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NASA RESEARCH ON STEEPENED APPROACHES FOR NOISE ALLEVIATION

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SUMMARY

The NASA, as part of the national effort to achieve noise reduction of modern aircraft, is conducting a study of the operating problems associated with the steepened approach path. To date, approach profile geometry, airplane type, navigational aids and pilot augmentation have been explored.

Considerable progress has been made in resolving the elements of a safe steep approach profile. Tests and analysis have indicated that a 6°-approach profile should be feasible, and -

1. The prime source of noise reduction is the power cutback to fly the steepened glide path and amounts to about 13dB in sound pressure level;

2. Pilot activity for glide path control can make a spread in noise level of 8dB for a nominal 6° approach;

3. Improved flight path control is required if steep approaches are to be made to low minimums of ceiling and visibility and to achieve reduced scatter about the lower noise level;

4. Improved engine response time would be a significant factor in assuring a safe steep approach;

5. Improved displays to guide the pilot through transition and flare will be needed.

INTRODUCTION

Studies of steep approach paths were initiated some four years ago in the interest of potential reductions in airspace and noise. The primary efforts have been aimed at the operating problems of accomplishing steep approach paths safely within the constraints imposed by the airplane, noise limitations and navigational equipment. The increased emphasis on noise abatement in the terminal area has intensified NASA efforts in regard to approach path operations and at the present time the current criterion is whether the steepened approach path technique will reduce approach noise.

The current studies are closely coordinated with the Federal Aviation Agency efforts and much of the present work could not be accomplished without material assistance in the form of test aircraft and crews. The approach has been that NASA efforts are in the area of defining problems and potential solutions with the advice of FAA and industry and that the FAA will develop and qualify the equipment, techniques and training procedures indicated by the research. If one considers the many ramifications involved in changing operating procedures it is obvious that the final solution must involve the best ideas and views of many interested groups.

At this time, many facets of the steep approach operations are under study but this paper will be confined primarily to the flight test results obtained to date. Current experience and views as to approach path geometry, aircraft capabilities, navigational aids and piloting techniques will be touched on. Since the report is one on progress of continuing effort, potential study areas and ideas will be indicated.

GENERAL CONSIDERATIONS

Noise.- The experimental data of figure 1 shows that for a representative jet transport the sound pressure level reduces almost linearly as the approach path is steepened from 3° to 6°. A reduction of about 13dB is obtained for constant speed approaches which involve reduced power as th approach angle is steepened. Figure 2 shows, however, that for constant thrust approaches at 3° and 6° the sound pressure level is reduced by about 6dB. The simple and obvious conclusion is that for the approach angles shown, the noise reduction is obtained primarily by reducing power and that the steeper approach path per se will not result in significant noise reduction.

On the basis of the preceding remarks, the problem evolves into developing safe paths and flight procedures for approaches at reduced power settings. The reduced power becomes the major constraint on the use of the steepened approach path and together with other constraints defines the limits of freedom in accomplishing the task. The second major constraint will be safe day-to-day operations by a pilot of average skill - a criterion difficult to define or evaluate.

Constraints.- Figure 3 is a listing of the constraints imposed on the task of flying steep approaches and the elements that can be varied to accom- [illegible] the task. There are other potential constraints such as engine-out flight, [illegible]., but these have not been considered in the exploratory work. [illegible]t, as previously mentioned, is that of commonality and compatibility with current aircraft and pilot skills. The elements that can be worked on are, of course, improvements to the aircraft and electronic and mechanical aids to the pilot. The variable of ceiling and visibility is based on the premise, with considerable justification, that increased ceiling and visibility can be traded for the potentially more difficult task of flying the steepened approach path.

Research variables.- The basic elements that appear amenable to research are:

a. The geometry of the approach path

b. The information type and form provided the pilot

c. The airplane and its associated automatic flight systems

The approach path configuration is significant in that changes in attitude or flight path must be within the capabilities of the airplane to maneuver and the ability of the average pilot to respond to the path commanded. The airplane capabilities are generally the outer physical limits that make success possible or impossible. The pilot capability will shrink the airplane limits due to response time and the amount of lead information provided.

The information to the pilot can take many forms, as in present systems, and old and new aids must be evaluated in the environment of the steep approach. It has been established many times by many investigators that the display and motion or noise cues can be the difference between a routine and impossible task.

The airplane and the various augmentation systems represent many methods of varying speed and flight path angle that can ease the pilot's task. Net drag can be varied by use of thrust and - reversers, spoilers, flaps and elevator, to name a few. The use of autothrottles, coupled autopilots and similar systems can simplify the control task when precision is required if such devices are on the particular aircraft. The aim is to explore these and other tools at our command to satisfy the constraints of the steepened approach path.

Research.- With the many variables involved, NASA has chosen a phased approach. The major phases are:

a. Preliminary flight and simulator studies such as reported in references 1 and 2, to become familiar with the task and the associated problems;

b. Exploratory tests to establish reasonable candidate approach paths, suitable research tasks, the capabilities of current aircraft and pilot navigational displays (radio control, cross pointers, attitude, etc.); (this phase is currently in progress and forms the basis of the present paper);

c. Analytical, aerodynamic and simulator studies on better methods of controlling speed, glide path and displays which are currently being implemented;

d. Flight evaluations or special tests of any improvements that may arise from either NASA or industry research.

As might be expected, these are parallel efforts. It should also be apparent that the noise reduction efforts by engine treatment are closely correlated with these studies.

APPROACH AND METHOD

At the present time, in consultation with FAA personnel, the candidate approach paths are a two-segment and a single-segment profile as shown on figure 4. The two profiles have their individual attractions. The two-segment approach has the apparent advantage that the final approach is along the standard 3°-glide path so that the final approach and landing maneuver is unchanged. Unless new equipment is developed, the two-segment approach will require an additional change in flight path at the 3° intercept and possibly two ILS beams. The single-segment approach is simpler to mechanize but will require a longer flare or perhaps a greater rotation of the aircraft. In the case of a rejected landing, the establishment of a positive rate of climb from a high rate of sink could require higher decision altitudes and increased concern for engine response. An added factor is that for a given approach speed, the higher sink rate of the steep approach will influence the effect of wind shear on the airplane. Current thinking is for the word "steep" to mean about 6°.

The NASA flight procedure being used varies somewhat, but the basic elements are:

a. Precision IFR task including glide-slope intercept with breakout at 200 feet;

b. Task evaluation with flight director and ILS needles as available in the cockpit;

c. Task evaluation with simulated autothrottle and split-axes autopilot;

d. Variation of 6/3 intercept from threshold to establish distance required for stabilization;

e. Effect of airplane configuration on task.

In general, preliminary tests are made at altitude to establish power levels and general characteristics that the pilots feel they can live with. All approaches are then made in VFR weather to permit the safety pilot to take over if required. On occasion, simulators have been utilized to check on procedures and airplane capability prior to flight tests.

SCOPE

The general characteristics of the airplanes used in the investigation are given in table I and table II. All aircraft except airplane B were turbine-powered while airplane B was piston-engine propeller aircraft of World War II vintage. Airplanes A and C were military fighter types that were available for preliminary studies. Airplane C was the more modern airplane with drag brakes and high power, including afterburning available to the pilot.

Airplanes A through D were utilized in preliminary studies to establish the task, equipment and problems that might be encountered. Airplanes E through G were thoroughly instrumented with control position recorders, glide-path indicators and standard motion recorders. The three aircraft were commercial four-engine jet transports and were flown in standard configuration.

While Flarescan-type equipment was utilized for preliminary path guidance (refs. 3 and 4), tests for all aircraft starting with D used a GSN-5 radar for approach guidance and position measurement (ref. 5). The majority of the tests have been made at the Chincoteague facility attached to the NASA Wallops Island Station. Early experience resulted in this location because of the difficulty in performing such tests from the runways of an active field such as Langley Air Force Base and some 90 approaches in three days have been performed at Chincoteague where the GSN-5 radar is located.

In most of the tests, research test pilots have been used as the basic subjects with pilots from airlines and the FAA being brought in as a cross check on the results. In the case of airplane D, a four-engine jet transport, restrictions required that the pilots be those of the contracting airline. It might be noted that a project pilot flies most of the approaches to obtain technical data on a consistent basis but other pilots are utilized to provide the practical viewpoints of operating personnel as to the findings.

Tables III and IV present a summary of the tests accomplished to date. While many of the variables such as mode of airplane control, are indicated; others such as the variation in flight-path configuration are not covered. Numerous short tests have been made to examine flare path geometry, transition geometry for two-segment profiles and segment length. In a progress report such as the present paper, it is not practical to include all of the detailed studies.

FLIGHT PATH GEOMETRY

Inspection of table IV indicates that all aircraft tested except airplane G negotiated the 6° single segment. The exception in the case of airplane G is that because of limited airplane availability, test runs could not be made, but it is highly probable that no difficulty would be experienced. Flight tests of airplanes A through D represent preliminary tests to establish methods and problems without particular regard to noise. In the case of airplane C, a military fighter, steeper glide slopes (9°) could be accomplished by means of the drag brake and the use of military power, a procedure not conducive to noise reduction. On the basis of the work to date, a single-segment 6° glide slope appears to be the highest common path that can be considered.

The sample time histories of figure 5 show that, for the 3° and 6° approaches, the pilot activity on the controls was about the same and was less than for the two-segment approach. Inspection of the elevator and throttle movements for the two-segment approach shows increasing activity starting at the transition from the 6° slope to the 3° slope. It would appear that the pilot effort to maintain speed and to stabilize on course for the new slope required almost constant adjustment of the elevator. It should be noted that all runs were below the nominal approach path.

The following figures represent vertical and lateral displacements in feet and angular deviations in degrees from the nominal glide slope and from the nominal course:

Figure 6.- Flight path deviations for airplane E at start of 3.5 sec/deg flare to touchdown from a 6° single-segment profile

Figure 7.- Flight path deviations for airplane F at start of 7.0 sec/deg flare to touchdown from a 6° single-segment profile

Figure 8.- Flight path deviations for airplanes E and G at completion of 3.5 sec/deg transition for a two-segment profile

Figure 9.- Flight path deviations for airplanes F and G at completion of 7.0 sec/deg transition

Figure 10.- Flight path deviations for airplanes E, F, and G, 5000 feet after glide slope capture

Figure 11.- Flight path deviations for airplanes E, F, and G at breakout to VFR conditions at 200 feet. Three degree single-segment profile, Section FF', $N = 40$

Figure 12.- Flight path deviations for airplanes E, F, and G, 5000 feet after 3° glide slope capture, Section GG', $N = 40$

Although the samples are small, the figures indicate that glide slope and course angular deviations were within 5° of the nominal for both the start of flare from the 6° single-segment and the end of transition for the two-segment approaches. Angular deviations were as much as 14° at 5000 feet beyond glide slope capture.

Inspection of many tracks such as shown in figure 5 indicate that the path is generally oscillatory in character with wave lengths of 5000 and 15000 feet so that the motion may be a characteristic of the airplane-pilot combination rather than an indication of action taken for course correction. In some cases plots made of aircraft deviation and velocity showed that the airplane was headed away from target position rather than back toward it. The short wave-length oscillation in both pitch and yaw appears to vary between pilots and could be pilot induced.

The study of rates of transition either from 6° to flare or 6° to 3° indicates a desired rate of change of about seven seconds per degree. While a rate of 3.5 seconds per degree can be negotiated, the pilots indicated that it was very difficult to track. For slower rates, say 14 seconds per degree, the transition was considered too long to be in a transitory flight condition without good reference. (Some pilots referred to the transition as "open loop" since the command indicators are flown but there is no way to cross check as to performance during the maneuver.)

For the two-segment transitions, it was found that the crews required at least 2.2 miles following transition to stabilize on the 3° glide slope. It is probable that a reasonable distance for stabilization would be at least 3 miles from touchdown and this of course means that, for this region, no noise reduction would be accomplished. Since quantitative criteria have not been established to date, and the amount of data is not sufficient for statistical confidence, firm conclusions must await further work.

Study of the vertical and lateral deviations for the "standard" 3° slope indicates about the same scatter as shown in figures 6 to 10. Figures 11 and 12 indicate that a possible exception is in the angular deviations from nominal glide slope where the maximum scatter is about $\pm 2^\circ$ at both the initiation of flare and glide slope acquisition. It would appear, therefore, that to date there is no significant difference in the flight path control for the 3° and 6° single-segment approaches. One might expect less vertical angular deviation since the pilots are performing a familiar task.

Study of the vertical and lateral deviations from flight path (figs. 6 through 10) indicate that in most cases the aircraft was below the glide path. Of the three jet transports, below profile characterized operations with two of the aircraft. The deviations plotted on figures 6 through 10 correspond to a line-of-sight deviation of about ± 0.2 degree for the three transition regions - glide slope acquisition, 6° to 3° transition, and flare. Laterally, the corresponding angular deviation was $\pm 2^\circ$. (These deviations should not be confused with the angles shown in figures 6 through 10 which represent the local flight path angles.)

AIRPLANE CHARACTERISTICS

Except for airplane B, the limitation on glide slope was set by available power settings and in a general sense, the crews selected power settings such that glide paths at least 2° steeper than nominal could be attained by setting the power at flight idle. Airplane B, a propeller-driven airplane, was the only aircraft that elicited adverse comments as to stability and control. Of the airplanes tested, airplane C, the fighter, enjoyed the best opinions due to the ability to use high power and drag, since these tests were made before the noise constraint was well defined. A strong impression is created that if engine response time could be reduced, the pilot task would be eased and his confidence increased in performing the steep approach.

A few flights were attempted on airplane F using the spoilers for flight path control but were not too successful. For these tests the spoilers are partially raised for the nominal flight path, and lift corrections were attempted by raising or lowering them. It was found that the characteristics were nonlinear in that the spoilers were quite effective in reducing lift and dropping the airplane but relatively slow and ineffective in increasing lift and raising the airplane. It appears from these few tests and general considerations that flight path control by direct action on wing lift rather than through use of the elevator and throttle will require special studies to be successful. Systems such as the Navy Direct Lift Control, reference 6, fall into this category when considered for use on large aircraft. Wind tunnel, simulator and flight studies are under consideration to study the application of direct lift principles to the steepened approach path.

No consideration was given to the use of drag devices or thrust reversers for approach path control since both methods violate the constraint of reduced power for noise reduction. From tests and studies to date, flight path modification methods appear to be limited to basic power settings and changes in lift to accomplish the task.

NAVIGATIONAL AIDS AND DISPLAYS

The three difficult regions are the glide slope acquisition, transition from 6° to 3°, and the flare. During these periods, comments of pilots indicated that lead information is needed for glide slope intercept, for the end of transition and start of flare. In many instances there was a marked over-all improvement in performance with a flight director, as compared to cross pointer information. During these transitory periods where nothing remains constant and the pilot must follow the command blindly, the feeling of insecurity deepens the longer the time period.

Studies and discussions indicate three approaches - a better display, special fan markers to signal the crew at critical points, and the possibility of spreading the beam at high altitudes to provide some lead on glide slope intercept. At this time little effort is being expended on this problem but a limited laboratory study of possible profile track displays is being developed. The many factors affecting the operation cannot be attacked simultaneously to manpower, money and equipment limitations.

For the straight segments of the approach, some of the pilots utilized the vertical speed indicator to assist in stabilization. Two pilots who initially had difficulty achieving stabilized flight from attitude and glide slope information were able to make excellent approaches by using the vertical speed indicator. How valid the vertical speed indicator will be in the general case has not been established but the characteristics of these indicators for both steady and maneuvering flight will require study to insure that they will contribute to a safe approach under all conditions.

AIRCRAFT SYSTEM AIDS

The preliminary studies indicate that the use of autothrottles and autopilot control of the lateral axis could result in significant improvements in pilot performance, but fully-coupled autopilots of current vintage are not adequate for controlling glide slope. Figure 13 shows sample approaches, fully manual, and with assistance from coupled modes. Inspection of figure 11 indicates a significant improvement in track for "split axes," that is, with the autopilot controlling the lateral-directional axes only, and, if anything, a degradation in performance for fully-coupled approaches. Discussions with aircraft personnel have indicated that the significant lack is in auto-pilot authority to negotiate the transition in glide slope. The study of autothrottles has been simulated by using the second pilot since the aircraft thus far incorporated in the NASA effort have not had autothrottles installed. In the two examples shown in figure 14, some improvement is indicated in the elevator trace due to an easing of the pilot task.

EFFECT OF PILOTING TECHNIQUE ON NOISE LEVEL

Control of an aircraft along the approach flight path involved control of deviations of airspeed from the target airspeed and of deviations of position, both vertical and lateral, from the flight path. The technique used in controlling these deviations with the use of the throttle, therefore, determines the variation in noise level produced along the ground track. For example, if frequent throttle adjustments are made to control the deviations to within small limits, the variation in noise level will be small. On the other hand, if the deviations are allowed to grow to large magnitudes before a correction is made, the variation in noise level can be large. For aircraft G, for example, an increase in thrust of 10,000 pounds can result in an 8dB increase in the sound pressure level. Such an increase in thrust could, therefore, essentially nullify the noise reduction obtainable through the use of noise abatement procedures at ground locations above which the large increases in thrust are made. Another example is illustrated in figure 15 where time histories of throttle position, lateral and vertical deviations from the flight path, and indicated airspeed are shown for two approaches for airplane E, under manual control. At the five-mile noise measuring station the thrust level for one of the approaches was sufficiently high to result in a 5dB-higher sound pressure level. At the three-mile station, the thrust and resulting noise level were practically the same.

In order to keep speed and position deviations to a minimum, and hence, avoid large variations in the sound pressure level, it appears desirable to make use of autothrottle and coupled approaches. For the noise abatement procedures, however, modifications are indicated in the autothrottle to allow operation over a wider range of thrust levels and in the autopilot to permit operation over a wider altitude range without recycling and, perhaps, with a greater force authority to allow negotiations of the transition for two-segment-type approaches. For manual control, improved guidance displays would be a necessity for the pilot.

GENERAL OBSERVATIONS

If steepened approach paths could be mechanized immediately, the work done to date indicates that minimum ceiling and visibility requirements would have to be increased. For rou ne operations, three improvements are indicated: better engine response, improved methods of flight path control, and improved displays of information to the pilot. While these observations represent an extrapolation of current work, consideration of the day-to-day environment, pilot training and experience, and airplane capability lend credence to the observation.

Experience indicates that the introduction of the steepened approach geometry into the terminal area would be an evolutionary process. The steps in implementation might be as follows:

1. Steepened approach path configuration usable with increased ceiling and visibility. If a two-segment approach were selected, the ceiling would be above transition maneuver from one glide slope to the other;

2. Improved displays and piloting techniques permitting lower minimums for two-segment approaches;

3 Single-segment to touchdown, constant approach speed and increased minimums;

4. Improved glide path and speed control permitting lower minimums;

5. Further refinement in approach techniques such as use of simultaneous altitude and airspeed bleed. This procedure may be found economically desirable to decrease approach time and increase block speed but will require considerable study before being classed as of a routine nature.

CONCLUDING REMARKS

The studies to date indicate that the 6° approach path at reduced power can reduce the approach noise of current jet transports by 13dB (sound pressure level). Particular features that have come to light are:

1. Unless the steepened glide path is accomplished by reducing power, the noise reduction does not appear significant.

2. The use of the throttle for glide path control should be a back up for a more direct method of controlling flight path.

3. Until better displays ("how goes it" information) are provided the pilot, operations involving transition from 6° to other slopes (including 0°) should be performed with adequate visibility and ceiling. The approach would be an instrument task bu visual contact would provide the pilot with situation information when needed.

4. Improved engine response would be of considerable assistance and may be required if lower ceilings are contemplated.

5. The single-segment approach appears to require less pilot effort than the two-segment path.

6. Unless piloting techniques can be consistently improved by training, improved control and displays, the power and flight path variations can negate the noise reduction over a given station, in many instances.

In conclusion, this progress report indicates that steepened approach paths are a feasible method of noise reduction but considerably more study and qualification of the task will be needed before it could be considered operational. As viewed at this time, the major obstacles are in the information provided the pilot, method of flight path control, and the problem of providing equivalent paths to those provided by the research radar equipment used in the tests.

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APPENDIX

SYMBOLS

γ	nominal glide slope angle, deg
γ_o	reference glide slope angle at any point along flight path, deg
γ_1	actual glide slope angle of aircraft, deg
ψ	actual angular deviation from reference course
X	horizontal distance from touchdown point
Y	lateral distance from reference course
Z	vertical distance from touchdown point
ΔY	course deviation; lateral displacement of aircraft from reference course
ΔZ	glide slope deviation; vertical displacement of aircraft from reference glide slope
δ_e	control column displacement
δ_a	control wheel displacement
δ_t	throttle displacement
N	number of data runs
V_{IAS}	indicated airspeed

ABBREVIATIONS

dots	indices of localizer and glide slope displacement display; full scale equal to 150 microamperes
SPL	Sound Pressure Level, decibels
VFR	Visual Flight Rules
IFR	Instrument Flight Rules
GS	glide slope
LOC	localizer

TABLE I.- GENERAL CHARACTERISTICS OF AIRPLANES USED IN TESTS

Airplane	Propulsion		Power plant		Maximum gross	Wing area, ft^2 (m^2)	Wing span, ft (m)	Guidance display	
	Type	No. of engines	Max. thrust/eng., lb (N)	Max. power/eng., hp (kW)	Weight, lb (Mass, kg)			ILS	Flt. Dir.
A	Turbojet	1	5,200 (23,129)	---	11,965 (5420)	237 (22)	39 (11.87)	GS/LOC	---
B	Piston	2	---	1200 (895.2)	31,000 (14043)	987 (91.8)	95 (28.9)	GS/LOC	---
C	Turbojet	1	10,900 (48,483)	---	27,000 (12231)	662 (61.5)	38 (11.58)	GS/LOC	---
D	Turbofan	4	18,000 (80,064)	---	315,000 (142,695)	2868 (267)	142 (43.2)	GS/LOC	LOC
E	Turbojet	4	11,650 (51,819)	---	193,000 (87,429)	2000 (186)	120 (36.5)	GS/LOC	LOC
F	Turbofan	4	16,100 (71,612)	---	244,000 (110,532)	2250 (209)	120 (36.5)	GS/LOC	LOC
G	Turbojet	4	12,000 (53,376)	---	203,000 (91,959)	2433 (226)	131 (39.8)	GS/LOC	GS/LOC

TABLE II.- OPERATING CONDITIONS

Airplane	Flaps, deg	Weight, lb (Mass, kg)	Stall speed, knots	Approach speed, knots	Glide slope, deg	
					Limit	Operational
A	45	11,000 to 13,000 4983 to 5889	90 to 97.5	115 to 120	**9	6
B	45	24,700 to 31,000 11,189.1 to 14,043	56.5 to 62.9	75 to 85	10	6
C	No flaps	23,000 to 24,000 10,419.0 to 10,872.0	*115 to 135	160 to 180	Above 9	Above 7
D	50	164,000 to 203,500 74,292.0 to 92,185.5	91 to 101.5	130 to 150	Not determined	6
E	44	112,000 to 158,000 50,736.0 to 71,574.0	92.3 to 110	130 to 153	7	6
F	50	149,400 to 195,200 67,678.2 to 88,425.6	101 to 117	143 to 164	8	6
G	50	121,500 to 181,000 55,039.5 to 81,993.0	82.1 to 99	117 to 137	9	6

*Minimum speed at which altitude may be maintained: military power, 115 knots; maximum power, 135 knots.

**At 150 knots.

Table III.- Summary of Preliminary Exploratory Tests

Airplane	Profile description	Glide slope, deg.	VFR	Simulated IFR	Number of runs
A	Single-Segment	9		x	6
		8		x	6
		7		x	6
		6		x	49
		2.5		x	40
Total					107
B	Single-Segment	10	x		1
		9		x	3
		8		x	3
		7		x	3
		6		x	54
		2.5	x		1
		2.5		x	20
Total					85
C	Single-Segment	9	x		1
		9		x	4
		7	x		2
		7		x	5
		5	x		2
		5		x	11
		3		x	4
Total					29
D	Single-Segment	6	x		7
		6		x	23
		5	x		1
		5		x	4
		4	x		1
		4		x	3
		3	x		3
		3		x	5
Total					47

TABLE IV.- SUMMARY OF CURRENT EXPLORATORY TESTS

Airplane E

Profile description	Glide slope, deg	VFR	Simulated IFR	Control mode		Throttle control			Flare rate, sec/deg	No. of runs
				Manual	Coupled	Manual const. speed	Sim. auto const. speed	Manual const. thrust		
Single-segment	3	x		x		x			3.5	2
	3		x	x		x			3.5	14
	3		x		complete	x			3.5	4
	4		x	x		x			3.5	4
	5	x		x		x			3.5	1
	5		x	x		x			3.5	7
	6	x		x		x			3.5	2
	6		x	x		x			3.5	8
	7	x		x		x			3.5	1
	7		x	x		x			3.5	2
Two-segment, 1.5 n. mi. intercept	6-3		x	x		x			3.5	11
	6-3		x		simulated split axes	x			3.5	2
	6-3		x	x				x	3.5	5
	6-3		x	x			x		3.5	8
	6-3		x		complete	x			3.5	8
	6-3		x		complete			x	3.5	3
Two-segment, 2.2 n. mi. intercept	6-3		x	x		x			3.5	9
	6-3		x	x			x		3.5	11
Two-segment, 3.0 n. mi. intercept	6-3		x	x		x			3.5	10
	6-3		x	x			x		3.5	14
	6-3		x		complete		x		3.5	10
									Total	136

TABLE IV.- SUMMARY OF CURRENT EXPLORATORY TESTS - Continued

Airplane F

Profile description	Glide slope, deg	VFR	Simulated IFR	Control mode		Throttle control			Flare rate, sec/deg	No. of runs
				Manual	Coupled	Manual const. speed	Sim. auto const. speed	Manual const. thrust		
Single-segment	3		x	x		x			3.5	12
	3		x	x			x		3.5	1
	4	x		x		x			3.5	1
	4		x	x		x			3.5	4
	5		x	x		x			3.5	4
	6	x		x		x			3.5	2
	6		x	x		x			3.5	11
Two-segment, 1.5 n. mi. intercept	5-3	x		x		x			7.0	3
	5-3		x	x		x			7.0	35
	5-3		x	x			x		7.0	2
	6-3	x		x		x			7.0	2
	6-3		x	x		x			7.0	29
	6-3		x	x			x		7.0	9
	6-3		x	x		x			5.5	4
	7-3	x		x		x			7.0	1
	8-3	x		x		x			7.0	2
Two-segment, 2.2 n. mi. intercept	6-3	x		x		x			7.0	5
	6-3		x	x		x			7.0	30
	6-3		x	x			x		7.0	11
	6-3		x		complete	x			7.0	1
									Total	169

TABLE IV.- SUMMARY OF CURRENT EXPLORATORY TESTS - Concluded

Airplane G

Profile description	Glide slope, deg	VFR	Simulated IFR	Control mode		Throttle control			Flare rate, sec/deg	No. of runs
				Manual	Coupled	Manual const. speed	Sim. auto const. speed	Manual const. thrust		
Single-segment	3	x		x		x			3.5	12
	3		x	x		x			3.5	12
Two-segment, 1.5 n. mi. intercept	5-3	x		x		x			7.0	2
	5-3		x	x		x			7.0	8
	5-3		x	x			x		7.0	4
	7-3	x		x		x			7.0	3
	8-3	x		x		x			7.0	3
	9-3	x		x		x			7.0	1
Two-segment, 2.2 n. mi. intercept	5-2.5	x		x		x			7.0	2
	5-2.5		x	x		x			7.0	9
	5-2.5		x	x			x		7.0	6
	6-3	x		x		x			7.0	4
	6-3		x	x		x			7.0	12
	6-3		x	x			x		7.0	8
	6-3		x	x		x			5.5	6
	6-3		x	x		x			3.5	6
	6-3		x		complete	x			7.0	1
									Total	99

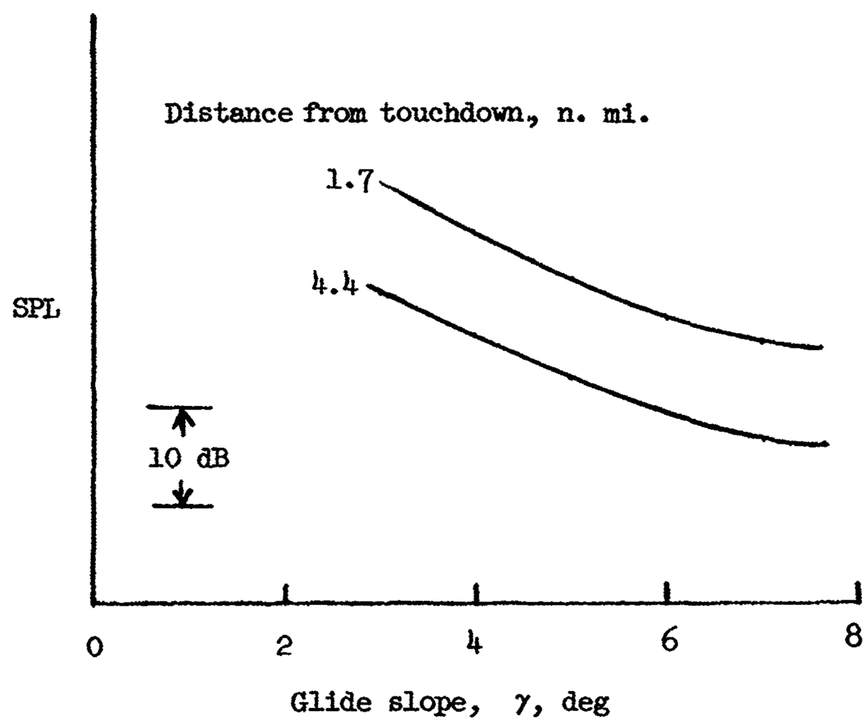


Figure 1.- Variation of sound pressure level with glide slope at ground stations 1.7 and 4.4 nautical miles from touchdown. Single-segment, constant-speed approaches.

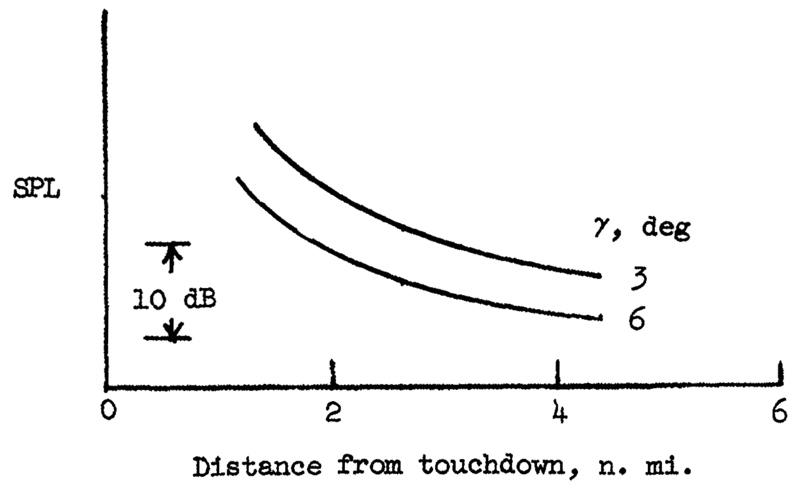


Figure 2.- Variation of SPL with distance from touchdown for single-segment approaches for same thrust on 6° as on 3°.

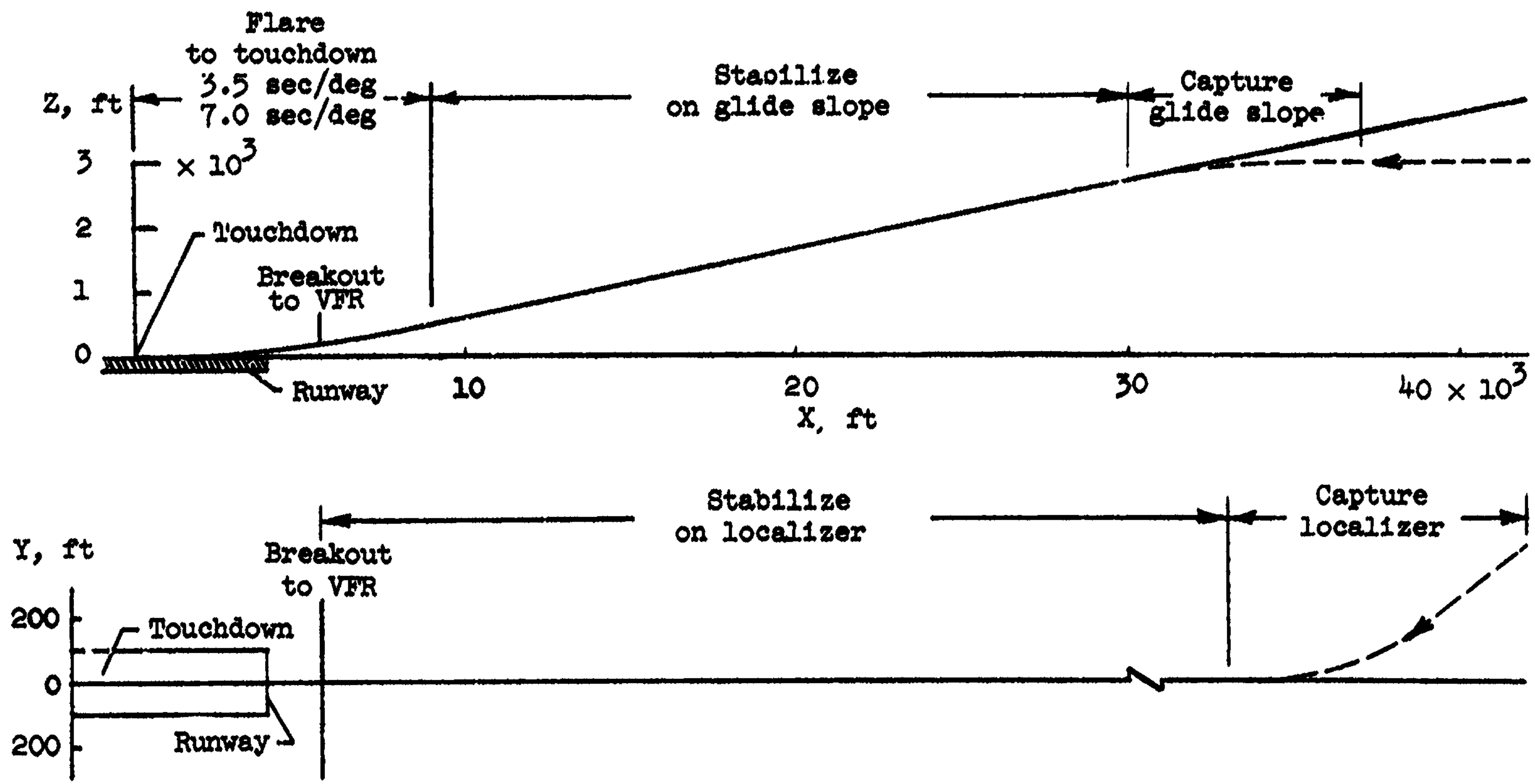
CONSTRAINTS:

Reduced power
Aircraft compatibility
Approach speed
Common approach path
Pilot skill
Stability and control

VARIABLES:

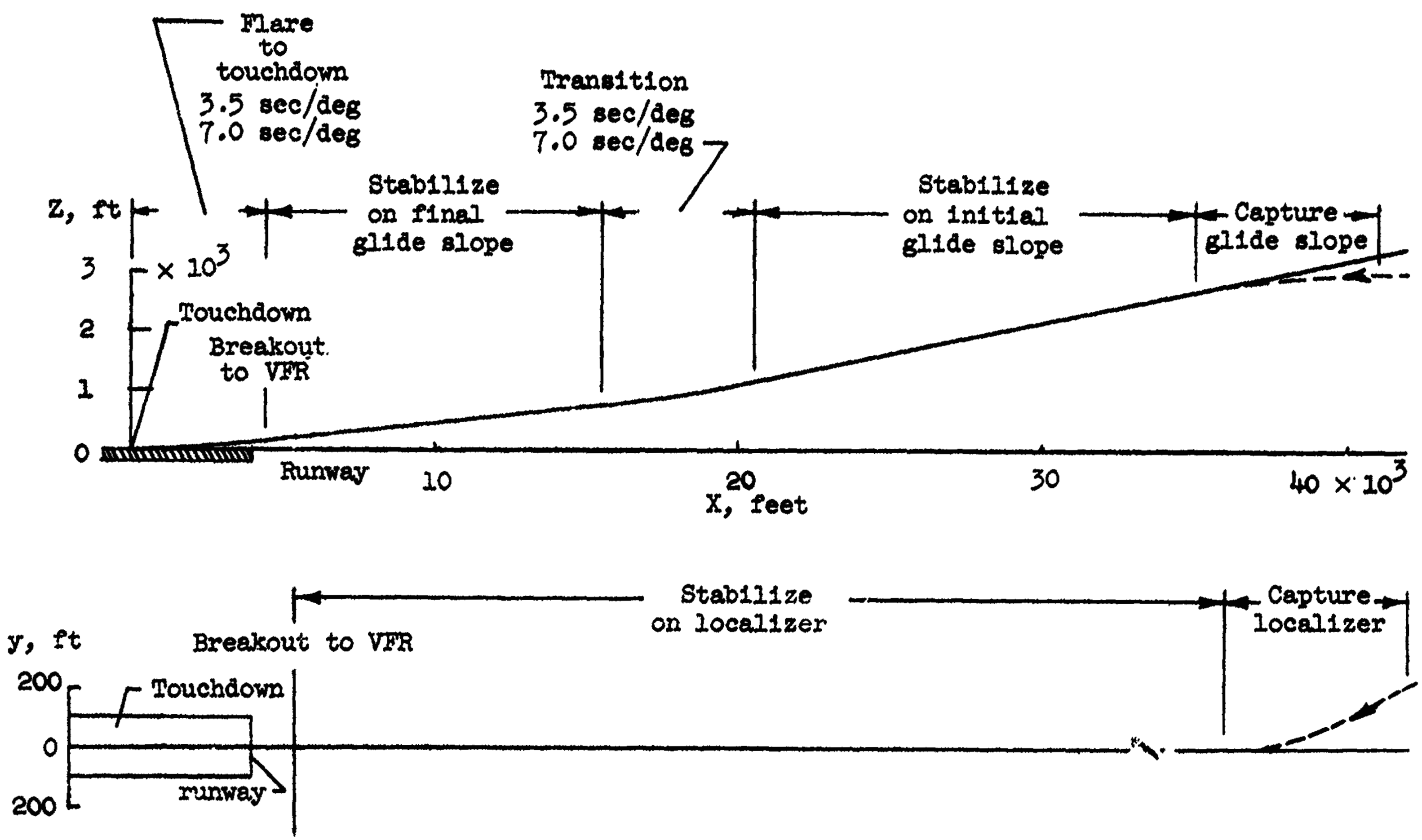
Navigational aids
Configuration changes for flight
path control
Autothrottle
Autopilot - Autoland
Ceiling and visibility

Figure 3.- Constraints and variables involved in flying steep approaches.



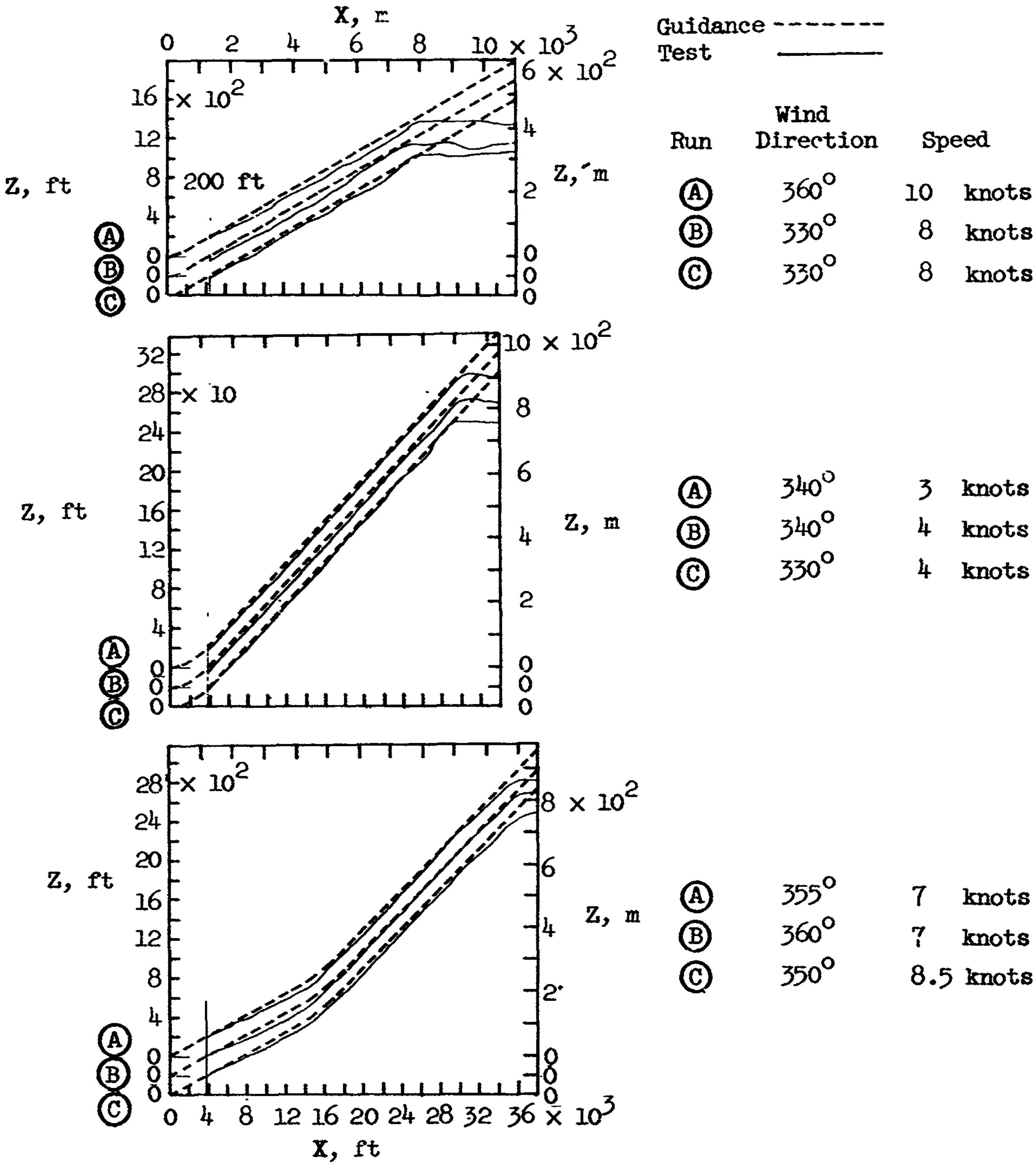
(a) Single-segment profile.

Figure 4.- Noise-abatement profiles.



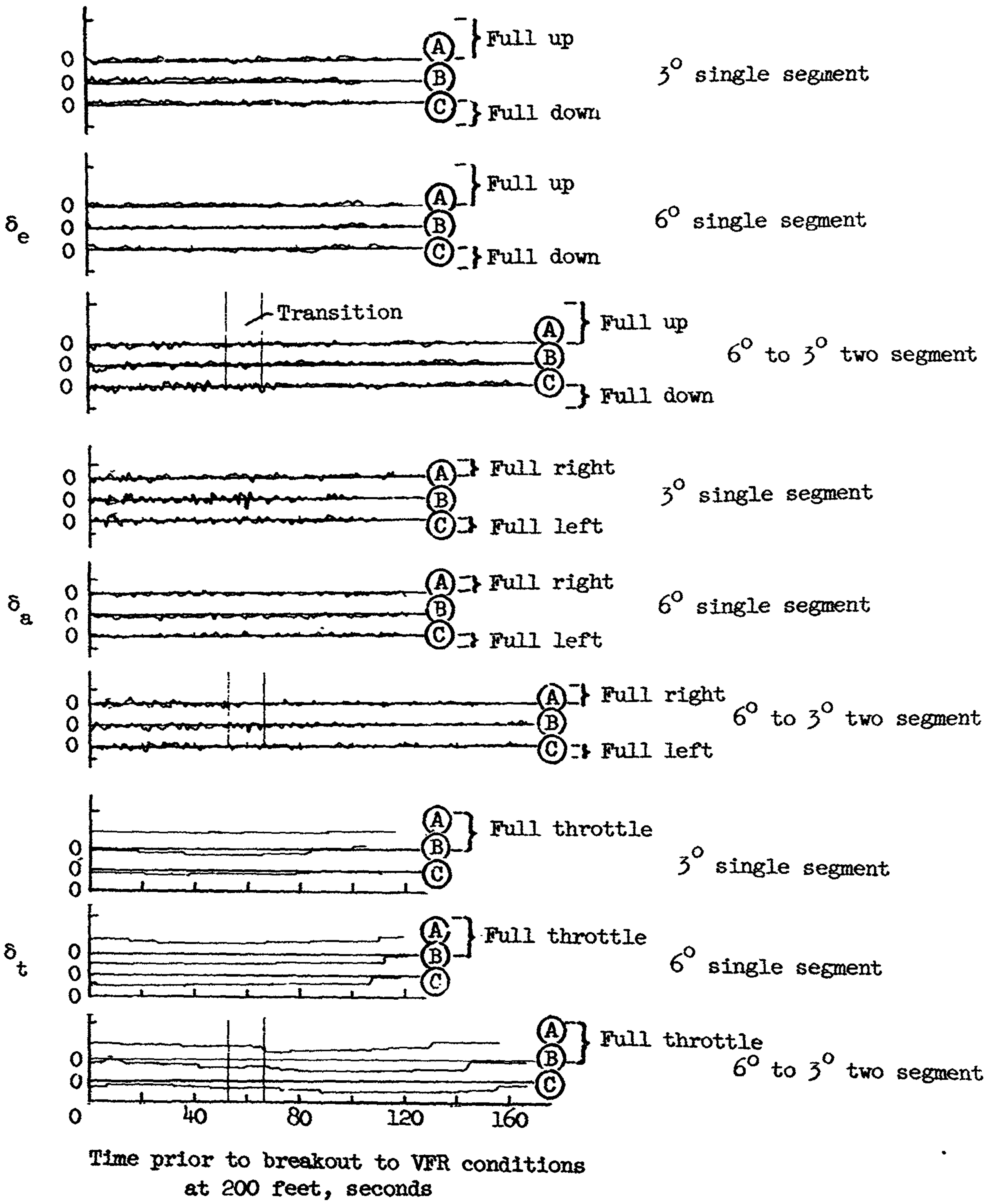
(b) Two-segment profile.

Figure 4.- Concluded.



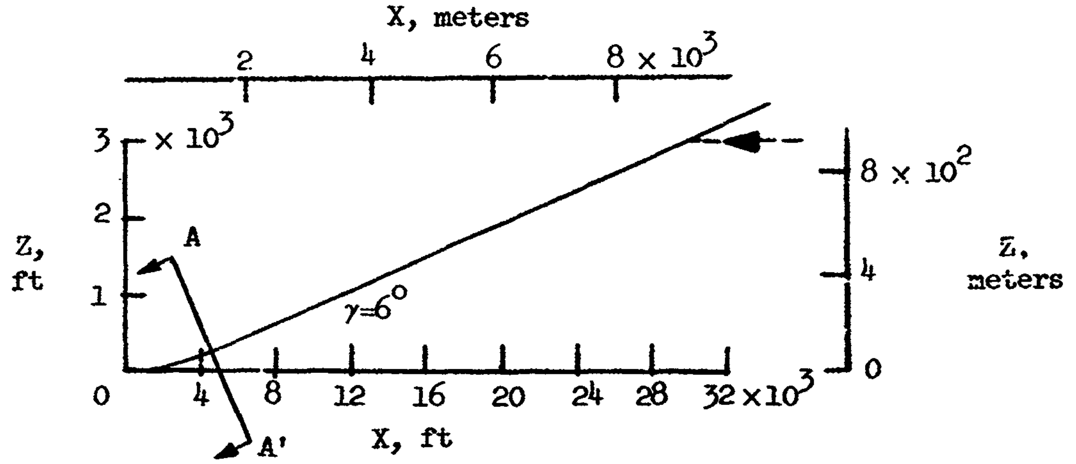
(a) Elevation profiles; approaches to runway 10. Breakout to Visual Flight Rule (VFR) conditions at 200 feet. Constant speed; manual operation of flight controls and throttles.

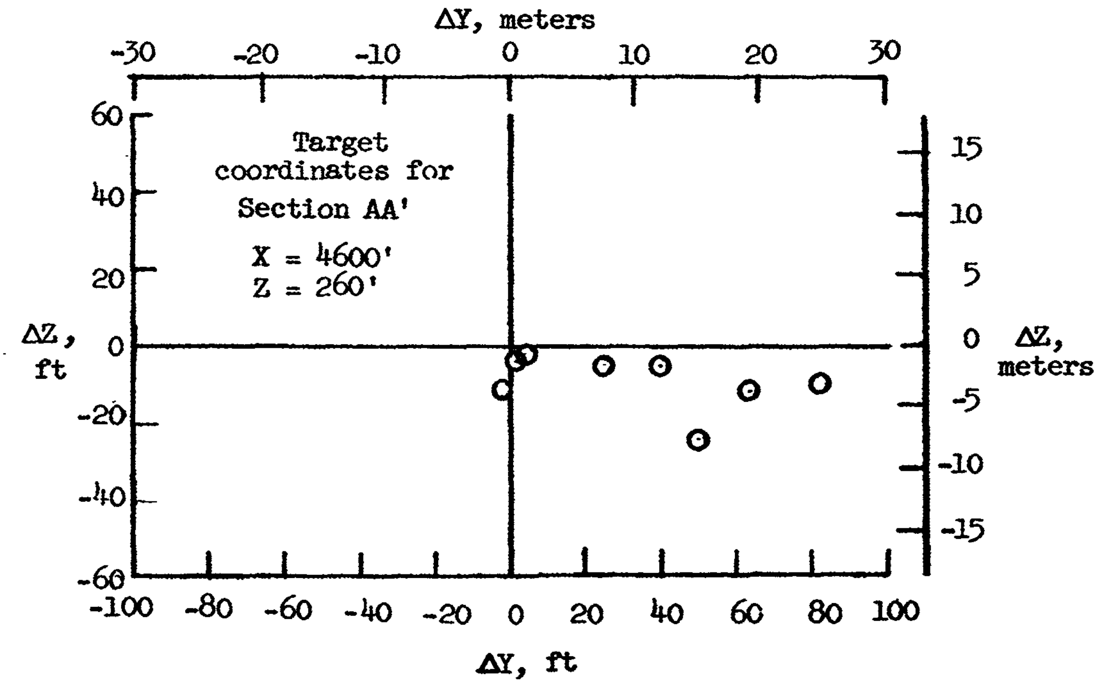
Figure 5.- Performance and pilot control inputs on typical conventional noise-abatement profiles.



(b) Time histories of pilot control inputs.

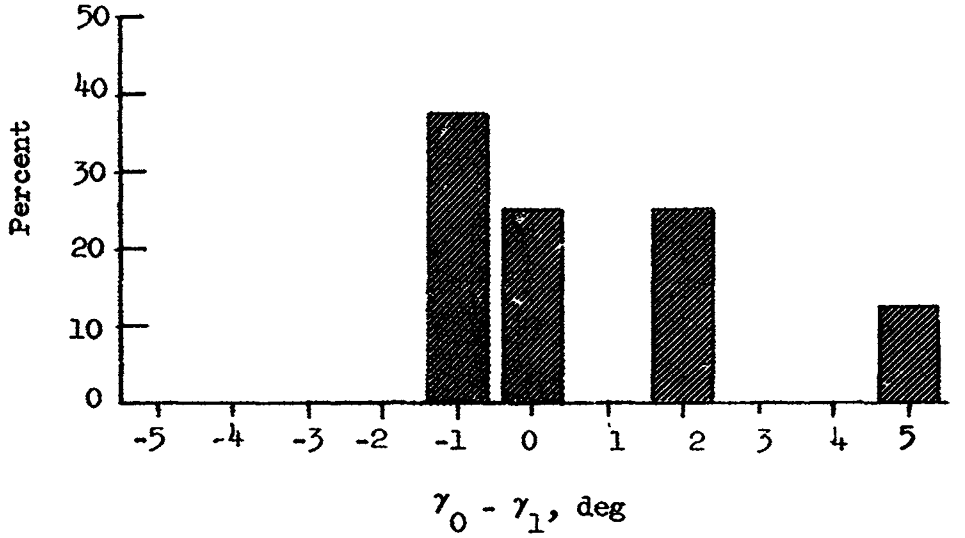
Figure 5.- Concluded.



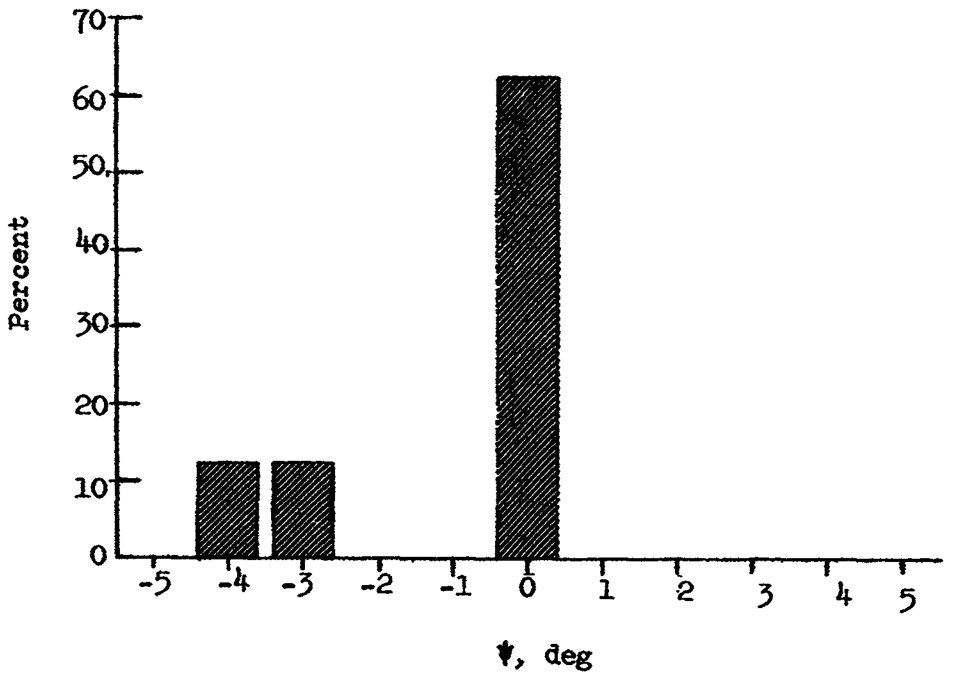


(a) Vertical and lateral displacements.

Figure 6.- Flight-path deviations for airplane E at start of 3.5 sec/deg flare to touchdown from 6° single-segment profile, Section AA', N = 8.

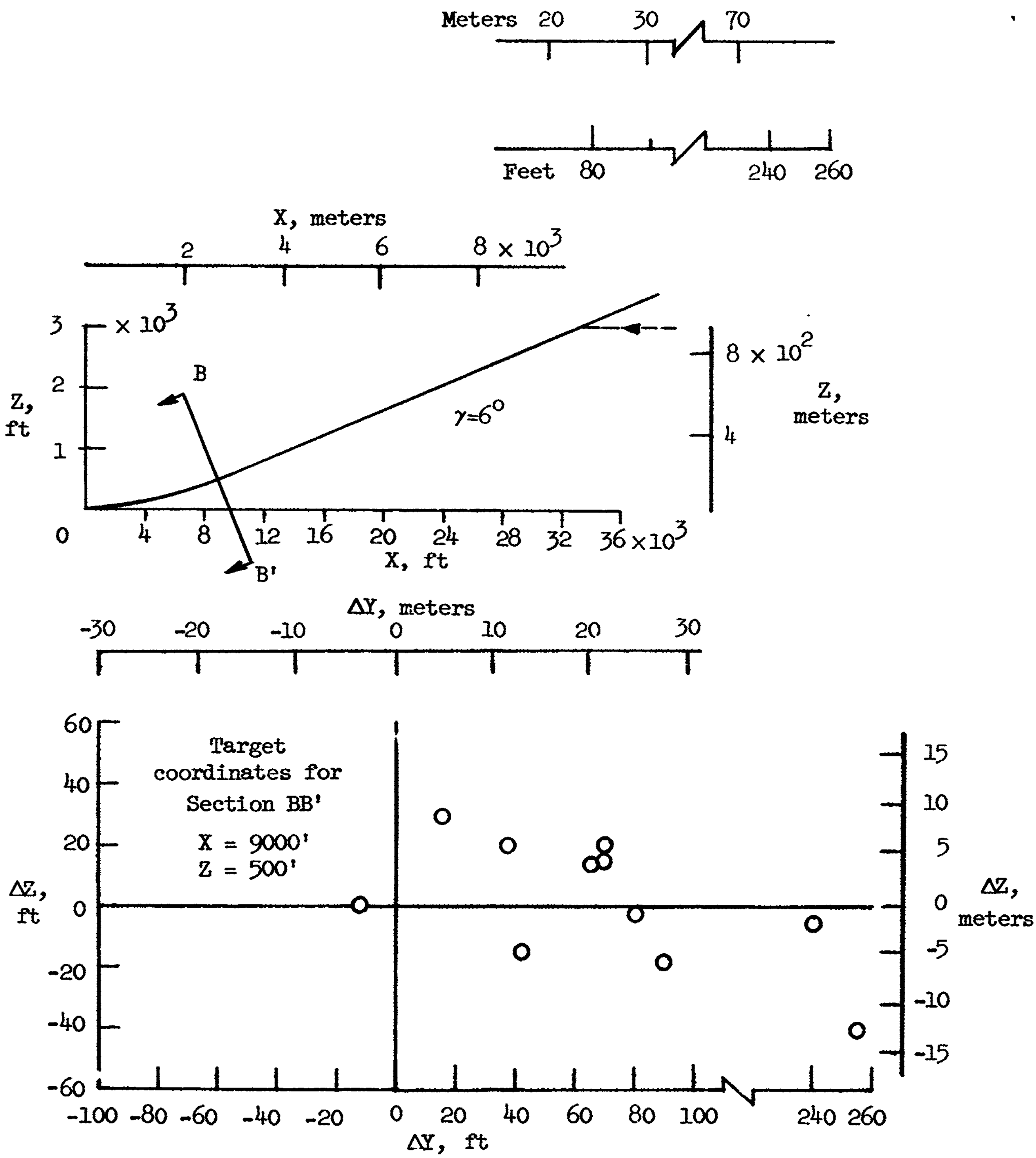


(b) Angular deviation from nominal glide slope, Section AA', N = 8.



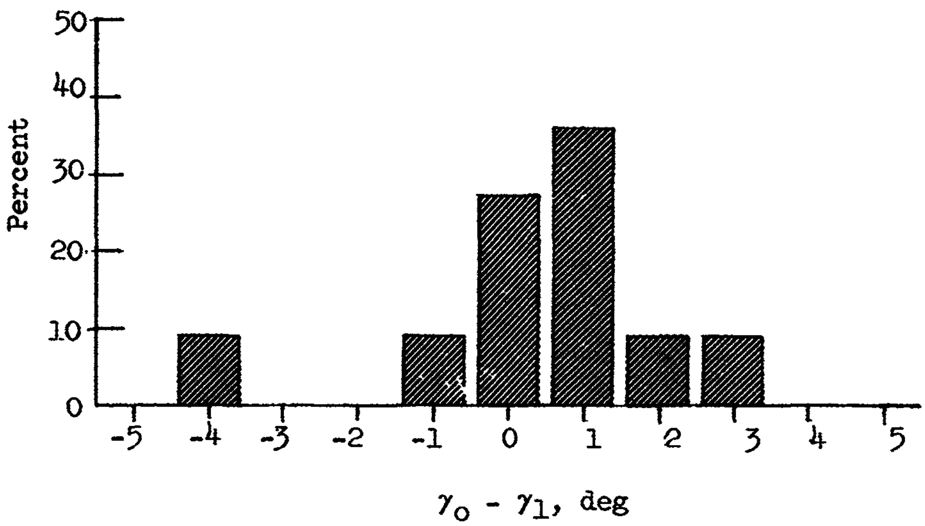
(c) Angular deviation from nominal course, Section AA', N = 8.

Figure 6.- Concluded.

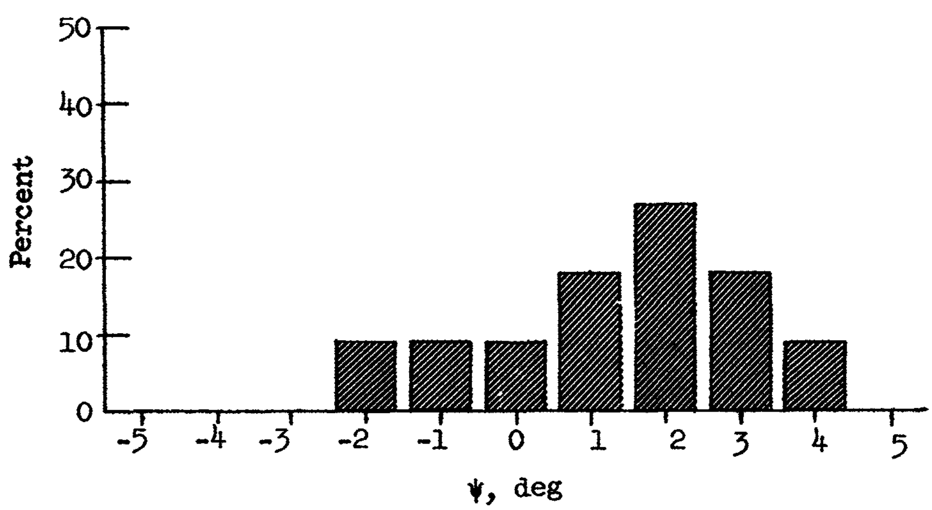


(a) Vertical and lateral displacements.

Figure 7.- Flight-path deviations for airplane F at start of 7.0 sec/deg flare to touchdown from 6° single-segment profile, Section BB', N = 11.

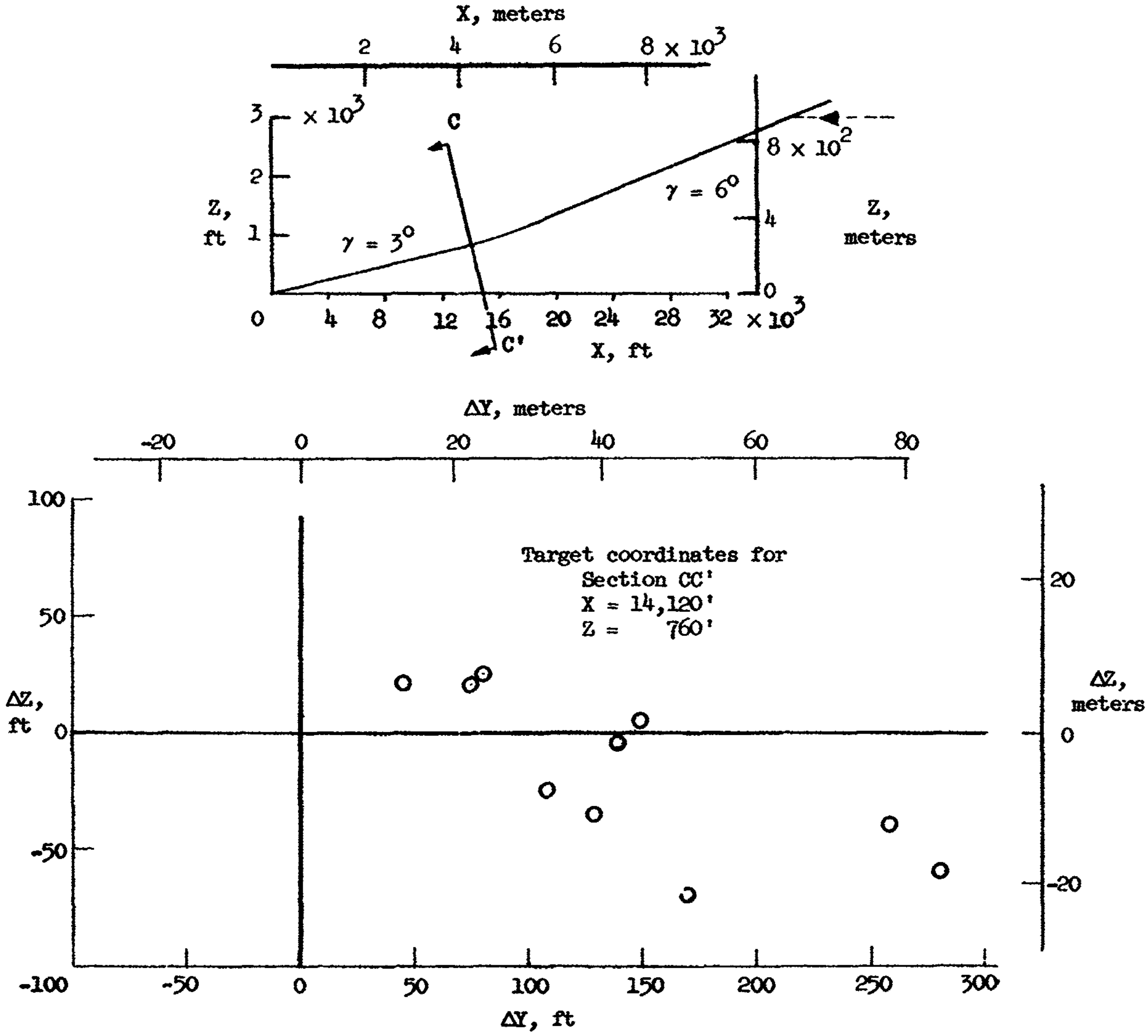


(b) Angular deviation from nominal glide slope, Section BB', N = 11.



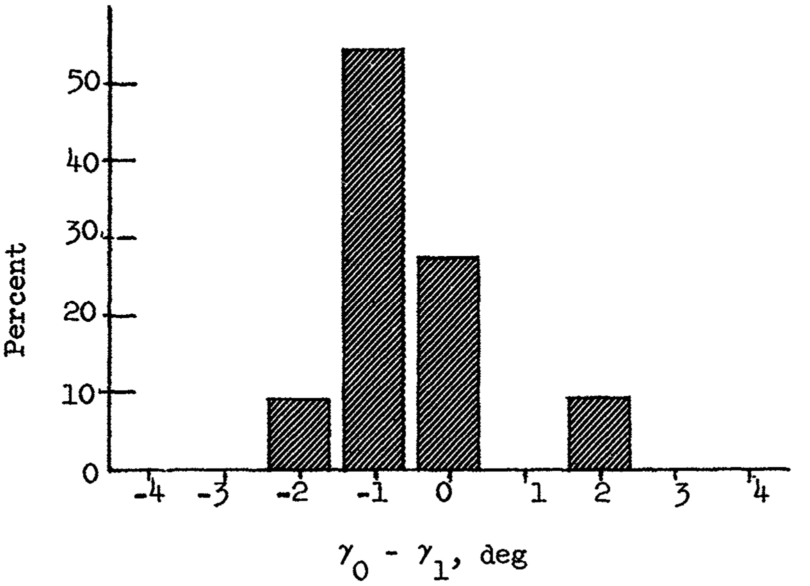
(c) Angular deviation from nominal course, Section BB', N = 11.

Figure 7.- Concluded.

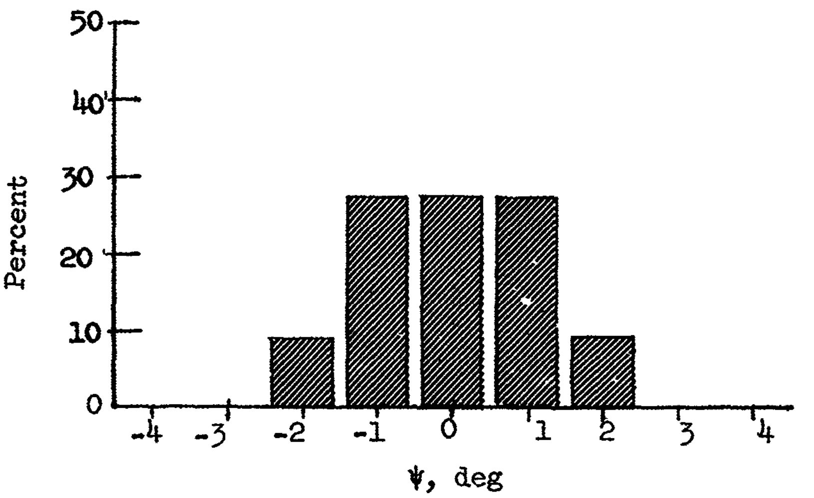


(a) Vertical and lateral displacements.

Figure 8.- Flight-path deviations for airplanes E and G at completion of 3.5 sec/deg transition, two-segment profile, Section CC', N = 11.

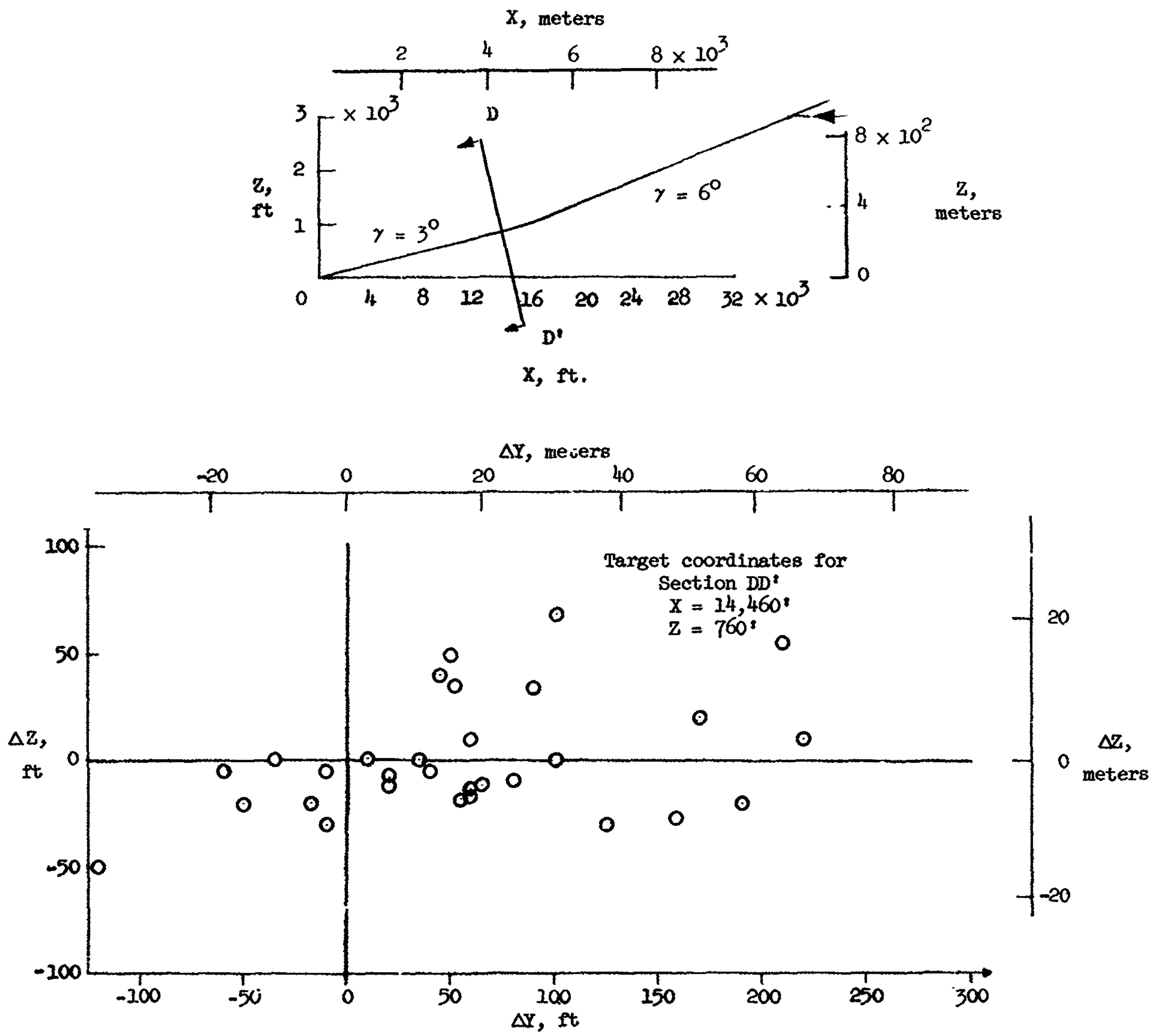


(b) Angular deviation from nominal glide slope, Section CC', N = 11.



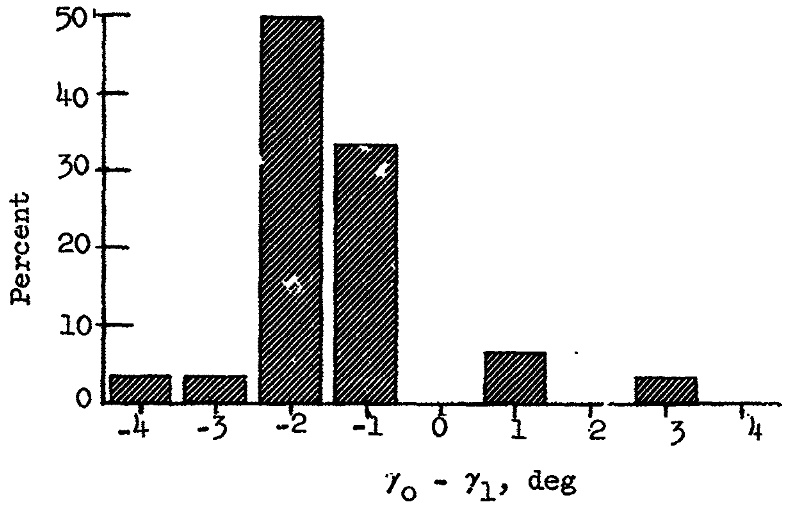
(c) Angular deviation from nominal course, Section CC', N = 11.

Figure 8.- Concluded.

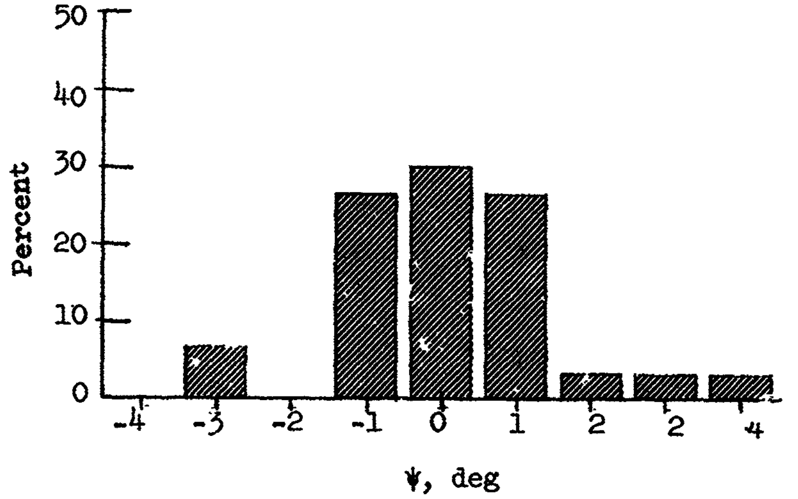


(a) Vertical and lateral displacements.

Figure 9.- Flight-path deviations for airplanes F and G at completion of 7.0 sec/deg transition, two-segment profile, Section DD', N = 30.

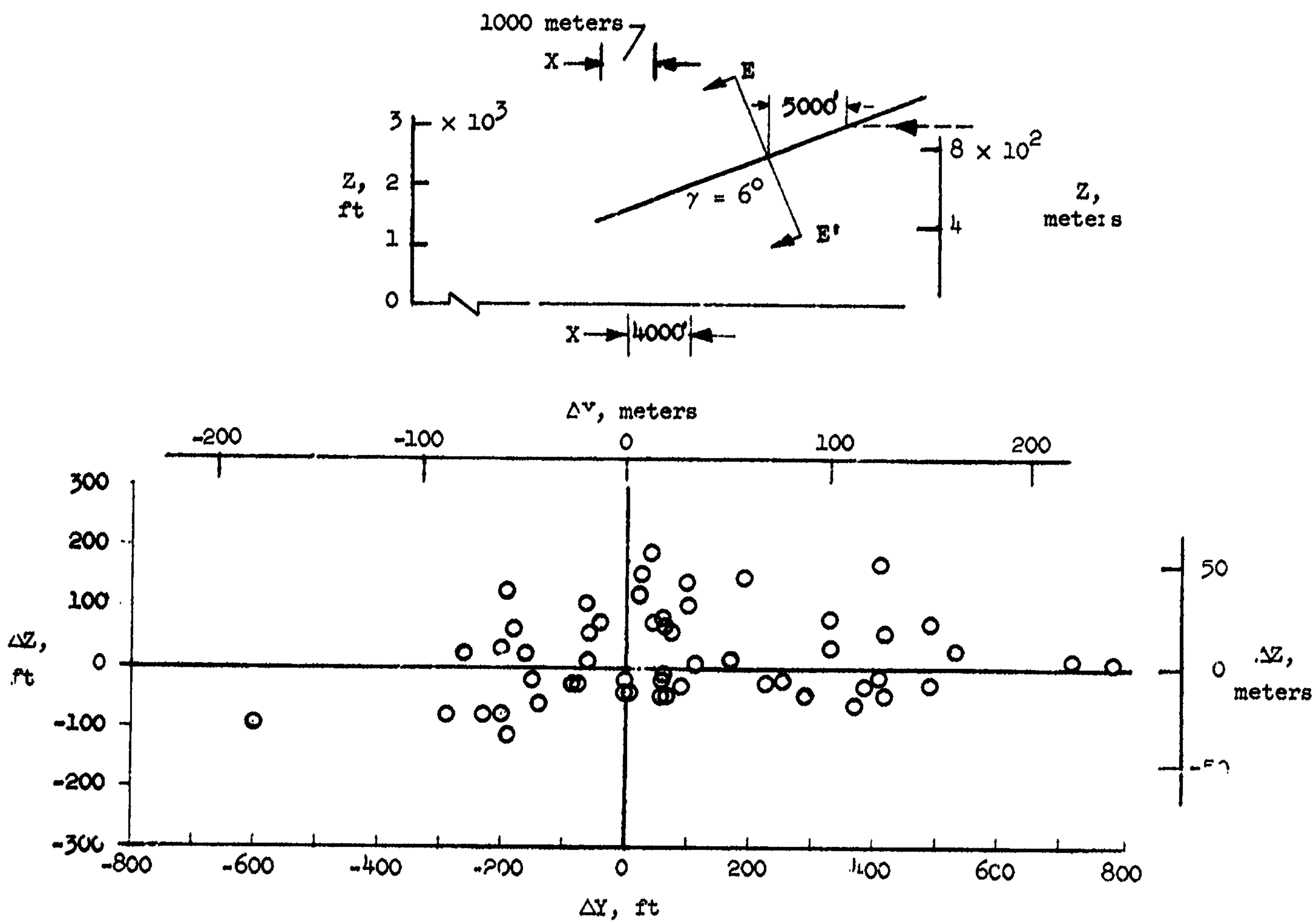


(b) Angular deviation from nominal glide slope, Section DD', N = 30.



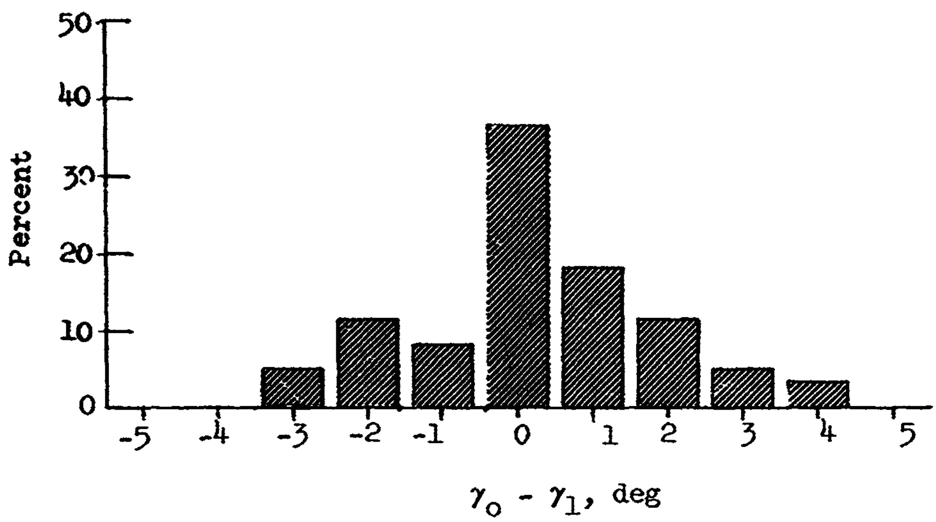
(c) Angular deviation from nominal course, Section DD', N = 30.

Figure 9.- Concluded.

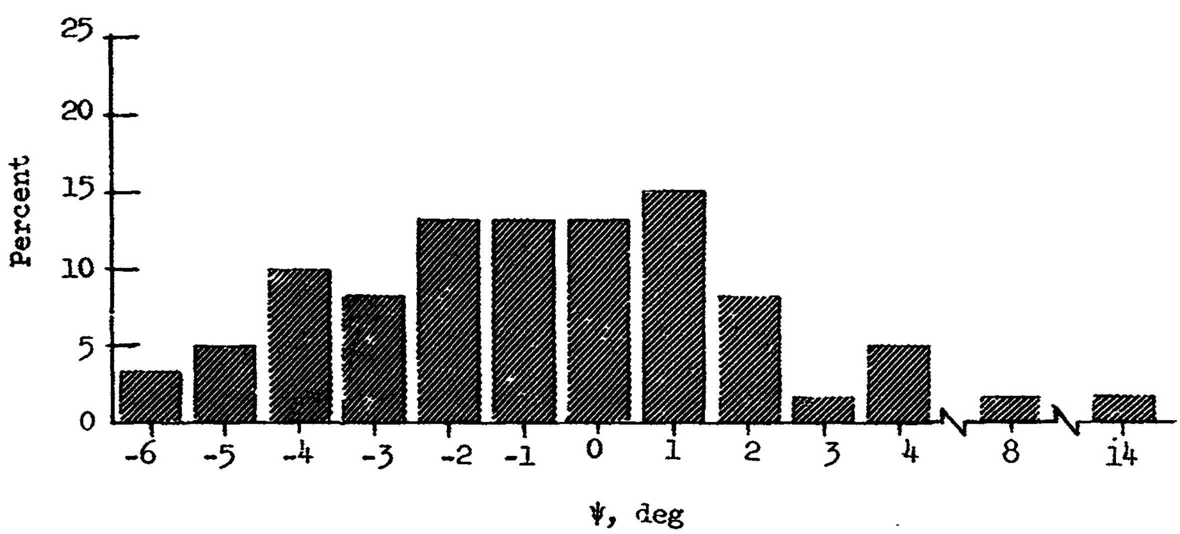


(a) Vertical and lateral displacements.

Figure 10.- Flight-path deviations for airplanes E, F, and G, 5000 feet after 6° glide-slope capture, Section EE', N = 60.

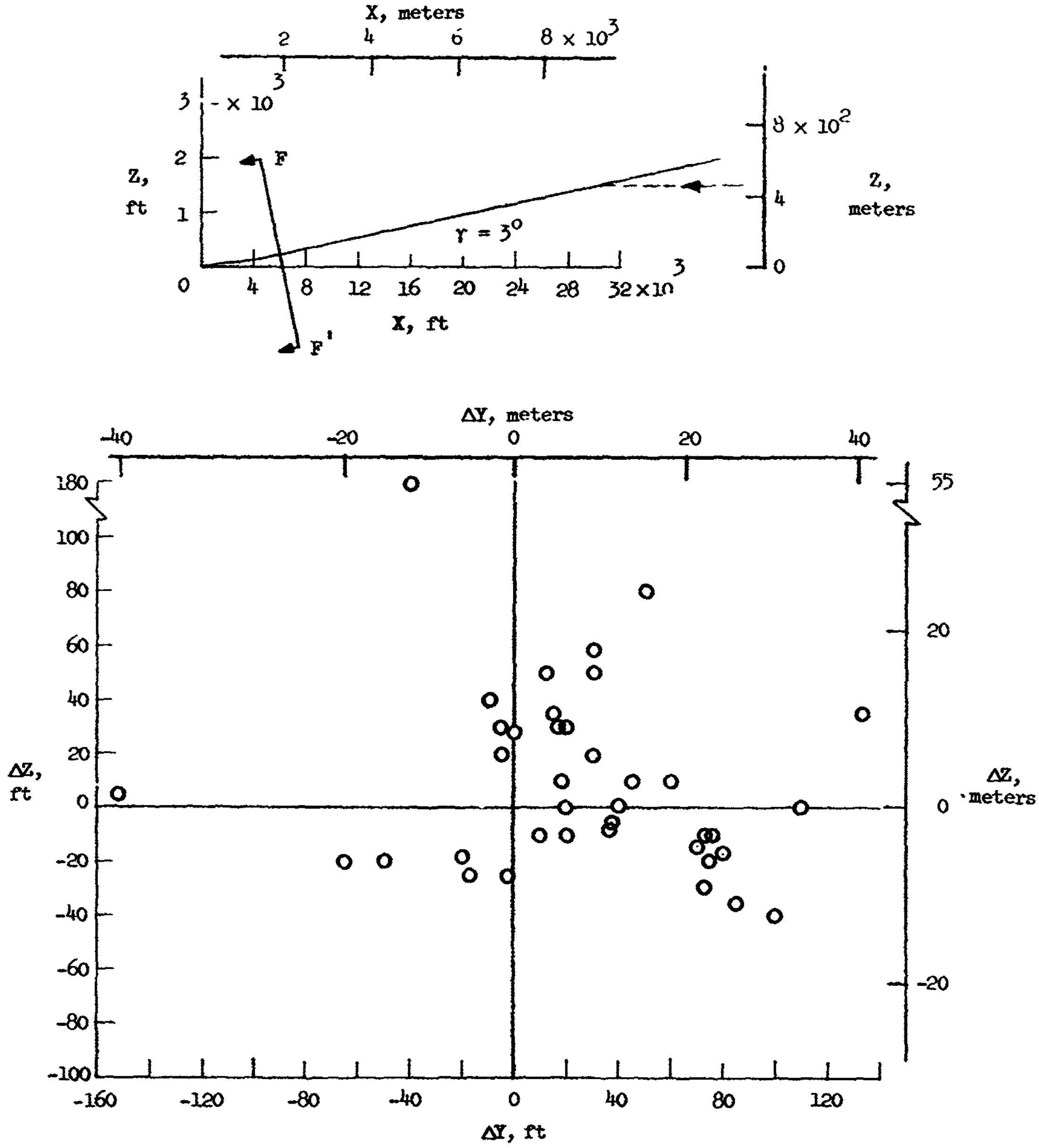


(b) Angular deviation from nominal glide slope, Section EE', N = 60.



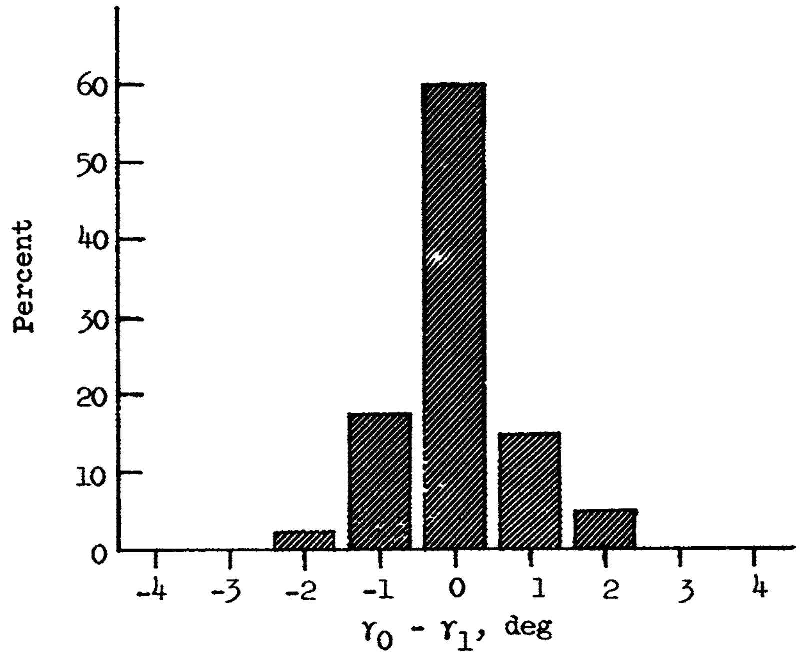
(c) Angular deviation from nominal course, Section EE', N = 60.

Figure 10.- Concluded.

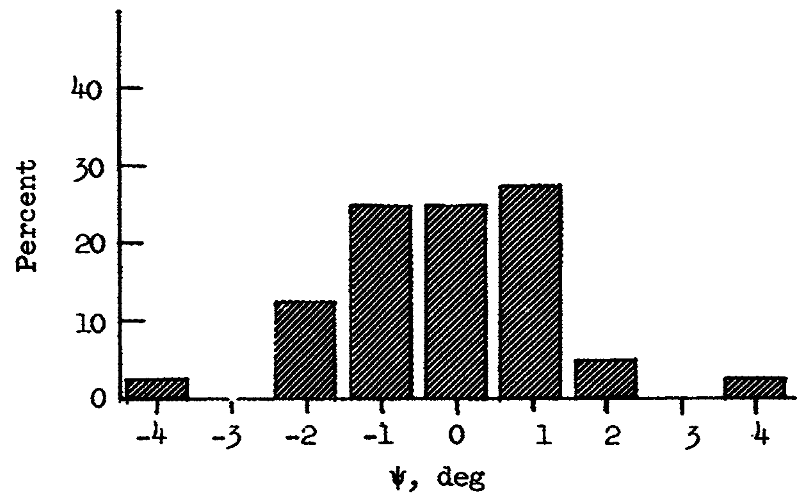


(a) Vertical and lateral displacements.

Figure 11.- Flight-path deviations for airplanes E, F, and G at breakout to VFR conditions at 200 feet. 3° single-segment profile, Section FF', N = 40.

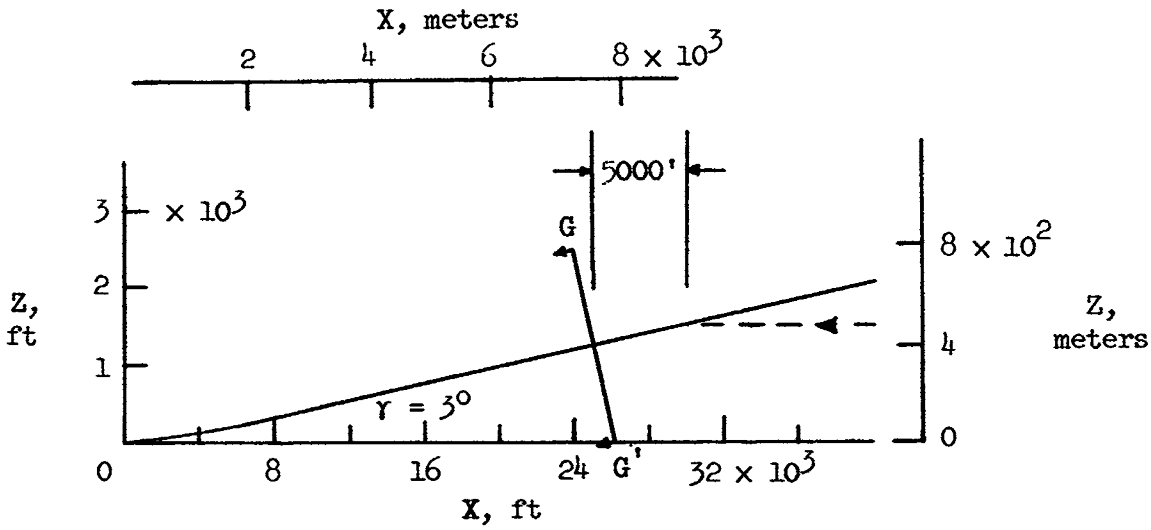


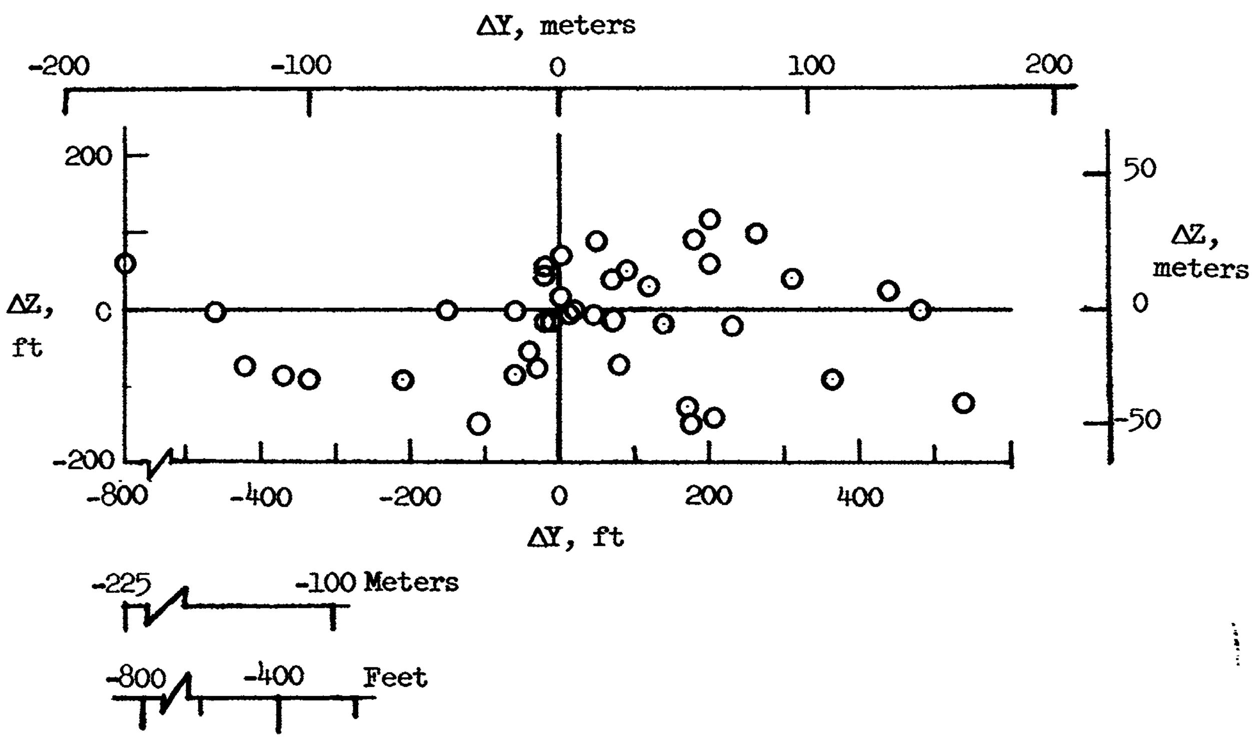
(b) Angular deviation from nominal glide slope, section FF', N = 40.



(c) Angular deviation from nominal course, section FF', N = 40.

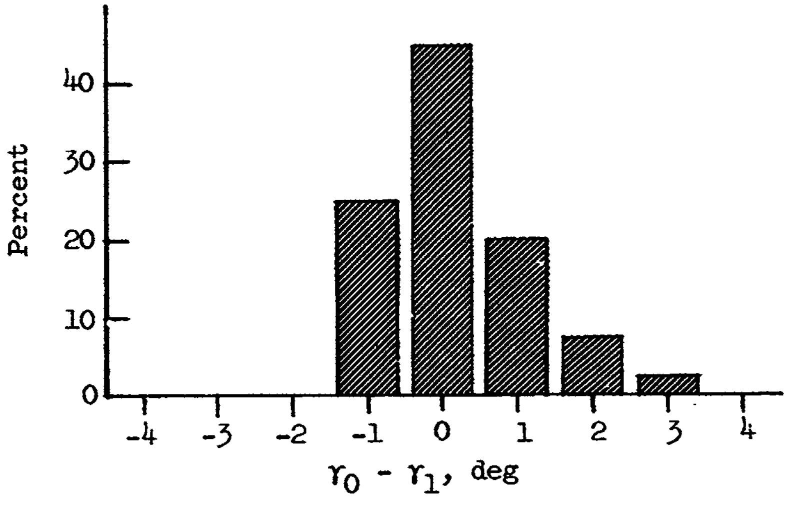
Figure 11.- Concluded.



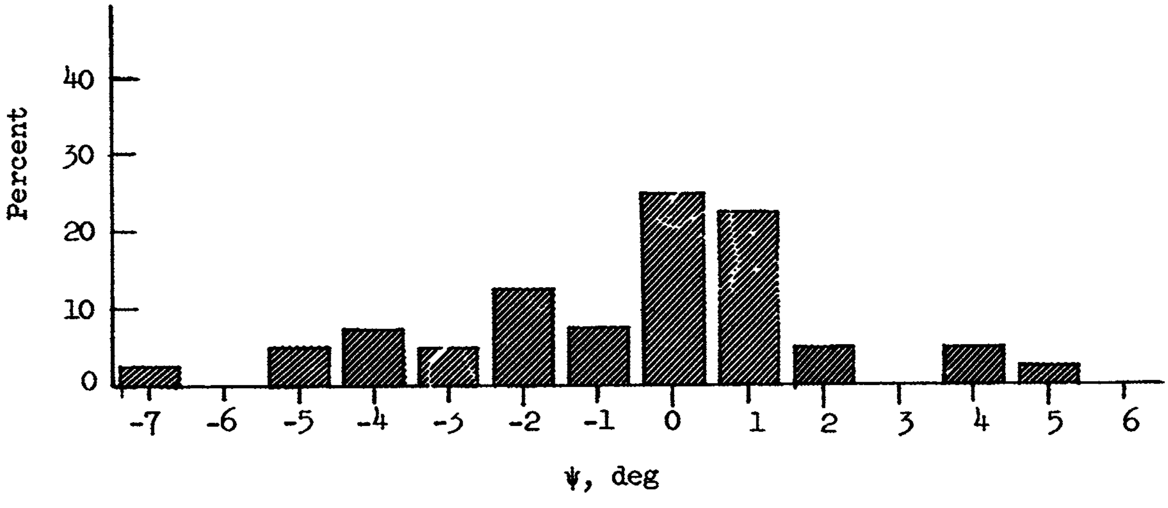


(a) Vertical and lateral displacements.

Figure 12.- Flight-path deviations for airplanes E, F, and G, 5000 feet after 3° glide-slope capture, Section GG', N = 40.



(b) Angular deviation from nominal glide slope, Section GG', N = 40.



(c) Angular deviation from nominal course, Section GG', N = 40.

Figure 12.- Concluded.

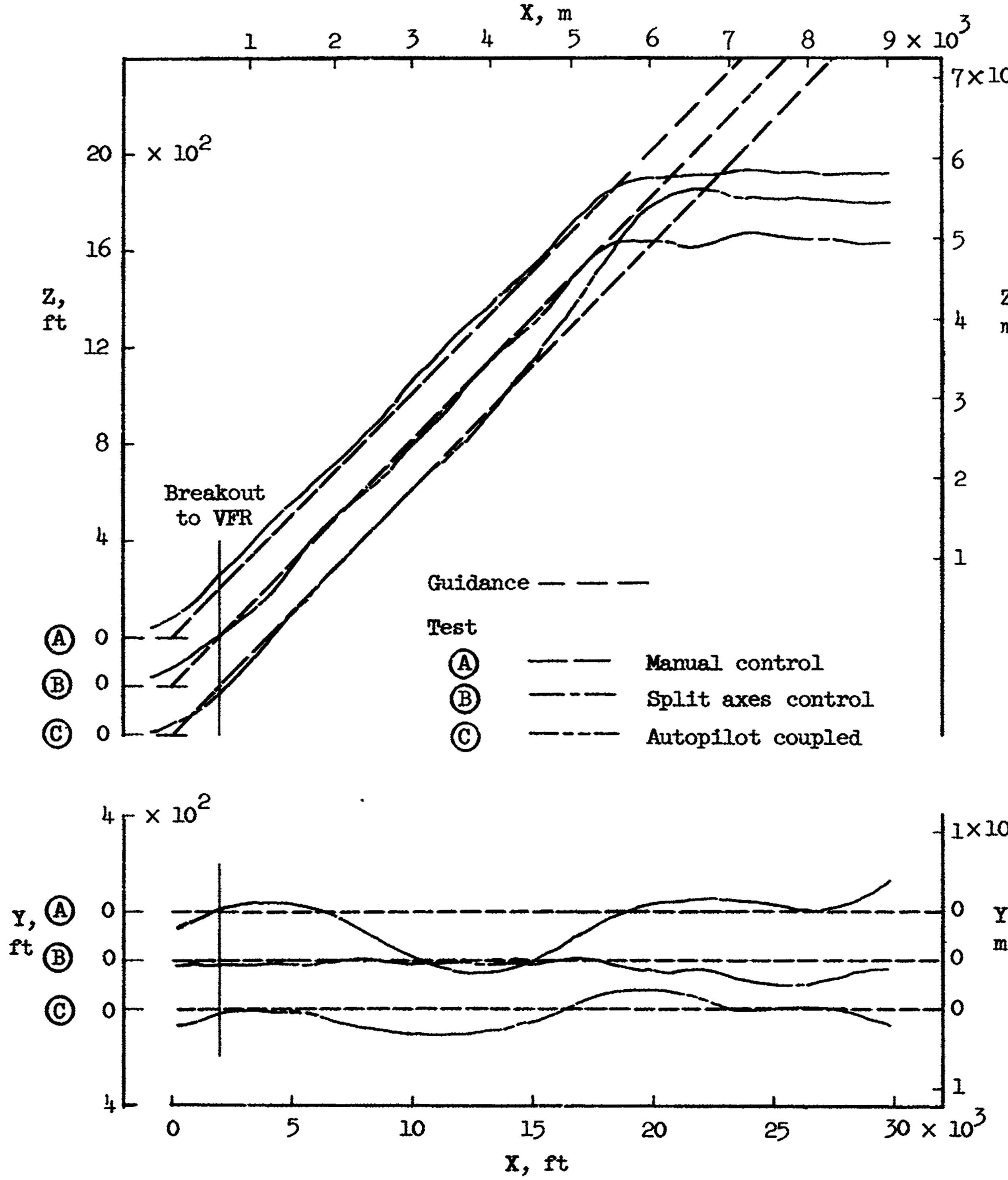


Figure 13.- Typical elevation profiles and ground tracks for airplane D for various control modes.

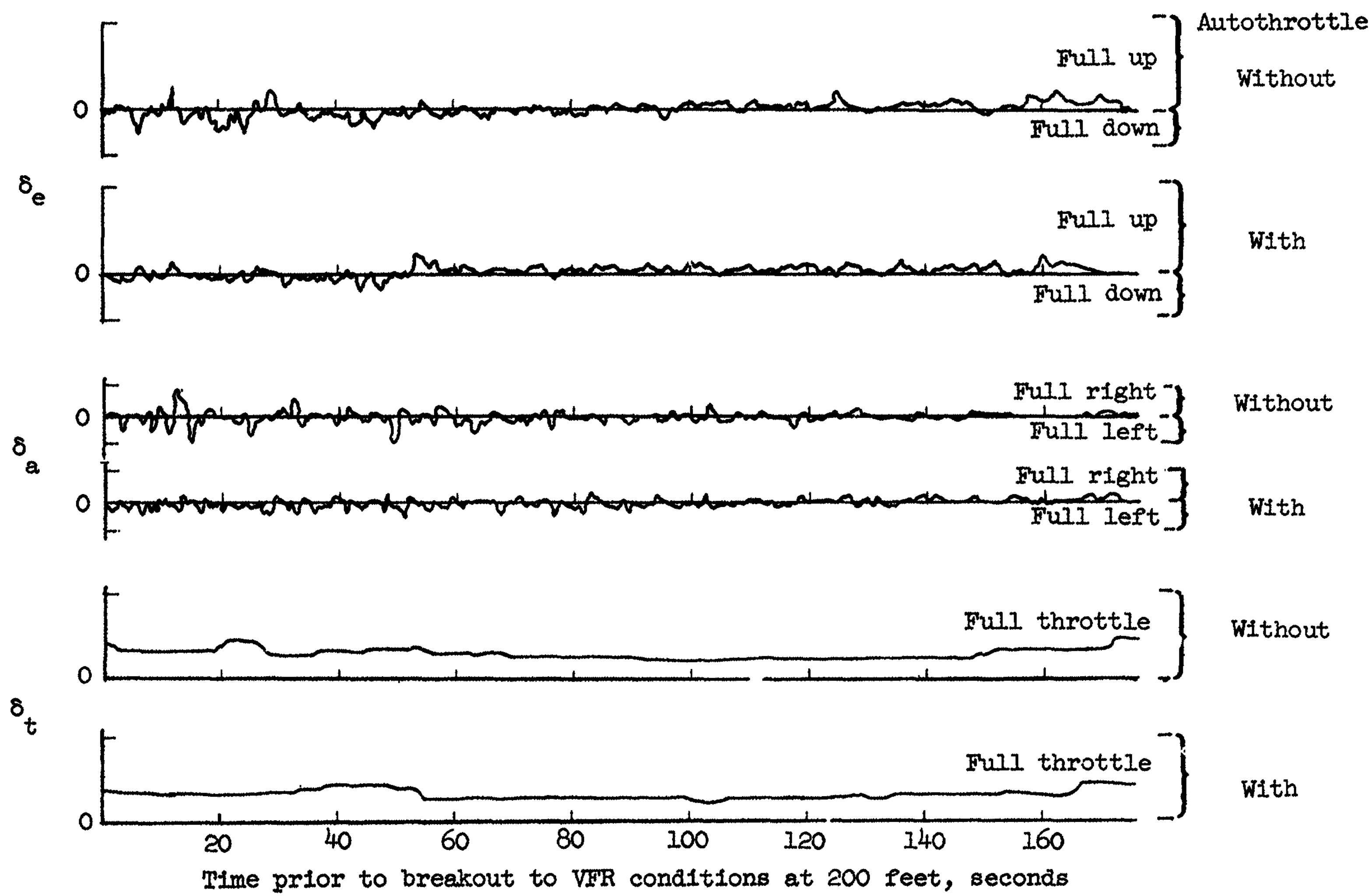


Figure 14.- The effect of simulated autothrottle on pilot control inputs.

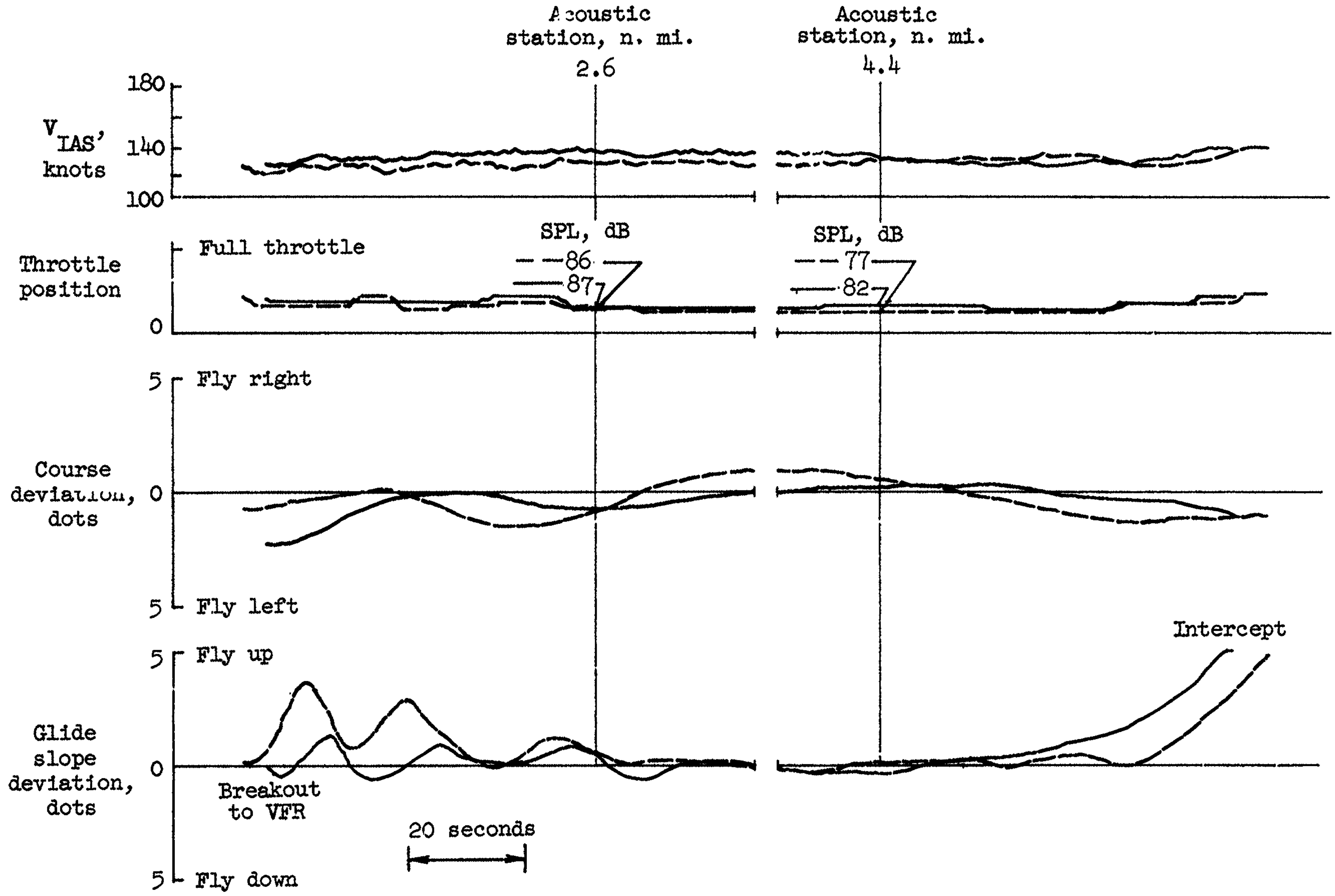


Figure 15.- Time histories of airspeed, throttle position, and course and glide-slope deviations; effect of throttle on sound pressure level indicated at 2.6- and 4.4-n.m. stations.

NASA-Langley, 1966