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STABILITY AUGMENTATION IN AIRCRAFT DESIGN

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ABSTRACT

A review is made of the use of stability augmentation in aircraft design, particularly from the point of view of potential benefits for aircraft handling and operation. The use of simple systems and of advanced control techniques are discussed, for both pilot and autopilot modes of flight, and for both conventional and VTOL aircraft. Possible performance gains with artificial stabilisation are considered, and the application of autocontrol techniques to load limitation is touched on.

I. INTRODUCTION

A general review of the state-of-the-art in relation to stability augmentation in aircraft design, with an attempt to produce a co-ordinated view on the philosophy of its application, is something that I have long felt I should like to see done - but not by myself. My initial reaction on being asked to present such a paper was that this would better come from those concerned with the development of auto-control systems, but on second thoughts, there appeared to be some merit in considering the situation from the point of view of one concerned with the more basic aspects of aircraft handling and operation, putting the emphasis, therefore, on what is required or desirable in these respects, rather than on how it might be achieved. This, then, is my first aim; to consider various possible areas of application of stability augmentation, and advanced control techniques, to aircraft design; my survey will not attempt to be comprehensive but rather, selectively illustrative; it will, however, extend out beyond the confines of pure aircraft design, to externally guided aircraft flight, and in particular automatic landing.

Stability augmentation can be provided for a variety of purposes. In its most elementary form, rate damping is used to improve not-very-satisfactory handling qualities of aircraft, but the addition of artificial stability can open up wider possibilities, including performance benefits. Advanced control techniques, such as manoeuvre demand or adaptive systems, enable consistent control characteristics to be provided over the wide range of flight conditions arising with V/STOL, or variable sweep, aircraft. All these developments have to be considered both in relation to piloted, and autopilot, control. In addition, auto-control systems may be used to limit manoeuvre loads and buffet region incursions. A further application of growing interest in recent years is to smoothing flight in rough air both for comfort and fatigue load relief, either by a relatively simple gust alleviator, or by a more complex, aero-structural mode coupling system. All these aspects will be touched on, but the main emphasis will be on the potentialities in relation to stability and control characteristics, on which more experience is directly available.

II. BASIC STABILITY AND CONTROL OF AIRCRAFT

The flying characteristics of conventional fixed-wing aircraft have been the subject of extended study over the years, and the basis of assessment of their flying qualities is reasonably well understood. Desirable handling qualities in the longitudinal plane have been shown to depend largely on the characteristics of the short period motion, which determines aircraft response in pitch. Based on experience with large numbers of aircraft, and also from variable stability aircraft tests, contour curves have been established(1, 2) as shown in Figure 1, for associated values of frequency and damping of the short period mode, providing different levels of satisfactoriness of handling qualities. Similar contours have been evolved for handling criteria in most modes of flight, for example, as shown for the lateral-directional, Dutch-roll mode in Figure 2; here again, as in general, the criteria are related to the frequency and damping, but also depend on the relative roll-yaw elements of the motion.

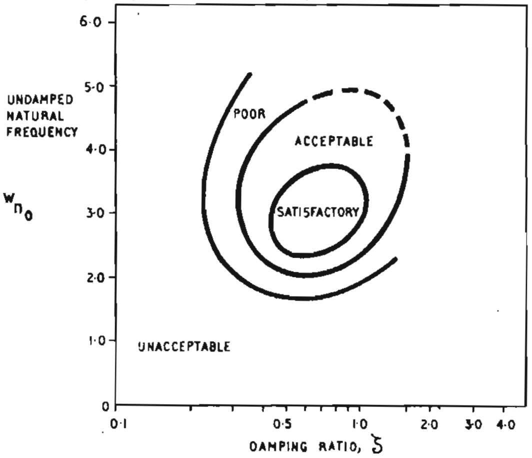


FIG.1 LONGITUDINAL SHORT PERIOD OSCILLATION PILOT OPINION CONTOURS.

It should be noted that handling criteria of this type refer basically to the stick-fixed characteristics of the aircraft, and generally to visual flight. The response of the aircraft to control action depends also on the control system dynamics, and the pilots impressions of the handling are influenced by the mechanics of control application, including sensitivity, control feel and so on. The pilot's impressions of the handling qualities of the aircraft can be somewhat different when he is flying on instruments; probably it will be less satisfactory with only a rudimentary instrument flying display, but more sophisticated display systems, for example, with a director instrument using phase-advanced information to aid the pilot, can ease the flying task and enable it to be executed with higher precision.

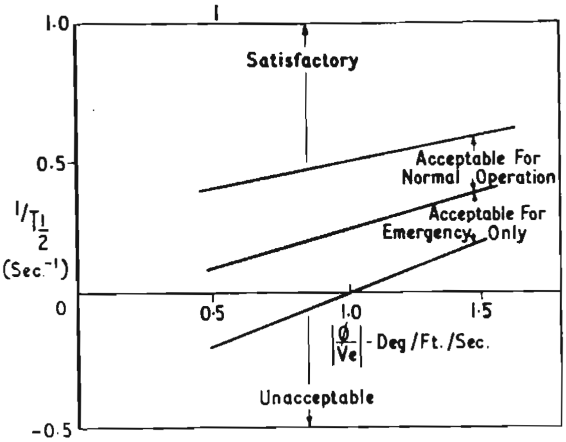


FIG. 2 PILOT OPINION BOUNDARIES FOR DUTCH ROLL CHARACTERISTICS.

The characteristics on which the aircraft handling depend include the basic aircraft dynamics, together with the added stability augmentation, which is of greater importance, the less manageable the unaugmented aircraft. Considerations of these kinds have led to questioning in some quarters as to how far handling criteria can be based solely on airframe dynamics. The power and flexibility of auto-control systems enables one to consider what are the most appropriate control laws to provide, rather than merely to bring existing control systems up to an acceptable level by traditional standards.

One recent line of thinking in this connection, and particularly in relation to high performance aircraft, has been that longitudinal response can not be adequately assessed in terms of the short period frequency and damping, because this over-emphasises the significance to the pilot of normal acceleration, n_z, of the aircraft. Pitch attitude cues are also important, more so at low speeds when accelerations are small, but to cover more fully the cues of which the pilot is aware, it appears necessary to take account of variation with time in a more general way, in a time history envelope. One way of doing this, proposed in reference (3), uses a combined response parameter, C*, in a form taking account of the various acceleration influences at the pilot's position:

$$C^* = \frac{V_c}{g}\dot{\theta} + (n - 1) + \frac{l}{g}\ddot{\theta}$$

where n = normal acceleration at C.G. in g units

V_c = cross-over velocity where $\dot{\theta}$ and $(n - 1)$ contributions are equal

l = distance of pilot ahead of C.G.

The assessment of aircraft handling is related to the time response envelope of this parameter, following a pilot's input, F_p. The significance of this criterion, C^*/F_p, is indicated in terms of modern control theory in Section III, and an example of the form of contours obtained for the criterion is given in Figure 3.

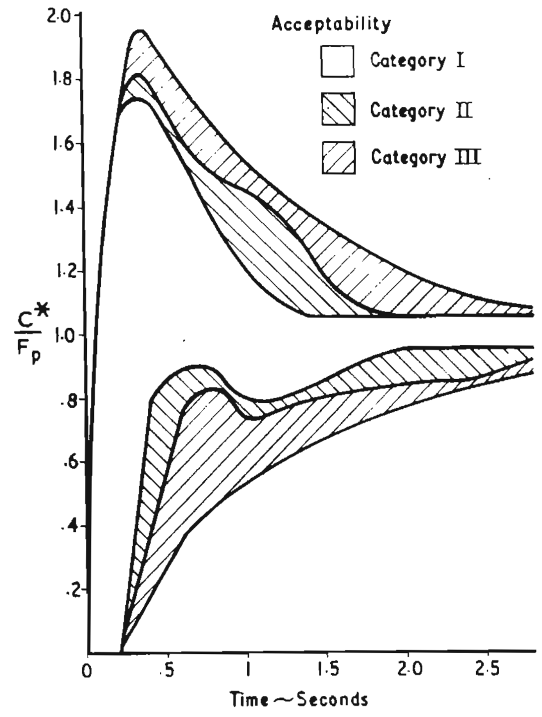


FIG. 3 $\frac{C^*}{F_p}$ STEP RESPONSE ENVELOPES

This parameter, C*, can be used as a measure of the response characteristics of the aircraft, but it can also be seen as the form of input, based on rate gyro and accelerations signals, fed into the auto-control system, or autopilot, to provide the desired aircraft response. The type of response required can vary with the type of aircraft and with the flight state, and also with whether flight is in manual or on autopilot. Some of the areas of application will be seen in the discussion of auto-control systems which follow.

III. AUTOSTABILISATION

The earliest applications of stability augmentation to aircraft were made to improve the basic aircraft stability and handling qualities, in some cases necessarily, to make these characteristics acceptable to pilots. These first systems, as for example in the case of pitch and yaw dampers, were added in series with the existing flight control system, and were of very limited authority. Generally a lot of effort was given to avoiding reliance on artificial stability aids, because of the extra complexity they introduced and the uncertain reliability associated with them.

However the increasing difficulty of meeting the design demands for larger aircraft, for aircraft in an ever widening envelope of flight operating conditions, together with the growing confidence resulting from successful experience and the evolvement of 'failure-survival' principles, has led to development of the application of stability augmentation systems. These make use of advanced practices, with electric signalling (that is fly-by-wire) and high-authority autostabilisation systems, but are still limited, however, in practice by the necessity to provide for reversion to a mechanical system. The additional complexity involved in providing the mechanical system may, however, itself compromise the performance of the primary system, and the situation is possibly aggravated if the control system is composed, as may be the case, of a set of dissimilar interconnected subsystems, all of which are normal working parts of the overall system. The design difficulties and uncertainties of complex systems of this type, however, are major disadvantages and there are obvious attractions in a control system achieving its reliability by means of multiple similar systems.

There is a distinction, of course, between the advantages to be gained from full reliance on electrical signalling, and from the further steps possible in the use of auto-control systems. Considering electrical signalling, first, apart from the obvious possible advantages, like ease of design installation, and weight saving, the electrical transmission of instructions from the pilot's controller to the power operated elevator, etc., control surfaces, can greatly ease the problems met in high speed, supersonic flight, such as the effects of aeroelasticity, differential expansion due to kinetic heating, the difficulties of passing mechanical couplings through pressurised bulk heads, and the greater control precision required. In addition, and more relevant to our present interests, an electrical system unlike a mechanical one, makes it easy to include autostabilisation inputs, and to make use of advanced auto-control laws; integration of the control system with autoland guidance, and navigation, equipment can also be more readily achieved. There are various ways, or degress of development, in which an integrated system can be designed in order to achieve good autostability and control, both under manual and autopilot control. The least advanced would use some integration of limited authority autostabilisation, but with an independent autopilot linking in directly to the aircraft control system. At the other extreme, the most advanced system would combine full reliance on electric signalling, with an integrated control system either of a manouevre demand or self-adaptive type, and with the autopilot control also incorporated in the main system. Some of these aspects of auto-stability and control are discussed in the following sections starting with potentialities in auto-control.

Advanced Control Techniques

It may be useful in considering the different control techniques, to restate briefly some of the basic principles of the closed loop operation on which advanced control systems depend.(4, 5) These systems depend on feedback control from the output to the input stage, and are effectively a servomechanism intended to make the output follow a variable input with little error. The basic block diagram of a simple linear feedback circuit is shown in Figure 4. F_p, a function of time, is the input or command signal, and C is the output or response, G(s) and H(s) are the aircraft transfer functions of the forward and feedback paths respectively, s being the differential operator, d/dt, while K represents the gain or amplification factor. The equation, in Laplace transforms, governing the performance of the system, leaving out input-shaping filters at this stage, is:

$$\frac{\bar{C}}{F_p} = \frac{KG(s)}{1 + KG(s)\,H(s)}$$

It will be seen that with a high gain system, in which K is large:

$$\frac{\bar{C}}{F_p} \dashrightarrow \frac{1}{H(s)}$$

Thus with a direct error feedback, for which $H(s) = 1$:

$$\frac{\bar{C}}{F_p} \dashrightarrow 1$$

This provides a direct response to the pilots control action, and this is the basis of optimum control response region in the C^*/F_p time response envelopes discussed in Section II. It will be seen that the feedback principle deals primarily with the error between input and output, and the effect of any external, for example, gust disturbance, is also eliminated by the feedback mechanism. The response equation for such a disturbance, X, is:

$$\frac{C}{X} = \frac{1}{1 + KG(s)\,H(s)}$$

If K is large, $\frac{C}{X} \dashrightarrow 0$.

A shaping filter, F(s), may be introduced between the pilot's input and aircraft block (Figure 4) to produce the desired handling qualities. This will usually be in the form of a lag circuit.

Since $\frac{C}{F_p} = \frac{KF(s)\,G(s)}{1 + KG(s)\,H(s)}$

it will be seen that for high gain, and $H = 1$,

$$\frac{C}{F_p} \dashrightarrow F(s)$$

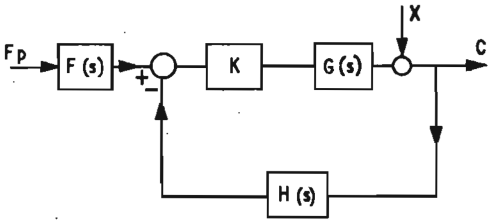


FIG. 4 CLOSED LOOP CONTROL SYSTEM

This produces a model-following, or adaptive, control system, and F(s) can be varied with flight conditions to give a fully self-adaptive system.

The reasons for aiming for an adaptive system have to be considered. The main advantage is the ability, by use of a closed loop system, to provide selected, and possibly, uniform stability and handling qualities throughout the aircraft flight envelope. This may be difficult by conventional methods for aircraft with extensive flight envelopes, such as variable geometry supersonic aircraft, and V/STOL aircraft. The reduced susceptibility to external disturbances of aircraft with adaptive control, is another major advantage.

There are various possibilities open in regard to the type of control laws, that may be produced with a closed-loop feedback system. For example, the so-called manoeuvre-demand or command control systems, are designed to achieve accurately and quickly some selected type of manoeuvre, such as pitch attitude, or pitch rate, or normal acceleration, and corresponding quantities in the roll plane. The general nature of the different types of response are illustrated in Figure 5; the pitch rate and normal acceleration systems produce responses comparable to those with conventional control system, but the attitude demand system shows significant differences, the normal acceleration, for example, decreasing when the attitude achieves the steady value demand. It has been found (6) that the attitude demand system was not satisfactory to pilots for manoeuvring in combat type aircraft, partly because of the sharp attitude changes in response to relatively rapid stick inputs, particularly in the lateral plane, and the other systems were much preferred. It is generally considered that an attitude demand system is more appropriate for VTOL aircraft, but its possible merits for large transport class aircraft do not appear to have been properly assessed. It is conceivable that a mixed system, combining attitude stabilisation, with normal acceleration demand, through a direct lift control (D.L.C.) scheme, would produce the most desirable aircraft operational characteristics, which include maintenance of attitude and control of the flight path. In the following sections, flight results with manoeuvre demand systems for conventional and VTOL aircraft are considered, and some conclusions are drawn from the results.

IV. MANOEUVRE DEMAND CONTROL ON CONVENTIONAL AIRCRAFT

Flight tests have been made with an experimental rate demand system on the Avro 707C, a small, two-seat, research aircraft, and tests are to be made of a practical, quadruplex system on a Hunter aircraft.(7, 8) The choice of a pitch rate rather than a normal acceleration system was taken partly on practical grounds, it being thought that the control system would be simpler and less vulnerable to vibration pick-up and structural mode-coupling with the pitch-rate system, but the latter also had some advantages from a performance point of view, and could provide the normal acceleration requirements reasonably easily.

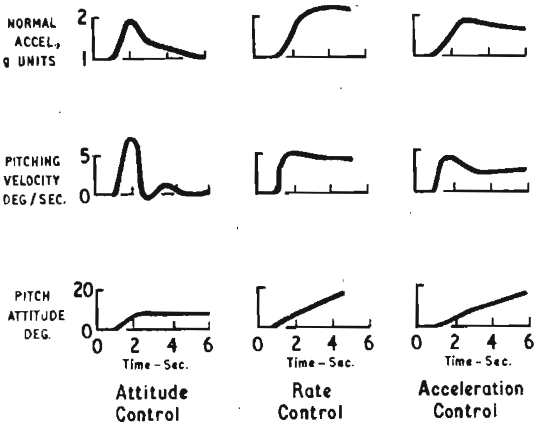


FIG. 5 RESPONSE IN PITCH TO STEP CONTROL INPUT FOR VARIOUS CONTROL LAWS (Ref. 6)

With a pitch-rate system, the closed loop transfer function equation is of the form:

$$\frac{q}{q_D} = \frac{KG(s)}{1 + KG(s)\,H(s)}$$

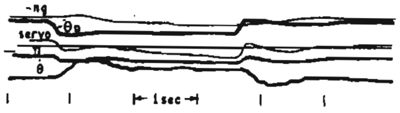
where q is the rate of pitch (or roll). q_D, the rate demanded, is related to the pilot's controller position, but the elevator control displacement, η, follows a law of the form:

$$\eta = F(s)\,(q - q_D)$$

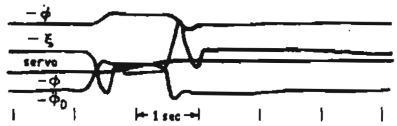
It should be noted that with stick fixed, the control system acts like a high authority conventional autopilot, aircraft pitching motion due to disturbances being sensed by rate gyros and fed back to the elevator control to eliminate the effects of the disturbance. In practice, this is an important advantage, because not only the effects of turbulence, but also of trim changes due to, for example, flap movement, and to ground effect, are quickly corrected.

The primary object of the system on the Avro 707C was the provision of rapid pitch or roll rate, in a uniform way throughout the flight envelope, and this was found to make possible very accurate manoeuvring, when the aircraft response to control was limited to normal levels, once pilots had learned to rely on the control system. There was a tendency, to start with, to over-controlling and pilot induced oscillations, which it was found was less marked with a miniature control stick. Special advantages were found in the case of making a take-off rotation manoeuvre, and in aerobatic manoeuvres. In a slow barrel roll, for example, the pilot only need demand a fixed small rate of roll, and rate of pitch and the aircraft follows these demands, the elevators trimming the aircraft during inverted flight and the yaw damper counters nose dropping when the aircraft is banked with wings vertical.

Flight records of the response of the Avro 707C to step control inputs in pitch and roll are shown in Figure 6. There are no records for comparison, of the aircraft in its basic state without rate demand control, but the higher activity of the servo traces compared to the control inputs is indicated by the $\dot{\theta}$ and $\dot{\phi}$ records.



(a) Step Demand In Pitch At 150 Knots



(b) Step Demand In Roll At 230 Knots

FIG. 6 RESPONSE TO RATE DEMAND CONTROL ON AVRO 707C

One feature of manoeuvre demand, and high authority auto-control systems in general, is that the control system can be using a large proportion of the available control power, for example, in landing approach, to counteract the effects of a cross wind, without the pilot being aware that the aircraft is close to the aerodynamic control limits. For this reason, and others, like limiting the consequences of a control system runaway failure, auto-control systems have in general, been given strictly limited control authority, which restricts the benefits that can be drawn from their use. In principle this difficulty can be overcome by indicating the control surface position to the pilot, and adding a warning device to provide a positive indication that a limiting control situation is being approached. This is accepted practice for stall-warning, but it is clearly undesirable to increase the number of warning indications to which the pilot has to respond, and furthermore the complexity of the auto-control system makes it difficult to predict all the likely limiting conditions that have to be taken into account. A preferable arrangement would be one in which the pilot is given, through his manual controller, an indication of the amount of control power available to him similar to that he gets from stick position in a conventional control system.

Desirable control laws for large transport aircraft

The advantages of manoeuvre demand control laws have been considered largely so far in relation to smaller, highly manoeuvrable, combat type, aircraft, and it is necessary to consider also the types of control which may be appropriate to large aircraft. Considerable attention has been given for many years to the definition of handling criteria for this class of aircraft with conventional control systems,(9) but there is a need for a comparable study of the handling characteristics appropriate to the various possible manoeuvre and adaptive control laws. Some progress may be possible from general considerations, but flight, and indeed operational experience is the only firm basis on which the relevant handling criteria can be defined.

It is made to appear at times that there is a diminishing need for consideration of the appropriate flying characteristics for piloted manual control, because so much of the flight operation of civil transports is now done in autopilot operation, from climb through cruise, in descent and increasingly through to autoland. However it still happens that in the more extreme flight situations, like very rough air in cruise flight, the pilot is required to act as a monitor of the flight condition, and to judge whether control is being satisfactorily maintained, and if necessary, to switch out autocontrol, and to take over in manual. Some of the so-called jet-upset incidents and accidents appear to have arisen to some extent from the characteristics of the auto-control system, and although understanding of the problems involved has advanced considerably in the study of such occurrences, further work is required to establish the most suitable auto-control modes for all types of rough air conditions.

Likewise with automatic landing systems, it is still thought advisable for safety reasons to limit the control authority of the system and to accept the limitations that this implies for the wind and gustiness conditions in which autoland operations may be made. This is very seldom a restriction on blind landing operation, but can result in the pilot being required to make the rougher air landings himself.

For such reasons, it is still very important to establish appropriate handling and control characteristics both for manual pilot flight and for auto-control operation.

In flight away from the ground, as in climb or cruise, steady flight at a given speed and flight path angle or height is the general aim, and apart from the effect of atmospheric disturbances, this would be satisfactorily achieved by any of the control laws providing auto-trimming. The different systems do not necessarily, however, produce the same flight results. The pitch rate and attitude demand systems attempt to hold the aircraft attitude at a constant value, while the normal acceleration systems attempt to maintain the flight path angle. There has been some difference of view as to what is the most appropriate mode for cruising flight in turbulent air, but attitude-hold appears to contain fewer uncertainties in extreme up - or down - draft conditions. Fluctuations in speed are a potential problem at altitude, particularly as some autotrim systems lead to neutral speed stability. Speed changes, however, occur slowly and can be corrected by the alert pilot, but where speed exceedance margins are small, a Mach number or speed hold mode may be desirable, and the use of an autothrottle has also been proposed.

In a landing approach, made at constant speed, the pilot is concerned with producing the appropriate aircraft descent path in relation to the runway, and also with controlling the rate of descent. Flight path angle is controlled by longitudinal control action producing normal acceleration, and thus also rate of descent, changes, while speed is maintained by throttle action, applied either by the pilot or by an autothrottle. This is the case both for deliberate changes in flight path angle, and in correcting the effects of atmosphere disturbances. Near the ground, rapid and accurate response to control changes is very desirable, and the pitch rate or acceleration demand systems have advantages in making the best use of the control power available.

If the aircraft is being flown down a radio approach beam, control action will be required to correct height displacements above or below the beam. Direct height control, however, would be achieved at the frequency of the phugoid longitudinal mode, and thus be slow in producing the required effects. The normal practice is to speed up the corrective action, either by the pilot taking account of rate of decrease of height as well as of the height error, or more effectively by means of a director display, or by a control demand system giving an acceleration or rate of descent response. The auto-trimming capabilities of the demand control systems have the important advantage of rapidly neutralising the effects of disturbances on aircraft attitude, which can assist in the maintenance of the flight path by the pilot. There are, of course, other factors to take into account when one considers autoland operation. (Section V)

Ability to control the approach path depends as we have seen, on the rapidity of aircraft response in the pitching plane. With very large aircraft, response to a conventional control system tends to become unacceptably slow, and this has led to the consideration of Direct Lift Control (D.L.C.) in which lift, and consequently normal acceleration, can be produced quickly and independently of the slow pitch response of the aircraft.(10) Various methods of rapid production of lift have been suggested and in some cases tried, such as lift flaps or spoilers. The significant improvement in response that can be achieved to counter the effect of a tail-gust is shown in Figure 7, and this clearly assists in accurate approach path holding. There would appear to be further advantages in a combination of attitude stabilisation and D.L.C., but the speed control with the latter is achieved to some extent at the expense of useable C_L max, as shown in Figure 8, and flight trials of a representative system will be necessary to enable judgement to be made of the possible gains and losses in the approach phase.

The characteristics of the aircraft in the yaw plane, as well as the pitching plane, are also important in a landing approach. The ability of an aircraft to maintain the desired direction of motion depends mostly on the roll response to aileron, the steadiness of the motion being influenced by the Dutch Roll mode, which is a combined yawing and rolling oscillation. Because of the coupling occurring in the lateral and directional motions, azimuth control of an aircraft is less straightforward than in the pitching plane. Correction of a lateral or directional displacement from the intended path can be made by aileron application proportional to the path error, but there would be some lag in the subsequent directional motion response, and aileron application would normally be increased to counter the tendency, as shown by angle of bank, to develop course deviations.

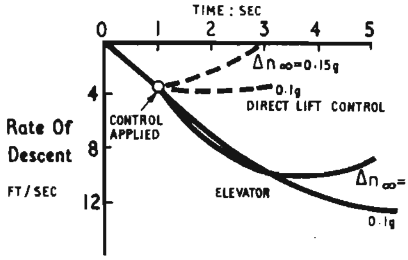


FIG. 7 COMPARISON OF RESPONSE TO ELEVATOR AND DIRECT LIFT CONTROL FOLLOWING TAIL GUST ON LARGE AIRCRAFT.

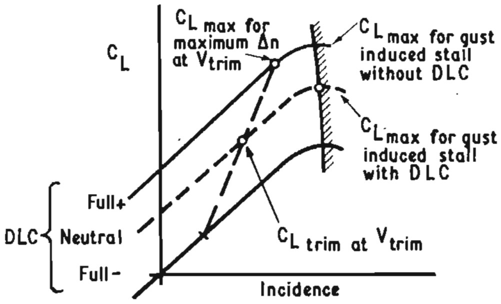


FIG. 8 STALL MARGINS AND MANOEUVRING LIMITATIONS WITH DIRECT LIFT CONTROL.

Motions in the lateral directional plane, are not only complex, but significantly different for conventional and inertially slender aircraft. Further the situation may be materially affected by some element of constraint, like control of bank angle by aileron. Pinsker (11) has shown there is a parallelism between this situation and the better known case in the longitudinal plane, where a speed instability in flight below the minimum drag speed was predicted for flight path controlled by elevator. It was brought to light in tests on the B.221, a slender wing research aircraft, in which directional type instability was experienced at incidences at which the aircraft was assessed to be laterally stable. Investigation has shown that this would arise in flight in which bank angle is constrained by aileron, the effect of adverse aileron yaw, $n_\xi > 0$, being to cause a reduction in the "effective" directional stability:

$$\bar{n}_v = n_v - l_v \frac{n_\xi}{l_\xi}$$

The lateral motion degenerates into a simple directional oscillation, which becomes divergent when $\bar{n}_v$ becomes negative. This criterion has particular importance for inertially slender aircraft, for which the Dutch Roll is virtually a rolling oscillation, so that loss of n_v is not important according to conventional stability analysis. An important consequence of the analysis with bank angle constraint is that the effective directional stability can be improved with favourable aileron yaw ($n_\xi < 0$), which can be artificially generated by a coupling link between aileron and rudder.

This assessment of flight control is for the case of flight on a set course, in a selected direction. Flight along a particular line, for example down a radio guidance beam, involves lateral positioning as well as direction keeping, and correction of errors involving a combination of a sideslip manoeuvre and azimuth heading adjustment, is a more demanding task for the pilot. In these circumstances manoeuvre demand controls could be of particular value if they enabled the pilot to make at least some part of the adjustment in a fully predictable manner. Most of these aspects of flight in the approach landing phase, have been more fully analysed for the auto-landing mode, than for manual operation by a pilot.

V. AUTOMATIC FLIGHT CONTROL

The greatest effort in the field of automatic flight control has been given to producing a reliable autoland system. Now that this has reached the stage of partial operational application, one finds attention being given to the wider question of auto-control of aircraft terminal area operations. The necessary systems are available in principle, and the main outstanding issue is one of reliability and the building up of operational confidence. The benefits of autoland in providing a blind landing capabilitiy are obvious, but it is also intended to improve operational safety. The latter aim would also apply to auto operation in terminal areas, but in this case the primary objective would be to improve and indeed optimise, the utilisation of airspace, which is becoming increasingly congested in the vicinity of major airports. The principles of autoflight control are the same in all cases, the use being involved of a radio guidance element, and of a control element. The latter may in practice in a blind landing system, be manual or partly manual, or automatic. In the manual system, the pilot is a link in the control loop making direct use of radio guidance information. In the automatic system, the pilot is outside the main control loop and checks the functioning of the system through a monitor display. The auto-system has been the subject of greatest attention and is the form which will be considered here.

Autoland

External aids are required in autoland for azimuth heading, and vertical approach and landing guidance. The I.L.S. glide path can be used for vertical guidance down to about 150 feet, but below that height, guidance is derived from radio altimeter information, and this is used as the basis for control of the flare and touch down. Azimuth guidance is provided by some form of localiser, such as a V.H.F. radio aid with two over-lapping beams, from which an aircraft receiver can determine displacement from the runway centre line.

The accuracy of the performance achieved on the I.L.S. glide path, as measured by positional error and the derivative of this error, can have a large effect on the aircraft touch down point on the runway, which is one of the key performance parameters of an automatic landing system. Investigations have been made of ways of improving beam holding in the presence of wind disturbances, both by increasing the gain of the coupling between the radio beam and the aircraft autocontrol system, and by the use of phase advance inputs. Flight tests have confirmed the findings of analytical studies, (12) that the addition of either rate of descent and pitch rate, or of rate of descent and normal acceleration terms, to the glide path control law, produces a large reduction in the scatter at the lower end of the I.L.S. glide path. (Figure 9)

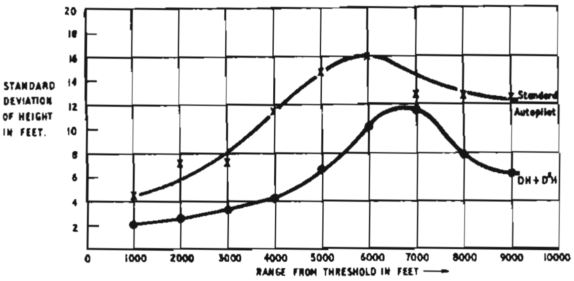


FIG. 9 REDUCTION IN HEIGHT SCATTER WITH RATE OF DESCENT AND ACCELERATION TERMS IN ILS CONTROL LAW.

More recently an analytical study has been made of the glide path autopilot mode of the Hunter aircraft fitted with a high gain pitch rate manoeuvre demand control system.(13) The addition of the "outer loop" controller for the glide path mode to the high gain manoeuvre demand "inner loop" (Figure 10) is not expected to raise major difficulties but further consideration has to be given to designing multi-loop system of this nature as a whole, rather than on a component basis. The results of the study indicate that with the system, much improved glide path performance can be achieved, the effects of I.L.S. imperfections and noise, being less marked as a result of being able to use, without instability, a higher gain with the manoeuvre demand inner loop, in combination with a lower value of outer loop gain. However, there are other issues, such as beam joining, which may affect the outer loop gain requirements, and this work has to be regarded as still in the development stage.

The control of airspeed during approach and landing is also important, and increasing use is being made of autothrottle systems for this purpose. Autothrottles are regarded as an essential element in autoland systems but they are becoming commonly used to reduce pilot work load in the

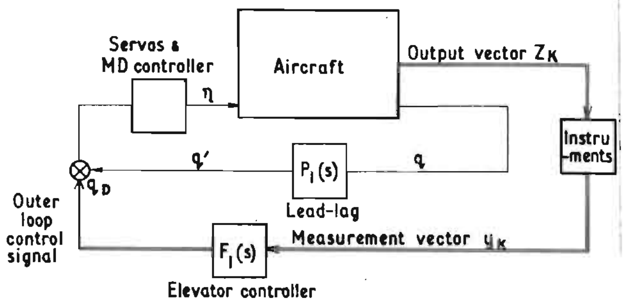


FIG. 10 OUTER LOOP GLIDE PATH MODE WITH MANOEUVRE DEMAND INNER LOOP

critical, landing, phase of flight, in general civil airline operations. The autothrottle basically works by applying throttle proportional to airspeed error, but a weak integral term is normally added to take out initial condition errors, and a pitch attitude term is included to compensate for short term changes in flight path. This type of system works well in still, or slowly changing, air conditions, but produces excessive throttle activity, disturbing to passengers, in turbulent conditions, and recent work has been devoted to developing a system which maintains steady conditions without reacting to the many short duration disturbances. Rather surprisingly, it has been found that a conventional autothrottle does not significantly reduce air speed fluctuations due to turbulence, and that a better measure of autothrottle performance is its effect on autopilot height holding on the glide path in turbulent conditions.(14)

An improved form of autothrottle has been tested(15) in which for small airspeed fluctuations, the speed input to throttle action is based on inertially determined, ground speed changes. For higher speed fluctuations a comparator switches throttle control over to an airspeed basis. A flight evaluation of the system on a Comet aircraft has shown that throttle activity could be reduced well below that with conventional autothrottles without degradation in height holding or increase in airspeed error fluctuations. (Figure 11) An interesting outcome of the tests, was that although the system had been designed with aims which pilots were in full agreement with, the pilots made some adverse comments from experience in the flight tests, on the slow recovery from small speed errors and on the large and rapid throttle movements associated with large gusts. The response to small speed errors could be improved at the expense of increased throttle activity, but it appears that height holding in glidepath flying would suffer if large rapid throttle action is not used to counter large gusts. However there is possible room for improvement in glidepath control and in reduction of throttle activity, through better combination of both elevator and throttle inputs for height holding, and further flight work is being done to study these aspects.

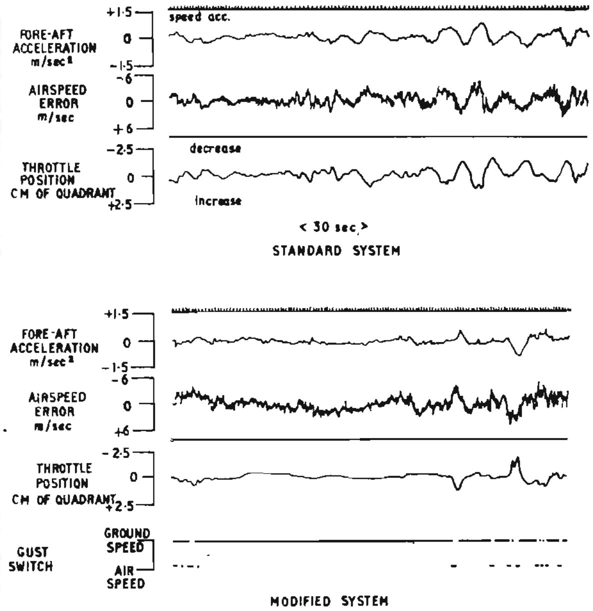


FIG. 11 COMPARISON OF AUTO THROTTLE PERFORMANCE, MODERATE TURBULENCE (1·3 m/sec. r.m.s.)

In the yawing plane, as we have already seen, control of the motion along a guidance beam, is more complex, but the control law necessary in autoflight for beam-holding is simple, and of the form:

$$\phi_D = k_1 y + k_2 \frac{dy}{dt}$$

where ϕ_D is the demand bank angle, y is the error signal and k_1 and k_2 are constants. This form of law is basically very effective, but because it includes the rate of change of radio signal as a stability term, it is susceptible to external noise disturbances. It appears possible that as in the case of glide path holding, the use of a high gain manoeuvre demand control system would result in a more rapid and stable control of direction of motion, and so improve azimuth beam holding performance, the control law phase-advance, offsetting to some extent the large lag in course correction following aileron application.

The latter stages of autoland, namely the flare and removal of drift prior to touchdown involve more complicated dynamic motions, in accordance with other predetermined laws. Removal of drift looks a more delicatedly balanced operation with the slower response of large aircraft, and the possibility of higher cross winds, in view of the current trend to unidirectional runway layouts, so that avoidance of the need to kick off drift by the use of drift undercarriages, appears a more attractive proposition. The slowness of response of large aircraft in pitch has led to consideration of the use of direct lift control. The prospects for exploiting D.L.C. look even better with an aircraft equipped with an automatic flight system than with manual control, because of the greater flexibility open for optimising the interconnection of the three controllers, that is elevator, D.L.C. and throttles. For a fully automatic landing system, there is no pilot work load constraint to limit the number and combinations of sensor signals fed into the controls, but in manual control, with the "pilot in the loop", the various intercorrections between the controllers must be presented to the pilot in a simply useable form. Optimisation of the control system for pilot operation will probably turn out differently from optimisation for automatic flight, but if takeover by the pilot in the event of a failure, is assumed, this has to be taken account of in the form of auto-control adopted.

Role of the Pilot

The extension of automation in flight control leads one to consider what the role of the pilot should be with an automatic flight control system. There is no doubt that in complex flying tasks like blind landing of a large transport aircraft, the use of automatics becomes essential, to reduce the cockpit workload to an acceptable level, and at the same time free pilot effort for monitoring how the flight is progressing, and decision taking on the basis of instrument and control activity. It has been suggested (16) that the overall reliability of the system with the pilot in the role of manager rather than operator, is not always enhanced compared to a more completely automatic system, but this has to be accepted, as long as we remain in the position where the pilot is expected to decide what to do, and if necessary to take-over control, when things go wrong. Clearly the aim has to be to present the managerial task to the pilot in a way that minimises the possibility of errors in selection tasks, such as flap position, height datum or the runway heading, and in decision-making, particularly in regard to auto-control system failures.

Some of the major uncertainties with auto-control systems are related to what the pilot can be expected to do in the event of a failure. The situation is not difficult if a part failure only occurs, which the pilot has to note, to prepare himself for some possible minor degradation of the performance of the system. If the pilot has been merely monitoring the system, it could be useful if at this first failure stage, he started to come partly into the control loop. This can help to prepare him for the much bigger step of taking control in the event of a more complete failure of the system. The possibility of this happening requires that the basic stability characteristics of the aircraft must keep the flying task within the pilot's capability, and if the pilot has not previously been actively in the control loop, the flying task will have to be relatively simple. In a large transport aircraft divided control between two or more pilots could be a means of coping with an excessively difficult task.

From the point of view of ability to cope with failure of the automatic system, it would be preferable for the pilot normally to be in the loop, rather than merely monitoring the motion performance. Even in this case, the relative degradation in the aircraft handling qualities due to system failure must not be too **great** for the pilot to re-adapt himself sufficiently quickly to retain satisfactory control. One way of ensuring that the pilot is adequately activated, and in practice, to cope with a failure situation of an automatic system, is to give the pilot the task, not of passively monitoring, but of controlling a simultaneous model of the aircraft system, to match the actual motion. The additional complexity of the system to do this, is of course a disadvantage, and itself a further possible source of nonreliability. A great deal of effort has gone into this question of the role of the pilot (17, 18), but pilot vehicle control is an area in need of continuing effort, until sufficient operating experience is accumulated to enable judgement to be made of the optimum arrangement for both performance and safety, and covering both the normal and failure states of operation.

VI. AUTO-CONTROL OF VTOL AIRCRAFT

The control of VTOL aircraft in hovering and low speed flight has to be obtained, not from aerodynamic control surfaces, because the dynamic pressures are too small, but from some scheme using propulsion power, such as the reaction jets used on a number of jet lift aircraft. The necessity to conserve power has led to consideration of the most effective control useage, and it has been found that control power used can be reduced if the control system is designed to stabilise the aircraft as well as to provide manoeuvrability for the pilot. In view of the wide range of flight conditions that arise in VTOL flight, it is clear that a manoeuvre demand control system could be particularly appropriate. It will be appreciated also that at low speeds aerodynamic stabilising forces available on VTOL aircraft are small, but that they can be sensitive to disturbances affecting the large air flows at the lift-engine intakes. Both the control and stability requirements can be met by an attitude demand control system, without conflict between excessive stability and manoeuvrability requirements, by shaping the control inputs to the system to give initially a rate demand. It may be necessary, however, to provide restrictions, which prevent control action taking the aircraft beyond the safe aerodynamic limits.

It is thus possible to produce an aircraft which is very stable in relation to disturbances and trim changes, but is still manoeuvrable. In addition the freedom to select the control system characteristics opens up the possibility of obtaining a form of stabilisation which makes the most economical use of control power, which is of primary importance when it is obtained at the expense of lifting and propulsive power, aiming, for example, at optimising the tightness of control over attitude, and the control demands to counter disturbances.

However although such systems can in principle provide ideal stability and control characteristics, they are still subject to the same types of difficulties and uncertainties enumerated in relation to conventional aircraft. Apart from the complexity and **questions** of reliability, the significance of the lack of cues from the pilot's control as to the amount of control power being used, for example, or from the response of the aircraft as to the speed, can only properly be assessed from flight experience, which so far is very limited. Tests to investigate such points are being made on experimental aircraft like the SC1, and some useful indications are coming out of the results being obtained.

Auto-control tests on SC1 VTOL Aircraft

The SC1 is a single seat jet lift research aircraft with four RB108 lift engines and a similar propulsive engine (Figure 12). It has two types of controls, conventional flap surfaces for use at adequate forward speeds, and reaction nozzle controls about all axes for use a low speeds where the aerodynamic controls are not effective.

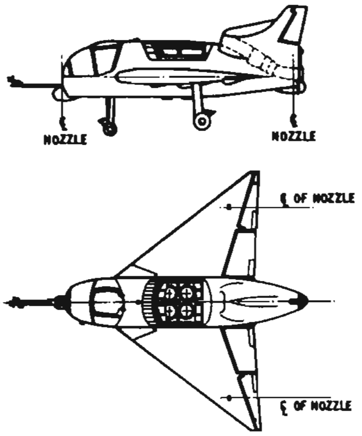
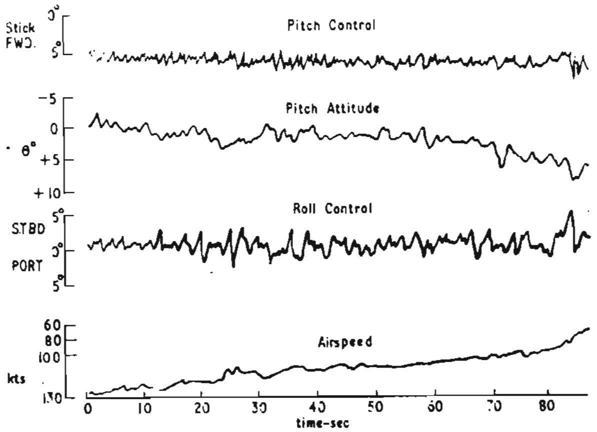


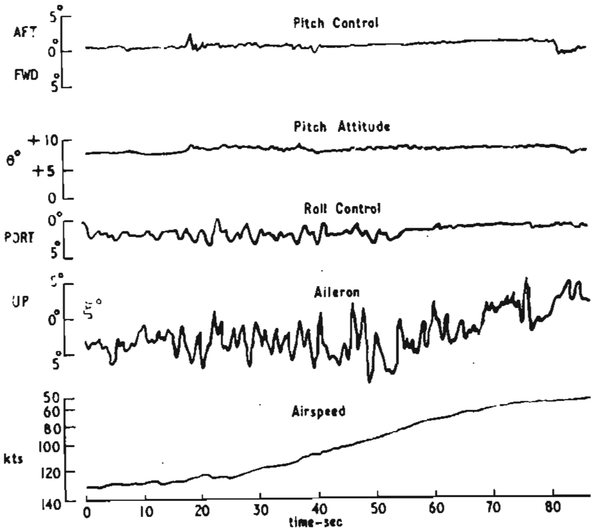
FIG. 12 GENERAL ARRANGEMENT OF THE SC1.

The aircraft is equipped with a triplex electrical control system, and a versatile, manoeuvre demand system with full authority over both sets of controls. The system can provide rate or attitude modes of control in pitch or roll, rate damping or artificial directional stability in yaw, and in addition a height compensator or damper system acting on the lift engines to maintain 1g normal acceleration.

The system has been tested throughout the flight envelope and has been found to have the expected benefits in easing the pilots task in correcting the effect of disturbances or trim changes. No difficulty was met in changing from an attitude to a rate mode of control; this was significant in roll, because the attitude law applied over a limited bank angle range, beyond which a rate law obtained to unrestricted angles. In general, the control systems gave the SC1 very good handling qualities. Records are shown in Figure 13 of decelerating transitions of the SC1, first with mechanical control, and then with attitude demand. There is an obvious improvement in attitude holding in the latter case; it was found in fact that the transition could be performed almost "hands-off", the autostabiliser taking care of disturbances and the large longitudinal trim change, with the pilot needing to make only minor adjustments to the aircraft's attitude. The reduction in the pilot's rate of activity in the attitude mode, is indicated by comparison of the roll control and aileron records.(19)



(a) Mechanical Control



(b) Attitude Mode

FIG. 13 DECELERATING TRANSITION ON SC1.

The lack of indication from the pilot's control of the extent to which control power was being used, was not felt to be serious in pitch, because pitch attitude is maintained fairly constant in VTOL flight, and in any case the aircraft was known to be stable even at extreme angles of incidence. The position in roll is less straightforward. At large angles of sideslip, the basic aircraft becomes laterally unstable and it is vital to ensure that an adequate margin of control is maintained to counter the results of sideslip arising from cross-wind effects or from sideslip effects arising in, for example, banking manoeuvres. The manoeuvre demand system overcomes the basic instability but in countering the sideslip effects can use a large proportion of the roll control without the pilot being aware of it. To avoid this danger requires careful monitoring of sideslip and control position indicators, and the eventual solution could lie with yaw stabilisation. Such a system providing artificial directional stability removes the need for the pilot to pay undue attention to sideslip, and was found to make manoeuvring easier and more accurate.

Attitude demand is sometimes stated to be preferable to rate demand for flying in I.F.R. because a level attitude can be obtained by centralising the stick. It can, however, result in the need for additional continued control application, for example in turns, or in holding off the effect of cross winds at low speeds.

The optimum control laws for VTOL flight are still in need of further study. Present indications seem to favour attitude control in pitch, but possibly rate control in roll, and these need to be assessed in representative operational situations. A first step in this direction will be made in tests on the aircraft fitted with a data link from a ground based radar, providing a display of positional information. This system will be used to study stability and landing problems in steep decelerating transitions. Height, and rate of descent control will be important performance parameters in these tests, and the height damper is likely to be of value, because inadvertent increases in rate of descent are likely away from the ground where the pilot's appreciation of ground cues becomes less certain.

Further aspects of VTOL handling in operation into typical sites, which are in need of investigation, include the implication of sideslip limitations in relation to cross wind operation. The efficient control of deceleration of speed during transition, in general effected by thrust vectoring, is another feature of importance.

VII. ARTIFICIAL STABILITY

We have seen, in considering auto-control systems, that in some cases, for example, with an attitude demand control law, the system provides artificial stabilisation, which counters disturbances and trim changes. It is also pertinent to consider the needs for artificial stability and its possible benefits.

The simplest form of stability augmentation consists in improving the damping of some aircraft mode of motion, through, for example, a pitch damper, or a yaw damper to improve the stability of the Dutch Roll oscillation. Stability augmentation may also be required because of actual instabilities, either static or dynamic. Artificial stabilisation in this way has to be produced by use of the aircraft controls, displacing them in response to the motion in a way that effectively changes some of the aerodynamic stability derivatives of the aircraft. Thus if the aircraft is statically unstable in the longitudinal plane, so that $C_{m\alpha} > 0$, elevator deflection proportional to incidence, α, $\eta = k\alpha$, would produce a change in $C_{m\alpha}$,

$$\Delta\ C_{m\alpha} = kC_{m\eta}$$

$C_{m\eta}$ is negative, so a positive k will lead to a negative $\Delta\ C_{m\alpha}$, and a favourable effect on stability.

Similarly, rudder power can be used to improve directional stability, and this has been done on various conventional aircraft, the low level strike aircraft, TSR2, being one notable example, and it is also being seen as of particular value at low speeds on some VTOL aircraft.

On TSR2, there were a number of reasons for adopting autostiffening in yaw, providing artificial augmentation of n_v. A small, but all-moving fin, could for example, give lower gust sensitivity in high speed low-level flight; it could also reduce aeorelastic effects and possibly ease expected problems of yaw trim and loss of rudder effectiveness at transonic speeds. As these expected benefits indicate, the primary reasons for the all-moving fin were for the alleviation of structural problems. The advantages in drag and weight reduction were accepted as a bonus, but they were in fact quite significant. To achieve the requisite stability using auto-stiffening, the moving fin was only half the size of the fixed fin needed for natural stability. This gave a 7 per cent decrease in profile drag, and from the consequential effects on performance the aircraft weight was found to be about 10 per cent less, with corresponding important savings in cost.(20)

For safety in operation a triplex system was used, and in the event of the failure of one lane, the system was switched out when an acceptably stable flight region was reached. Some difficulties were met in the development phase, for example in fin flutter clearance, and also due to coupling of the autostabiliser system with structural modes. At the time of cancellation of the project, the impression was that the autostiffening system was hardly justified because of the large technical efford involved, but in retrospect the performance and cost gains appear worthy of reconsideration.

Encouraging results in artificially improving the directional stability have been obtained on experimental VTOL aircraft, including the SC1. The primary objective in providing yaw stabilisation was to relieve the pilot of the need to pay undue attention to the control of sideslip in manoeuvres; in addition it is a means of stabilising the Dutch Roll of the roll-unstabilised aircraft. Adjustment of the gains of the rate of yaw and lateral acceleration signals, providing respectively the damping and stiffness of the system, involved some compromise between damping of the Dutch Roll and avoiding the need for rudder in turns. The compound, reaction-nozzle plus rudder, directional control on the SC1, made it difficult to achieve a fully satisfactory solution throughout the speed range, because the rudder effectiveness reduced at low speed, but the generally improved handling down to speeds of 50 kt., was sufficient indication of the benefits that can be obtained from yaw stabilisation.

The ability to stabilise artificially a longitudinally unstable aircraft can be used to advantage from the point of view of aircraft performance. The simplest gains can be obtained by moving the C.G. aft, making the aircraft less stable and thereby reducing the up-elevator required for trim, and the associated trim-drag; if this trend is taken to the extent of making the aircraft unstable, down-elevator, which contributes to lift, is required for trim. An indication of the gains in trimmed lift as the static margin is reduced, is given in Figure 14;(21) these are more marked with a small control moment arm, and for tail-less slender wing configurations. The performance benefits include higher take-off weights and reduced cruise drag.

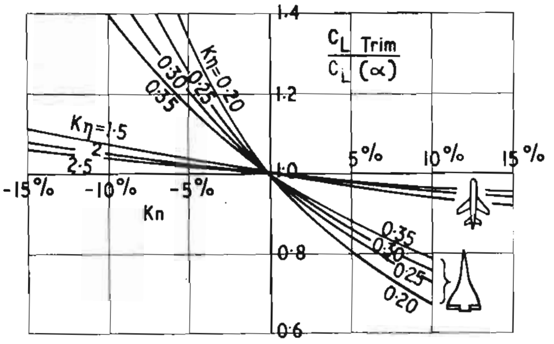


FIG. 14 EFFECT OF STATIC MARGIN K_n AND ELEVATOR MOMENT ARM K_η ON TRIMMED LIFT.

If reliance can be placed on artificial stabilisation in this way, its use can be extended further, and consideration can be given to deliberately designing the aircraft without natural stability, for example by providing smaller tail stabilising surfaces, with consequent reduction in weight and drag. In the pitching plane, the tail size has to be large enough to provide trim throughout the flight envelope, and there has to be sufficient control power for all necessary manoeuvres, such as raising the nose in take-off. These requirements are in fact in general eased by moving the C.G. aft, but the gains have to be balanced against the necessity to correct the negative stability artificially.

VIII. WIDER APPLICATIONS OF AUTO-CONTROL SYSTEMS

The emphasis so far in the consideration of auto-controls has been mainly on improvements in stability and handling. There are clear advantages in the optimisation of handling from the point of view of ease and accuracy of operational handling, but it may be open to question whether these benefits alone justify the complexity and cost of the auto-stabilisation required, although they also contribute to operational safety. However, such auto-systems have in addition potential beyond that of just raising the standard of handling, and can, in principle, be used to further improve safety by restricting manoeuvres, by inhibiting stalling and associated effects like buffeting; they can also be used to improve structural efficiency and comfort in flight by alleviating the effects of gusts, and by smoothing out structural vibrations by the use of auto-structural mode coupling techniques.

In considering the use of auto-control systems for load alleviation, it has to be appreciated that there are complex interactions between structural loading and dynamic excitation and stability control and handling aspects.(22) Improvements in aircraft rigid body dynamic response due to auto-stabilisers can lead to significant reductions in gust loads and improvements in ride qualities. The behaviour of conventional autopilots and autostabilisers can on the other hand, be significantly affected by the motion sensors picking up response in the elastic modes, the resulting control deflections either increasing or decreasing the aircraft response, depending on phase. Conversely, structural mode damping can be achieved by specifically positioning sensors to detect the particular elastic modes, and by suitable processing, control signals are fed back to reduce the structural oscillations. These systems differ from earlier gust alleviators(23) in that no attempt is made to measure the gusts directly, and they are aimed primarily at controlling the elastic modes.

Structural mode damping techniques applied in this way can contribute to crew comfort as shown in Figure 15.(24) They can also have a major effect on fatigue loading effects as shown in Figure 16.(25)

It is evident that an integrated approach is required to flight control systems, to cover both handling qualities and structural elastic response.

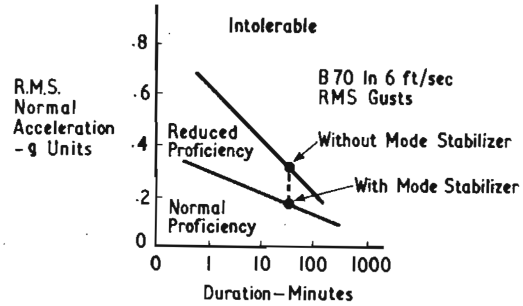
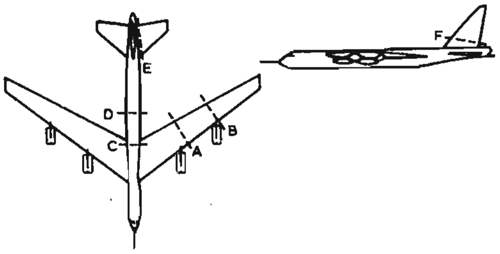


FIG. 15 CREW ENDURANCE TO R.M.S. 'g's (Ref. 24)



POSITION	A	B	C	D	E	F
FACTOR OF IMPROVEMENT IN FATIGUE DAMAGE RATE	5·75	1·83	6·45	3·9	2·18	5·9

FIG. 16 THEORETICAL IMPROVEMENT IN FATIGUE DAMAGE RATE BY AUTO-CONTROL OF AEROELASTIC RESPONSE. (Ref. 25)

IX. CONCLUDING DISCUSSION

Having surveyed the field of stability augmentation in aircraft, it is pertinent to consider whether any main trends are evident, or alternatively whether major gaps exist in our knowledge or technology, which are holding back further advances in the use and application of stability augmentation systems.

It has to be remembered that the picture given has only covered certain aspects of the subject, concentrating on what the systems can do, without attempting a considered assessment of the practical possibilities of system integrity or reliability. A great deal of work has been done on reliability and it is probably fair to say that the principles on which sound reliable systems can be based are understood and that there is a growing body of practical experience on their implementation in practice. This is encouraging because there are clearly many things one would like to see being done with auto-controls and artificial stabilisation in aircraft design, providing airworthiness standards are not prejudiced.

Not all lines of development appear equally useful, however, and varying impressions were formed in different areas. For example, the value of sophisticated control laws in piloted flight is not really well-established. They seem promising in certain applications, such as variable geometry aircraft and V/STOL, but more systematic study of such systems is needed in ground based flight simulators. A useful start was made (26) for VTOL aircraft, but surprisingly little has been done for conventional aircraft, and more practical evidence is needed on the theoretical benefits predicted.

More definite ideas have been developed on suitable control laws for automatic flight, as in autoland. However the need to provide for reversion to pilot control complicates the situation, and the role of the pilot with auto-systems stands out as an issue in need of clarification. It is being actively worked on in connection with autoland system development and some co-ordination of ideas in different places is taking place.

Artificial stabilisation has been considered no more than a fanciful dream by the conservative in aircraft design, but the potential performance benefits are sufficient to warrant more serious consideration than this concept has been given in the past, particularly now that adequate system reliability is a practical possibility.

In making this plea for a harder look at the possible advantages of artificial stability, I must also sound a warning against using such systems unnecessarily. An example has been cited in the paper of a lack of directional stability being corrected by mechanical coupling of ailerons and rudder, and many stability problems may be better resolved by getting to the aerodynamic root of the difficulty rather by artificial means. However the balance in efficiency in achieving the desired stability by one means or another, may not always be clearly defined, and one is led to suggest that there is a need for the application of design optimisation techniques, including consideration of the benefits of artificial stabilisation.

The case for accepting dependence on auto-stabilisation in aircraft design is strengthened by the numerous indirect benefits it can bring in its train, such as manoeuvre load restriction, buffet and stall avoidance, etc. The logical outcome, when system reliability is proved, is a comprehensive, integrated, automatic control system, embracing all aspects of the aircraft motion.

ACKNOWLEDGEMENT

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