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AN EXPLORATORY STUDY OF FLYING QUALITIES OF VERY LARGE SUBSONIC TRANSPORT AIRCRAFT IN LANDING APPROACH

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Abstract.

Airplanes much larger than our present generation Jumbo jets will be used in the not too distant future for reasons of efficiency and reduction of airspace congestion. Undoubtedly the approach and landing flight phase will be the most demanding phases of flight from the point of view of flying qualities. For two hypothetical subsonic jet transports with aircraft weights of two respectively eight times those of our contemporary Jumbo jets, estimated characteristic parameters for the handling qualities are presented and discussed in the light of contemporary regulations. Controllability in vertical windshear and manoeuvre performance for lateral-directional control during the lateral offset manoeuvre are discussed. The need for command augmentation flight control systems and direct lift control is clearly established.

Nomenclature.

C_{ℓ_β}	nondimensional dihedral effect
C_{n_p}	nondimensional yawing acceleration due to roll rate
g	gravitational acceleration
h	altitude
L_p	roll damping
L_r	rolling acceleration due to yaw rate
L_β	dihedral effect
L_{δ_a}	aileron effectiveness
N_p	yawing acceleration to roll rate
N_r	yaw damping
N_{δ_r}	rudder effectiveness
n_α	steady state normal acceleration change per unit angle of attack change at constant speed
s	Laplace operator, $s = \sigma + j\omega$
T_{en}	time constant of first order approximation of engine response lag
T_{man}	manoeuvre time
T_{p_1}, T_{p_2}	time constants of phugoid mode
T_R	roll mode time constant
T_{wo}	washout time constant
T_{θ_2}	time constant of $\left[\frac{\theta}{\delta_e}\right]$ transfer function numerator
U_o	steady state airspeed along the X-axis
u	airspeed perturbation along the X-axis
u_w	magnitude of wind velocity perturbation vector
β	sideslip angle
δ_a	aileron deflection
δ_e	elevator deflection
δ_r	rudder deflection
δ_T	throttle setting variation
ζ_d, ω_d	Dutch - roll damping ratio and natural frequency
ζ_p, ω_p	phugoid damping ratio and natural frequency
ζ_{sp}, ω_{sp}	short-period damping ratio and natural frequency
θ	pitch attitude
σ	real part of s
φ	bank angle
φ_M	phase margin
ω	imaginary part of s
ω_c	crossover frequency

Subscripts.

c	command signal
h	altitude feedback
ε	error signal
θ	pitch attitude feedback

Miscellaneous

PR	pilot rating (Cooper scale)
$\doteq$	approximately equal to

I Introduction.

For reasons of efficiency in air transportation and reduction of the number of aircraft movements with the aim to relieve airspace congestion, the emergence of airplanes much larger than our present generation Jumbo jets is to be expected. It is anticipated that limits on aircraft size / weight will be reached for the reason of unsatisfactory flying qualities when these extreme large aircraft are fitted with conventional flight control systems as used nowadays on subsonic jet transports. A study to indicate the areas where improvements in stability and control are most needed, seems therefore warranted.

Handling qualities of extreme large airplanes will have to be adequate to manoeuvre under manual control with great precision during approach and landing. Undoubtedly advanced types of cockpit displays will be developed to assist the pilot in controlling the airplane during the approach and landing, but these displays will never compensate for bad handling characteristics of the aircraft.

It is interesting to note that for most of the handling quality problems, which will be considered in this paper, an analogy exists between extreme large CTOL and much smaller powered lift STOL transport aircraft. For the STOL's the attainable aerodynamic stabilizing and control moments tend to decrease due to decreasing airspeed, while for extremely large CTOL's these parameters decrease due to the increase in inertias at constant airspeed so that for both the ratio of inertias to aerodynamic moments increases.

In this paper some primary features of two hypothetical configurations for large subsonic jet transports, with aircraft masses of two respectively eight times those of the two largest transport aircraft now in operation (Boeing 747, Lockheed C-5A) will be discussed. Both longitudinal and lateral-directional handling qualities and performance aspects are dealt with.

II VLAC-sizes, masses and inertias.

The characteristics of the two hypothetical very large aircraft (VLAC) have been derived, assuming geometry and mass distribution similar to those of the Boeing 747 aircraft (ref. 1). As "size"-parameter the landing weight has been taken, being 453600 kg(1×10^6 lbs) for the VLAC-1 and 1814400 kg (4×10^6 lbs) for the VLAC-4.

The dimensions of these hypothetical aircraft have been determined, using the square-cube extrapolation method. The relation between the aircraft's landing weight and its wing loading, based on this extrapolation method is visualized in fig. 1. As a consequence of this method, wing loading increases proportional to the dimensions, which seems to become critical with respect to structural properties and required runway lengths. Therefore also extrapolation methods have been applied, resulting in a smaller increase of wing loading than the square-cube extrapolation suggests, assuming also geometry and mass distribution similar to those of the Boeing 747, but smaller densities. A method closely related to the extrapolation as presented in ref. 2 has also been taken into consideration. As a result only little differences proved to exist between the handling quality parameters considered for the hypothetical aircraft, obtained according to the different extrapolation methods. In general, slightly worse handling qualities were observed for the square-cube extrapolation. Based on these results only the hypothetical aircraft derived according to the square-cube extrapolation have been taken into consideration for further investigation. As a consequence the established trend

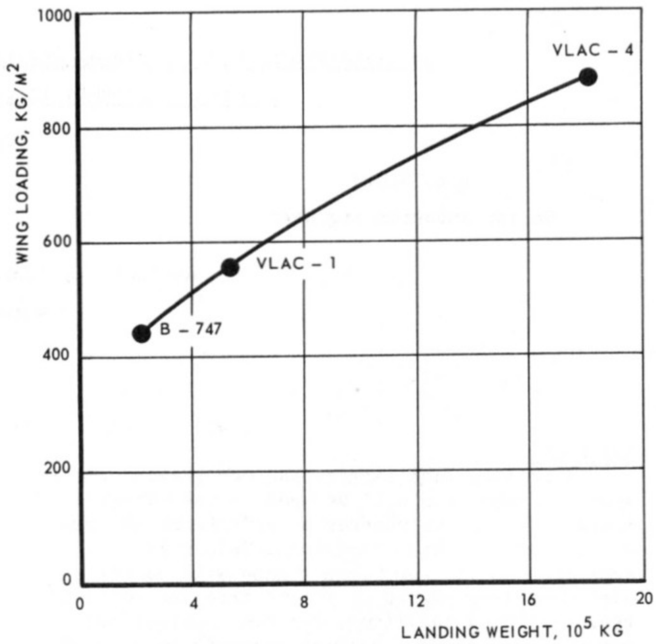

Fig. 1 Wing loading square-cube extrapolation

in handling qualities based on these VLAC types is considered to be somewhat conservative.

Moments of inertia for the hypothetical aircraft have been derived from those of the Boeing 747. Using the square-cube extrapolation, inertias increase as the fifth power of the dimensions, so that very high values are obtained for the hypothetical aircraft.

The approach speed of the VLAC-1, has been chosen equal to the approach speed of the Boeing 747, which implies an increase maximum lift coefficient of about 25 %, assuming equal stall margins. For the VLAC-4 an increase in maximum lift coefficient of 100 % relative to the Boeing 747 would be necessary to provide for the same approach speed. As this large increase of the maximum lift coefficient is considered to be highly improbable and as a 25 % increase relative to the Boeing 747 is considered to be rather impressive, equal maximum lift coefficients for both hypothetical aircraft are assumed, resulting in a higher approach speed for the VLAC-4.

Based on the characteristics of the hypothetical aircraft as described above, the stability derivatives have been estimated by analytical and empirical methods, presented in the literature. The nondimensional control effectivenesses for the hypothetical aircraft have been chosen from data presented in ref. 3 and ref. 10.

III Longitudinal handling qualities.

In this section the type of limitations in aircraft stability and control reached for the hypothetical aircraft will be discussed in the context of the present-day knowledge about the criteria for good handling qualities of large transports already in operation.

Unfortunately this knowledge about criteria for satisfactory handling qualities is in some areas fragmentary because little experimental handling qualities research has been devoted to this flight phase for this class of airplanes up to now. The characteristics of the VLAC-1 and 4 will be compared to those of the Mc Donnel Douglas DC-8, Boeing 747 (further indicated here as B-747) and Lockheed C-5A aircraft, see table 1 and 3. The Boeing data (B-747) are obtained from ref. 3, while the Lockheed data (C-5A) are based on ref. 4 and ref. 5.

Statements about the handling qualities will be related to "Levels" (U.S. Mil.Spec.), Pilot-Ratings and the boundary condition "satisfactory"/ "acceptable", according to the source of information. In this discussion the Level 1/Level 2 boundary and satisfactory/acceptable boundary is considered to be equal to Pilot-Rating 3.5. In general it can be stated, as shown by the available criteria, that due to the more demanding landing performance of military transports, the handling quality requirements for this group are more stringent than for civil transports.

Longitudinal manoeuvres performed in the approach and landing are glide path tracking with turbulence and wind shear disturbance effects, flare and touchdown.

A discussion of the characteristics of the phugoid, being not different from those of present-day transports, as well as speed stability effects is not very relevant because in general "large" subsonic jet transport airplanes considered here are operating at the bottom or positive side of the power required versus speed curve (neutral or positive speed stability) and will undoubtedly be flown with auto-throttle (incorporated because of an automatic approach / landing system anyway) in the landing approach.

The short-period mode, however, is the predominant longitudinal controlling mode both for manoeuvring and coping with the effects of atmospheric turbulence.

Estimated values of ω_{sp} for the VLAC aircraft presented in tab. 1 are based on data from ref. 1, 3 and 6.

Was the main attention during the early development of handling qualities criteria for manoeuvring paid to frequency-damping combinations for the short-period mode, the contemporary view, is directed at the combination of frequency and normal acceleration sensitivity. The discussions as to what parameter for the normal acceleration sensitivity, n_α or $1/T_{\theta_2}$, is the most appropriate to be used in requirements are not yet ended.

However it can be shown that both parameters are closely related and with good approximation: $n_\alpha \doteq U_o/gT_{\theta_2}$.

In fig. 2, specification requirements (US Mil. Spec.) and other proposed boundaries are presented. A double horizontal scale is incorporated in which n_α and $1/T_{\theta_2}$ are given assuming a speed of 140 knots. As can be seen, the first limit reached will be the low short-period frequency limit of 0.7 - 0.8 rad/sec as based on data from ref. 7*), 8 and 9. Low values for this parameter are associated with "sluggish" response to elevator inputs. VLAC-1 is already outside the satisfactory boundary while the VLAC-4 is close to Level 2 (PR = 6.5). Research described in ref. 4 leads to more severe requirements on ω_{sp} (1.00 and 0.63 rad/sec for Level 1 respectively 2) for the very demanding landing task as conducted in C-5A operation.

Table 1.

Longitudinal Dynamics.

Parameter		DC-8	B-747	C-5A	VLAC-1	VLAC-4
U_o	m/sec	73.5	68.0	61.5	68.0	85.6
ω_{sp}	rad/sec	1.47	0.81	0.88	0.62	0.50
ζ_{sp}		0.49	0.61	0.68	0.69	0.69
$1/T_{\theta_2}$	sec^{-1}	0.63	0.49	0.50	0.37	0.29
n_α	g/rad	4.73	3.42	3.14**)	2.54	2.54
ω_p	rad/sec	0.17	0.16	0.21	0.18	0.14
ζ_p		0.06	0.06	0.02	0.01	0.01

*) Boundary based on AIAA paper 69-898 by I.L. Ashkenas.

**) Calculated from U_o and $1/T_{\theta_2}$.

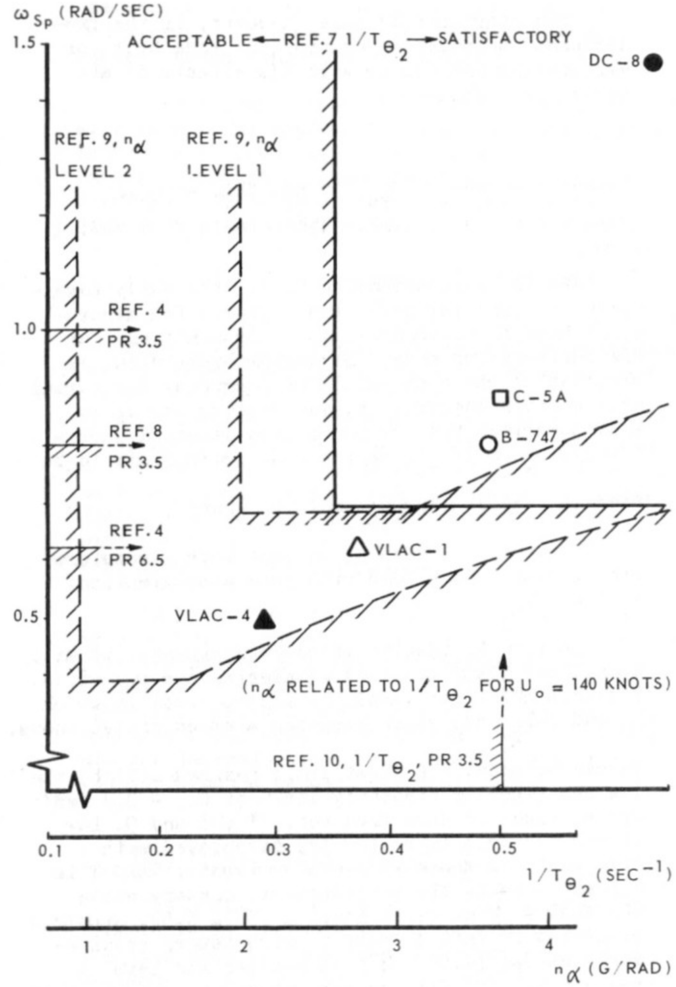

Fig. 2 Boundaries for short-period frequency - normal acceleration sensitivity combinations.

Figure 2 also shows that the normal acceleration sensitivity parameter is critical for the VLAC-aircraft. This parameter determines the flight-path to pitch attitude modal response ratio. Different sources quote rather different values for this parameter as can be seen by the appreciable range between ref. 10, PR = 3.5 and ref. 9, Level 1 boundaries. The VLAC-1 is a limit case according to the $1/T_{\theta_2}$-boundary of ref. 7 while the value for the VLAC-4 is clearly too low. Simulator data of ref. 10 indicate that the B-747/C-5A are already critical in this respect. The damping ratio for the short-period mode of approximately 0.7 for the VLAC's does not present a problem. The application of the criteria discussed above, is to a certain degree questionable because those criteria are valid only when no appreciable interaction exists between the phugoid and short-period mode. Problems will exist, however, in this area especially with auto-throttle-off operation. While for the DC-8 ω_{sp}/ω_p is 8.5 this ratio is around 3.5 for the VLAC-aircraft. Published information on the C-5A, with a ratio of around 4.2, indicates the special attention paid to this problem for this aircraft. In ref. 5 it is mentioned thata pitch rate damper is installed to damp phugoid motions (evidently the damping of the short-period mode is increased also). In the next section, the behaviour of the VLAC aircraft in the approach disturbed by wind-shear is analysed.

IV Effects of wind shear.

To investigate possible deterioration of longitudinal control during glide path tracking - deficiencies have already been indicated in the preceding section-an (servo-system) analysis of the pilot-aircraft system disturbed by wind shear has been carried out and reported in ref. 11. This analysis is based on the assumption of a horizontal wind varying linearly with height.

Observing the equations of motion under these circumstances, a bipartite influence of this wind shear disturbance can be discovered. The first part proves to be dependent on the flight path angle perturbation and forms therefore part of the homogeneous system of equations of motion. This is illustrated in fig. 3 by means of the position of the phugoid poles as a function of wind shear magnitude. The root locus is presented for decreasing head wind during the landing approach, as assumed further in this section. The short-period characteristics are hardly affected by wind shear disturbance. As can be seen in fig. 3 the phugoid poles become real; one stable and one unstable root are obtained for sufficiently large wind gradients. The second part of the wind shear disturbance can be regarded as the real external disturbance and is a function of the

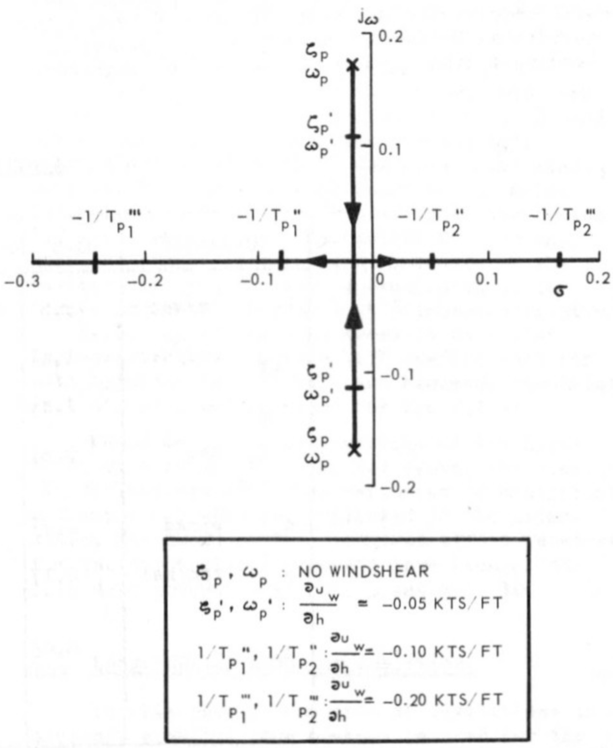

Fig. 3 Effect of wind shear on phugoid poles (B-747).

wind gradient and the initial rate of descent. Similar observations with respect to the effects of wind shear on the longitudinal motion of airplanes have been made in ref. 12 and ref. 13.

In order to follow the glide path with constant airspeed in spite of the wind shear disturbance, altitude and airspeed will have to be controlled. For the system analysis it was assumed that airspeed was controlled by an autothrottle while altitude control by means of elevator was allocated to the pilot, which was represented by a mathematical model. Results of investigations concerning altitude control (ref. 14) clearly established the need of an attitude innerloop for equalization purposes. From the different ways in which this multiloop system can be realized - series closure or parallel closure - the former type has been chosen here on the basis of the low values of ω_{sp} for the aircraft considered, as recommended in ref. 14. A block diagram of the total control system is given in fig. 4.

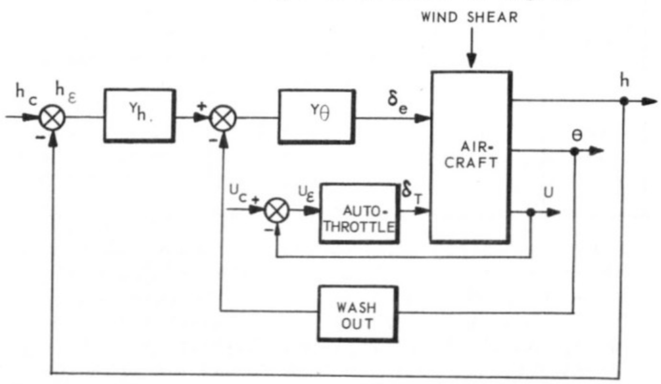

Fig. 4 Block diagram of the total control system.

In this diagram the pilot's contribution is approximated by the transfer functions Y_θ and Y_h, being

$$Y_\theta = K_\theta (T_{L_\theta} s + 1)\, e^{-\tau_e s} \;;\; Y_h = K_h\, e^{-\tau_e s} \;.$$

The generation of lead is supposed to be possible only for the attitude inner loop, whereas both loops comprise a time delay τ_e, to account for the pilot's transport delay and neuromuscular lag. In order to reduce the steady state airspeed deviation due to the wind shear disturbance to zero an integrating function has to be incorporated in the autothrottle. For zero steady state glide path deviation both θ-washout and h-retrim is needed. In order to restrict the number of parameters involved, only θ-washout is included, implying a constant steady state height deviation from the glide path. This simplification is considered to be of minor influence with respect to the qualitative results.

A constant crossover frequency of 1 rad/sec for the airspeed control loop has been selected, resulting in a satisfactory system performance. K_θ and T_{L_θ} have been selected on the basis of a constant attitude inner loop performance, characterized by $(\omega_c)_\theta = 2$ rad/sec and $(\varphi_M)_\theta = 30°$, while K_h is selected in such a manner that a phase margin of $15°$ was maintained in the altitude outer loop. The lead time constant T_{L_θ} and the altitude loop crossover frequency $(\omega_c)_h$ will be used to predict pilot opinions qualitatively. The values of the θ-washout time constant T_{wo} and the effective time delay τ_e have been chosen equal for the different aircraft ($T_{wo} = 10$ sec; $\tau_e = 0.25$ sec).

For two magnitudes of wind shear, $\frac{\partial u_w}{\partial h} = -0.05$ kts/ft (typical value) and $\frac{\partial u_w}{\partial h} = -0.2$ kts/ft (extrememly large value), the system parameters have been determined according to the above-described design rules. The results, presented in table 2, show no great sensitivity with respect to the magnitude of wind shear. Considering K_u for the different aircraft, about the same values can be observed, implying about the same thrust variation for the same airspeed deviation. Table 2 shows relatively large differences in T_{L_θ} for the different aircraft, from

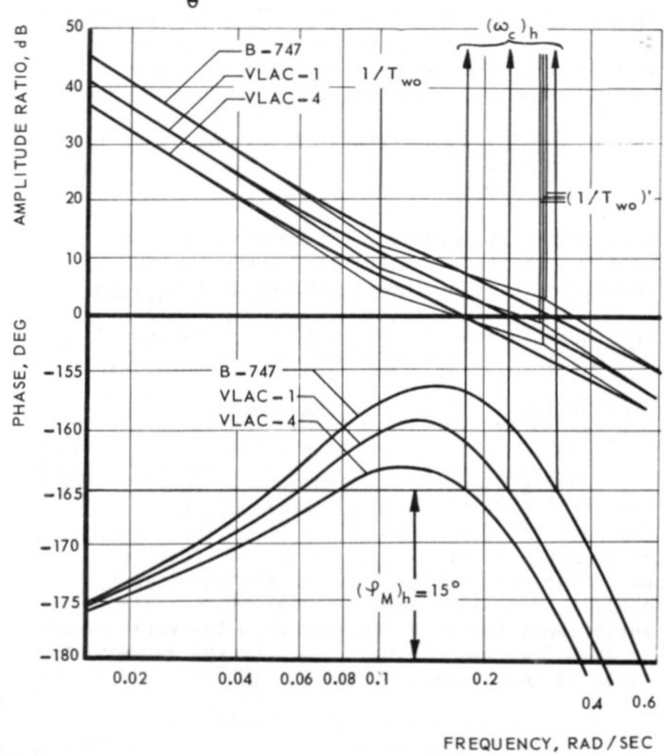

Fig. 5 Bode diagram of altitude ($h \rightarrow \delta_e$) control ($u \rightarrow \delta_T$, $\theta \rightarrow \delta_e$ loops closed, $\frac{\partial u_w}{\partial h} = -0.05$ kts/ft).

Table 2

Developed control system parameters and performance indicators.

	B-747		VLAC-1		VLAC-4	
$\frac{\partial u_w}{\partial h}$(kts/ft)	- 0.05	-0.20	-0.05	- 0.20	- 0.05	- 0.20
K_u $^1/m$ sec^{-1}	0.268	0.266	0.261	0.272	0.242	0.264
K_θ	- 10.4	- 10.3	- 13.9	- 15.1	- 20.7	- 21.8
T_{L_θ} sec	0.18	0.18	0.27	0.27	0.34	0.34
K_h $^{rad}/m$	0.0061	0.0041	0.0041	0.0037	0.0025	0.0017
$(\varphi_M)_h$ deg	15	15	15	15	15	15
$(\omega_c)_h$ $^{rad}/sec$	0.31	0.26	0.22	0.22	0.17	0.16

which it can be concluded that due to this lead generation, larger aircraft will be rated less favourable. Increased values of T_{L_θ} are mainly caused by the decreasing values of ω_{sp} for the larger aircraft. Moreover, the indicated deterioration in the altitude control performance, expressed by the decreasing crossover frequency $(\omega_c)_h$ (table 2), illustrated by the Bode diagram of the $\left[\frac{h}{h_\varepsilon}\right]_{\substack{u \to \delta_T \\ \theta \to \delta_e}}$ transfer function (fig. 5), will certainly degrade pilot opinion. This decreasing altitude control performance is mainly associated with decreasing values of $1/T_{\theta_2}$. The same conclusions with respect to low values of ω_{sp} and $1/T_{\theta_2}$, although reached for a system controlling altitude only, have been drawn in ref. 14.

Analog computer studies clearly demonstrated the vital importance of the speed control loop (by means of autothrottle) on glide path tracking at constant airspeed. Therefore the effect of an engine response time delay, approximated by a first order time lag on the altitude control performance has been studied. From the root locus in fig. 6 of the dominant roots of the denominator of the transfer function $\left[\frac{h}{h_\varepsilon}\right]$ (B-747, $\frac{\partial u_w}{\partial h} = -0.2$ kts/ft) including an engine response lag time constant of 2 sec, it can be concluded that a significant decrease of the altitude control performance will occur. About the same deterioration may be expected for the other aircraft considered, using the same lag time constant, so that the qualitative result discussed above, is retained. However, if increased engine response time delays are unavoidable for the engines in larger aircraft, increasing deterioration of altitude control performance will occur, especially when a wind shear is encountered during the landing approach.

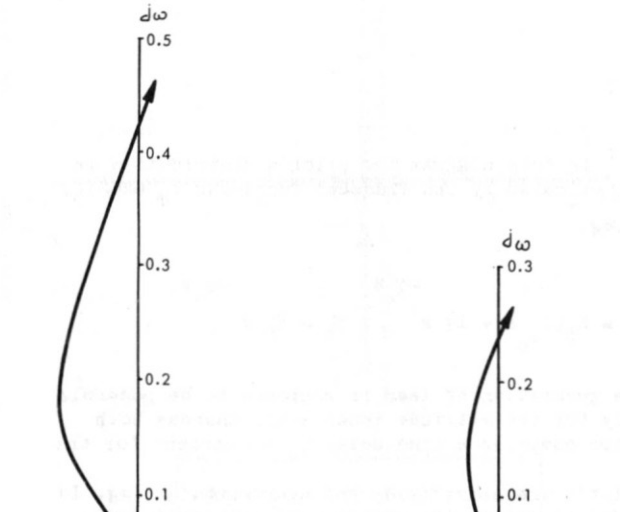

Fig. 6 Effect of engine response lag (B-747, $\frac{\partial u_w}{\partial h} = -0.20$ $^{kts}/ft$)

V Lateral-directional handling qualities.

Three types of typical manoeuvres are considered with respect to lateral directional characteristics of the aircraft: tracking the localizer, large turns and the de-crab manoeuvre. Roll control being the primary lateral controlling mode for manoeuvring will be discussed first. The widely used criterion for rolling qualities is expressed in terms of the wingtip helix angle. However, results of recent experiments have shown that specified roll angles obtained in a certain time (or specified time for certain roll angles) are more relevant criteria, at least for large subsonic jet transports. A good agreement exists between various proposals for the minimum value of roll control power as a function of roll mode time constant as required for satisfactory ratings; the boundary proposed in ref. 15 and 16 is indicated in fig. 7. In ref. 16 the prescribed maximum rolling power for a given roll mode time constant is based on a time to bank 60° and stop of 6.5 sec. Nearly the same boundary results when prescribing the time to roll through 30° ($t_{30^{\circ}}$) in 3.5 sec [(15)]. In ref. 16 the level of required rolling power is related to the side step performance while the author of ref. 15 relates the roll control power to the ability to raise a wing after a roll-upset by an atmospheric gust. The specification in ref. 9 is more stringent as it it requires a $t_{30^{\circ}}$ of 2.5 sec for Level 1 and $t_{30^{\circ}} = 3.2$ sec for Level 2. A recently reported flight evaluation, ref. 17, confirms the control power boundary proposed in ref. 15 and 16 for an aircraft with a roll mode time constant of 1 sec.

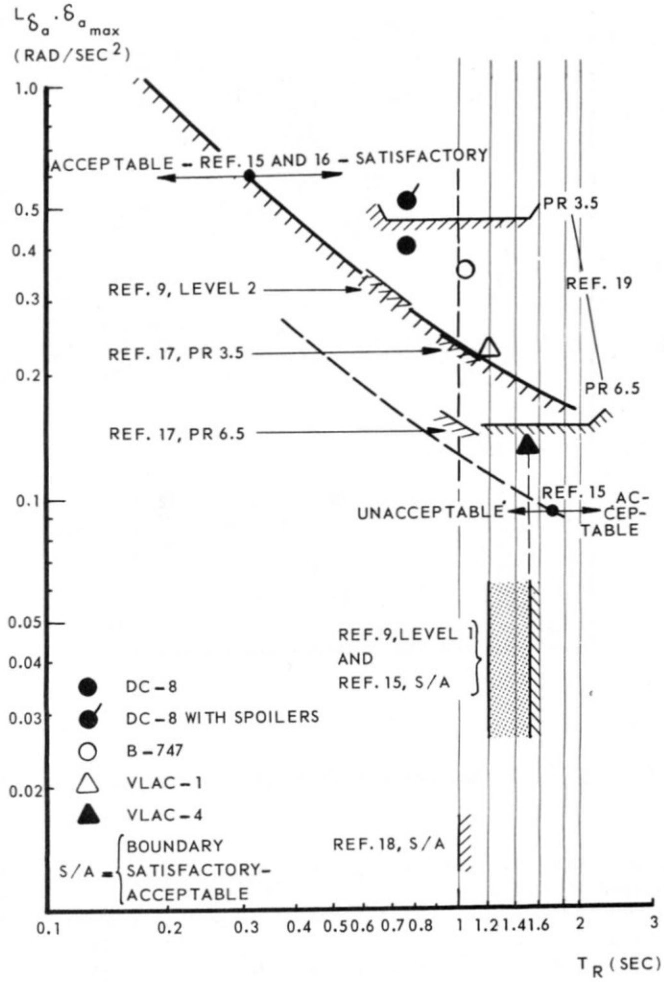

Fig. 7 Boundaries for roll manoeuvring characteristics.

Figure 7 presents the boundaries with data of the aircraft considered here. As far as the boundary of ref. 15 and 16 is concerned, it can be observed that the VLAC-4 is far below the desired value. According to the requirement of ref. 9 the VLAC-1 is also below the "satisfactory/acceptable" boundary. As can be seen in the figure an upper limit exist for allowable values of the roll mode time constant. Different researchers concluded on different values for this parameter, partly because of the different aspects of the flight task which were weighted heavily in their evaluations. Most probably a suitable boundary will be inside the 1.2-1.5 sec bracket. The basis for the severe requirement proposed in ref. 18 ($T_R < 1.0$ sec), is formed by results from an servo-analysis of the closed loop pilot-airframe system. Reference 15 relates the maximum value of T_R among other things to a "manoeuvre time", the maximum available time for performing a sidestep manoeuvre, by proposing $T_R/T_{man} < 0.1$. The proposed criterion results in $T_R < 1.2$ sec when a manoeuvre time of 12 seconds is assumed for an approach with a conventional glide path angle, a ceiling of 200 ft and a flare initiation height of 70 ft.

Besides on characteristics in the area of lateral control as just discussed, aircraft will be judged heavily on the characteristics of the Dutch-roll oscillatory mode. This mode is unintentionally excited by lateral control inputs as well as by turbulence. Beside a whole series of important parameters associated with the Dutch-roll mode, damping has been and will be a prime feature. Early requirements for Dutch-roll damping were formulated in terms of total damping alone as expressed by time to half amplitude, $(T_{1/2})_d = 0.693/\zeta_d\omega_d$. Recently developed specifications [(9)] require total damping as well as minima on the values of ζ_d and ω_d. Figure 8 presents these requirements together with proposed values of ref. 15 and a SAS design requirement presented in ref. 20.

The SAS-design handling qualities criterion presented in fig. 8 is based on results of a flight-simulator research program executed during the development of a stability augmentation system for the improvement of the structural response (reduction of peak structural loads and fatigue damage rates) of the B-52. The DC-8, C-5A and

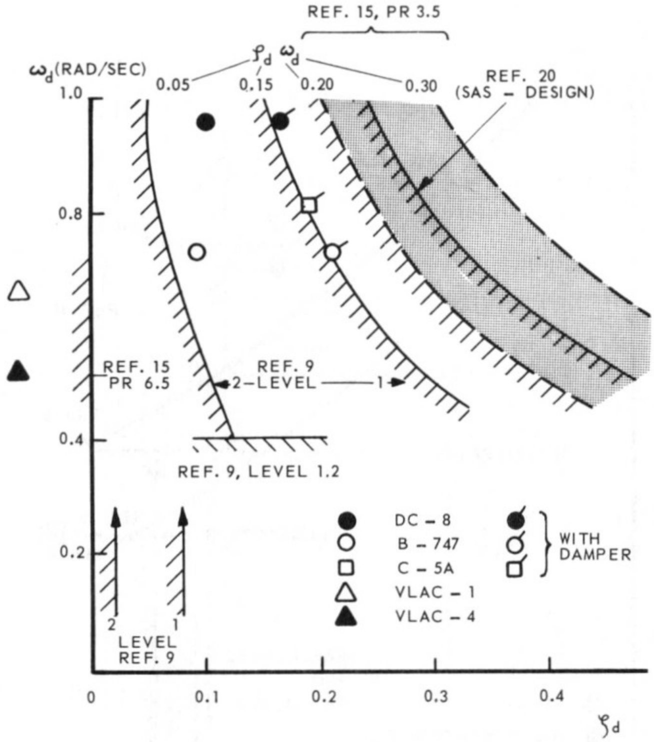

Fig. 8 Boundaries for Dutch-roll damping.

B-747 data are plotted together with -unaugmented - VLAC-1 and 4 data. The DC-8 and B-747 without damper are in the acceptable area, between the Level 1 and 2 boundaries of ref. 9, while the VLAC-aircraft with an unstable Dutch - roll mode do not even meet the PR 6.5 rating line, according to ref. 15. Redundant("hardened") SAS design is unavoidable therefore to cope with this Dutch-roll damping problem for the hypothetical aircraft. The marked decrease in ζ_d for the VLAC-aircraft as compared to the B-747 is mainly due to the high values of effective dihedral (C_{ℓ_β}) which is the result of the sharply increased lift coefficients at the approach speeds.

A complete picture of all lateral-directional characteristics is very complex but two characteristics can be recognized as being of fundamental importance: the bank angle to side slip ratio in the Dutch-roll oscillation and the excitation of the Dutch-roll by lateral control inputs. Both can lead to the need for additional damping as is indicated in ref. 15. As far as the first characteristic is concerned, calculations of roll to side slip ratio of the VLAC's have indicated that no problems are to be expected in this respect for the designs studied here. Dutch-roll excitation by lateral control inputs is closely related to the yaw due to lateral control derivative and the yaw due to roll rate derivative. Because the former derivative is very difficult to estimate, no discussion can be devoted here to this aspect of lateral-directional response. It is expected that in the case unfavourable situations exist in this respect, aileron-to-rudder interconnects as well as roll rate-to-rudder feedbacks can cure inadequacies in some cases.

Turn co-ordination *) - very important during sidestep manoeuvres as discussed later- is evidently related to the Dutch-roll excitation just mentioned. The complex of required dynamic rudder application during turn entries and exits and the constant rudder application in large turns may be very demanding. A roll attitude-to-rudder feedback may relieve the pilot from the constant rudder input during steady turns.

A discussion of the spiral stability of the VLAC's is not very relevant because actual spiral characteristics will be very dependant on the augmentation systems which will be installed. This will be at least a Dutch-roll damping system as stated above.

Up to now not much attention has been given to the formulation of quantitative requirements for the parameters important for the de-crab manoeuvre (conducted just prior to touch-down in a crosswind approach flown with drift-angle). Control aspects of this manoeuvre are closely related to engine out recovery. Reference 18, however, presents some "ball park" values for dimensional rudder effectiveness N_{δ_r} and the L_β/L_{δ_a} ratio, both closely related to the manoeuvre. The first because of the yaw control power needed to kick-off drift angles in a short time, the second because of the roll power needed to counteract rolling moments due to side slip. The proposed minimum value of N_{δ_r} of - 0.2 sec^{-2} indicates (see table 3) that the B-747 is critical, and that the yaw control power for the VLAC- 1 and 4 is insufficient. As far as L_β/L_{δ_a} is concerned all aircraft (DC-8 up to VLAC-4) fall short of the proposed value ($L_\beta/L_{\delta_a} < 1$). Assuming that the DC-8 with spoilers (see table 3) is nevertheless just satisfactory in this respect, the B-747 would require a very small improvement in L_{δ_a} while the VLAC 1 and 4 would require a 35% increase in this derivative. For the VLAC-1 this would mean that the de-crab manoeuvre rather than the manoeuvres pertaining to fig. 7 would be determining for the required roll power of the VLAC-1; this is, however, not the case for the VLAC-4, for which both manoeuvres are equally exacting.

VI The sidestep manoeuvre.

The sidestep is a manoeuvre which is required when the aircraft has a lateral deviation from the runway centerline at the end of an IFR approach. With respect to the very large aircraft, this manoeuvre is considered to be one of the most demanding lateral manoeuvres, which therefore justifies a rather extensive treatment.

*) The C-5A uses feedback of roll rate and roll attitude-to-rudder and the B-747 of roll rate-to-rudder for turn coordination.

Table 3

Lateral-directional Dynamics

Parameter	DC-8	B-747	C-5A	VLAC-1	VLAC-4
T_R sec	0.76	1.03	1.00	1.18	1.49
ω_d rad/sec	0.96	0.73	0.81	0.67	0.53
ζ_d	0.100/0.166*	0.094/0.210*	- /0.188*	- 0.059	- 0.059
$L_{\delta_a} \cdot \delta_{a_{max}}$ rad/sec^2	0.41/0.51**	0.31†	—	0.20†	0.13†
N_{δ_r} sec^{-2}	- 0.38	- 0.17	—	- 0.11	- 0.067
L_β sec^{-2}	- 1.93	- 1.36	—	- 1.02	- 0.64
L_{δ_a} sec^{-2}	- 0.81/-1.00**	- 0.62	—	- 0.39	- 0.25
L_β / L_{δ_a}	2.4/1.9**	2.2	—	2.6	2.6

* With damper; ** Assumed 25 % improved L_{δ_a} with spoilers.

† Including spoilers.

According to tests described in ref. 21, the co-ordinated turn showed to be more effective than the sideslipping turn with wings level to perform the sidestep. Due to the high values of C_{n_p} for the very large aircraft considered, relatively large adverse yawing moments occur due to roll rate, a result of the high lift coefficients used. Also, large values of "effective dihedral" (C_{ℓ_β}) exist for these aircraft, so that only small sideslip angles result in relatively large adverse rolling moments, limiting the lateral performance of these aircraft considerably. Turn co-ordination is therefore, of great importance.

However, problems exist for the pilot with respect to the control of sideslip for these low directional stability (low ω_d) airplanes because of the low accelerations experienced by him. Another complicating factor in turn co-ordination is the location of the pilot in these very large aircraft, with respect to the centre of gravity. Because of his position far forward of and above the centre of gravity, it is very difficult for him to perceive true sideslip. It is therefore obvious that co-ordination of bank and yaw for these aircraft during the sidestep is an extremely difficult task. Application of an augmentation system, assisting the pilot in his co-ordination task will therefore be necessary. In case a good turn co-ordination system is installed, an effective sidestep can be performed by the pilot using lateral control only.

In order to predict the sidestep performance (lateral displacement achievable in a certain manoeuvre time while alignment with the runway is regained) on a theoretical basis, the simplified analysis of the co-ordinated manoeuvre as introduced in ref. 21, assuming sinusoidal variations of bank angle, can be used. The relation between φ_{max} and T_{man} based on this analysis is presented in fig. 9 (a and b) for a lateral offset of 200 ft, a value often used with respect to sidestep performance evaluations.

In order to determine the values of $\delta_{a_{max}}$ and $\delta_{r_{max}}$, associated with this relation between φ_{max} and T_{man}, the amplitude ratios

$$\left| \left[\frac{\delta_a}{\varphi}(s) \right] \right|_{\beta=0} \quad \text{and} \quad \left| \left[\frac{\delta_r}{\varphi}(s) \right] \right|_{\beta=0} \quad \text{have been derived.}$$

Rather simple approximations for these ratios can be obtained from the aircraft's lateral equations of motion

$$\left[\frac{\delta_a}{\varphi}(s) \right]_{\beta=0} \doteq \frac{1}{L_{\delta_a}} \left(s^2 - L_p s - L_r \frac{g}{U_o} \right)$$

$$\left[\frac{\delta_r}{\varphi}(s)\right]_{\beta=0} \doteq -\frac{1}{N_{\delta_r}}\left\{(N_p - \frac{g}{U_o})s + N_r\frac{g}{U_o}\right\}$$

The value of s in these relations is determined by the value of T_{man} which is related to the period of the sinusoidal variations.

Curves indicating values of $\delta_{a_{max}}$ and $\delta_{r_{max}}$, based on the above-mentioned expressions, as a function of T_{man}, are drawn in fig. 9a and 9b respectively. It is of importance to notice that these curves are valid only for the control effectivenesses as given in table 3. Having chosen about the same value, say 30°, for $\delta_{a_{max}}$ and $\delta_{r_{max}}$, the minimum achievable value of T_{man} is for the B-747, VLAC-1 and VLAC-4 determined by the maximum available rudder deflection, whereas for the DC-8 the minimum manoeuvre time is restricted by the maximum available roll power. It is of importance to note, that L_{δ_a}, as given in table 3, also includes the rolling moment due to spoiler deflection, except for the DC-8, considered here, which is not equipped with flight spoilers. The necessity of high yaw control power for the B-747 and hypothetical aircraft is mainly caused by the large adverse yawing moments due to roll rate.

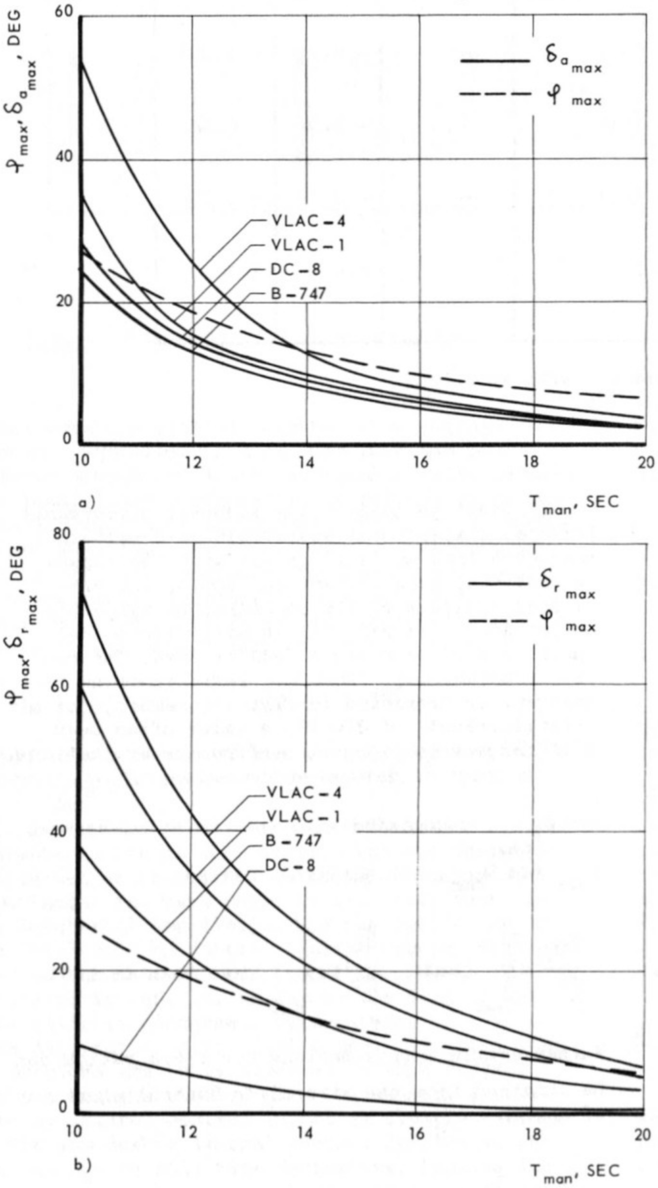

Fig. 9 Maximum values of bank, aileron and rudder for a sinusoidal co-ordinated sidestep of 200 ft.

Considering minimum values of T_{man}, it is necessary that the maximum bank angle obtained has a value below the maximum admissible value, being smaller for the larger aircraft assuming about the same wingtip clearance.

From fig. 9a and b the minimum manoeuvre time to correct a lateral offset of 200 ft can be determined (table 4). As general accepted criteria do not exist for sidestep performance, an impression of this performance for the aircraft considered can be obtained by qualitative judgement.

According to simulator experiments of ref. 5 the correction of 200 ft lateral offset started at 200 ft altitude is for the C-5A considered to be the maximum achievable sidestep performance. In this connection the minimum value of T_{man} for a 200 ft sidestep is for the very large aircraft compared with the available time to perform the manoeuvre, starting at 200 ft altitude (Cat. I weather minima). Assuming a glide slope of 3° and a flare height, determining the end of the manoeuvre, of 70 ft, the values of the available manoeuvre time, also given in table 4, are obtained. From this table it can be concluded that only the DC-8 and the B-747 are capable to achieve a 200 ft lateral distance from 200 ft altitude. In order to accomplish a similar performance for the VLAC-1, the yaw control power will have to be increased by about 45 % (fig. 9b). For the VLAC-4 a similar performance cannot be attained because of the inadmissibly large maximum bank angle associated with the small available time for the sidestep from 200 ft altitude. More accurate approach and landing systems will have to be used in that case so that smaller lateral deviations are to be corrected at the end of the instrument approach.

As mentioned in the section on lateral-directional handling qualities, values of the ratio T_R/T_{man} less than 0.1 are desired according to ref. 15 for acceptable correspondence between pilot's roll control inputs and airplane's roll rate during the sidestep manoeuvre. Considering the available time from an altitude of 200 ft, the values of $T_R/(T_{man})_{av}$, presented in table 4 are obtained. It appears from these values that the VLAC-1 and the VLAC-4 do not comply with the recommendation of ref. 15. Thus in addition to the problems with respect to control power and turn co-ordination, also difficulties due to high values of T_R are to be expected for the very large aircraft in performing a sidestep manoeuvre. These difficulties can be solved by applying an augmentation system which decreases the effective value of T_R.

Table 4

Sidestep manoeuvre performance.

	DC-8	B-747	VLAC-1	VLAC-4
T_{man} (sec) achievable for 200 ft offset	9.9	10.8	12.4	13.4
T_{man} (sec) available from 200 ft altitude	10.3	11.1	11.1	8.85
$T_R/(T_{man})_{av.}$	0.074	0.093	0.106	0.168

VII Future developments.

In the following a few remarks will be made with respect to systems needed for control augmentation along a line perpendicular to the flight path and stability and control augmentation around the three rotary axis of the aircraft. Moreover the effect of structural dynamics will be mentioned.

As was shown in the section on longitudinal handling qualities, one of the limits exceeded by the VLAC-aircraft was the boundary value for $1/T_{\theta_2}$. Moreover detrimental effects of low $1/T_{\theta_2}$ on altitude control was demonstrated in the section on wind shear. By gearing lift modulating devices (e.g. spoilers, flaps, symmetrical aileron with incorporation of elevator interconnects) to the pilot's longitudinal control it is possible to increase the effective value of $1/T_{\theta_2}$. This concept is often called "blended" Direct Lift Control. Evidence is available from sources in the literature discussed later that DLC capability of plus and minus 0.1 g leads to substantial improvements.

Three reasons for improved longitudinal control attained with DLC (even improved quality over the standard of present-day jets) can be formulated: excellent flight path control during steep approaches (noise-abatement), improved flare control needed when lowering flare initiation height (with possible advantages for low weather minima operations) and improved touch-down control. Up to now only a very modest effort is put in research to investigate all possible benefits of Direct Lift Control for large aircraft although it can be noticed that present-day research directed at automatic all weather operations is paying more attention to the concept.

A DLC system on a DC-8 Super 63 (long body) was flight tested as reported in ref. 23. Computer studies before the flight tests had indicated that spoilers already incorporated in the aircraft were the most appropriate means for lift-modulation. Results from flight tests showed that corrections on glide path were accomplished with smaller pitch attitude changes than without DLC, a decrease in flare initiation height from 60 to 30 feet was observed and better touch-down control existed. The overall conclusion [23] was, "DLC is benificial to the flying qualities of large aircraft and to the pilots who fly them". A recently completed NASA study [24], directed at the implementation of noise-abatement landing approaches included an evaluation of a DLC system. The potential advantages of DLC in steep approaches in arresting a high rate of descent quickly in case of an emergency were clearly established. Moreover improved flare and touch-down control was highly appreciated by the evaluation test pilots.

It must be noticed that to enable a pilot of a "large" aircraft to make full use of the response characteristics offered by DLC in flare and touch-down, he must be provided with appropriate flare and touch-down guidance information.

We now turn to stability and control augmentation around the three aircraft axis. Deteriorating characteristics in flying qualities due to high inertias and high lift coefficients during the approach should be resolved by suitable augmentations systems.

Two cases of insufficient control power have been indicated in the section on lateral-directional handling qualities; they are inadequate maximum roll control power and yaw control power. It seems likely that improved roll control power might be obtained by differential "blowing" at the wing trailing edges. The requirements for rudder control power are about the same for the sidestep and the crosswind landing manoeuvres. Dropping the requirement for a sidestep manoeuvre completely could lead to lower values of rudder control power when a crosswind landing gear is applied.

Due to extremely high control surface hinge moments the pilot has no capability of directly controlling the aerodynamic surfaces and therefore the application of a mechanical connection between the pilot controls and the surface actuation systems becomes questionable. Reliability of electrical and electronic systems have to be brought to a "as safe as the structure" standard as already indicated by the need for a redundant "hardened" yaw damper design. The development of very reliable electrical systems has been and will be stimulated by the all weather automatic landing requirements for transport aircraft. Electrical transmission of pilot commands into "closed-loop" control systems without mechanical back-up can be expected. The application of side-stick controllers in this situation seems very probable. Certain cues important to the pilot and with contemporary control feel systems "sensed" through the control system have to be generated in other ways. Probably the most important cue in this respect, the "speed feel" should artificially be generated by a form of "electronic down spring". Hybrid forms of electrical/mechanical transmission are already in use (C-5A electrical column and wheel travel feed forward, with wash-out, for quickening of pitch respectively roll response).

The level of augmentation required for the VLAC aircraft in pitch is not easily described because it will be strongly interrelated to the Direct Lift Control mechanization (Control augmentation - perpendicular to the flight path). Pitch-rate command/attitude hold features, which means an effective increase in ω_{sp}, will be desirable and it is already shown, ref. 24, that for more demanding approach profiles (noise-abatement steep approach) this feature is essential. Roll augmentation can best be effectuated in the form of feed back of roll rate to the lateral control to decrease the roll subsidence time constant; mechanization in the form of a roll-rate command system does not have the roll rate limiting effect of a simple roll damper. Augmentation in the yaw axis will apart from yaw rate to rudder feed back for Dutch-roll damping consist of feed-backs for turn co-ordination. This aspect is important for comfort as well as a need for obtaining best possible roll performance. Turn co-ordination for the aircraft studied here will most probably be obtained by aileron to rudder interconnect, roll rate and roll attitude to rudder feed backs to decrease or eliminate dynamic adverse yaw and obviate the need for rudder application by the pilot in steady turns.

In conclusions of this section a brief observation pertaining to the effect of structural dynamics is made.

Introduction of materials with higher specific strength and relatively lower stiffness together with more optimized construction technology all needed to defeat the square cube law, will lead to a more flexible aircraft structure and associated lower structural frequencies. Riding qualities will be affected adversely by these lower structural frequencies. According to ref. 6 the ratio of the short-period frequency to the first wing symmetric bending frequency will increase and therefore the frequencies will approach each other. Coupling of modes will exist in the sense that when the pilot wants to manoeuvre or stabilize the airplane he has to cope with higher order responses. Because pilots appreciation of the dynamic system he is controlling will be based on the total response motion he is subjected to, stability augmentation systems incorporated to improve handling qualities for these airplanes, must be designed to increase damping of the lower structural modes as well(22).

VIII Conclusion.

The established trend of deteriorating flying qualities for larger aircraft, based on an assumed extrapolation of aircraft size, is, in general, caused by increasing values of the inertias, the actual lift coefficient and the wing loading.

In conclusion it can be stated that augmentation systems with a high degree of redundancy will be needed to be able to handle very large subsonic jet transports during the landing approach. Augmentation systems needed for manual control as discussed in this paper will most probably be functional innerloops of automatic approach and landing systems for these aircraft. Definite data on desired dynamic characteristics of-closed-loop-pitch rate command systems when combined with DLC systems do not exist as yet. Handling quality criteria available for roll control and lateral-directional characteristics are adequate and prescribed levels of stability and control do not indicate fundamental obstacles for the very large aircraft considered here.

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