NASA TECHNICAL NOTE

NASA TN D-5862

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SIMULATOR STUDY OF THE INSTRUMENT LANDING APPROACH OF A HEAVY SUBSONIC JET TRANSPORT WITH AN EXTERNAL-FLOW JET-FLAP SYSTEM USED FOR ADDITIONAL LIFT

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • JUNE 1970

1. Report No. NASA TN D-5862	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle SIMULATOR STUDY OF THE INSTRUMENT LANDING APPROACH OF A HEAVY SUBSONIC JET TRANSPORT WITH AN EXTERNAL-FLOW JET-FLAP SYSTEM USED FOR ADDITIONAL LIFT		5. Report Date June 1970
		6. Performing Organization Code
7. Author(s) William D. Grantham, Perry L. Deal, and Robert W. Sommer		8. Performing Organization Report No. L-7039
		10. Work Unit No. 721-01-11-03
9. Performing Organization Name and Address NASA Langley Research Center Hampton, Va. 23365		11. Contract or Grant No.
		13. Type of Report and Period Covered Technical Note
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

The results indicated that no unusual piloting techniques were required to fly the landing approach on the simulated external-flow jet-flap airplane. However, a lateral-directional augmentation system was required and an autospeed control system was very beneficial. With the stability augmentation and autospeed control systems incorporated the average pilot rating assigned to the flying qualities of the simulated jet-flap configuration was 3 to $3\frac{1}{2}$. In addition, the results indicated that the use of spoilers or thrust modulation for direct lift control (DLC), in combination with autospeed control, was an effective system for tracking the glide slope, and both DLC systems were preferred over use of the elevator.

17. Key Words (Suggested by Author(s)) External-flow jet flap; Handling qualities; Stability and control; Automatic speed control; Direct lift control		18. Distribution Statement Unclassified – Unlimited	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 35	22. Price* $3.00

*For sale by the Clearinghouse for Federal Scientific and Technical Information
Springfield, Virginia 22151

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SUMMARY

A fixed-base simulator study was conducted to determine the flying qualities and to investigate various piloting techniques for the instrument landing approach of a heavy subsonic jet-transport airplane with an external-flow jet-flap system used for additional lift. The flare and touchdown characteristics were not evaluated. An important qualification on the results of the investigation is that the particular configuration studied had only the power normally installed in a subsonic jet transport, of the weight class used, and did not have extra power installed just for lift augmentation. The major significance of this qualification is that the reduction in approach speed from the use of the jet flap was modest (from 138 knots without jet-flap operation to 106 knots with jet-flap operation).

The results indicated that no unusual piloting techniques were required to "fly" the landing approach on the simulated external-flow jet-flap airplane, but a lateral-directional augmentation system was required and an autospeed control system was very beneficial. With the stability-augmentation and autospeed-control systems incorporated, the average pilot rating assigned to the flying qualities of the simulated jet-flap configuration was 3 to $3\frac{1}{2}$. In addition, the results indicated that the use of spoilers or thrust modulation for direct lift control (DLC), in combination with autospeed control, was an effective system for tracking the glide slope, and both DLC systems were preferred over use of the elevator.

INTRODUCTION

Recently, a great deal of interest has been shown in the external-flow jet-flap principle as a means of achieving high lift coefficients. In the external-flow jet-flap system, the jet exhaust from pod-mounted engines is deflected upward through slotted flaps to induce additional lift on the wing. Recent wind-tunnel tests (ref. 1) on a model of a heavy logistics transport using an external-flow jet-flap system showed that this system was effective in producing high lift coefficients and offered a promising means of achieving improved take-off and landing performance of such an airplane. There is little information available, however, on how such systems may affect the piloting techniques required to land. Consequently, the present study was undertaken to investigate the piloting problems for the landing approach of heavy subsonic jet transports when an external-flow jet-flap system is used to obtain additional lift and to determine the effects of the jet-flap system on the overall low-speed handling qualities of the airplane.

The airplane configuration represented was one with a conventional amount of thrust relative to its weight; that is, no additional thrust was added just to produce additional powered lift. Therefore, there was only a very modest amount of powered lift. The major significance of this qualification is that the reduction in approach speed from the use of the jet flap was modest (from 138 knots without jet-flap operation to 106 knots with jet-flap operation) and that the thrust vectoring by the flap system was much less than would be the case for a jet-flap STOL (short take-off and landing) airplane which would be expected to have considerable extra power installed just to produce additional lift. A fixed-base simulator was utilized for the investigation, and the primary task was the instrument landing approach using the instrument landing system (ILS). Measured low-speed wind-tunnel aerodynamic data were used as inputs. Two primary pilots and two secondary pilots "flew" the simulator with the main objective of investigating piloting problems and techniques for the landing approach. This included a determination of the effects of automatic speed control and of several direct-lift-control (DLC) devices on the piloting task and on the ability of the pilot to track the glide slope and to correct for glide-slope offsets. Additional objectives of the program were to determine the stability and control characteristics of the unaugmented configuration, and to determine the values of the aerodynamic parameters, obtained through stability augmentation, that would be required to make the handling qualities satisfactory.

SYMBOLS

In order to facilitate international usage of data presented, dimensional quantities are presented in both U.S. Customary Units and in the International System of Units (SI).

a_n normal acceleration, g units (meters/second^2)

b wing span, feet (meters)

$C_{1/2}$ cycles required for oscillation to damp to one-half amplitude

C_D drag coefficient

C_L	lift coefficient
$C_{L,max}$	maximum lift coefficient
C_l	rolling-moment coefficient
C_m	pitching-moment coefficient
C_n	yawing-moment coefficient
C_T	thrust coefficient
C_X	longitudinal-force coefficient
C_Y	side-force coefficient
C_Z	vertical-force coefficient
$\bar{c}$	mean aerodynamic chord, feet (meters)
F_c	force input to control column, pounds (newtons)
g	acceleration due to gravity, feet/second^2 (meters/second^2)
h	altitude, feet (meters or kilometers)
I_X,I_Y,I_Z	moments of inertia about X-, Y-, and Z-body axes, respectively, slug-feet^2 (kilogram-meters^2)
I_{XZ}	product of inertia, slug-feet^2 (kilogram-meters^2)
n	load factor, g units
P	period, seconds
p,q,r	rolling, pitching, and yawing angular velocities, respectively, radians/second
T	thrust, pounds (newtons)

$t_{1/2}$ time to damp to one-half amplitude, seconds

t_R roll time constant, seconds

V airspeed, knots or feet/second

W airplane weight, pounds force (newtons)

α angle of attack, degrees or radians

β angle of sideslip, degrees or radians

β_1 first peak angle of sideslip, degrees or radians

γ flight-path angle, degrees

δ_a aileron deflection, positive for right roll command, degrees

δ_c column deflection, positive for pull force, degrees

δ_e elevator deflection, positive for trailing-edge down, degrees

δ_f flap deflection, degrees

δ_{f1} forward trailing-edge flap-segment deflection, degrees

δ_{f2} rearward trailing-edge flap-segment deflection, degrees

δ_p pedal deflection, inches (centimeters)

δ_r rudder deflection, positive when trailing edge is deflected to left, degrees

δ_s spoiler deflection, negative when trailing edge is deflected up, degrees

δ_{sl} leading-edge slat deflection, degrees

δ_t horizontal-tail deflection, positive when trailing edge is deflected down, degrees

δ_v	deflection of vane (δ_{f2}) from null position, degrees
δ_w	wheel deflection, degrees
ϵ_h	glide-slope linear error, feet (meters)
ϵ_Y	localizer error, degrees
ϵ_Z	glide-slope angular error, degrees
ζ	damping ratio
ζ_d	Dutch roll damping ratio
ζ_{sp}	longitudinal short-period damping ratio
θ	angle of pitch, degrees or radians
ϕ	angle of bank, degrees or radians
ϕ_1	first peak angle of bank, degrees or radians
ψ	angle of yaw, degrees or radians
ω_d	undamped natural frequency of Dutch roll mode, radians/second
ω_{sp}	longitudinal short-period undamped natural frequency, radians/second
ω_ϕ	undamped natural frequency appearing in numerator quadratic of ϕ/δ_a transfer function, radians/second

Abbreviations:

DLC	direct lift control
ILS	instrument landing system
PR	pilot rating

RMS root mean square

SAS stability augmentation system

Coefficients:

$C_{l_\beta} = \frac{\partial C_l}{\partial \beta}$ $C_{n_\beta} = \frac{\partial C_n}{\partial \beta}$ $C_{Y_\beta} = \frac{\partial C_Y}{\partial \beta}$

$C_{X_{\delta e}} = \frac{\partial C_X}{\partial \delta_e}$ $C_{Z_{\delta e}} = \frac{\partial C_Z}{\partial \delta_e}$ $C_{m_{\delta e}} = \frac{\partial C_m}{\partial \delta_e}$

$C_{X_{\delta f2}} = \frac{\partial C_X}{\partial \delta_{f2}}$ $C_{Z_{\delta f2}} = \frac{\partial C_Z}{\partial \delta_{f2}}$ $C_{m_{\delta f2}} = \frac{\partial C_m}{\partial \delta_{f2}}$

$C_{X_{\delta s}} = \frac{\partial C_X}{\partial \delta_s}$ $C_{Z_{\delta s}} = \frac{\partial C_Z}{\partial \delta_s}$ $C_{m_{\delta s}} = \frac{\partial C_m}{\partial \delta_s}$

$C_{X_{\delta t}} = \frac{\partial C_X}{\partial \delta_t}$ $C_{Z_{\delta t}} = \frac{\partial C_Z}{\partial \delta_t}$ $C_{m_{\delta t}} = \frac{\partial C_m}{\partial \delta_t}$

$C_{L_{\delta v}} = \frac{\partial C_L}{\partial \delta_v}$ $C_{D_{\delta v}} = \frac{\partial C_D}{\partial \delta_v}$

$C_{l_{\delta a}} = \frac{\partial C_l}{\partial \delta_a}$ $C_{n_{\delta a}} = \frac{\partial C_n}{\partial \delta_a}$ $C_{Y_{\delta a}} = \frac{\partial C_Y}{\partial \delta_a}$

$C_{l_{\delta r}} = \frac{\partial C_l}{\partial \delta_r}$ $C_{n_{\delta r}} = \frac{\partial C_n}{\partial \delta_r}$ $C_{Y_{\delta r}} = \frac{\partial C_Y}{\partial \delta_r}$

$C_{l_p} = \frac{\partial C_l}{\partial \frac{pb}{2V}}$ $C_{n_p} = \frac{\partial C_n}{\partial \frac{pb}{2V}}$ $C_{Y_p} = \frac{\partial C_Y}{\partial \frac{pb}{2V}}$

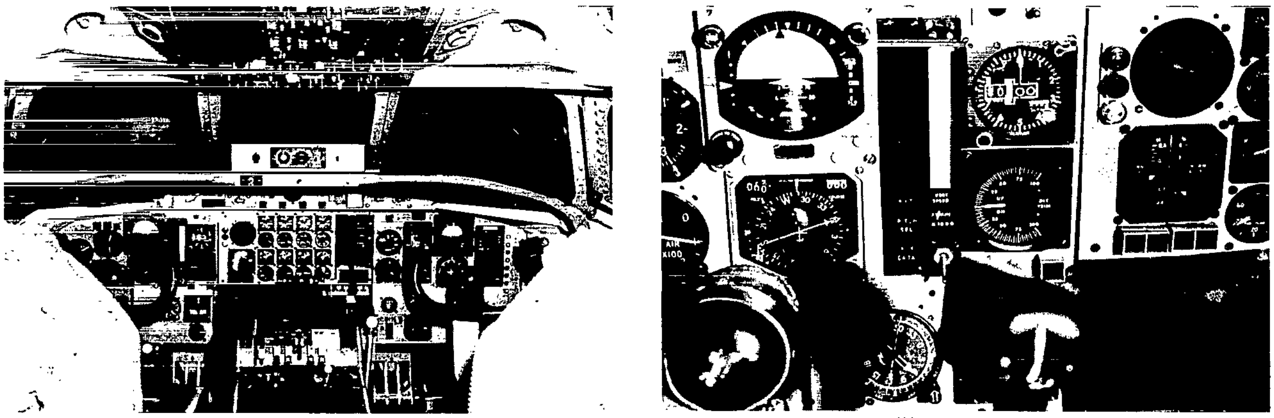
$C_{l_r} = \frac{\partial C_l}{\partial \frac{rb}{2V}}$ $C_{n_r} = \frac{\partial C_n}{\partial \frac{rb}{2V}}$ $C_{Y_r} = \frac{\partial C_Y}{\partial \frac{rb}{2V}}$

$C_{m_q} = \frac{\partial C_m}{\partial \frac{q\bar{c}}{2V}}$ $C_{n_{\dot\beta}} = \frac{\partial C_n}{\partial \frac{\dot\beta b}{2V}}$

A dot over a symbol indicates a derivative with respect to time.

THE FIXED-BASE SIMULATOR

The fixed-base simulator presented the pilot with the essential elements of the task of performing an instrument-landing-system (ILS) approach. It had a transport-type cockpit which was equipped with conventional flight and engine thrust controls and with a flight instrument display representative of those found in current transport airplanes. (See fig. 1.) In addition, a direct-lift-control (DLC) thumb controller, spring-loaded to neutral position, was mounted on the right horn of the control yoke. (An instrument was installed in the display panel that indicated to the pilot the direction and amount of DLC being commanded.) All approaches were terminated at an altitude of 200 feet (61 meters) – flare and touchdown characteristics were not evaluated. Control forces were provided by a hydraulic servo system and were functions of control displacement and rate. The control characteristics used are defined in table I, and the engine thrust-response characteristics used are presented in figure 2. Real-time digital simulation techniques were used wherein a digital computer was programed with the equations of motion for six degrees of freedom.



(a) Simulator cockpit. L-69-4124

(b) DLC controller. L-69-4122

Figure 1.- Photographs of simulator cockpit and instrument display.

TABLE I.- SIMULATOR CONTROL CHARACTERISTICS

Control	Gearings from cockpit control to control surface	Breakout force, lbf (N)	Force gradient, lbf/in. (N/cm)
Pitch	$\delta_e/\delta_c = -4.00$	3.0 (13.3)	8.6 (15.1)
Roll.	$\delta_a/\delta_w = 0.33$	1.5 (6.7)	2.9 (5.1)
Yaw	$\delta_r/\delta_p = -8.2$ deg/in. (-3.2 deg/cm)	4.0 (17.8)	25.9 (45.4)

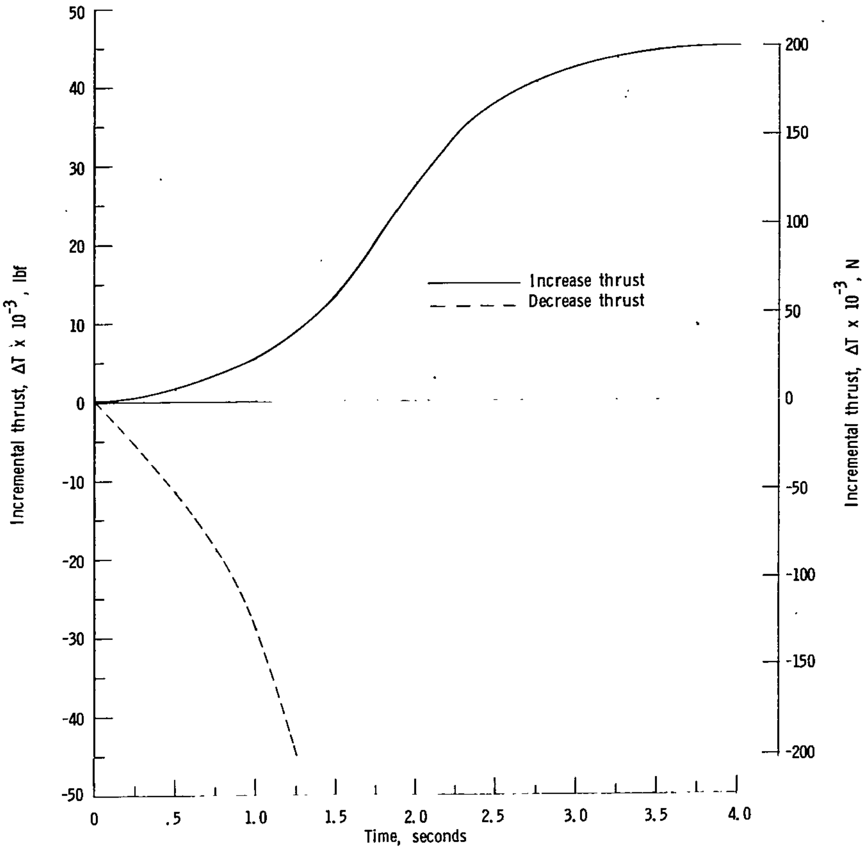


Figure 2.- Maximum incremental thrust variation with time. Four engines operating.

AIRPLANE DESIGN AND TEST CONFIGURATIONS

The airplane design used in this study was the four-engine subsonic jet transport configuration shown in figure 3. The wing incorporated leading-edge slats and double-slotted trailing-edge flaps which were set at $\delta_{f1}/\delta_{f2} = 30^{\circ}/60^{\circ}$ for the approach condition. The engines were high-bypass-ratio turbofan engines and were tilted 3° nose down so that the jet exhaust impinged directly on the trailing-edge flap system. (See fig. 4.) The four engines were assumed to provide a total installed maximum thrust of 164 000 pounds (729 508 newtons) or $T/W = 0.30$. The mass and dimensional characteristics of the simulated airplane are presented in table II, and the aerodynamic characteristics are presented in table III. These aerodynamic characteristics were taken from references 1, 2, and unpublished data.

In order to afford a standard for comparison, a preliminary evaluation of the general flying qualities of the airplane was made wherein it was considered not to be a jet-flap design. For this preliminary evaluation the $C_T = 0$ aerodynamic data of table III were used and thrust was assumed to have no effect other than to produce a forward force. For the main part of the study, the airplane was evaluated as a jet-flap design

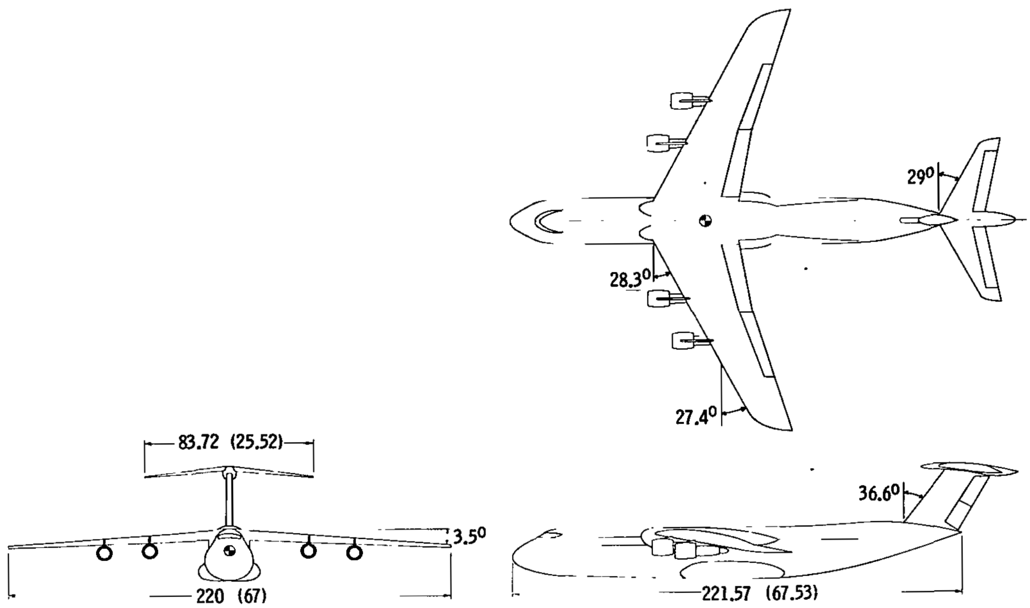


Figure 3.- Three-view drawing of simulated airplane. All linear dimensions are in feet (meters).

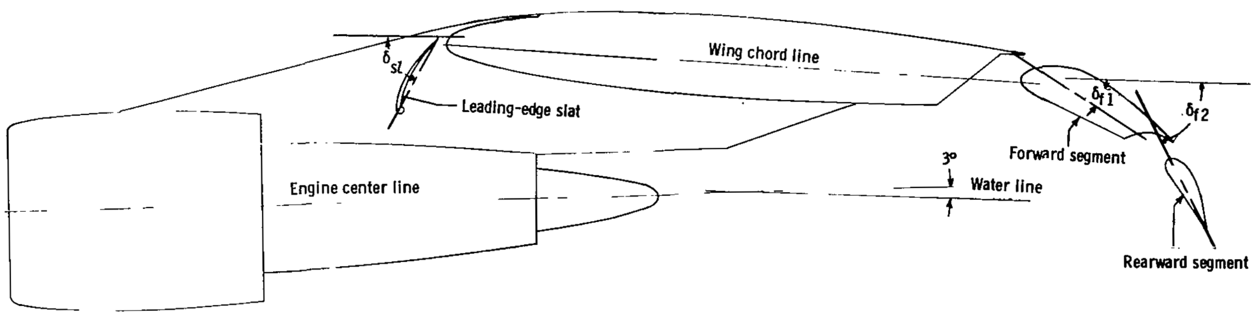


Figure 4.- Detailed drawing of flap assembly and engine pylon. $\delta_{sl} = 60^{\circ}$; $\delta_{f1}/\delta_{f2} = 30^{\circ}/60^{\circ}$.

TABLE II.- MASS AND DIMENSIONAL CHARACTERISTICS

Weight, lbf (N)	546 667 (2 431 695)
Wing area, ft^2 (m^2)	6 237 (579)
Wing span, ft (m)	220 (67)
Mean aerodynamic chord, ft (m)	31 (9.4)
Center-of-gravity location, percent $\bar{c}$	25
I_X, slug-ft^2 $(kg\text{-}m^2)$	17.5×10^6 (23.73×10^6)
I_Y, slug-ft^2 $(kg\text{-}m^2)$	27.0×10^6 (36.61×10^6)
I_Z, slug-ft^2 $(kg\text{-}m^2)$	51.0×10^6 (69.16×10^6)
I_{XZ}, slug-ft^2 $(kg\text{-}m^2)$	0.5×10^6 (0.68×10^6)
Maximum control-surface deflections:	
δ_e, deg	±25
δ_t, deg	±20
δ_a, deg	±20
δ_r, deg	±35

TABLE III.- BASIC AERODYNAMICS USED IN SIMULATION

$\left[\delta_{f1}/\delta_{f2} = 30^{\circ}/60^{\circ}\right]$

(a) Derivatives used as function of α and C_T

α, deg	$C_T = 0$	$C_T = 0.38$	$C_T = 0.78$	$C_T = 1.26$	$C_T = 1.70$	$C_T = 0$	$C_T = 0.38$	$C_T = 0.78$	$C_T = 1.26$	$C_T = 1.70$	$C_T = 0$	$C_T = 0.38$	$C_T = 0.78$	$C_T = 1.26$	$C_T = 1.70$
			C_X					C_Z					C_m		
0	-0.200	0.080	0.360	0.750	1.100	-1.000	-1.450	-1.700	-1.930	-2.150	0.300	0.140	0.060	-0.010	-0.100
2.5	-.167	.113	.385	.766	1.136	-1.208	-1.667	-1.945	-2.179	-2.413	.250	.135	.055	-.030	-.113
5.0	-.130	.157	.434	.817	1.178	-1.387	-1.914	-2.211	-2.458	-2.678	.200	.110	.030	-.060	-.130
7.5	-.077	.214	.497	.875	1.239	-1.563	-2.160	-2.476	-2.739	-2.974	.150	.060	-.030	-.090	-.145
10.0	0	.296	.568	.934	1.300	-1.726	-2.425	-2.763	-3.054	-3.337	.100	-.035	-.100	-.165	-.205
12.5	.086	.389	.644	1.023	1.383	-1.866	-2.679	-3.043	-3.368	-3.606	.050	-.115	-.170	-.255	-.285
15.0	.121	.448	.721	1.108	1.475	-1.883	-2.830	-3.233	-3.596	-3.880	.020	-.170	-.260	-.340	-.370
17.5	.118	.476	.781	1.182	1.554	-1.871	-2.838	-3.308	-3.716	-4.029	0	-.200	-.315	-.390	-.420
			$C_{X_{\delta e}}$					$C_{Z_{\delta e}}$					$C_{m_{\delta e}}$		
0	0	0	0	0	0	-0.0060	-0.0080	-0.0130	-0.0220	-0.0350	-0.0170	-0.0150	-0.0170	-0.0200	-0.0280
2.5	.0003	.0004	.0007	.0012	.0016	-.0074	-.0093	-.0165	-.0279	-.0360	-.0188	-.0170	-.0184	-.0234	-.0313
5.0	.0007	.0009	.0016	.0026	.0032	-.0080	-.0100	-.0181	-.0296	-.0369	-.0205	-.0183	-.0195	-.0250	-.0310
7.5	.0009	.0011	.0023	.0036	.0050	-.0071	-.0084	-.0173	-.0273	-.0377	-.0210	-.0181	-.0208	-.0224	-.0298
10.0	.0010	.0015	.0027	.0047	.0067	-.0059	-.0083	-.0154	-.0266	-.0382	-.0208	-.0176	-.0190	-.0220	-.0285
12.5	.0011	.0022	.0030	.0058	.0085	-.0049	-.0098	-.0135	-.0261	-.0383	-.0200	-.0168	-.0169	-.0220	-.0275
15.0	.0014	.0023	.0033	.0063	.0101	-.0052	-.0085	-.0122	-.0236	-.0377	-.0220	-.0156	-.0172	-.0220	-.0260
17.5	.0018	.0020	.0034	.0062	.0114	-.0057	-.0064	-.0107	-.0196	-.0362	-.0245	-.0136	-.0205	-.0220	-.0230
			$C_{X_{\delta f2}}$					$C_{Z_{\delta f2}}$					$C_{m_{\delta f2}}$		
0	-0.0050	-0.0080	-0.0100	-0.0130	-0.0200	0.0020	-0.0070	-0.0070	-0.0120	-0.0020	0	-0.0040	-0.0010	-0.0040	-0.0020
2.5	-.0050	-.0088	-.0097	-.0114	-.0200	-.0002	-.0050	-.0064	-.0145	-.0009	0	-.0045	-.0005	-.0050	-.0007
5.0	-.0048	-.0081	-.0084	-.0081	-.0191	-.0024	-.0107	-.0068	-.0111	.0003	.0010	-.0010	-.0020	-.0020	.0010
7.5	-.0088	-.0082	-.0091	-.0110	-.0200	-.0050	-.0142	-.0073	-.0085	.0064	0	-.0060	0	-.0010	-.0005
10.0	-.0051	-.0096	-.0065	-.0118	-.0182	-.0001	-.0149	-.0093	-.0050	.0110	0	-.0035	0	-.0005	.0005
12.5	-.0063	-.0097	-.0068	-.0115	-.0190	-.0007	-.0165	-.0107	-.0036	.0163	0	-.0035	-.0020	.0025	.0075
15.0	-.0048	-.0087	-.0056	-.0106	-.0197	-.0013	-.0137	-.0139	-.0028	.0196	-.0020	-.0030	0	.0040	.0070
17.5	-.0026	-.0095	-.0056	-.0120	-.0209	-.0019	-.0078	-.0154	-.0017	.0196	.0030	0	.0005	.0040	.0070
			$C_{X_{\delta s}}$					$C_{Z_{\delta s}}$					$C_{m_{\delta s}}$		
0	0.0033	0.0033	0.0033	0.0033	0.0033	-0.0267	-0.0223	-0.0303	-0.0313	-0.0337	-0.0020	-0.0028	-0.0035	-0.0040	-0.0046
2.5	.0033	.0032	.0036	.0037	.0038	-.0266	-.0240	-.0337	-.0356	-.0378	-.0015	-.0015	-.0039	-.0055	-.0080
5.0	.0030	.0027	.0039	.0040	.0043	-.0262	-.0231	-.0361	-.0378	-.0414	-.0002	-.0005	-.0035	-.0055	-.0091
7.5	.0022	.0017	.0036	.0038	.0042	-.0260	-.0221	-.0369	-.0379	-.0410	.0009	0	-.0019	-.0043	-.0069
10.0	.0021	.0022	.0041	.0047	.0062	-.0253	-.0257	-.0362	-.0401	-.0484	.0009	-.0004	-.0017	-.0032	-.0054
12.5	.0023	.0035	.0050	.0065	.0083	-.0239	-.0296	-.0360	-.0429	-.0510	.0001	-.0017	-.0017	-.0032	-.0060
15.0	.0022	.0038	.0058	.0082	.0105	-.0212	-.0270	-.0346	-.0435	-.0521	.0017	-.0011	-.0017	-.0049	-.0069
17.5	.0021	.0032	.0068	.0099	.0126	-.0165	-.0200	-.0313	-.0411	-.0498	.0027	0	-.0017	-.0045	-.0062
			C_{l_β}					C_{n_β}					C_{Y_β}		
0	-0.00040	-0.00250	-0.0029		-0.0036	0.0016	0.0007	0.0002		0.0003	-0.0120	-0.0120	-0.0115		-0.0140
2.5	-.00105	-.00265	-.0035		-.0043	.0016	.0009	.0003		.0004	-.0123	-.0123	-.0117		-.0141
5.0	-.00175	-.00290	-.0040		-.0047	.0016	.0010	.0005		.0007	-.0130	-.0130	-.0125		-.0149
7.5	-.00260	-.00350	-.0038		-.0044	.0018	.0008	.0008		.0012	-.0135	-.0120	-.0129		-.0155
10.0	-.00290	-.00440	-.0033		-.0039	.0018	.0004	.0009		.0015	-.0140	-.0110	-.0130		-.0154
12.5	-.00250	-.00590	-.0037		-.0045	.0020	.0001	.0008		.0010	-.0150	-.0110	-.0130		-.0151
15.0	-.00240	-.00580	-.0045		-.0049	.0020	.0004	.0002		.0004	-.0150	-.0110	-.0133		-.0155
17.5	-.00240	-.00500	-.0053		-.0053	.0020	.0010	-.0007		-.0001	-.0150	-.0110	-.0142		-.0171
			C_{l_p}					C_{n_p}					C_{Y_p}		
0	-0.510	-0.530	-0.545		-0.600	-0.105	-0.120	-0.193		-0.167	0.095	0.270	0.170		0.210
2.5	-.475	-.540	-.550		-.630	-.145	-.142	-.190		-.183	.080	.300	.200		.235
5.0	-.440	-.560	-.580		-.670	-.158	-.168	-.182		-.200	.070	.300	.220		.248
7.5	-.420	-.575	-.620		-.690	-.150	-.180	-.204		-.215	.190	.300	.220		.250
10.0	-.370	-.560	-.610		-.680	-.120	-.184	-.204		-.210	.190	.280	.190		.250
12.5	-.290	-.420	-.560		-.620	-.080	-.180	-.182		-.180	.160	.240	.150		.250
15.0	-.260	-.180	-.380		-.590	-.080	-.110	-.130		-.160	.170	.180	.020		.240
17.5	-.220	-.110	-.140		-.520	-.070	-.015	-.042		-.140	.160	.140	.015		.180
			C_{m_q}					C_{n_r}							
0	-28	-28	-28		-28	-0.170	-0.168	-0.200		-0.180					
2.5	-33	-33	-33		-33	-.164	-.156	-.185		.175					
5.0	-36	-36	-36		-36	-.160	-.143	-.170		.175					
7.5	-40	-40	-40		-40	-.169	-.138	-.178		.186					
10.0	-42	-45	-45		-42	-.150	-.146	-.178		.175					
12.5	-40	-55	-51		-45	-.121	-.160	-.170		.149					
15.0	-40	-62	-57		-45	-.133	-.175	-.154		.120					
17.5	-37	-62	-62		-50	-.167	-.184	-.167		.091					

TABLE III.- BASIC AERODYNAMICS USED IN SIMULATION – Concluded

$\left[\delta_{f1}/\delta_{f2} = 30^{\circ}/60^{\circ}\right]$

(b) Derivatives used as function of α only

α, deg	$C_{X_{\delta t}}$	$C_{Z_{\delta t}}$	$C_{m_{\delta t}}$	$C_{l_{\delta r}}$	$C_{n_{\delta r}}$	$C_{Y_{\delta r}}$
0	-0.0022	-0.0140	-0.0365	0.00017	-0.00114	0.00257
2.5	-.0026	-.0131	-.0400	.00017	-.00114	.00243
5.0	-.0028	-.0143	-.0432	.00011	-.00114	.00229
7.5	-.0034	-.0156	-.0465	.00010	-.00114	.00229
10.0	-.0077	-.0176	-.0485	.00006	-.00114	.00229
12.5	-.0096	-.0206	-.0500	.00003	-.00109	.00214
15.0	-.0065	-.0235	-.0520	0	-.00103	.00200
17.5	-.0022	-.0248	-.0523	0	-.00091	.00186
α, deg	C_{l_r}	C_{Y_r}	$C_{l_{\delta a}}$	$C_{n_{\delta a}}$	$C_{Y_{\delta a}}$	
0	0.275	0.650	0.00395	0.00070	0.0005	
2.5	.300	.625	.00415	.00065		
5.0	.325	.600	.00430	.00055		
7.5	.325	.550	.00435	.00045		
10.0	.325	.525	.00440	.00035		
12.5	.375	.470	.00430	.00022		
15.0	.450	.400	.00400	.00002		
17.5	.525	.275	.00345	-.00022		

and the aerodynamic data were used as a function of C_T. Several configurations, including the stability augmentation system (SAS) being on and off, were evaluated during both the preliminary and main parts of the study; and these various configurations are indicated in the following table:

Configuration	No jet flap	Jet flap
1	No SAS	No SAS
2	SAS on	SAS on
3	SAS and autospeed	SAS and autospeed
4	SAS, autospeed, and spoilers for DLC	SAS, autospeed, and various DLC systems: (a) Second segment of trailing-edge flap for DLC (b) Spoilers for DLC (c) Thrust modulation for DLC

TESTS AND PROCEDURES

The low-speed flight characteristics of the various configurations evaluated are presented and discussed in relation to pilot ratings and opinions. In general, the test procedures were as follows:

(1) Evaluate the flying qualities of the unaugmented configuration in level flight in the approach configuration and at the approach speed.

(2) Determine SAS required to make handling qualities satisfactory.

(3) Evaluate the piloting task and piloting technique for the landing approach of the configuration with SAS on, and of various combinations of autospeed and DLC with SAS on.

Four pilots participated in the simulation program; two primary pilots flew all configurations and two secondary pilots flew only the more pertinent ones. (Standard flight-test procedures (ref. 3, for example) were used in the evaluation of each test configuration.) Throughout the discussion of the results the pilot ratings (PR) listed for the various configurations will be an average of the ratings from all of the pilots who flew that particular configuration. See table IV for the pilot-rating system used.

TABLE IV.- PILOT-RATING SYSTEM

<table>
<tr><td rowspan="9">Controllable
Capable of being controlled or managed in context of mission, with available pilot attention.</td><td rowspan="6">Acceptable
May have deficiencies which warrant improvement, but adequate for mission.
Pilot compensation, if required to achieve acceptable performance, is feasible.</td><td rowspan="3">Satisfactory
Meets all requirements and expectations, good enough without improvement.
Clearly adequate for mission.</td><td>Excellent, highly desirable.</td><td>1</td></tr>
<tr><td>Good, pleasant, well behaved.</td><td>2</td></tr>
<tr><td>Fair. Some mildly unpleasant characteristics. Good enough for mission without improvement.</td><td>3</td></tr>
<tr><td rowspan="3">Unsatisfactory
Reluctantly acceptable. Deficiencies which warrant improvement. Performance adequate for mission with feasible pilot compensation.</td><td>Some minor but annoying deficiencies. Improvement is requested. Effect on performance is easily compensated for by pilot.</td><td>4</td></tr>
<tr><td>Moderately objectionable deficiencies. Improvements are needed. Reasonable performance requires considerable pilot compensation.</td><td>5</td></tr>
<tr><td>Very objectionable deficiencies. Major improvements are needed. Requires best available pilot compensation to achieve acceptable performance.</td><td>6</td></tr>
<tr><td rowspan="3">Unacceptable
Deficiencies which require mandatory improvement. Inadequate performance for mission even with maximum feasible pilot compensation.</td><td rowspan="3"></td><td>Major deficiencies which require mandatory improvement for acceptance. Controllable. Performance inadequate for mission, or pilot compensation required for minimum acceptable performance in mission is too high.</td><td>7</td></tr>
<tr><td>Controllable with difficulty. Requires substantial pilot skill and attention to retain control and continue mission.</td><td>8</td></tr>
<tr><td>Marginally controllable in mission. Requires maximum available pilot skill and attention to retain control.</td><td>9</td></tr>
<tr><td colspan="3">Uncontrollable
Control will be lost during some portion of mission.</td><td>Uncontrollable in mission.</td><td>10</td></tr>
</table>

The ILS approach was initiated with the airplane in the power-approach condition (power for level flight) at an altitude of 2000 feet (0.61 kilometer) and 8.7 nautical miles (16 kilometers) from the runway. The initial conditions for the non-jet-flap airplane were determined from the civil regulations of reference 4 and were $\alpha \approx 3.5^{\circ}$ and $V \approx 138$ knots. The initial conditions for the jet-flap airplane were determined from the requirements for powered-lift flight used in the analysis of reference 1. Figure 5, which

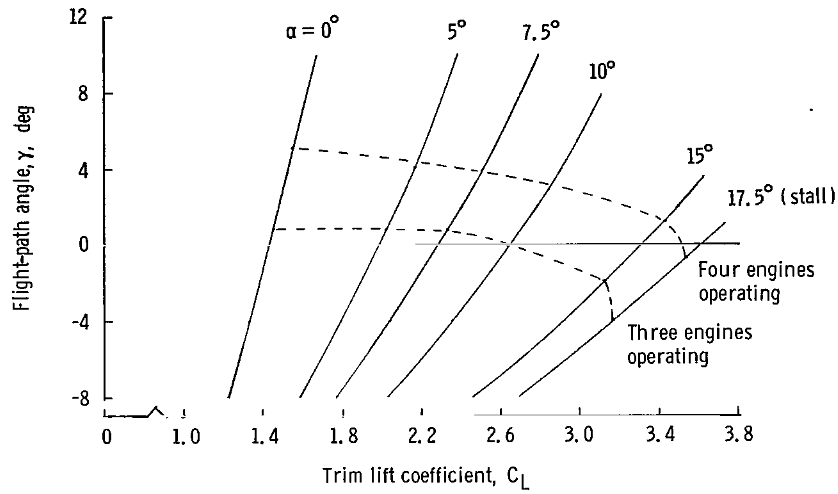


Figure 5.- Effects of engine thrust on trim lift coefficient and flight-path angle. $\delta_{f1}/\delta_{f2} = 30^{\circ}/60^{\circ}$.

was constructed from the aerodynamic data of table III, indicates that the requirements were met at $\alpha = 7.5^{\circ}$ and $C_L = 2.3$ ($V = 106$ knots). The principal requirements were as follows: (1) 10° margin, or more, of angle of attack from the stall, (2) a speed of at least 1.2 times the minimum power-on level-flight speed, and (3) level-flight capability with three engines without change of speed or flap deflection. (Although flight with three engines was considered in determining the initial conditions, the effects of losing an engine during the ILS approaches were not evaluated by the pilots.) In addition to the foregoing initial conditions, each approach was initiated with the airplane offset to the left of the localizer and below the glide slope. (See fig. 6.) A glide slope of 3° was used for the majority of the simulated approaches.

The simulator cockpit indicator presented essentially only localizer and glide-slope deviations; a standard flight director was available, but since it was not optimized, it was used primarily to minimize the localizer tracking task. The pilot's task was to capture the localizer and glide slope and to maintain them as closely as possible until the 200-foot (61-meter) altitude termination point was reached. Flight in both smooth air and rough air was evaluated. (The rough air was simulated by introducing noise with a Gaussian noise generator.) In addition, 200-foot (61-meter) vertical offsets from the glide slope were sometimes introduced at random intervals during the approach. By cor-

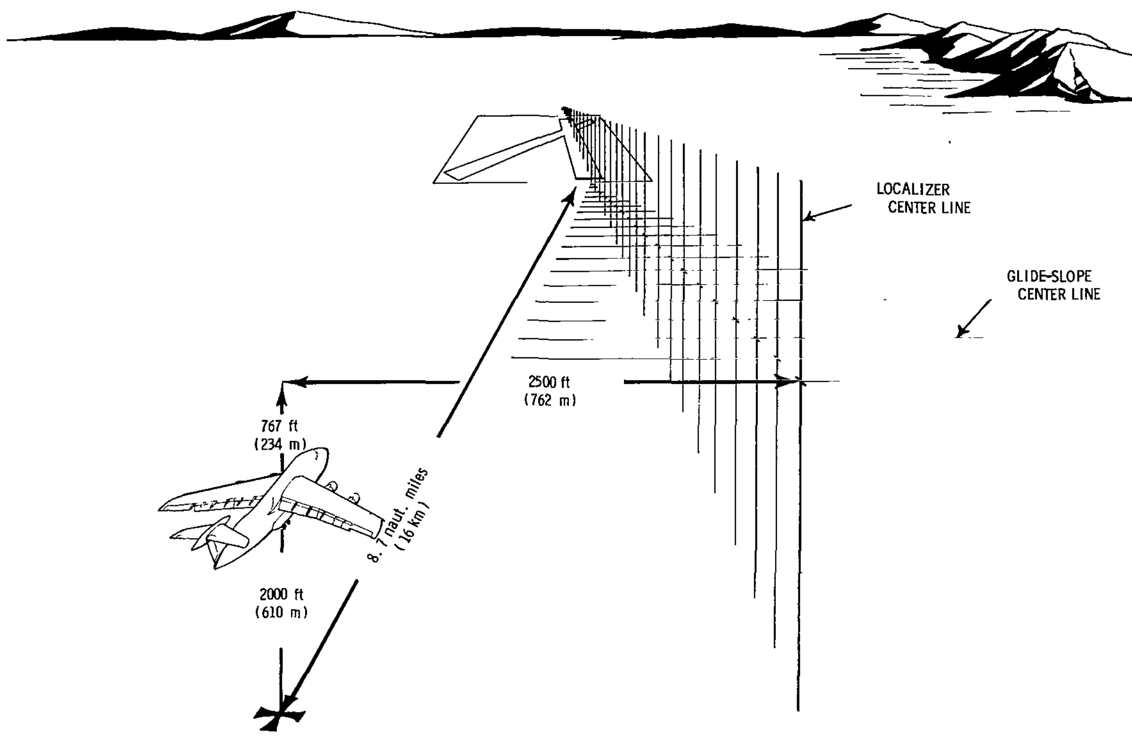


Figure 6.- Sketch indicating position of airplane relative to runway, glide slope, and localizer at time zero. All dimensions are in feet (meters) unless otherwise specified.

recting for these random offsets, the pilot was able to see how quickly and easily the airplane could be maneuvered to the desired position.

PRELIMINARY EVALUATION OF NON-JET-FLAP AIRPLANE

Flying Qualities

The longitudinal- and lateral-directional dynamic stability characteristics of the unaugmented and augmented non-jet-flap airplane are shown in table V. It will subsequently be seen that these calculated dynamic stability characteristics agree quite well in important particulars with the pilot's comments.

The pilot ratings assigned to the longitudinal flight characteristics of the unaugmented configuration were from 3 to $3\frac{1}{2}$, with the only objection being the sluggish initial pitch response; therefore, since this corresponds to a "satisfactory" rating, no longitudinal augmentation was incorporated.

A pilot rating of 5, which corresponds to an unsatisfactory but acceptable rating, was assigned to the lateral-directional flight characteristics. The pilots' objections were as follows:

(1) Poor Dutch roll characteristics: The period of the Dutch roll mode was con-

TABLE V.- DYNAMIC STABILITY CHARACTERISTICS

Parameter	Non-jet flap		Jet flap	
	Unaugmented	Augmented	Unaugmented	Augmented
		Short period		
ω_{sp}	0.989		0.962	
P	9.0		10.0	
ζ	.748		.750	
		Long period		
P	42.0		35.0	
ζ	.118		.055	
		Roll mode		
t_R	0.919	0.528	0.920	0.380
$t_{1/2}$	.637	.366	.640	.260
		Spiral mode		
$t_{1/2}$	-19.0	-22.0	60.0	364.0
		Dutch roll		
ω_d	0.527	0.635	0.467	0.561
P	12.3	10.4	13.6	12.4
ζ_d	.240	.317	.140	.430
$C_{1/2}$	.447	.330	.800	.230
$\left(\frac{\omega_\phi}{\omega_d}\right)^2$	.668	.960	.330	.980

sidered to be too long (P = 12 seconds) and the Dutch roll motion was too easy to excite $\left(\zeta_d < 0.25\right)$.

(2) High adverse yaw: The aileron yaw parameter $\left(\omega_\phi/\omega_d\right)^2$ was less than 0.7, which indicates high adverse yaw. (A value of unity for this parameter would indicate zero adverse yaw.)

(3) Poor turn coordination: The combination of poor Dutch roll characteristics, high adverse yaw, and low directional stability made the turn coordination poor.

(4) Low roll damping: Although the time to damp to half-amplitude for the roll mode would seem adequate $\left(t_{1/2} \approx 0.6 \text{ second}\right)$, the pilots preferred that the roll damping be increased.

In order to make the lateral-directional handling qualities satisfactory, the following changes were required: (1) the static directional stability derivative C_{n_β} and the damping-in-yaw derivative C_{n_r} were doubled in order to improve the Dutch roll characteristics; (2) the rudder was driven in conjunction with the roll-control wheel $\left(\delta_r/\delta_w = -0.33\right)$ in order to improve the adverse yaw characteristics (note that the foregoing combination of the increased C_{n_β} and the driving of the rudder in response to wheel deflection also aided the turn coordination); and, finally, (3) the roll-damping derivative C_{l_p} was increased by 75 percent. With these modifications to the non-jet-flap airplane the average pilot rating of the lateral directional flying qualities was 3 to $3\frac{1}{2}$.

Piloting Techniques

As just discussed, the average pilot rating assigned to the flight characteristics of the augmented non-jet-flap airplane was 3 to $3\frac{1}{2}$ for both the longitudinal and the lateral directional axes when conventional cockpit controls were used to fly the landing approach. In order to determine the effects of having automatic speed control and the advantages of using symmetrical spoiler deflection for direct lift control on the pilot's ability to track the glide slope, these systems were incorporated.

The autospeed system used during the evaluation of the non-jet-flap configuration increased or decreased engine thrust as airspeed deviated from a desired value. (The gain for $\Delta T/\Delta V$ was 522 lbf (2322 N) per knot.) The pilots stated that the autospeed feature was very desirable because of the reduced pilot workload and the better speed control provided when flying the landing approach.

The spoilers were up-rigged 15° in order that they might be used for direct lift control, and this up-rigging of the spoilers caused the approach speed to be increased from 138 knots to 152 knots to maintain the same speed margin from the stall speed. Use of this DLC system, which was operated by a spring-centered thumb-control wheel located on the right yoke horn (see fig. 1(b)), improved the pilot's capability to make large and rapid flight-path changes. The pilots stated that this DLC system, in conjunction with the autospeed, was an excellent means of glide-path control, especially for the increased glide-slope sensitivity at the lower altitudes when small, rapid, and precise corrections are required. They also stated that this technique of tracking the glide slope takes all the pilot effort out of the longitudinal mode and assigned a pilot rating of 2 to the longitudinal flying qualities when this technique was used. The DLC system was also evaluated with the spoilers up-rigged 8°, but the effectiveness was so low that the pilots stated that the DLC could be used only for very small corrections to the glide slope.

RESULTS AND DISCUSSION

As stated previously, the two major objectives of the present study were to determine the overall low-speed flying qualities of the jet-flap configuration and to investigate the piloting problems and techniques for tracking the glide slope. The results of the investigation will be discussed in terms of these two objectives.

Flying Qualities

The dynamic-stability characteristics of the simulated jet-flap airplane $\left(\delta_{f1}/\delta_{f2} = 30^{\circ}/60^{\circ}\right)$ for stability augmentation off and on are presented in table V.

No stability augmentation.- The average pilot rating assigned to the longitudinal handling qualities of the unaugmented jet-flap configuration was $4\frac{1}{2}$, with the major objections being the sluggish initial pitch response and the difficulty in establishing a trimmed condition on the glide slope. Although the pilots complained about the sluggish initial response to column inputs and the poor thrust response to throttle inputs, the longitudinal maneuver characteristics were considered to be adequate for any normal situation encountered during the approaches. (For a steady pullup maneuver, δ_c/n is approximately 19 deg/g, and F_c/n is approximately 81 lbf/g (360 N/g).)

Sluggish initial pitch response is normally associated with poor short-period characteristics; however, as can be seen from table V, the short-period characteristics of this jet-flap configuration are approximately the same as those for the non-jet-flap configuration, which was also judged to be sluggish but satisfactory $\left(PR = 3\frac{1}{2}\right)$. In addition, the short-period characteristics of this jet-flap configuration compare favorably with the characteristics of present-day subsonic jet transports, which are normally considered to be satisfactory. (See fig. 7.) Therefore, the poorer pilot rating assigned to the jet-

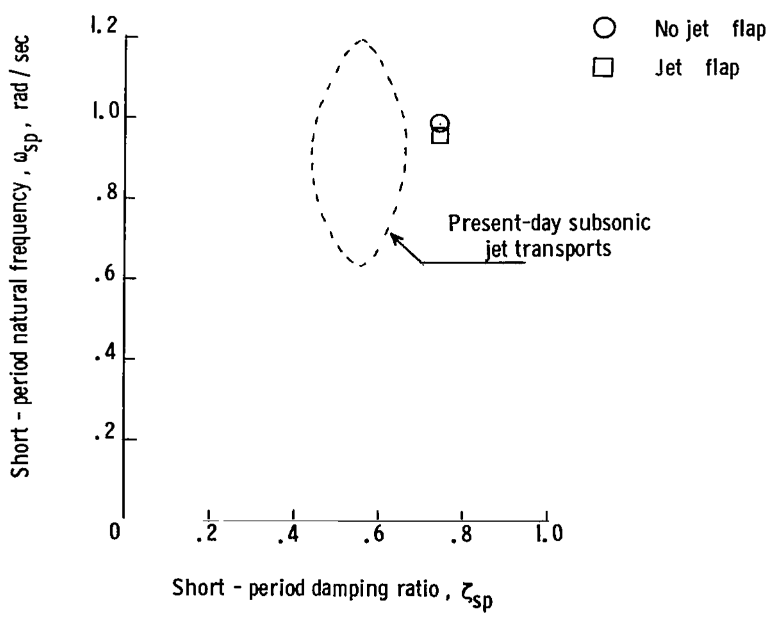


Figure 7.- Comparison of short-period natural frequency and damping ratio of the simulated airplane with that of present-day subsonic jet transports.

flap configuration $\left(PR = 4\frac{1}{2}\right)$ must result from characteristics other than the short-period mode, specifically, speed control, which was the other pilot complaint.

All of the pilots felt that the airplane response for increasing airspeed was poor, whereas the response for decreasing airspeed was good. It is believed that this was not only because of the engine response characteristics (fig. 2) but also was due to the fact that the jet exhaust was being deflected by the flap. Therefore, an increase in thrust gave less direct forward thrust and also induced additional lift with an accompanying increase in induced drag, which further reduced the net increase in forward force. Two additional factors probably affected the pilot's control of airspeed: operation on the backside of the "thrust-required curve" and pitch trim changes associated with thrust. For example, one pilot stated, "An increase in pitch attitude results in a higher sink rate, which would indicate your being on the backside of the thrust-required curve." He further stated, however, that since the pilot must fly a tight-loop control on this configuration anyway, his being on the "backside" did not create any additional problems. (The variation of thrust required with airspeed $\frac{\partial(T/W)}{\partial V}$ was approximately -0.0012 per knot at the approach speed of 106 knots.)

The pilots also complained about the pitch trim changes associated with thrust. For most large subsonic jet transports a slight noseup trim change is experienced with increased thrust; however, for this jet-flap configuration an increase in thrust has an opposite effect (nosedown for thrust increases). Ideally, the pilots would like to see no changes in pitch attitude associated with changes in thrust.

The conclusion is made that the poorer pilot rating assigned to the longitudinal flying qualities of this jet-flap configuration $\left(PR = 4\frac{1}{2}\right.$ compared with $3\frac{1}{2}$ for the non-jet-flap configuration$\left.\right)$ was due to the poorer speed-control capability rather than to any degradation in the short-period dynamic-stability characteristics.

An average pilot rating of $7\frac{1}{2}$ was assigned to the lateral-directional handling qualities, and the major objections were poor roll control, an unacceptable amount of adverse yaw, and poor Dutch roll characteristics and low directional stability. These three characteristics are examined one by one in the subsequent paragraphs.

Poor roll control: The pilots commented that the roll control was poor and that the inability to make precise bank-angle changes further degraded the already poor heading control. The roll-control power and sensitivity were said to be low. The initial roll response was said to be satisfactory; and this evaluation is supported by the data of table V which show that the roll-mode time constant t_R is less than 1 second. The longer term roll response was unsatisfactory, however, because of the high tendency for sideslip to develop in roll maneuvers, which in turn adversely affected the roll rate after a short period of time. An illustration of the lateral response characteristics of this unaugmented jet-flap configuration is shown in figure 8, where the roll rate, yaw rate,

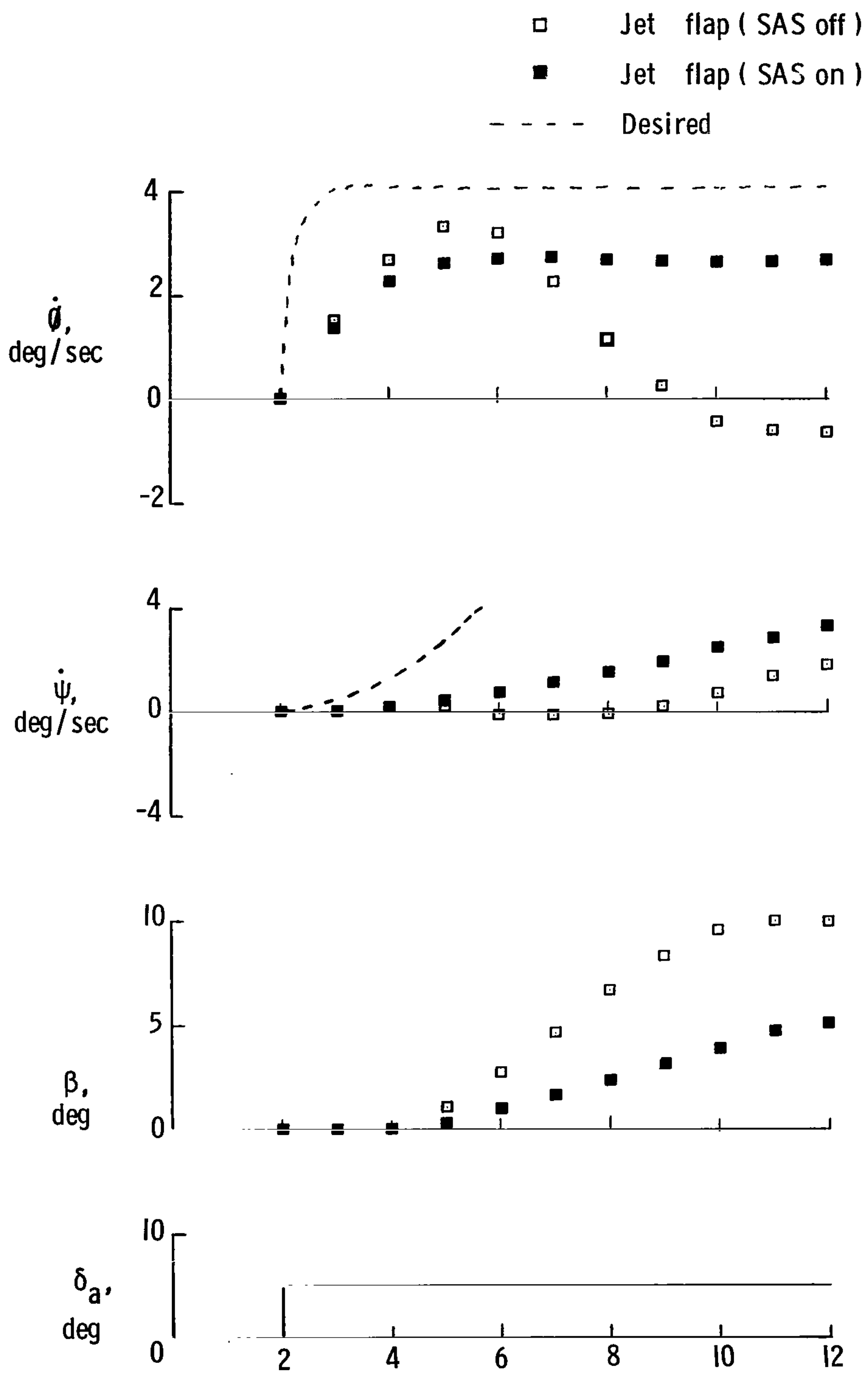


Figure 8.- Indication of sideslip, rate of change of heading, and roll-rate response to an aileron step input.

and sideslip response to an aileron step input are presented as a function of time. The desired response to a step aileron input, indicated by the dashed curves, should give an increase in roll rate to the maximum roll capability and at the same time the yaw rate should respond in the same direction without appreciable lag. For this unaugmented configuration, undesirable oscillations in roll rate as well as an appreciable lag in yaw-rate response were experienced.

Unacceptable amount of adverse yaw: The pilots also complained about the unacceptably high adverse yaw experienced with this configuration. As shown in table V, $\left(\omega_{\phi}/\omega_{d}\right)^2 \approx 0.330$, which indeed indicates very high adverse yaw.

Poor Dutch roll characteristics and low directional stability: The directional stability was low. The pilots stated that the Dutch roll was very easy to excite and, once excited, was practically impossible to control. Although the number of cycles required for the oscillation to damp to one-half amplitude was less than one, the pilots complained about the long period of the Dutch roll oscillation, which was greater than 13 seconds. The low directional stability is, of course, a major contributor to the turn-coordination problem. Figure 9 presents a plot of β_1/ϕ_1 against pilot rating, as taken from reference 5, and indicates the location of the subject jet-flap configuration $\left(\beta_1/\phi_1 = 0.88\right)$. It

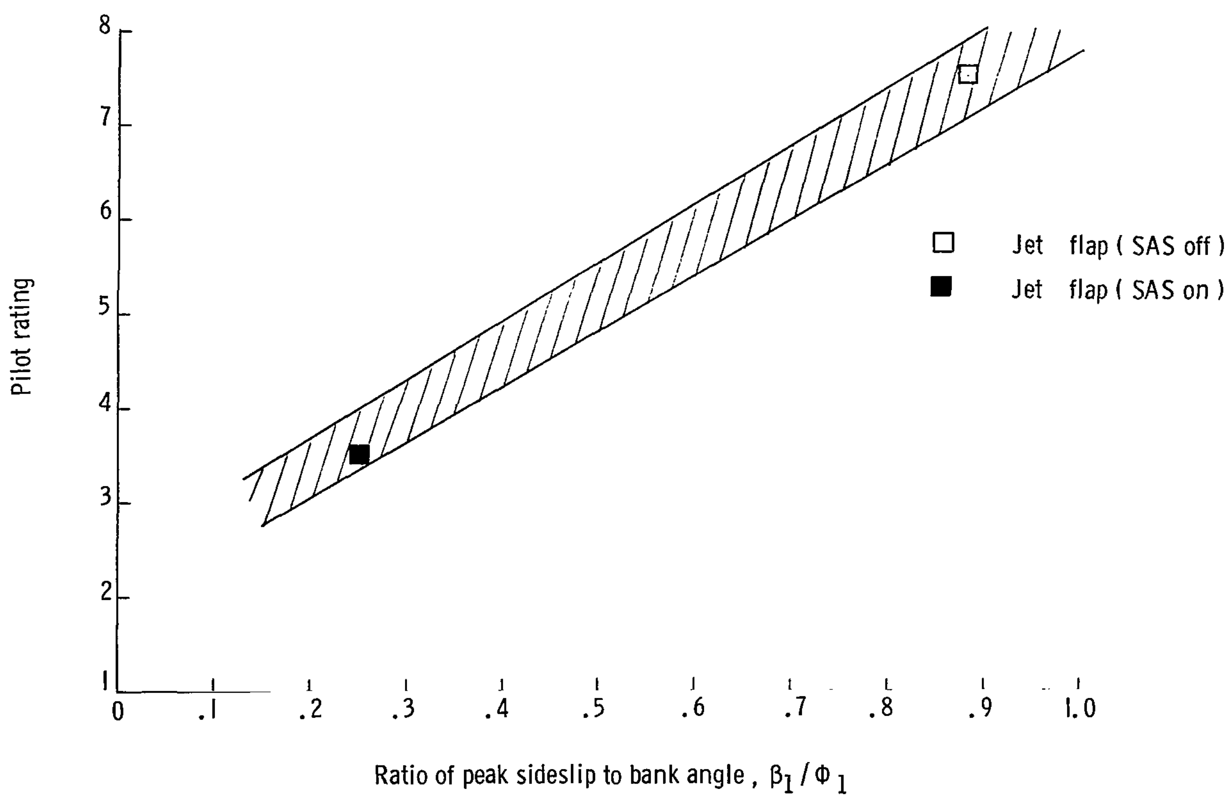


Figure 9.- Variation of pilot rating with ratio of peak sideslip to bank angle for turn entries. Boundaries are from reference 5.

can be seen that the pilots' evaluation of the lateral-directional characteristics of this airplane agrees very well with those of previous studies. It is also indicated in figure 9 that, in order for an airplane to have a satisfactory pilot rating, the value of β_1/ϕ_1 should probably be less than 0.30.

Figure 10(a) shows a typical ILS approach for the unaugmented jet-flap configuration. It can be seen that the pilot was working constantly in an attempt to remain on the glide slope and keep the wings level.

Stability-augmentation system on.- Since the lateral-directional handling qualities needed the most improvement for this jet-flap airplane, no longitudinal augmentation was incorporated until it was determined whether the pilot rating of $4\frac{1}{2}$ for the longitudinal characteristics would be improved with an improvement in the lateral-directional characteristics and the incorporation of an autospeed control system.

In order to make the lateral-directional handling qualities satisfactory, the following changes were necessary:

(1) The directional stability parameter C_{n_β} was increased by a factor of 5.

(2) A $\dot{\beta}$ damper was used that was equivalent to increasing $C_{n_{\dot{\beta}}}$ from 0 to 0.02 per radian.

(3) The damping-in-yaw derivative C_{n_r} was increased by a factor of 4.

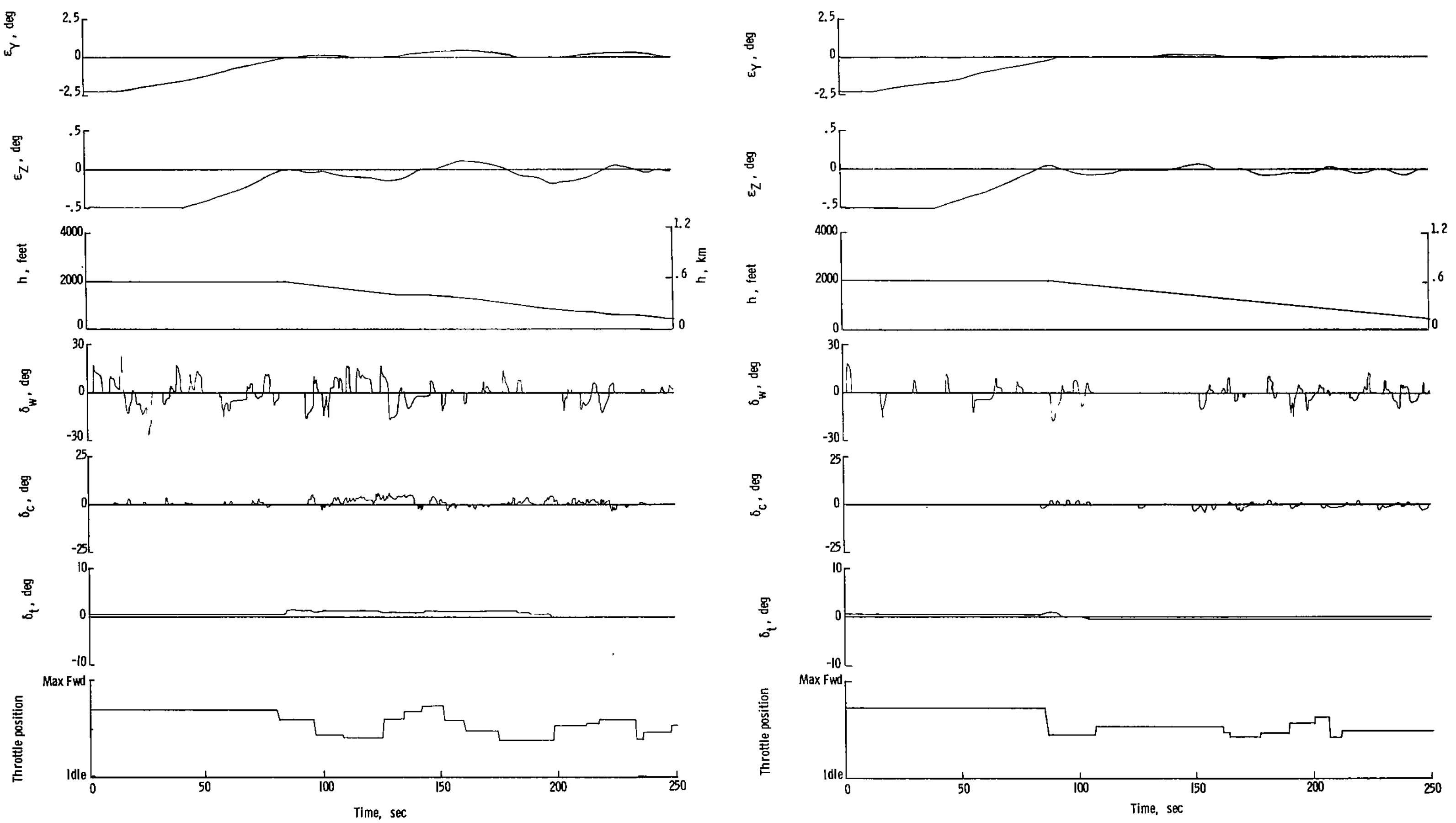
(4) A turn coordinator δ_r/δ_a was used that was equivalent to increasing $C_{n_{\delta a}}$ by a factor of 6.

(5) The damping-in-roll derivative C_{l_p} was increased by a factor of 2.5.

(6) The roll-control-effectiveness parameter $C_{l_{\delta a}}$ was increased by a factor of 2.

With these modified lateral-directional parameters, the average pilot rating of the lateral-directional handling qualities was $3\frac{1}{2}$, and the average pilot rating of the longitudinal handling qualities improved from $4\frac{1}{2}$ to between $3\frac{1}{2}$ and 4. The subsequent discussion is concerned with various effects of the stability-augmentation system.

All of the aforementioned changes in the effective derivatives were necessary to improve the objectionable characteristics of the unaugmented configuration; but, of all the changes, the effects of increasing the directional stability C_{n_β} were undoubtedly the most beneficial. Figure 11 presents C_{n_β} plotted against α for both the non-jet-flap and the jet-flap configurations for the unaugmented and augmented conditions. It may be noted that the non-jet-flap C_{n_β} curve was only doubled in order to attain satisfactory pilot ratings, whereas the jet-flap C_{n_β} curve was increased by a factor of 5. However, it can be seen from figure 11 that the resultant values of C_{n_β} are similar for both augmented configurations in the angle-of-attack range of interest ($\alpha = 0^\circ$ to 10°). It should also be mentioned that although this particular jet-flap airplane design experienced



(a) Unaugmented. (b) Augmented.

Figure 10.- Typical ILS approach on jet-flap configuration using conventional cockpit controls.

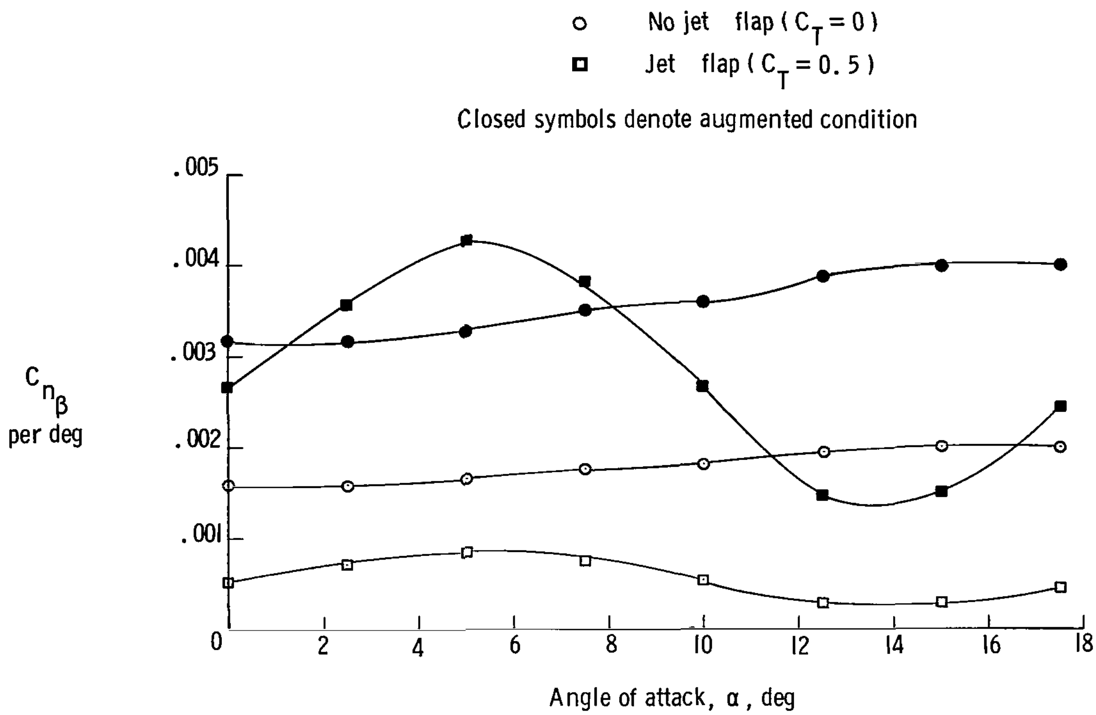


Figure 11.- Variation of static directional stability derivative with angle of attack.

a loss in C_{n_β} as C_T was increased, this change is not necessarily a characteristic of jet-flap airplanes. For example, it is shown in reference 6 that C_{n_β} increased as C_T was increased for the configuration of that study.

From figure 9 it can be seen that, as a result of the use of stability augmentation, the value of β_1/ϕ_1 has been decreased from 0.88 to 0.25 and the corresponding improvement in pilot rating is in agreement with the results of reference 5. In addition, as shown in table V, the use of stability augmentation increases the aileron yaw parameter $\left(\omega_\phi/\omega_d\right)^2$ from 0.330 to 0.980, thereby indicating that the very high adverse yaw to which the pilots objected for the unaugmented configuration has practically been eliminated.

The remaining major objection that the pilots had to the unaugmented jet-flap configuration, that is, poor roll-control characteristics, was also rectified by the stability-augmentation system. Actually, after the sideslip problem was reduced, most of the problems of roll control were eliminated. However, at the request of the pilots, the roll damping was increased and this change required that the roll-effectiveness parameter $C_{l_{\delta a}}$ be increased. Figure 8 compares the roll-response characteristics for the augmented and unaugmented jet-flap configurations and shows the marked improvement resulting from the use of the augmentation.

Typical ILS approaches for the unaugmented and augmented jet-flap configurations are presented in figure 10 and show that the pilot "flew" the localizer and glide slope much better and with much less control activity for the augmented condition.

Piloting Techniques

Throughout the study of the effects of various piloting techniques used in "flying" the landing approach on the jet-flap configuration the previously discussed lateral-directional augmentation was used.

Conventional controls.- The pilots commented that no unusual piloting techniques were required to fly the landing approach on this jet-flap configuration. Although simultaneous changes in both column and throttles were generally used to maintain the proper airspeed and keep the glide-slope error to a minimum, the piloting technique used to fly the approach was the same as that used for conventional airplanes and was, basically, as follows:

(1) When the glide slope was intercepted, the pilot used the pitch trim δ_t and column deflection δ_c to initiate and stabilize on the desired rate of descent.

(2) The column was then used to make small attitude corrections to remain on the glide slope.

(3) Throughout this sequence of events the throttles were used to control airspeed.

Figure 10(b) presents a time history of a typical ILS approach where conventional cockpit controls were used.

As mentioned previously, 200-foot (61-meter) vertical offsets from the glide slope were sometimes introduced, at random intervals, during the approach. By correcting for these offsets, the pilot was able to determine how quickly and easily each configuration could be returned to the desired flight path. The technique used to correct for these offsets was as follows:

(1) After the pilot was stabilized on the glide slope, the ±200-foot (61-meter) vertical offset was introduced.

(2) The pilot would then increase or decrease the rate of descent by approximately 500 ft/min (2.53 m/sec) by using the column, with a corresponding power correction. Then, he would intercept and capture the glide slope by again reestablishing the desired rate of descent.

(3) Once the pilot had restabilized on the glide slope the 200-foot (61-meter) offset was taken out, thus requiring the pilot to recapture the original glide path.

It was found to be more difficult to follow the glide-slope offsets on this jet-flap configuration than on the non-jet-flap configuration because of the previously mentioned speed-control problems experienced when the flaps were used to deflect the jet exhaust. Figure 12(a) shows how well the pilot followed the glide-slope command when using the column to correct for the ±200-foot (61-meter) vertical offsets. Figure 12(b) indicates the amount of time the pilot takes to reduce the rate of descent from approximately 560 ft/min (2.84 m/sec) to zero following a 200-foot (61-meter) offset by using the elevator. As can be seen, about 10 seconds is required.

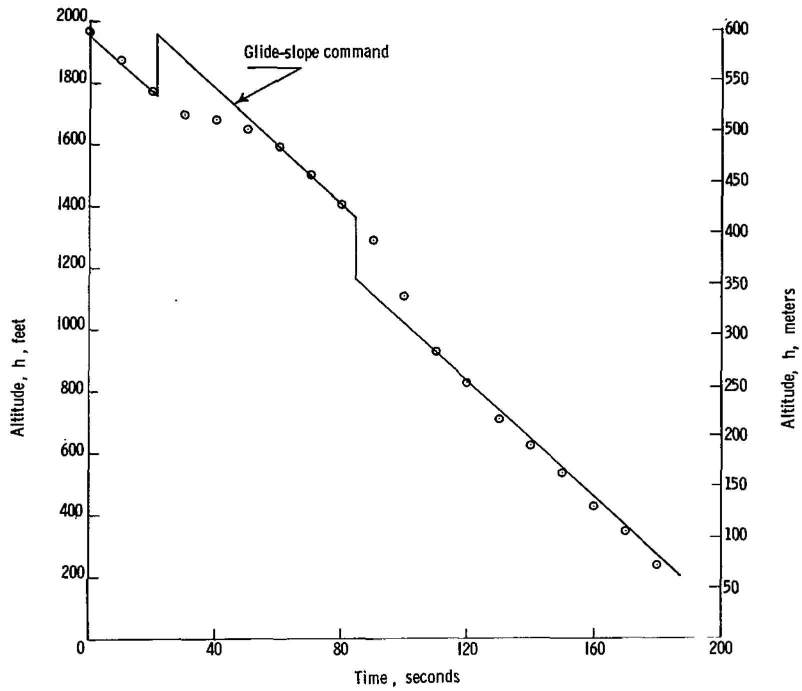
Figure 13(a) presents the maneuver range when the column is used to maneuver the airplane and indicates that a range of ΔC_L of ±0.5, which corresponds to an incremental normal acceleration greater than ±0.2g, could have been obtained. However, the pilot chose not to use the maximum allowable amount of column, or available Δa_n, in order to follow the offsets in glide slope. The pilots stated that the technique used for this maneuver was simply to achieve a value of $\dot{h}$ of near zero as soon as possible without overshooting. The pilot would deflect the column a small amount, wait to see what happened, and then either add to the column input or subtract from it in order to achieve near-zero rate of descent in the smoothest possible maneuver; and, as shown in figure 12(b), the pilots generally took about 10 seconds.

Conventional controls plus autospeed.- The autospeed system used during the evaluation of the jet-flap configuration consisted of driving the second segment of the double-slotted flap, hereinafter referred to as the vane, as a function of changes in airspeed (that is, $\delta_v/\Delta V$). It was also necessary to balance the pitching moments produced by deflection of the vane from its null position ($\delta_v = 60^{\circ}$), and this was done with an elevator-vane interconnect (that is, δ_e/δ_v). With this autospeed system and with the gains set at $\delta_v/\Delta V = \frac{6\text{ deg}}{\text{ft/sec}}\left(\frac{10\text{ deg}}{\text{knot}}\right)$ and $\delta_e/\delta_v = -0.25$, the airspeed variation was less than ±2 knots during the various maneuvers performed.

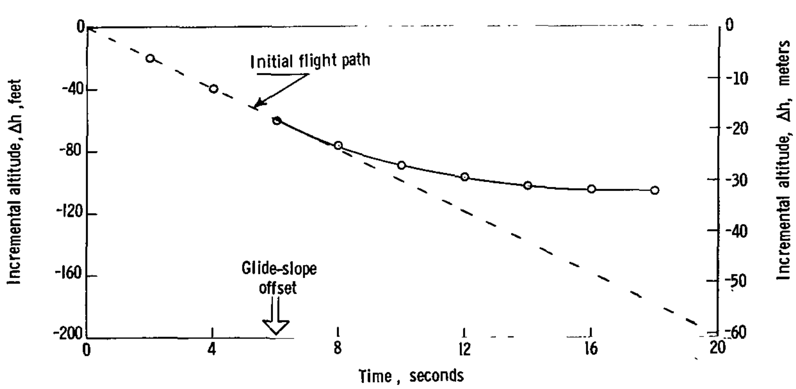
The pilots commented that this autospeed-control system was very beneficial in that it held the desired airspeed closer than they could by using the throttle and, of course, because the pilot workload was considerably reduced. The average pilot rating of the longitudinal control task was improved to 3; therefore, no longitudinal stability augmentation was used throughout this investigation.

Symmetrical vane deflection for DLC.- An attempt was made to use the second segment of the double-slotted flaps (δ_{f2} or δ_v) for direct lift control. In order to do this, the thrust was varied in conjunction with vane deflection $\Delta T/\delta_v$ in an attempt to balance the drag due to vane deflection and thus not allow the airspeed to vary when DLC was used. Tests were made both with and without use of the previously discussed autospeed system, $\delta_v/\Delta V$ and δ_e/δ_v.

When the autospeed system was not used, this DLC scheme was rated unsatisfactory. Because of the slow engine response (fig. 2), the thrust could not change fast enough to

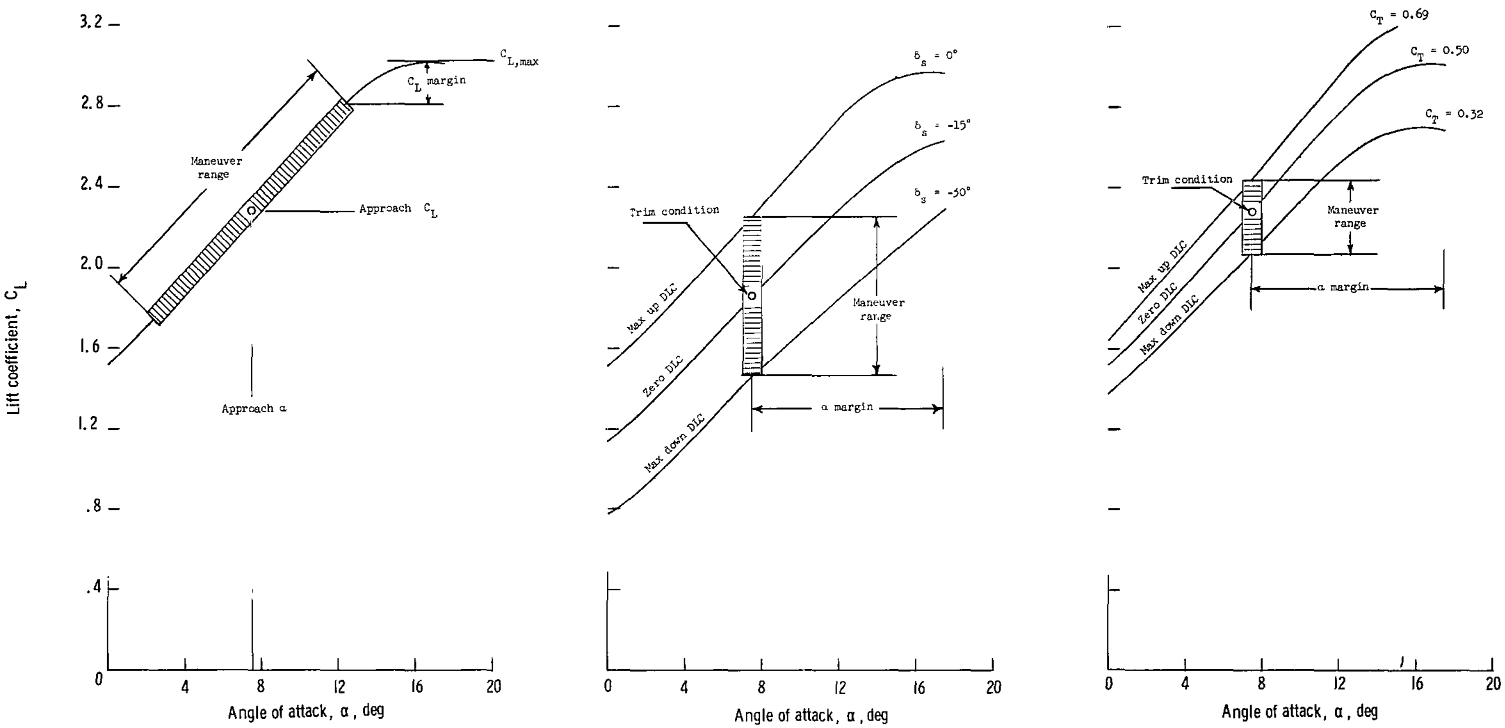


(a) Indication of how well pilot follows ±200-foot (±61-meter) offsets in glide slope by using elevator.



(b) Indication of time pilot takes to reduce rate of descent to zero by using elevator.

Figure 12.- Time history of pilot using elevator to track glide slope.



(a) Elevator for longitudinal control.

(b) Spoilers for direct lift control.

(c) Thrust modulation for direct lift control.

Figure 13.- Indication of longitudinal maneuver range when using various control techniques to track glide slope.

balance the drag created by the vane being deflected and, therefore, the airspeed varied considerably when DLC was used. The pilots also stated that the airplane response to this DLC system was much too slow, especially when an attempt was made to arrest the rate of descent. It was not surprising that the rate of descent could be increased faster than it could be decreased with this DLC system because the vane was actually as much a drag controller as a lift controller, as indicated by figure 14, and because the thrust

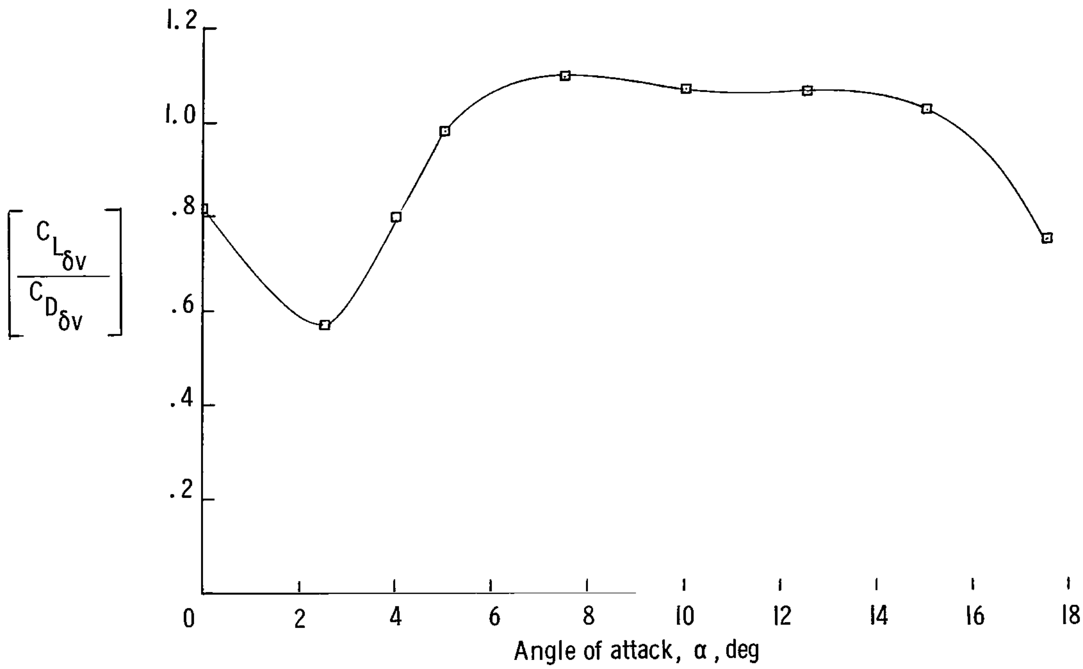


Figure 14.- Variation of incremental lift-drag ratio, due to vane deflection, with angle of attack. $C_T = 0.50$.

response accompanying vane deflection was much more rapid for decreasing thrust than for increasing it. The pilots stated that this DLC system was not satisfactory for large corrections to the glide slope, but that it might be acceptable for very small glide-slope corrections. When the airplane was flown in smooth air the pilots assigned pilot ratings of 3 to this DLC system at altitudes greater than 400 feet (122 meters) and of 6 at altitudes less than 400 feet (122 meters), where the glide-slope sensitivity increases and requires quicker airplane response. The pilots all agreed that they would prefer to fly the approach by using conventional controls rather than by trying to use this DLC system.

With the autospeed system being used in conjunction with the vane DLC system, the pilots had practically the same comments as when the autospeed was not used. A typical pilot comment was: "Although the autospeed controller keeps the airspeed variations within an acceptable limit when DLC is used, the response of the airplane to DLC inputs is still much too slow." (It should be noted that the autospeed system tended to cancel part of the δ_V deflections for DLC because of $\delta_V/\Delta V$ being used for speed control.)

Again, the pilots stated that they would prefer to use conventional controls rather than use this DLC system.

Symmetrical spoiler deflection for DLC.- As stated previously, with the spoilers closed $\left(\delta_s = 0^o\right)$ the approach airspeed for this jet-flap configuration was 106 knots compared with 138 knots for the non-jet-flap configuration, a difference of 32 knots. In order to use symmetrical spoiler deflections for direct lift control, however, the spoilers were up-rigged 15^o, which resulted in an increase in the approach speed from 106 knots to 118 knots.

The average pilot rating of the landing-approach task with this configuration and with spoilers used for DLC was 2. The response of the airplane to DLC inputs was said to be good. The pilots commented that it was very easy to make quick and precise corrections to the glide slope with this DLC system and that the benefits gained with this system offset the penalty of having to approach 12 knots faster.

The piloting technique used in flying the approach with this DLC system was as follows:

(1) After the glide slope was intercepted, the pilot used δ_t to initiate the rate of descent.

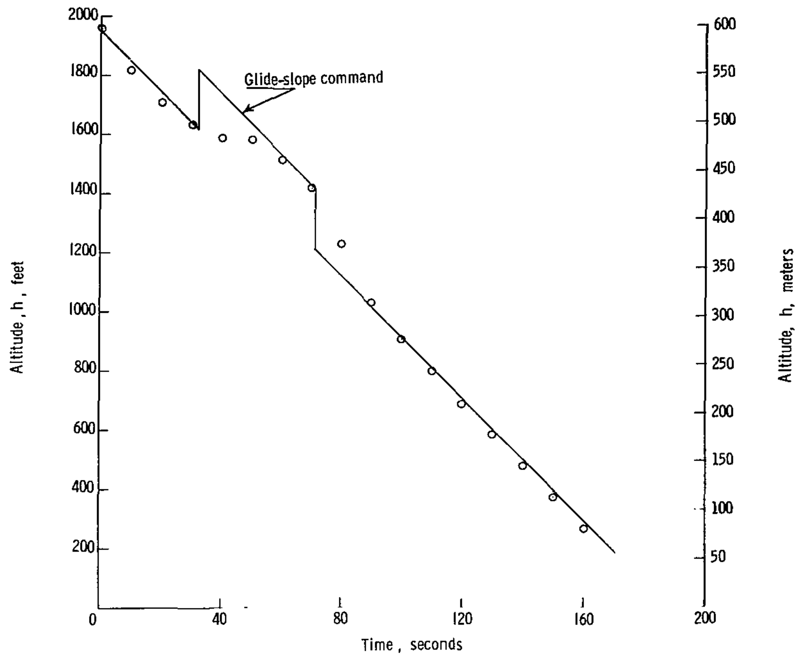
(2) He used a combination of δ_t and δ_c to stabilize near the correct rate of descent $\left(\epsilon_Z \approx 0\right)$.

(3) Then, he used only the DLC to make any further corrections to the glide slope.

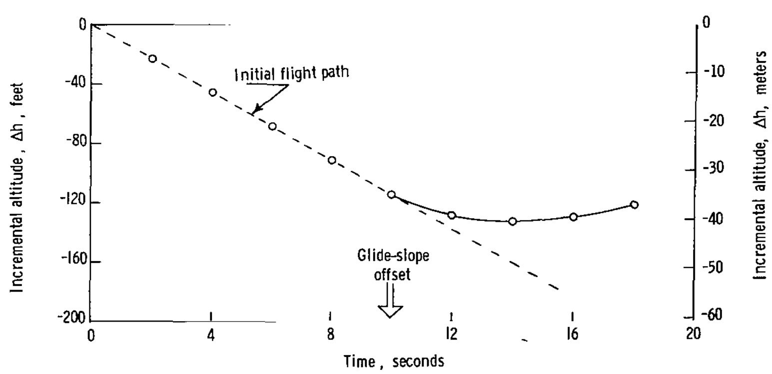
Figure 13(b) presents the maneuver range when 15^o of symmetrical spoilers are used for DLC, and it is indicated that an incremental normal acceleration of approximately $\pm 0.2g$ from trim was available. Figure 15(a) presents a typical time history of altitude variation as the pilot corrected for ±200-foot (61-meter) offsets in the glide slope by using spoilers for DLC. In addition, figure 15(b) indicates the amount of time the pilot takes to reduce the rate of descent to zero when correcting for a 200-foot (61-meter) offset in glide slope, and it may be seen that approximately 3.5 seconds were required which would indicate good control response with this DLC system.

Thrust modulation for DLC.- An attempt was made to use thrust modulation for direct lift control. In order to do this, the vane was deflected in conjunction with the thrust commanded by the DLC controller to balance the incremental drag due to thrust changes; also, the elevator was used in an attempt to balance any pitching moments due to DLC inputs. (The autospeed controller consisting of $\delta_v/\Delta V$ and δ_e/δ_v was not used in this instance.)

The average pilot rating assigned to this DLC system was $3\frac{1}{2}$. One pilot stated: "Although the 'power' of this DLC system is adequate, you have to anticipate making corrections to the glide slope since the response of the airplane to DLC inputs is slow.



(a) Indication of how well pilot follows ±200-foot (±61-meter) offsets in glide slope by using spoilers for DLC.



(b) Indication of time pilot takes to reduce rate of descent to zero by using spoilers for DLC.

Figure 15.- Time history of pilot using spoilers for DLC to track glide slope.

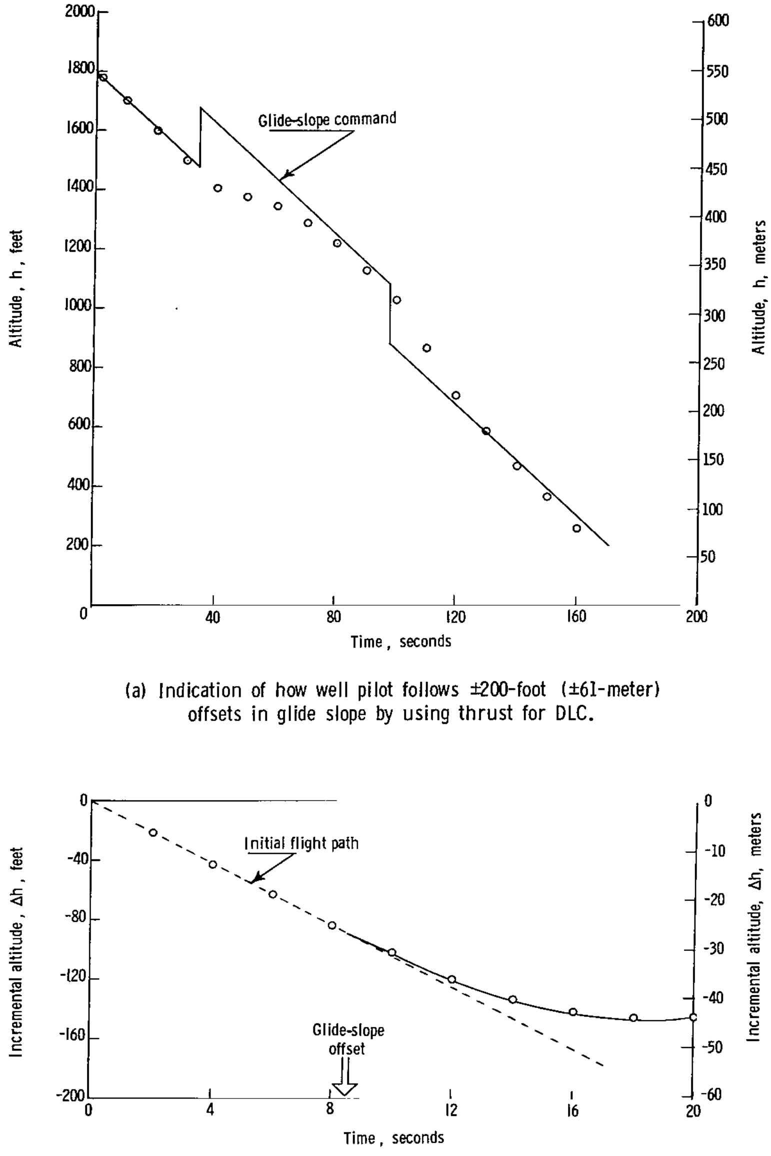
Actually, the response is quite good when attempting to increase the rate of descent by 500 ft/min (2.53 m/sec), but it is much less than desired when attempting to decrease the rate of descent by 500 ft/min (2.53 m/sec). The changes in airspeed and pitch attitude with DLC inputs are acceptable but both are more than desired. Although quite small changes in both airspeed and attitude are experienced when small corrections to the glide slope are made, for large corrections, where the DLC must be held in for a long time, the ΔV and $\Delta \theta$ become more than would be desirable."

When the autospeed control $\delta_V/\Delta V$ and δ_e/δ_V was used with this DLC system the average pilot rating assigned to the longitudinal-control task was $2\frac{1}{2}$ to 3. Again, the response for decreasing the rate of descent (positive increment in thrust) was said to be slow and not very precise. After a given rate-of-descent change from trim of 500 ft/min (2.53 m/sec) is achieved by using 100 percent DLC, about 50 to 75 percent of DLC is required to hold that rate of descent. The pilots commented that the pitch-attitude changes with DLC inputs were apparent but were not large enough to be bothersome. Also, the airspeed changes with DLC inputs were practically zero during the entire approach, even when correcting for the 200-foot (61-meter) glide-slope offsets. The pilots stated that the only objections to this DLC system, when used in conjunction with autospeed control, were the slow response of the airplane and the lack of precision when attempting to make corrections to the glide slope.

The reason for the slow response of the airplane to this DLC system is, of course, the slow response of the engine to thrust-change commands; and the engine response also accounts for the different response of the airplane to commands to increase or decrease rate of descent.

Figure 13(c) indicates the maneuver range of this DLC system. At an angle of attack of $7\frac{1}{2}^{\circ}$ the maneuver range indicates that a value of ΔC_L of approximately 0.19 can be achieved with 100 percent of DLC – which corresponds to an incremental normal acceleration of less than 0.10g, even if the incremental thrust commanded could be realized instantaneously. It should be mentioned that although the pilots thought the "power" of this DLC system to be adequate for the task they were performing, that is, flight on a 3° glide slope, they further stated that for glide-slope angles larger than 3°, the effectiveness of this DLC system would be considered marginally acceptable since 100 percent DLC changes the rate of descent by only ±500 ft/min (±2.53 m/sec).

In regard to the response of this DLC system, figure 16(a) presents a typical time history of altitude variations as the pilot corrected for ±200-foot (±60-meter) offsets in glide slope. Also, figure 16(b) indicates the time required to arrest the rate of descent when 100 percent of DLC is used. As can be seen from figure 16(b), approximately 9 seconds were required to obtain a value of $\dot{h}$ of zero. Although this length of time is approximately the same time that the pilots took to arrest the rate of descent with column (the pilot rating is the same as when the column was used), the pilots stated that they would prefer to "fly" the glide slope with this DLC system rather than with the column – the reason being the reduction in workload that the thumb-operated DLC system affords.



(a) Indication of how well pilot follows ±200-foot (±61-meter) offsets in glide slope by using thrust for DLC.

(b) Indication of time pilot takes to reduce rate of descent to zero by using thrust for DLC.

Figure 16.- Time history of pilot using thrust for DLC to track glide slope.

Summation of results obtained by using various piloting techniques to track the glide slope.- A comparison of the various piloting techniques used for tracking the glide slope may be obtained from the following descriptive summary and from the information presented in table VI:

TABLE VI.- ROOT-MEAN-SQUARE INFORMATION FOR ILS APPROACHES MADE ON JET-FLAP CONFIGURATIONS

Configuration	Pilot rating		Root-mean-square values of –				
	Longitudinal	Lateral directional	ϵ_Z	ϵ_h	ϵ_Y	V	a_n
Unaugmented	$4\frac{1}{2}$	$7\frac{1}{2}$	0.089	27.7	0.347	2.3	0.026
Augmented	$3\frac{1}{2}$ to 4	$3\frac{1}{2}$	0.072	19.6	0.071	1.9	0.023
Augmented and autospeed	$2\frac{1}{2}$ to 3	$3\frac{1}{2}$	0.059	20.8	0.083	1.7	0.016
Augmented, autospeed, and spoilers DLC (thumb)	2	$3\frac{1}{2}$	0.036	14.8	0.066	1.1	0.044
Augmented, autospeed, and thrust DLC (thumb)	$2\frac{1}{2}$ to 3	$3\frac{1}{2}$	0.052	20.0	0.098	1.6	0.019

(1) Conventional cockpit controls $\left(PR = 3\frac{1}{2} \text{ to } 4\right)$: The pilots experienced speed-control problems with this technique because of the slow engine-response characteristics and because the pitch trim changes associated with thrust, nose down for thrust increase, were in the opposite direction from those of most jet transports.

(2) Conventional cockpit controls plus autospeed $\left(PR = 2\frac{1}{2} \text{ to } 3\right)$: The pilots commented that the autospeed control system was very beneficial in that it held the desired airspeed closer than they could by using the throttle and, of course, the pilot workload was considerably reduced.

(3) Symmetrical vane deflection for DLC (PR = 6): The pilots stated that they would prefer to use conventional controls rather than use this DLC system because the response of the airplane to DLC inputs was much too slow.

(4) Symmetrical spoiler deflection for DLC (PR = 2): With this DLC system it was easy to make quick and precise corrections to the glide slope, and the pilots commented that the benefits gained with this system offset the penalty of having to approach 12 knots faster.

(5) Thrust modulation for DLC $\left(PR = 2\frac{1}{2} \text{ to } 3\right)$: Using this system was better than using conventional controls because of the reduction in pilot workload. However, the airplane response to this DLC system was slow because of the slow engine-response characteristics.

The information presented in table VI indicates the average of the pilot ratings assigned to the handling qualities of the jet-flap airplane when various piloting techniques were used to "fly" the landing approach; the root-mean-square (RMS) values of several pertinent parameters during the approach are also presented. (The RMS values indicated were calculated from the time the glide-slope signal was intercepted until the "flight" was terminated at an altitude of 200 feet (61 meters).) It can be seen from table VI that the precision with which the pilots could track the glide slope and localizer signals generally corresponds quite well with the pilot ratings assigned. For example, it is obvious that the pilots tracked the localizer and the glide slope much more closely for the augmented configuration than they did for the unaugmented configuration. It is also apparent that the pilots tracked the glide slope much more closely when spoilers were used for DLC, in conjunction with autospeed, than they did for any other system.

CONCLUSIONS

A fixed-base simulator study was conducted to determine the flying qualities and to investigate various piloting techniques for the instrument landing approach of a heavy subsonic jet-transport airplane with an external-flow jet-flap system used for additional lift. An important qualification on the results of the investigation is that the particular configuration studied had only the power normally installed in a subsonic jet transport and did not have extra power installed just for lift augmentation. The major significance of this qualification is that the reduction in approach speed from the use of the jet flap was modest (from 138 knots without jet-flap operation to 106 knots with jet-flap operation) and that the thrust vectoring by the flap system was much less than would be the case for a jet-flap STOL (short take-off and landing) airplane which would be expected to have considerable extra power installed just to produce additional lift. The conclusions of the present investigation are presented as follows:

1. The pilots commented that no unusual piloting techniques were required to "fly" the landing approach on the simulated external-flow jet-flap airplane.

2. Considerable stability augmentation was required before the lateral-directional handling qualities were rated as being satisfactory, and a similar result was obtained for the non-jet-flap configuration.

3. Using the autospeed control for both the jet-flap and non-jet-flap configurations was found to be very beneficial to the pilots in that the desired airspeed could be maintained more closely than by using the throttles, and the pilot workload was appreciably reduced.

4. No longitudinal-stability augmentation was required for the jet-flap configuration, or for the same configuration without the jet flap, when the lateral-directional axes were augmented and autospeed control was used. The nose-down pitching moments associated with an increase in thrust were in the opposite direction from those normally experienced on jet transports and were somewhat bothersome to the pilots.

5. The pilots were not disturbed by the fact that they were flying a powered-lift system (jet-flap configuration), which was operating on the backside of the power-required curve, when flying a glide slope of 3°.

6. The use of spoilers for direct lift control, in combination with autospeed control, was the most effective system evaluated for tracking the glide slope. Up-rigging the spoilers the required 15°, however, brought about a 12-knot increase in the approach speed.

7. Using thrust modulation for direct lift control, in combination with autospeed, was preferred over using the elevator to fly the glide slope, even though the thrust response was undesirably low.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., March 18, 1970.

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