A BACKGROUND TO THE HANDLING QUALITIES OF AIRCRAFT

1. INTRODUCTION

This Item presents a background to the handling qualities of aircraft, examining those factors that play a role in the ease and safety with which a pilot flies an aircraft. Such factors encompass the stability and response characteristics of the aircraft, the operation of the aerodynamic control surfaces and the engine thrust levels which enable the pilot to:

(i) trim an aircraft,

(ii) maintain control during continuous disturbances

and (iii) manoeuvre an aircraft.

It is implicitly assumed that when a pilot exercises control of an aircraft the mental and physical workload entailed is comfortably within his capabilities.

A distinction is made in this Item between "handling qualities" and "flying qualities", terms that are often used interchangeably elsewhere. The former term is used to describe those parameters that characterise the stability, control and response of an aircraft and so govern the ease and precision with which a pilot is able to fly an aircraft. Flying qualities, in contrast, relate to the pilot assessments of how well he is able to fly an aircraft to complete the range of tasks required and are wholly subjective in character.

Two other terms are meaningful in the context of the present topic. The first is "handling quality criteria" which relate to the identification and quantification of those parameters that characterise the handling qualities. The second term is the "flying quality requirements" which are the statutory regulations to which all aircraft must conform in order to be certificated to fly and are laid down by the government bodies responsible for aviation in the various countries.

For civil aviation in the UK, Requirements are issued by the Civil Aviation Authority (CAA) and consist of various documents published either as Joint Airworthiness Requirements (JAR)[8] jointly agreed upon by a number of European countries, or as British Civil Airworthiness Requirements (BCAR)[7]. In the USA the regulation authority is the Federal Aviation Agency (FAA)[17]. The requirements, both in the UK and USA, usually consider light aeroplanes $(< 5700 \text{ kg})$ and large aeroplanes $(> 5700 \text{ kg})$ separately.

The military specification in the UK is the "Design and Airworthiness Requirements for Service Aircraft"[20], Def. Stan. 00-970 published by the Ministry of Defence. These correspond wherever possible with the USA "Military Specification, Flying Qualities of Piloted Airplanes"[10], MIL-F-8785C, published in 1980 which was superseded in 1987 by Military Standard MIL-STD-1797[11] .

The nature of both the civil and military requirements is qualitative, expressing the conditions for safe flight throughout the designated flight envelope. However, in the military field, a great deal of research combined with flight experience of experimental, prototype and production aircraft has been carried out in many countries for many years. The results of these studies have been incorporated in the specifications for aircraft flying qualities and provide fairly comprehensive quantitative information in terms of the handling quality criteria for acceptable means of compliance with the requirements. The military requirements can encompass civil aircraft operation as well as military.

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2. NOTATION

Any coherent system of units may be used.

A, B	symbols used in Sketch 4.4
CAP	Control Anticipation Factor (see Equation (4.1))
C_D, C_L	drag and lift coefficients, respectively
$C_{L\alpha}$	lift curve slope
DB	dropback (see Sketch 4.4)
F_s/n	gradient of pitch control force versus normal acceleration factor
G	factor used in Equation (5.3)
g	acceleration due to gravity
H_m	manoeuvre margin
k	factor used for specification of increments of sideslip (see Equation (5.4))
l_ξ	rolling moment derivative due to aileron deflection
M	Mach number
n_z	incremental normal acceleration factor
n_α	ratio of steady-state normal acceleration factor change to angle of attack change (approximately equal to $(C_L)_{trim}/C_{L\alpha}$)
p, q, r	angular velocities about the x-, y- and z-axes, respectively
t	time
t_γ	flight path angle time delay
t_θ	attitude lead time constant
$t_{1/2}$, t_2	time to half amplitude and time to double amplitude, respectively
u, v, w	aircraft velocity relative to air in x-, y- and z-directions, respectively
V_0	datum value of total aircraft velocity (the subscript 0, rather than the usual symbol e, is used to conform to that used in the requirements)
α	incidence angle
β	sideslip angle
γ	angle of climb (flight path angle)

ζ	damping ratio
ζ	rudder deflection
η	elevator deflection
θ	pitch perturbation angle
ξ	aileron deflection
ϕ	roll perturbation angle
ψ	yaw perturbation angle
ω_n	natural undamped frequency

Subscripts

D	denotes Dutch Roll mode
min	denotes minimum
P	denotes Phugoid mode
R	denotes Roll mode
S	denotes Spiral mode
SP	denotes Short Period mode
ss	denotes steady-state
$trim$	denotes trimmed state

3. GENERAL DESCRIPTION

It is mandatory, as laid down by airworthiness requirements, that an aircraft shall be capable of being flown throughout its flight envelope and in all but the severest of weather conditions by a typical (average) pilot. The pilot must be able to manoeuvre and to retain control of the aircraft at all times. In the rare event that the pilot loses control, for example in a stall or spin, a safe recovery must be provided.

The designer has always sought to provide the pilot with such a machine by utilising criteria that have emerged from theoretical studies of the aircraft's trimmed or quasi-steady states, its stability, its response to control application and its response to atmospheric disturbances. How precisely a pilot flies an aircraft and the extent to which he can adapt his actions to compensate for any perceived shortcomings of the aircraft, and the limit to which he is happy to do so, are all matters that are not well understood. Attempts to describe the pilot in quantitative terms are still primitive.

The test pilot has been the final arbiter on the flying qualities of each prototype aircraft. The task was to assess how easily and how well an average pilot, that is, a pilot who has followed a recognised form of training but without exceptional skills, could accomplish the various tasks which make up the operational use of the type of aircraft in question. The search has been for a means by which the pilots' subjective assessments could be translated to an objective assessment that the designer could incorporate in the design process.

A list of the aircraft stability, control and response parameters that are common to the design process and flight testing may be compiled. For a “conventional” aircraft such a list for longitudinal motion could comprise:

(i) stick displacement and throttle setting to trim,

(ii) stick displacement/change in trim speed and stick force/change in trim speed,

(iii) stick displacement/g and stick force/g
(for aircraft with powered controls stick force/g is provided solely by the artificial feel system),

(iv) response time to steady acceleration,

(v) overshoots in normal acceleration response and pitch rate response,

(vi) time lag and response to throttle changes,

(vii) initial pitch acceleration/g

(viii) time at peak pitch rate,

(ix) flight path angle time delay

and (x) response to discrete and sinusoidal gusts.

A similar list of parameters would identify lateral motion. The above list is not complete but is representative of the sort of parameters that identify the aircraft flight dynamics. A number of the parameters listed can be alternatively expressed in terms of the frequencies and damping ratios of the “classic” stability modes of a “conventional” aircraft.

A ‘conventional’ aircraft is taken to be one devoid of any significant augmentation system in which there is little physical coupling between the longitudinal and lateral modes of response. The aircraft is designed to be stable. Such aircraft normally exhibit ‘classic’ stability modes of response, which are, in longitudinal motion, a Short Period oscillation and a Long Period or Phugoid oscillation, and in lateral motion, two first-order modes, namely a Roll mode and a Spiral mode, and a second-order oscillation called the Dutch Roll (see Reference 15).

3.1 Aircraft Role and Flight Phase Definitions

Since a pilot's perception of flying qualities depends on the type of aircraft, aircraft are divided into four classes as indicated in Table 3.1. In the civil field aircraft are segregated into light and large aeroplanes, namely less than and greater than 5700 kg, respectively, and other differences in capability expected from an aircraft type are implicitly recognised in the requirement that the aircraft be flown throughout the specified flight envelope.

TABLE 3.1 Aircraft Classes

CLASS	I	II	III	IV
Description	Small, light aircraft. Maximum mass ≈ 5700 kg (390 slug)	Medium weight, low-to-medium manoeuvrability aircraft. Mass between 5700 and 30000 kg (390 to 2056 slug)	Large, heavy, low-to-medium manoeuvrability aircraft. Mass greater than 30000 kg (2056 slug)	High manoeuvrability aircraft
Examples of role and aircraft.	light utility. Primary trainer. Light observation. Cessna Caravan. Pilatus Islander. Piper Tomahawk. Shorts Tucano. Turboporter. Optica.	Heavy utility/search and rescue. Light or medium transport/cargo/tanker. Early warning/electronic counter-measures/airborne command, control or communications relay. Anti-submarine. Assault transport. Reconnaissance. Tactical bomber. Heavy attack. Trainer for CLASS II. Hercules C130. ATP. 146. 737. DC9. Grumman E2. 125.	Heavy transport/cargo/tanker. Heavy bomber. Patrol/early warning/electronic counter-measures/ airborne command, control, or communications relay. Trainer for CLASS III. 747. A300. DC10. (KC10). B52. 707.	Fighter interceptor. Attack. Tactical reconnaissance. Observation. Trainer for CLASS IV. F16. Tornado. Jaguar. F111. Harrier. Hawk. Yak 50. Zlin 50L. Buccaneer.

The military specifications subdivide a flight or sortie into a sequence of flight phases categorised into types A, B and C as shown in Table 3.2, where typical examples of tasks within each phase are given. Phases A, B and C are distinguished by the differing rates of required manoeuvrability and degrees of precision flight path control. A category Flight Phase D is included in the specifications when V/STOL techniques are used in combination with precise flight path control.

TABLE 3.2 Flight Phases

Phases	A	B	C
Description	Rapid manoeuvring, precision tracking or precise flight path control.	Gradual manoeuvres without precision tracking. Accurate flight path control may be required	Normally gradual manoeuvres and usually precise flight path control.
Typical examples of tasks	Air-to-air combat. Ground attack. Weapon delivery/Launch. Reconnaissance. Air-to-air refuelling. Terrain following. Maritime search and support. Aerobatics. Close formation flying.	Climb. Cruise. Loiter. Air-to-air refuelling. Descent. Aerial delivery.	Take-off. Approach (includes instrument approaches). Overshoot. Landing (includes arrested landing).

Each and every task on each type of aircraft is extensively investigated on a prototype in a flight test programme and the level of flying qualities is measured as defined in Table 3.3.

TABLE 3.3 Flying Quality Levels

LEVEL	1	2	3†	BELOW 3
Task	Task achieved without excessive pilot workload.	Some degradation in task effectiveness, or increase in pilot workload or both.	Aeroplane can be controlled but with severe task degradation. The total workload of the pilot is approaching the limit of his capacity	Inability to complete task required. Allowed only in special circumstances.

† Category A Flight Phases can be terminated safely.

On a production aircraft within the operational flight envelope (defined by those parameters of speed, altitude and normal acceleration factor defining the limits of operation of a given manoeuvre), Level 1 flying qualities are mandatory. The requirements are relaxed to Level 2 qualities within the service flight envelope (defined by parameters relating to aircraft limits as opposed to task limits). The levels assume an aircraft is in its normal state, defined as one in which no component or system failure exists and mass and configuration are correct for the task being completed.

The failure states of an aircraft, and the components and/or systems related to them, that significantly affect flying qualities must be fully defined by the aircraft manufacturer. “Special failure states” relate to the failure of certain components and systems that have an extremely low probability of failure. Other than for such special failures flying quality levels after a failure are tied into the probability with which that system failure will occur. For example it is desirable to have

– at least LEVEL 2 after failures that occur less than once per 100 flights,

– at least LEVEL 3 after failures that occur less than one per 10 000 flights.

The flying quality levels required do not generally distinguish between flight in calm air and in turbulence; however, it is assumed that numerical values assigned to flying qualities contain some allowance for atmospheric disturbances. Flying qualities are inevitably degraded by turbulence, which increases the workload of the pilot and may impair task effectiveness. If turbulence is sufficiently intense, the level of flying qualities may drop below the level otherwise appropriate to the flight phase.

3.2 Piloting Techniques

Many of a pilot's actions in either initiating or counteracting a particular aircraft motion derive from learnt processes acquired during training and subsequent experience. Motions are perceived visually and/or by the natural mechanisms of the body, particularly in the inner ear. Because the sensed cues are unreliable pilots are trained not to rely on these cues. The basic instruments enable the pilot to determine height, airspeed, pitch attitude, bank and heading angles as well as rates of climb or sink. These instrument-generated cues always supplement and not infrequently wholly replace those coming from external sources.

The main parameters that provide the pilot with his awareness of the orientation of the aircraft are its attitude angles, either derived from external cues arising from the position of the horizon relative to its nose or wing tips, or from instruments. An experienced pilot will also monitor the rate of change of attitude thus having a measure of the angular velocities in pitch, roll and yaw.

Specific demanded tasks usually introduce the use of additional cues. Examples of such tasks are:

(1) landing, either ship or land based

and (2) tracking as in air-to-air refuelling or formation flying.

For this type of task it is necessary to monitor the line-of-sight, which is affected by a number of flight parameters and requires a more or less simultaneous or sequential application of more than one control. Because the pilot does not usually possess a direct measure of the aircraft flight path angle he is forced to use the related attitude angle to sense the error between his actual and desired state of flight.

A number of basic piloting tasks may be identified and are elaborated upon in the following discussion: these are the increase or decrease of speed at constant altitude, a climb or descent, a turn at constant altitude, an approach to land and a longitudinal or lateral 'g' manoeuvre.

To increase speed at a constant altitude, on a conventional aircraft, a pilot uses a combination of forward stick displacement (down elevator) and an opening of throttle matched so as to keep an almost trimmed state throughout. In a slow-down the inputs are in the reverse sense.

To initiate a climb, aircraft stick (up elevator) is applied which through the action of the Short Period motion of the aircraft results in attitude angle and flight path angle changes. The throttle is opened to produce the thrust necessary to maintain the climb angle. When the stick is returned to its original setting the aircraft still climbs.

In executing level, ascending or descending turns the pilot uses the aileron as his primary control with simultaneous co-ordinated rudder and elevator inputs to suppress the sideslip engendered by the aileron and offset the lift loss, respectively.

At the start of the approach to land, the pilot trims the aircraft on to a specified glide path. Throughout the approach the pilot co-ordinates his use of stick and throttle closely controlling both the flight path angle and the airspeed. The control technique adopted by the pilot to correct any departure from the given glide path is influenced by the degree of coupling between flight path angle and airspeed arising from changes in stick position and in throttle setting. It is interesting to note that pilots flying light propeller-driven aircraft are taught to lead with use of throttle in a thrust/attitude co-ordination while on heavier jet powered aircraft the reverse tends to be true. The fact that propeller powered aircraft experience a slipstream induced lift may account for the difference.

To manoeuvre the aircraft in the longitudinal plane, that is, to initiate a "*g*" pull up or pull out from a dive, the pilot applies backward stick (up elevator) displacement. For a given control input the pilot has, by virtue of his training and experience, an expectation of the ensuing response of the aircraft in that he expects a small delay, an initial acceleration, a magnitude of response, a modest overshoot and a time to reach a steady-state. Thus an experienced pilot on a given aircraft has a concept of an ideal response with which the actual response is mentally compared. Should the two responses differ to a degree that the pilot is unwilling to accept, the pilot is likely to resort to what is known as compensation in an attempt to bring the two responses into line. A pilot attempts to compensate for response inadequacies by applying additional control actions over and above those that ideally would generate the manoeuvre characteristics required. For example a pilot faced with an aircraft exhibiting a sluggish response would apply initially more aircraft stick than required and then during the succeeding response apply a series of control actions to keep the response characteristics, such as overshoot, within bounds. An aircraft with good handling qualities is one in which the need for any compensation is minimal. The degree of shortfall of the responses determines how far down the scale of flying qualities the aircraft is rated.

As mentioned in Section 3.1 and displayed in Table 3.2, military specifications divide a sortie into flight phases A, B and C. Within the same table are given examples of tasks that arise within each flight phase. To some extent certain tasks are specific to a particular class of aircraft and some are common to all as indicated by a comparison of Tables 3.1 and 3.2.

The tasks range from those requiring rapid manoeuvring to those for which gradual manoeuvres suffice. In tracking manoeuvres in air-to-air combat the tracking pilot aims to keep his flight path directed towards the target, which itself is performing evasive manoeuvres. This necessitates tight control of the flight path angle(s) through the attitude angle(s). Usually these manoeuvres involve both lateral and longitudinal motion, as do ground attack manoeuvres. Accordingly the pilot has expectations of response in roll, akin to those he has in pitch, which are expressible in terms of the initial acceleration, the oscillatory nature of the response, and time to achieve a given bank angle.

This discussion does not exhaust the tasks within all the phases of flight listed in Table 3.2 but should be sufficient to indicate the nature of the interrelation between the task and the aircraft characteristics.

All piloting tasks are rendered more difficult by atmospheric disturbances, some, such as precision tracking and/or precise flight path control, more so than others. To keep the pilot's overall workload and stress within bounds the stability characteristics of the aircraft should provide an acceptable degree of damping of the disturbances. The pilot is trained not to attempt to filter out the higher frequencies of atmospheric turbulence and will generally react only to the gross effects of a gust.

3.3 Development of Pilot Opinion Ratings

In the determination of the flying qualities of an aircraft the pilot will seek to assess, in a wholly subjective manner, the degree of acceptability and suitability for use in a specific role for general flying.

To arrive at such an evaluation the test pilot has to consider those factors that affect the wide range of handling characteristics of an aircraft, such as controllability, manoeuvrability, trim, lag and overshoot in response to the control elements at his disposal (the stick which operates the elevators, ailerons, rudder, or their equivalents, and the engine throttle).

Any shortcoming in one or more of the above can affect the ease with which a pilot executes the tasks associated with the operational flying of a particular aircraft. Additionally the overall assessment may be influenced by cockpit layout, view and the instrument display of flight information. Stress and workload are important factors that influence the overall assessment made by the pilot.

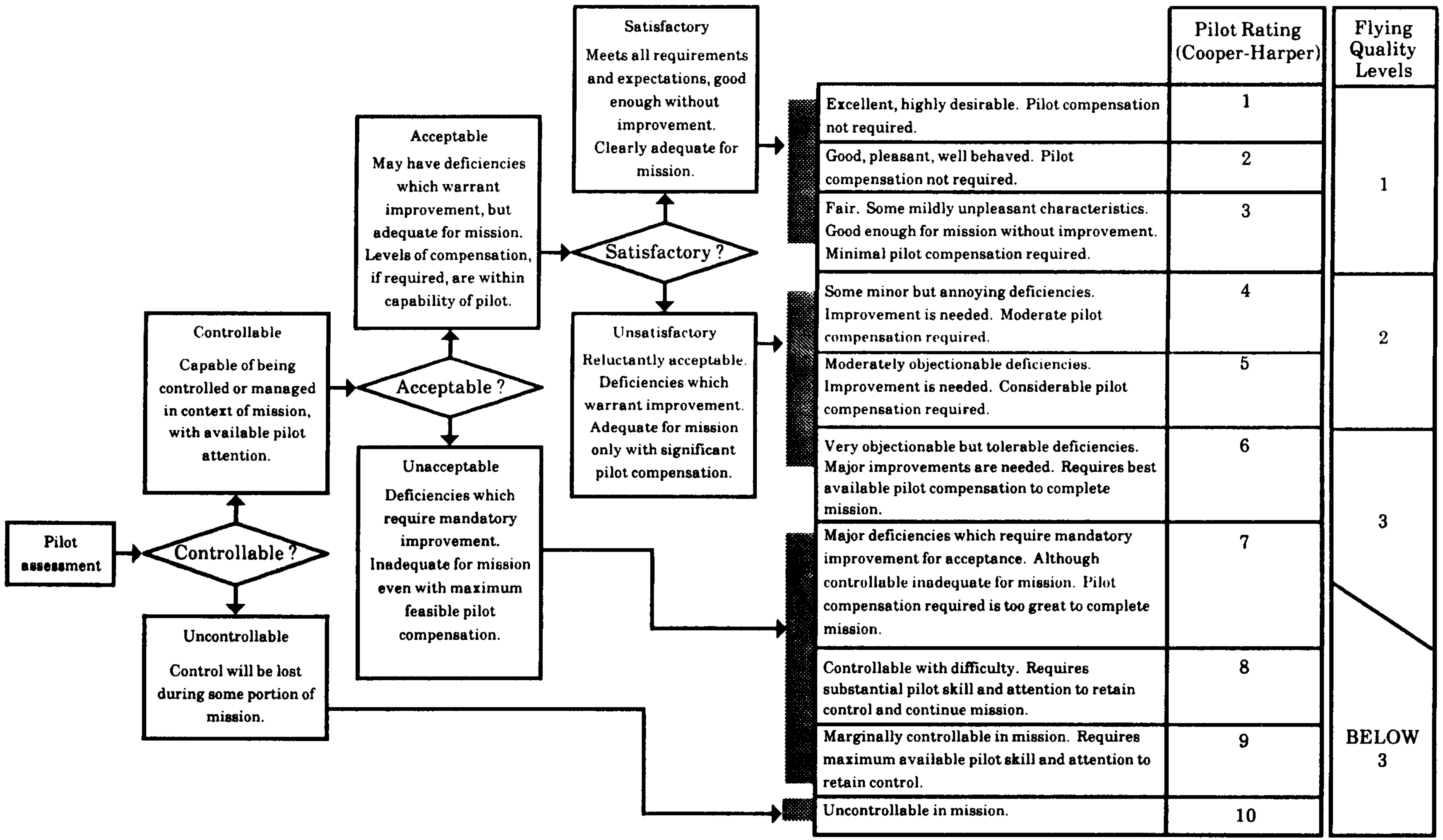
Controllability is that quality of an aircraft that enables a pilot to initiate and maintain a manoeuvre. A primary essential of controllability is that the application of any primary control is followed by a reaction in the normally expected sense, for example, a backward pull on the stick results in a nose-up pitching moment on the aircraft, and that the reaction is neither too fast nor too slow. Controllability extends somewhat beyond this basic property in that it concerns the ease or difficulty of maintaining a manoeuvre.

Manoeuvrability expresses the capability of the aircraft cum pilot system to effect controlled changes in the flight path, angular rates and speed of the aircraft and includes such matters as time lags, overshoots and the compensation necessary on the part of the pilot during entry into a manoeuvre and maintenance of a steady-state acceleration, and return to normal flight. For example, a pull-out manoeuvre, entry into and recovery from a dive, and entry and exit from a banked turn involve all the above since they relate to appreciable flight path changes.

In general the aim of the flight tests into flying qualities of aircraft is to produce a more or less uniform scheme of pilot opinion ratings that is superimposed on plots of the flying qualities or compared with the numerical values of the aircraft parameters used in the design process. These parameters, previously listed, can be measured in the course of flight tests of a particular aircraft. In this way the range of pilot opinion is correlated with measures of the aircraft dynamics, which thereby supplies the designer with a basis upon which he can design the aircraft to a standard with an expectancy of high pilot rating.

Descriptive terms such as a pilot might use have been formed into a decision process culminating in numerical ratings and associated level of flying qualities. The most commonly in use is the Cooper-Harper[9] scale illustrated in Sketch 3.1. This sketch refers to an overall assessment covering all phases of flight and all such tasks as the role of the aircraft will impose upon it. Cooper and Harper have provided in their paper a fuller procedure with a guide questionnaire for briefing and debriefing the pilot. Effectively the broad brush of flying qualities in Table 3.3 is broken down into ten Cooper-Harper ratings.

Considerable importance is placed upon the underlying concepts of terms used in the sketch and the descriptions supplementary to the sequential decision terms that lead to a rating. The major decision terms are seen to be controllable, acceptable and satisfactory and the pilot at each stage assesses whether the term has been met relative to the intended use of the aircraft. The best category is defined as “excellent, highly desirable” and is associated with a satisfactory level of pilot workload since the pilot has no need to compensate for deficiencies in the manoeuvre performance of the aircraft. In each of the ratings the term compensation refers to the level of pilot effort and attention required, relative to a rating of 1 or 2, to maintain a given level of manoeuvre performance.



Sketch 3.1 Pilot Assessment Rating of flying qualities (Cooper-Harper)

4. HANDLING QUALITIES CRITERIA

On the basis of direct flight experience pilot's opinions were obtained on a range of prototype, production and experimental aircraft covering an extensive range of tasks. The data base so gathered was greatly augmented by the advent of the variable-stability aircraft and flight simulators.

These pilot opinion ratings obtained were compared with the design parameters from a classic modal response analysis of a conventional aircraft and form the basis of the recommended values given in the airworthiness requirements.

The stability and control characteristics of an aircraft may be defined by reference to its motion following a small disturbance from a steady trimmed condition. Such a motion can be described by linearised quasi-steady perturbation equations developed from rigid-body equations of motion as described in References 14, 15 and 16. An aircraft's response to control inputs for single input cases (less obviously so for multi-input cases) may be written in the form of transfer functions where the denominator is the characteristic equation of the system, the roots of which determine its stability.

4.1 Short Period Mode

The Short Period oscillation is essentially a motion in which the incidence, attitude and flight path angle of the aircraft change while the airspeed remains constant. The motion can consequently be resolved into components of vertical translation and pitching only.

Responses to elevator input on the basis of the Short Period mode approximation yield a number of handling qualities that influence a pilot's assessment of an aircraft. These are

(i) time to peak pitch rate,

(ii) response time (settling time) to steady pitch rate and steady normal acceleration,

(iii) ratio of peak to steady pitch rate,

(iv) initial pitch acceleration (related to *CAP*),

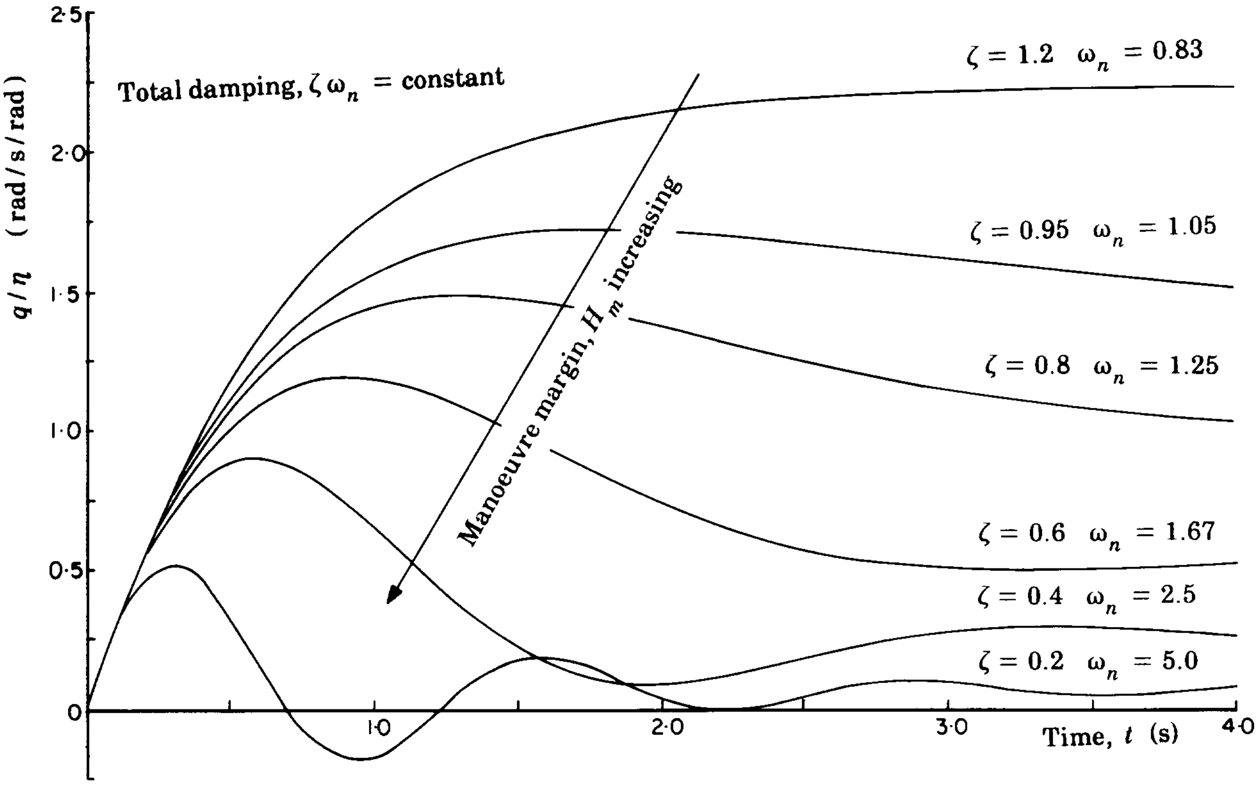
(v) pitch attitude dropback (overshoot), *DB*

and (vi) flight path angle time delay, t_γ.

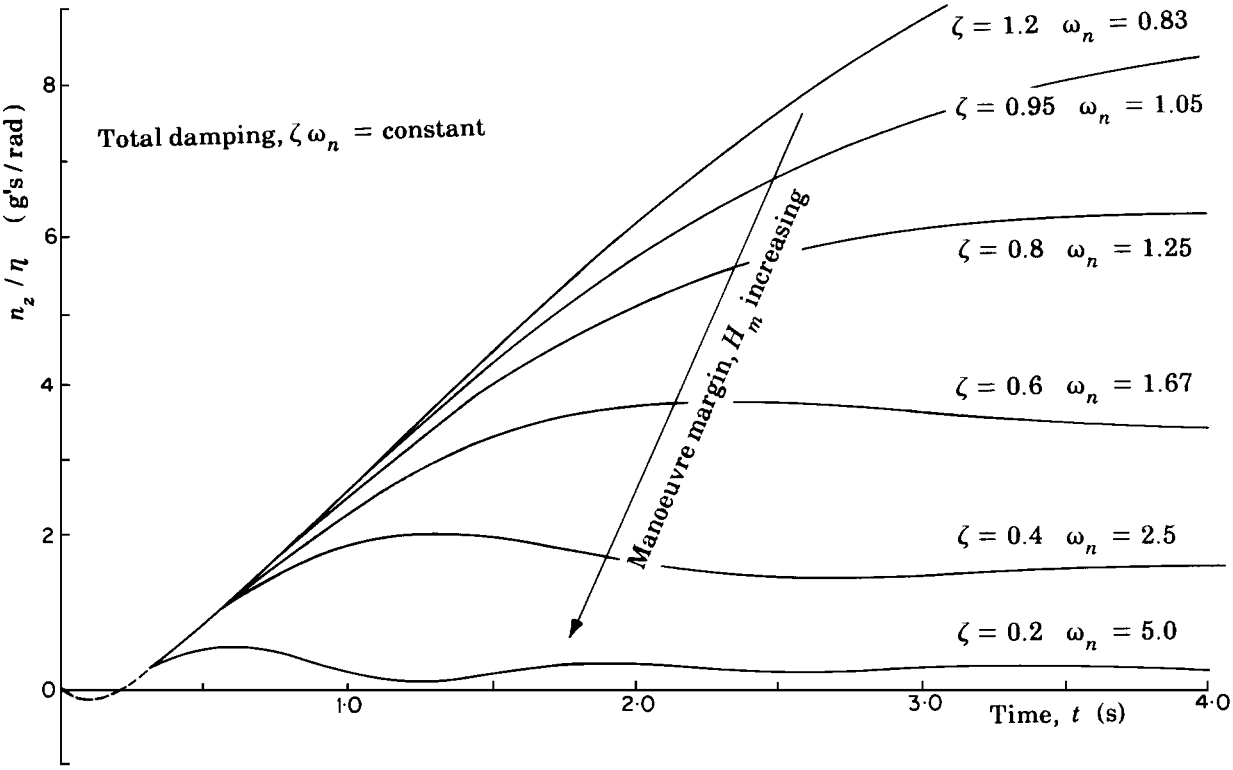
All of these measures may be expressed in terms of the parameters that occur in the Short Period approximate solutions, namely ζ_{SP}, $(\omega_n)_{SP}$ and t_θ (the attitude lead time constant).

Pitch rate and normal acceleration step responses per unit elevator deflection are shown plotted in Sketches 4.1 and 4.2, respectively. They are given for an aircraft with fixed total damping for various positions of the centre of gravity, denoted by variation in the manoeuvre margin, H_m. Changes in H_m effect changes in both the damping ratio, ζ_{SP}, and the natural undamped frequency, $(\omega_n)_{SP}$. The fastest response, *i.e.* the response with the shortest elapsed time to cross what will become the steady-state value, is obtained with the highest value of manoeuvre margin and lowest damping ratio, $\zeta_{SP} = 0.2$. However, this quick response is obtained at the expense of overshoot and the time taken to settle finally at the steady-state. Conversely at the lowest manoeuvre margin, at a damping ratio of $\zeta_{SP} = 1.2$, sluggish response is obtained with zero overshoot and a long time to achieve a steady-state value. The middle of the range response of $\zeta_{SP} = 0.6$ is seen to provide a compromise between the factors of overshoot, rise time and settling time. For a given value of damping ratio an increase of rate of response results from an increase of the natural frequency of the aircraft.

The results of systematic studies of frequency and damping variations have been charted into regions of pilot opinion and have shown that for combat aircraft and light aircraft a Short Period damping and frequency combination of $\zeta_{SP} = 0.6$ and $(\omega_n)_{SP} = 3.0$ rad/s is a good optimum for all general tasks. Sketch 4.3 shows a typical example of pilot opinion contours where regions of satisfactory, acceptable, poor and unacceptable are charted. Also indicated on the sketch are comments relating to responses away from the optimum. For transport aircraft in the Class III category a damping/frequency combination of $\zeta_{SP} = 0.6$, $(\omega_n)_{SP} = 1.5$ rad/s is more appropriate. However, considerable quantitative differences exist between the results of various tests. These differences are due to the uncertainties in the assessments and the fact that pilot opinions are based on other factors as well as ζ_{SP} and $(\omega_n)_{SP}$.



Sketch 4.1 Pitch rate step response



Sketch 4.2 Normal acceleration step responses

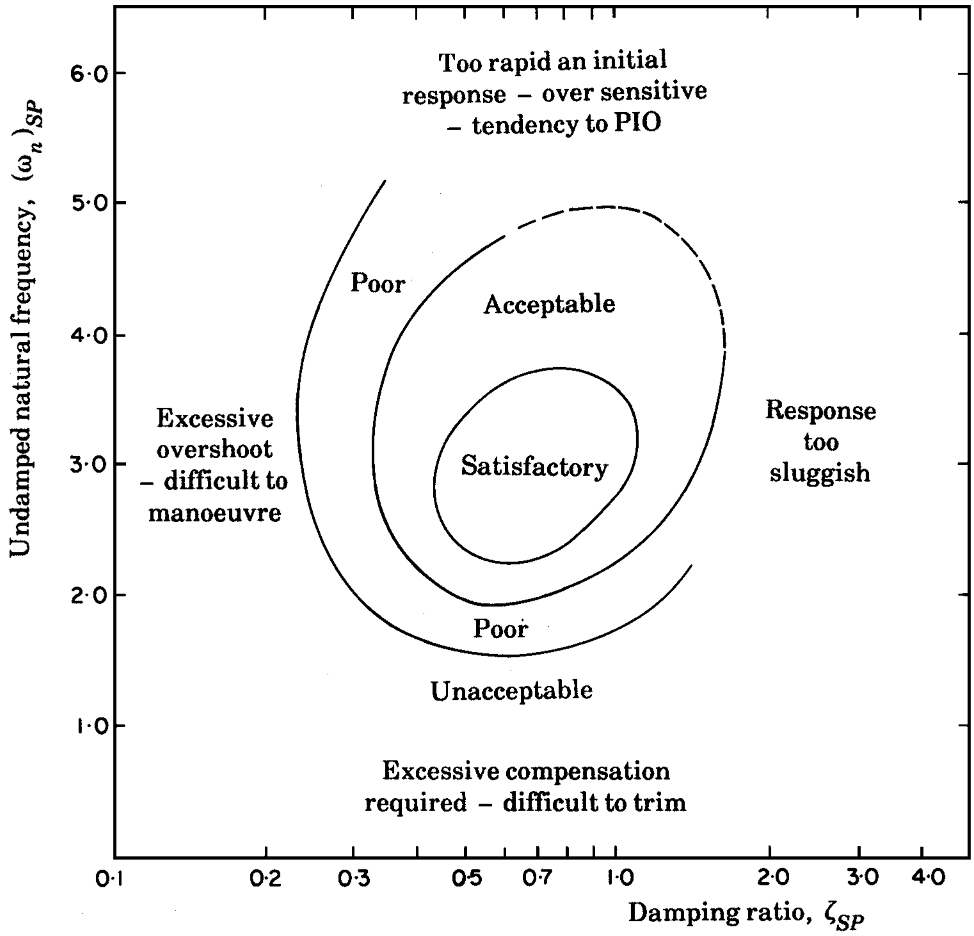
To resolve the lack of agreement in the results, an additional parameter, n_a, was chosen, which is defined as the ratio of steady-state normal acceleration factor change to angle of attack change. This parameter is incorporated in Bihrle's Control Anticipation Factor[4], known as *CAP*, which is the ratio of initial pitching acceleration to steady state load factor, given by

$$CAP = \frac{(q)_{t \to 0}}{(n_z)_{ss}} . \tag{4.1}$$

It can be shown[21] that Equation (4.1) is equivalent to

$$CAP = \frac{(\omega_n)_{SP}^2}{n_a} , \tag{4.2}$$

where n_a is is approximately equal to $(C_L)_{trim}/C_{L\alpha}$. The parameter *CAP* tends to be invariant with speed and is chosen to set limits on abrupt or sluggish attitude response. This may be interpreted as the compatibility of flight path response to initial sensation of pitch control input.



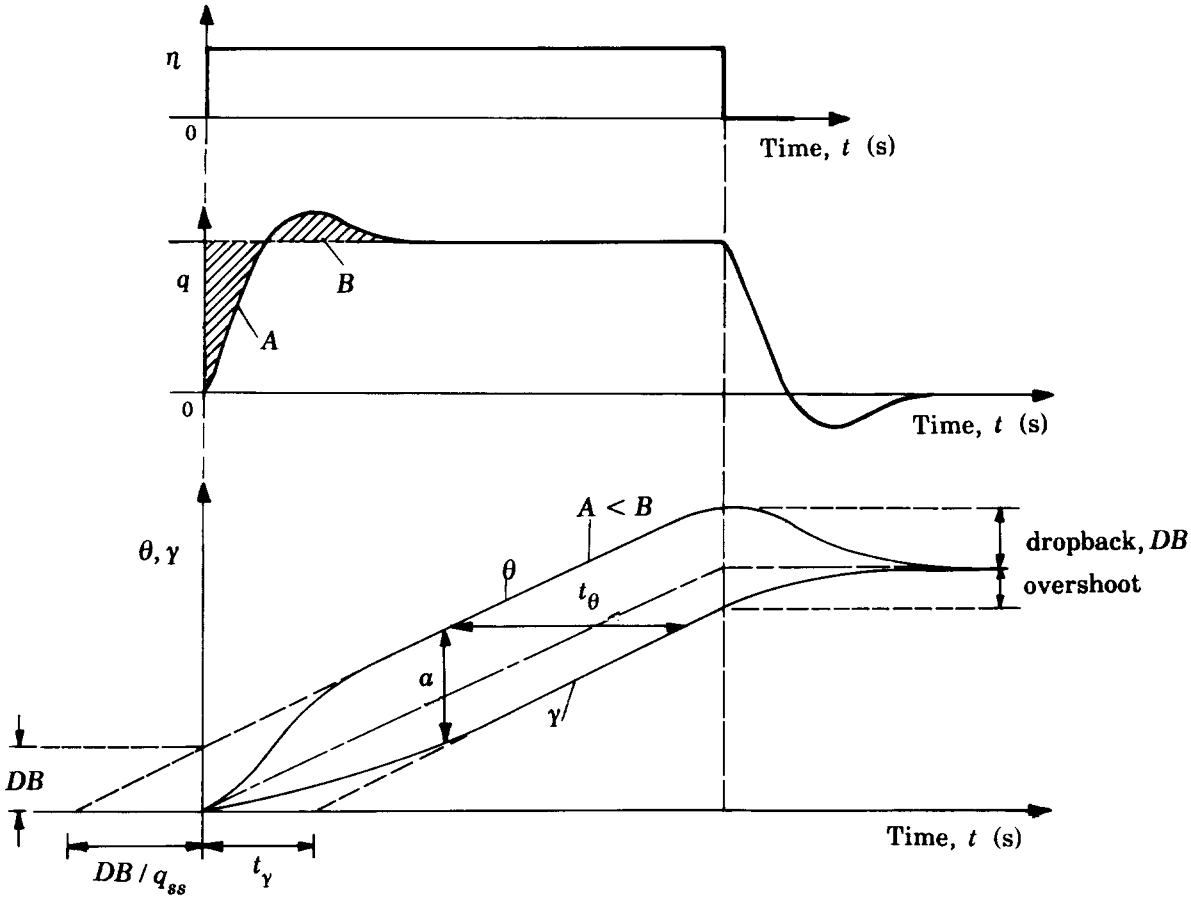
Sketch 4.3 Typical pilot opinion contours for Short Period

The quantities *DB* and t_γ are important in manoeuvres in which tight control of flight path is necessary, *e.g*. tracking. To assign values to these parameters the aircraft's pitch response to an elevator step input is examined; it is expressed in terms of the change of attitude angle and flight path angle. Typical responses are illustrated in Sketch 4.4.

Sketch 4.4(a) illustrates an elevator step input versus time where the step is applied at some instant, held constant for a period and then reversed. Sketch 4.4(b) shows a trace of the pitch rate response, *q*, produced from both the applied control and the control reversal. Shaded areas are labelled *A* and *B*. The pitch attitude, θ, and flight path angle, γ, responses are shown together in Sketch 4.4(c) with the former leading the latter by t_θ. The pitch attitude trace is given for the case when the area *A* is less than *B*, which gives rise to a dropback, *DB*, as shown. Cases in which *A* is greater than *B* would produce overshoots (negative dropbacks) equivalent to pitch rate responses that would be heavily damped.

The flight path angle is seen to overshoot at control reversal and finally settle after a time delay, t_γ, at a steady-state value where $\theta = \gamma$ and consequently a pilot controlling pitch attitude, θ, is also controlling flight path angle, γ. The time delay, t_γ, is equivalent to the extrapolation of the flight path angle back to the time axis as shown in the sketch. Similarly the time delay of the pitch attitude angle can be expressed as DB/q_{ss} also shown in the sketch. The sum of these delays is equal to the attitude lead time constant, t_θ. Faster flight path responses would be obtained at the expense of a more abrupt pitch attitude response with greater dropback and consequently greater pitch rate overshoot. For good attitude control, in-flight simulations have indicated that dropback values between 0 and 0.25 seconds for the parameter DB/q_{ss}

assure excellent fine tracking. Negative values or overshoots result in sluggish unpredictable response in flight path control and tracking.



Sketch 4.4 Pitch angle and flight path angle responses

Too large a value of dropback implies a too abrupt response and a tendency to continuous oscillations in tracking manoeuvres. Small values of t_γ (flight path time delay) seem advantageous but are not essential for gross manoeuvring.

4.2 Phugoid or Long Period Mode

The Phugoid is generally a lightly-damped low-frequency oscillation in which interchanges of height and airspeed occur at essentially constant incidence. The pilot experiences little difficulty in controlling this motion since he generally maintains fairly tight control of attitude. Even when tight control is relaxed the Phugoid will remain fairly insignificant providing the period of the oscillation is large. Its significance lies mainly in the degree to which monitoring speed may distract from other tasks. The results of flight tests have shown that positive damping was preferred but a damping ratio greater than 0.15 was found to be of no benefit.

4.3 Stability on the Approach

If a pilot restrains an aircraft to follow a rectilinear flight path using stick only (throttle setting is kept fixed) the Phugoid mode is replaced by an aperiodic mode with a time constant given by

$$t_{1/2} = V_0 \log_e 2 / \left\{ 2g \left(\frac{C_D}{C_L} - \frac{\partial C_D}{\partial C_L} \right) \right\}. \tag{4.3}$$

Above the minimum drag speed this time constant is positive and speed errors will decrease. Below the minimum drag speed a speed instability is experienced with a time to double amplitude given by the same equation. Use of the throttle can stabilise this divergence.

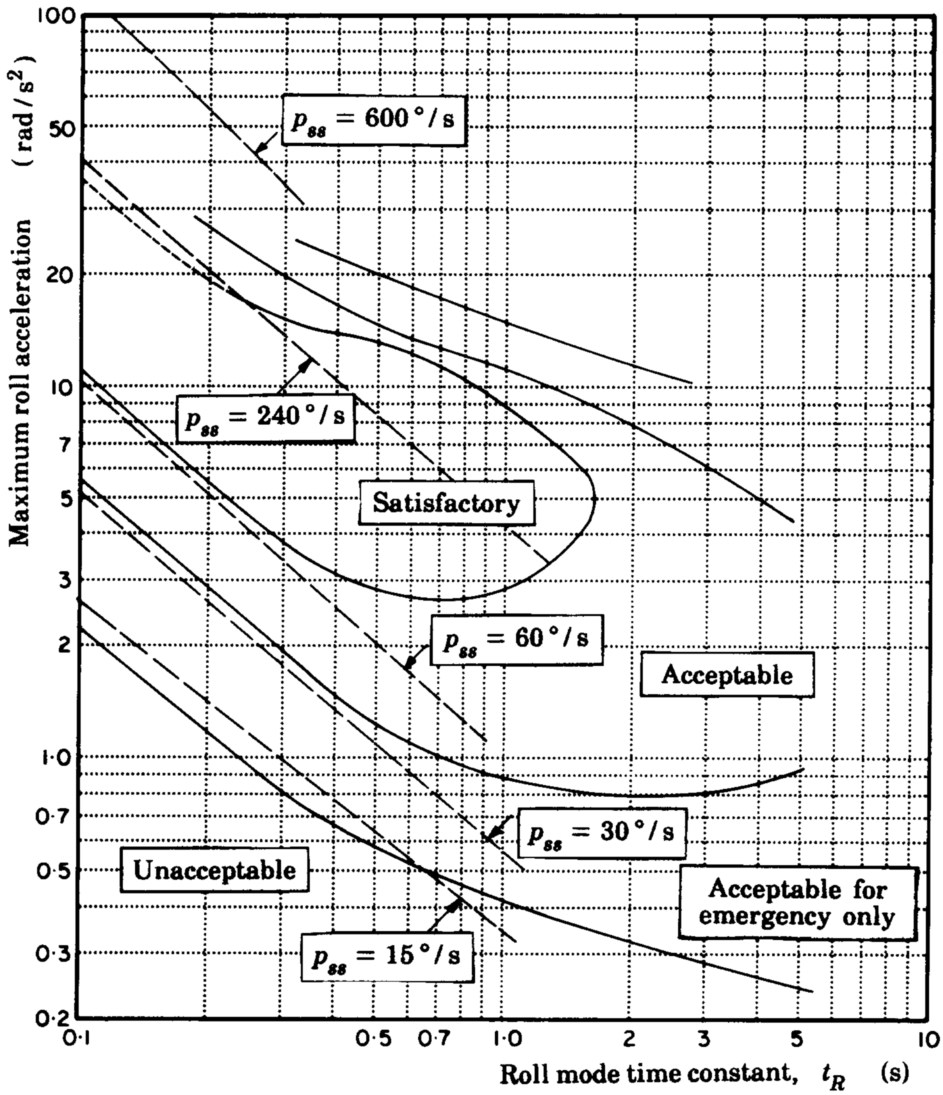
With an aircraft in initial steady-state flight there is another effect associated with minimum drag speed. If a decrease of speed is introduced using the elevator, throttle setting fixed, the new steady-state associated with this change results in a climb when above the minimum drag speed and a descent when below. Pilots prefer the former behaviour, *i.e.* when the aircraft is above the minimum drag speed.

4.4 Roll Mode

The predominant lateral controlling manoeuvre is rolling; it is used for keeping wings level in disturbances and for changing heading. The ideal roll control would be one that involves pure roll response and achieves a steady rate of roll quickly. Quite good approximations to this ideal occur in practice. The motion consequently is completely defined by the roll time constant, t_R, and the control power, $l_\xi \xi$. The control power is the maximum (initial) roll acceleration. Pilot opinion boundaries for the roll response, for fighter-type aircraft, are shown in Sketch 4.5, where the maximum roll acceleration is shown versus the roll mode time constant. At low values of t_R the pilot opinion boundaries correspond closely to the curves of constant values of steady roll rate, p_{ss}. The sketch also shows that t_R values greater than about 1.5 seconds are not satisfactory regardless of the control power available. The roll response acceptable boundary is greatly affected by the control system characteristics, the control displacement and the force to produce roll manoeuvres. The control displacement must not be too large, *e.g.* for a transport aircraft with a wheel type control 90° should not be exceeded. However, an upper limit in the sensitivity can be as high as 0.5°/s rate of roll per degree of wheel displacement for satisfactory operation. In terms of control force sensitivity there appears to be a tendency for a higher sensitivity to be associated with high rates of roll and vice versa.

4.5 Spiral Mode

The spiral motion may be considered to be a slowly varying motion where it is assumed that the radius of the spiral path and the rate of roll are changing so slowly that their rates of change are neglected. Also the side forces due to rates of bank, yaw and sideslip are neglected and the angles of bank, yaw and sideslip are assumed small. Spiral stability is a measure of the ability of an aircraft to maintain a given course when trimmed; it rarely affects handling significantly in general flight but may be of importance in the approach. An aircraft with an unstable spiral mode will require active controlling when maintaining a constant heading and will have to ‘hold off bank’ in steady turns since there will be a tendency to roll into the turn. The converse will also be true, *i.e.* a spirally stable aircraft will ‘hold on bank’ and resist heading changes. Pilots are usually unaware of the spiral mode providing its time constant is sufficiently large.



Sketch 4.5 Roll response pilot opinion boundaries for fighter aircraft

4.6 Dutch Roll Mode

The Dutch Roll mode is a short period oscillation having components in yaw, roll and sideslip. For most practical purposes it may be described by the period, the damping and a parameter, such as the amplitude ratio of bank to sideslip, that defines the degree to which the principal freedoms are coupled in this motion. Since this mode involves all three freedoms, yaw, roll and sideslip, it is not easy to present a simplified approximation such as that used for the longitudinal characteristics. Various approximations to the lateral oscillation can be made by suppressing one of the aircraft freedoms, such as allowing only rolling and sideslipping while the yawing is suppressed or suppressing rolling and allowing only yaw and sideslip. These approximations may, in some cases, provide sensible results for the Dutch Roll oscillation but, since the motion depends in a complicated manner on the derivatives, it is extremely difficult to predict when the approximations will be adequate

For low altitude flight the problem is one of yawing and how quickly this damps out, whereas for high speed aircraft, operating at high altitudes, rolling motion becomes more prominent. For the yawing type motion the pilot is most affected by cyclic damping, while for the motion including rolling the pilot requires increased damping and is sensitive to the roll/sideslip ratio.

5. FLYING QUALITY REQUIREMENTS

Flying quality requirements are intended to ensure that satisfactory flying and handling qualities are obtained in flight and on the ground, regardless of the type of aircraft. The civil and military requirements do not differ in this basic objective, namely that the aircraft must be safely controllable and manoeuvrable during all phases of flight and that the pilot must not need exceptional piloting skill, alertness or strength to achieve this requirement.

The civil airworthiness requirements are qualitative in nature and do not provide a comprehensive means of compliance, but the military requirements provide a full detailed set of guidelines that relate particularly to conventional aircraft. The following is an extraction of the most important parts of the UK Design and Airworthiness Requirements for Service Aircraft.

5.1 Longitudinal Flying Qualities

5.1.1 Trim

The aircraft must be capable of being trimmed throughout the flight envelope. The variations of pitch control force and pitch control position with trim airspeed should be smooth and local gradients should be at least neutrally stable. Stable gradients are those involving pull forces and aft displacement of the pitch control to obtain slower airspeeds and the opposite to obtain faster airspeeds. The combined effect of centring, break-out force, stability and force gradient shall not produce undesirable flight characteristics.

Requirements may be relaxed in the transonic and supersonic speed range provided any divergent motion or reversals of gradients of pitch control force are gradual. During rapid variations in speed the control force and position gradients with speed must not be so stable as to cause pilot difficulties. Also in the transonic region the local gradients must not change so rapidly that the pilot experiences difficulty in maintaining a desired pitch attitude or normal acceleration factor.

5.1.2 Long period (or Phugoid) response

The requirement is that the Phugoid oscillation, pitch controls fixed or free, does not cause piloting difficulties incompatible with the required flying quality levels. An acceptable means of complying with this requirement for subsonic flight when the Phugoid and Short Period frequencies are well separated, *i.e.* $(\omega_n)_P < 0.1(\omega_n)_{SP}$, is given in Table 5.1.

TABLE 5.1 Phugoid Damping Ratio Limits

LEVEL	1	2	3
Characteristics	ζ_P at least 0.04	ζ_P at least 0.0	An undamped oscillatory mode with t_2 at least 55 seconds

5.1.3 Low speed flight

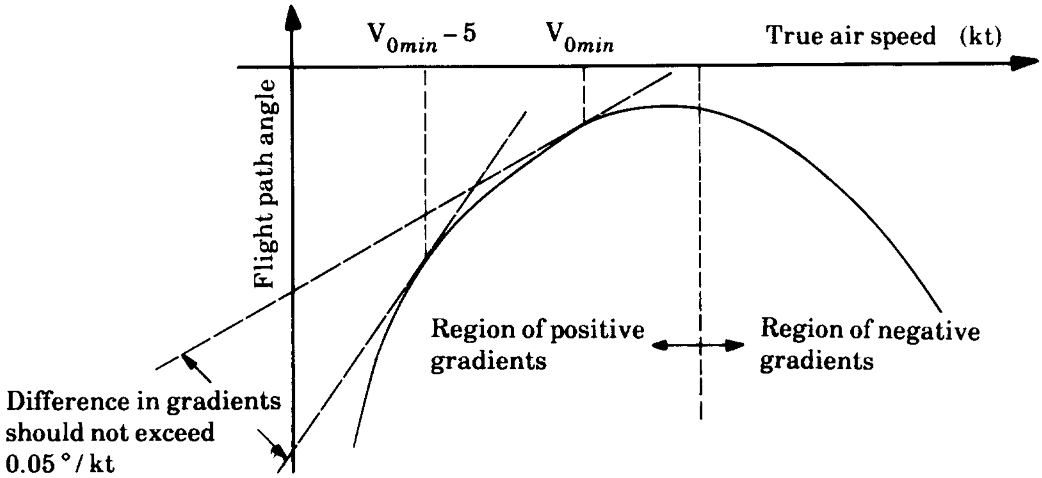
In cases when the flight path is constrained and low speed flight is required, such as in the approach, the gradient of the flight path angle versus true trim airspeed using elevator at constant throttle shall be negative or not so positive as to cause pilot workload inappropriate to flying quality level. Also, the gradient of this curve with decreasing airspeed shall not be so rapid as to cause pilot difficulties. In such a case when pitch control is used to follow a rectilinear flight path the usual phugoid response degenerates into a simple subsidence or divergence and the stability of this mode can be expressed in terms of the rate of change of flight path angle with airspeed. During the approach flight phase this mode will have its greatest effect and suggested gradients of flight path angle versus true airspeed, evaluated at the minimum operational speed,

V_{0min}, should be negative or less positive than the values given in Table 5.2.

TABLE 5.2 Speed Stability Characteristics

LEVEL	1	2	3
Maximum positive gradient of flight path angle versus true airspeed @ V_{0min} (°/kt)	0.0	0.15	0.24

To comply with the requirements for rate of change of flight path angle with airspeed this gradient at 5 knots slower than at V_{0min} should not be more than 0.05°/kt more positive than the slope at V_{0min} (see Sketch 5.1).



Sketch 5.1 Flight Path Angle versus True Airspeed

5.1.4 Short Period response

The Short Period frequency boundaries for acceptability are shown in Figures 5.1, 5.2 and 5.3. These boundaries are functions of the change of the steady-state normal acceleration factor per unit angle of attack. The three figures relate to the three flight phases, Categories A, B and C (see Table 3.2).

The Short Period frequency and the ratio of the steady-state normal acceleration factor change to angle of attack change are related to the manoeuvre margin, H_m, by the following approximate expression:

$$H_m \propto (\omega_n)_{SP}^{\ 2}/n_a, \qquad (5.1)$$

and therefore lines of constant $(\omega_n)_{SP}^{\ 2}/n_a$ represent lines of constant manoeuvre margin.

The Short Period oscillation damping ratio, ζ_{SP}, limits are given in Table 5.2. These values are considered appropriate for flight in severe turbulence conditions. The footnote to Table 5.2 reflects the reduction of turbulence intensity with altitude.

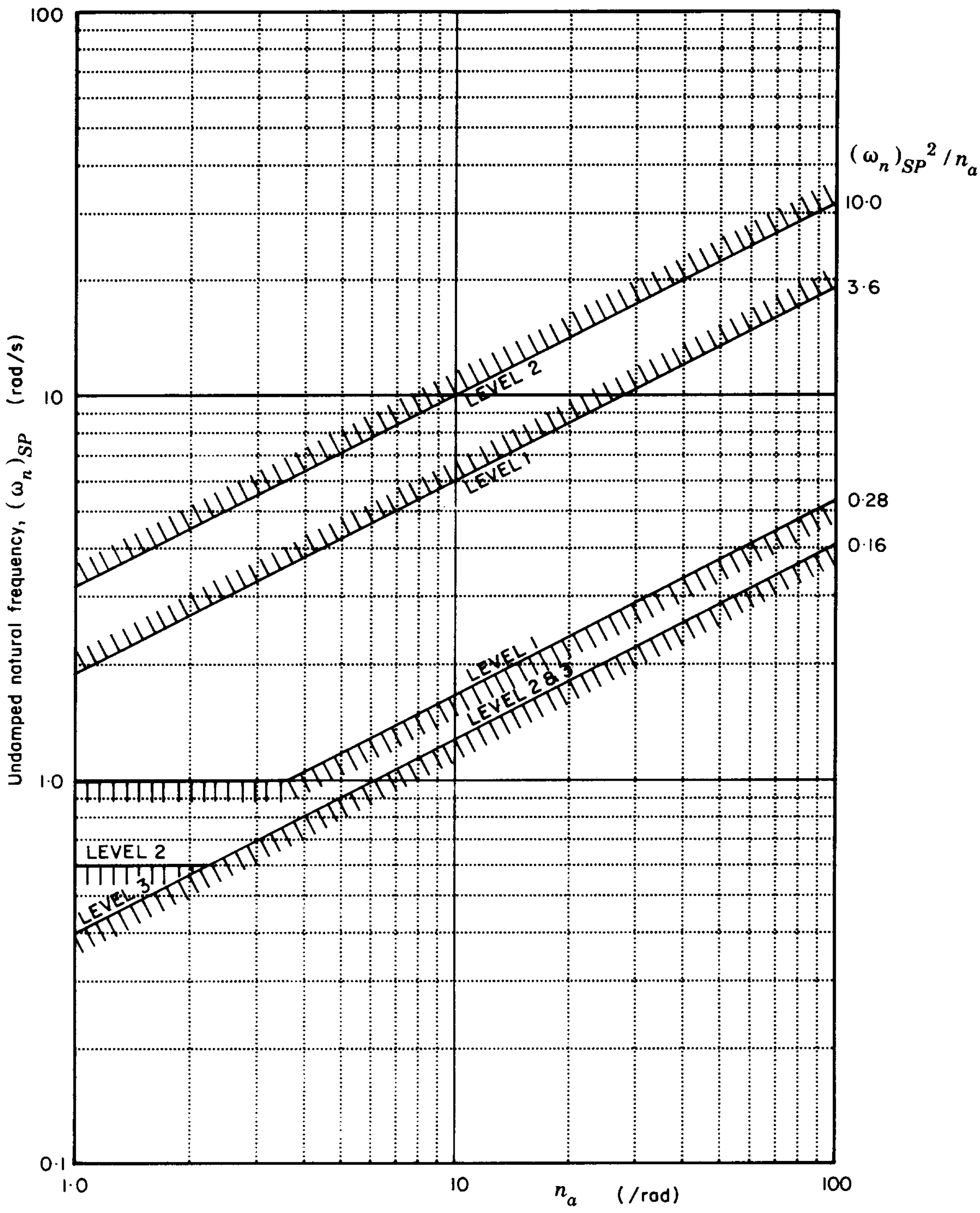


FIGURE 5.1 Short period frequency characteristics Category A Flight Phase

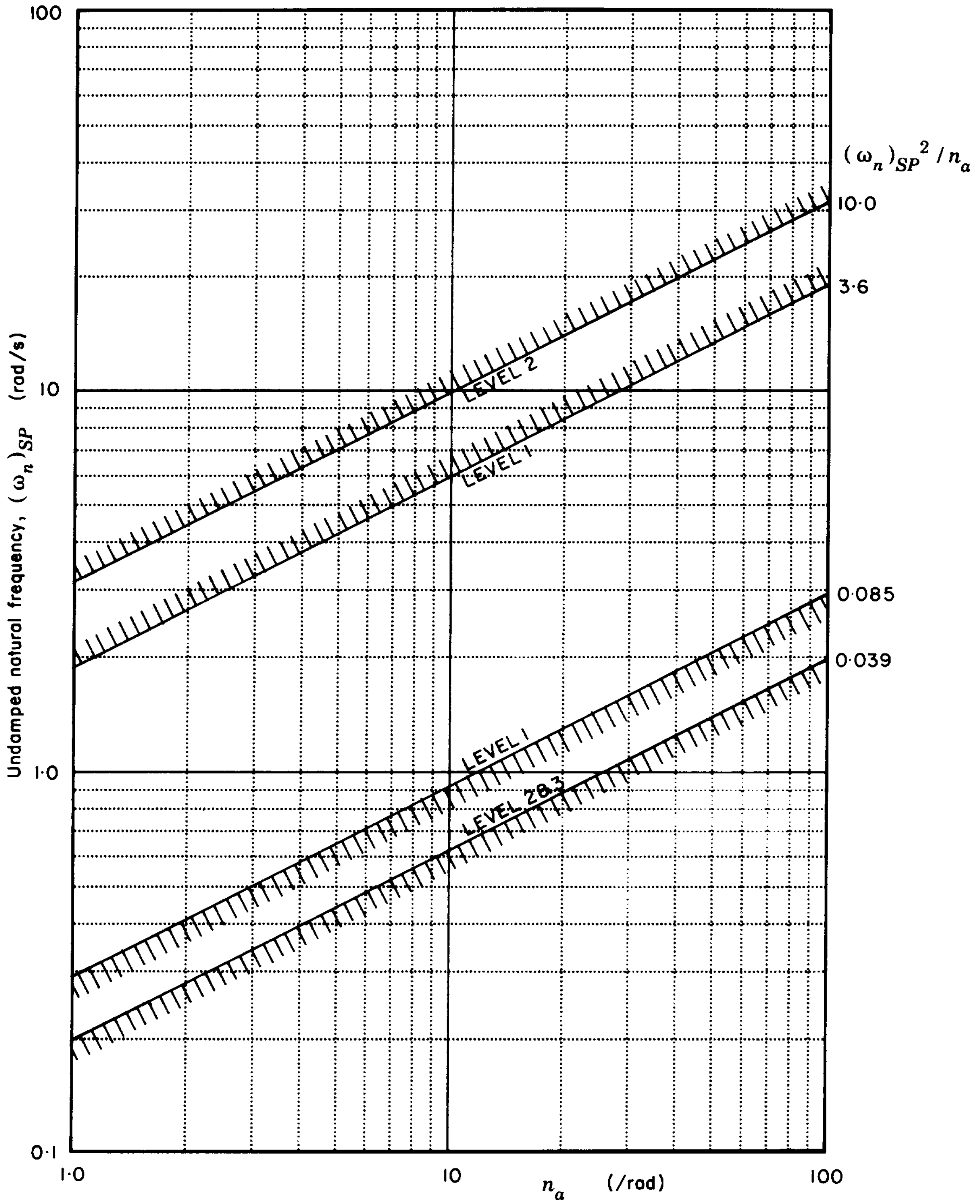


FIGURE 5.2 Short period frequency characteristics Category B Flight Phase

Minimum values of n_a	$V_0 < 100$ kt	$V_0 > 100$ kt
* LEVEL 1 boundary ** LEVELS 2 & 3 boundary	1.67 1.0	V(kt) / 60 V(kt) / 100

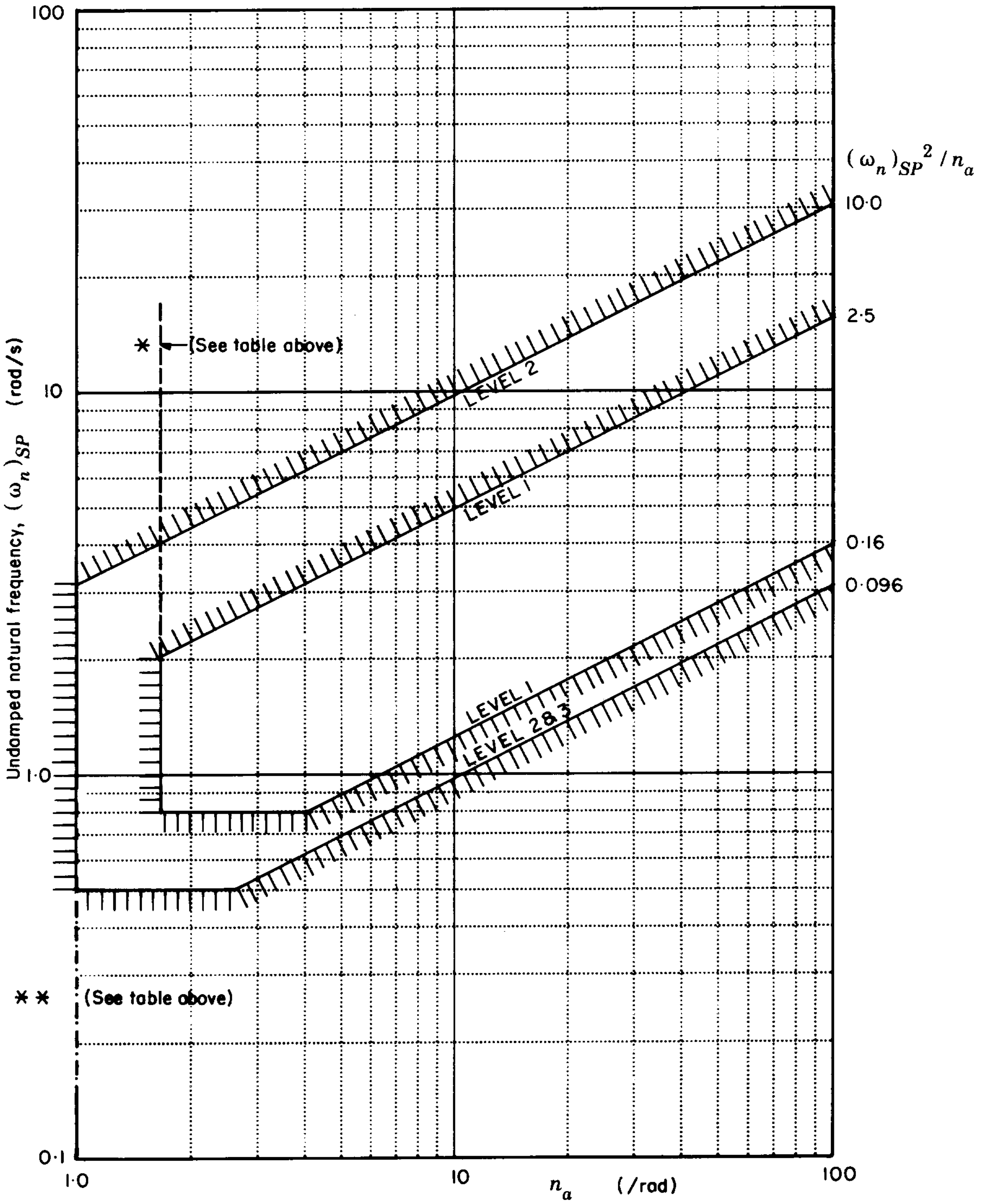


FIGURE 5.3 Short period frequency characteristic Category C Flight phase

TABLE 5.3 Short Period Damping Ratio Limits

FLIGHT PHASE CATEGORY	LEVEL 1		LEVEL 2		LEVEL 3	
	Min	Max	Min	Max	Min	Max
A	0.35	1.30	0.25	2.00	0.10†	–
B	0.30	2.00	0.20	2.00	0.10*	–
C	0.50	1.30	0.35	2.00	0.25	–

† These values, by agreement, may be reduced for altitudes greater than 20 000 ft.

5.1.5 Control feel in manoeuvring flight

The suggested limits for pitch control force gradients are given in Table 5.4 but do not apply within the pre-loaded break-out force and friction band.

TABLE 5.4 Pitch Control Manoeuvring Force Gradients, F_s/n (N/g)

Control Column Type	Level	Maximum Gradient $(F_s/n)_{max}$	Minimum Gradient $(F_s/n)_{min}$
Centre Stick Type	1	$\frac{5000}{(n_z-1)n_a}$ but not more than 125 nor less than $\frac{250}{(n_z-1)}$	The higher of $\frac{500}{(n_z-1)n_a}$ and $\frac{90}{(n_z-1)}$ but not more than 70
	2	$\frac{7500}{(n_z-1)n_a}$ but not more than 185 nor less than $\frac{375}{(n_z-1)}$	The higher of $\frac{50}{(n_z-1)}$ and 9.0
	3	240	9.0
Wheel Type	1	$\frac{10000}{(n_z-1)n_a}$ but not more than 500 nor less than $\frac{500}{(n_z-1)}$	The higher of $\frac{1000}{(n_z-1)n_a}$ and $\frac{180}{(n_z-1)}$
	2	$\frac{15000}{(n_z-1)n_a}$ but not more than 750 nor less than $\frac{750}{(n_z-1)}$	The higher of $\frac{150}{(n_z-1)}$ and 25
	3	1000	25

5.2 Lateral and Directional Flying Qualities

5.2.1 Roll mode

Acceptable values of the roll mode time constant, t_R, are given in Table 5.5. There is some evidence to suggest that the parameter

$$\frac{1}{V_0 \omega_D}\left[\frac{\phi}{\beta}\right]_D \qquad (5.2)$$

may influence the value of t_R required to give satisfactory control in turbulence. As a rough guide the values of t_R quoted in Table 5.5 should prove adequate when this parameter is less than 0.005 approximately. If the parameter exceeds 0.01 the values in Table 5.5 should be halved to ensure good control in turbulence.

TABLE 5.5 Maximum Values of Roll Mode Time Constant, t_R

CLASS	FLIGHT PHASE CATEGORY	t_R (s)		
		LEVEL 1	LEVEL 2	LEVEL 3
I, IV	A	1.0	1.4	Insufficient evidence to define an upper limit. Limited evidence suggests a value of 6 to 8 seconds for all flight phases and aircraft classes.
II, III	A	1.4	3.0	
All Classes	B	1.4	3.0	
I, IV	C	1.0	1.4	
II, III	C	1.4	3.0	

Coupling between the roll and spiral modes can lead, it is believed, to inferior task performance or excessive workload or both. This condition should be avoided or shown not to limit the aircraft role.

5.2.2 Spiral mode

Spiral mode acceptability is assessed in terms of the minimum time to double the bank angle for an aeroplane initially in trimmed level flight with zero yaw and stick free but following a disturbance in bank of up to 20°. Minimum values are given in Table 5.6. These values are considered to make sufficient allowance for the effects of turbulence.

TABLE 5.6 Minimum Time to Double Bank Angle, t_2 (s)

FLIGHT PHASE CATEGORY	LEVEL 1	LEVEL 2	LEVEL 3
A, C	12	8	5
B	20	8	5

5.2.3 Dutch Roll mode

Minimum Dutch Roll frequency and damping requirements are given in Table 5.7.

TABLE 5.7 Minimum Values of Natural Frequency and Damping Ratio for the Dutch Roll Oscillation

CLASS	FLIGHT PHASE CATEGORY	Minimum values								
		LEVEL 1			LEVEL 2			LEVEL 3		
		ζ_D	$\zeta_D\omega_D$ (rad/s)	ω_D (rad/s)	ζ_D	$\zeta_D\omega_D$ (rad/s)	ω_D (rad/s)	ζ_D	$\zeta_D\omega_D$ (rad/s)	ω_D (rad/s)
IV	A (CO, GA)	0.4	–	1.0	0.02	0.05	0.5	0.0	–	0.4
I, IV	A	0.19	0.35	1.0	0.02	0.05	0.5	0.0	–	0.4
II, III	A	0.19	0.35	0.5	0.02	0.05	0.5	0.0	–	0.4
All Classes	B	0.08	0.15	0.5	0.02	0.05	0.5	0.0	–	0.4
I, IV	C	0.08	0.15	1.0	0.02	0.05	0.5	0.0	–	0.4
II, III	C	0.08	0.10	0.5	0.02	0.05	0.5	0.0	–	0.4

Note: The governing damping requirement is that yielding the larger value of ζ_D except for Class III for which $\zeta_D = 0.7$ is the maximum required.

The values of damping given in Table 5.7 should ensure adequate handling qualities in moderate turbulence. For aircraft designed to operate in severe turbulence the minimum values of $\zeta_D\omega_D$ should be increased and should not be less than that obtained from

$$\zeta_D\omega_D = G\left(\frac{\omega_D^{\,2}}{V_0}\left[\frac{\phi}{\beta}\right]_D\right) - 0.15\,, \tag{5.3}$$

where G is obtained from Table 5.8.

TABLE 5.8 Values of G for Calculating $\zeta_D\omega_D$ in Severe Turbulence

Level	G	
	V_0 (m/s)	V_0 (ft/s)
1	3.4	11.1
2	1.6	5.15
3	0.95	3.10

5.2.4 Manoeuvring characteristics

When the roll response to step inputs in roll control contains an oscillatory component, the roll rate at the first minimum following the first peak should be of the same sign and not less than the percentages given in Table 5.9. The change in bank angle must always be in the same direction as that of the roll command for all levels.

TABLE 5.9 Roll Rate at the First Minimum as a Percentage of Roll Rate at the First Peak

Flight Phase Category	Percentage†	
	Level 1	Level 2
A and C	60	25
B	25	0

† These conditions should be met with the roll control held fixed until the bank angle has changed by at least 90° for Category A and 60° for Categories B and C.

The allowable increments in sideslip angle following a step roll control command should be less than the values specified in Table 5.10, where the parameter k is defined as

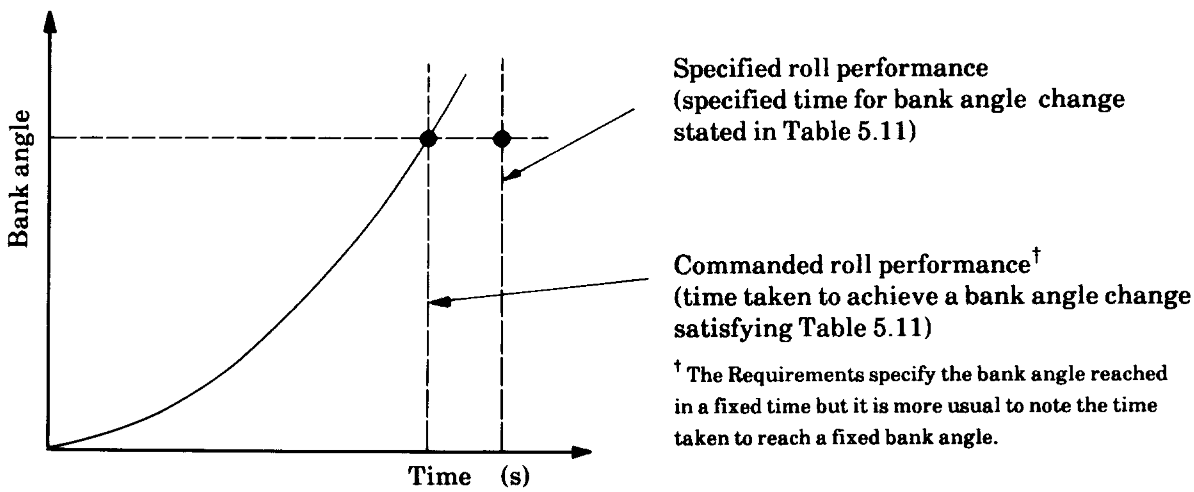
$$k = \frac{\text{commanded roll performance}}{\text{specified roll performance}} \tag{5.4}$$

and is illustrated in Sketch 5.2.

TABLE 5.10 Maximum Increments of Sideslip (degree)

Flight Phase	Adverse Sideslip (Right roll command causes sideslip to the right)†		Proverse Sideslip (Right roll command causes sideslip to the left)†	
	Level 1	Level 2	Level 1	Level 2
A	6 k	15 k	2 k	4 k
B and C	10 k	15 k	3 k	4 k

† The footnote to Table 5.9 applies



Sketch 5.2 Bank Angle versus Time

The roll performance of an aircraft is specified in terms of the time taken to achieve a given change of bank angle, as detailed in Table 5.11. The performance requirements apply to roll commands to right or left initiated from wings level flight or from steady bank angles.

TABLE 5.11 Roll Performance

Class	Flight Phase Category	Time to achieve stated change of bank angle		
		Level 1	Level 2	Level 3
I	A B C	60° in 1.3 s 60° in 1.7 s 30° in 1.3 s	60° in 1.7 s 60° in 2.5 s 30° in 1.8 s	60° in 2.6 s 60° in 3.4 s 30° in 2.6 s
II II II	A B C	45° in 1.4 s 45° in 1.9 s 30° in 2.5 s	45° in 1.9 s 45° in 2.8 s 30° in 3.5 s	45° in 2.8 s 45° in 3.8 s 30° in 5.0 s
III	A B C	30° in 1.5 s 30° in 2.0 s 30° in 3.0 s	30° in 2.0 s 30° in 3.0 s 30° in 4.5 s	30° in 3.0 s 30° in 4.0 s 30° in 6.0 s
IV†	A B C	90° in 1.3 s 60° in 1.7 s 30° in 1.0 s	90° in 1.7 s 60° in 2.5 s 30° in 1.3 s	90° in 6.0 s 60° in 3.4 s 30° in 2.0 s

† Roll performance requirements that take precedence over these listed here are given in Table 5.12.

TABLE 5.12 Alternative Roll Performance for Class IV Aircraft

	Air-to-air combat. Time to roll through		Ground attack with external stores.
Level	90°	360°	Roll performance:
1 2 3	1.0 s 1.3 s 1.7 s	2.5 s 3.7 s 4.4 s	90° in 1.7 s 90° in 2.6 s 90° in 3.4 s

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THE PREPARATION OF THIS DATA ITEM

The work on this particular Data Item was monitored and guided by the Dynamics Committee, which first met in 1962 and now has the following membership:

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