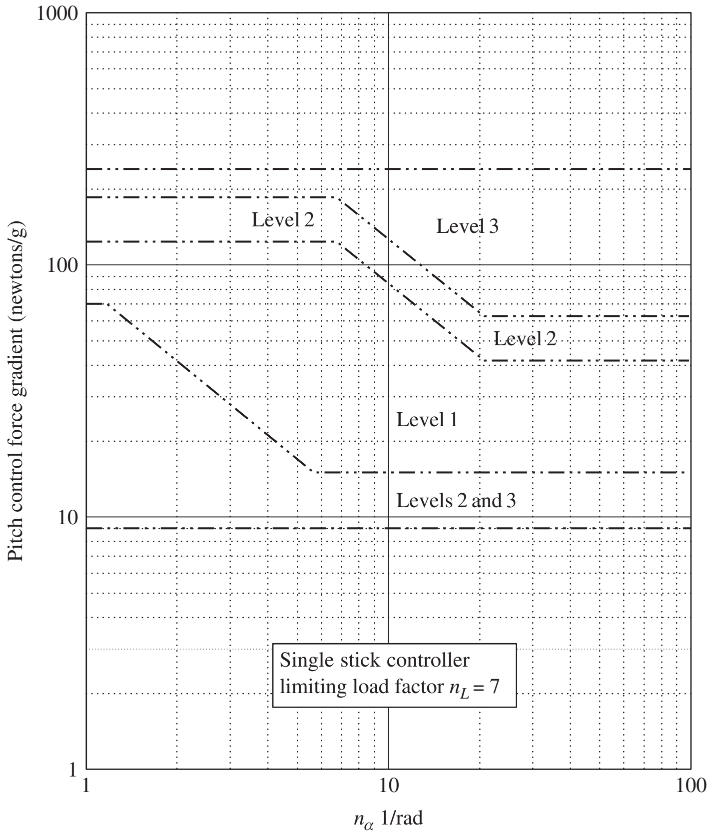

FIGURE 10.8 Typical pitch control manoeuvring force gradients.

The initial pitch acceleration may be derived by assuming a unit elevator step input and applying the initial value theorem, equation (5.34), to equation (10.22). Whence

$$\dot{q}(0) = \lim_{s \to \infty} \left(s \frac{m_\eta s(s - z_w)}{(s^2 - (m_q + z_w)s + (m_q z_w - m_w U_e))} \frac{1}{s} \right) = m_\eta \tag{10.23}$$

Similarly, the steady-state normal acceleration may be derived by assuming a unit elevator input and applying the final value theorem, equation (5.33), to equation (10.5). Whence

$$a_z(\infty) = \lim_{s \to 0} \left(s \frac{m_\eta z_w U_e}{(s^2 - 2\zeta_s \omega_s s + \omega_s^2)} \frac{1}{s} \right) = \frac{m_\eta z_w U_e}{\omega_s^2} \tag{10.24}$$

The dimensionless normal acceleration, or load factor, is given by

$$n_z(\infty) = -\frac{a_z(\infty)}{g} = -\frac{m_\eta z_w U_e}{g\omega_s^2} \tag{10.25}$$

and CAP is given by

$$\mathrm{CAP} = \frac{\dot{q}(0)}{n_z(\infty)} = -\frac{g\omega_s^2}{z_w U_e} = \frac{g\omega_s^2 T_{\theta_2}}{U_e} \tag{10.26}$$

since, approximately, $T_{\theta_2} = -1/z_w$.

With reference to equation (10.12), an alternative and more commonly used expression for CAP follows:

$$\mathrm{CAP} = \frac{\omega_s^2}{n_\alpha} \tag{10.27}$$

This is the boundary parameter shown in Fig. 10.7.

Now, equation (8.62) states that

$$\omega_s^2 = \frac{1/2\rho V_0^2 S\bar{\bar{c}}a}{I_y} H_m \tag{10.28}$$

With reference to Appendix 2, it may be shown that

$$z_w \cong \frac{\mathring{Z}_w}{m} = \frac{1/2\rho V_0 S Z_w}{m} \tag{10.29}$$

assuming, as is usually the case, that $\mathring{Z}_w << m$. With reference to Appendix 8, it may be determined that

$$Z_w \cong -\frac{\partial C_L}{\partial \alpha} \equiv -a \tag{10.30}$$

which is the lift curve slope.

Thus, substituting equations (10.28), (10.29), and (10.30) into equation (10.26), the expression for CAP reduces to the important result,

$$\mathrm{CAP} = \frac{mg\bar{\bar{c}}}{I_y} H_m = \frac{g\bar{\bar{c}}}{k^2} H_m \tag{10.31}$$

where k denotes the *longitudinal radius of gyration*. Since aircraft axes are assumed to be wind axes throughout, $U_e \equiv V_0$. Thus it is shown that CAP is directly proportional to the controls-fixed manoeuvre margin H_m and that the constant of proportionality is dependent on aircraft geometry and mass distribution.

10.8 Lateral-directional flying qualities requirements

10.8.1 Steady lateral-directional control

Unlike the longitudinal flying qualities requirements the lateral–directional requirements do not address static stability in quite the same way. In general, lateral-directional static stability is independent of cg position and flight condition and, once set by the aerodynamic design of the aeroplane, does not change significantly. The main concerns centre on adequate control power for maintaining control in steady asymmetric flight conditions or in otherwise potentially limiting conditions in symmetric flight. Further, it is essential that the control forces required to cope with such conditions not exceed the physical capabilities of the average pilot.

General normal lateral-directional control requirements specify limits for the roll stick and rudder pedal forces, and require that the force gradients have the correct sense and do not exceed prescribed limits. The control requirement for trim is addressed, as is the requirement for roll-yaw control coupling, which must be correctly harmonised. In particular, it is important that the pilot can fly properly coordinated turns with similar and acceptable degrees of effort in control of both roll and yaw.

The lateral-directional requirements relating to asymmetric, or otherwise potentially difficult control conditions, are concerned with steady sideslip, flight in crosswind, steep dives, and engine out conditions resulting in asymmetric thrust. For each condition the requirements specify the maximum permissible roll and yaw control forces necessary to maintain controlled flight up to relatively severe adverse levels. Since the specified conditions interrelate and have to take into account aircraft class, flight phase, and level of flying qualities, many tables of quantitative limits are needed to embrace all eventualities. Thus, the flying qualities requirements relating to steady lateral-directional flight are comprehensive and of necessity substantial.

10.8.2 Lateral-directional dynamic stability

Roll subsidence mode

Since the roll subsidence mode describes short term lateral dynamics, it is critical in the determination of lateral handling qualities. For this reason the limiting acceptable values of its time constant are specified precisely as listed in Table 10.6.

There seems to be no common agreement as to a suitable maximum value of the time constant for Level 3 flying qualities. It is suggested in DEF-STAN 00-970 that a suitable value is in the range 6 s $< T_r <$ 8 s, whereas MIL-F-8785C quotes a value of 10 s.

Table 10.6 Roll Subsidence Mode Time Constant

Aircraft Class	Flight Phase Category	Maximum Value of T_r (s)		
		Level 1	Level 2	Level 3
I, IV	A, C	1.0	1.4	-
II, III	A, C	1.4	3.0	-
I, II, III, IV	B	1.4	3.0	-

Spiral mode

A stable spiral mode is acceptable irrespective of its time constant. However, since its time constant is dependent on lateral static stability (dihedral effect), the maximum level of stability is determined by the maximum acceptable roll control force. Because the mode gives rise to very slow dynamic behavior, it is not too critical to handling unless it is very unstable. For this reason, minimum acceptable degrees of instability are quantified in terms of time to double bank angle T_2 in an uncontrolled departure from straight and level flight. The limiting values are shown in Table 10.7.

For analytical work it is sometimes more convenient to express the spiral mode requirement in terms of time constant T_s rather than time to double bank angle. If it is assumed that the unstable mode characteristic gives rise to a purely exponential divergence in roll, it is easily shown that the time constant and the time to double bank angle are related by the following expression:

$$T_s = \frac{T_2}{\log_e 2} \tag{10.32}$$

Thus, the requirement may be alternatively quantified as listed in Table 10.8.

Table 10.7 Spiral Mode Time to Double Bank Angle

Flight Phase Category	Minimum Value of T_2 (s)		
	Level 1	**Level 2**	**Level 3**
A, C	12	8	5
B	20	8	5

Table 10.8 Spiral Mode Time Constant

Flight Phase Category	Minimum Value of T_s (s)		
	Level 1	**Level 2**	**Level 3**
A, C	17.3	11.5	7.2
B	28.9	11.5	7.2

Dutch roll mode

Since the dutch roll is a short-period mode, it has an important influence on lateral-directional handling and, as a consequence, its damping and frequency requirements are specified in some detail. This mode is approximately the lateral-directional equivalent of the longitudinal short-period mode and has frequency of the same order because pitch and yaw inertias are usually similar in magnitude. However, yaw damping is frequently low as a result of the design conflict with the need to constrain spiral mode instability with dihedral. Although the longitudinal short-period mode and the dutch roll mode are similar in bandwidth, the latter is not as critical to handling. In fact, a poorly damped dutch roll is seen more as a handling irritation than a serious problem.

The acceptable minima for damping ratio, undamped natural frequency, and damping ratio-frequency product are specified for various combinations of aircraft class and flight phase category in Table 10.9.

Table 10.9 Dutch Roll Frequency and Damping

Aircraft Class	Flight Phase	Minimum Values							
		Level 1			Level 2			Level 3	
		ζ_d	$\zeta_d\omega_d$	ω_d	ζ_d	$\zeta_d\omega_d$	ω_d	ζ_d	ω_d
I, IV	Cat. A	0.19	0.35	1.0	0.02	0.05	0.5	0	0.4
II, III	Cat. A	0.19	0.35	0.5	0.02	0.05	0.5	0	0.4
All	Cat. B	0.08	0.15	0.5	0.02	0.05	0.5	0	0.4
I, IV	Cat. C	0.08	0.15	1.0	0.02	0.05	0.5	0	0.4
II, III	Cat. C	0.08	0.10	0.5	0.02	0.05	0.5	0	0.4

10.8.3 Lateral-directional manoeuvrability and response

The lateral-directional manoeuvrability requirements are largely concerned with limiting roll oscillations, sideslip excursions, and roll and yaw control forces to acceptable levels during rolling and turning manoeuvres.

Oscillation in roll response to controls occurs whenever the dutch roll is intrusive and poorly damped. For this reason, limiting the magnitude and characteristics of oscillation in roll effectively imposes additional constraints on the dutch roll mode when it is intrusive. Oscillation is also possible in cases when the roll and spiral modes couple to form a second pair of complex roots in the lateral-directional characteristic equation. However, the influence of this characteristic on handling is not well understood, and it is recommended that the condition be avoided.

Sideslip excursions during lateral-directional manoeuvring are normal and expected, especially in entry and exit to turning manoeuvres. It is required that the rudder control displacement and force increase approximately linearly with an increase in sideslip response for sideslip of modest magnitude. It is also required that the effect of dihedral is not too great; otherwise, excessive roll control displacement and force may be needed to manoeuvre. Remember that too much stability can be as hazardous as too little! It seems that the main emphasis is on acceptable levels of roll and yaw control displacement, with particular concern for entry and exit to turning manoeuvres, which after all represent lateral-directional manoeuvring flight.

10.9 Flying qualities requirements on the *s*-plane

In Chapter 9, the mapping of the roots of the characteristic equation onto the *s*-plane was illustrated to facilitate graphical interpretation of aircraft stability. By superimposing boundaries defined by the appropriate flying qualities requirements onto the same *s*-plane plots, the stability characteristics of an aeroplane may be assessed directly with respect to those requirements. This graphical approach is particularly useful for analysis and design and is employed extensively in flight control system design.

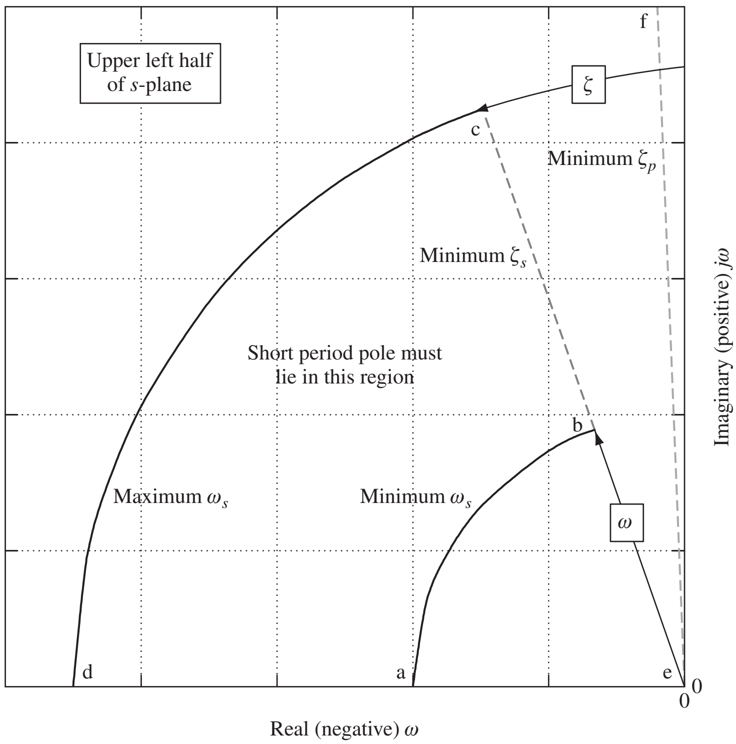

FIGURE 10.9 Longitudinal flying qualities requirements on the *s*-plane.

10.9.1 Longitudinal modes

Typical boundaries describing the limits on longitudinal mode frequency and damping on the s-plane are shown in Fig. 10.9. It is not usually necessary to show more than the upper left half of the s-plane since stable characteristics are of primary interest and the lower half is simply the mirror image of the upper half reflected in the real axis.

The upper and lower short-period mode frequency boundaries are described by arcs cd and ab, respectively. The frequency limits are determined from charts like Fig. 10.7 and depend on the operating flight condition, which is determined by n_α. Alternatively, the boundaries may be determined from a consideration of the limiting CAP values, also given in charts like Fig. 10.7, at the flight condition of interest. Note that when the s-plane is drawn to the same scale on both the x and y axes, the frequency boundaries become circular arcs about the origin. When the scales are not the same, the arcs become ellipses, which can be more difficult to interpret. The minimum short-period mode damping ratio is obtained from Table 10.4 and maps into the line bc radiating from the origin. The maximum permitted damping ratio is greater than 1, which obviously means that the corresponding roots lie on the real axis. Thus when the short-period mode roots, or poles, are mapped onto the s-plane, they must lie within the region bounded by abcd and its mirror image in the real axis. If the damping ratio is greater than 1, the pair of roots must lie on the real axis in locations bounded by the permitted maximum value of the damping ratio.

The minimum phugoid damping ratio is given in Table 10.5 and, for Level 1 flying qualities, maps onto the s-plane as the boundary ef. Thus, when the phugoid roots, or poles, are mapped onto the s-plane, they must lie to the left of the line ef to meet Level 1 flying qualities requirements. The Level 3 requirement on phugoid damping obviously allows for the case when the poles become real, one of which may be unstable and thereby give rise to divergent motion. In this case, the limit implicitly defines a minimum acceptable value for the corresponding time constant. This is mapped on to the s-plane in exactly the same way that the lateral-directional spiral mode boundary is mapped, as described next.

10.9.2 Lateral-directional modes

Typical boundaries describing the limits on lateral-directional mode frequency and damping on the s-plane are shown in Fig. 10.10. Again, the upper left half of the s-plane is shown but now with a small extension into the upper right half to include the region appropriate to the unstable spiral

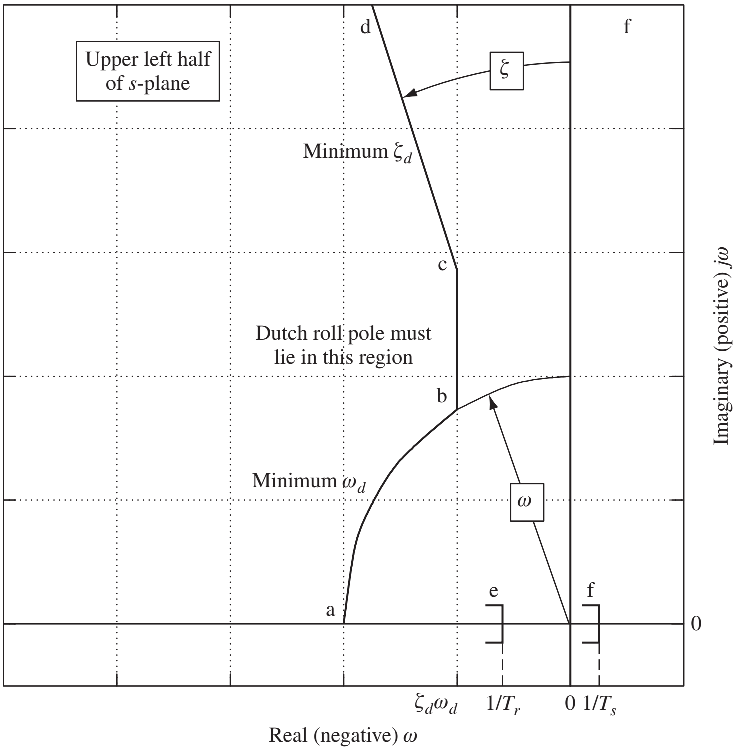

FIGURE 10.10 Lateral-directional flying qualities requirements on the s-plane.

mode. As for the longitudinal case, interpretation implicitly includes the lower half of the s-plane, which is the mirror image of the upper half of the s-plane in the real axis.

The maximum permitted value of the roll subsidence mode time constant is given in Table 10.6 and maps into the boundary e since the corresponding real root is given by the inverse of the time constant T_r. Further, since the mode must always be stable, it always lies on the negative real axis. The precise location of the boundary e is determined by aircraft class, flight phase category, and required flying qualities. However, at the appropriate operating flight condition, the pole describing the roll subsidence mode must lie on the real axis to the left of the boundary e.

The location of the spiral mode boundary f is established in the same way. Since the required limits apply to the mode only when it is unstable, the corresponding boundary lies on the right half of the s-plane. The precise location of the boundary may be determined from the minimum acceptable value of the time constant T_s, given in Table 10.8 and, again, this depends on aircraft class and required flying qualities. Thus, the spiral mode pole must always lie on the real axis to the left of the boundary f.

The limiting frequency and damping requirements for the dutch roll mode are given in Table 10.9 and are interpreted in much the same way as the requirements for the longitudinal short-period mode. The minimum permitted frequency boundary is described by the arc ab and the minimum permitted damping ratio boundary, by the line cd. The minimum permitted value of $\zeta_d\omega_d$ maps into the line bc to complete the dutch roll mode boundary and, as before, the boundary has its mirror image in the lower half of the s-plane. The dutch roll mode roots, or poles, must therefore always lie to the left of the boundary abcd at the flight condition of interest. Clearly, the precise location of the boundary is determined by the appropriate combination of aircraft class, flight phase category, and required level of flying qualities.

EXAMPLE 10.4

To illustrate the application of the flying qualities requirements, consider the McDonnell F-4 Phantom, the following data for which were obtained from Heffley and Jewell (1972). Since the available data are limited to the equations of motion and some supporting material, this assessment is limited to basic stability and control characteristics only.

For the case selected, the general flight condition parameters given are:

Altitude	h	35000 ft
Mach number	M_0	1.2
Weight	mg	38925 Lb
Trim airspeed	V_0	1167 ft/s
Trim body incidence	α_e	1.6 deg
Flight path angle	γ_e	0
Normal load factor derivative	n_α	22.4 g/rad
Control anticipation parameter	CAP	1.31 1/s^2
"Elevator" angle per g	η/g	3.64 deg/g

The Phantom is a high-performance combat aircraft; thus, for the purposes of assessment, it is described as a *class IV* aircraft. The flight task to which the data relate is not stated. Therefore, it may be assumed that the aircraft is either in steady cruising flight, flight phase category B, or is manoeuvring about the given condition, in which case flight phase category A applies. For this illustration, *flight phase category A* is assumed sine it determines the most demanding flying qualities requirements. It is interesting to see that the parameter *"elevator" angle per g* is given, which is of course a measure of the controls-fixed manoeuvre margin.

Consider the longitudinal stability and control characteristics first. Sufficient information about the stability characteristics of the basic airframe is given by the pitch attitude response to "elevator" transfer function, which for the chosen flight condition is

$$\frac{\theta(s)}{\eta(s)} \equiv \frac{N_\eta^\theta(s)}{\Delta(s)} = \frac{-20.6(s+0.0131)(s+0.618)}{(s^2+0.0171s+0.00203)(s^2+1.759s+29.49)} \tag{10.33}$$

The essential longitudinal stability and control parameters may be obtained on inspection of transfer function (10.33) as follows:

Phugoid damping ratio	$\zeta_p = 0.19$
Phugoid undamped natural frequency	$\omega_p = 0.045$ rad/s
Short-period damping ratio	$\zeta_s = 0.162$
Short-period undamped natural frequency	$\omega_s = 5.43$ rad/s
Numerator time constant	$T_{\theta_1} = 1/0.0131 = 76.34$ s
Numerator time constant (incidence lag)	$T_{\theta_2} = 1/0.618 = 1.62$ s

Since the Phantom is an American aeroplane, it would seem appropriate to assess its basic stability characteristics against the requirements of MIL-F-8785C. However, in practice it would be assessed against the requirements document specified by the procuring agency.

With reference to Table 10.5, which is directly applicable, the phugoid damping ratio is greater than 0.04 and, since $\omega_p/\omega_s < 0.1$, the phugoid achieves Level 1 flying qualities and is unlikely to give rise to handling difficulties at this flight condition.

With reference to the short-period mode frequency chart for flight phase category A, which is the same as in Fig. 10.7, at $n_\alpha = 22.4$ g/rad and for Level 1 flying qualities, it is required that

$$2.6\ \text{rad/s} \le \omega_s \le 9.0\ \text{rad/s}$$

or, equivalently,

$$0.28\ 1/\text{s}^2 \le \omega_s^2/n_\alpha\ (\text{CAP}) \le 3.6\ 1/\text{s}^2$$

Clearly, the short-period undamped natural frequency achieves Level 1 flying qualities. Unfortunately, the short-period mode damping ratio is less than desirable. A table similar to Table 10.4 indicates that the damping achieves Level 3 flying qualities only; to achieve Level 1 it would need to be in the range $0.35 \le \zeta_s \le 1.3$.

Considering now the lateral-directional stability and control characteristics, sufficient information about the stability characteristics of the basic airframe is given, for example, by the roll rate response to aileron transfer function, which for the chosen flight condition is

$$\frac{p(s)}{\xi(s)} \equiv \frac{N_{\xi}^{p}(s)}{\Delta(s)} = \frac{-10.9s(s^2 + 0.572s + 13.177)}{(s + 0.00187)(s + 1.4)(s^2 + 0.519s + 12.745)} \tag{10.34}$$

The essential lateral-directional stability and control parameters may be obtained on inspection of transfer function (10.34) as follows:

Roll mode time constant	$T_r = 1/1.4 = 0.714$ s
Spiral mode time constant	$T_s = 1/0.00187 = 535$ s
Dutch roll damping ratio	$\zeta_d = 0.0727$
Dutch roll undamped natural frequency	$\omega_d = 3.57$ rad/s
Dutch roll damping ratio-frequency product	$\zeta_d\omega_d = 0.26$ rad/s

At this flight condition the spiral mode is clearly stable with a very long time constant. In fact, it approaches neutral stability for all practical considerations. Since the mode is stable, it achieves Level 1 flying qualities and is most unlikely to give rise to handling difficulties.

A table similar to Table 10.6 indicates that the roll subsidence mode damping achieves Level 1 flying qualities since $T_r < 1.0$ s.

The dutch roll mode characteristics are less than desirable since its damping is very low. A table similar to Table 10.9 indicates that the damping ratio achieves only Level 2 flying qualities. To achieve the desirable Level 1 flying qualities the mode characteristics would need to meet the following:

Dutch roll damping ratio	$\zeta_d \geq 0.19$
Dutch roll undamped natural frequency	$\omega_d \geq 1.0$ rad/s
Dutch roll damping ratio-frequency product	$\zeta_d\omega_d \geq 0.35$ rad/s

It is therefore concluded that both the longitudinal short-period mode and the lateral-directional dutch roll mode damping ratios are too low at the flight condition evaluated. In all other respects, the aeroplane achieves Level 1 flying qualities. The deficient aerodynamic damping of the Phantom, in common with many other aeroplanes, is augmented artificially by a feedback control system.

It must be emphasised that this illustration is limited to an assessment of the basic stability properties of the airframe only. This determines the need, or otherwise, for stability augmentation. Once the stability has been satisfactorily augmented by an appropriate control system then, further and more far reaching assessments of the control and handling characteristics of the augmented aeroplane would be made. The scope of this kind of evaluation may be appreciated by reference to the specification documents discussed earlier. In any event, analytical assessment requires the addition of a simulation model developed from the linearised equations of motion in order to properly investigate some of the dynamic control and response properties.

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PROBLEMS

10.1 What are flying and handling qualities requirements? In the context of flying and handling qualities requirements, explain the following:
Flight envelope
Aircraft class
Flight phase category
Level of flying quality
Cooper-Harper rating scale

(a) The pitch rate response to elevator control transfer function for the Northrop F-5 Tiger aircraft in level flight cruise at an altitude of 30,000 ft is given by

$$\frac{q(s)}{\eta(s)} = \frac{-14.6s(s+0.0159)(s+0.474)}{(s^2+1.027s+7.95)(s^2+0.0169s+0.0031)} \quad 1/\mathrm{s}$$

Evaluate the flying qualities of the aircraft at this flight condition. Note that $n_\alpha = 12.9$ 1/rad for this flight condition.

(b) With the aid of MATLAB or Program CC, draw a root locus plot to show the effect of pitch rate feedback to elevator and show both modes clearly. Draw the flying qualities boundaries on the plot and hence determine a suitable value for the feedback gain k_q to ensure that the aircraft meets the requirements. Compare the characteristics of the stability modes at this gain with those of the unaugmented aircraft.

(CU 1985)

10.2 Describe the service and operational flight envelopes for an aircraft and explain how they are related. In the context of flying and handling qualities, what is meant by flight phase category? Why are the stability requirements associated with each flight phase category different?

(CU 1986)

10.3 The Lockheed Jetstar is a small four-engined utility transport aircraft. When cruising at Mach 0.5 at an altitude of 40,000 ft, the roll and yaw transfer functions are given by

$$N_\xi^p(s) = 0.929(s-0.0133)(s^2+0.133s+0.79) \; 1/\mathrm{s}$$
$$N_\zeta^r(s) = -0.511(s+0.36)(s^2+0.114s+0.335) \; 1/\mathrm{s}$$
$$\Delta(s) = (s-0.0008)(s+0.5)(s^2+0.009s+1.59)$$

(a) Evaluate the stability mode characteristics at this flight condition against the flying qualities requirements.

(b) What negative feedback is required to improve the stability characteristics of this aircraft? Illustrate your answer with a italic of the appropriate root locus plot(s), and state the most significant effects of the feedback with reference to the requirements.

(CU 1990)

10.4 Explain why the characteristics of the short term stability modes are critical to good flying qualities.

(CU 2001)