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RESEARCH MEMORANDUM

INVESTIGATION OF A TILTING-WING VERTICAL-TAKE-OFF-AND-LANDING JET AIRPLANE MODEL IN HOVERING AND TRANSITION FLIGHT

By Robert H. Kirby and James L. Hassell, Jr.

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Langley Field, Va.

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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INVESTIGATION OF A TILTING-WING VERTICAL-TAKE-OFF-AND-LANDING JET AIRPLANE MODEL IN HOVERING AND TRANSITION FLIGHT*

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SUMMARY

This paper presents the results of an investigation of the dynamic stability and controllability of a proposed supersonic-cruise, vertical-take-off-and-landing airplane configuration. The configuration employs a tilting wing and engines to accomplish vertical take-off and landing while maintaining a fuselage-level attitude. The wing, which is effectively a flat nacelle housing six jet engines, has an aspect ratio of 1.07.

The investigation showed that the configuration had satisfactory take-off, landing, and hovering characteristics. It was possible to perform the transition from hovering to normal forward flight, but the stability and control characteristics of the model in this flight range were considered unsatisfactory. In the transition range the wing interference and downwash of the low-aspect-ratio tilting wing on the horizontal tail were so critical that satisfactory longitudinal stability and trim could not be achieved over the entire speed range from hovering to normal forward flight with any horizontal-tail size or height which was considered practical. Unstable lateral oscillations were also encountered at several stages of the transition and it was necessary to use artificial stabilization in roll and yaw to enable the pilots to control the model.

INTRODUCTION

A research program is being conducted at the Langley Aeronautical Laboratory to determine the characteristics of a proposed supersonic-cruise, vertical-take-off-and-landing (VTOL) airplane configuration. The configuration employs the tilting-engine-and-wing-concept to accomplish vertical take-off and landing while maintaining a fuselage-level

*Title, Unclassified.

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attitude and is intended to cruise in the Mach number range of 2 to 3. It was thought that the wing of such a VTOL airplane could be designed for the supersonic-cruise condition instead of being compromised by the usual take-off-and-landing considerations of conventional airplanes and that the airplane might therefore have superior performance in addition to having the benefits of vertical take-off and landing. The configuration chosen for investigation utilized six turbojet engines. It was found in laying out this configuration that the plan form of the engines and inlets afforded more wing area than was required for the supersonic-cruise condition. There was, therefore, no need for a separate wing since the flat nacelle of the six engines could serve as the wing. This nacelle, formed by placing three engines side by side as close together as possible on each side of the fuselage, resulted in a wing with an aspect ratio of 1.07.

References 1 to 4 present the results of force-test investigations conducted at the Langley Laboratory on this general configuration. Results of force tests made at supersonic speeds in the Langley 9-inch supersonic tunnel without jet flow simulated and in the Langley 4- by 4-foot supersonic pressure tunnel with the jet flow simulated by cold-air jets are reported in references 1 and 2. Force tests made in the Langley full-scale tunnel at low speeds with the jet flow simulated with cold-air jets are discussed in reference 3. Reference 4 includes a force-test investigation of the effect of ground proximity on the free-flight model of the present investigation.

The present investigation was made by the Langley Free-Flight Tunnel Section to determine the dynamic stability and control characteristics of a model of the proposed airplane configuration in take-offs and landings, in hovering flight, and during the transition from hovering to normal forward flight. Model propulsion was provided by compressed-air jets.

The investigation consisted primarily of flight tests. A limited number of force tests were also made to determine the static stability and control characteristics of the flight-test model for the purpose of correlation with flight-test results.

SYMBOLS

The force-test data are referred to the stability axes. The definitions of the symbols used in the present paper are as follows:

C_m pitching-moment coefficient, M_Y/qSc

ΔC_l rolling-moment coefficient resulting from roll control deflection, $\Delta M_X/qSb_w$

M_Y pitching moment, ft-lb

ΔM_X rolling moment resulting from roll control deflection, ft-lb

q dynamic pressure, $\frac{1}{2}\rho V^2$, lb/sq ft

ρ air density, slugs/cu ft

V velocity, ft/sec

S wing area, sq ft

c wing chord, ft

b_w wing span, ft

b_t horizontal-tail span, ft

i_w wing incidence measured from fuselage longitudinal axis, deg

α_f fuselage angle of attack, deg

I_X moment of inertia about longitudinal body axis, slug-ft^2

I_Y moment of inertia about lateral body axis, slug-ft^2

I_Z moment of inertia about vertical body axis, slug-ft^2

APPARATUS AND TESTS

Model

The model had an aspect ratio 1.07 wing of rectangular plan form which represented the flat nacelle needed for six jet engines in a side-by-side arrangement. A photograph of the model is shown in figure 1 and a drawing of the model is shown in figure 2. It should be noted that the photograph shows the model with the horizontal tail in a high position, whereas the drawing of figure 2 shows the tail in a low position. Tail position and size were two of the major variables covered in this investigation. Figure 3 shows the various tail arrangements investigated and figure 2 and table I give the details of the final low-tail configuration.

The jet engines were simulated in this model by small high-pressure compressed-air nozzles exhausting into ejector tubes to give a jet of approximately proper size to represent afterburning turbojet engines. The lower front surface of the wing was hinged to form the inlet as shown in the photograph of figure 1. A configuration of this type would require a variable-geometry inlet because of its wide flight-speed range, but for these tests, the model inlets were set at 35° (see fig. 2) to approximate the conditions expected on a full-scale airplane for the speed range covered in this investigation. For take-off, the wing was in a vertical position $(i_w = 90^\circ)$ to direct the jet exhaust downward, and for forward flight, the wing was rotated into a horizontal position. In the first part of the investigation the wing was pivoted at 65 percent chord, but later the wing was shifted so that it was pivoted at 55 percent chord. The fuselage station at which the wing was pivoted remained fixed. This change was made for two reasons. First, it moved the center of gravity forward with respect to the wing chord in the forward-flight condition and second, it allowed the center of gravity to be moved still farther forward in the model since in hovering flight the pitch nozzles had a longer moment arm to provide pitch trim. The center-of-gravity positions given in this paper are those for the model with the wing at $i_w = 0^\circ$. The model center of gravity varied as the wing was rotated. With the wing pivoted at 65 percent chord, the model center of gravity moved rearward approximately 1 percent chord when the wing was rotated from $i_w = 0^\circ$ to $i_w = 90^\circ$. With the wing pivoted at 55 percent chord, the model center of gravity moved forward approximately 3 percent chord when the wing was rotated from $i_w = 0^\circ$ to $i_w = 90^\circ$.

The fuselage was a parabolic body of revolution and had a fineness ratio of 13.8. A canopy was added at the front of the model and a large fillet was added behind the wing to fair out the blunt base of the wing center section.

In hovering flight, where the usual control surfaces were not effective, pitch, yaw, and roll control were all provided in the initial tests by swiveling nozzles on the six jets at the rear of the wing. For hovering flight, these nozzles could be deflected laterally for roll control, fore and aft for pitch control and differentially fore and aft for yaw control. In later tests a jet-reaction control was added in the nose of the fuselage, which was directed up or down for pitch control and left or right for yaw control. When the nose jet control was installed, only roll control was obtained from the wing nozzles. In normal forward flight with the wing at or near 0° incidence, the conventional elevator and rudder provided pitch and yaw control while the swiveling nozzles of the engines generally provided roll control. In a few later transition and forward flight tests, roll control was obtained from differential elevator deflection in addition to deflection of the swiveling nozzles. The controls were deflected by flicker-type (full-on or off) pneumatic actuators which were remotely operated by the pilots. In addition, the model was equipped with electric-motor trimmers on the controls which could be operated either in conjunction with or independently of the flicker controls. The swiveling nozzles were deflected, either together or differentially, about 8° which deflected the jets 6.5° for flicker control, but these nozzles were capable of deflecting the jets for trim about 12° in any direction. The jet control in the nose of the fuselage produced ±16 foot-pounds for pitch control and ±8 foot-pounds for yaw control.

In some of the transition flights, various artificial stabilizing devices were used to move the controls automatically in proportion to the rate of roll or rate of yaw. The sensing elements for the devices were rate gyroscopes, which in response to rate of roll or rate of yaw, provided signals to proportional control actuators. These actuators moved the controls to oppose the rolling or yawing motion. A pilot-operated override was provided in the gyroscope-operated devices which cut out the damping action and gave all the available control power to the pilot on demand.

Test Setup and Flight-Test Technique

Figure 4 shows the test setup for the flight tests which were made in the Langley full-scale tunnel. The sketch shows the pitch pilot, the safety-cable operator, and the thrust controller on a balcony at the side of the test section. The roll pilot was located in an enclosure in the lower rear part of the test section, and the yaw pilot was at the top rear of the test section. An additional operator (not shown in fig. 4) was located on the balcony near the pitch pilot in order to control the wing incidence. The pitch, roll, and yaw pilots were located at the best available vantage points for observing and controlling the particular phase of the motion with which each was concerned. Motion-picture records were obtained with fixed cameras mounted near the pitch and yaw pilots.

The air for the main propulsion jets and for the jet controls was supplied through flexible plastic hoses and the power for the wing-tilting motor and the electric control solenoids was supplied through wires. These wires and tubes were suspended overhead and taped to a safety cable (1/16-inch braided aircraft cable) from a point approximately 15 feet above the model down to the model. The safety cable, which was attached to the model above the wing pivot point, was used to prevent crashes in the event of a power or control failure or in the event that the pilots lost control of the model. During flight the cable was kept slack so that it would not appreciably influence the motions of the model.

The test technique is best explained by describing a typical flight. The model hung from the safety cable and the power was increased until the model was in steady hovering flight. At this point the tunnel drive motors were turned on and the airspeed began to increase. As the airspeed increased, the attitude of the fuselage was kept essentially horizontal, the wing incidence was reduced, and the power was adjusted in order to provide the thrust required to balance the drag of the model. The controls and power were operated to keep the model as near as possible to the center of the test section until a particular phase of the stability and control characteristics was to be studied. Then the pilots performed the maneuvers required for the particular tests and observed the stability and control characteristics. The flight was terminated by gradually taking up the slack in the safety cable while reducing the power to the model.

The same testing technique was used for the take-off, hovering, and landing tests except that the wind tunnel was not necessary and most of the tests were made outdoors in still air.

Tests

Flight tests.- The investigation consisted primarily of flight tests to determine the stability and control characteristics of the model in vertical take-offs and landings in still air, in hovering flight in still air, and during the transition between hovering and normal forward flight. The test results were obtained both from the pilots' observations and opinions of the behavior of the model and from motion-picture records of the motions of the model.

The take-off tests were made by rapidly increasing the power to the model until it took off. The model was then hovered at various heights above the ground to study the stability and control characteristics of the model in and out of ground proximity. In these tests the ease with which the model could be flown in steady hovering flight and maneuvered from one position to another was studied. Landings were made by reducing the model power slightly so that the model descended slowly until the power was cut off abruptly as the landing gear touched the ground.

The transition flight tests were made in the Langley full-scale tunnel. These flights, which were made at airspeeds from 0 to 65 knots, corresponded to slow constant-altitude transitions. Since small corrections or adjustments to the tunnel airspeed could not be made quickly, the pitch pilot and power operator had to make adjustments continually in order to hold the model in the center of the test section. Flights were also made in which the airspeed was held constant at intermediate speeds so that the stability and control characteristics at constant speed could be studied.

Static force tests.- A limited number of force tests were made to determine some of the static stability and control characteristics of the flight-test model for the purpose of correlation with flight-test results. The longitudinal and lateral stability and control characteristics of the model were studied in the wing-incidence range of 0° to 30° for a range of values of thrust coefficient. All force tests were made in the 12-foot octagonal section of the Langley free-flight tunnel with a vertical-strut support system and strain-gage balances. No wind-tunnel corrections have been applied to the data.

RESULTS AND DISCUSSION

A motion-picture film supplement to this paper has been prepared and is available on loan. A request-card form and a description of the film will be found at the back of this paper, on the page immediately preceding the abstract and index pages.

Hovering Flight

The model could be flown smoothly and easily in hovering flight and could be maneuvered to any desired position at will. The swiveling nozzles on the jets at the rear of the wing provided good controllability in all three directions, pitch, roll, and yaw. The jet-reaction control on the nose of the fuselage, which was installed on the model during the later part of the investigation for pitch and yaw control, also gave good controllability in hovering flight.

The motions of the model in pitch and roll were very steady. Since the stability was not studied in detail, it is not known whether the model had unstable pitching and rolling oscillations such as had been experienced previously with tilting-wing propeller-driven models (ref. 5). It was clear, however, that the model did not tend to start an oscillation as quickly as the propeller-driven models and was consequently easier for the pilots to fly. The yawing motions, as would be expected, seemed about neutrally stable in hovering flight.

Take-offs and landings were easy to perform with this model and when the model was flown close to the ground there was no noticeable difference in the flying characteristics or in control effectiveness. This result is in agreement with the force-test data presented in reference 4 which included an investigation of the effect of ground proximity on this same model.

Transition Flight

Preliminary tests.- The transition tests from hovering to normal forward flight were started with the model center of gravity at 0.58 chord, with the wing pivot at 0.65 chord, and with the horizontal tail in the high position. At high wing-incidence angles (75° to 65°) the model experienced large nose-up pitching moments which could not be trimmed by combined deflection of the jet nozzles and horizontal stabilizer. After the model reached a certain speed, it pitched up despite full-down control and drifted back in the test section as the airspeed of the tunnel continued to increase. In an effort to overcome this difficulty, various changes in the model configuration were made. Three different horizontal-tail heights (high, mid, and low as shown in fig. 3) were tried. Tail spans from $\frac{b_t}{b_w} = 1.00$ to 1.50 were tried. Various high-lift devices on the all-movable horizontal tail were tried in an attempt to improve its effectiveness. None of these changes, however, provided enough improvement in longitudinal stability and control. In order to get still more control moment and more stability, the wing pivot was moved forward to 55 percent chord and the model center of gravity was moved to 48 percent chord, which was the most forward position at which the model could be trimmed in hovering flight. With these changes the model could be flown from a wing incidence of 90° down to about 30°, but at this point a violent pitch-up occurred.

At this point in the investigation the force-test data of references 1 to 3 became available and showed that only a low horizontal-tail position would give satisfactory stability in a normal flight condition at both subsonic and supersonic speeds and that a tail span of about $\frac{b_t}{b_w} = 1.25$ was required. A tail position below the wing-chord plane was ruled out in order to keep the wing jets from passing over the tail as the wing was tilted. It was decided, therefore, to continue the investigation with the low horizontal position shown in figures 2 and 3 and with $\frac{b_t}{b_w} = 1.25$. This tail was on the same plane as the wing, so the jet nozzles were deflected downward approximately 3° in an attempt to keep the jet from impinging on the tail when the wing incidence was 0°. Since the high vertical tail was no longer needed to support the horizontal tail and since it was thought that a ventral vertical tail would be in a more favorable flow region and thereby more effective, the vertical tail was changed to the configuration shown in figure 2. The remainder of the discussion deals only with this final configuration.

Longitudinal stability and control characteristics.- With the results of the preliminary flight tests as a guide, some exploratory force tests were made on the flight-test model. It was found in these tests that the best longitudinal stability in the 30° wing-incidence range was obtained with 0° tail incidence and that this tail incidence provided about as good stability over the entire wing-incidence range as could be obtained with a variable-tail-incidence arrangement. Even with 0° tail incidence, however, the horizontal tail was not effective enough to make the model statically stable at 30° wing incidence, apparently because of the variation in downwash across the tail span. Tuft studies of the flow pattern at the horizontal-tail position showed that the center portion of the tail span was stalled by the wing downwash while the tips of the tail were stalled from the upwash resulting from the wing-tip vortices. Only a very small portion of the tail span between these two regions was effective in the 30° wing-incidence range. When the model was flight-tested with the horizontal tail fixed at 0° and with an elevator installed, it was found that the model was too unstable at $i_w = 30^\circ$ to permit the transition to be completed consistently with the center of gravity at 48 percent chord.

In order to permit the center of gravity to be moved farther forward, a jet-reaction control was installed at the nose of the fuselage to provide the increased trim required for hovering flight. This jet was then used as the reaction pitch and yaw control instead of the swiveling nozzles on the wing.

Figure 5 shows some representative pitching-moment curves obtained from the exploratory force tests on the final configuration (shown in fig. 2) for a range of wing-incidence angles from 0° to 30°. These pitching-moment data are referred to 34 percent chord, the most forward position at which the model could be trimmed and flown in hovering flight with the nose-jet pitch control. These data were obtained by interpolating between the results of various force tests to obtain pitching-moment curves for the case in which the thrust was equal to the drag and the pitching moment was zero at approximately the angle of attack at which the model was actually flown at each wing incidence. The top curve of figure 5 shows that the model was about neutrally stable at $i_w = 30^\circ$ with a fuselage angle of attack of 0° and was unstable at positive fuselage angles. The curves also show that the model was stable at wing-incidence angles of 20° or less. In order to fly with $i_w = 0^\circ$ at the speed at which the transition was to be completed in these tests, the fuselage angle of attack had to be about 15° to obtain the necessary lift from the wing. Since, for stability, the fuselage angle of attack α_f had to be kept near 0° at $i_w = 30^\circ$, α_f was brought up from 0° to 15° approximately as indicated by the dashed line on figure 5 as the wing incidence was reduced from 30° to 0°. The data of figure 5 have been plotted for a condition of appropriate elevator deflection and pitch-jet deflection to trim the model at the fuselage angle of attack indicated at each wing incidence. These data show that both stability and pitch trim could be obtained at $i_w = 20^\circ$ or less.

With this final model configuration (low tail, tail incidence fixed at 0°, nose jet, and center of gravity at 0.34 chord) the transition between hovering and normal forward flight could be completed successfully and consistently by keeping the fuselage angle of attack about 0° for wing-incidence angles of 30° and above and by gradually bringing α_f up as i_w was reduced from 30° to 0°. The longitudinal stability and control of the model was considered satisfactory except at wing-incidence angles near 30°. The pitch pilot had to use extreme care to avoid a pitch-up at $i_w = 30^\circ$ and therefore did not consider the stability satisfactory. At wing-incidence angles above 30° the model seemed stable at low fuselage angles of attack but would pitch up if α_f was allowed to become too high. In general, however, at the higher wing-incidence angles the airspeed was low and the model motions were relatively slow, so the pitch pilot found the model relatively easy to control. At wing-incidence angles of 20° or less the model was stable throughout the angle-of-attack range and was easy to fly.

Lateral stability and control characteristics.- The model could not be flown through the transition from hovering to forward flight without artificial stabilization in yaw and roll. There were two wing-incidence ranges in which lateral oscillatory instability was encountered. One was at very low forward speeds where the wing incidence was 70° or 80°. In this condition an unstable lateral oscillation, which appeared to be predominantly a yawing oscillation, developed and the pilots could not stop this motion. A rate-type yaw damper installed to actuate the wing jet nozzles for yaw control stabilized the oscillation and made the model easy to fly in this high-wing-incidence range. The rate-gyroscope sensing element for this damper was mounted on the wing so that it provided yaw damping in hovering flight and roll damping in forward flight where the wing had been rotated to 0° incidence. In addition, a rate damper was installed on the rudder surface which provided yaw damping when the rudder surface became effective as the tunnel airspeed increased.

With the addition of artificial yaw damping the model was easy to fly from lateral considerations down to a wing incidence of about 20° but at this point the model developed a violently unstable lateral oscillation of relatively high frequency which the pilot could not control. This oscillation appeared to be a pure rolling oscillation, probably because the yaw damper on the rudder surface offered considerable restraint in yaw. The use of a rate damper operating on the jet nozzle for roll control seemed to make the lateral oscillation slightly stable but the lateral motions were still uncontrollable. The reason for this was, apparently, as follows: The roll pilot observed that the roll control was relatively weak at wing-incidence angles of 20° or less. With this low control effectiveness, he did not have a positive control to fly the model steadily near the center of the test section. In trying to control the model the roll pilot had to give relatively long control inputs and since his control overrode the rate damper, the damping action was cut out for relatively long periods. This cutting out of the damper evidently resulted again in the development of an uncontrollable rolling oscillation.

A few static force tests were made with the flight model to determine the effectiveness of the jet nozzles for roll control in the wing-incidence range from 20° to 0°. The results of these tests are shown in figure 6 for the horizontal tail on and off along with the results of force tests made to determine the effectiveness of differential elevator deflection for roll control. Figure 6 shows that the horizontal tail reduced the rolling effectiveness of the jet nozzles by approximately one-half at a wing-incidence angle of 20° and a fuselage angle of attack of about 5°, which was one flight condition, and by approximately the same amount at a wing-incidence angle of 0° and a fuselage angle of attack of 15°, which was another flight condition. The data of figure 6 also show that differential elevator deflection was effective in producing roll control, particularly at 0° wing incidence.

With a rate damper on the jet nozzle for roll control and the roll pilot controlling only differential deflection of the elevator for manual control, the transition could be completed to normal forward flight consistently. The differential elevator roll control gave the roll pilot a more positive control to stop the motions of the model and also allowed the rate damper on the jet nozzles to work full time.

CONCLUDING REMARKS

This investigation of the stability and control characteristics of a vertical-take-off-and-landing airplane model with a tilting-wing-and-engine arrangement has shown that the model had satisfactory take-off, hovering, and landing characteristics. The model could be flown easily in hovering flight without artificial stabilization, and satisfactory control could be obtained easily either entirely from swiveling nozzles on the jet engines or from auxiliary jet-reaction pitch and yaw controls in the fuselage used in conjunction with roll control from the swiveling nozzles on the jet engines. Ground proximity had no effect on the hovering characteristics of the model.

It was possible to perform the transition from hovering to normal forward flight, but the stability and control characteristics of the model in this flight range were considered unsatisfactory. In the transition range the wing interference and downwash of the low-aspect-ratio tilting wing on the horizontal tail were so critical that satisfactory longitudinal stability and trim could not be achieved over the speed range from hovering to normal forward flight with any horizontal-tail size or height which was considered practical. Unstable lateral oscillations were also encountered at several stages of the transition and it was necessary to use artificial stabilization in roll and yaw to enable the pilots to control the model.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., June 18, 1958.

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TABLE I

MASS AND GEOMETRIC CHARACTERISTICS OF MODEL IN FINAL LOW-TAIL CONFIGURATION WITH $i_w = 0^\circ$

Weight, lb	41.00
Center of gravity, percent of wing chord	34.00
Moments of inertia:	
I_X, slug-ft^2	0.67 (approx.)
I_Y, slug-ft^2	5.25 (approx.)
I_Z, slug-ft^2	5.90 (approx.)
Wing:	
Aspect ratio	1.07
Area, sq in.	960
Span, in.	32.00
Dihedral angle, deg	0
Vertical tail:	
Aspect ratio	1.02
Area, sq in.	153
Mean aerodynamic chord, in.	12.5
Tail arm (length from 0.25 M.A.C. of tail to model center of gravity), in.	52.5
Horizontal tail:	
Aspect ratio	5.71
Area, sq in.	280
Mean aerodynamic chord, in.	7.00
Tail arm (length from 0.25 M.A.C. of tail to model center of gravity), in.	54.5

Figure 1.- Photograph of model in high-tail configuration. L-95469

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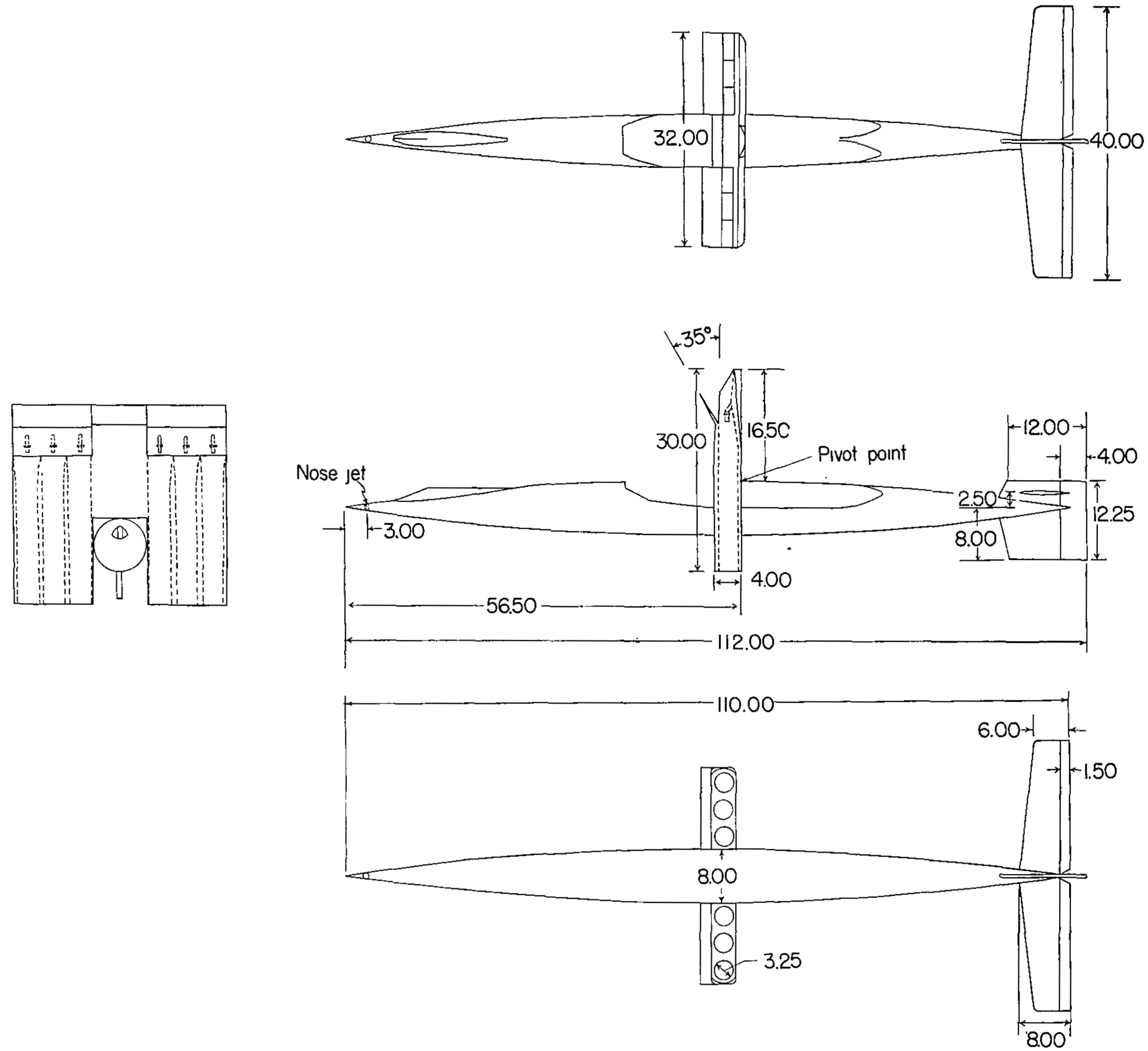

Figure 2.- Drawing of model in final low-tail configuration. All dimensions are in inches.

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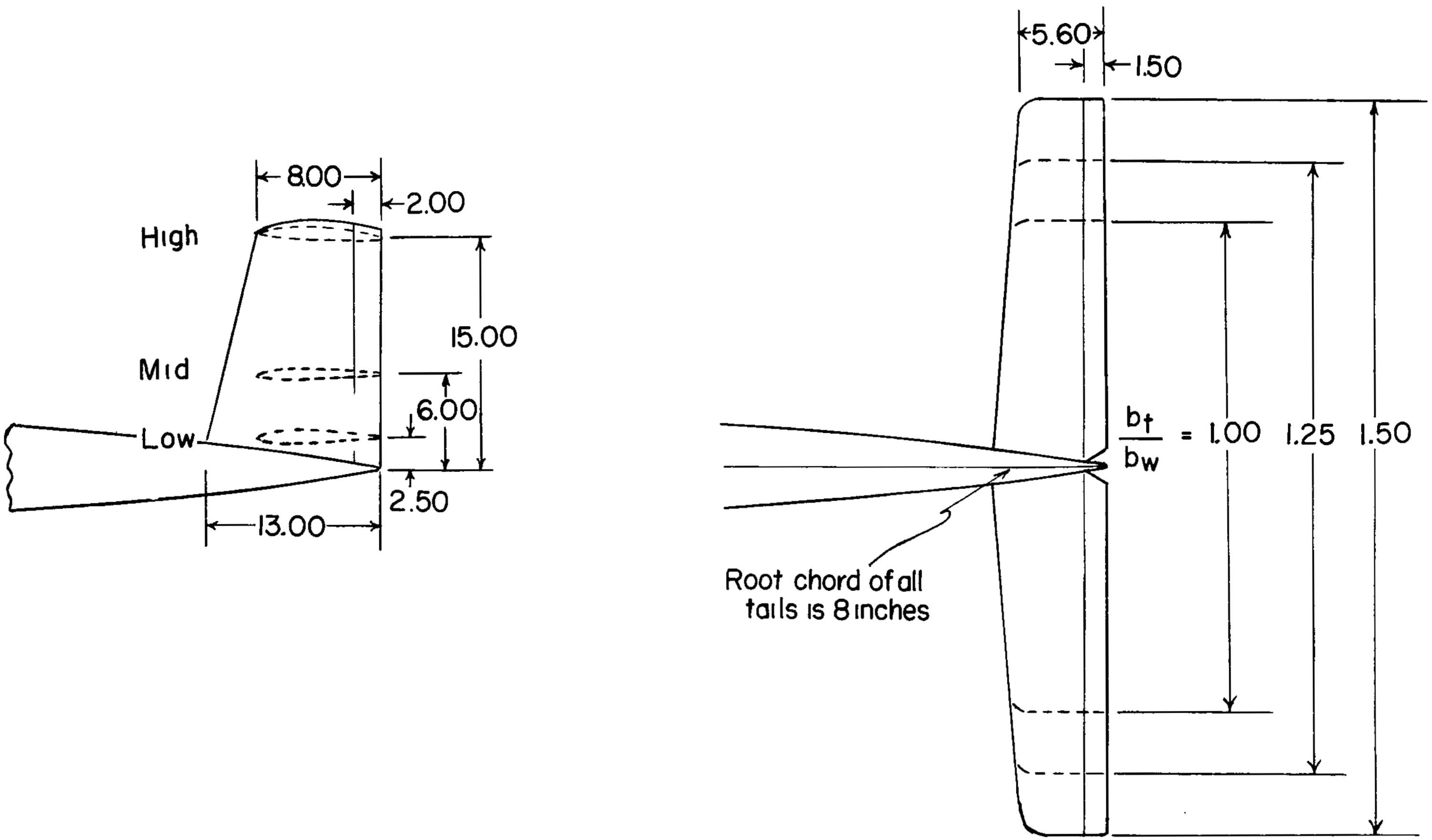

Horizontal tail positions

Horizontal tail spans

Figure 3.- Tail sizes and positions tried during flight-test program. All dimensions are in inches.

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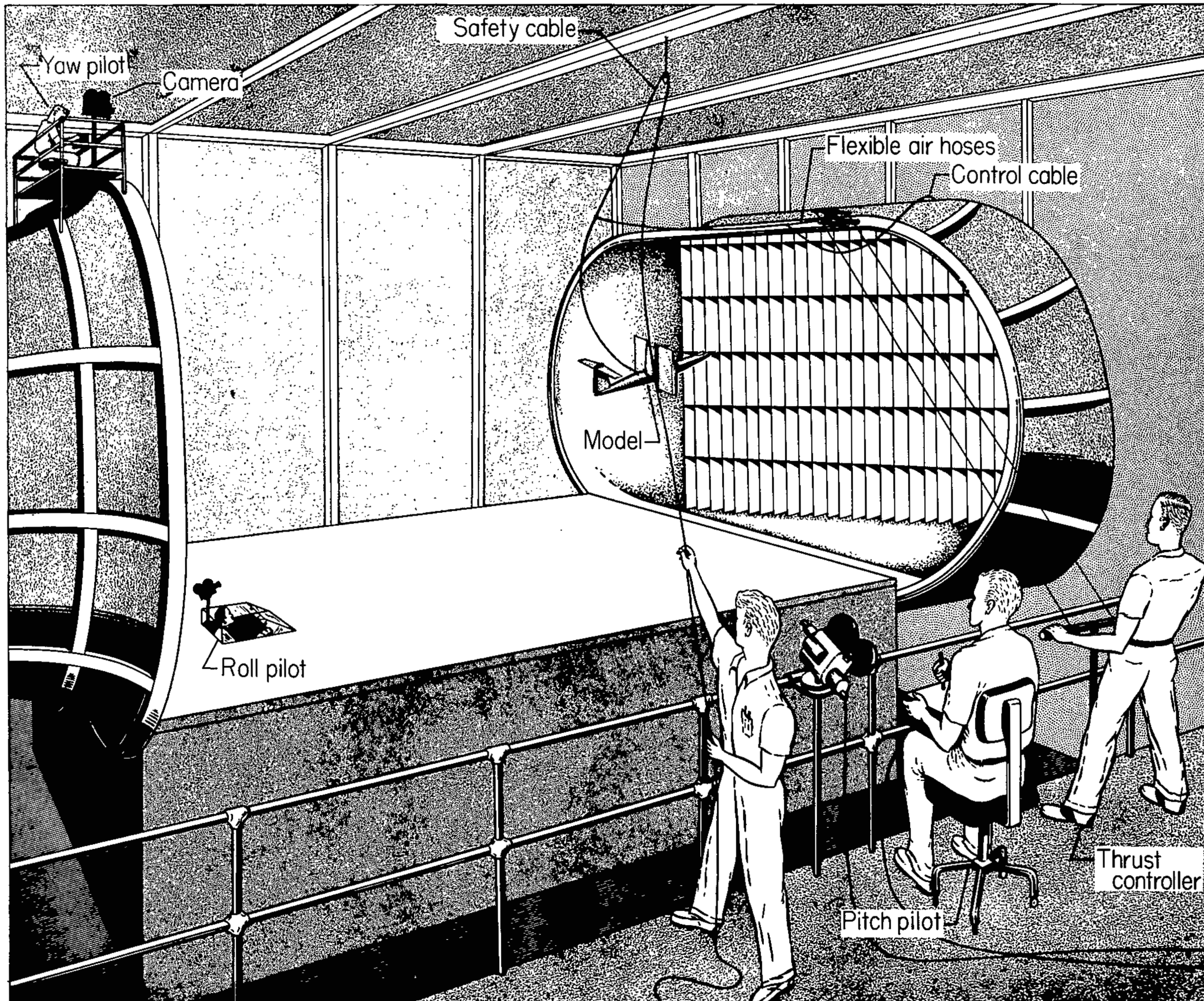

Figure 4.- Transition test setup in Langley full-scale tunnel.

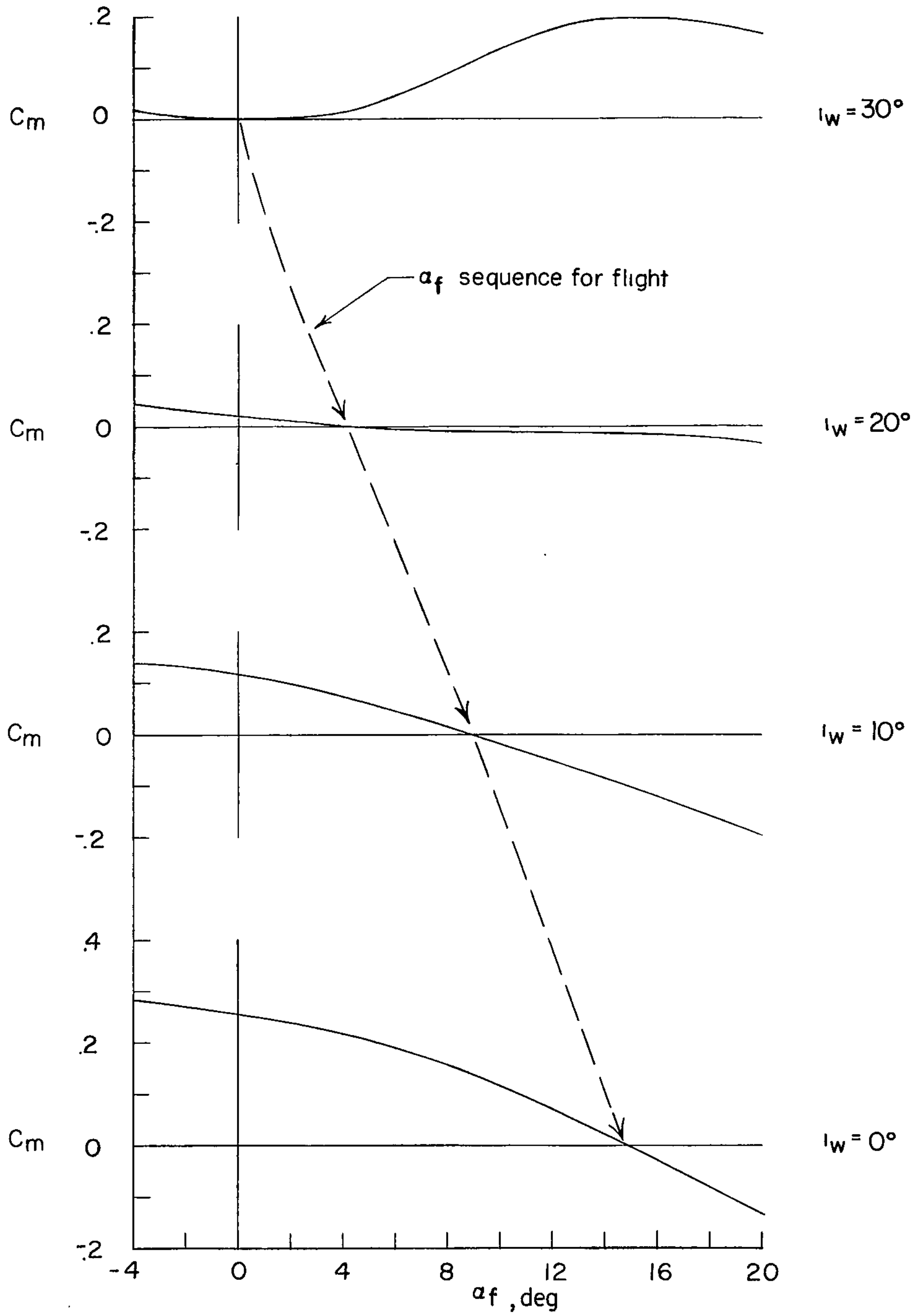

Figure 5.- Representive pitching-moment curves for final configuration in the 0° to 30° wing-incidence range for the case of thrust equal drag at α_f at which $C_m = 0$. C_m referred to 34 percent chord.

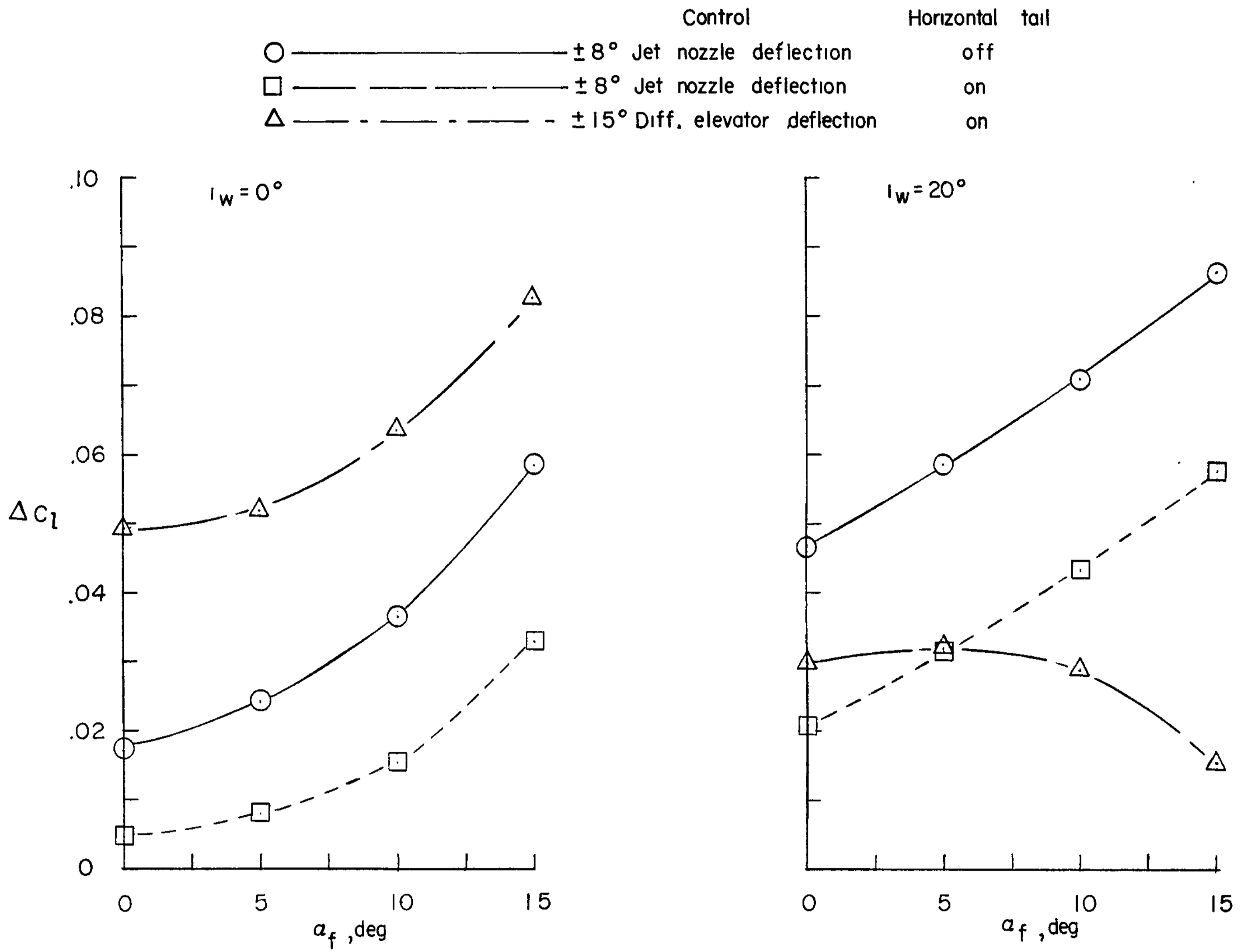

Figure 6.- Roll control effectiveness for final configuration.

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