PREDICTION OF AIRCRAFT FLYING QUALITIES BY FLIGHT SIMULATORS AND OTHER METHODS, WITH FLIGHT COMPARISONS

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ABSTRACT

The factors affecting a pilot's impressions of the flying characteristics of an aircraft are considered. The ways in which flying qualities may be assessed in terms of known handling criteria are illustrated, and also the determination of some aspects of the overall flight dynamics from free-flying models. The extent to which flight simulators enable pilots' assessments to be made, and the importance of visual and motion cues are discussed. Examples are given comparing predicted characteristics with flight values.

INTRODUCTION

In any exercise directed at the assessment of aircraft flying qualities, whether by theoretical estimation or by the use of experimental techniques like flight simulation, it is useful first of all to consider what the handling characteristics depend on. It is self-evident that the flying behaviour of an aircraft depends on some physical characteristics which may be defined in quantitative terms, such as dynamic response, control feel, and so on, but a pilot's impressions are also affected by other features including cockpit position and layout, view, instrument display, and in fact the whole flight environment in which he has to operate. The way in which all these features present themselves to the pilot effectively establishes his subjective assessment of the handling qualities of the aircraft. The relative importance which the pilot attributes to the different types of sensory information he is receiving can be expected to vary according to the flying task with which he is concerned, and the reliability and accuracy of an assessment of

flying qualities will depend on the extent to which the different factors can be taken into account and on the balance of significance given to them.

Various methods are used to predict handling qualities, taking different aspects into account, and to varying degrees, either directly or indirectly. The basic stability and response characteristics of the aircraft, for example, can within certain limits be estimated, making use of wind-tunnel aerodynamic data, and compared against known handling criteria, derived empirically from flight experience. Some dynamic motions, however, such as spinning, and the transition from wing-borne to jet-borne flight on VTOL aircraft, are beyond the scope of conventional linearised analysis. Although analogue computers may extend the field open to analysis, the study of more complicated motions, where, for example, nonlinear and cross-coupling effects are important, may be satisfactorily made only by the use of dynamically scaled free-flight models. This has long been the practice in connection with spinning behaviour, but the method has more recently been applied to the investigation of other dynamic motions, including the low-speed characteristics of highly swept-wing configurations.

With both of these approaches to the assessment of flying qualities, there may still be uncertainty as to how the pilot will react to, and control, unfamiliar combinations of oscillatory motions, coupling between motion in different degrees of freedom and so on; also, how handling criteria based on handling investigations on particular aircraft, extrapolate to aircraft differing in certain respects, even of an apparently secondary nature, such as view and cockpit position. The nature of the task for which an assessment is required may also differ from that for which the criteria were established. There can be circumstances, therefore, in which a reliable assessment is possible only when direct pilot participation is included, and increasing use has been made in recent years of facilities which make this possible, like ground-based simulators and variable stability aircraft. The aim in both of these methods is to provide a representative flight environment for the pilot, through visual and other sensory information, to permit handling assessment in situations not covered by existing aircraft experience.

Some progress has also been made with a theoretical method for the prediction of flying qualities. This makes use of the techniques of servomechanism analysis, and the pilot's action is represented by a transfer or "describing" function; it is postulated that the values of the parameters in the describing function necessary to achieve the desired closed-loop response in, for example, a tracking task, are related to the pilot's rating of the system he is operating.

In this paper, a brief account is given of some recent R.A.E. work in connection with the prediction of flying qualities, which has related particu-

larly to handling criteria [1], the study of flight dynamics by free flight models [2], and the development of ground based flight simulator techniques [3]. Illustrative examples are given showing the comparison between predicted and actual flight characteristics.

EVALUATION OF FLYING QUALITIES FROM HANDLING CRITERIA

It has been pointed out that a pilot's impressions of the flying characteristics of an aircraft depend on all the sensations and information reaching him which may influence his assessment of the flight state; the range of factors involved is indicated in Fig. 1. However, up to present, the development of a method for a generalised evaluation of handling, in this broad sense, has not been found practicable, and attention has been given more to what might be termed the "primary" handling aspects—that is, the basic stability and response characteristics of aircraft and control systems, represented by the "aircraft dynamics" and "control system" blocks in Fig. 1. The aircraft is considered to have "good" handling characteristics if desired states of flight can be maintained, or manoeuvres completed, with little mental or physical effort, and conversely bad handling characteristics if large effort is required.

Over the years much data have been gathered together, both from particular aircraft types but also from extensive work on variable stability aircraft and simulators, and correlating pilots' opinions of handling with aircraft stability characteristics. Analysis in this way has helped understanding of pilots' assessments, which naturally have been in general descriptive terms like "sensitive or sluggish," "light and heavy" and so on. Adopting the common assumption in stability theory of treating longitudinal and lateral motions independently (not always rigorously correct in
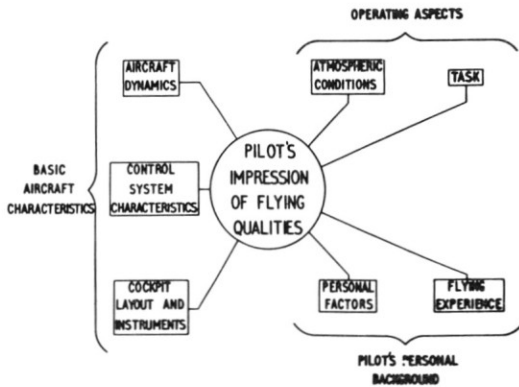

Figure 1.   Factors affecting pilot's impressions of flying qualities.

practice) iso-opinion charts have been produced relating pilot opinion to some of the main parameters of the motion in different planes. The familiar types of opinion contours for the longitudinal short period oscillation (involving pitching and normal acceleration), are shown in Fig. 2, as a function of the undamped natural frequency and damping ratio. It will be seen that the aircraft is deemed sluggish at lower natural frequencies, at medium frequencies there is a tendency to pilot induced oscillatory motions, while if the frequency is too high, response can be too fast and over sensitive.

Charts of this type so far produced, mainly relate particularly to fighter type aircraft, but recently effort has been given in R.A.E. to extending the handling criteria to make them specifically applicable to large aircraft, taking into account available data and allowing for the reduced manoeuvre requirement of larger aircraft. Attention has been concentrated most on the low-speed regions appropriate to takeoff and landing, because large aircraft spend a large proportion of their high-speed flight time under automatic control, and the low-speed phases tend to be most critical from a handling point of view.

The resultant longitudinal handling contours are qualitatively similar to those for the fighter-type aircraft in Fig. 2. However, certain novel flight characteristics of large aircraft of elongated longitudinal shape [4]—so-called inertially slender types—including delay in control response following initiation of a flare, for example, may require reconsideration when further flight experience is available.

For lateral-directional handling, three distinct modes have to be considered—the dutch roll, roll subsidence, and spiral mode. Basically the pilot is not concerned with the character of these modes, but with the behaviour of the aircraft in response to his control demands and to external disturbances. This behaviour is, of course, determined by the stability
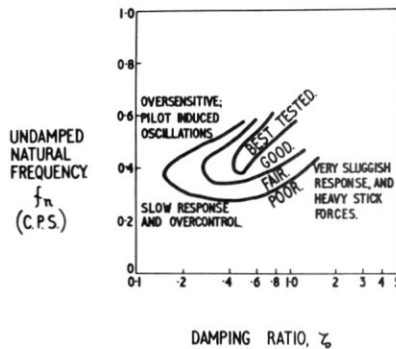

Figure 2.   Pilot's handling and short period oscillation characteristics.

characteristics and by other parameters such as control sensitivity. When aileron excitation of the dutch roll is not excessive, roll-control power required appears to be a function of the roll-subsidence time constant only, as shown in the contours in Fig. 3. Spiral stability is a measure of an aircraft's ability to maintain a given course when trimmed. It is not normally of great consequence to the pilot, providing its time constant is sufficiently long—that is, if it is approximately of neutral stability. Providing aileron yawing moments do not complicate the control problem, pilots' impressions of the dutch-roll behaviour on the approach appear to be influenced only by the period, damping, and a roll-yaw parameter, such as ϕ/β, which defines the degree to which the principal freedoms are coupled. In the iso-opinion contours shown in Fig. 4, it will be seen that pilots' assessments
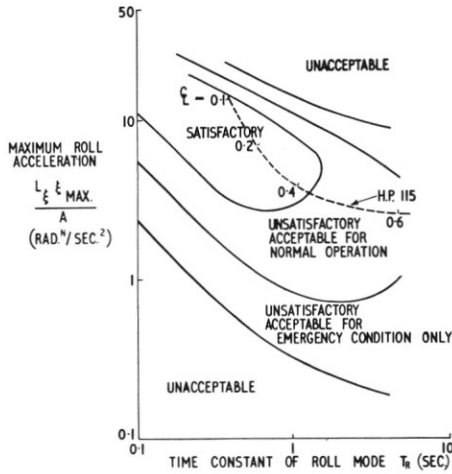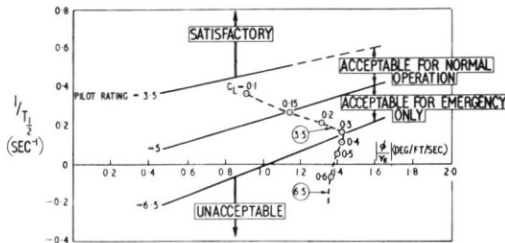

Figure 3.   Roll power requirements.

FIGURES IN CIRCLES DENOTE APPROXIMATE
PILOT OPINION RATINGS OF H.P.115 IN MODERATE TURBULENCE.

Figure 4.   Pilot's opinions of dutch roll characteristics.

have been expressed in terms of the well-known Cooper scale [5], defining ease or difficulty of handling in numerical terms.

It has long been known that pilots' opinions of lateral characteristics can be much affected by control coupling between the roll and oscillatory modes. Recently it has been found by the application of closed-loop servo analysis to a study of the pattern of aileron control of lateral motion that the principal factors affecting pilots' control are the dutch-roll damping, and ω_ϕ/ω_d, a parameter in the aircraft transfer function; ω_ϕ/ω_d is in fact a measure of the yaw excitation generated by roll control. Servo analysis suggests that the achievement of good closed-loop stability becomes more difficult as ω_ϕ/ω_d increases. On the other hand, for $\omega_\phi/\omega_d < 1$ undesirable adverse aileron yaw effects arise, and for $\omega_\phi/\omega_d < 0.7$, rolling reversal is likely to occur. It has been suggested, although there is as yet little experimental evidence to work from, that for compromise between stability and manoeuvre requirements ω_ϕ/ω_d should be nearer 1.0.

In the past, lateral control power determined by manoeuvring requirements has been more than sufficient in general to deal with disturbances due to turbulence. With highly swept wings, however, which can be sensitive to turbulence, this may no longer be true, and proposals have recently been put forward for a requirement defining the maximum proportion of aileron control permissible to limit bank angle to 5° in response to a 10-knot step side gust. Difficulty may arise from the possibility that the relatively large control powers determined on this basis might tend to exceed the upper limit of acceptability for manoeuvring.

APPLICATION TO PARTICULAR AIRCRAFT

Whatever analytical methods are proposed for the assessment of the aircraft flight dynamics, their reliability depends on the accuracy with which the characteristics, aerodynamics, inertia, etc., can be predicted. Developments in wind-tunnel testing have made possible more complete measurements of dynamic derivatives, including oscillatory stiffness and damping derivatives, in both subsonic and supersonic wind tunnels. The determination of aircraft inertia characteristics has provoked more difficulty than might have been expected. Estimates, even when made with the benefit of detailed weight data during construction, have been found to be significantly in error, especially in the prediction of the inclination of the principal inertia axis. Accurate measurements have been achieved up to the present only with small aircraft, and this only by most thorough methods, to ensure absence of flexibility in supports, and accuracy of measurements made. Major difficulties are foreseen in making accurate inertia measurements for large aircraft.

During the design stages of an aircraft, existing handling criteria have to be used for guidance as to the probable handling qualities of the project, and in some cases design modification may be required because of indications of unsatisfactory handling characteristics. The situation is kept under review as better wind-tunnel and inertia data become available, but very seldom is there a final detailed comparison made between the predicted handling characteristics and those found in flight, or even between the wind-tunnel and flight measurements of aerodynamic characteristics.

An interesting example of where such comparison has been possible was on the HP-115 slender delta research aircraft, comparison having been made both of aerodynamic derivatives and handling. The handling qualities predicted for the HP-115 during the design stage, based on existing criteria and limited, rather crude, simulator tests were far from encouraging; two features giving particular cause for concern were the dutch-roll characteristics, at the lower flight speeds, and the sensitivity to cross winds and side gusts. In practice, handling has proved to be remarkably easy, even in cross winds and in turbulence levels, relatively high for an aircraft of this low wing loading. First indications from flight measurements, analysed using estimated inertias, were that some of the main aerodynamic derivatives were more favourable than tunnel tests had shown; in particular at high C_L conditions n_v appeared greater and $-l_v$ less. However, when measured inertia values became available these apparent discrepancies were largely removed, as shown in Fig. 5. The actual dutch-roll behaviour does not differ greatly from that predicted, and the measured characteristics are compared with conventional handling criteria for the landing approach in Fig. 4. It will be seen that the HP-115 would be rated unacceptable for
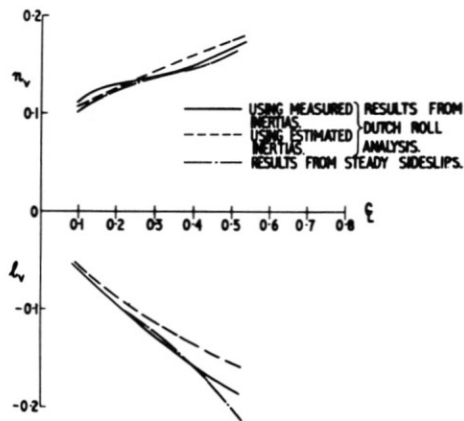

Figure 5. Effect of inertia differences on aerodymanic derivatives.

speeds less than about 95 knots ($C_L > 0.3$) but in practice the pilot ratings were much better than this. The reasons for the unexpectedly favourable opinions are not fully understood, but pilots' comments indicate a keen awareness of the high-rolling accelerations, and suggest that instinctive reaction to these accelerations, coupled with suitable roll control (see Fig. 3), is sufficient to check disturbances from developing.

It may also be noted, however, that the values of ω_ϕ/ω_d for the lower speed conditions, are much less than the postulated optimum value of near 1.0. There is clearly more to be learned about appropriate handling criteria for slender-wing configurations.

STUDY OF FLIGHT DYNAMICS BY FREE-FLIGHT MODELS

The study of the motion of free-flight models has the attraction of providing direct evidence of an aircraft's dynamic characteristics without the need for analytical formulation of aerodynamic data, which is required for the solution of the theoretical equations of motion. Techniques employing models which are both geometrically and dynamically similar to an aircraft can be used to study the stability and response over a wide range of flight conditions, since apart from aerodynamic scale effects the flight paths of the models reproduce the actual flight situation on a reduced scale. The free-flight model may be the only practicable method of investigation when the aerodynamic derivatives are markedly nonlinear and frequency dependent, or where cross coupling terms are important.

The method has been extensively used for many years for the investigation of the spinning characteristics of fighter aircraft. Dynamic scale models are released from a helicopter, with controls set in a pro-spin position. As the model glides down, a preset programme of recovery control movements is operated mechanically within the model. In this way, a full picture is obtained of the spinning characteristics, including entry and recovery.

It is also of interest that techniques have been in use for some time in the United States, in which the dynamic characteristics of aircraft have been studied by the use of controlled and power free-flying models which are "flown" by a team of "pilot" operators. The method has been applied particularly to the investigation of the dynamic motions of V/STOL aircraft, such as the transition from vertical to forward wing-borne flight. Stability derivatives have been evaluated in this way, and assessments made of handling qualities, but the latter may be of uncertain validity since several "pilots" are involved, relying solely on visual stimuli and operating on the contracted time scale of the model. Fairly elaborate facilities are required for this type of test and it has not been widely adopted

outside the United States. The free-dropping-model technique, however, does appear to offer simple possibilities for more extended use, the phenomenon of inertia cross-coupling being an obvious example of a theoretically complex and dangerous motion, which could usefully be studied in this way. An example is given here of the experimental application of the method to the study of the flight dynamics of slender-wing aircraft configurations, and in particular of the conditions in which the dutch-roll mode becomes undamped.

In tests of this nature, to ensure that aerodynamic scale effects are small, it is generally considered that the Reynolds number (based on mean chord) should be not less than 10^6. While the size of model can be larger than is possible in most wind tunnels, the advantage of this larger scale may be offset by the lower speed required to maintain dynamic similarity; in the case of dynamically similar models (which have the same density at corresponding parts as the full-scale aircraft) there is a fixed relationship between model and full-scale Reynolds numbers.

$$(RN)_m = RN \frac{\nu}{\nu_m} n^{3/2}$$

where $n = l_m/l$ is model scale

$\nu = \mu/\rho$ is kinematic viscosity.

The model span required to achieve a Reynolds number of 10^6 is shown in Fig. 6; it can be seen that models of economic size can be employed when the aspect ratio is low, and the method is particularly suitable for slender-wing configurations.
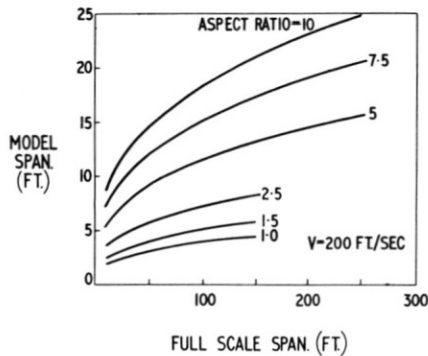

Figure 6. Span of dynamically similar model for mean chord Reynolds number of 10^6.

A disadvantage of this technique is that the model wing loading, being proportional for dynamic similarity to the scale n, is much lower than full-scale. The model is therefore more sensitive to turbulence, and smooth air conditions are necessary for tests.

Tests have been made with slender-wing models to measure stability derivatives and to explore the onset of dutch-roll instability. The models were towed beneath a helicopter and released in forward flight at approximately the trimmed speed; this ensured that there was not a large initial phugoid disturbance. Mechanical operation of the elevator was provided to enable a range of flight conditions to be covered; both internal instrumentation and kine recording were employed.

Derivatives like m_q and m_η have been determined from longitudinal response tests, but it has been found that for the necessary accuracy, high-quality instrumentation is required. In the lateral instability tests, at moderate incidences the dutch-roll mode was well damped, but the damping decreased to zero as a critical incidence value was reached, and became negative beyond this incidence. The undamped oscillations stabilised at amplitudes which appeared to be related to the margin by which the critical incidence was exceeded. Illustrations are given in Fig. 7 of a case in which the dutch-roll oscillation was building up as speed decreased, and of a sustained oscillation of smaller amplitude. A range of model pitch-roll inertia ratios was investigated but the mass distribution did not exert a decisive influence on the onset of dutch-roll instability, which occurred at incidences in the region of 17° to 18°, the corresponding lift coefficients being 0.45 to 0.50. Lateral oscillations of large amplitude were accompanied by a sharp drop in C_L, compared with steady conditions at the

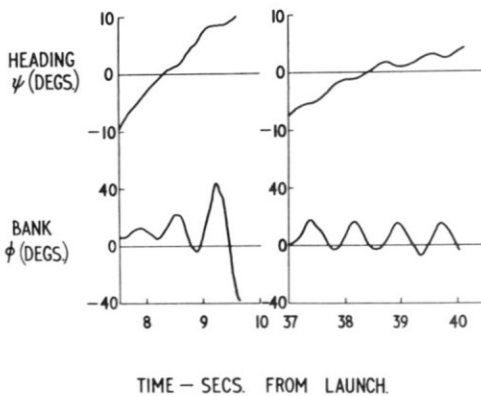TIME — SECS. FROM LAUNCH.

Figure 7.   Lateral oscillations of free flight model.

same incidence, indicating the occurrence of a major breakdown in flow; in fact, Gray has shown that the two leading-edge conical vortices burst alternately during each cycle of the oscillation.

Flight measurements on the HP-115 showed that the dutch-roll damping decreased to zero at a C_L of about 0.55, the corresponding incidence being 19°. The aircraft has, however, been flown to higher incidences without difficulty. The dutch-roll oscillation has been allowed to diverge at low airspeed, with stick fixed, stabilising eventually at bank amplitudes in the region of ±30°; the pilot found he was able quickly and without difficulty to restore a wing's level conditions at the same airspeed.

THE USE OF FLIGHT SIMULATORS FOR HANDLING ASSESSMENTS

The methods considered so far, provide for the estimation or measurement of flight characteristics, and their assessment against known handling criteria. The parameters taken into account in this process include the period and damping of oscillatory modes, coupling between various freedoms, control characteristics, and so on, but at best covering only a limited part of the task of flying the aircraft, which the pilot experiences as a complex whole. The advantages of flight simulators for making handling assessments are that more of these extra elements in the flight situation can be included in the assessment, and—most important—that the pilot himself is enabled to experience the proposed stability and control characteristics, and possibly try out variations on these, at an early stage in a new design.

A flight simulator attempts to provide a form of synthetic aircraft, using a computer to solve the equations of motion continuously and in the correct time scale, and conveying information on the flight state to the pilot in an appropriate form of cockpit. The value of the flight simulation depends on the adequacy of the representation of the flight environment to the pilot. The information required and used by the pilot may vary with the task, and the necessity for full representation may be less important when a generalised or comparative study is being made of desirable flying qualities, than when a handling assessment is being made for a new aircraft design. These questions are considered in the next section.

FACTORS IN FLIGHT SIMULATION

The main factors which have to be considered in making a simulator investigation are shown in Fig. 8. The left-hand group corresponds to the factors shown in Fig. 1 as affecting the aircraft's dynamic behaviour; the middle group represents items which are specific to simulation, that is the

devices used to produce the appropriate flight environment for the pilot, and the third group is concerned with the techniques used in the experiment. The devices for simulation have to include a more-or-less representative cockpit controls system, instrument display, and possibly some external world display and cockpit motion. It is important that the instruments used should correspond closely to normal flight instruments, and the control movement and feel must be to appropriate aircraft standard, because the pilot is acutely sensitive to any deficiencies in this respect. The degree of realism necessary in simulation may be open to debate, but in general it is found that anything further enhancing the illusion of real flight is beneficial. Simulating aerodynamic and engine noise, for example, helps to create the correct atmosphere, and may at the same time hide extraneous noises from the simulator which could be distracting.

Various methods are used to provide an external world display for the pilot, and to reproduce to a limited extent, some of the sensations of movement experienced in the air. In the simulator at R.A.E. Bedford, for example, the cockpit is situated in a planetarium-like building, and a projector mounted just above the pilot's head (Fig. 9) casts an image of the sky and horizon on the surrounding screen. This form of display provides no detail of the ground below the horizon, and no indication of forward movement, and serves only as an attitude reference, suitable for flight studies
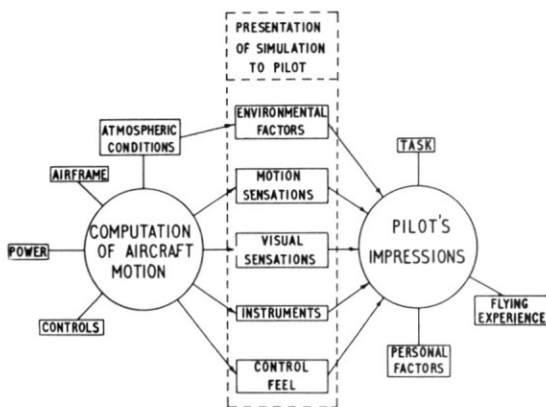

Figure 8.   Factors affecting pilot's impressions of simulated aircraft.

away from the ground. It has been found, however, to provide a more precise attitude reference than a flight-instrument display, because small angular movements are more readily detected through the pilot's peripheral vision.

Figure 10 shows the view seen with a development of the projection equipment, giving a limited amount of ground detail, in the form of a shadow pattern intended to convey the principal perspective features of a runway as seen during landing. The device has proved useful for investigating control problems, such as sidestep manoeuvres, at earlier stages in landing, and for studying positional control during hovering on VTOL aircraft.

A simple method used for simulating a limited visual field presents a line pattern on a television tube in the forward windscreen aperture, to convey the perspective features of a landscape. At the present time a closed-circuit television system is being installed showing a picture taken by a camera moving over a scale model of an airfield. This facility should extend the scope and realism of landing and takeoff investigations very considerably. For low-speed and VTOL applications, a development of the direct projection technique is being used in which a projected image of a detailed transparent three-dimensional model is displayed on the screen beneath and around the simulator cockpit.

The other feature of real flight which it is important to try to simulate, to some extent at least, is the sensation of movement resulting from flight accelerations. It is obviously impossible to reproduce all accelerations fully, but attempts have been made to reproduce motion cues in part, usually by representing only the initial acceleration phase of a manoeuvre. There is some justification for this procedure in that the motion cue in aircraft control often serves primarily to advise the pilot of changing attitude or flight path, before it becomes apparent from the cockpit angular orientation, or from the flight instruments.

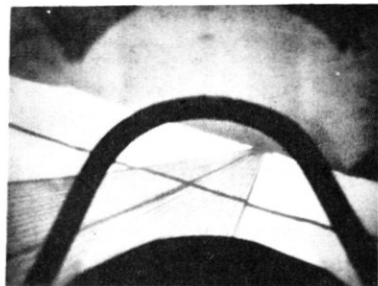Figure 9.   Simulator visual display.

Figure 10.   Runway shadow display.

The cockpit in the simulator at Bedford has two degrees of motion free-dom, giving 30° of travel in pitch (corresponding to 3 ft vertical movement at the pilot's position), and ±15° in roll. Certain subterfuges are necessary to give realistic sensations in manoeuvres. In a steady turn, for example, the cockpit cannot be kept in a banked attitude as this gives a feeling of slipping sideways; instead the cabin attitude applied initially to represent rolling into or out of a turn, is leaked away, and at the same time the indica-tion of the banked attitude is transferred over to the visual presentation. Illusions of this sort about spatial orientation have been found in general relatively easy to achieve in practice, but for realism all motions have to be very smoothly produced.

For effective simulation of some flight manoeuvres, cockpit motion in other degrees of freedom would also be required. The absence of yawing at sideways motion has already been found a deficiency in some cases, and the problems of satisfactorily representing motion when the pilot is remote from the aircraft c.g., as in some large long aircraft, have still to be studied.

The third group of factors in Fig. 8 is concerned with the techniques used in making experiments with the simulator. Even if all the important physical sensations are adequately reproduced, major differences from flight can remain because of absence of operational atmosphere, and the pilot's mental approach to the simulation task is obviously a vital element. It helps to create atmosphere if simulator exercises are treated in a similar way to real flight tests, but it is also important to plan simulator tests in ways that do not strain the pilot's credulity too much in making the mental switch necessary to accept the simulation as equivalent to flying, which some pilots find more difficult than others. More reliable handling assessments are possible on a comparative basis, in which the pilot effec-tively calibrates the simulator in terms of an aircraft he knows, before attempting to study a new type. Much of the uncertainty that relates to simulator assessments is, of course, of the same kind that applies to air-craft-handling assessments, for both rely on pilots' subjective judgement. Some means of measuring pilots' effort and stress in performing a given task is required, but although a number of promising proposals have been made in this connection none has yet been brought to a practical form of development.

THE VALUE OF VISUAL AND MOTION CUES

The importance in simulation of the various visual and motion cues, and of the way in which they are presented to the pilot is still a subject for study. It has been suggested, for instance, that cockpit motion is not essential in certain investigations, like the takeoff and landing of large

transports, for which manoeuvres are slow and gentle, and it results in a useful simplification of equipment if this is confirmed to be true. However, the results in Fig. 11 of experiments to examine the effect of different visual and motion cues for a slender-wing configuration indicate that cockpit motion can be important at least in simulated turbulent conditions. These results relate to the lateral control of an aircraft on meeting a large isolated side gust. Bank angle histories show that the first and second peak angles developed using a television line pattern display and a fixed cockpit, were little less than for the uncontrolled aircraft. With the projection type of display, the peak angles were significantly reduced. With the projection display and the moving cockpit, the bank angles were very much reduced, and in addition much greater consistency was achieved in a number of trials. The aileron records show that the time for the pilot to take corrective action was reduced from 0.7 sec in the first case, to 0.4 sec with the moving cockpit, and the aileron movements are also larger and more decisive.

Another experiment to investigate the effect of simulator motion on lateral control in continuous heavy turbulence showed similar reduction in the spectral densities of bank-angle disturbances. The bank angles without cockpit movement were about three times larger than with movement in the frequency range corresponding to periods of 3 to 4 sec. At higher frequencies, however, the spectral density for the moving cockpit was larger; this can be associated with the brisker and more decisive control movements made by the pilot, the dominant part of the spectral density of aileron angle also showing a shift to higher frequencies when the motion cue is provided.
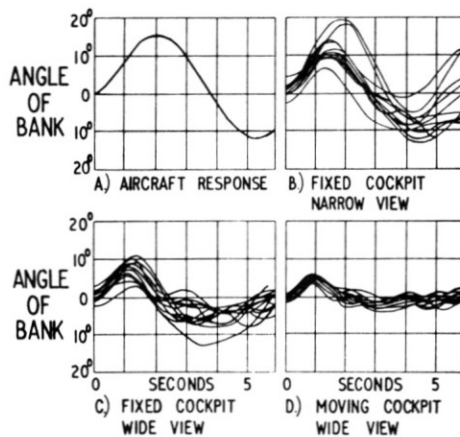
Figure 11.   Bank angle response with various simulator cues.

COMPARISON OF FLIGHT AND SIMULATOR RESULTS

The measure of how well simulation is achieved is the degree of correlation that can be shown with pilots' assessments in actual flight tests. It appears necessary, however, to compare, not only overall handling assessments, for which the same general level can be built up in different ways, but also, for example, flying accuracy, manoeuvring and operating techniques, pilot's control usage, and so on. A range of aircraft of different types have now been tested in the Bedford simulator, and some of the examples already available of comparison with flight results, are given below.

Landing Approach on the Fairey Delta Aircraft. A limited programme of tests has been made to compare flight and simulator assessments of handling qualities in the landing approach, and in a sidestep type of manoeuvre, on the Fairey Delta, a 60° delta supersonic research aircraft. Pilots' impressions in the approach were that the simulator represented the aircraft dynamic motions fairly well, but with differences in some important details. Thus, for example, the simulator provided only pitching and rolling, but not yawing, motion cues; in addition, the sideslip indication was less definite, so that the pilot was much less conscious than on the aircraft, of untidy lateral and directional motions, the correction of which tended to produce a higher work load in the aircraft. This, however, was offset by the fact that the additional motion cues in the aircraft made it easier to assess the flight state at all times. Although the tasks were not identical, raw ILS being provided in the simulator, whereas no approach aids were available on the aircraft, it is still of interest to note that pilots gave approximately the same Cooper scale rating for the handling for both aircraft and simulator.
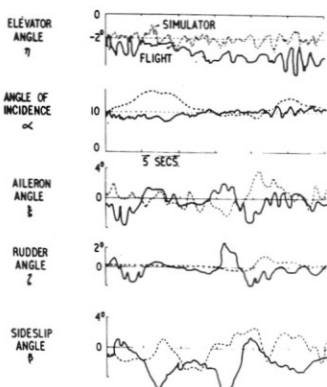

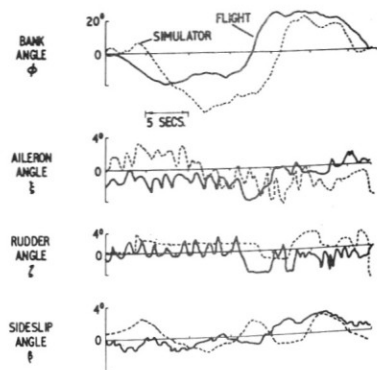Figure 12.   Flight and simulator
approaches of F.D.2.

Figure 13.   Flight and simulator
sidestep manoeuvre on F.D.2.

The records of control angles, incidence, etc., in Fig. 12 show that larger amplitude rudder and possibly elevator angles were used in flight than on the simulator. The incidence variations were considerably larger on the simulator, but attitude variations rather less; these differences might be associated with the provision of ILS on the simulator, but might also be due to the simulator display providing a more definite attitude indication than the pilot normally has in flight. On the other hand, it does not appear that the pilot achieved a notable reduction in sideslip angles in flight despite his greater awareness of directional disturbances.

The records in Fig. 13 of a sidestep manoeuvre show comparable lateral-directional control features. The pilot was asked in both flight and simulator to make as rapid a sidestep manoeuvre as he felt reasonable; the bank-angle records show that he was prepared to go, as might be expected, to a more extreme angle in the simulator than in flight. Aileron useage was similar in both cases, but much freer use of rudder was made in flight than in the simulator where rudder was applied only for specific manoeuvres, and the sideslip angles developed in the initial period were much less in flight than in the simulator. This tends to confirm the pilots' impressions of greater awareness of directional disturbances on the aircraft.

Sideways Movement on SC-1 Jet-Lift Aircraft. A comparison in shown in Fig. 14 of the motions and control actions in a sideways movement of 120 ft on the SC-1 aircraft in moderate wind conditions, with the corresponding records obtained for a simulated VTOL aircraft with similar control sensitivity and damping, in a 100-ft lateral displacement.
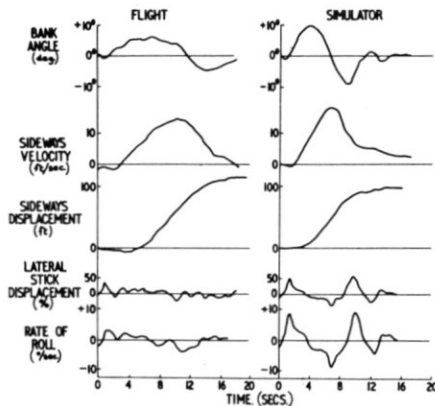

Figure 14. Sideways movement of SC-1 in flight and on simulator.

The aircraft motions in the manoeuvre, bank angle, sideways velocity, etc., are reasonably comparable, in general being rather less in flight. As in the case of the Fairey Delta, however, there is some difference evident in the pilots' control actions, as shown by the lateral-stick-displacement records. In the simulator, control movements are largely linked to manoeuvres, but in flight, manoeuvring demands are overlaid by irregular movements, through which the pilot presumably feels the responsiveness of the aircraft and ensures that he keeps things under control. Some of the difference might be ascribed to the fact that the flight tests were made in moderately windy conditions, but the irregular motions have also appeared in flight records for almost calm conditions.

Takeoff Director Tests on Comet Aircraft. Comparison of the results of takeoff tests on a Comet aircraft, with and without a director aid, has been made with similar results from the simulator, using the projected runway shadow display for the takeoff run and climbout. This comparison provided a useful introductory assessment of the simulation of takeoff, and at the same time gave experience of the simulation of larger aircraft.

Records taken in a large number of takeoffs in flight and on the simulator have been analysed to determine the scatter occurring in such parameters as the rotation speed V_R, the maximum rate of pitch developed in nose up rotation, the maximum elevator angle used, and so on. In general the correlation between simulator and flight is reasonably good. As an example, in Fig. 15 histograms are shown of the wing-lift coefficients at 50 ft; the range of scatter occurring is similar for flight and simulator, and the distributions of C_L values were also comparable.
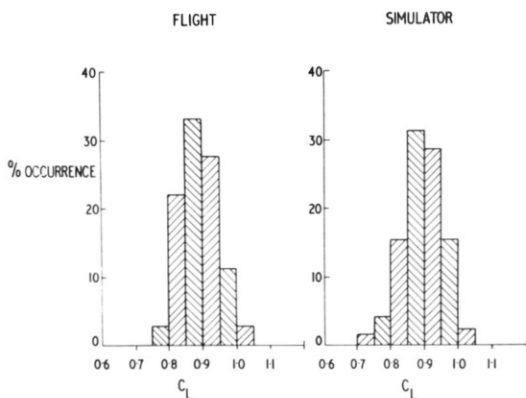

Figure 15.   Histograms of C_L at 50 ft. above ground.

Agreement has also been found between the operating techniques used in the simulator and in flight. An interesting illustration of this was that a difference noted in the takeoff techniques of two pilots on the aircraft was found to carry over to the simulator. In the records in Fig. 16, the variation of lift coefficient with time following unstick shows that pilot A's control application produced a quick direct flare up to high C_L followed by a steady decrease to a lower value both in flight and the simulator; pilot B, on the other hand, flared up to a lower C_L, maintained however for a longer time, and again both in flight and on the simulator.

It has also been found that pilots have been able to learn in the simulator how to control the rotation more accurately, and have subsequently been able to maintain a more consistent performance on the aircraft.

The Handling Characteristics of the HP-115. Tests of the HP-115 aircraft on various fixed based simulators, resulted in handling assessment ratings inferior to those based on actual flight tests. It appears that the pilot is particularly affected in the simulator (for this laterally sensitive aircraft), by the absence of motion stimuli, and tests are now being made with the moving-cockpit simulator. Detailed results are not yet available but first indications are that the cockpit movement does render the simulation more satisfactory to the pilot. Pilots' handling ratings are, in consequence, significantly improved compared to earlier tests and more in keeping with flight assessments.
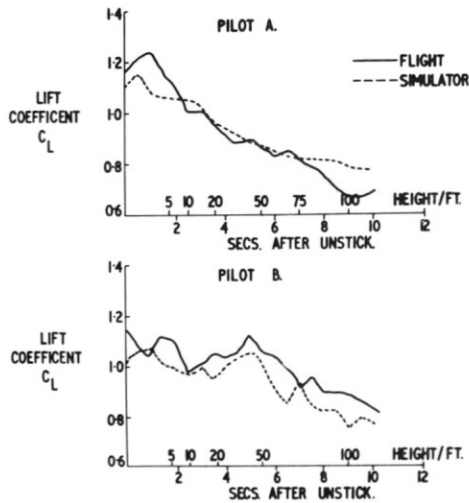

Figure 16. Wing lift coefficients during flare-up.

THE VALIDITY OF SIMULATOR ASSESSMENTS

The comparisons made between flight and simulation results give good grounds for concluding that in general, reliable assessments of handling qualities should be possible from flight simulators. Intelligence and some degree of art, are necessary in interpreting the results of tests, particularly in picking out aspects of which the simulator may be different from flight. It is already clear that, as might be expected, pilots' assessments can be affected by the nature of the visual display and by the extent of cockpit motion, and allowances for inadequacies in these respects may have to be made. One of the interesting general results already noted is that pilots' control actions on the simulator tend to include less random control than in flight, particularly when there is no motion simulation.

CONCLUDING REMARKS

The various methods of predicting handling qualities can be seen to be complementary. Comparison of estimated flying characteristics with existing criteria is the first guide for a new project. For unconventional designs, the relevance of available handling criteria is uncertain, and a flight simulator then offers the simplest way to a handling assessment, the validity of which depends on the representativeness of the simulation. The reliability of the results also depends, of course, on the accuracy of the data used and on the completeness of the mathematical analysis. For more complex motions, and also for an overall check on studies of simple motions, the free-flight model technique is invaluable. The final answer is the flying aircraft, and the dependability of all methods can be determined and improved by more detailed comparisons of predicted and flight results.

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COMMENTARY

G. H. LEE (*Handley Page, Ltd., London England*): When designing the HP-115 we made a very crude simulator (there was no time or money to do better). There was a wooden seat, pilot's controls with feel provided by adjustable springs and representation of the aeroplane (or the horizon) by a line on a cathode-ray tube; in addition, sideslip was shown by a voltmeter. There was no simulation of the appearance of the cockpit and, of course, no cockpit movement.

Despite these severe limitations, the simulator proved valuable. It showed very early that the ailerons originally proposed would have been much too heavy and spring tabs were consequently incorporated, with much subsequent benefit.

The simulator was much harder to fly than the aeroplane subsequently proved to be. The pilot had earlier flown another highly swept airplane, the Short SB-5; we therefore set up this aeroplane on the simulator and so enabled him to "calibrate" the simulator in his mind. This was successful; both aeroplanes were easier in flight than on the simulator, and in both cases the HP-115 was easier than the SB-5.

There is no doubt that cockpit movement is essential for proper simulation; but even for the HP-115 (described by a pilot as "A bundle of rolling accelerations") the very simple simulator was most useful. As Mr. O'Hara said, the use of simulators requires "intelligence and art"; perhaps it needs luck as well.

REPLY

It is true, as Mr. Lee states, that experience with the early crude simulator was helpful in relation to development of the HP-115; this is an illustration of the fact that even relatively simple simulators can be valuable if used with proper understanding. With regard to the need for luck, I think that in this connection, luck will come to those that deserve it—by working for it.