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A background to the handling qualities of aircraft

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The Dynamics Committee, which first met in January 1962, has the co-operation of many engineers and scientists in industry, research establishments and universities from whom much assistance and unpublished information is being received.

A BACKGROUND TO THE HANDLING QUALITIES OF AIRCRAFT

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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 kg) and large aeroplanes (> 5700 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-1797¹¹.

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.

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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).