R. &. M. No. 3629

R. & M. No. 3629

MINISTRY OF TECHNOLOGY

AERONAUTICAL RESEARCH COUNCIL
REPORTS AND MEMORANDA

# The Control Characteristics of Aircraft Employing Direct-Lift Control

By W. J. G. PINSKER

Aerodynamics Dept., R.A.E., Bedford

LONDON: HER MAJESTY'S STATIONERY OFFICE
1970
PRICE £1 10*s* 0*d* [£1·50] NET

# The Control Characteristics of Aircraft Employing Direct-Lift Control

By W. J. G. PINSKER

Aerodynamics Dept., R.A.E., Bedford

*Reports and Memoranda No.* 3629*
*May*, 1968

*Summary.*

The theory is developed for the control characteristics of aircraft in which direct lift is commanded directly by the pilots' stick. Basic requirements are established for acceptable response characteristics; of particular importance is the location at which direct lift acts relative to the centre of gravity, the aerodynamic centre, and manoeuvre point. The affective line of action of the control lift can be controlled by mechanical interconnections between the conventional pitch control and direct-lift systems. Potential benefits of direct-lift control include improved precision in landing large aircraft, more effective control of gust effects, and reduced possibility of stalling.

*Replaces R.A.E. Technical Report 68 140—A.R.C. 30 835.

# LIST OF CONTENTS

1. *Introduction.*

The helicopter and other forms of VTOL aircraft use direct-lift control as their principal *modus operandi*. The elevator of the conventional aircraft also produces lift, though here the amount of lift generated is by itself insignificant, but, acting at a relatively large moment arm with respect to the centre of gravity of the aircraft, it produces a powerful pitching moment and through this is able to control the aircraft's angle of attack. The vertical response of this class of aircraft is therefore essentially governed by $\alpha$-generated lift. In fact with the traditional rear elevator location, the 'direct lift' generated by the control is in the opposite sense to that ultimately intended. The transient in the aircraft's longitudinal response to pilot's control, until the desired normal acceleration is established, is largely defined by the so-called short-period pitching mode, i.e. by its period and damping. The response of the aircraft in this mode can be said to impose a time lag between the pilot and the desired lift response and broadly, this lag is proportional to the period of the short period oscillation. The adverse nature of the direct elevator lift makes a further contribution to the overall lag, which can become very significant in the case of designs featuring relatively short tails or which are indeed tailless. As aircraft increase in size or more specifically as their pitching inertia increases, the short period motion becomes inevitably slower and so will their response to elevator. This trend can be expected to make greater and greater demands on pilots' anticipation especially during approach and landing where the highest requirements for precise control coincide usually, with the slowest pitch response. This argument has been elaborated in Refs. 1–3 and need not be pursued in detail here. There were two main conclusions. First that there must be an upper limit to aircraft size beyond which traditional control techniques will no longer permit the safe and efficient performance of landings. Secondly it was suggested that these difficulties could be positively removed by the use of direct-lift control. With pure direct-lift control, it can be argued, aircraft size has no effect at all on longitudinal response, which is now fully defined by the amount of $C_L$ or normal acceleration ($\Delta n$) commanded by the lifting mechanism, i.e. only by its aerodynamic efficiency. Aircraft dynamics play a role only insofar as vertical velocity is the integral of $\Delta n$, and height the integral of vertical velocity.

Apart from the promise of allowing the aircraft designer to build giant airliners without any deterioration in longitudinal control characteristics, direct-lift control offers in principle a much wider range of potential benefits. Some of these have already been appreciated, such as the possibility of utilizing the superior flare capability to allow steeper approaches with consequent gains in fly-over noise. Others may only become apparent when the consequences of such a radically new form of control are fully explored.

Past references to direct-lift control are based on the vague assumption that an aircraft is equipped with a control mechanism which generates directly and without the involvement of incidence changes, the lift or some portion of the lift required for control purposes. Whether such a system can in fact be engineered and what characteristics it has to have to achieve this ideal, has not been seriously considered. Further, no clear ideas have materialised about the way in which the pilot is expected to use direct lift. One might think of direct lift as being commanded by a separate cockpit control equivalent to the collective pitch lever in the helicopter or alternatively one might conceive of direct lift as being 'geared' directly to the stick. In the latter case it is not apparent what role a conventional elevator might play or indeed if it is necessary at all.

These questions form the basis of the present enquiry. First, classical longitudinal stability and control theory is developed for application to direct-lift control. The form adopted is in fact a generalisation which covers the complete spectrum of possible longitudinal control systems ranging from conventional tailplanes at one extremity to foreplane control at the other and including direct lift as a specific band in this spectrum. This treatment has indicated that direct-lift control can in fact be operated directly from the control stick and that a conventional pitch control surface (elevator or foreplane) will still be needed, but it will be shown that in some respect its function is then more equivalent to that of the flap selector on the conventional aircraft.

The theory has been developed to derive design criteria and especially to suggest regions within which the aerodynamic centre of the direct lift must lie in order to provide acceptable control response and general performance characteristics. It will also be shown how a linkage between the direct lift system and a pitch control surface can be utilized to control this 'effective aerodynamic centre' of the control lift.

Finally the consequences of direct-lift control are investigated for some specific flight phases, in particular landing and take off. In the ensuing discussion of the potential performance of the aircraft controlled by direct lift, a number of suggestions are made as to how the aircraft designer and operator may utilize the drastically changed properties of such a design in a wide range of applications. These range from the possibility of reducing undercarriage design loads to some reconsideration of low speed stall and speed margins.

One of the areas in which direct-lift control has long been recognised as the potential answer to the exacting demands in approach control is carrier-borne naval aviation. This form of operation raises some special problems which are not considered in the present enquiry. Nevertheless, the principal argument advanced in this report will apply to the naval aircraft as much as to land-based aircraft.

## 2. *Stability and Response Theory of the Aircraft employing Direct-Lift Control.*

### 2.1. *The Elevator as a Lift and Moment Generator.*

The elevator (or tailplane) of a conventional aircraft generates lift. However for such a system to be efficient, the surface generating this lift must be located as far as possible from the centre of gravity. The principal effect utilized by the designer is in fact the pitching moment provided by this control lift and the direct contribution of the lift itself can largely be ignored or treated as of secondary importance. In the usual case of a rear control this effect is in fact, adverse, i.e. opposite to the lift which the application of pitch control is desired to achieve. Only with a controlled foreplane do the control lift and the 'trimmed lift' act in the same sense, but here too the direct lift generated by the foreplane makes only a minor contribution and the principal function of the control is again to change the angle of attack which is the primary lift generator. Direct-lift control, on the other hand is understood to utilize a control mechanism by which lift is generated without or largely without significant change of aircraft incidence, and ideally is meant not to generate pitching moment.

With conventional control through the mechanism of a pitching-moment generator, longitudinal control is inseparably linked with and applied through the short period pitching oscillation of the aircraft and 'stability' and 'control' are closely interrelated. The most important parameter in this situation is the manoeuvre margin, which defines the effective stability of the uncontrolled pitching oscillation and equally the response to elevator. When the centre of gravity is moved aft (i.e. towards the 'manoeuvre point') the manoeuvre margin ultimately vanishes, and the aircraft's longitudinal motion then tends towards divergence and at the same time the elevator effectiveness in its most important sense, i.e. the normal acceleration commanded by a given elevator angle, becomes excessive.

One would imagine the ideal direct-lift control system to break this interdependence of control and stability so that the response of the aircraft to control is entirely defined by the characteristics of the control system whereas its stability and, for instance, response to gusts is conventionally determined by its incidence-dependent characteristics.

We shall now investigate what the requirements are for this condition to exist if indeed it is practicable at all.

The following analysis will show that it may be necessary to combine direct-lift control with some form of conventional pitch control. To allow for this contingency and at the same time to reduce the mathematical treatment to its simplest form we shall first reduce any possible multiplicity of control activators by introducing the concept of an effective overall control lift and moment arm. If the pilots control commands simultaneously a number of distinct lifts (*see* Fig. 1)

$$L_1, L_2 \ldots L_n$$

acting at distinct moment arms (with respect to some given reference point, not necessarily the centre of gravity)

$$x_1, x_2 \ldots x_n$$

we can calculate the resultant control lift as

$$L(\eta) = \sum_{i=1}^{n} L_i \tag{1}$$

and the resultant pitching moment as

$$M(\eta) = \sum_{i=1}^{n} L_i\, x_i \tag{2}$$

The resultant lift $L(\eta)$ therefore acts at an effective moment arm $x_\eta$ given by

$$x_\eta = \frac{M(\eta)}{L(\eta)} = \frac{\sum_{i=1}^{n} L_i\, x_i}{\sum_{i=1}^{n} L_i} \tag{3}$$

We retain here the symbol $\eta$ as representing the deflection of the longitudinal control irrespective of whether it is designed primarily as a moment generator or as a lift generator. In fact the term 'elevator' (with which this symbol is normally associated) appears particularly appropriate for a direct-lift control.

2.2. *Normal Acceleration Response to Generalised 'Elevator' Control.*

We assume the aircraft to be equipped with a control system which applies a control lift $L(\eta)$ at an effective moment arm $x_\eta$ with respect to the centre of gravity. Incidence generated lift $L(\alpha)$ acts at an aerodynamic centre which is located at a distance $x_\alpha$ from the centre of gravity. This distance defines the c.g. margin

$$K_n = -\frac{x_\alpha}{l} = -\frac{m_\alpha}{C_{L_\alpha}} \tag{4}$$

where $l$ is a reference length, usually a reference chord, and if we assume linear aerodynamics, we can treat this as invariant over a range of flight conditions.

Using this notation and the lift slopes

$$C_{L_\alpha} = \frac{\partial C_L}{\partial \alpha} \qquad C_{L_\eta} = \frac{\partial C_L}{\partial \eta}$$

we can write the equations for steady longitudinal motion as:

$$C_{L_\alpha} \frac{x_\alpha}{l} \alpha + m_q \frac{l}{V} q + C_{L_\eta} \frac{x_\eta}{l} \eta = 0 \tag{5}$$

$$\frac{\rho}{2} V^2 S \{C_{L_\alpha} \alpha + C_{L_\eta} \eta\} = m\, g\, \Delta n. \tag{6}$$

In this analysis we consider only increments with respect to level flight and ignore $C_{L_q}$. With the kinematic relationship

$$q = \frac{\Delta n}{V} g \tag{7}$$

these equations can be solved for:

$$\frac{dn}{d\eta} = C_{L_\eta} \frac{\rho V^2}{2W/S} \frac{\frac{x_\alpha}{l} - \frac{x_\eta}{l}}{\frac{x_\alpha}{l} + \frac{m_q}{\mu}}. \tag{8}$$

The distance $(x_\eta - x_\alpha)$ is the distance of the aerodynamic centre of the control lift from the aerodynamic centre of the $\alpha$-generated lift, i.e. from the aircraft aerodynamic centre. This control lift moment arm has the advantage of being independent of centre of gravity position and after division by the reference length $l$ takes the non-dimensionalised form:

$$K_\eta = \frac{x_\alpha - x_\eta}{l}. \tag{9}$$

This 'margin' (Fig. 2) is defined in the same way as the conventional margins of longitudinal stability theory, being positive if the control lift acts aft of the reference point, in our case the aerodynamic centre of the $\alpha$-lift.

The expression in the denominator of equation (8) will be recognised as the manoeuvre margin

$$H_m = -\frac{x_\alpha}{l} - \frac{m_q}{\mu}$$

Hence we can rewrite equation (8) as

$$\frac{\Delta n_\infty}{\Delta \eta} = -C_{L_\eta} \frac{\rho V^2}{2W/S} \frac{K_\eta}{H_m} \tag{10}$$

This equation is generally applicable whether the aircraft is controlled by a conventional elevator, a fore-plane or a direct lift system. The definition of the control and stability margins used here is illustrated in Fig. 2.

The initial response in normal acceleration to a step application of control is simply given by

$$\frac{\Delta n_0}{\Delta \eta} = C_{L_\eta} \frac{\rho V^2}{2W/S}. \tag{11}$$

Comparing equations (11) and (10) we see that the ratio $(K_\eta/H_m)$ defines an amplification of the direct control lift, i.e. the ratio of steady final normal acceleration to the initial value.

For a flap type control $C_{L_\eta} = \partial C_L/\partial \eta$ is positive. Equation (10) permits a general discussion of the steady manoeuvring response for any type of lift control system. First we see that as with conventional elevator control the steady manoeuvering response is generally dominated by the manoeuvre margin. $H_m$ is therefore as important to the designer of an aircraft with direct-lift control as it was to the designer of more conventional aircraft.

Apart from giving proper controllability in steady manoeuvres the longitudinal control of an aircraft must also provide an acceptable transient response. The transient in normal acceleration from the initial value given by equation (11), to the final steady value given by equation (10), is defined by the short period characteristics of the aircraft. Holding these constant, and varying the control moment arm, $K_\eta$, to cover the whole spectrum from the conventional rear tailplane to a foreplane control, we get a set of characteristic responses as shown in Fig. 3. In this example the aircraft is assumed to have a constant damping ratio $\zeta = 0{\cdot}8$ and a constant natural frequency, which is unspecified as it does not change the form of the response but only its timescale—provided that in changing the period we do not also change the ratio $K_\eta/H_m$.

We shall now consider the typical cases illustrated by these transient responses in some detail. In this discussion the manoeuvre margin is assumed to be positive throughout.

*Fig. 3a.* $K_\eta >> H_m$. Rear elevator or moving tailplane. The steady final response is much larger than, and in the opposite sense to, the initial response. If the elevator moment arm is sufficiently large, the initial adverse response will be hardly noticeable and for all practical purposes the control can be treated as a pure pitching-moment generator.

*Fig. 3b* $K_\eta > H_m$. Tailless aircraft with elevons. The above remarks apply again, but now the relative magnitude of the initial adverse lift is no longer negligible and is reflected in a noticeable delay in the response of the aircraft to pilots control.

*Fig. 3c* $K_\eta = H_m$. An extreme case of adverse initial response, as could be obtained with the trailing-edge control of a tailless aircraft.

*Fig. 3d* $K_\eta = 0$. The control lift acts at the centre of the incidence generated lift. This is of course a situation which might easily arise with direct lift control and therefore merits particular attention. The steady manoeuvering response is zero, that is to say that apart from imparting an initial lift impulse to the aircraft, the control is unable to control normal acceleration. This is clearly an impermissible situation if direct lift control is the aircraft's only or primary form of longitudinal control.

*Fig. 3e* $0 < (-K_\eta) < H_m$. This case implies a control lift mechanism with an aerodynamic centre forward of the aircraft aerodynamic centre but by an amount smaller than the manoeuvre margin. Direct lift acting through the aircraft centre of gravity would normally be such a case. Initial acceleration response and final steady response are now in the same sense and generally of comparable magnitude, but the steady normal acceleration is less than the initial value. The reduction in $\Delta n$ following the initial peak is the result of an 'adverse' response in aircraft incidence, which partly cancels the lift directly produced by the control itself. Aerodynamically this is a rather uneconomic mechanism, if steady manoeuvering power is taken as a criterion.

*Fig. 3f* $K_\eta = -H_m$. This is the condition for 'pure' direct lift control. The initial $\Delta n$ commanded by the control is identical to the steady response. There is still a just discernible transient, but of no practical consequence, and it can be said that the pilot has practically instantaneous control over lift. The condition $K_\eta = -H_m$ implies that the control lift acts at a point which is as far forward of the aircraft aerodynamic centre as the manoeuvre point is aft of the centre of gravity. All the lift commanded by pilots control is now generated by the control mechanism without utilizing the potential of the aircraft to produce lift *via* incidence, even as a long term response. Aerodynamically one must consider this as poor utilization of the lifting potential of the configuration and this technique is not really attractive in flight conditions where performance, and hence economy, is determined by maximum available lift. This applies in particular to the approach where $V_a$ or the permissible landing weight is defined normally by the available $C_{L_{max}}$.

*Fig. 3g* $(-K_\eta) > H_m$. If the control lift acts further forward, i.e. if $K_\eta$ becomes more negative the initial direct control lift will be further amplified by the incidence response of the aircraft. Although this represents a departure from the ideal form of direct lift control discussed in the previous paragraphs, we still have the advantage of a large immediate response to control but much better lift utilization for sustained manoeuvres. It would seem that this is in fact the most attractive regime for a practical direct lift control system.

*Fig. 3h* $(-K_\eta) >> H_m$. This case represents control lift acting a long way ahead of the aerodynamic centre of the aircraft, in other words a foreplane. The direct lift contribution to the aircraft response is now relatively small, but favourable. Otherwise the response shows the same general characteristics as that of a conventionally controlled aircraft. The major portion of the lift commanded by the control is derived from change in incidence and the development of this lift is governed by the pitch response characteristic of the aircraft.

The practical regime of direct-lift control is clearly that bracketed by the conditions illustrated in Fig. 3e to g, with Case d defining an absolute rear limit for the aerodynamic centre of the control lift. If aerodynamic efficiency, and not just controllability, is a consideration, the practical range available to the designer is further reduced by excluding Case e.

We can summarize these findings into a few design criteria:

(a) *The manoeuvre margin* $H_m$ plays the same role in stability and control as with conventional aircraft featuring pitch control and must be positive. In order to make longitudinal control less sensitive to variations in centre of gravity position, $H_m$ will have to be given a certain minimum positive value.

(b) The aerodynamic centre of the lift generated directly by a direct-lift control system *must* lie forward of the aerodynamic centre of the aircraft but to achieve acceptable utilization of the lift generated by the control system in terms of aircraft manoeuvering power, the control lift should be engineered to act reasonably far forward and especially one should assume that $(-K_\eta)$ is not smaller than the manoeuvre margin $H_m$.

It is interesting to consider the effect of changes in centre of gravity position on the response of an aircraft to direct-lift control, assuming that it satisfies in the first place these two criteria. Equation (10) implies that the ratio between steady and initial normal acceleration is given by

$$\frac{\Delta n_\infty}{\Delta n_0} = -\frac{K_\eta}{H_m} \tag{12}$$

$K_\eta$ is by definition independent of centre of gravity position, which only affects the manoeuvre margin. Hence we see that in the same way as for the conventionally controlled aircraft rearward movement of the centre of gravity and therefore a reduction in the manoeuvre margin increases the control sensitivity, i.e. the final steady normal acceleration $\Delta n_\infty$ resulting from a given control demand. This is illustrated in Fig. 4 by two examples, in which the manoeuvre margin is successively halved. We observe that in the extreme forward centre of gravity case ($H_m = 10\%$) the steady $g$ response is severely restricted. With the rear centre of gravity case ($H_m = 2{\cdot}5\%$) the direct control power is amplified but the general response begins to be rather delayed and one is clearly moving away from the 'pure' direct-lift response which is more closely approximated by the case where $H_m = -K_\eta = 5\%$.

The condition that the aerodynamic centre of the control lift be forward of the aerodynamic centre of the aircraft may present some practical difficulties, especially when the system employs trailing edge devices which tend to generate rather rearward—centred lift. The answer to this problem was indicated in the discussion at the end of Section 2.1, i.e. the pilots control must be connected to a second lift generator having a different moment arm from the principal control lift and so geared that the combined lift from these two controls acts at the desired point. The obvious means for this purpose is the elevator.

Take as an example an aircraft with a direct-lift control acting aft of the aircraft's aerodynamic centre at a relative moment arm $K_{\eta D} = +0{\cdot}05$ and a lift slope $C_{L\eta D} = 1{\cdot}0$. The desired control lift margin shall be $K_\eta = -0{\cdot}05$. The aircraft has a conventional tailplane with $K_{\eta T} = +2{\cdot}0$ and a lift slope $C_{L\eta T} = 0{\cdot}2$.

Equation (3) can be written for a two element control system in the form

$$K_\eta = \frac{C_{L\eta D}\,\eta_D\,K_{\eta D} + C_{L\eta T}\,\eta_T\,K_{\eta T}}{C_{L\eta D}\,\eta_D + C_{L\eta T}\,\eta_T} \tag{13}$$

where suffix $D$ denotes the direct lift control and suffix $T$ the tailplane contribution. This equation can be solved for the ratio $\eta_T/\eta_D$, i.e. for the gearing between the direct-lift control and the tail control:

$$\frac{\eta_T}{\eta_D} = \frac{C_{L\eta D}\,(K_\eta - K_{\eta D})}{C_{L\eta T}\,(K_{\eta T} - K_\eta)}. \tag{14}$$

For our example this equation gives $\eta_T/\eta_D = -0{\cdot}25$. To obtain the desired effective centre of overall control lift at $K_\eta = -0{\cdot}05$ the tailplane must be geared to the direct-lift control so that 4 degrees of direct-lift control commands $-1°$ of tailplane. Since the lift slope of the tailplane is 1/5 of that of the direct lift system, the direct effectiveness of the combined system is reduced by $1/5 \times 0{\cdot}25$, i.e. by 1/20. The operation just discussed can of course also be interpreted as the elevator acting as an automatic trim compensator.

2.3 *Speed Stability and Trim.*

Controllability and stability of speed are usually considered from two distinct aspects. Classical stability theory has derived the concept of the static margin which is then associated with elevator angles or stick forces to trim in steady rectilinear flight. We can formulate the requirement for stable speed control in the general form:

The increment in longitudinal control to effect a reduction in trimmed speed must have the same sign as that required in the short term to produce a positive increment in normal acceleration and *vice versa.*

This formulation avoids the necessity for introducing the sign of the control angle, which may create confusion if we change from an aft control (conventional elevator) to a fore control (foreplane). For the simple case where the effects of speed, Mach number, aeroelasticity etc. can be ignored, we can derive the static trim conditions from the lift equation

$$C_L = C_{L_\alpha}\alpha + C_{L_\eta}\eta + C_{L_0} = \frac{2W/S}{\rho V^2} \tag{15}$$

and the pitching-moment equilibrium for $q = 0$, and assuming $m_u = 0$ and $C_{m_0} = 0$,

$$C_{L_\alpha}\frac{x_\alpha}{l}\alpha + C_{L_\eta}\frac{x_\eta}{l}\eta = 0 \tag{16}$$

Equation (15) establishes a unique relationship between $V$ and $C_L$ so that we can use $C_L$ as a measure of trimmed speed, which has the advantage of permitting linearisation of the analysis and we get,

$$\frac{d\eta}{dC_L} = \frac{1}{C_{L_\eta}}\frac{1}{1-\dfrac{x_\eta}{x_\alpha}} \tag{17}$$

From equation (9) we note that

$$\frac{x_\eta}{l} = -K_\eta + \frac{x_\alpha}{l}$$

In the absence of Mach number effects etc. the centre of gravity margin is identical with the static margin:

$$H_n = K_n = -\frac{x_\alpha}{l}. \; *$$

Hence equation (17) can be reduced to

$$\frac{d\eta}{dC_L} = -\frac{1}{C_{L_\eta}}\frac{K_n}{K_\eta}. \tag{18}$$

*In Appendix A a general expression for the static margin $H_n$ is derived which allows variations of $C_L$ and $C_m$ with speed to be considered.

The corresponding trim characteristics for the short term normal acceleration responses are defined by the inverse of equation (10)

$$\frac{d\eta}{dn} = -\frac{1}{C_{L_\eta}} \frac{2W/S}{\rho V^2} \frac{H_m}{K_\eta}. \tag{19}$$

Provided that the aircraft stability margins $K_n$ and $H_m$ are positive, i.e. if the aircraft itself is stable, the sign of $K_\eta$ affects both trim characteristics in the same sense. If the control lift acts aft of the aircraft aerodynamic centre (i.e. $K_\eta > 0$) both $d\eta/dC_L$ and $d\eta/d(\Delta n)$ will be negative and if $K_\eta < 0$ both will be positive. In either case our requirement for stable speed trim as stated at the beginning of this section is satisfied. Equation (18) holds—as does equation (19)—for any form of longitudinal control, and direct-lift control, requiring small negative values of $K_\eta$ does not introduce any new considerations.

Another form of flight control which introduces the problem of speed stability is that of close control of flight path by pilot's elevator usage. Neumark has shown that in this condition speed diverges if the aircraft flies below minimum-drag speed. This condition is therefore fully defined by the performance characteristics of the aircraft, i.e. by the curve of drag *versus* trimmed speed at constant throttle setting. If thrust can be assumed invariant with speed, the time constant $\tau$ of this speed stability mode is given by

$$\frac{1}{\tau} = \frac{\rho g V}{W/S} \left\{ C_{D_0} - \frac{\partial C_D}{\partial C_L^2} C_L^2 \right\}. \tag{20}$$

The parasitic drag $C_{D_0}$ is stabilizing and the induced drag $\partial C_D/\partial C_L^2$ is destabilizing. For the conventionally controlled aircraft the elevator required to trim usually makes only a small contribution to the drag, so that in the above equation the terms $C_{D_0}$ and $\partial C_D/\partial C_L^2$ can usually be interpreted as those obtained from the controls-fixed drag polar. This cannot be normally expected also to be true for a direct lift control system, which may utilize a mechanism for generating lift which is aerodynamically less efficient than incidence, and as a consequence the induced drag factor $\partial C_D/\partial C_L^2$ may be somewhat larger. This will result in less favourable speed stability characteristics which must be properly established by using the appropriate trim drag of the aircraft with control by direct lift.

## 3. *Aerodynamic Efficiency and Control Performance of Direct-Lift Control.*

### 3.1. *General Observations.*

The principal area for the application of direct-lift control is low speed flight and specifically approach and landing. High-speed aspects will be briefly discussed in Section 8. What will be said here is mainly applicable within the specific context of low-speed flight.

The aerodynamic efficiency of an aircraft design with respect to low-speed performance is largely defined by the maximum usable $C_L$. With conventional high aspect ratio wings this $C_L$ value is generally determined by the stall, i.e. by $C_{L_{max}}$; with low aspect ratio wings other handling difficulties may precede the stall and set a practical limit to low-speed performance. Again this limit can usually be associated with a certain value of $C_L$, which then replaces $C_{L_{max}}$ or its equivalent. Since the important airworthiness requirements relate the usable approach performance to a demonstrable low-speed limit, i.e. in practice to $C_{L_{max}}$, an aircraft designed to these requirements will have to be given a longitudinal control which makes this maximum usable $C_L$ value accessible to the pilot, even though he is not expected to and is indeed discouraged from making use in operation of this extreme range. If this is not done, i.e. if a direct-lift control system used as the primary longitudinal control is unable (without some independent change of configuration) to command $C_{L_{max}}$, this condition cannot be demonstrated and potential performance is then lost in complying with the airworthiness rules. This applies equally to the maximum $\Delta n$ which can be achieved at $V_a$ and to the minimum demonstration speed.

These questions become important when discussing direct-lift control, because with this form of control, the simple relationship which exists for conventional aircraft between control and the aircraft lift slope no longer applies.

For the conventional aircraft it is usually possible to ignore elevator lift in static trim considerations and we can define for each flap configuration a relationship:

$$C_L = C_{L_0} + C_{L_\alpha}\alpha = \frac{2W}{\rho V^2 S}. \tag{21}$$

It implies that increasing speed demands a reduction in $C_L$ and hence in incidence. With direct-lift control we can no longer ignore $C_{L_\eta}$ and must consider equation (15) in full. From equations (15) and (16) we can derive an expression relating the trimmed lift slope to the basic aircraft lift slope $C_{L_\alpha}$ as:

$$\frac{dC_L/d\alpha}{C_{L_\alpha}} = \frac{1}{1+\dfrac{K_n}{K_\eta}} \tag{22}$$

or by inversion

$$\frac{(d\alpha/dC_L)_{\text{TRIM}}}{(d\alpha/dC_L)_{\text{UNTRIMMED}}} = 1+\frac{K_n}{K_\eta}. \tag{23}$$

Equation (22) can be interpreted as an amplification of the basic lift slope of the aircraft as applicable to speed control resulting from the effect of control lift. With equation (21) we obtain a relationship between $\alpha$ and speed which reads:

$$\frac{d\alpha}{dV} = -\left(\frac{d\alpha}{dC_L}\right)_{\text{TRIM}} \frac{4W/S}{\rho V^3}. \tag{24}$$

Hence if $(d\alpha/dC_L)_{\text{TRIM}}$ changes sign, $(d\alpha/dV)$ will do so too. Equations (22) and (23) are plotted in Figs. 5 and 6. We observe that when $(-K_n) < K_\eta < 0$ the normal relationship between speed and incidence is reversed. It would seem that this regime would create some rather undesirable flying characteristics and cannot therefore be recommended as a suitable operational condition for direct lift control. In the absence of Mach number effects or other terms generating $m_u$, the neutral point coincides with the aerodynamic centre of the basic aircraft, so that then the point $K_\eta/K_n = 1$ defines control lift acting at the centre of gravity. In order to avoid reversal of the normal relationship between speed and incidence, a direct-lift system must have its aerodynamic centre forward of the aircraft centre of gravity. It must be noted, however, that reversal of the $\alpha$–$V$ relationship does not by itself imply reversal of the relationship between control angle and speed which would be a much more serious matter. This problem was discussed in the previous section.

This diversion was necessary to allow us to consider now the problem of lift utilization, the question, in other words, as to how the $C_L$ potential of a given aircraft is used when one employs direct-lift control as the primary longitudinal control. This question cannot be disassociated from the type of mechanism by which control lift is generated, i.e. whether DLC is produced by a trailing-edge flap, by a spoiler, by boundary-layer control or by some form of powered lift. All these are potential means for DLC and all create their own specific problems in this application. To discuss them all in an adequately meaningful manner would require a much more extensive report than it is intended to present here. However, it is thought that the general principles which must be considered when employing such a radically new way of controlling the longitudinal motion of an aircraft, can be established by treating one particular form in detail. This should provide a means of assessing the alternative direct-lift mechanisms not specifically covered here. The mechanism selected for general discussion here is the most common type of lift control system, namely the flap. The spoiler, which is frequently quoted as a particularly attractive solution for DLC is sufficiently closely related to this type of control that most of the following discussion can be applied to it as well.

3.2. *Control Operating Characteristics in the $C_L(\alpha)$ Regime.*

It can generally be stated that the effective lift regime of an aircraft is defined by the familiar lift carpet $C_L = (\alpha, \eta)$ where $\eta$ is now considered as the lift control angle.

Depending on the effect of the flap design on the stall characteristics of the wing, this lift carpet will generally be of the form indicated in Figs. 7a and b. This lift carpet defines the total $C_L$ regime available to the aircraft designer and to the pilot, and also a potential maximum value $C_{L_{max}}$. It is the purpose of the longitudinal control system to permit the pilot access to this lift regime or at least to a portion of it adequate to satisfy all control demands.

With conventionally controlled aircraft the pilot selects an appropriate flap setting and in each such configuration, the lift regime available for continuous control (not involving configuration changes) shrinks to a line. This 'operating line', as it will be referred to here, is practically identical to the lift curve $C_L(\alpha)$ for the selected $\eta_{FLAP}$ = const. In practice it will have a slope—the trimmed lift slope as indicated in Fig. 8—slightly less steep than the basic aircraft lift slope. Strictly speaking, there is a slight difference between that applicable to manoeuvering and to speed control, but these differences are usually small and can be ignored in a broad discussion. We may note specific features. First, unless maximum flap is selected, this operating line does not give access to $C_{L_{max}}$ and secondly sufficiently large elevator application can increase incidence beyond the stall.

We shall now consider the corresponding situation if direct-lift control is applied. First, and very briefly, let us assume that an upper surface spoiler is used, the flap again being fixed at a selected value. The spoiler is only capable of reducing lift. Without making any specific assumptions about the inter-relation between incidence and stick control, one can say that the lift carpet available for control in this case has the form depicted in Fig. 9. The particular case illustrated assumes maximum flap, so that at the stalling incidence with the spoiler fully retracted, we obtain $C_{L_{max}}$.

In view of the negative effect of the spoiler on lift it is appropriate to call the fully retracted position $\eta_{max}$, and the fully extended position $\eta_{min}$. When a smaller flap angle $\eta_{FLAP}$ is selected, the control-lift carpet will be moved correspondingly down in relation to the position shown in Fig. 9 and $C_{L_{max}}$ is no longer included. A detailed discussion of the way in which by suitable engineering of the control system, these lift carpets are actually utilized by a practical direct-lift control, will be given below for the example of a flap-type DLC arrangement. This will be generally applicable to the spoiler as well. There is, however, a specific point, which perhaps may be made here. It has been suggested that if a spoiler is used for DLC and because of its one-sided aerodynamic effect, the spoiler will have to be used differentially from a normal position which corresponds roughly to $\frac{1}{2}$ deflection and that as a consequence potential aircraft lift is sacrificed. A similar argument can be advanced when flap is used for DLC.

Whereas the first part of this statement is obviously true, the second does not automatically follow. Fig. 9 certainly contains $C_{L_{max}}$ within the potentially available range. To obtain controlled access to this point, the aircraft control system must be so designed that the combination of incidence for $C_{L_{max}}$ and spoiler 'fully in' is reached simultaneously. The requirements for this will be developed in the following discussion on flap operated DLC, and the parallel to the spoiler situation will be obvious.

We have already established in equation (22) and shown in Fig. 6 that the trimmed lift slope of an aircraft under direct-lift control may differ materially from the basic lift slope $C_{L_\alpha}$ of the aircraft as such. This lift slope applies to steady level flight, i.e. it establishes the relationship between $C_L$, $\alpha$, and speed. Whereas for conventionally controlled aircraft this $C_L(\alpha)$ relationship applies practically equally to manoeuvres with $n \neq 1$, this is no longer true for the aircraft under direct-lift control. Using equations (5)–(9) we can derive the rate of change of $C_L$ with $\alpha$ for stabilized normal acceleration response as:

$$\left(\frac{dC_L}{d\alpha}\right)_{\Delta n} = C_{L_\alpha} \frac{K_\eta}{K_\eta + H_m}$$

is that now the maximum potential $C_{L\max}$ is not achievable.

An increase in $K_n$ by 50 per cent, i.e. forward movement of the centre of gravity results in the picture presented in Fig. 12b. The general control situation is now even more attractive than that shown in Fig. 11. The aircraft cannot now be stalled by pilot's control, although gusts may still lead to exceedence of the stall boundary. At the same time virtually all the potentially available $C_L$ can be utilized by the pilot. Considering that between Figs. 11 and 12b the static margin has been varied by a large factor (3), this discussion suggests that direct-lift control offers most attractive properties over and above the promise for much more positive response to pilots control, which is perhaps the main argument for direct-lift control.

### 3.3. *Control Limitations and Stall Margins.*

With conventionally controlled aircraft all control aspects at low speed are effectively limited by the stall and this applies equally to manoeuvres, to minimum level-flight speed and to the stall margin protecting the aircraft against vertical gusts. As Fig. 13a shows, the $C_{L_{\max}}$ (and $\alpha_{\max}$) values appropriate to these three limiting cases are practically identical. From this fact springs the traditional requirement, that the aircraft shall approach at not less than 1·3 $V_{\mathrm{STALL}}$ and that at $V_A$ it shall be capable of demonstrating a controlled normal acceleration of $n = 1{\cdot}3^2 g = 1{\cdot}69\, g$. This combination of requirements may be more difficult to satisfy with direct-lift control.

With direct-lift control, as Fig. 13b shows, manoeuvering, speed control, and gust induced stalling are each governed by separate considerations and so are, as a consequence, the corresponding control limits.

The manoeuvering capability is limited by the intersection of the manoeuvre line with the $C_L(\alpha)$ curves for $\eta_{\max}$ and $\eta_{\min}$ respectively. In the case shown the $C_{L_{\max}}$ defined by this condition is less than the 'absolute' $C_{L_{\max}}$ of the aircraft.

The lowest speed at which the aircraft can just be controlled ($V_{\mathrm{STALL}}$) is defined by the intersection of the speed trim line with the stall boundary and the $C_L$ available for this case is again smaller than the 'absolute' $C_{L_{\max}}$.

A vertical gust would of course only increase $\alpha$. Hence such a gust would increase $C_L$ along the basic lift slope of the configuration and this would define a stall limit at a $C_L$ value again substantially smaller than the 'absolute' $C_{L_{\max}}$. This means that when DLC is used the stall margin, i.e. the incidence margin against gust-induced stalling, is inevitably smaller than that available on the same aircraft under conventional elevator control.

The absolute $C_{L_{\max}}$ of the aircraft can, however, be reached by an infinite number of combinations of control actions and gusts. A full discussion of these possibilities would demand a separate paper and will not be attempted here.

One can say generally, that with DLC used as the primary flight control the stall margins available individually with respect to manoeuvering, speed trim and gust are less than one would have with conventional control, but that the total stall margin available for combinations of these contributions is unchanged. It is obvious that the basic philosophy of stall margins may need some considerable revision if DLC is introduced in this form. In such a discussion the apparent restrictions to the available individual stall or manoeuvering margins must be weighed against the very real advantage of those features which can make the aircraft practically unstallable by pilot's control. Also it can be argued that the much more positive control response available with DLC should permit a possibly substantial relaxation of the requirements for steady control power in such terms as $\Delta n_{\max}$.

It will be apparent that most of these problems are beyond the scope of mere theoretical speculation and must be resolved by flight testing.

When considering the significance of the so-called manoeuvering lines it must be appreciated that these define only the steady normal acceleration response characteristics of the aircraft and do not give a complete picture of the transient to a given distinct control input. Such a transient can be represented as a trace in the $C_L(\alpha)$ diagram. The transient response to a step application of control will be of the form depicted in Fig. 14 and this response then transforms into a $C_L(\alpha)$ trace as shown in the same figure. The initial instantaneous increase in lift appears as a vertical rise in $C_L$ at $\alpha$ = const. The subsequent motion occurs at $\eta$ = const. and traces out a loop along the appropriate $C_L(\alpha)$ line, settling finally at the point defined by the intersection of the line with the manoeuvre line. If the aircraft has a poorly damped pitching oscillation, there will be a noticeable overshoot of the steady-state value of $\alpha$ (and $C_L$). This peak could conceivably penetrate beyond the stall boundary even though the manoeuvre line itself does not cross into this region.

3.4. *Effect of Location of Control Lift Centre.*

To complete the discussion of the manoeuvering regime of the aircraft under direct-lift control, we shall now consider some more extreme conditions.

First we look, however, at the condition one might consider as the ideal form of direct-lift control, the case where $K_\eta = -H_m$, giving the response depicted in Fig. 3f. Here, all the manoeuvre lift comes from the control and—apart from a relatively unimportant transient—none from aircraft incidence. Hence the manoeuvering lines are now vertical lines in the $C_L(\alpha)$ carpet as shown in Fig. 15. The speed trim line is defined by $(dC_L/d\alpha)_{TRIM}$ and since $K_n$ is normally smaller than $H_m$, this will have a finite positive slope. As distinct from the situation discussed previously (Figs. 11–12) the range of $C_L$ available for normal acceleration control is now distinctly smaller than that available for control of speed.

When $(-K_\eta) < H_m$ the manoeuvering lift slope becomes negative. For the particular case where $K_\eta = -K_n$, $(dC_L/d\alpha)_{TRIM}$ would become infinite, resulting in the situation shown in Fig. 16. This clearly does not utilize the available $C_L$ range effectively.

Finally we complete the discussion with the condition where $K_\eta = 0$, i.e. where the control lift acts at the aircraft neutral point. Both operating lines are now identical with one another, as shown in Fig. 17 and lie along $C_L$ = const. Direct lift can now control neither speed nor $\Delta n$.

So far we have assumed that the aircraft has only one pilot's control, i.e. the direct lift control is geared directly to the stick although this does not preclude the possibility of mixing direct lift and a conventional elevator to place the resultant control lift at the desired location. The operating lines with this form of control sweep diagonally across the $C_L$ range (as distinct from conventional aircraft where this requires the separate operations of flap selection and elevator control) and it would seem conceivable that the stick may in fact be the only cockpit control required and no additional selector equivalent to the flap selector is needed.

3.5. *The Role of the Elevator in the Aircraft with Direct-Lift Control.*

If the aircraft has a conventional elevator, which is most probably already geared to the direct-lift control mechanism, one could also allow the pilot to control this surface independently.

To investigate the potential role of a conventional elevator on an aircraft with direct-lift control, we consider the general effect of an independently applied pitching moment. This will apply not only to deliberate changes in pitch control setting but equally to trim changes from other causes, e.g. undercarriage lowering etc.

With conventional aircraft a change in pitching moment trims the aircraft to a higher or lower $C_L$ value along a line of $C_L(\alpha)$ for otherwise fixed configuration, e.g. flap = constant. This must equally be true for the aircraft under direct-lift control, if this control is held fixed. Let us assume that an aircraft is initially trimmed in level flight to a given $C_L$ value in the $C_L(\alpha)$ carpet, i.e. to the appropriate point on the speed trim generating line for our aircraft as shown in Fig. 18, then the application of a pure pitching moment will shift $C_{L_{TRIM}}$ along the line $C_L(\alpha)$ for $\eta$ = const = $\eta_0$. The lift slopes $(dC_L/d\alpha)_{TRIM}$ and $(dC_L/d\alpha)_{\Delta n}$ of the control operating lines are of course not affected by this process and as a consequence they will shift bodily with $C_{L_{TRIM}}$. This is illustrated for the case of a speed trim operating line in Fig. 18. The manoeuvre line will be similarly moved.

This argument now indicates that with aircraft under direct-lift control pitch trim changes have very much the same effect as have changes in flap angle on the conventional aircraft, namely to change the operating regime into another part of the $C_L(\alpha)$ carpet.

We can therefore draw two main conclusions. An external trim change will change the effective $C_L(\alpha)$ regime of the aircraft under direct-lift control. If it is countered by the stick deflection appropriate to restore the original $C_L$, the aircraft will now be at a different attitude, greater as a result of a nose up pitching moment and *vice versa*. If this is to be avoided, the trim change must be countered by an equivalent opposite application of pitching moment with a conventional elevator.

Secondly, we see that the initial positioning of the operating lines for direct-lift control requires an appropriate setting of the pitch control, which one can now visualize as the proper equivalent to the flap selector of the conventional aircraft.

3.6. *Summary.*

The discussion so far has established two important features of direct-lift control. These concern firstly the form of the aircraft response to pilots stick demands as shown in Fig. 3 and secondly the operational regimes of direct-lift control as presented by what we have termed operating lines in the $C_L(\alpha)$ carpet. It was shown that all the important characteristics relevant to longitudinal control are defined by the location of the aerodynamic centre of the control lift in relation to the aircraft centre of gravity, the neutral point and the manoeuvre point. This information is summarized in a single picture in Fig. 19. All the material presented there has already been discussed so that no further introduction to this summary is necessary.

4. *Specific Stall Considerations.*

The stalling characteristics of the aircraft controlled by direct lift have already been discussed in Section 3.3.

In the discussion so far, we have however, glossed over the detailed characteristics of the aircraft in the stall region, especially when deriving the 'operating lines'. The mathematical theory derived earlier in this Report only applies to that range in which the aerodynamic properties of the aircraft are linear and therefore not properly to the stall. When a specific design is considered and all relevant aerodynamic data are available, the appropriate operating lines can be established with no difficulty, but this may involve rather tedious algebra which it is not intended to elaborate here. However, there is one important feature which may have sufficient generality to warrant discussion. If the pitching-moment curve $C_m(\alpha)$ is linear though the stall region the intersection of an operating line with the boundary of $C_L(\alpha)$ for $\eta_{max}$ can be determined from the intersection of the extrapolated linear portion of the appropriate lift slopes. This is illustrated in Fig. 20. If the pitching-moment curve departs from linearity say by $\Delta C_m$ at a particular point, this effect can be treated in the same way as we have shown earlier in Fig. 18. In other words, a nose down change in $C_m(\alpha)$ will have the effect of bending the operating line to the left and *vice versa*. This is also illustrated in Fig. 20. It can be seen that a nose-down trim change prior to the stall will have the effect of moving the operating line away from the stall boundary. In the case shown this would in fact make this aircraft, unstallable by pilots control, whereas more superficial analysis would suggest that there is a small stalling regime at the lowest trimmable speed. The opposite is of course true when the trim change is in the nose up sense. Good aerodynamic design always demands a nose-down trim change as the stall is approached and this rule is again seen to be beneficial with direct-lift control.

There is one other aspect in the characteristic response of an aircraft to direct-lift control which may need to be considered in the context of the stall. We had already indicated the effect of the aircraft's transient response to sudden direct-lift control application in Fig. 14. We can apply the same reasoning to a situation where the aircraft is flying initially close to the stall limit and the pilot, alerted to the hazard, pushes the stick hard forward to effect recovery. This results in the response shown as a $C_L(\alpha)$ trace in Fig. 21. Here the excursion into the stall is produced by the initial dip in the normal acceleration response following the immediate step. This dip is the result of an adverse response in $\alpha$ (not attitude). It is interesting to note that in this case the stall would occur at a lower $C_L$ than that at which the aircraft was initially flown.

To assess the practical relevance of this adverse response peak $\Delta n_{PEAK}$ and the corresponding $\Delta\alpha$ value, an approximate expression has been derived in Appendix B from the Taylor expansion

$$\Delta n(t) = \Delta n_0 + \Delta \dot{n}_0\, t + \Delta \ddot{n}_0 \frac{t^2}{2}$$

and this reads:

$$\frac{\Delta n_{\text{PEAK}}}{n_0} = -\tfrac{1}{2}\frac{1}{1+\dfrac{\mu_B}{C_{L_\alpha}}\dfrac{x_n}{k_y}} \tag{29}$$

where $\mu_B = 2W/S/\rho\, g\, k_y$

$k_y$ = inertia radius in pitch.

This function has been plotted in Fig. 22 for the range over which it is valid. The corresponding dip in incidence $\Delta\alpha$ is given by

$$\Delta\alpha_{\text{PEAK}} = -\Delta n_{\text{PEAK}}\,\frac{\mu}{C_{L_\alpha}}\left(\frac{l}{V}\right)^2. \tag{30}$$

Whether this feature in the response to direct-lift control does in fact have any real significance depends on the shape of the stall boundary; if this has the form shown in Fig. 7a, it is clearly of less practical importance.

5. *Pilot's Control of Flight Path and Landing Performance.*

The case for direct-lift control has arisen in the main from the realization that the traditional method of controlling the longitudinal motion of aircraft imposes some severe and important limits on the precision with which the path of an aircraft can be controlled. This problem becomes most acute during approach and landing and tends to worsen with increasing aircraft size. In fact it has been argued that there must be an upper limit to aircraft size beyond which conventional elevator control will no longer permit safe landing control, especially if one takes into account the effect of atmospheric turbulence.

During the landing flare and for touchdown control the required accuracy in height control is measured in terms of feet and that of vertical velocity in terms of a few feet per second. Such precision is of course unnecessary in general flying where available airspace is measured in hundreds if not thousands of feet. In fact the principal requirement for high precision control in flight away from the ground has arisen from gun aiming and in this case it is mainly control of fuselage attitude—carrying the sight line—with which one is concerned and in this respect the conventional elevator as a pitch control would appear most appropriate.

To explore height control as a dominating requirement we must therefore turn to the problems posed to the pilot during approach and landing and perhaps also during take off. It is in this area that improvements in longitudinal controllability may be expected to have the greatest consequences.

What then is the landing task? One can define it as the requirement to bring the wheels of the aircraft into contact with the runway as closely as possible to the runway threshold and with as little vertical velocity as possible from an approach during which the aircraft descends towards the threshold along a predetermined glide path. In modern practice this glide path is fixed at an angle $\gamma_A$, usually between $2\frac{1}{2}$ to 3° to the horizontal, so that the initial vertical velocity which has to be absorbed by the flare manoeuvre is

$$\dot{H} = \gamma_A V_A \tag{31}$$

This quantity is plotted in Fig. 23, where the currently used range is indicated as a shaded area. We see that the maximum vertical velocity of the present day large transport aircraft approaching at 140–145 knots $V_A$ is 13 ft/sec at most. The aircraft designer is required to stress the undercarriage (and very often a good deal of airframe as well) to accept an impact velocity of typically 10 ft/sec and statistical data indicate that touchdowns approaching this limit do in fact occur from time to time. This implies then that the pilot cannot be depended on to reduce the initial descent rate of the initial approach by more than a fraction in a significant number of occasions. This also indicates why we cannot readily employ steeper approach paths in spite of their obvious advantages in obstacle clearance and fly-over noise.

Similarly disappointing is the apparent difficulty which pilots have in controlling the point of touchdown. Statistical evidence[1] suggests for instance that in 1 in 100 landings present day jet transport touchdown as far as 3000 ft from the threshold. At a speed of 140 knots, this means that the aircraft has travelled over the runway for 12·5 sec before it eventually settles down.

One cannot help but conclude that such poor performance is only explicable if one assumes that the pilot is, strictly speaking, unable to *control* the landing but that at best he attempts to *manoeuvre* the aircraft into a position from which an acceptable touchdown will and must eventually result.

The most commonly quoted factor in this context is approach speed. It may be interesting therefore to compare the aircraft situation with the control of another vehicle travelling at comparable speed, namely the racing car. The appropriate control freedom of the car is of course lateral steering. It is readily apparent that the car employs acceleration control, i.e. steering wheel deflection produces a proportional amount of lateral acceleration. The transfer function of lateral position to steering demand is then of the form

$$\frac{Y}{\eta} = \frac{K}{s^2} \tag{32}$$

where $K$ is the ratio between steering wheel demand and front wheel deflection (in terms of an equivalent lateral acceleration), $Y$ lateral displacement and $\eta$ the control angle.

This transfer function is exactly identical to that defining the height response of an aircraft to ideal lift control. So one could argue that the observed steering performance of the racing car might be a relevant pointer to the potential height control performance of an aircraft employing direct lift control. It is of course commonly known that the wheels of a racing car even at speeds much greater than typical aircraft approach speeds can be placed consistently lap after lap to within inches of certain markings on the road, moreover that this precision is maintained during violent turns in the presence of other 'road users'. Of course the racing driver may have exceptional skills, and less regard for his own life than we expect of the airline pilot, but the comparison cannot be entirely invalidated by such considerations.

If one accepts this argument it would not seem unreasonable to expect a pilot, given direct-lift control, to control the vertical motion of an aircraft at landing contact with precision not substantially different from that the driver of a fast car achieves in placing the vehicle at a certain line on the road. The comparison may be somewhat oversimplified as the judgement of lateral displacement is assisted by powerful optical clues, such as line markings or a distinct curb on the road, whereas vertical position, i.e. height above ground of an aircraft cannot be directly judged by an equivalent optical reference and its appreciation must be expected to be subject to a substantial degree of uncertainty. However, even if one allows for these factors it would still seem possible for a pilot to be able to control touchdown within perhaps only tens of yards of the desired touchdown point and at the same time to constrain vertical velocity to 1 or 2 ft/sec. Of course to enable him to utilize such a potential we must place the pilot in a position he can actually see the wheels of the aircraft or give him some appropriate aid and not simply put him 100 ft ahead and 30 ft above this point.

Another way of looking at the landing problem is to consider the flare as a means of dissipating the vertical velocity of the aircraft arriving down the glide path. We have already established the value for this vertical velocity as plotted in Fig. 23. It is now interesting to estimate what in fact is required to reduce this rate of descent to zero, if we had a means of applying instantaneous normal acceleration, in other words if the aircraft were equipped with direct-lift control. The height $\Delta H$ used up in reducing an initial vertical velocity $\dot{H}_0$ to zero is

$$\Delta H = \tfrac{1}{2}\frac{\dot{H}_0^2}{\ddot{H}}$$

where $\ddot{H}_0$, the normal acceleration is assumed to be constant throughout the manoeuvre. With equation (31) this can be written:

$$\Delta H = \frac{1}{2}\frac{\gamma_A^2 V_A^2}{\Delta n\, g} \tag{33}$$

and the time consumed in the manoeuvre is

$$\Delta t = \frac{\gamma_A V_A}{\Delta n\, g}. \tag{34}$$

For $\Delta n = 0{\cdot}1\, g$, which represents, approximately 1/6 of the steady manoeuvre capability of present day aircraft at approach speeds, these quantities have been calculated and are presented in Fig. 24. Again, the currently appropriate range of glide-path angles and $V_A$ is indicated by shading. We can see that, even if only such a modest amount of manoeuvering lift is applied, the flare of even the fastest aircraft approaching at a 3° glide slope could be accommodated within 25 ft from the ground and would take no more than 4 seconds to complete. If the pilot were to apply twice the normal acceleration, i.e. $\Delta n = 0{\cdot}2\, g$, we would still only consume 1/3 of the available manoeuvering capability and as a result the above figures would be halved to $\Delta H = 12{\cdot}5$ ft and $\Delta t = 2$ seconds respectively. Seen in this way, there appears to be little of a basic problem for the pilot in the flare, if he would and could use control in the implied manner. The assumption is that the aircraft responds instantaneously in normal acceleration to pilots control and that the pilot makes decisive stick movements to initiate and to terminate the manoeuvre.

With the present aircraft neither of these assumptions apply. A typical flare is initiated in the modern jet transport at heights ranging from 50 ft to 100 ft and the control action is so cautious that it is often impossible to determine where the flare actually begins.

There are of course many factors involved to explain this difference but a major contributor must surely be the nature of the aircraft response to stick demands. In Fig. 25 the time history of the height response of a very large transport aircraft to conventional pitch control is compared to that obtained by application of the same amount of manoeuvre lift directly. Two cases of direct-lift control are considered, ideal direct-lift with $K_\eta = -H_m$ and a case where $K_\eta = 1{\cdot}5\,(-H_m)$. The advantage of direct-lift control is very obvious in reducing by about 2·5 seconds the lag in height response.

However, this picture perhaps does not fully illuminate the fundamental nature of the potential of direct-lift control which becomes clearer when we consider the frequency response characteristics of the two forms of control. The transfer function of the aircraft in height and vertical velocity to elevator control is approximately given as

$$\frac{H(s)}{\eta(s)} = K\frac{1}{s^2\,(s^2+2\zeta\,\omega_n s+\omega_n^2)} \tag{35}$$

$$\frac{\dot{H}(s)}{\eta(s)} = K\frac{1}{s\,(s^2+2\zeta\,\omega_n s+\omega_n^2)} \tag{36}$$

where $K$ is the steady control effectiveness and $\zeta$ and $\omega_n$ are the damping ratio and the natural frequency of the short-period pitching oscillation. With ideal direct-lift control the second order effect of the short-period oscillation is eliminated and we have instead

$$\frac{H(s)}{\eta(s)} = K\frac{1}{s^2} \text{ and } \frac{\dot{H}(s)}{\eta(s)} = K\frac{1}{s}. \tag{37}$$

This transfer function is an over simplification except in the case of pure DLC, the more complete form will be derived in Appendix C and take the form illustrated in Fig. 28.

If we provide aircraft with the same manoeuvering power in terms of $\Delta n$/stick movement and hence the same gain $K$, equations (37) gave the same answer irrespective of shape, size, speed or any other factor. With conventional elevators on the other hand the high frequency end of the response is completely dominated by the short-period characteristics, especially by $\omega_n$ which tends to be reduced as size increases. The result is illustrated in Figs. 26 and 27 for the height response and the vertical velocity response respectively. Three cases are considered representing major aircraft classes, a small fighter with $\omega_n = 2\pi$ rad/sec $\equiv$ 1 cps, a medium sized transport aircraft with $\omega_n = 0{\cdot}6\pi$ rad/sec $\equiv$ 0·3 cps, and a very large transport aircraft with $\omega_n = 0{\cdot}2\pi$ rad/sec $\equiv$ 0·1 cps. It is assumed to be 0·6 in all cases.

The frequency response to direct lift is common to all, it has constant phase throughout and a steady attenuation of amplitude with increasing frequency.

The response to conventional pitch control on the other hand looks entirely different. As frequency is increased toward the natural frequency $\omega_n$, the aircraft height response lags more and more behind the control input, at $\omega_n$ it is 90° out of phase. Beyond $\omega_n$ the phase swings to $-180°$, in other words the aircraft responds now in the opposite sense to low frequency control. At the same time, the amplitude is powerfully attenuated which in the circumstances might be considered a relief. The pilot (and similarly an automatic pilot) will therefore find the range of frequencies over which he can *sensibly* used such a control system severely restricted, and considering the phase characteristics, this limit will certainly be the natural frequency if not substantially below. Being an adaptive controller, he will therefore have to adopt a control strategy which does not involve useless if not detrimental attempts at rapid control and teach himself a technique which aims at long-term effects rather than immediate results. If the aircraft is small and $\omega_n$ high (as in our fighter example) this may be of little consequence, as the usable bandwidth may well cover the full range of frequencies at which he is physically capable of operating. (A frequency of somewhat less than 1 cps is often quoted as such a limit.) But with the larger aircraft this limitation severely curtails his potential.

None of these effects apply to direct-lift control which remains sensibly effective up to the highest frequencies at which the pilot manages and cares to react.

This argument then indicates two principal consequences of the sluggish pitch response of the large aircraft to elevator. First, as instanced in Fig. 25 the response of the aircraft to control input is physically limited by comparison with that produced by direct-lift control and this sets an absolute limit to the manoeuvre capability, whatever the pilot may do. Secondly and of equal importance are the properties that emerge from frequency response considerations, namely that they will force the pilot to adopt an altogether more restrained method of control, as hasty action may lead to an adverse result.

If one were to give the pilot direct-lift control one would expect not only to improve the aircraft response as such but allow him to adopt a much more decisive form of action with substantially more control over timing.

The reader familiar with automatic-control theory will readily see that for all the control forms considered, loop closure by letting the pilot (or an automatic pilot) control vertical velocity ($\eta = G_{\dot{H}} \dot{H}$) or height ($\eta = G_H H$) will not lead to instability, as in neither response does the phase lag exceed $-180°$. However, it is equally apparent that with a conventional elevator controlling height, the system may become unstable if there were an additional first-order lag whereas with direct-lift control even an additional second-order lag cannot make the situation unstable for any value of gain $G_H$. In this sense one can say, that direct-lift control leaves a substantial stability margin when compared with traditional pitch control.

The argument used here had been mainly speculative, as no firm prediction can be made regarding pilots control. Also tests on a properly engineered direct-lift control system have not been made yet. Indeed it is hoped that the present report will give added impetus to such efforts and guide the designer of such an experiment towards a full realization of the potential advantage of direct-lift control.

If one accepts the premise that direct-lift control will allow a substantial improvement in precision control during approach and landing then it may be possible to realize a wide range of benefits with repercussion throughout many areas of aircraft design and operation. As we are dealing here with a problem in which the pilot is an essential element, no quantitative forecasts can be made on the basis of theory alone. However, it is possible at least to list the areas in which benefits might accrue.

(i) Reductions in vertical velocity at touchdown by perhaps a very significant amount. This could lead to a reduction in undercarriage design requirements and hence in undercarriage weight.

(ii) If touchdown conditions can be substantially eased it will be possible to soften the oleo suspension of the undercarriage and this in turn will reduce taxying loads and again permit savings in structure weight and improve fatigue life.

It may be noted here that with the modern transport aircraft up to 50 per cent of the fatigue loading arises from landing and taxying.

(iii) These benefits could be traded off for steepened approaches, improving obstacle clearance and fly-over noise.

(iv) Control over the point of touchdown should improve and this will permit better utilization of available runway length which may be most appreciated in wet or icy conditions.

(v) If the possibility discussed earlier of reducing stalling tendencies can be realized, a new approach may be made towards reducing low-speed margins and this may lead to significant gains in potential landing performance.

(vi) As with manual control, control by an automatic pilot will be materially improved and much tighter control and improved performance should be possible.

6. *Suppression of Gust-Induced Disturbances during the Landing Flare.*

We have seen that the sluggish longitudinal response, especially of the larger aircraft, sets some definite limits to the precision with which height can be controlled by the pilot using conventional pitch control. To a certain extent one may expect a well-trained pilot to be able to compensate for these deficiencies of the aircraft by exercising his powers of anticipation, i.e. to flare and land an aircraft by executing a programme of control action, which he has learnt in practice to lead to a consistently acceptable touchdown. Such concepts have a degree of plausibility as long as the whole control situation can be said to be fully predictable and no unforeseen influences contribute. This argument must break down immediately one considers the atmosphere supporting the aircraft as other than perfectly calm. Atmospheric gusts are of course entirely unpredictable in any but a statistical sense. Each gust or sequence of gusts can only be controlled by the pilot, or by an automatic pilot for that matter, after it has struck the aircraft and after its effect on the aircraft is recognised by the pilot. In this situation the response of the aircraft to pilot's control becomes vital, each second delay in the aircraft response allows the gust to push the aircraft further from its intended flight path. The most damaging gust for an aircraft in the final flare before touchdown is perhaps the tailgust as has been argued in Refs. 2 and 5. The tailgust produces a simultaneous reduction in lift or an equivalent reduction in normal acceleration

$$\Delta n = 2\frac{u_g}{V_0} \tag{38}$$

A vertical gust affects aircraft incidence and its effect is soon removed by the aircraft weathercocking into the new flow direction. The tailgust does not change the aircraft incidence and its effect can only be equalised by the aircraft after it has increased speed to make up the deficiency. This process is governed by the phugoid mode and is too slow to affect the aircraft response for a relatively long period of time. One can therefore obtain an adequate representation of the initial response to a fore and aft gust by simply integrating equation (38), giving

$$\Delta\dot{H} = \int ng\,dt = 2\frac{u_g}{V_0}g\,t \tag{39}$$

$$\Delta H = \int \dot{H}\,dt = \frac{u_g}{V_0}g\,t^2 \tag{40}$$

where these increments are deviations from the flight path the aircraft would have followed in the absence of the gust. A tailgust equivalent of 5 per cent of an aircraft's approach speed generates 0·1 $g$ downwards acceleration and will increase vertical velocity every second by 3·2 ft/sec.

The response in vertical velocity and height to this gust is shown in Fig. 29. Also shown in Fig. 29 is the effect the application by the pilot of elevator control has on the recovery from this upset. We assume the aircraft to be a very large transport aircraft with the longitudinal response characteristics defined in Fig. 25. We assume the pilot to take one second to recognise the disturbance and apply control in the form of a sudden step. If the aircraft is equipped with a conventional tail control this control reaction would have the effect illustrated on the left hand side of Fig. 29. It is seen that up to 3 seconds after the encounter with the gust the application of control has an adverse effect on vertical velocity and practically no effect up to $t = 4$ sec on the height response. Only after $t = 3$ does elevator application begin to reduce the effect of the gust on $\dot{H}$, the effect increasing with the amount of applied elevator which is indicated by $\Delta n_{\infty}$, the final steady $g$ appropriate to the applied elevator angle. It can be concluded that the aircraft would suffer an increase in vertical velocity of at least 10 ft/sec whatever the pilot does, and if this incident occurs when the aircraft is close to the ground in the landing flare, a severe touchdown is inevitable. With direct-lift control at his command, on the other hand the pilot, reacting as quickly as in the case discussed above, can stop the increase in vertical velocity at a maximum increment of 3·2 ft/sec and, as shown in Fig. 29, quickly effects a complete recovery to undisturbed flight. What with conventional elevator control as a potential hazard, is little more than a minor irritation for the aircraft equipped with direct-lift control, whatever its size. It is hoped that this simple argument demonstrates what is perhaps the most important advantage of direct-lift control. It is this condition which poses the most untractable problem of aircraft exceeding in size by a significant margin that of the present large airliner.

Disturbances by atmospheric gust are perhaps the largest contributors to the wide scatter in touchdown rate experienced by aircraft today and if direct-lift control can enable the pilot to cope with this problem undercarriage requirements may be drastically revised.

### 7. *Take-Off under Direct-Lift Control.*

There is no inherent need to use direct-lift control for take-off, if provisions are made to allow for reversion to conventional elevator control. However, it may be necessary to perform touch-and-go landings and in this case the form of control used during landing must allow the pilot to lift off again. For take-off two essential conditions must be satisfied. First the control must enable the pilot to achieve lift-off at an attitude which leaves sufficient ground clearance, and secondly, the aircraft must be aerodynamically in a configuration which permits satisfactory performance during initial climb-out.

A thorough discussion of all these requirements is beyond the scope of this report and can only be made meaningfully on the basis of a design defined in considerable detail. The discussion here will restrict itself to some broad principles.

Fig. 30 illustrates the terms involved for nose lifting. If $L(\eta)$ is the control lift and $L(\alpha_G)$ the basic aircraft lift generated at the ground attitude $\alpha_G$, we can define the requirements for nose lifting as

$$M_0 + L(\eta)(x_\eta + x_w) - W x_w + L(\alpha_G)(x_\alpha + x_w) > 0 \tag{41}$$

if wheel friction is ignored.

For a broad assessment one may ignore $L(\alpha_G)(x_\alpha + x_w)$ as relatively insignificant, and in the absence of a pitching-moment couple $M_0$ we get simply

$$L(\eta)\left(1 + \frac{x_\eta}{x_w}\right) > W. \tag{42}$$

This relationship states that if the control lift acts at the aircraft centre of gravity ($x_\eta = 0$) the control lift must exceed the aircraft weight to lift the nose. (We note that this condition is not defined by $K_\eta = 0$ but

$K_\eta = -K_n$.) Clearly this implies that the aircraft would lift off without any rotation and noselifting is no longer a relevant requirement. It is quite conceivable that in some designs this condition can actually be met and this could lead to a major departure from current practice. It must be realized that with direct-lift control the pilot may have at his immediate command full flap deflection and this would substantially increase the lift available to him over that normally provided in the take-off configuration, where performance considerations preclude the use of more than a modest amount of high-lift flap. The drag penalty associated with the application of very large flap deflection may not be serious since this would only be needed for a very brief period from lift-off until in free flight the aircraft incidence is increased to a value normally used during the initial climb-out. If we recall what was discussed earlier about the function of elevator trim (Fig. 18) it will be apparent that for the aircraft to trim after lift-off in the desired configuration, i.e. with an amount of flap angle acceptable for good performance, it is vitally important that the appropriate pitch trim is selected prior to take off. This may in fact be the most difficult condition to satisfy, especially for an aircraft with a small static margin.

It is not suggested, however, that the mode of take-off described above is that inevitably associated with direct-lift control. We had seen earlier that for a variety of reasons direct lift control must be so engineered that the total lift commanded by the pilot acts sensibly forward of the centre of gravity of the aircraft. In this case a more conventional take-off will take place with lift-off being preceeded by noselifting and rotation. But even then one would expect lift-off at a lower attitude than normal if the pilot applies a large amount of direct lift, say in the form of flap angle.

A proper discussion of all the details of this process is best carried out with the aid of two diagrams, defining the lifting capability of the aircraft (a) with the main wheels on the ground and (b) in free flight. An example of such a set is shown in Fig. 31. Further refinements—not shown in Fig. 31—which a full analysis must consider are aerodynamic ground effect and also the effect of pre-selected elevator trim. This would replace the single $C_L(\alpha)$ operating line shown in Fig. 31b by a family of such lines. In addition, to cover noselifting, pitching moments for the ground-borne phase must also be considered. A full discussion of all these aspects is beyond the scope of the present report and deserves more thorough analysis elsewhere.

Once the aircraft is airborne, the general observations about the operating regime in the $C_L(\alpha)$ carpet apply again. One of the advantages of a direct lift-controlled aircraft is that as speed increases during climb-out, flap angle is automatically reduced by the pilot maintaining control trim and no schedule of flap reductions need be carried out. At the same time, the pilot will always have access to the full $C_{L_{max}}$ defined by the appropriate manoeuvre line, much more than would normally be at his disposal. This may make a useful contribution to the manoeuvering capability during the initial climbout.

One might consider selecting a substantial amount of nose-up trim with the conventional elevator to ease the nose-lifting requirements. However, the discussion in Section 3 has shown that such an application of positive pitching moment would shift the airborne operating regime into an undesirable portion of the $C_L(\alpha)$ carpet as can be seen from Fig. 18. In the extreme one could arrive at a situation where the aircraft stalls as soon as the wheels leave the ground. This argument again emphasises that the proper selection of pitching-moment trim is as vital an operation prior to a take off with direct-lift control, as flap selection is for the conventionally controlled aircraft.

The aircraft with direct-lift control offers another possible advantage during take-off, namely that during the take-off run, flap (i.e. the control stick) can be held at any position and scheduled to achieve the best possible performance.

One may conclude by saying that take-off requirements may pose one of the more demanding tasks for the designer of an aircraft using direct-lift control, but that these requirements are not incompatible with those derived for efficiency in other flight conditions.

It will be apparent that the ideas developed here are strongly favoured by the assumption that direct lift is generated by a high-lift flap system. The utilization of other forms of direct lift mechanisms will require separate consideration.

## 8. *High-Speed Flight.*

Direct-lift control has been conceived as a low speed mode of longitudinal control. High-speed flight, on the other hand, would hardly seem the proper regime for such a system. It may be necessary therefore to provide for reversion to conventional control for flight conditions other than take-off and landing. Nevertheless, if an aircraft is provided with a direct-lift control system, it possesses then automatically the essential ingredient for a gust alleviator and this possibility should not be left unnoticed in an argument for or against direct lift.

Direct-lift control has, however, another attraction which may be relevant to flight at modest speed as well as during take-off and landing in the narrower sense. This is greatly improved obstacle avoidance capability, which again accrues from the more immediate response to control.

9. *Some Brief Remarks on Direct-Lift Control Systems with Relatively Restricted Authority.*

The treatment of direct-lift control in this report, although making no specific assumptions about the mechanism by which control lift is generated, leans heavily on the general aerodynamic characteristics which would result from the use of high-lift flaps for this purpose. In the discussions on the performance aspects the illustrations were generally drawn so as to imply that the full range of the aircraft's lift-augmentation mechanism is available for control. If one considers the engineering problems implied by such a proposition, one may well find that such an ambitious scheme is impracticable.

In practice the designer may be able to allocate to the pilots' control only a limited portion of the full $C_L(\alpha)$ range of the aircraft, say, a limited range of flap angle. Depending on the independently selected flap angle the operational envelope available for direct-lift control would then be reduced for example to the areas indicated in Figs. 32a and b. These regimes are still wider than that available to pilots control if the aircraft had a conventional elevator, where the operating regime would shrink to a line $C_L(\alpha)$ for the selected flap angle. However, the actual $C_L(\alpha)$ range controlled by the application of direct lift, as was discussed in detail in Section 3, is defined by the slopes of the speed and manoeuvre operating lines and especially by the termination of these lines at $\eta_{max}$ and $\eta_{min}$. This is illustrated by two examples in Fig. 33a and b. It is seen there that a satisfactory control range is provided if these operating lines are not too steeply inclined with respect to the basic lift slope of the aircraft (Fig. 33a) but this $C_L$-range would become severely limited if these lines are very steep, which results from a rather aft location of the aerodynamic centre of the control lift. More than in the cases discussed so far, direct-lift control with relatively small authority requires a rather forward location of the centre of pressure, which we remember can be produced by gearing the direct-lift control mechanism to a conventional elevator or foreplane.

Since in most practical cases such an interconnection between the direct-lift mechanism and a traditional pitch control is necessary anyway, one might consider a direct-lift control system where this pitch control is allowed to continue to respond to stick movements beyond the point where the authority over direct lift is exhausted. This will permit the control regime to be extended as shown in Fig. 34a for speed trim and in Fig. 34b for manoeuvering. Now we have combined direct-lift control with conventional pitch control. In the process we shall have lost the possibility of some of the stall protection which pure direct-lift control offers, but we have made accessible to the pilot, control over a practically unlimited incidence range. The control will now have non-linear characteristics. As an example we have shown in Fig. 35 the difference in the response of the aircraft to a stick demand within or exceeding the direct-lift authority. This picture by itself does not suggest a too severe problem, but such parameters as stick force per $g$ etc will change at the discontinuity in control. This problem is further investigated in Appendix D, where it is shown that these changes are in fact surprisingly small for the more practical conditions. The results of this analysis are summarised in Fig. 36.

The detailed discussion of such refinements goes beyond the scope of the present report. It has been shown, however, that there are no insuperable difficulties if direct-lift control is limited by practical design consideration to relatively small increments in $C_L$. In particular it was suggested that such a system can still be linked directly to the principal pilots control and may be superimposed on conventional elevator control.

Perhaps the most efficient use of a limited amount of direct lift would be, however, to superimpose it in transientised form upon conventional elevator control. If washout is used for the direct lift demand, the quasi-steady response of the aircraft to pilot's control, whether with respect to manoeuvering under $g$ or to speed changes will remain as without direct lift, only the initial response to stick demands will be affected. The ideal 'transient' is clearly to obtain immediate normal acceleration equal to the quasi-steady normal acceleration obtained by elevator alone and to maintain this level until the quasi-steady response is established, in other words that indicated in Fig. 3f. The effect of such a device on the normal acceleration response to a step demand by the pilot is indicated in Fig. 37. Since the washout has the effect of allowing the direct-lift control to return to its neutral setting after each control demand, the facility of the direct-lift mechanism to speed up the transient response to a further stick demand is maintained. With such a system the benefit of direct-lift control to manoeuvering response is then equivalent to that provided by a large authority system, as long as an individual control demand by itself does not exceed the limited authority of the lift system.

It should be noted that in order to achieve the form of total response indicated in Fig. 37c it may be necessary to subject to washout not only the signal to the lift-producing surface as such but rather the total direct-lift demand optimised with respect to its point of action as discussed earlier in this report and summarized in Fig. 19. Unless the lift generator used happens to have its centre of pressure near this desired point, elevator co-ordination will be required in the same way as in the untransientized case and the washout must therefore be applied equally to the signal routed to the lift control and to the associated elevator demand. The resulting control scheme is indicated diagrammatically in Fig. 37. The criterion by which the effective point of action of the transientized control lift is to be optimised may differ from that applicable to the design of an untransientized DLC system. We had shown that for untransientized operation the efficient utilisation of the overall lifting capability of the aircraft is an important consideration indicating the choice of a more forward location of the effective centre of control lift. This implies a high gearing of the associated elevator control. When DLC is transientized the long term response and trim characteristics of the aircraft are entirely conventional and the addition of DLC does not materially interfere with the usable $C_L$ regime. This allows the DLC contribution then to be optimised solely for control response. In practice this will mean that a more rearward point of action will be chosen, requiring less elevator geared to the DLC channel.

The detailed design of a transientised DLC system therefore raises some problems which go beyond the scope of the present report. Amongst these is the choice of the precise form of the transientising transfer function and of the gains and time constants involved. Simulation would appear the most appropriate tool for such an investigation and such work has been completed since the original issue of this report.

## 10. *Conclusions.*

The present report has outlined the basic longitudinal control characteristics one may expect from an aircraft under direct-lift control. It has not considered the engineering problems or the detailed aerodynamics of a direct lift mechanism. The discussion was based on the assumption that direct-lift control by the pilot is commanded by a conventional longitudinal control and it was shown that it is indeed feasible to use direct lift in this way, without the need for an additional cockpit control equivalent to the collective pitch lever of the helicopter. If such a scheme is adopted, it will still be necessary to provide the aircraft with a conventional pitch-control surface, either in the form of a rear elevator or as a foreplane.

This control has then three distinct functions.

(i) It may be geared permanently to the direct-lift control circuit so as to place the centre of pressure of the control lift commanded by the stick at the desired location, generally ahead of the centre of gravity of the aircraft.

(ii) It may be operated by an independent selector in the cockpit to achieve an effect very much like that traditionally affected by flap selection in the conventional aircraft.

(iii) It may be used as the primary longitudinal control in high-speed flight or to extend the control range of a limited-authority direct-lift control system.

Direct-lift control cannot be treated simply as a device for applying lift without any regard to the general dynamic properties of the aircraft. The control characteristics of the aircraft under direct-lift control are as much affected by the manoeuvre and static margins of classical longitudinal stability as with conventionally controlled aircraft. In addition, however, the distance of the aerodynamic centre of the control lift from the aerodynamic centre of the aircraft becomes a crucial parameter for the control and response characteristics obtained with direct-lift control. The effect of the location of the point at which the control lift acts on the aircraft response characteristics is summarised in Fig. 19.

Of particular interest is a point ahead of the aircraft aerodynamic centre by a distance equal to the manoeuvre margin. If control lift acts through this 'ideal point' we get a close approximation to the situation envisaged as direct-lift control, i.e. lift increases in proportion to control application and the aircraft does not otherwise respond to the control input.

If control lift has its centre of pressure aft of this ideal point, the aircraft will respond in incidence in such a way as to reduce the lift directly produced by the control. The extreme case for this situation exists if control lift acts at the aerodynamic centre of the aircraft. In this case, direct lift control is unable to produce any control over sustained normal acceleration or speed trim.

The most efficient range for direct lift to act is forward of the 'ideal point', in general therefore reasonably forward of the centre of gravity of the aircraft. In this case, the direct action of the applied lift is further amplified by a favourable response in aircraft incidence.

With direct lift control, the limits of manoeuverability of an aircraft are no longer necessarily related to the stall as with conventional control. In fact, manoeuvering, speed control, and gust response are each governed by separate considerations, and are subject to different limitations. These are discussed in detail in the body of this report. It was shown that DLC offers the possibility of providing aircraft with a control system which cannot induce stalling but which at the same time allows the pilot to utilize practically all the available $C_L$ range of the configuration. However, vertical gusts and to a certain extent dynamic response transients lead to incidence excursions which must be allowed for by appropriate stall margins, and in some cases the incidence margins are less with DLC than with conventional control. It appears that present airworthiness concepts do not readily apply to this novel situation, however, because control response is faster with DLC, and a careful reappraisal of low-speed safety rules seems to be required.

The principal benefit from direct-lift control is the prospect of a major improvement in the precision with which aircraft height and vertical velocity can be controlled. The potential for such improvements becomes more marked for larger aircraft, which exhibit inevitably more sluggish response to conventional pitch control. With direct-lift control aircraft height response to stick demands can be entirely independent of aircraft size, shape and speed and this should allow pilots flying even a very large aircraft to perform landings with the precision only possible at present with very small aircraft. This could in turn lead to substantial reductions in scatter over touchdown control and in vertical velocity at touchdown and hence greatly reduce undercarriage design requirements. There are many other potential benefits which are discussed in detail in Section 5.

The possibility of taking off under direct-lift control has also been examined. Nose lifting may perhaps pose the most stringent requirements, but none that are incompatible with the achievement of good control characteristics in other flight conditions and especially landing.

In the last section, some consideration was given to direct-lift control systems having relatively little lift authority. It was shown that in such a case it may be possible to mix direct-lift control and conventional elevator control so that direct lift is used mainly for small control movements from a given trimmed state and conventional pitch control takes over when the authority of the direct lift mechanism is exhausted.

The most efficient use of a limited amount of direct lift available for DLC, however, may be to add it in transientized form to a conventional control system. In this form DLC can be used to provide the benefit of rapid initial height response to elevator demands without affecting the basic trim and manoeuvering characteristics of the aircraft.

# LIST OF SYMBOLS

| | |
| --- | --- |
| $B$ | Inertia in pitch |
| $C_L = \dfrac{L}{\rho/2 V^2 S}$ | Lift coefficient |
| $C_{L_\alpha} = \dfrac{\partial C_L}{\partial \alpha}$, $C_{L_\eta} = \dfrac{\partial C_L}{\partial \eta}$, $C_{L_u} = \dfrac{\partial C_L}{\partial \left(\dfrac{u}{V}\right)}$ | Lift-coefficient derivatives |
| $C_m = \dfrac{M}{\rho/2 V^2 S l}$ | Pitching-moment coefficient |
| $g$ | Gravitational acceleration |
| $H$ | Height |
| $H_m$ | Manoeuvre margin |
| $H_n$ | Static margin |
| $i_B = \dfrac{B}{ml^2} = \left(\dfrac{k_y}{l}\right)^2$ | Non-dimensional pitch inertia |
| $K_n = -\dfrac{m_\alpha}{C_{L_\alpha}}$ | C.g. margin |
| $K_\eta = -\dfrac{x_\eta}{l}$ | Non-dimensional control-lift moment arm with respect to the aircraft aerodynamic centre |
| $k_y$ | Inertia radius in pitch |
| $L$ | Lift |
| $L(\alpha)$ | Lift due to aircraft incidence |
| $L(\eta)$ | Lift due to control |
| $l$ | Reference length |
| $L_\alpha = \dfrac{\partial L}{\partial \alpha}$, $L_\eta = \dfrac{\partial L}{\partial \eta}$ | Dimensional lift slope |
| $M$ | Pitching moment |

| | |
|---|---|
| $M_\alpha = \dfrac{\partial M}{\partial \alpha}$, $M_q = \dfrac{\partial M}{\partial q}$, $M_{\dot{\alpha}} = \dfrac{\partial M}{\partial \dot{\alpha}}$, $M_\eta = \dfrac{\partial M}{\partial \eta}$ | Dimensional pitching-moment derivatives |
| $m_\alpha = \dfrac{\partial C_m}{\partial \alpha} = l_\alpha \dfrac{x_\alpha}{l}$ | Static-stability derivative |
| $m_\eta = \dfrac{\partial C_m}{\partial \eta} = l_\eta \dfrac{x_\eta}{l}$ | Control pitching-moment derivative |
| $m_q = \dfrac{\partial C_m}{\partial \left(\dfrac{ql}{V}\right)}$ | Pitch damping derivative |
| $m_{\dot{w}} = \dfrac{\partial C_m}{\partial \left(\dfrac{\dot{\alpha} l}{V}\right)}$ | Incidence damping derivative |
| $m_u = \dfrac{\partial C_m}{\partial \left(\dfrac{u}{V}\right)}$ | Rate of change of pitching moment with speed |
| $m = W/g$ | Aircraft mass |
| $n$ | Normal acceleration |
| $\Delta n = n-1$ | Increment in normal acceleration |
| $n_0$ | Initial normal acceleration directly produced by control application |
| $n_\infty$ | Final steady normal acceleration |
| $q$ | Rate of pitch |
| $S$ | Reference wing area |
| $t$ | Time |
| $u = V - V_0$ | Increment in speed |
| $V$ | Speed |
| $V_i$ | Equivalent air speed |
| $V_A$ | Approach speed |
| $W$ | Aircraft weight |
| $x$ | Longitudinal distance with respect to the centre of gravity of the aircraft |
| $x_\alpha$ | Distance of aircraft aerodynamic centre from centre of gravity |
| $x_\eta$ | Distance of aerodynamic centre of control lift from aircraft aerodynamic centre |

| | |
|---|---|
| $x_n$ | Distance of neutral point from aircraft centre of gravity |
| $\alpha$ | Angle of incidence |
| $\eta$ | Control deflection |
| $\mu = \dfrac{2m}{\rho S l}$ | Relative density |
| $\mu_B = \dfrac{2m}{\rho S k_y}$ | Relative density relating to aircraft inertia radius in pitch |
| $\phi$ | Phase angle |
| $\omega$ | Frequency |
| $\omega_n$ | Undamped natural frequency of the short-period oscillation |
| $\omega_E$ | Elevator response factor (*see* Appendix C) |
| $\zeta$ | Damping ratio of the short-period oscillation |
| $\zeta_E$ | Elevator response factor (*see* Appendix C) |
| $\rho$ | Air density |

## REFERENCES

| *No.* | *Author(s)* | *Title, etc.* |
|---|---|---|
| 1 | W. J. G. Pinsker .. .. | Features of large transport aircraft affecting control during approach and landing. AGARD Report 421, January 1963. |
| 2 | W. J. G. Pinsker .. .. | Some observations on the dynamics of large slender aircraft. Paper given at the AGARD Flight Mechanics Panel Meeting at Cambridge (U.K.) September 1966. |
| 3 | C. C. Flora .. .. .. | Dynamic motions of aircraft—survey and introduction. Paper given at the AGARD Flight Mechanics Panel Meeting at Cambridge (U.K.) September 1966. |
| 4 | J. C. Hall .. .. .. | The effect of low altitude gusts on automatic landing. Paper given at the AGARD Flight Mechanics Panel Meeting at Cambridge (U.K.) September 1966. |
| 5 | W. J. G. Pinsker .. .. | The landing flare of large transport aircraft. A.R.C. R. & M. 3602, November 1967. |

## APPENDIX A

*Static Stability when $C_L$ and $C_m$ are Functions of Speed.*

Direct-lift control is not considered as an attractive method for high speed flight control. Mach number and aeroelasticity can therefore be ignored in the stability analysis. Nevertheless, there may be other factors which may make the lift and pitching-moment characteristics of an aircraft vary with speed. In particular this will be so if propulsion is used as a technique to augment lift. We shall therefore broaden the treatment of static stability to include the appropriate speed-dependent terms in the equations in the form

$$C_{L_u} = \frac{\partial C_L}{\partial\left(\dfrac{u}{V_0}\right)}$$

and

$$m_u = \frac{\partial C_m}{\partial\left(\dfrac{u}{V_0}\right)}$$

where $u$ is an increment in speed in relation to a datum speed $V_0$.

Equation (15) can be written in incremental form

$$\Delta C_L = C_{L_\alpha}\alpha + C_{L_\eta}\eta + C_{L_u}\left(\frac{u}{V_0}\right) = \frac{W/S}{\rho/2}\left(\frac{1}{(V_0+u)^2} - \frac{1}{V_0^2}\right) \tag{A.1}$$

and we add $m_u$ to equation (16) to read

$$C_{L_\alpha}\alpha\frac{x_\alpha}{l} + C_{L_\eta}\eta\frac{x_\eta}{l} + m_u\left(\frac{u}{V_0}\right) = 0. \tag{A.2}$$

We can use equation (A.1) to establish a relationship between $u$ and $C_L$. If $u << V_0$, we can write

$$\Delta C_L = \frac{2W/S}{\rho V_0^2}\left(\frac{1}{1+2\dfrac{u}{V_0}} - 1\right) = C_{L_0}\left(\frac{1}{1+2\dfrac{u}{V_0}} - 1\right)$$

and

$$\left(1+2\frac{u}{V_0}\right)\Delta C_L = -C_{L_0}2\frac{u}{V_0}.$$

By observing that $u << V_0$ we can simplify this to

$$\Delta C_L = -C_{L_0}2\left(\frac{u}{V_0}\right). \tag{A.3}$$

This expression defines $(u/V_0) = -\Delta C_L/2C_{L0}$ and we can substitute this into equations (1) and (2) which now read:

$$\Delta C_L = C_{L\alpha}\alpha + C_{L\eta}\eta - C_{Lu}\frac{\Delta C_L}{2C_{L0}} \tag{A.4}$$

$$C_{L\alpha}\alpha\frac{x_\alpha}{l} + C_{L\eta}\eta\frac{x_\eta}{l} - m_u\frac{\Delta C_L}{2C_{L0}} = 0\,. \tag{A.5}$$

This system of equations can be reduced to

$$\Delta C_L\left\{1 + \frac{C_{Lu}}{2C_{L0}} - \frac{m_u}{2C_{L0}}\frac{l}{x_\alpha}\right\} = C_{L\eta}\eta\left\{1 - \frac{x_\eta}{x_\alpha}\right\}. \tag{A.6}$$

Introducing the c.g. margin $K_n = -\frac{x_\alpha}{l}$ and $K_\eta = -\frac{x_\eta}{l} + \frac{x_\alpha}{l}$ this equation then defines the speed trim characteristics as

$$\frac{d\eta}{dC_L} = \frac{1}{l_\eta}\,\frac{K_n\left(1 + \frac{C_{Lu}}{2C_{L0}}\right) + \frac{m_u}{2C_{L0}}}{K_\eta}\,. \tag{A.7}$$

The term in the numerator

$$K_n\left(1 + \frac{C_{Lu}}{2C_{L0}}\right) + \frac{m_u}{2C_{L0}} = H_n \tag{A.8}$$

defines the static margin of the aircraft when both $C_L$ and $C_m$ are functions of speed. The corresponding neutral point lies at a distance

$$x_n = H_n l \tag{A.9}$$

behind the centre of gravity of the aircraft and no longer coincides with the aerodynamic centre.

One should note that generally the static margin is now a function of $C_{L0}$, i.e. of speed $V_0$ and that therefore $d\eta/dC_L$ and equally the trimmed lift slope $dC_L/d\alpha$ is no longer constant throughout the operating range of the aircraft. This would only be the case if

$$\frac{C_{Lu}}{2C_{L0}} = \text{const} \quad \text{and} \quad \frac{m_u}{2C_{L0}} = \text{const} \tag{A.10}$$

If a speed invariant thrust $T$ acts at a fixed moment arm $z_T$ (positive below the aircraft centre of gravity) and at a fixed inclination to the aircraft longitudinal axis say at an incidence $\alpha_T$, this does in fact produce values of $C_{L_u}$ and $m_u$ satisfying equations (A.10) of the form

$$C_{Lu} = \frac{\partial C_L}{\partial\left(\frac{u}{V_0}\right)} = -2C_{L0}\frac{T}{W}\alpha_T \tag{A.11}$$

$$m_u = \frac{\partial C_m}{\partial\left(\frac{u}{V_0}\right)} = -2C_{L0}\frac{z_T}{l}\frac{T}{W}; \tag{A.12}$$

## APPENDIX B

*Estimation of the Adverse Initial Peak in the Normal Acceleration Response to a step demand of a Direct-Lift Control.*

The response in normal acceleration to a control lift applied forward of a point defined by $(-K_\eta) > H_m$ shows a marked adverse dip after the instantaneous rise in $\Delta n_0$ as the immediate result of the control action. Since by definition the control lift $L(\eta)$ is constant for $t > 0$ the difference

$$\Delta n(t) = n(t) - n_0 \tag{B.1}$$

must be due to the response in angle of attack $\alpha(t)$ and from equation (6) we get

$$\alpha(t) = \mu_1 \left(\frac{l}{V}\right)^2 \frac{\Delta n(t)}{l_\alpha} \tag{B.2}$$

The dip $\Delta n_{PEAK}$ referred to may have important repercussions on the stall-avoidance characteristics of an aircraft with direct-lift control and a rapid method for assessing this quantity might be desirable.

Since we are essentially concerned with the initial portion of a relatively smooth function it would seem appropriate to try a solution using the first *three* terms of the Taylor expansion

$$\Delta n(t) = \Delta n_0 + \Delta \dot{n}_0 t + \Delta \ddot{n}_0 \frac{t^2}{2} + \ldots \tag{B.3}$$

where the dots define differentiation with respect to time and suffix $o$ denotes values at $t = 0$.

These initial value derivatives are defined by the equations of motion which we find convenient to write in the form:

$$M_\alpha \alpha + M_{\dot{\alpha}} \dot{\alpha} + M_q q + M_\eta \eta = \dot{q} B \tag{B.4}$$

$$L_\alpha \alpha + L_\eta \eta = (q - \dot{\alpha}) mV = gm \, \Delta n \, . \tag{B.5}$$

The derivatives are in dimensional form and defined as

$$M_\alpha = \frac{\partial M}{\partial \alpha}, \quad L_\alpha = \frac{\partial L}{\partial \alpha} \quad \text{etc.}$$

The variables $\alpha$, $\eta$, $q$ etc. are incremental values with respect to trimmed flight.

Equation (B.5) defines the kinematic relationship

$$V(q - \dot{\alpha}) = g \, \Delta n \tag{B.6}$$

which we shall also require.

The function described by equation (B.3) will have a minimum or maximum when

$$\Delta \dot{n}(t) = \Delta \dot{n}_0 + \Delta \ddot{n}_0 \, t_1 = 0 \tag{B.7}$$

hence

$$t_1 = -\frac{\dot{n}_0}{\ddot{n}_0}. \tag{B.8}$$

Therefore

$$\Delta n_{\text{PEAK}} = \Delta n - \Delta n_0 = \Delta \dot{n}_0 \, t_1 + \Delta \ddot{n}_0 \frac{t_1^2}{2}$$

for convenience we drop the symbol $\Delta$ and substituting equation (B.8) get:

$$\Delta n_{\text{PEAK}} = -\dot{n}_0 \frac{\dot{n}_0}{\ddot{n}_0} + \frac{\ddot{n}_0}{2} \frac{\dot{n}_0^2}{\ddot{n}_0^2} = -\tfrac{1}{2} \frac{\dot{n}_0^2}{\ddot{n}_0}. \tag{B.9}$$

We can further generalise this expression by relating it to $\Delta n_0$, the acceleration produced directly by the control lift and write:

$$\frac{\Delta n_{\text{PEAK}}}{\Delta n_0} = -\tfrac{1}{2} \frac{\dot{n}_0^2}{\Delta n_0 \, \ddot{n}_0}. \tag{B.10}$$

The main labour now consists in finding the initial values $\Delta n_0$, $\dot{n}_0$ and $\ddot{n}_0$.

We consider the case where $\eta = \text{const}$ for $t > 0$ and $\eta = 0$ for $t < 0$, i.e. a step application of control. We shall indicate later how the procedure can be extended to cover any form of control application provided it is analytic for $t > 0$.

We also assume that initially the aircraft is in steady level flight so that

$$\alpha_0 = 0, \quad q_0 = 0 \quad \text{and} \quad \eta_0 = \eta .$$

Equation (B.5) together with equation (B.1) gives

$$\Delta n_0 = \frac{L_\eta \eta}{gm} \tag{B.11}$$

since

$$\alpha_0 = 0, \quad \Delta n - \Delta n_0 = 0 .$$

Equation (B.5) also gives

$$mV(\dot{\alpha}_0 - q_0) = -L_\alpha \alpha_0 - L_\eta \eta$$

since $\alpha_0 = q_0 = 0$

$$mV \dot{\alpha}_0 = -L_\eta \eta . \tag{B.12}$$

If we now differentiate equation (B.5)

$$L_\alpha \dot{\alpha} + L_\eta \dot{\eta} = gm \, \dot{n} . \tag{B.13}$$

At $t = 0$:

$$L_\alpha \dot{\alpha}_0 + L_\eta \dot{\eta}_0 = gm \, \dot{n}_0 \tag{B.14}$$

since $\eta(t) = \eta = \text{const}$, $\dot{\eta}_0 = 0$ and thus:

$$\dot{n}_0 = L_\alpha \dot{\alpha}_0 \frac{1}{gm} = \frac{L_\alpha \dot{\alpha}_0}{gm} .$$

substituting for $\dot{\alpha}_0$ equation (B.12) we get

$$\dot{n}_0 = -\frac{L_\alpha L_\eta \eta}{gm^2 V}. \tag{B.15}$$

To obtain $\ddot{n}_0$ for the solution of equation (B.10) we proceed with the same technique, differentiating equation (B.13), i.e. double differentiation of equation (B.5) gives

$$L_\alpha \ddot{\alpha} + L_\eta \ddot{\eta} = gm\,\ddot{n}. \tag{B.16}$$

Since $\ddot{\eta} = 0$ we can write for $t = 0$

$$\ddot{n}_0 = \frac{L_\alpha \ddot{\alpha}_0}{gm}. \tag{B.17}$$

Now we require $\ddot{\alpha}_0$, which we find by differentiating equation (B.6)

$$\dot{q} - \ddot{\alpha} = \frac{g}{V}\dot{n} \tag{B.18}$$

i.e. at $t = 0$

$$\ddot{\alpha}_0 = -\frac{g}{V}\dot{n}_0 - \dot{q}_0. \tag{B.19}$$

$\dot{n}_0$ is given in equation (B.15) and $\dot{q}_0$ can be obtained from equation (B.4) by substituting the appropriate initial values for $\eta_0$, $\dot{\alpha}_0$, but $\alpha_0 = q_0 = 0$.

It may not be necessary to reproduce here all the further algebra, which becomes more involved. However, the final expression for $\Delta n_{\text{PEAK}}$ when all the appropriate terms are substituted, reduces to the simple form:

$$\frac{\Delta n_{\text{PEAK}}}{\Delta n_0} = -\tfrac{1}{2}\frac{1}{1+\dfrac{\mu}{C_{L_\alpha} i_B}\left(\dfrac{x_\eta}{l}-\dfrac{m_{\dot{\alpha}}}{\mu}\right)} \tag{B.20}$$

and the time at which this peak is reached

$$t_1 = \frac{l}{V}\frac{1}{\dfrac{C_{L_\alpha}}{\mu}+\dfrac{1}{i_B}\left(\dfrac{x_\eta}{l}-\dfrac{m_{\dot{\alpha}}}{\mu}\right)}. \tag{B.21}$$

Since $\mu$ is normally a large quantity a reasonable approximation for equation (B.20) is

$$\frac{\Delta n_{\text{PEAK}}}{\Delta n_0} \approx -\tfrac{1}{2}\frac{1}{1+\dfrac{\mu}{C_{L_\alpha} i_B}\dfrac{x_\eta}{l}}. \tag{B.22}$$

As in this expression the reference length $l$ appears directly and again in

$$\mu = \frac{2W/S}{\rho\, g\, l}$$

it is convenient to remove this physically irrelevant quantity and define

$$\mu_B = \frac{2W/S}{\rho\, g\, k_y} \tag{B.23}$$

where $k_y$ is the inertia radius in pitch and we can then write equation (A.22) as:

$$\frac{\Delta n_{\mathrm{PEAK}}}{\Delta n_0} = -\tfrac{1}{2}\frac{1}{1+\dfrac{\mu_B}{C_{L_\alpha}}\dfrac{x_\eta}{k_y}}. \tag{B.24}$$

Since the inertia radius is always positive, a positive value of $x_\eta/k_y$ defines a lift control acting aft, and a negative $x_\eta/k_y$ a control acting forward of the centre of gravity. The solution of equation (B.24) or the more accurate equation (B.20) is only physically meaningful if the peak value $\Delta n_{\mathrm{PEAK}}$ occurs relatively early in the response where the truncated Taylor series is likely to give an adequate approximation, in particular of course, before the response function $n(t)$ experiences an inflection, which requires terms of higher than second order to reproduce. Another irrelevant solution is obtained if $t_1$ is negative.

For the range where the solution is applicable, equation (B.24) has been computed and plotted against $x_\eta/k_y$ and $\mu_B/l_\alpha$ as parameters in Fig. 22.

If control is applied as a general function $\eta(t)$, the derivatives of $\eta(t)$ and hence the initial values $\dot{\eta}_0$, $\ddot{\eta}_0$ etc. will no longer be zero. In the process outlined above it will be necessary to substitute these values at the appropriate steps in the calculations, e.g. in equation (B.14).

## APPENDIX C

*Frequency Response in Normal Acceleration, Vertical Velocity and Height to Generalised Elevator Control.*

We can write the longitudinal equations of motion at constant speed and ignoring $L_q$ and $L_{\dot{\alpha}}$ as negligible:

$$M_q q - B\dot{q} + M_\alpha \alpha + M_{\dot{\alpha}} \dot{\alpha} = -M_\eta \eta \tag{C.1}$$

$$mV(-q+\dot{\alpha}) + L_\alpha \alpha = -L_\eta \eta . \tag{C.2}$$

It should be noted that when treating the short-period characteristics of an aircraft by ignoring speed variations, i.e. by assuming $V$ = const it is more correct to consider the vertical motion in true wind axes, (in the lift axis) than in body fixed $Z$ axes. Only then is the condition $V$ = const satisfied. If body axes are used, by definition $u$ = const and since $V = \sqrt{u^2+w^2}$, V $\neq$ const if $w \neq$ const. The numerical difference between the answers given by the two alternative approaches is rarely significant but it is clearly absurd to go to the additional trouble of evaluating $Z_w$ rather than using the readily available lift derivation $C_{L_\alpha}$ for instance, if by so doing one only offends the basic assumption in the approximation.

Equations (1) and (2) can be written as a response determinant

$$\begin{vmatrix} q & \alpha \\ \frac{M_q}{B} - s & \frac{M_\alpha}{B} + \frac{M_{\dot{\alpha}}}{B} s \\ -1 & \frac{L_\alpha}{mV} + s \end{vmatrix} = \begin{vmatrix} \\ -\frac{M_\eta}{B}\eta \\ -\frac{L_\eta}{mV}\eta \end{vmatrix} \tag{C.3}$$

Which can be solved for $q$ and $\alpha$ and by using the kinematic relationship:

$$\Delta n = (q - \dot{\alpha}) \frac{V}{g} \tag{C.4}$$

we obtain the transfer function

$$\frac{\Delta n(s)}{\eta(s)} = \frac{L_\eta}{mg} \frac{s^2 + 2\zeta_E \omega_E s + \omega_E^2}{s^2 + 2\zeta \omega_n s + \omega_n^2} \tag{C.5}$$

or

$$\frac{\Delta n(s)}{\eta(s)} = \frac{C_{L_\eta}}{\mu} \frac{V^2}{lg} \frac{s^2 + 2\zeta_E \omega_E s + \omega_E^2}{s^2 + 2\zeta \omega_n s + \omega_n^2} \tag{C.6}$$

since

$$\dot{H} = \int \Delta n \, g \, dt$$

and

$$H = \int \dot{H}\, dt$$

we get

$$\frac{\dot{H}(s)}{\eta(s)} = \frac{C_{L_\eta}}{\mu} \frac{V^2}{l} \frac{1}{s} \frac{s^2+2\zeta_E\,\omega_E\, s+\omega_E^2}{s^2+2\zeta\,\omega_n\, s+\omega_n^2} \tag{C.7}$$

and

$$\frac{H(s)}{\eta(s)} = \frac{C_{L_\eta}}{\mu} \frac{V^2}{l} \frac{1}{s^2} \frac{s^2+2\zeta_E\,\omega_E\, s+\omega_E^2}{s^2+2\zeta\,\omega_n\, s+\omega_n^2}. \tag{C.8}$$

By substituting $j\omega = s$ these transfer functions are transformed into frequency response functions. The factors $\zeta$ and $\omega_n$ are the damping ratio and the undamped frequency of the short period oscillation and $\zeta_E$ and $\omega_E$ are elevator response parameters.

Introducing the non-dimensional form for the derivatives and expressing the moment derivatives $M_\alpha$ and $M_\eta$ by the corresponding lift derivatives multiplied by their respective moment arms $x_\alpha$ and $x_\eta$ these factors are given by

$$\omega_n^2 = -\frac{1}{\mu}\left(\frac{V}{l}\right)^2 \frac{C_{L_\alpha}}{i_B}\left\{\frac{x_\alpha}{l}+\frac{m_q}{\mu}\right\}$$

or

$$\omega_n^2 = +\frac{1}{\mu}\left(\frac{V}{l}\right)^2 \frac{C_{L_\alpha}}{i_B} H_m \tag{C.9}$$

where $H_m$ is the manoeuvre margin.
Similarly

$$\omega_E^2 = -\frac{1}{\mu}\left(\frac{V}{l}\right)^2 \frac{C_{L_\alpha}}{i_B}\left\{\frac{x_\alpha}{l}-\frac{x_\eta}{l}\right\}$$

or

$$\omega_E^2 = -\frac{1}{\mu}\left(\frac{V}{l}\right)^2 \frac{C_{L_\alpha}}{i_B} K_\eta. \tag{C.10}$$

If $K_\eta > 0$, i.e. for conventional tail control, $\omega_E$ would be imaginary. In this case the second order factor in the numerator of the transfer functions (C.6)–(C.8) would be replaced by two first-order factors, one of which will have a negative time constant. The ratio between $\omega_E$ and $\omega_n$ is clearly a most important parameter in constructing the frequency responses defined in equations (C.6)–(C.8) in the form of Bode-diagrams and it is interesting to note that this ratio is simply

$$\frac{\omega_E}{\omega_n} = \sqrt{-\frac{K_\eta}{H_m}}. \tag{C.11}$$

The damping ratio $\zeta$ is given by

$$\zeta = \frac{1}{\mu}\left(\frac{V}{l}\right)\left\{C_{L_\alpha} - \frac{m_q}{i_B} - \frac{m_{\dot{w}}}{i_B}\right\}\frac{1}{2\omega_n} \tag{C.12}$$

and

$$\zeta_E = -\frac{1}{\mu}\left(\frac{V}{l}\right)\left\{\frac{m_q}{i_B} + \frac{m_{\dot{w}}}{i_B}\right\}\frac{1}{2\omega_E}. \tag{C.13}$$

The ratio between these two factors is

$$\frac{\zeta_E}{\zeta} = \sqrt{-\frac{H_m}{K_\eta}}\,\frac{1}{1 - \dfrac{C_{L_\alpha} i_B}{m_q + m_{\dot{w}}}}. \tag{C.14}$$

Using these relationships the Bode-diagram of the height response/frequency response can be readily drawn. Three examples representative of the range of direct-lift control are shown in Fig. 28, assuming the same steady state response $\Delta n_\infty/\eta$ in all cases. For pictorial clarity the examples shown are for rather extreme cases $K_\eta/H_m = -4$ and $K_\eta/H_m = -\frac{1}{4}$. For values nearer $(-1)$ the difference from the ideal shape as shown in Fig. 26 would be much less.

---

## APPENDIX D

*Direct-Lift Control with Limited Authority.*

Let us assume a direct-lift control system in which the direct-lift mechanism as such, generating $l_{\eta_D}$ and $K_{\eta_D}$, is geared to a conventional tail control with $l_{\eta_T}$ and $K_{\eta_T}$, so that the combined system produces effective control lift at some desired value $K_\eta$. From equation (14) we see that this requires a gearing between the tail control angle $\eta_T$ and the lift control deflection $\eta_D$ as

$$\frac{\eta_T}{\eta_D} = \frac{C_{L\eta_D}(K_\eta - K_{\eta_0})}{C_{L\eta_T}(K_{\eta_T} - K_\eta)} \tag{D.1}$$

In the control regime where direct lift is available, the steady normal acceleration response $\Delta n_\infty$ is given according to equation (10) as

$$\Delta n_\infty = \frac{\rho V^2}{2W/S}\left\{\frac{K_{\eta_T}}{H_m} C_{L\eta_T}\,\eta_T + \frac{K_{\eta_D}}{H_m} C_{L\eta_D}\,\eta_D\right\} \tag{D.2}$$

If we assume that the pitch control is allowed to carry on beyond the point where the authority of the direct-lift system $\eta_{D_{\max}}$ is reached, the additional normal acceleration response in this case is reduced to

$$\Delta n_\infty = \frac{\rho V^2}{2W/S}\,\frac{K_{\eta_T}}{H_m} C_{L\eta_T}\,\eta_T \tag{D.3}$$

If we now assume that the tail control angle $\eta_T$ is proportional to pilots control, we can express the elevator effectiveness in the two cases as

$$\left(\frac{d\Delta n_\infty}{d\eta_T}\right)_{D+T} = \frac{\rho V^2}{2W/S}\left\{\frac{K_{\eta_T}}{H_m} C_{L\eta_T} + \frac{K_{\eta_D}}{H_m} C_{L\eta_D}\,\frac{\eta_D}{\eta_T}\right\} \tag{D.4}$$

and for pure tail control

$$\left(\frac{d\Delta n_\infty}{d\eta_T}\right)_{T} = \frac{\rho V^2}{2W/S}\left\{\frac{K_{\eta_T}}{H_m} C_{L\eta_T}\right\} \tag{D.5}$$

We can now substitute in equation (D.4) for $\eta_D/\eta_T$ the expression given by equation (D.1) and form the ratio

$$\frac{\left(\dfrac{d\Delta n_\infty}{d\eta_T}\right)_T}{\left(\dfrac{d\Delta n_\infty}{d\eta_T}\right)_{D+T}} = \frac{1}{1 + \dfrac{K_{\eta_T} - K_\eta}{K_\eta - K_{\eta_D}}\,\dfrac{K_{\eta_D}}{K_{\eta_T}}} \tag{D.6}$$

If we assume that the pitch-control moment arm is substantially larger than the arm at which the direct lift acts, i.e. $K_{\eta T} >> K_{\eta D}$ this expression reduces to

$$\frac{\left(\dfrac{d\Delta n_\infty}{d\eta_T}\right)_T}{\left(\dfrac{d\Delta n_\infty}{d\eta_T}\right)_{D+T}} \approx 1-\frac{K_{\eta D}}{K_\eta} \tag{D.7}$$

This expression will give a negative answer if $K_{\eta D}/K_\eta > 1$. As we had seen from the discussion in the main body of this report that $K_\eta$ must always be negative for acceptable direct-lift control, the above situation would imply that the direct-lift mechanism acts by itself forward of this desired centre of pressure, a most unlikely condition. A negative result from equation (D.7) would of course imply, that elevator response changes sign if the direct-lift component is removed.

If the direct lift by itself acts at the aerodynamic centre of the aircraft $K_{\eta D} = 0$ and equation (D.7) then states that removal of direct lift from the longitudinal control circuit does not change the steady manoeuvering response. The initial response is of course entirely different. If the direct control lift were to act by itself aft of the aerodynamic centre of the aircraft, $K_{\eta D} < 0$ and its removal would then increase the effective steady elevator power.

If the direct lift mechanism would produce lift at the desired location by itself $K_{\eta D} = K_\eta$, no elevator gearing would be needed and in this case equation (D.7) gives the corresponding answer 0. Obviously no control is available once the authority of the direct lift mechanism is exhausted. Again it seems rather improbable that the aerodynamicist could provide direct lift acting so far forward, and this condition is of no practical consequence.

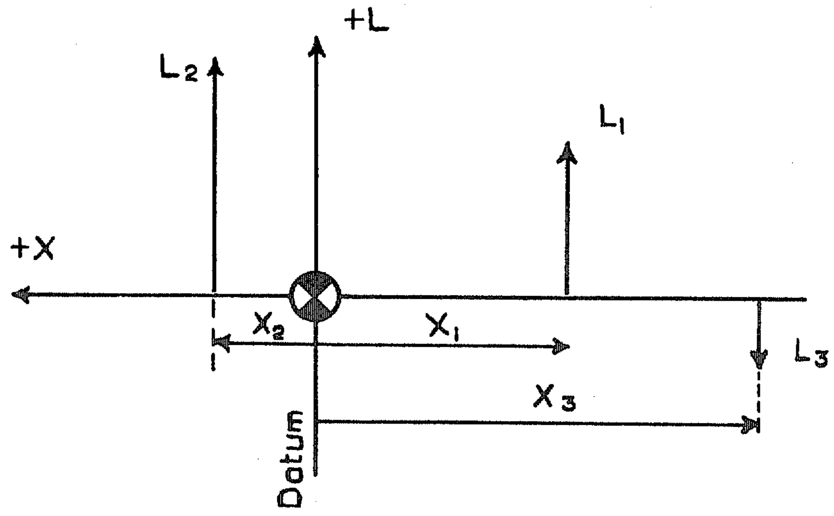



FIG. 1. Definition of lift and moment arm for a multi-element aircraft control system.

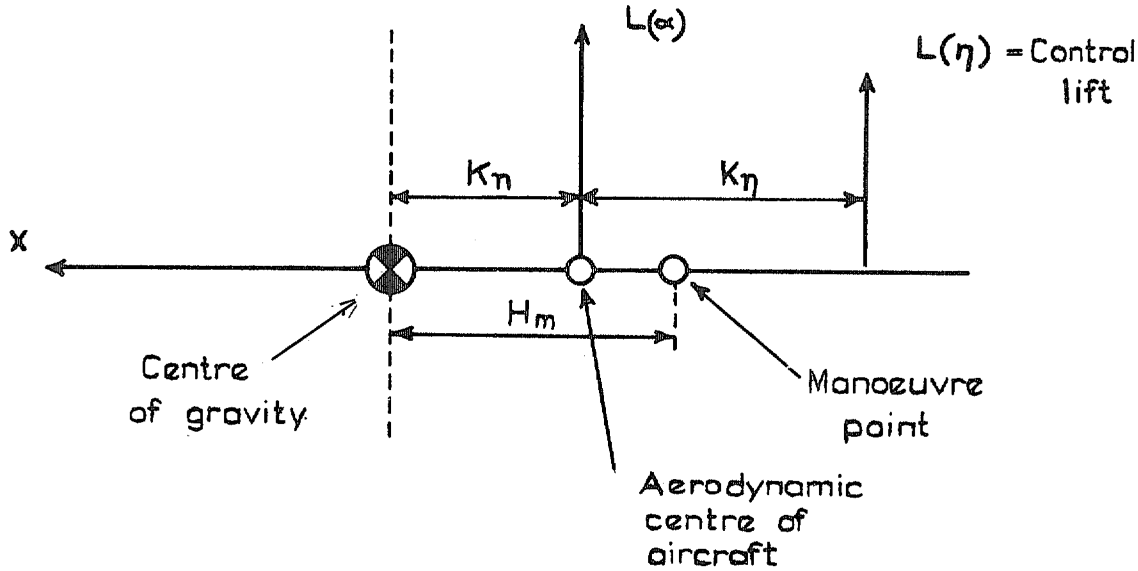



FIG. 2. Definition of longitudinal stability and control margins (all margins shown are positive).

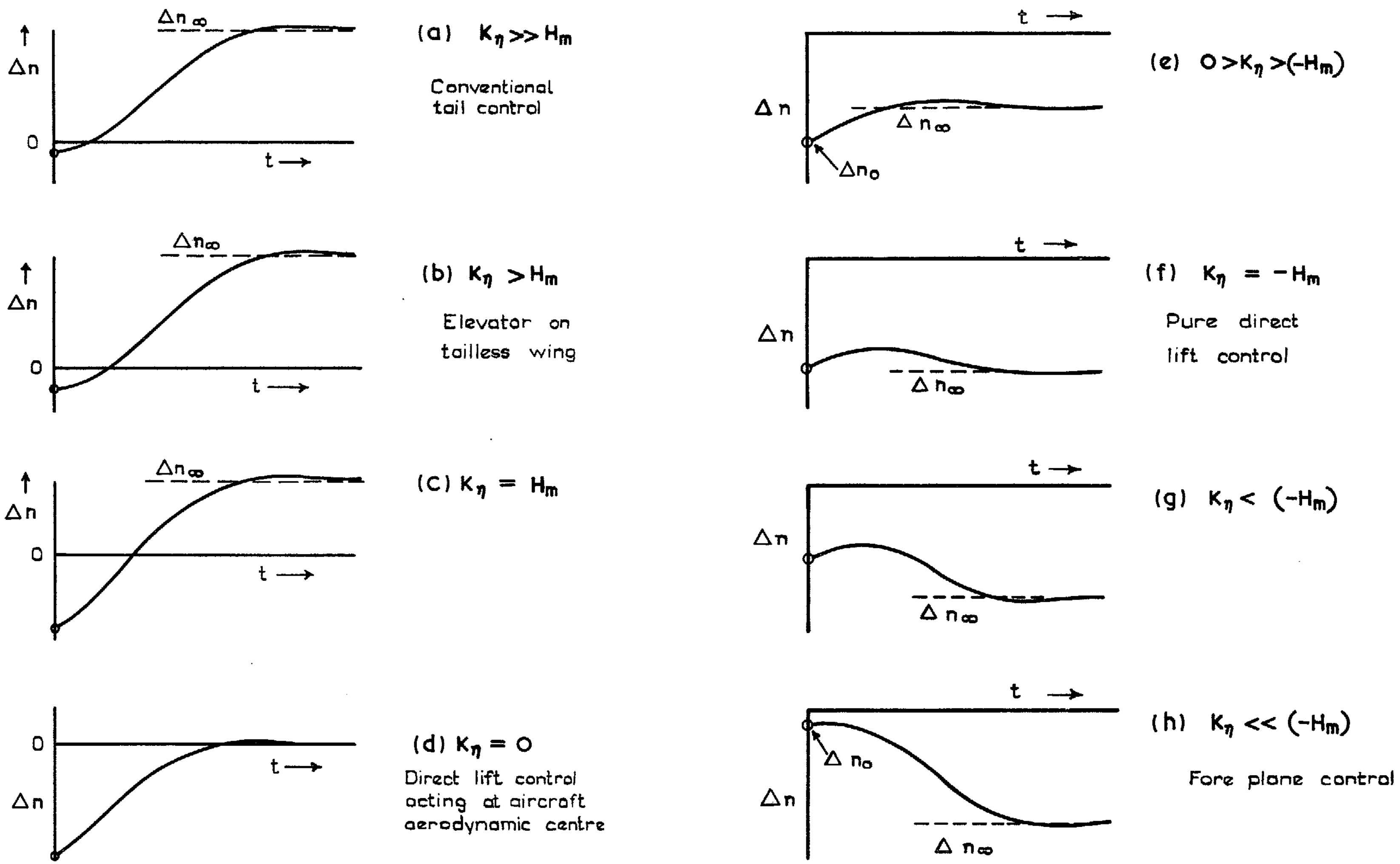



FIG. 3 a to h. Normal acceleration response to a step application of longitudinal control as the aerodynamic centre of the control lift changes from aft to forward of the aircraft aerodynamic centre.

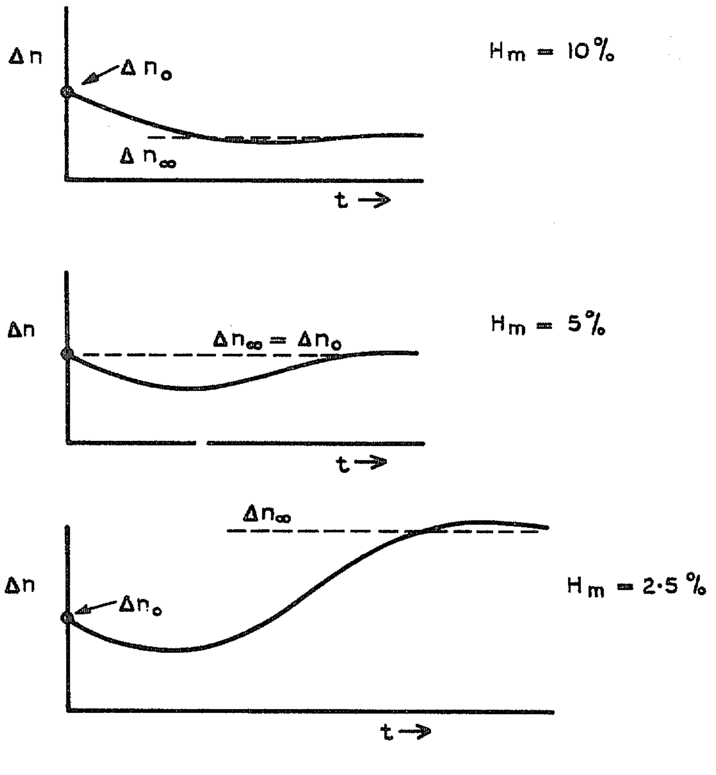



FIG. 4. Effect of changes in centre of gravity position i.e. manoeuvre margin $H_m$ on the response to a direct-lift control system with $K_\eta = -0{\cdot}05$.

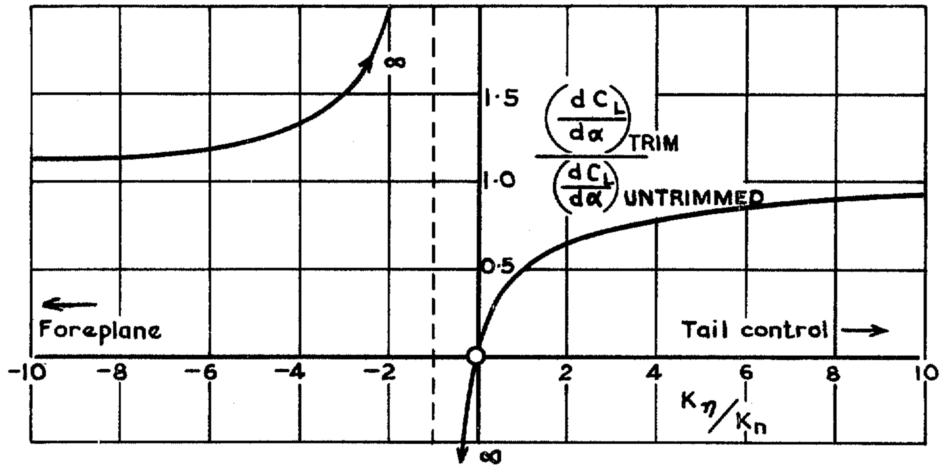



FIG. 5. Amplification of basic aircraft lift slope for steady trim as a function of control location.

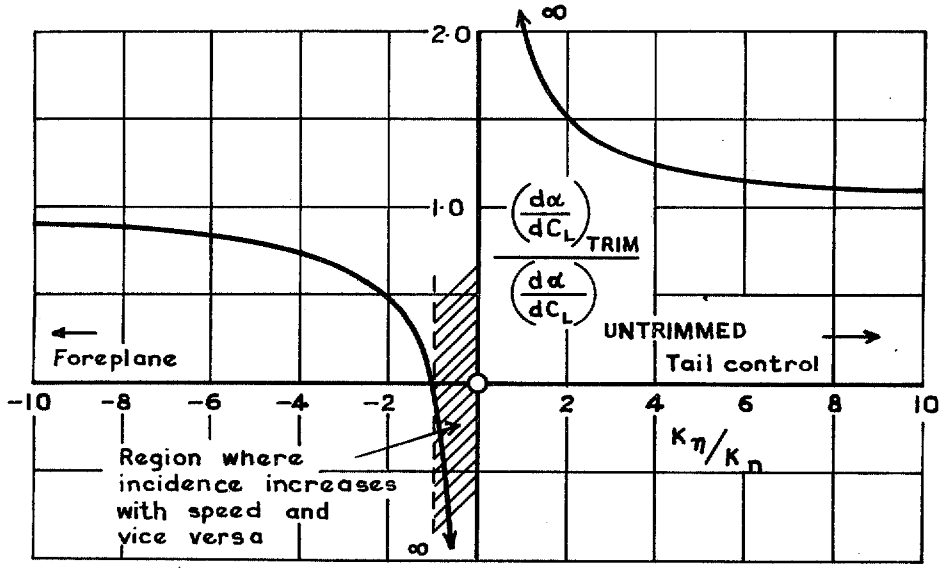



FIG. 6. Steady-flight trim characteristics as a function of control-moment arm $K_\eta$ and static margin $K_n$.

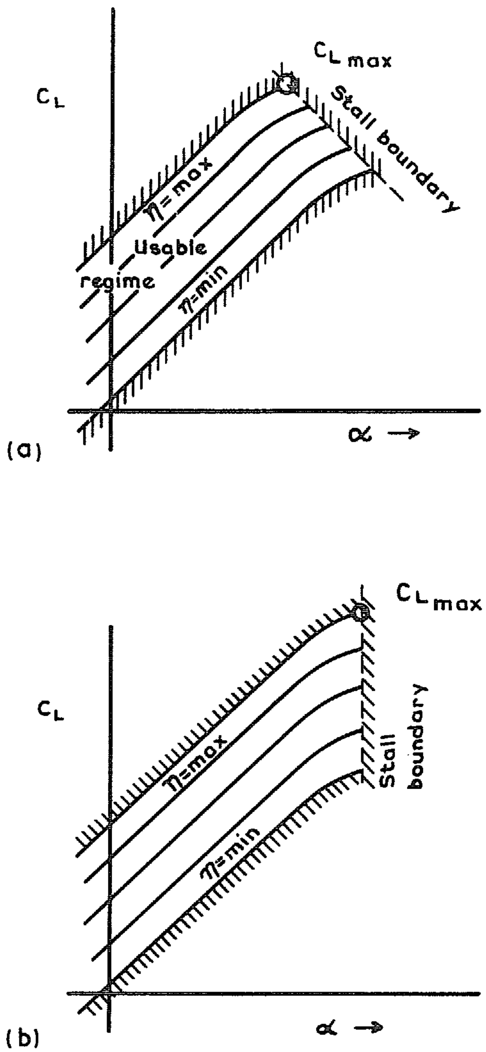



FIG. 7 a & b. Typical forms of lift carpet $C_L(\alpha, \eta)$ for an aircraft with a lift augmentation system.

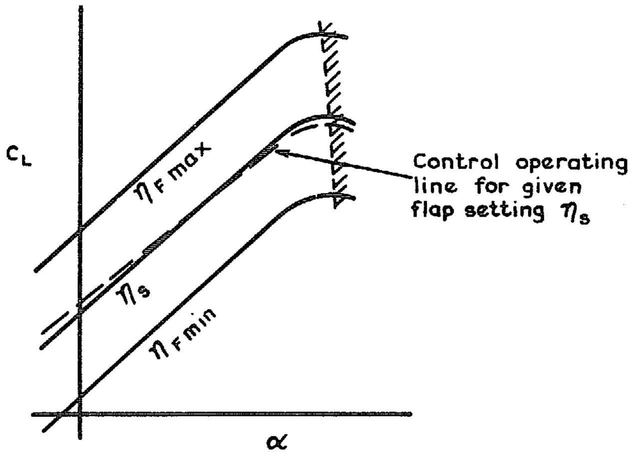



FIG. 8. Lift regime (operating line) available to pilot using conventional elevator control at a given flap setting.

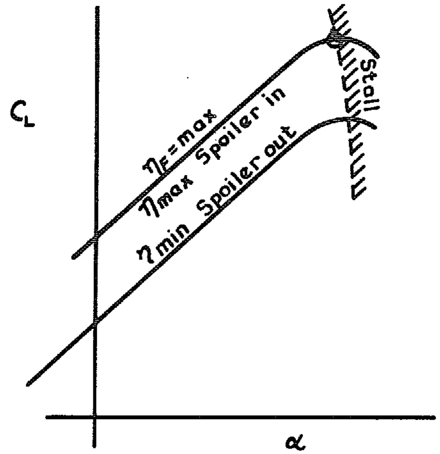



FIG. 9. Lift regime available for pilot control if an upper surface spoiler is used for direct-lift control (flap assumed set at $\eta_{F\max}$).

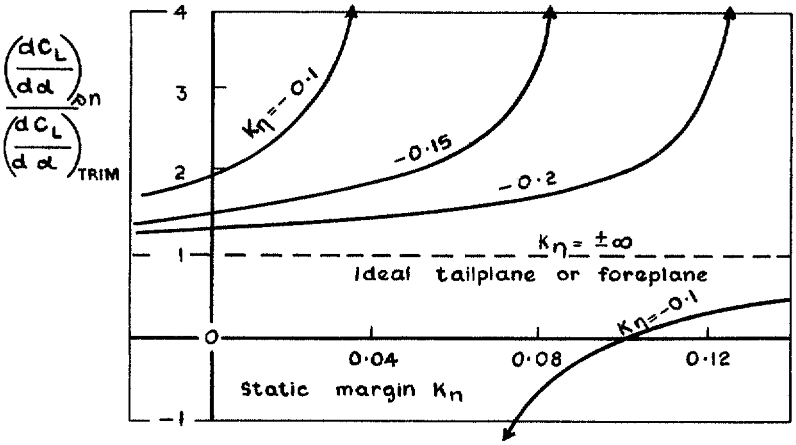



FIG. 10. Ratio between effective lift slopes relevant to manoeuvres ($\Delta n$) and to speed trim (TRIM) within the range applicable to direct-lift control. (Assumed $\Delta H = -mq/\mu = 0{\cdot}05$).

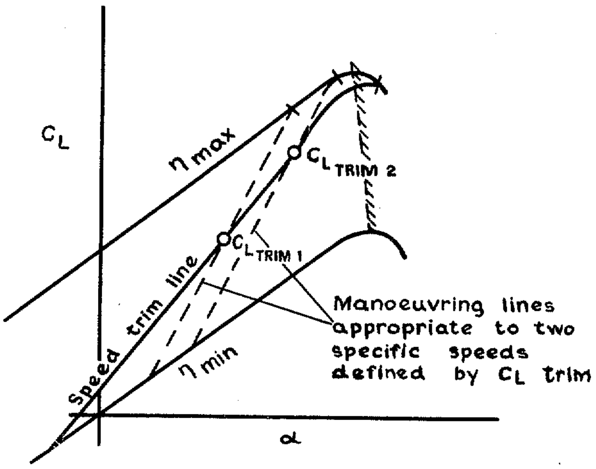



FIG. 11. Speed trim and manoeuvering operating lines for an aircraft with direct-lift control.

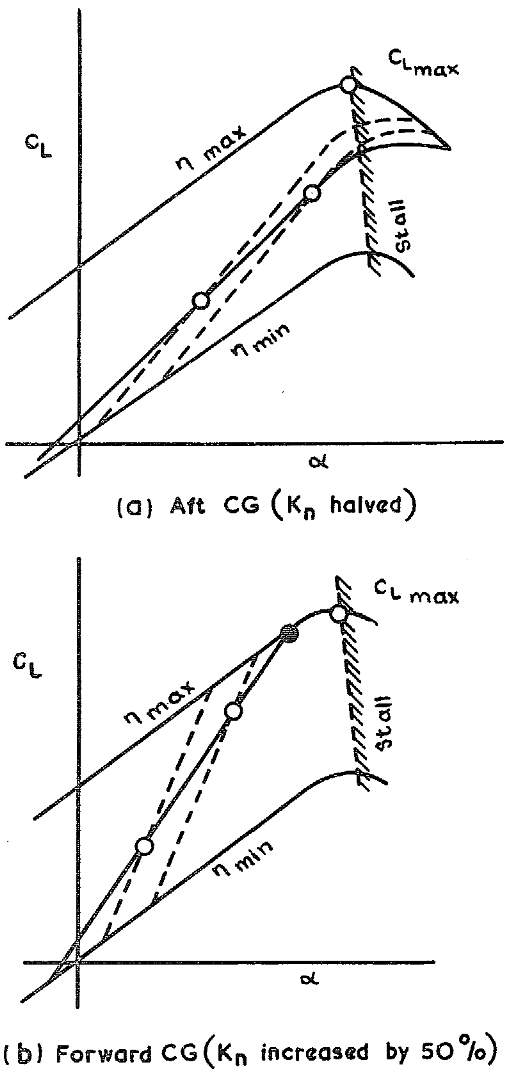



FIG. 12 a & b. Effect of changes in centre of gravity on the operating characteristics of the direct-lift control case of Fig. 11.

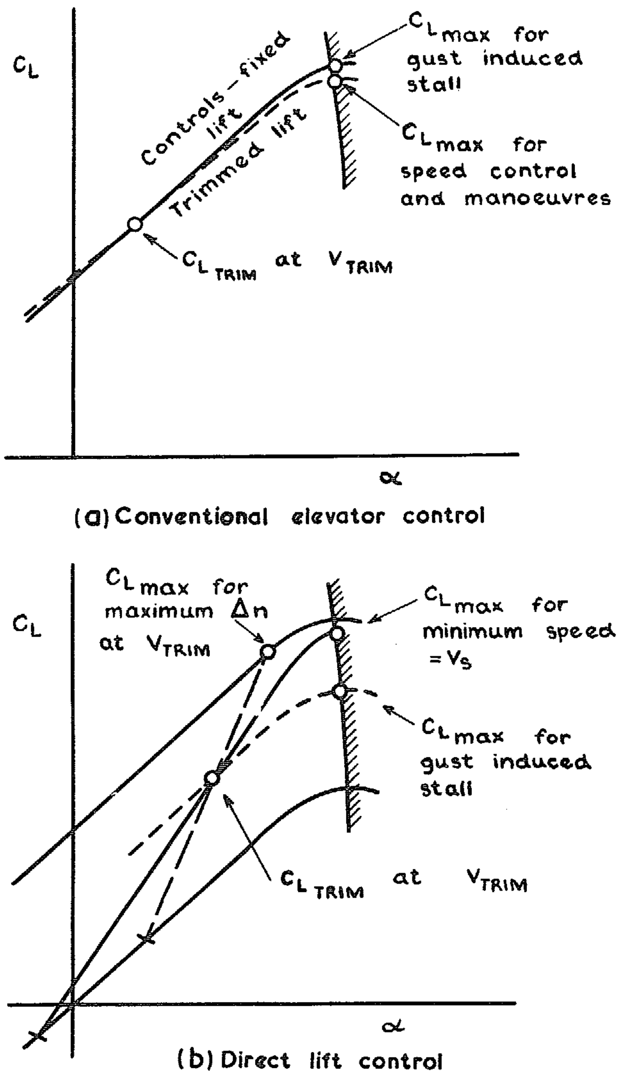



FIG. 13 a & b. Stall margins and manoeuvering limitations with conventional and direct-lift control.

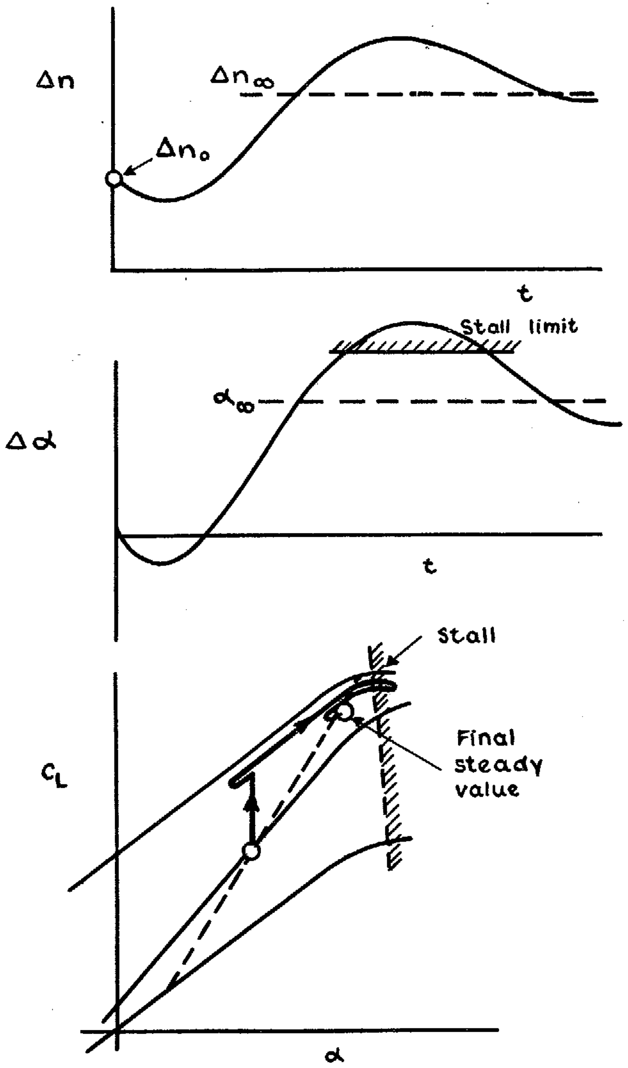



FIG. 14. Transient response trace in the $C_L(\alpha)$ carpet of an aircraft with a poorly damped longitudinal oscillation.

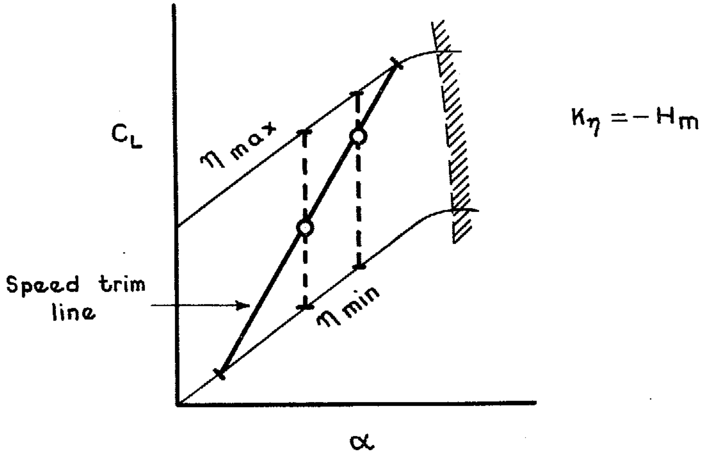



FIG. 15. Control operating lines in the $C_L(\alpha)$ carpet when $K_\eta = -H_m$. (Manoeuvre response at constant $\alpha$).

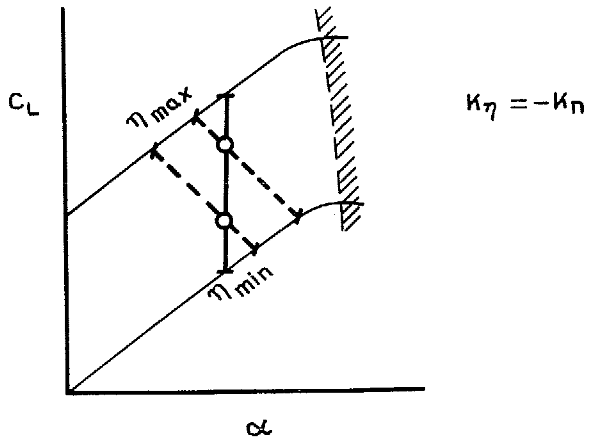



FIG. 16. Operating lines in the $C_L(\alpha)$ carpet when $K_\eta = -K_n$. (Speed trim at constant $\alpha$).

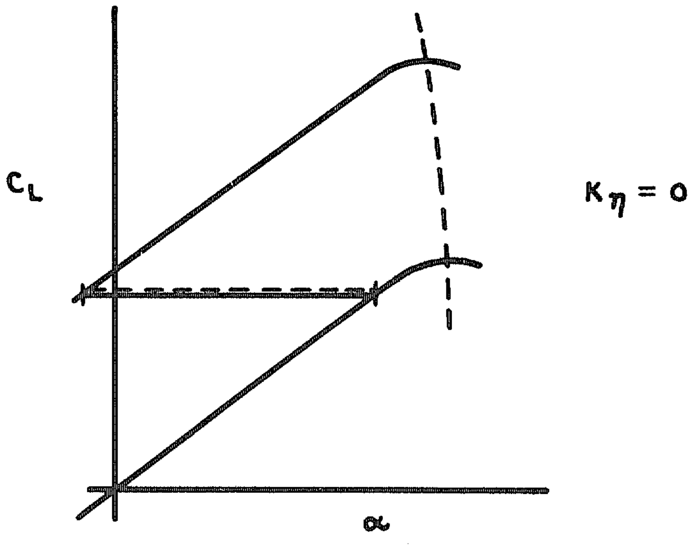



FIG. 17. Control lift acting at the aerodynamic centre of the aircraft.

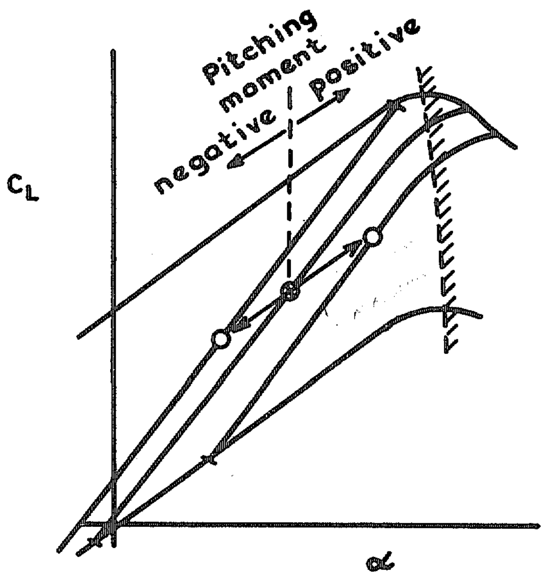



FIG. 18. Effect of applied pitching moment on the speed trim line of an aircraft with direct-lift control.

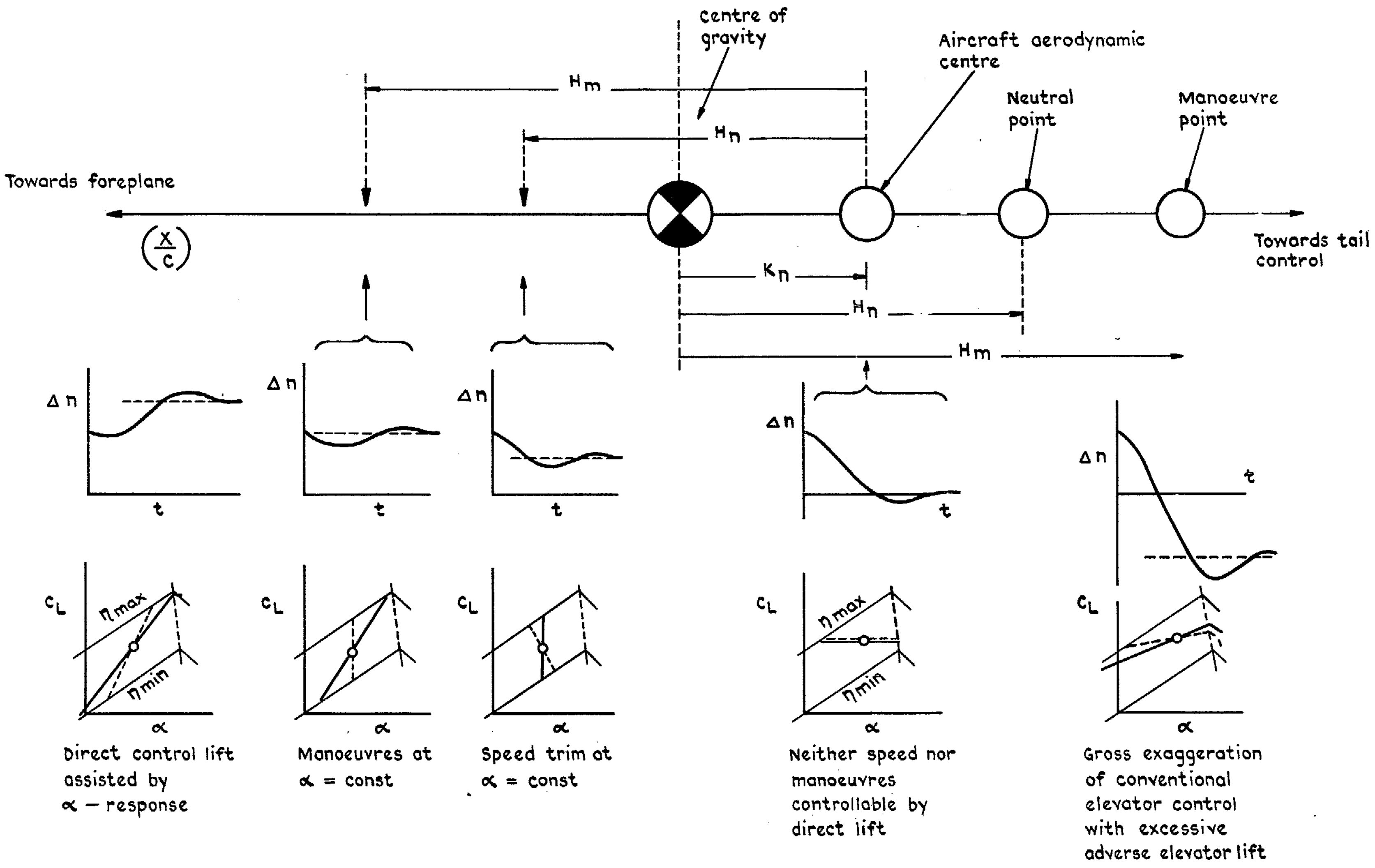



FIG. 19. Change of aircraft control characteristics with location of centre of control lift.

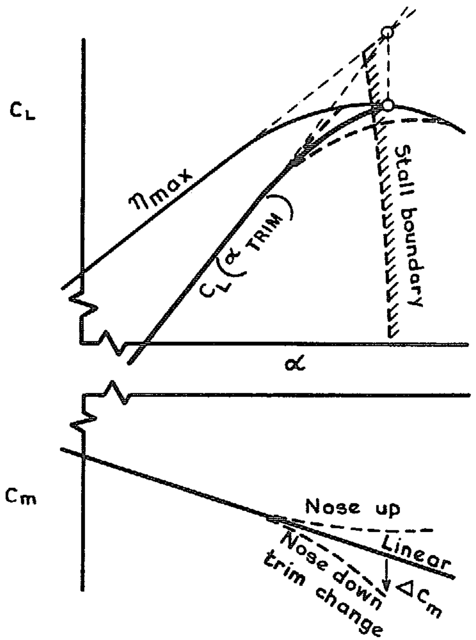



FIG. 20. Effect of non-linear pitching-moment characteristics on the operating characteristics of direct-lift near the stall.

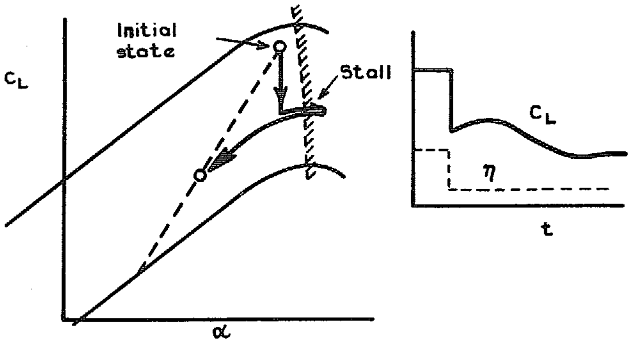



FIG. 21. Significance of the adverse initial response to direct-lift control in a rapid attempt at recovery from near stall.

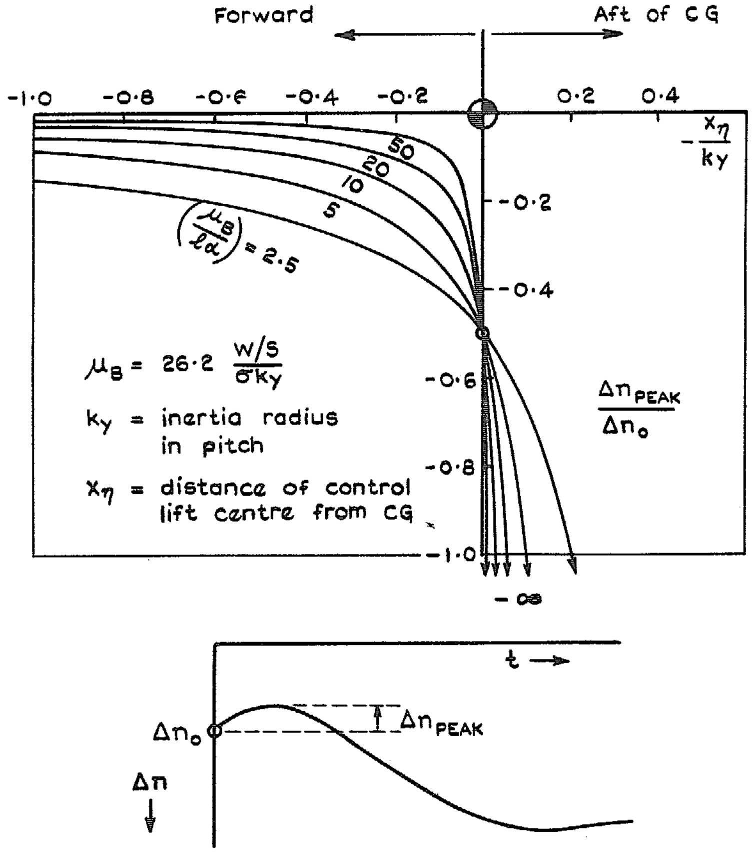



FIG. 22. Diagram for the determination of the initial adverse normal acceleration peak in response to a longitudinal lift control ($m_{\dot{\alpha}}$ ignored).

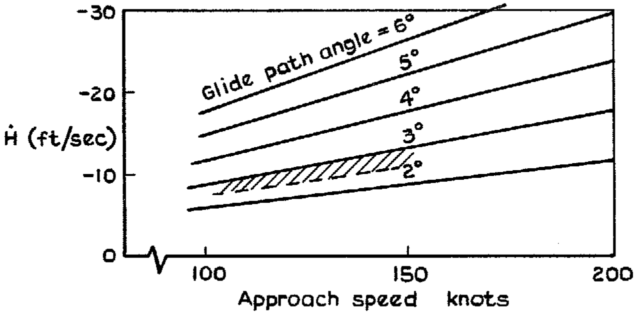



FIG. 23. Vertical velocity $\dot{H}$ in the approach.

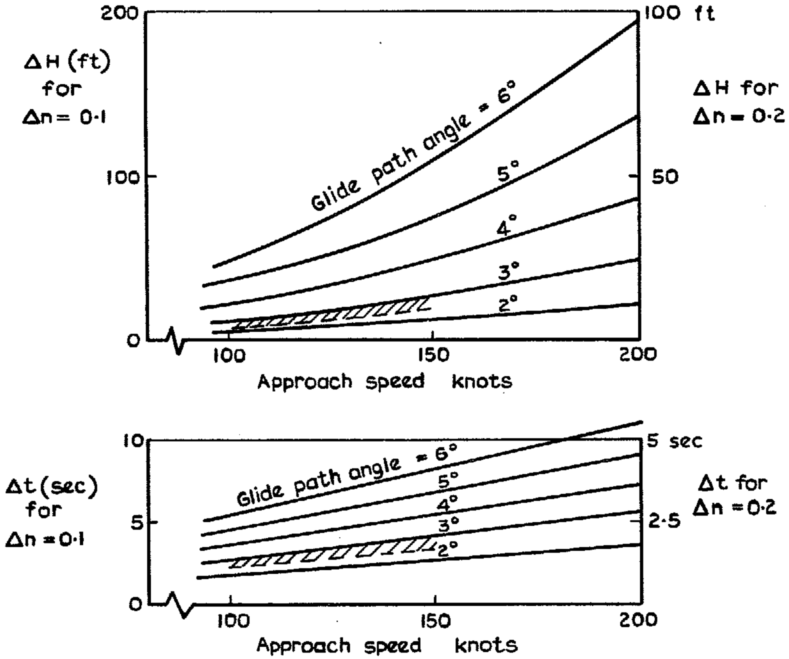



FIG. 24. Height $\Delta H$ and time $\Delta t$ consumed in reducing vertical velocity in the initial approach to zero if normal acceleration $\Delta n$ is applied instantaneously.

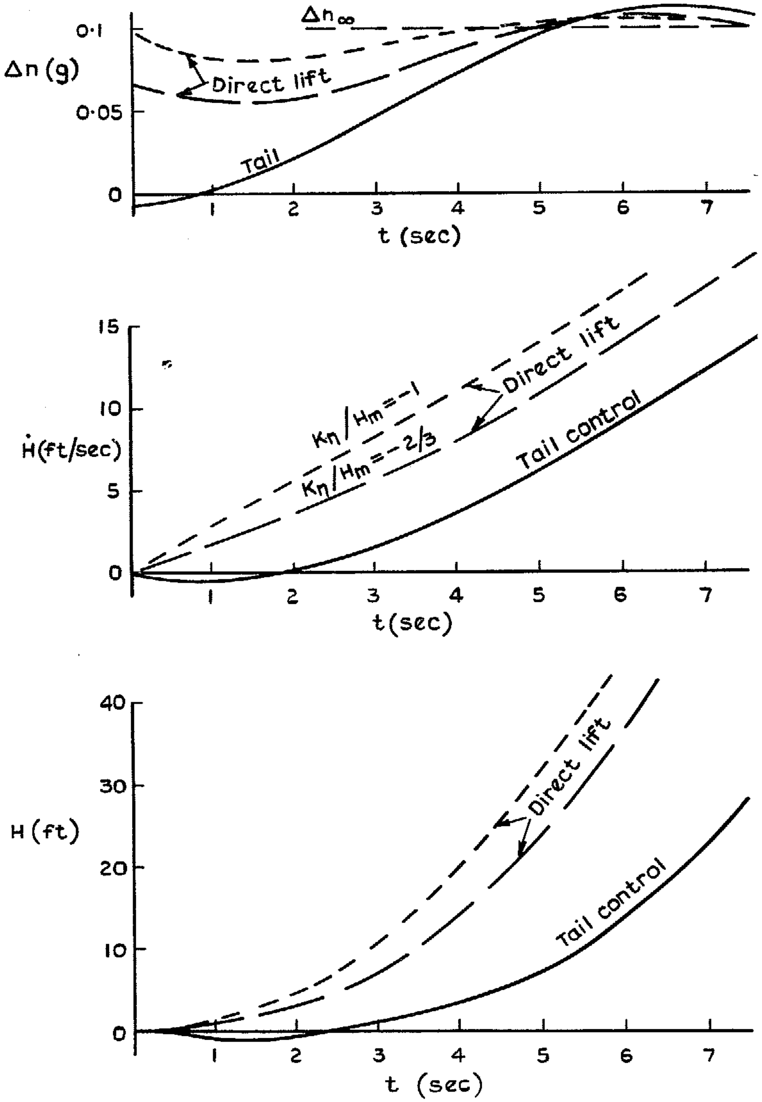



FIG. 25. Vertical response to step demand in tail elevator or direct-lift control of a Jumbo type transport aircraft on the approach.

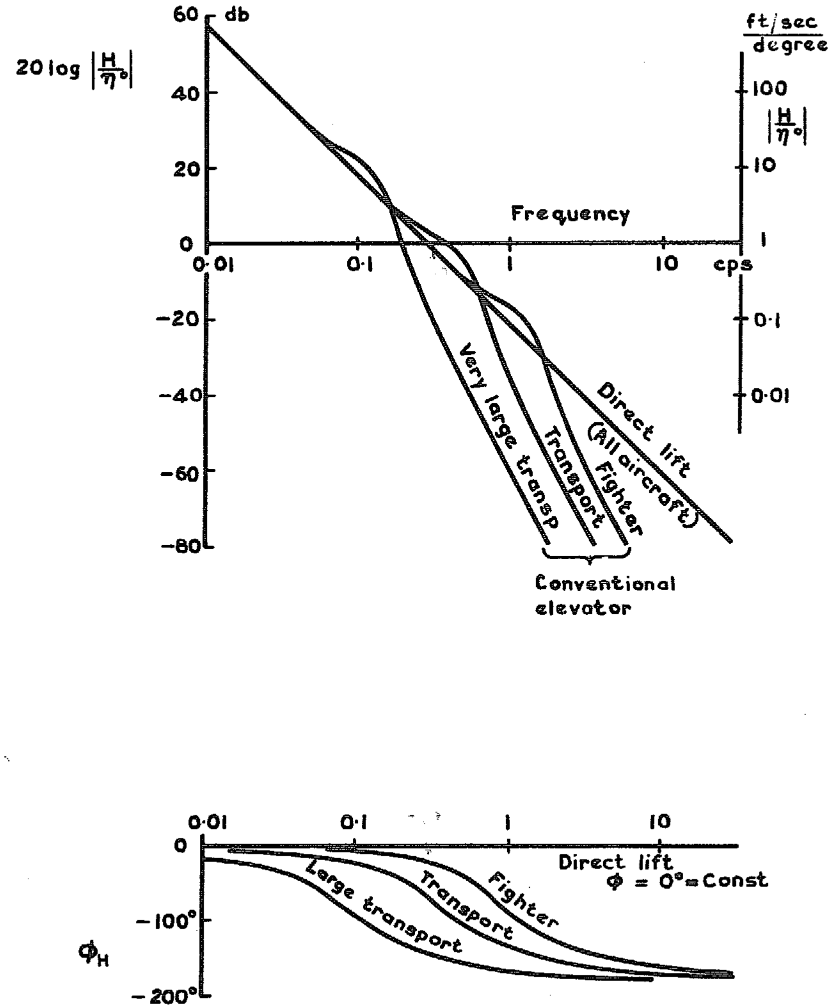



FIG. 26. Effect of aircraft size and method of control on the frequency response of height to elevator angle.

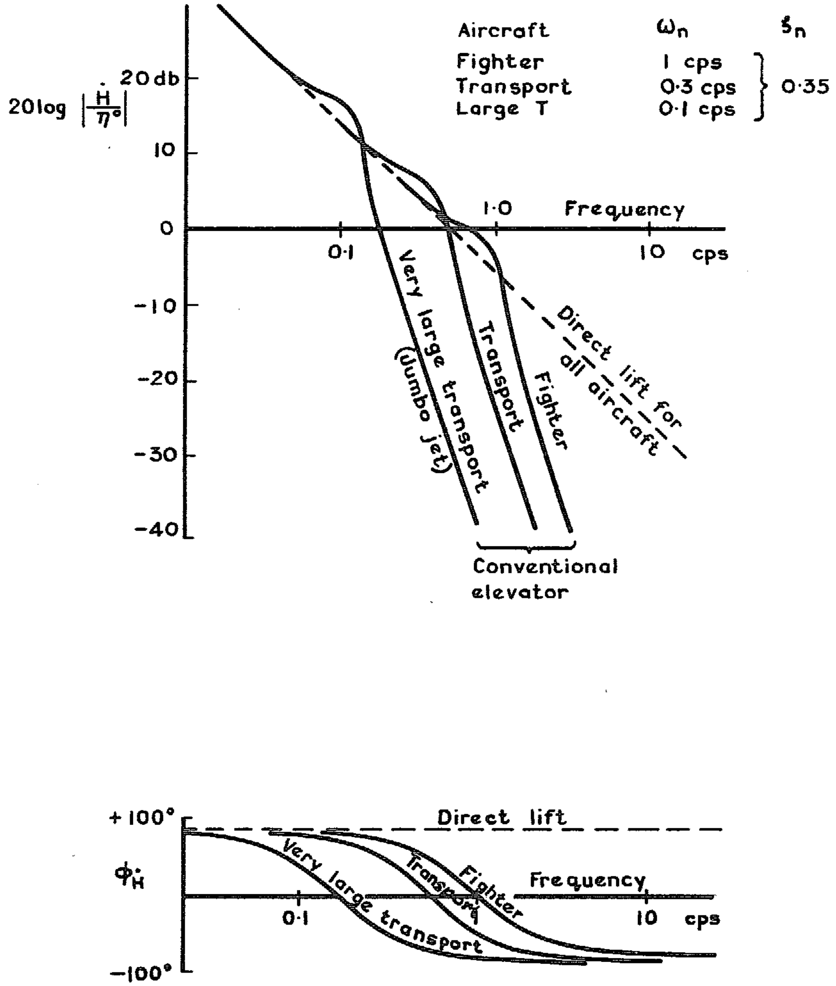



FIG. 27. Effect of aircraft size on vertical velocity response to pilots control for conventional elevators and direct-lift control.

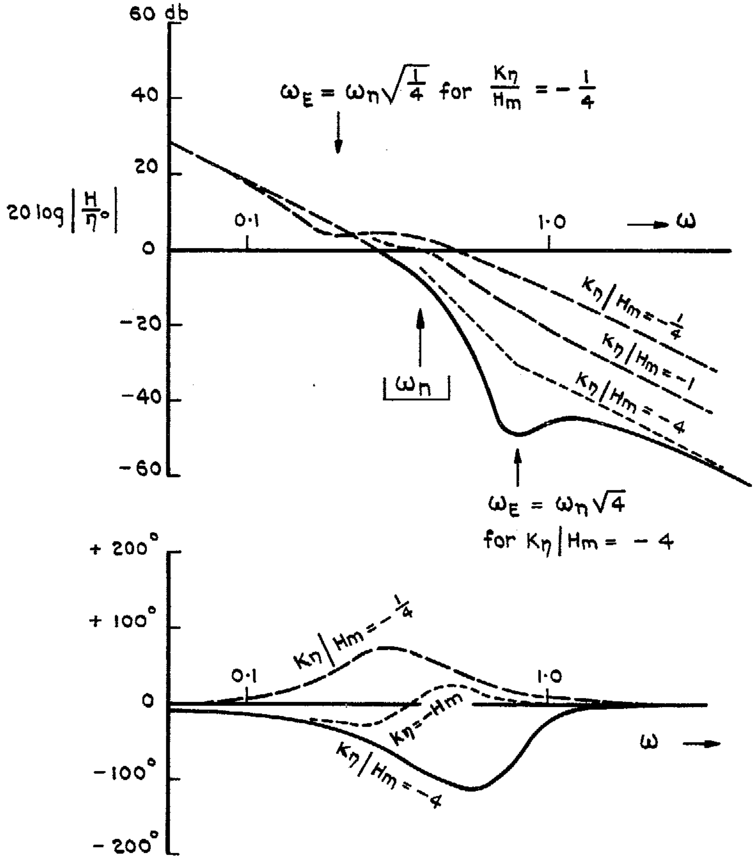



FIG. 28. Detailed frequency response in height to direct-lift control for $K_\eta | H_m = -4, \ -1, \ -\frac{1}{4}$ $(\zeta_n = 0{\cdot}35)$.

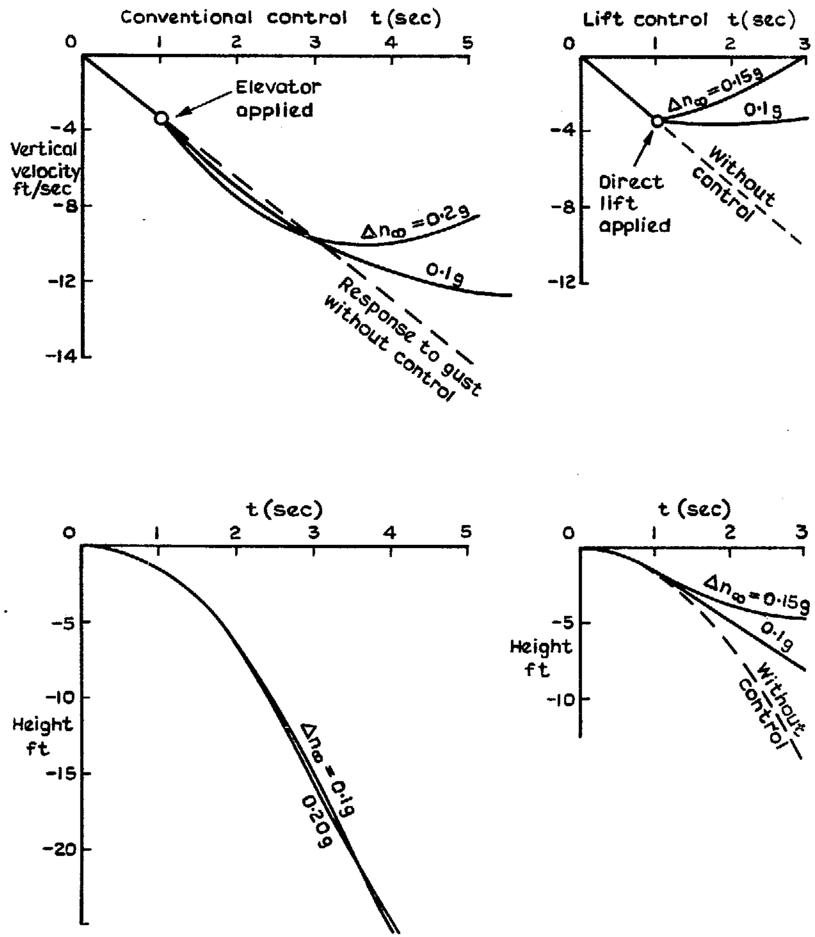



FIG. 29. Effect of tail gust equivalent to 5 per cent of airspeed on aircraft and recovery by application of conventional tailplane or direct lift respectively.

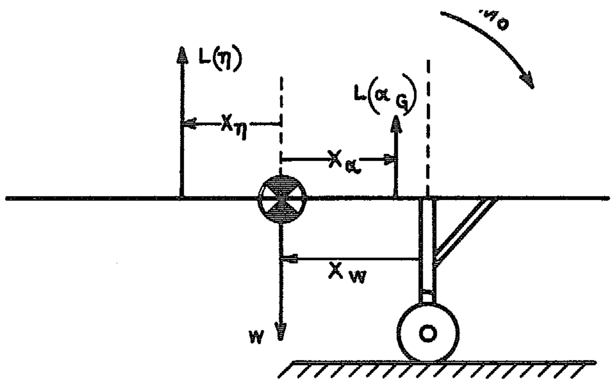



FIG. 30. Definition of terms relevant to nose lifting.

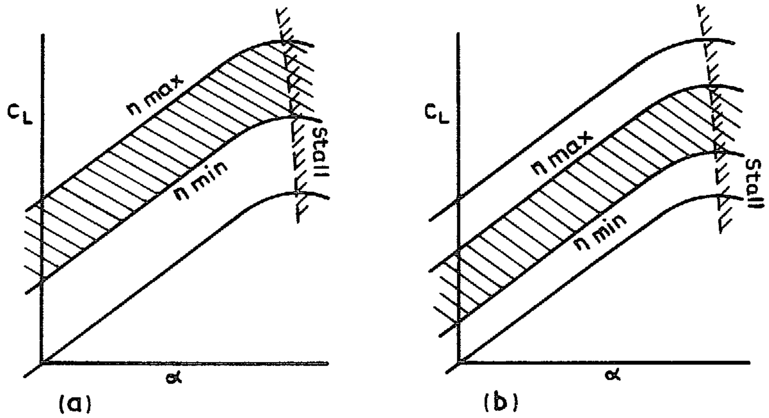



FIG. 32 a & b. Portion of the $C_L(\alpha)$ carpet available for direct-lift control with limited authority.

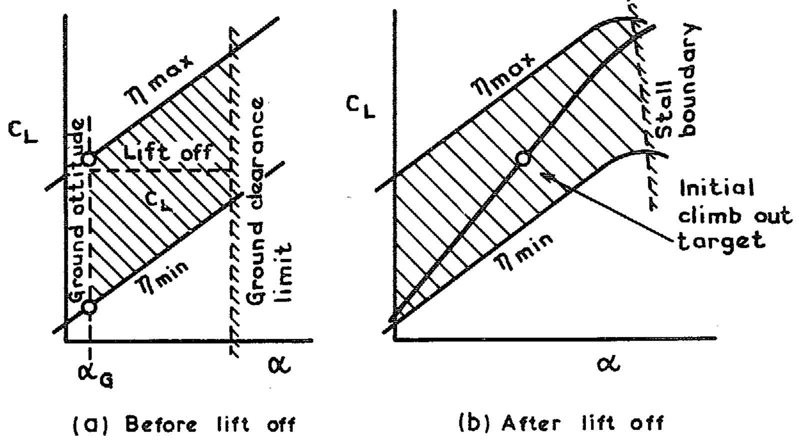



FIG. 31. $C_L(\alpha)$ carpets relevant to take off before and after lift off.

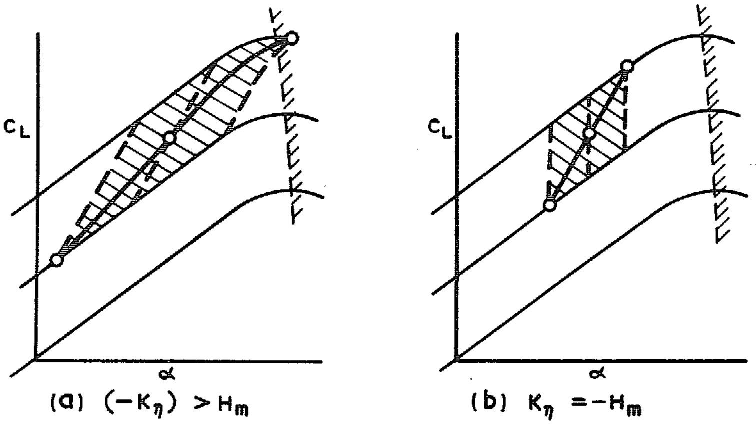



FIG. 33 a & b. Speed and manoeuvering control operating regime for direct-lift control with limited authority.

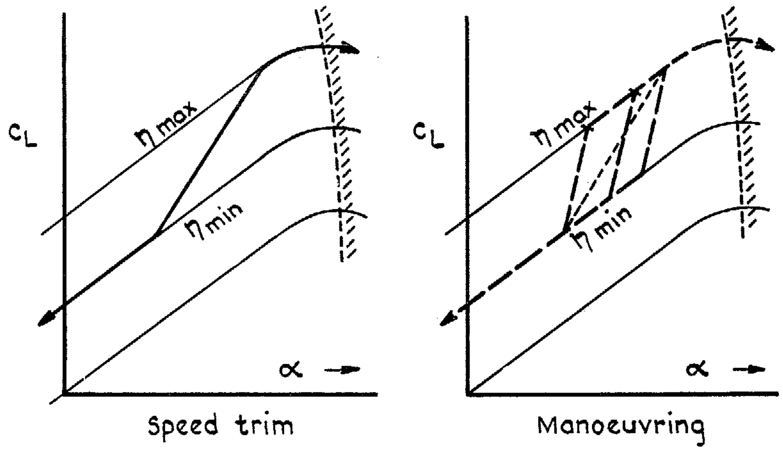
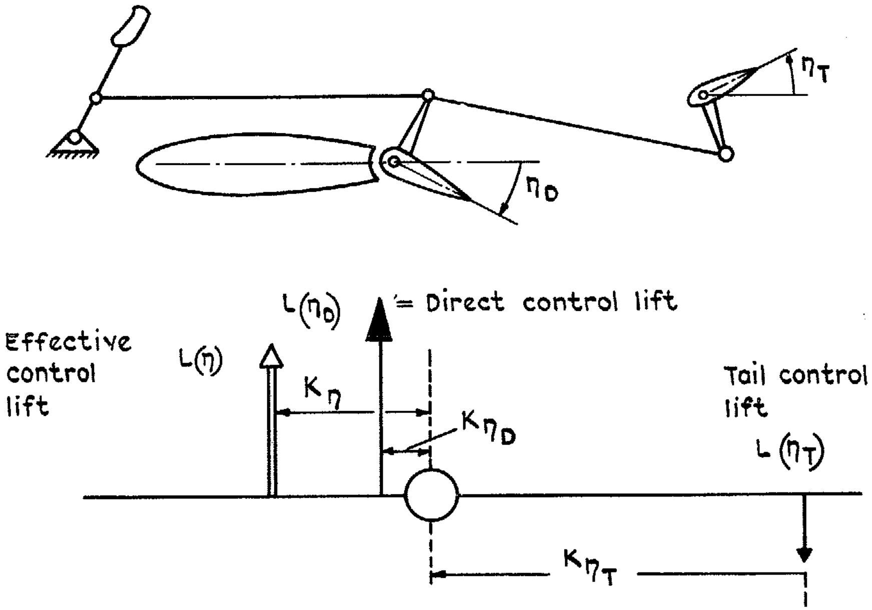



Fig. 34. Extension of control regime for a limited authority direct-lift control system by allowing pitch control to proceed when direct lift mechanism reaches $\eta_{max}$ and $\eta_{min}$.



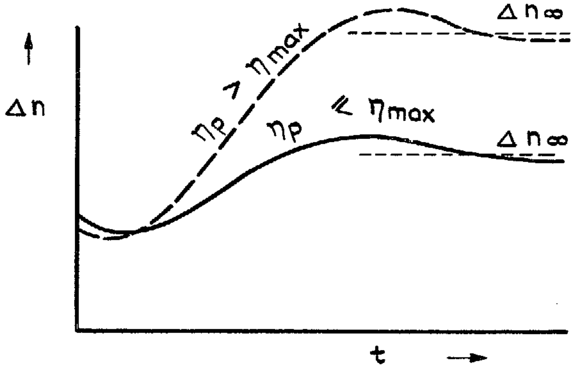




Fig. 35. Time response to step control when pilots stick demand $\eta_p$ is either less or greater than the authority of direct-lift control, $\eta_{max}$.

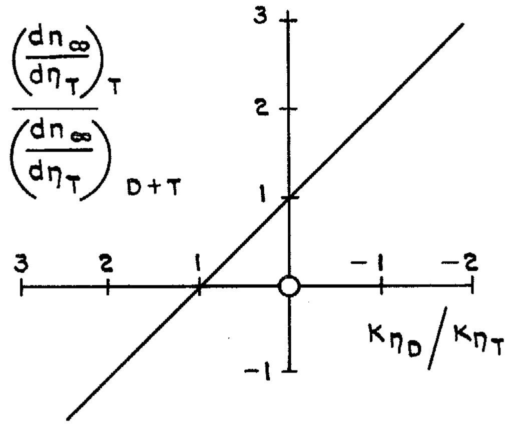



Fig. 36. Ratio of effective control power using tail control alone to that obtained with combined use of direct-lift mechanism and tail control.

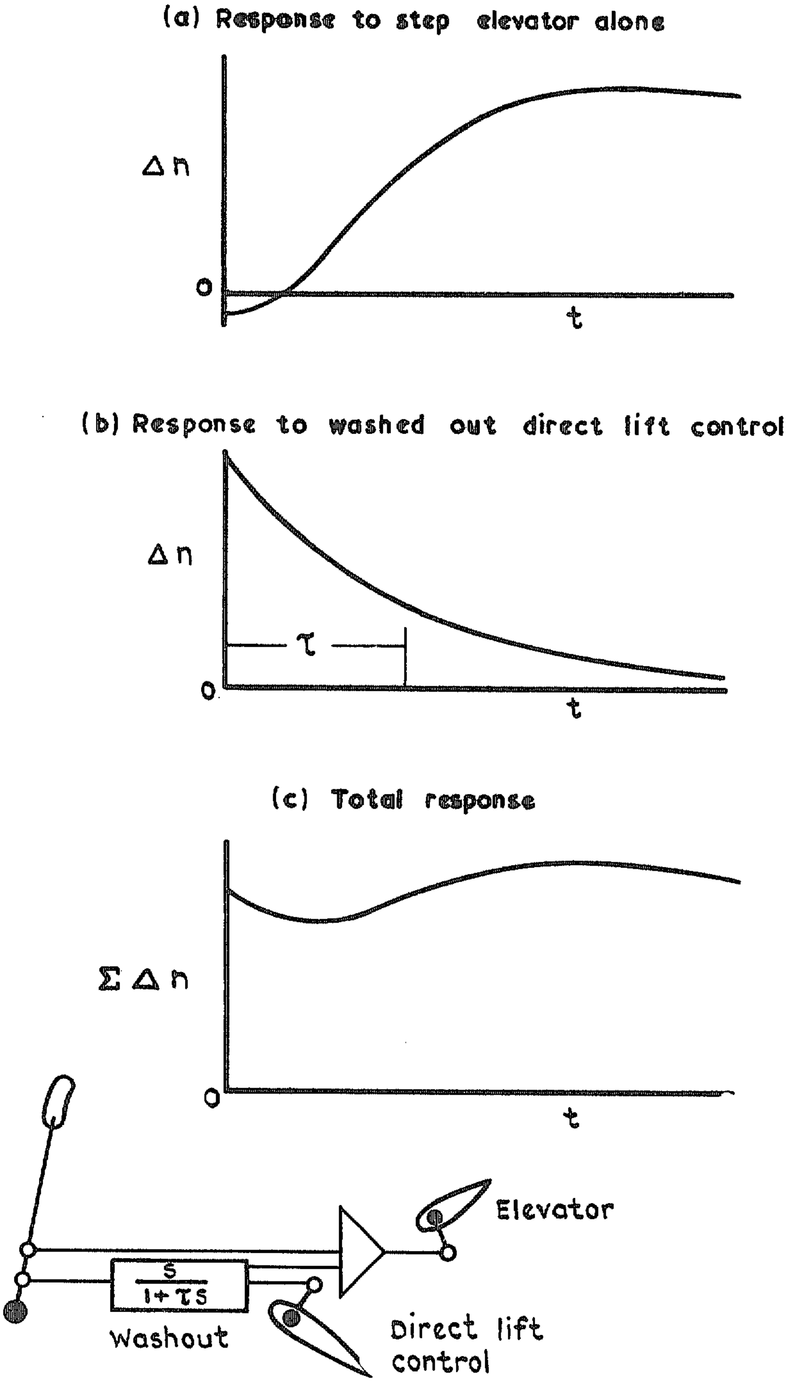



FIG. 37. Washed out direct lift superimposed on conventional elevator control.

Printed in Wales for Her Majesty's Stationery Office by Allens Printers (Wales) Limited
Dd. 146916 K.4.

R. & M. No. 3629



Published by
HER MAJESTY'S STATIONERY OFFICE

To be purchased from
49 High Holborn, London W.C.1
13a Castle Street, Edinburgh EH2 3AR
109 St. Mary Street, Cardiff CF1 1JW
Brazennose Street, Manchester M60 8AS
50 Fairfax Street, Bristol BS1 3DE
258 Broad Street, Birmingham 1
7 Linenhall Street, Belfast BT2 8AY
or through any bookseller

R. & M. No. 3629
SBN 11 470329 9