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LONGITUDINAL STABILITY AND CONTROL OF A TILT-WING VTOL AIRCRAFT MODEL WITH RIGID AND FLAPPING PROPELLER BLADES

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LONGITUDINAL STABILITY AND CONTROL OF A TILT-WING VTOL AIRCRAFT MODEL WITH RIGID AND FLAPPING PROPELLER BLADES

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SUMMARY

An experimental investigation has been conducted to compare the effects of rigid and flapping propellers on the dynamic longitudinal-stability and control characteristics of a tilt-wing vertical-take-off-and-landing aircraft model in hovering and in the transition range from hovering to normal forward flight. The model had two interconnected three-blade propellers rotating in opposite directions with the thrust axes parallel to the wing chord. The investigation included both static force tests and flight tests with the model center of gravity at various locations.

In hovering flight, the pitching motions of the rigid-propeller configuration could be more easily controlled than those of the flapping-propeller configuration for similar conditions. In transition flight the model experienced large nose-up pitching moments that had to be trimmed out at low transition speeds, and these pitching moments were somewhat lower for the rigid-propeller configuration than for the flapping-propeller configuration. Consequently, with the same amount of pitch control available, the configuration with the rigid propellers could be controlled with a center-of-gravity location about 2-percent wing chord more rearward for the rigid-propeller configuration than for the flapping-propeller configuration.

INTRODUCTION

The relative merit of rigid and flapping propellers for use on tilt-wing VTOL aircraft is a subject of interest to aircraft designers from consideration of aerodynamic and structural problems. In an attempt to provide some aerodynamic information on this subject, the present investigation has been made with both rigid and flapping propellers on a tilt-wing VTOL aircraft model and has included dynamic longitudinal stability and control tests in both hovering and transition flight. The two sets of propellers used in these tests were identical except that one had conventional (rigidly mounted) blades, whereas the other had the blades mounted with flapping hinges. The flight tests included hovering well above the ground and slow constant-altitude transitions from hovering to forward flight. The force tests consisted of longitudinal stability and control tests in the transition-speed range.

SYMBOLS

F_D'	drag, lb
F_L	lift, lb
i_t	horizontal-tail incidence, positive trailing edge down, deg
i_w	wing incidence, deg
M_Y	pitching moment, ft-lb
V	scaled-up aircraft velocity, knots
α	angle of attack of fuselage, deg

APPARATUS AND TESTS

Model

The 1/4-scale model of the VZ-2 (Vertol 76) tilt-wing VTOL aircraft used in the tests of references 1 to 4 was also used in this investigation. A photograph of the model is shown in figure 1 and a three-view sketch showing some of the more important dimensions is shown in figure 2. Tables I and II list the geometric and mass characteristics of the model.

The wing was pivoted at the 37-percent-chord station and could be rotated between incidences of 4° and 86° during flight. The model was powered by a 6-horsepower electric motor which drove the two propellers through shafting and right-angle gear boxes. The speed of the motor was changed to vary the thrust of the propellers. The blade-form curves of the propellers are shown in figure 3.

The closeup photographs of the three-blade propeller hubs, which are seen in figure 4, show details of both the rigid and flapping propeller hubs. The flapping propeller provided for blade-flapping freedom and variable blade pitch, whereas the rigid propeller hub was variable only in blade pitch. In order to change from the flapping to the rigid configuration or vice versa, the complete propeller assemblies (including the hubs) were interchanged on the propeller shafts. The flapping propeller was designed for pure flapping motion with a flapping hinge offset 5/8 inch from the axis of rotation and with no drag hinges, no feathering, and no cyclic pitch. The three blades for any given hub were collectively controllable in pitch $\pm 1\frac{1}{2}^{\circ}$ from a 12° setting (at the 0.75 blade radius) for roll control in hovering and low-speed flight with the pitch of the right and left propellers being varied differentially.

For pitch and yaw control in hovering flight, the model had jet-reaction controls in the rear of the fuselage instead of the recessed tail fans in the horizontal and vertical tails which are used on the full-scale aircraft. The model also had an all-movable horizontal tail and conventional aileron and rudder controls for forward flight.

The controls were deflected by flicker-type (full on or off) pneumatic actuators which were operated remotely by the pilots by means of solenoid-operated valves. The control actuators were equipped with integrating-type trimmers which trimmed the controls a small amount each time a control was applied. With actuators of this type, a model becomes accurately trimmed after flying a short time in a given flight condition.

Test Equipment and Setup

The static force tests were conducted in the Langley full-scale tunnel under the same conditions as the tests presented in reference 1. The model was strut mounted, and the forces and moments were measured by using an internal strain-gage balance.

The transition-flight investigation was also conducted in the Langley full-scale tunnel with the test setup illustrated in figure 5. The electric power and compressed air are supplied to the model through a slack overhead line which also acts as a safety cable to prevent the model from crashing if it should go out of control. A more complete description of the test technique used in making free-flight model tests is given in reference 2. The hovering- and pitching-oscillation tests were made with an almost identical setup in a large building that provided protection from inclement weather and the random effects of outside air currents.

Flight Tests

Flight tests were made with both the rigid- and flapping-propeller configurations in hovering and transition flight. The detailed flight-test results for the flapping-propeller configuration have been presented previously in reference 2. The results that are most pertinent with regard to the comparison of the flapping- and rigid-propeller configurations are repeated herein for comparison with the test results obtained with the rigid-propeller configuration. Since the comparison of the flapping- and rigid-propeller configurations relies to a considerable extent on the pilot's qualitative observations, it is important to note that the flight tests for the two configurations were made within a week of each other under comparable conditions.

Hovering-flight tests were made to determine the stability of the uncontrolled pitching motions and the ease with which the pilot could control these motions. The hovering flights were made with a pitch jet force of ±3.6 percent of the model weight. Transition-flight tests representing slow constant-altitude transitions were made with both the flapping- and the rigid-propeller configurations in order to study the stability and control characteristics of the model and to determine the effects of center-of-gravity position.

The center of gravity of the model for the hovering-flight tests was located 1-percent chord forward of and 15.8-percent chord below the wing pivot. For the transition flight tests the model was ballasted to several different center-of-gravity conditions. Actually, for the transition condition, the center of gravity of the model moved downward approximately 5-percent chord and forward approximately 5-percent chord as the wing rotated from 86° to 4° incidence.

Force Tests

Force tests were made to measure the longitudinal-stability and control characteristics of the flapping- and rigid-propeller configurations in the transition condition. The data for the flapping-propeller configuration have been previously presented in reference 1 scaled up to represent the full-scale VZ-2 aircraft at a weight of 3,139 pounds. Some of these data are repeated in this paper for comparison with data for the rigid-propeller configuration which are scaled up to the same condition. The tests were made with power settings (propeller rotational speed) which, with the fuselage at zero angle of attack, gave zero forward acceleration at wing incidences of 20°, 40°, 60°, and 80°. The angle of attack was varied from -15° to 20° with the horizontal tail either off or set at a 15° angle of incidence. Since conventional aerodynamic coefficients approach infinity and lose their significance as the airspeed approaches zero, the data have been scaled up to a full-scale weight of 3,139 pounds, and the center-of-gravity locations of the full-scale aircraft are listed in table III.

RESULTS AND DISCUSSION

Hovering

When the model was first flown with the rigid propellers, after having been flown previously with the flapping propellers, the pitch pilot was immediately impressed by the fact that the model was steadier in pitch and that the pitching motions could be controlled more easily for normal hovering flight for the same center-of-gravity position and with the same amount of pitch control available. When the pitch pilot subsequently allowed the unstable controls-fixed pitching oscillation to build up and then tried to stop the oscillation and regain control of the model, the difference was also very apparent. With the rigid propellers installed, the pitch pilot was able to stop the oscillation consistently and to regain control of the model fairly easily; whereas, with the flapping-propeller configuration, he was unable to stop the oscillation, as pointed out in reference 2. This difference in steadiness and ease of control probably resulted from the fact that the model seemed to have more damping in pitch and a less unstable pitching oscillation with the rigid blades than with the flapping blades.

The present investigation was intended only as a study of longitudinal stability and control, and no attempt was made to determine the characteristics of the model in roll and yaw; however, there was no effect of the change in propeller configuration on the rolling or yawing behavior of the model that was sufficiently pronounced to be noted by the roll and yaw pilots, who were only concerned with controlling their phases of the model motion as smoothly as possible to facilitate the study of the pitching motions.

Transition

The model developed a large nose-up pitching moment as it started through transition as pointed out in reference 2. This same characteristic was observed in flight tests of the full-scale VZ-2 aircraft as indicated in references 5 to 7 which might be of interest in connection with the present investigation. The nose-up moment during the low-speed part of the transition, together with the ability of the pitch control to trim it out, establishes the rearward end of the allowable center-of-gravity range. Force and flight tests were made to establish any difference in the allowable rearward center of gravity between the rigid- and flapping-blade configurations.

Force tests.- The basic force-test data in figure 6 are presented for both the flapping- and rigid-propeller configurations in the transition range for angles of wing incidence from 80° to 20°. A cross plot of the pitching-moment data of figure 6 at 0° fuselage angle of attack against forward velocity is presented in figure 7 to illustrate more clearly the trim problems at low speeds in the transition-flight range.

The trim problem due to the large nose-up pitching moments at low speeds has been discussed in reference 4 for the flapping-propeller configuration and would apply similarly to the rigid-propeller configuration. That is, there is a tendency with both the rigid- and flapping-propeller configurations for the nose-up pitching moments on the model to build up to a maximum at the start of transition and then to decrease with buildup of forward speed. The nose-up pitching moments reach a higher maximum for the flapping-propeller configuration than for the rigid-propeller configuration, and tend to remain higher with increasing forward speed. It can thus be seen from the force tests that for a given margin of pitch control, a pilot could control a rigid-propeller aircraft with a center-of-gravity location slightly more rearward than for a flapping-propeller aircraft. In fact, calculations based on the fairing of the curves shown in figure 7 indicate that the model could have been trimmed with the center of gravity about 2-percent wing chord farther rearward for the rigid-propeller configuration than for the flapping-propeller configurations.

Flight tests.- The flight tests also showed that the model experienced a large nose-up pitching moment at the lower speeds during the transition and that this nose-up moment was larger for the flapping-propeller configuration than for the rigid-propeller configuration. This fact was evident to the pilot in a qualitative way in that he had to apply considerable nose-down trim at low transition speeds and the amount of trim required for a given center-of-gravity position was greater for the flapping-propeller configuration. It was also evident in a more qualitative way in that with the same amount of pitch-control moment available, the rigid-propeller configuration could be flown with a center of gravity 3-percent wing chord farther rearward for the rigid-propeller configuration than for the flapping-propeller configuration. This value of 3 percent should be considered only approximate, however, since the center of gravity was moved in 3-percent increments.

Inasmuch as the forward end of the center-of-gravity range, which was established by the ability of the pilot to trim the model in hovering flight as shown in reference 2, would not be changed by the use of rigid propellers, the effect of the propellers on the rearward end of the center-of-gravity range would indicate that the model would have an allowable center-of-gravity range about 3-percent wing chord larger with rigid propellers than with flapping propellers.

Here again, it seems worthwhile to point out that the differences in propeller configuration (flapping or rigid) had no effects on the rolling and yawing behavior of the model that were great enough to be noticed by the roll and yaw pilots, who were primarily concerned with controlling their phases of the model motion as steadily as possible in order to facilitate the study of the characteristics of the model in pitch.

CONCLUSIONS

The results of this investigation of the longitudinal stability and control can be summarized as follows:

1. The pilot found that the model could be controlled more easily in hovering flight with the rigid-propeller configuration than with the flapping-propeller configuration under similar conditions, apparently because of greater damping in pitch and a less unstable pitching oscillation for the rigid-propeller configuration.

2. In transition flight, the model experienced large nose-up pitching moments that had to be trimmed out at low transition speeds; these pitching moments were somewhat lower for the rigid-propeller configuration than for the flapping-propeller configuration. Consequently, with the same amount of pitch control available, the pitch pilot could control the rigid-propeller configuration with a center-of-gravity location about 2-percent wing chord more rearward for the rigid-propeller configuration than for the flapping-propeller configuration.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., April 12, 1962.

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1. Newsom, William A., Jr., and Tosti, Louis P.: Force-Test Investigation of the Stability and Control Characteristics of a 1/4-Scale Model of a Tilt-Wing Vertical-Take-Off-And-Landing Aircraft. NASA MEMO 11-3-58L, 1959.

2. Tosti, Louis P.: Flight Investigation of the Stability and Control Characteristics of a 1/4-Scale Model of a Tilt-Wing Vertical-Take-Off-And-Landing Aircraft. NASA MEMO 11-4-58L, 1959.

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TABLE I

SCALED-UP GEOMETRIC CHARACTERISTICS OF THE MODEL

Propellers (3 blades each rotor):	
Diameter, ft	9.33
Solidity	0.239
Chord, ft	1.0
Flapping hinge offset, ft	0.208
Wing:	
Pivot station, percent chord	37
Sweepback (leading edge), deg	0
Airfoil section	NACA 4415
Aspect ratio	5.42
Chord, ft	4.75
Taper ratio	1.0
Area, sq ft	118.2
Span, ft	24.88
Dihedral angle, deg	0
Ailerons (each) -	
Chord, ft	1.22
Span, ft	5.83
Hinge line, percent chord	74.1
Vertical tail:	
Sweepback (leading edge), deg	0
Airfoil section	NACA 0012
Aspect ratio	1.25
Chord, ft	4.0
Taper ratio	1.0
Area, sq ft	20
Span, ft	5.0
Rudder (hinge line perpendicular to fuselage center line) -	
Chord, ft	1.25
Span, ft	5.0
Horizontal tail:	
Sweepback (leading edge), deg	0
Airfoil section	NACA 0012
Aspect ratio	3.10
Chord, ft	3.0
Center-section chord, ft	4.21
Area (including center body), sq ft	33.2
Span, ft	9.90
Dihedral angle, deg	0

TABLE II

COMPARISON OF MASS CHARACTERISTICS OF MODEL (SCALED-UP)

AND FULL-SCALE AIRCRAFT

	Model (scaled-up)	Full-scale aircraft
Gross take-off weight (including one pilot and research instrumentation), lb	3,533	3,290
Rolling moment of inertia, I_X, slug-ft^2 (hovering configuration)	3,280	1,811
Pitching moment of inertia, I_Y, slug-ft^2 (hovering configuration)	3,890	2,851
Yawing moment of inertia, I_Z, slug-ft^2 (hovering configuration)	5,330	3,779

TABLE III

CENTER-OF-GRAVITY LOCATIONS FOR VARIOUS WING INCIDENCE ANGLES

[Weight, 3,139 lb]

i_w, deg	Center-of-gravity position (from wing pivot), ft	
	Horizontal (forward)	Vertical (below)
4	0.490	1.310
20	.460	1.228
40	.394	1.120
60	.297	1.057
80	.180	1.023

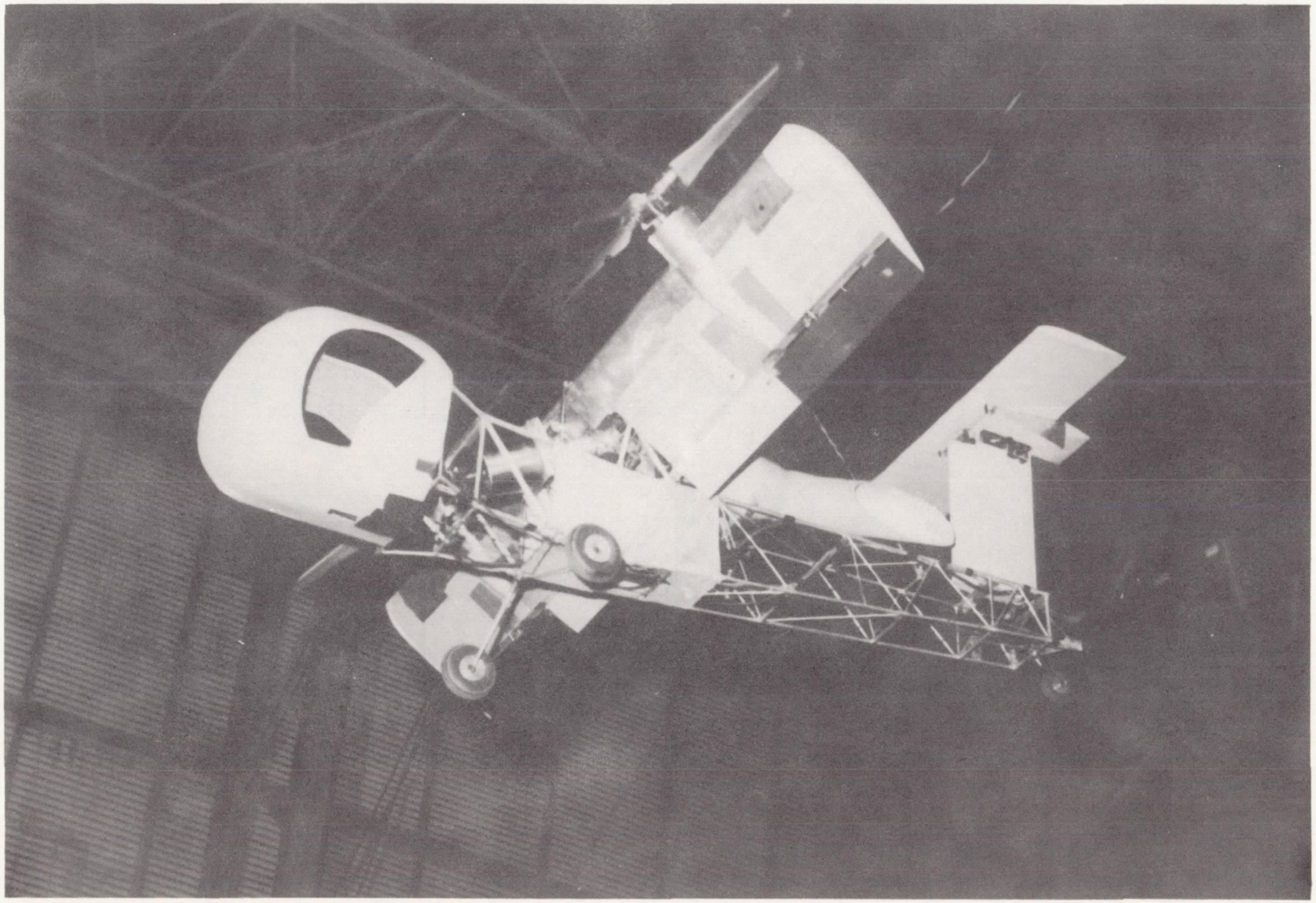

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Figure 1.- Photograph of tilt-wing VTOL model during transition flight in Langley full-scale tunnel.

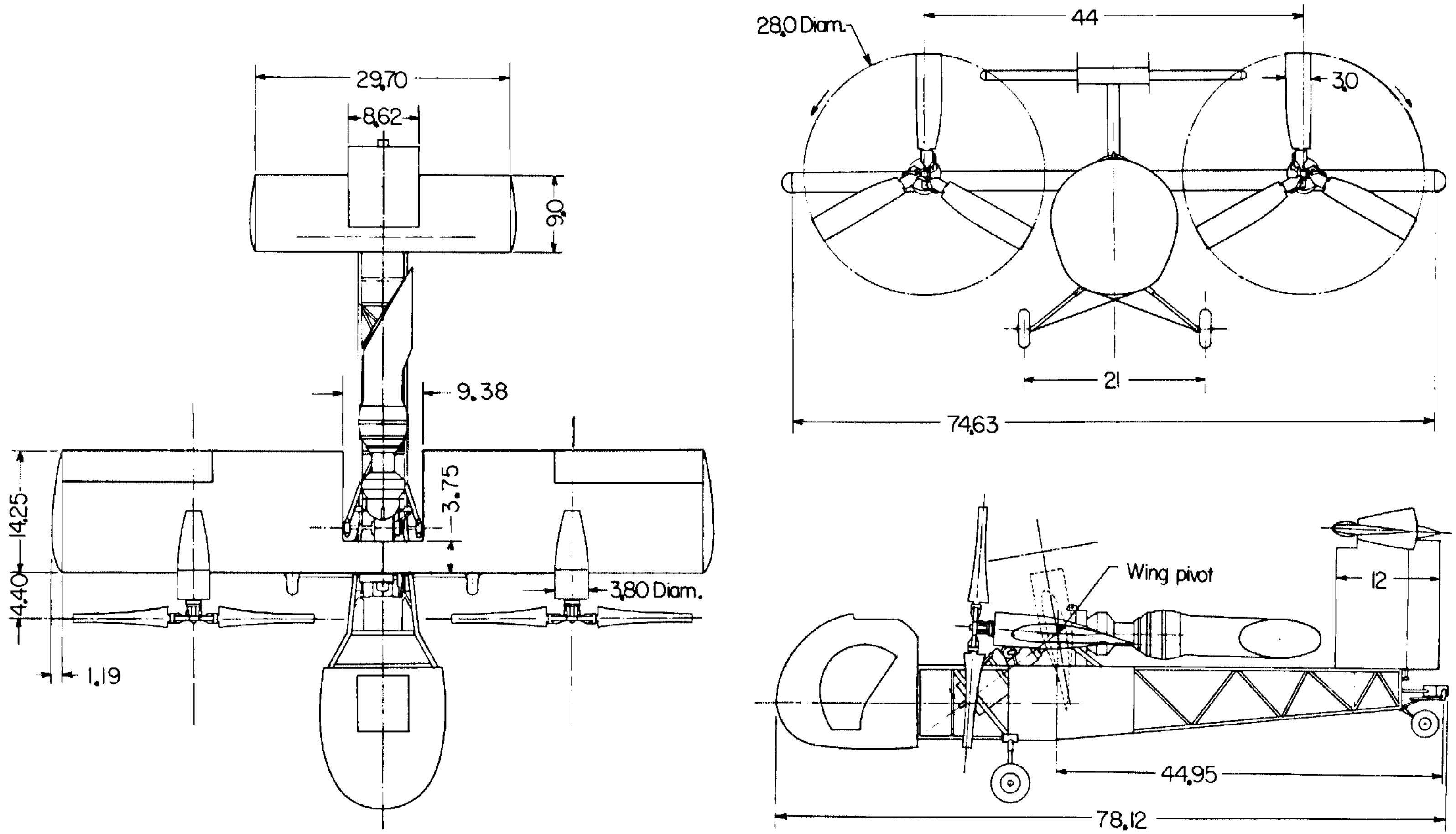


Figure 2.- Three-view sketch of model. All dimensions are in inches.

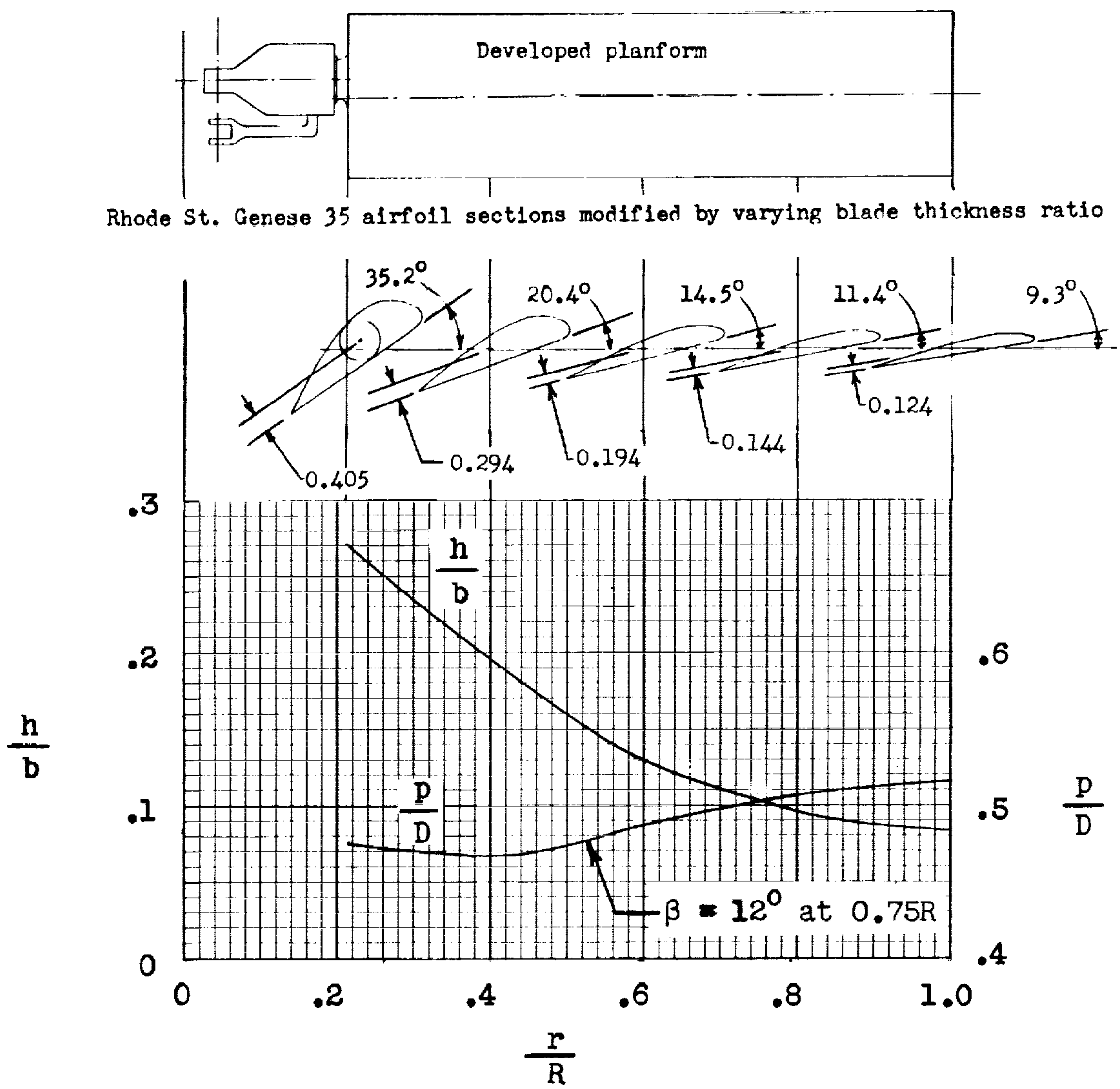
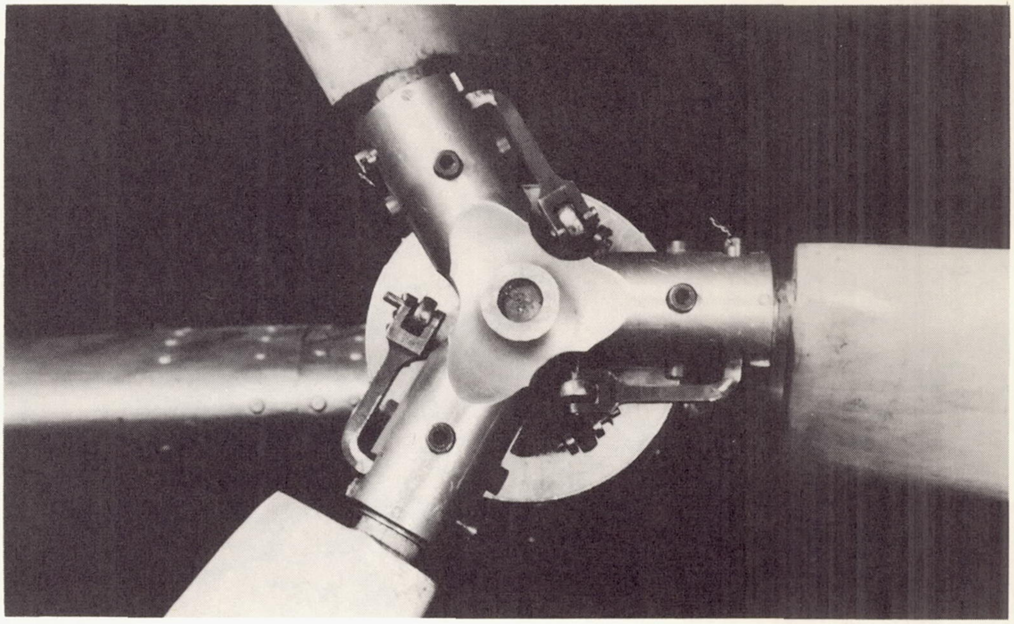
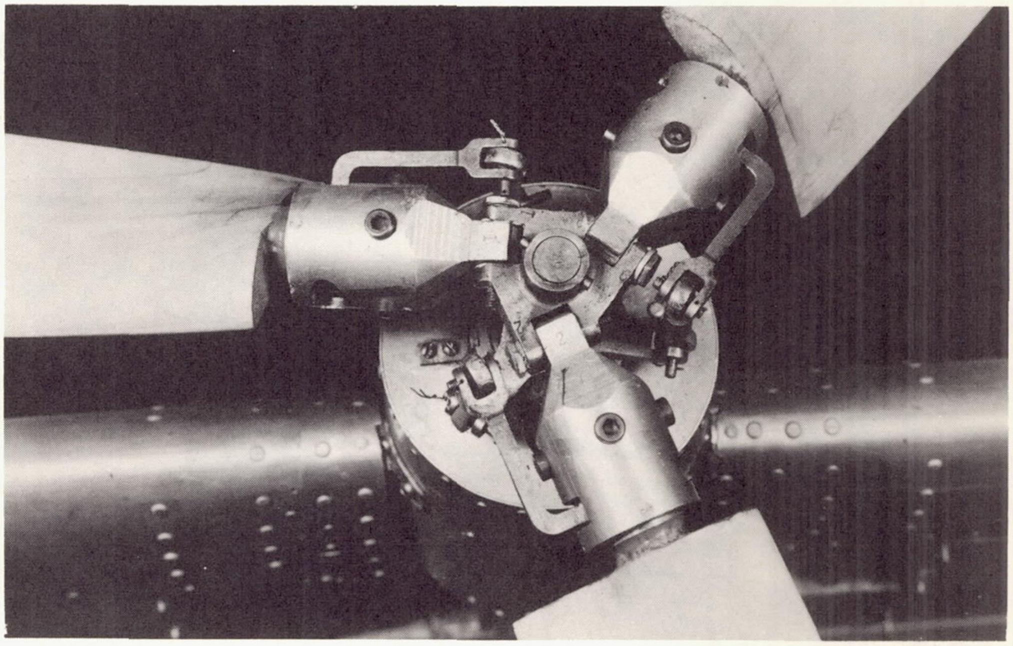


Figure 3.- Blade-form curves. In this figure, symbols are as follows: D, diameter (D = 28 in.); R, radius; r, station radius; b, section chord (b = 3.0 in.); h, section thickness; p, geometric pitch ($p = 2\pi r \tan \beta$); β, section blade angle.



(a) Rigid-propeller hub. L-59-3696



(b) Flapping-propeller hub. L-59-3695

Figure 4.- Photographs of hubs of rigid and flapping propellers.

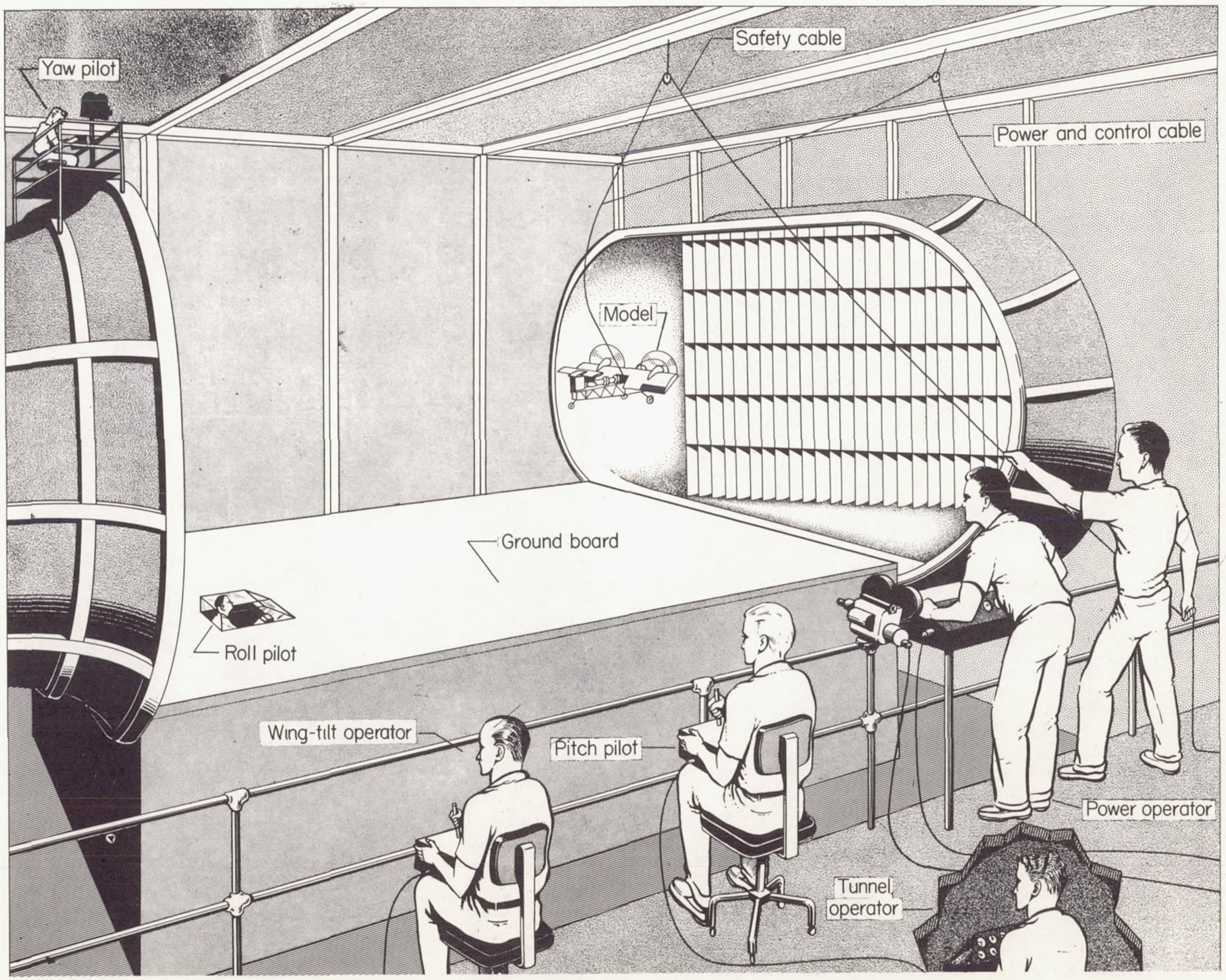
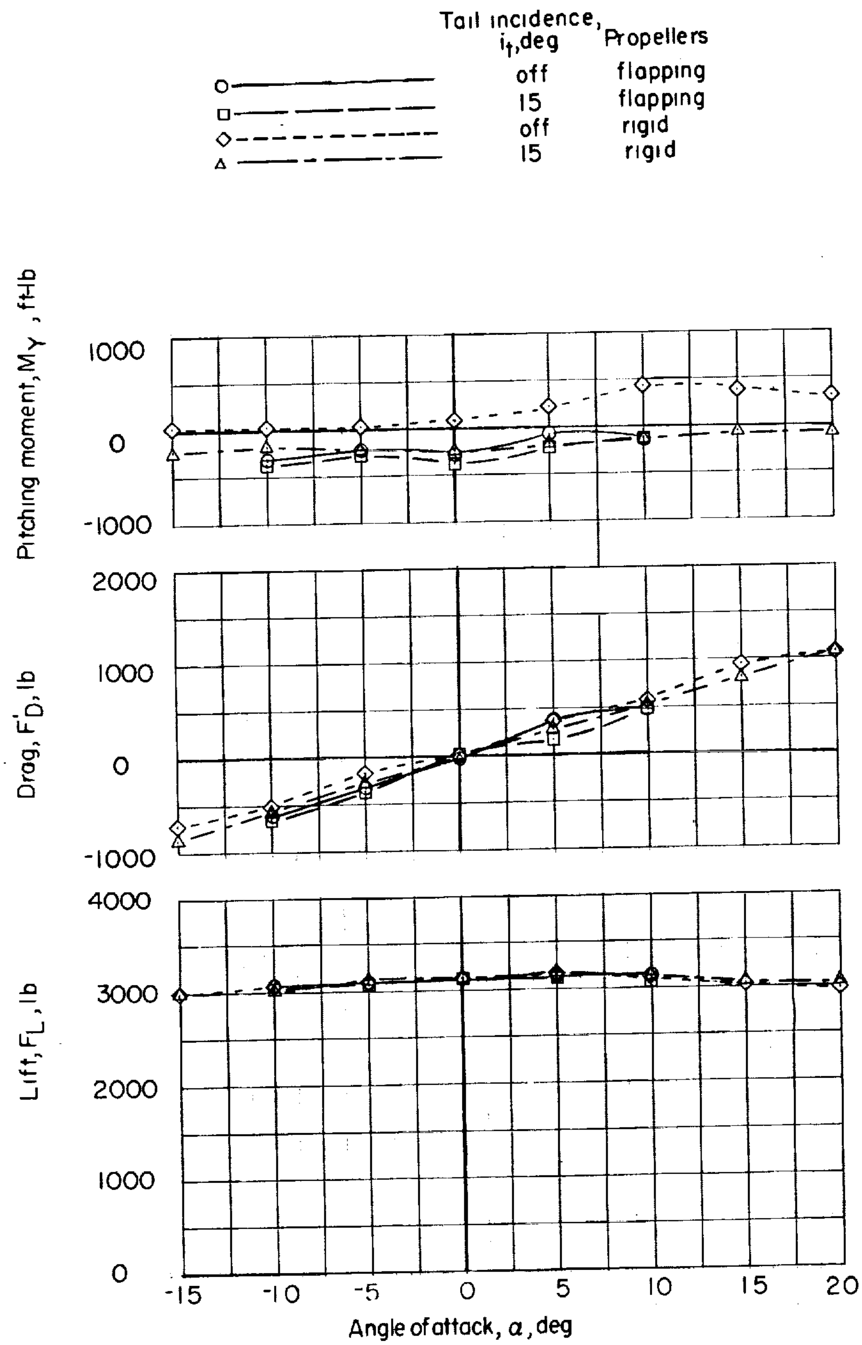
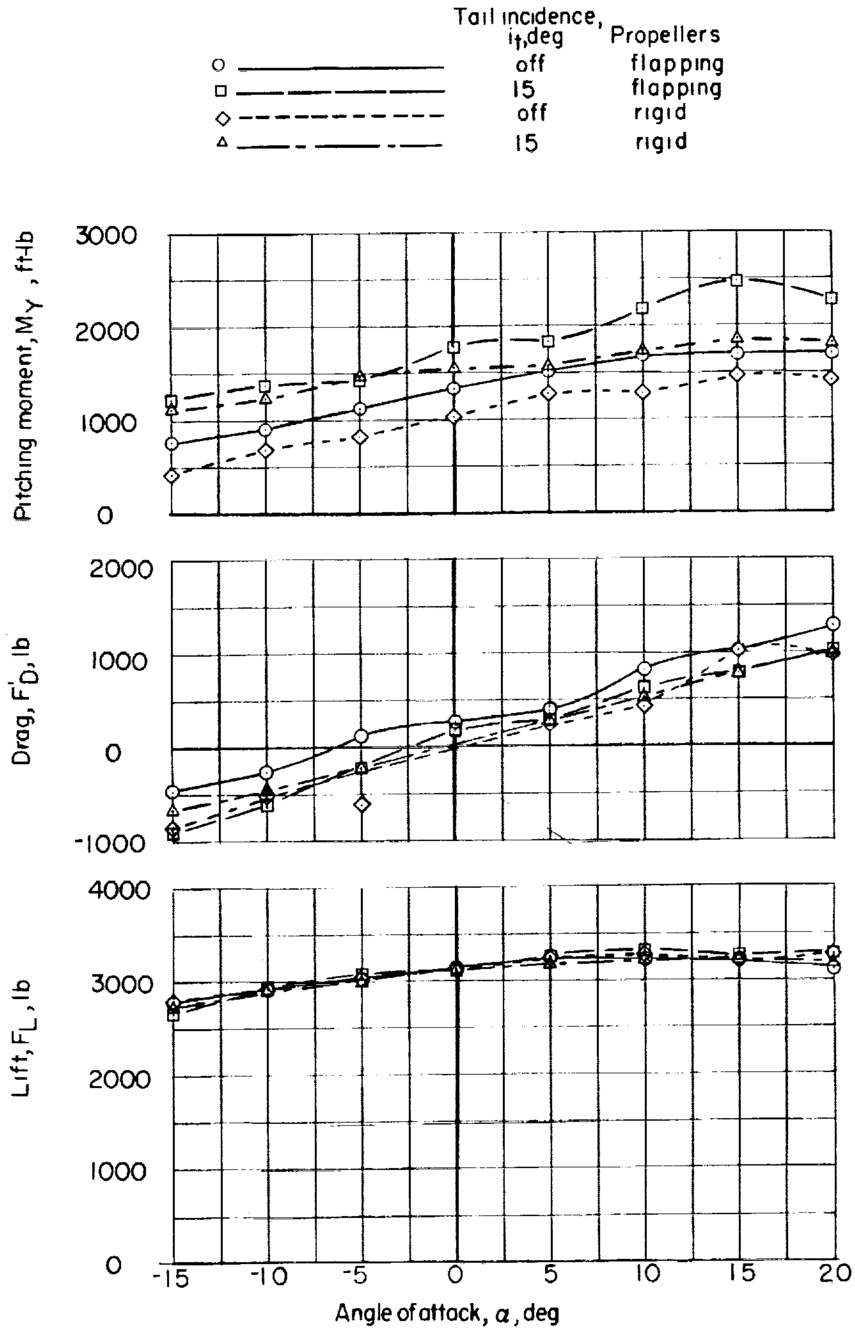


Figure 5.- Sketch of the flight-test setup in the Langley full-scale tunnel.



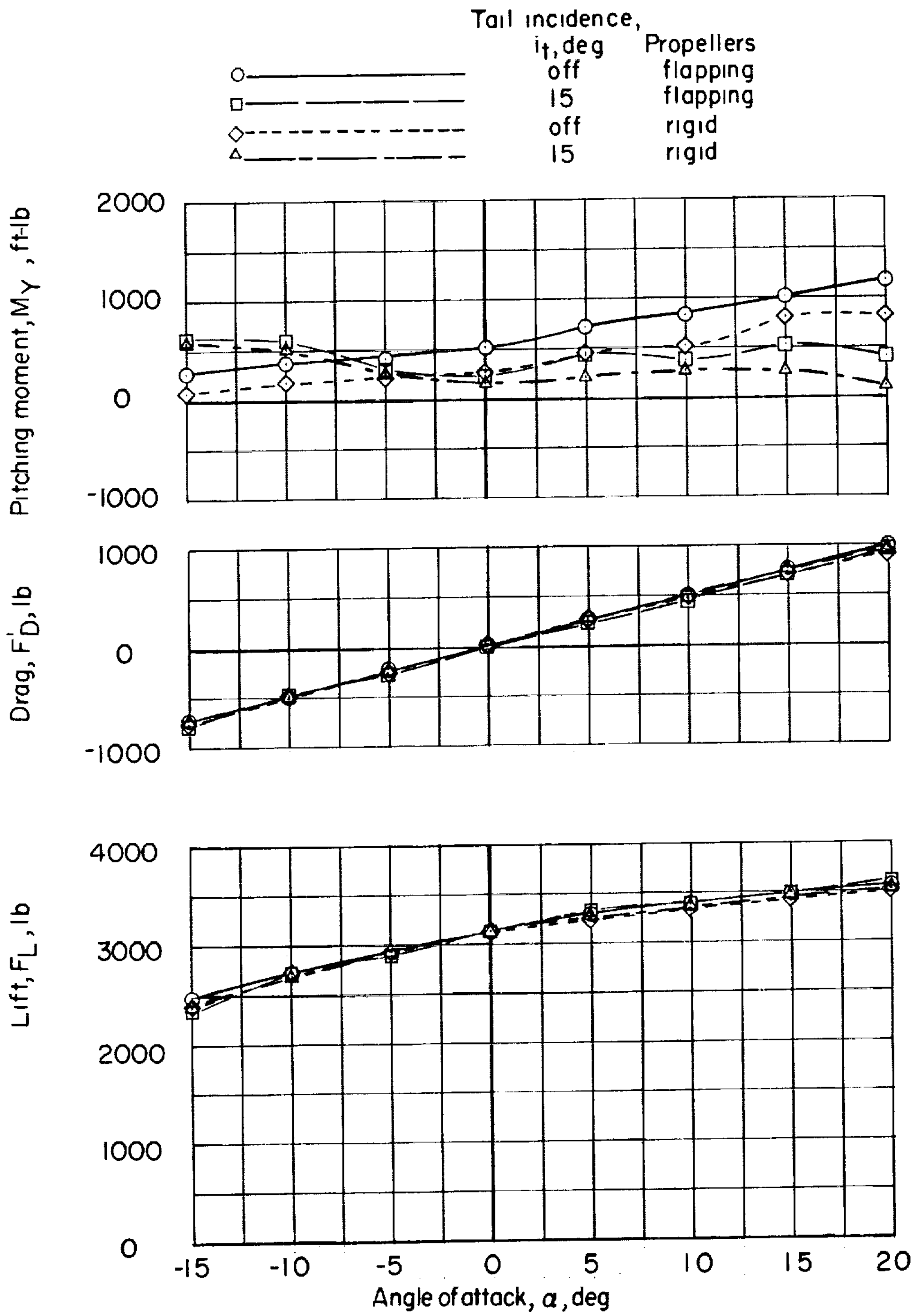
(a) $i_w = 80^\circ$; V = 8.5 knots.

Figure 6.- Effects of flapping and rigid propellers on the longitudinal stability and control characteristics in transition flight.



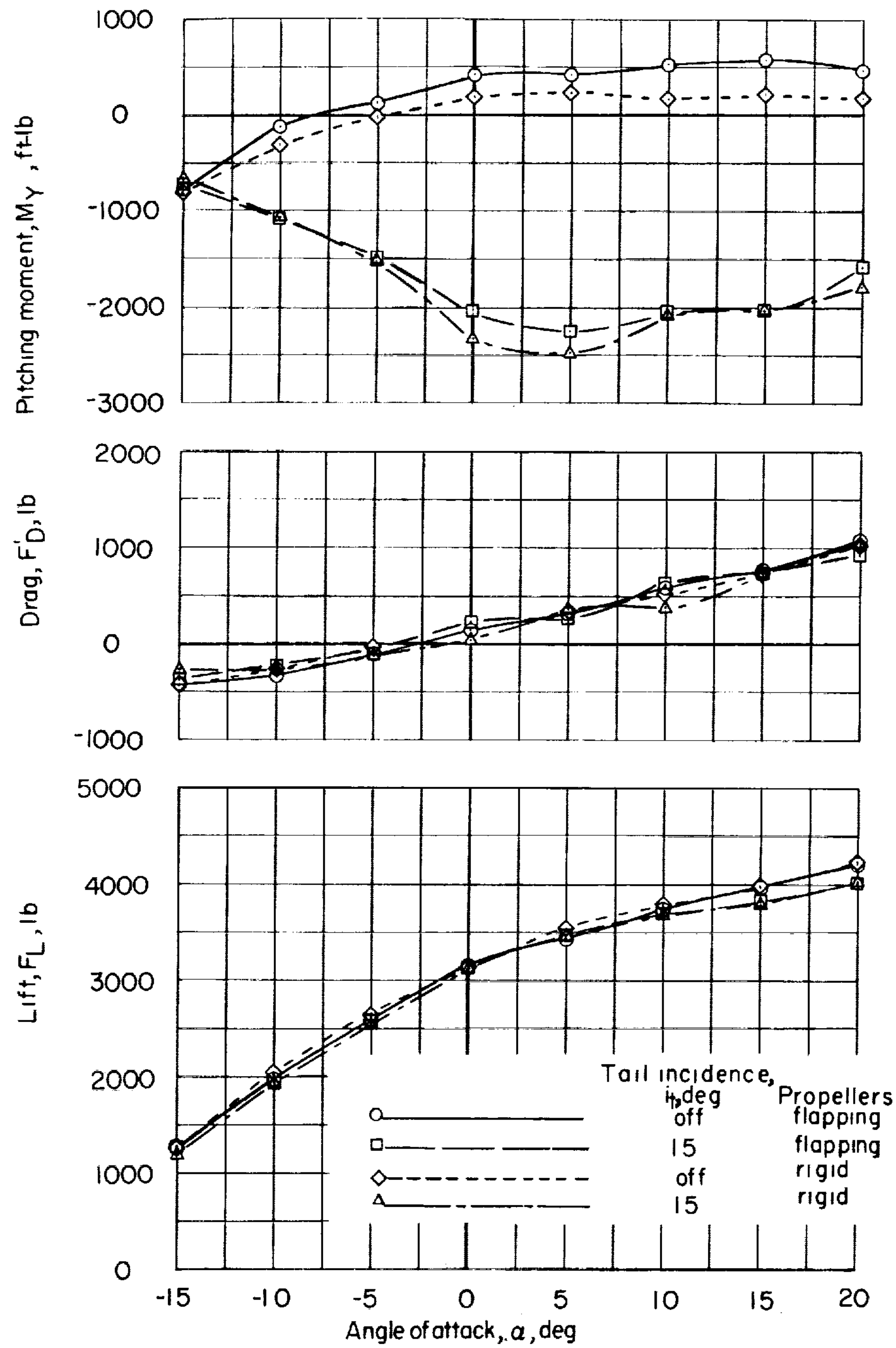
(b) $i_w = 60^{\circ}$; V = 29.8 knots.

Figure 6.- Continued.



(c) $i_w = 40^o$; V = 43.0 knots.

Figure 6.- Continued.



(d) $i_w = 20^o$; V = 68.5 knots.

Figure 6.- Concluded.

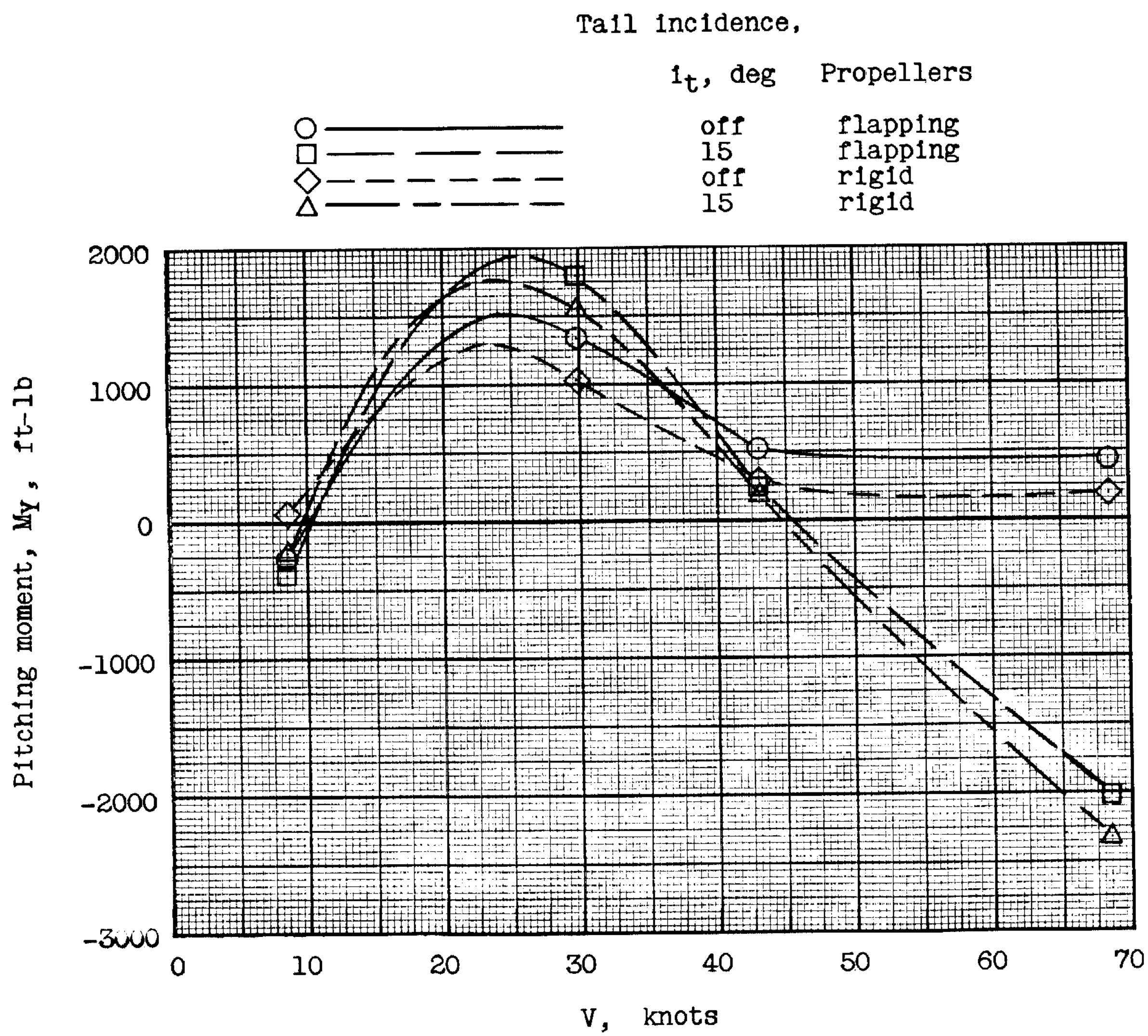


Figure 7.- Effect of flapping and rigid propellers on the pitching moment in transition flight at $\alpha = 0^{\circ}$.