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SUMMARY

An investigation of the static and dynamic stability and control characteristics in hovering and at low forward speeds has been made on a small-scale flying model of an aerial vehicle supported by two unshrouded propellers that were fixed with respect to the airframe so that the propeller plane of rotation was horizontal for hovering flight. The model in its basic configuration consisted of a boxlike body in the center, with the two propellers mounted in tandem on struts in front of and behind the body and guard rings around the propellers.

The investigation showed that in hovering, the controls-fixed pitching and rolling motions of the model were unstable oscillations. Since the periods of the oscillations were relatively long, however, the model could be controlled fairly easily in hovering without artificial stabilization. In forward flight, the basic model required an increasing nose-down attitude for drag trim as the forward speed was increased and became very difficult to control longitudinally at speeds above 21 knots, mainly because of increasing static longitudinal instability of angle of attack. For reasonably satisfactory stability and control characteristics in forward flight, and particularly for speeds above 21 knots (38 knots, full scale), horizontal and vertical tails were required.

INTRODUCTION

The National Aeronautics and Space Administration has investigated simplified models of a number of configurations that might be suitable for a light, general-purpose VTOL aerial vehicle. As originally visualized, these vehicles would be able to hover or fly forward at speeds up to about 60 knots and would carry a payload of about 1,000 pounds. Basically, they consist of a body for the engine, pilot, and cargo supported by two or more propellers that are either shrouded or unshrouded. The propeller plane of rotation is horizontal for hovering flight and, for most configurations, is fixed with respect to the airframe.

The results of an investigation of a 1/3-scale model of a vehicle having two fixed shrouded propellers are reported in references 1 and 2, and the results of a similar investigation of a model with four shrouded propellers are reported in reference 3. Two rather serious problems brought out in these tests which seem inherent in any simple shrouded-propeller configuration in forward flight are an undesirably large nose-down pitch attitude required for trim at the higher speeds and a nose-up pitching moment which increases rapidly with increasing forward speed.

One approach to the problem of excessive nose-down pitch attitudes required for higher speeds is to tilt the shrouded propellers with respect to the airframe. Reference 4 gives the results of an investigation of a model that had three shrouded propellers in a triangular arrangement, one in front and two at the rear, that could be tilted with respect to the airframe.

Another approach to the problem of the undesirable pitching-moment and pitch-attitude characteristics of the fixed shrouded-propeller configurations is the use of unshrouded propellers because of the smaller pitching moment and drag resulting from translational velocity. References 5 and 6 give the results of an investigation made with a model which had four unshrouded propellers that were fixed with respect to the airframe so that the propeller plane of rotation was horizontal for hovering flight.

The present investigation was made with a model which had two unshrouded propellers in tandem that were fixed with respect to the airframe so that the propeller plane of rotation was horizontal for hovering flight. This paper presents the results of a series of free-flight tests and static force tests performed in the Langley full-scale tunnel to obtain the static and dynamic stability and control characteristics of the model in hovering and in forward flight. The flight-test results were obtained mainly from pilots' observations and from studies of motion-picture records of the flights.

SYMBOLS

The longitudinal forces and moments were determined with respect to the wind axes and the lateral forces and moments were determined with respect to the body axes. The axes originated at the center of gravity of the model.

c — chord of horizontal tail, in.

F_L — lift force, lb

F_D — drag force, lb

F_Y — side force, lb

M_Y — pitching moment, ft-lb

M_X — rolling moment, ft-lb

M_Z — yawing moment, ft-lb

M_{Y_α} variation of pitching moment with angle of attack, ft-lb/deg

M_{Y_V} variation of pitching moment with forward speed, ft-lb/knot

F_{Y_β} variation of side force with angle of sideslip, lb/deg

M_{X_β} variation of rolling moment with angle of sideslip, ft-lb/deg

M_{Z_β} variation of yawing moment with angle of sideslip, ft-lb/deg

i_t horizontal-tail incidence relative to fuselage axis, positive when trailing edge is down, deg

α angle of attack of fuselage axis relative to horizontal (tilt angle), deg

β angle of sideslip, deg

APPARATUS AND TESTS

Model

The basic model is shown in the photograph of figure 1 and the sketch of figure 2. The model was a simplified research vehicle that was not intended to represent any specific full-scale machine but the size was such as to represent approximately a 0.3-scale model of proposed full-scale machines. The model was designed to have the same size cargo box and the same width as the earlier models in references 1, 3, and 5.

The model propellers were of laminated-wood construction and had fixed blade angles of 13° at 0.75 radius. The propellers were driven through gearboxes and interconnecting shafting by a pneumatic motor which was controlled by a throttling valve. The propeller guard rings were intended to protect the propellers without appreciably affecting the propeller characteristics and therefore were made of relatively small diameter tubing and located so as to provide a large tip clearance. The center of gravity of the model was at the geometric center of the model and in the plane of the propellers.

Figure 3 shows the horizontal- and vertical-tail surfaces that were added to the basic configuration. The horizontal tails had an airfoil shape and were mounted outboard of the propeller guard rings. The vertical tail was a flat plate and was mounted under the rear half of the rear propeller.

For all of the tests the model control moments (pitch, roll, and yaw) were provided by small compressed-air jets located at the side and rear of the model as shown in figure 3. These jet-reaction controls were operated by the pilots who controlled them remotely through the use of flicker-type (on or off) electro-pneumatic actuators. The actuators were equipped with integrating-type trimmers which trimmed the control a small amount in the direction the control was moved each time a control deflection was applied. With actuators of this type, a model becomes accurately trimmed after flying a short time in a given flight condition.

The flicker-control moments used during the tests were about ±17 foot-pounds in pitch, ±6 foot-pounds in roll, and ±9 foot-pounds in yaw. Total travel on the pitch jet-reaction control (flicker control plus trim) provided ±28 foot-pounds of moment which resulted in ±11 foot-pounds of pitch trim being available before a reduction of flicker control occurred.

The weight and mass characteristics of the model varied somewhat from one phase of testing to another, as tails, ballast weights, etc., were added or removed. The following values are felt to be reasonably representative of average values for the model and varied not more than ±10 percent during the tests.

Weight, lb	52
Moment of inertia about pitch axis, slug-ft^2	4.1
Moment of inertia about roll axis, slug-ft^2	1.6
Moment of inertia about yaw axis, slug-ft^2	5.6

Tests and Testing Techniques

Flight tests.- The flight tests were made to determine the dynamic stability and control characteristics of the basic model in hovering flight in still air and in forward flight up to a model speed of about 33 knots (60 knots, full scale). In addition, horizontal- and vertical-tail surfaces were added to improve the stability and control characteristics at the higher forward speeds.

Figure 4 shows the test setup for the flight tests 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 and yaw pilots were located in an enclosure in the lower rear part of the test section. All of these operators 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 at the side and at the upper rear of the test section.

The air to drive the propellers and for the jet-reaction controls was supplied to the model through flexible plastic hoses, and the power for the electric control solenoids was supplied through wires. These wires and tubes were suspended from overhead and taped to a safety cable of 1/16-inch aircraft cable from a point approximately 15 feet above the model down to the model. The safety cable, which was attached to the model at the center of gravity, 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 during the normal course of the tests.

The test technique is best explained by describing a typical flight. The model hung from the safety cable with the tunnel airspeed at zero, the model power was increased until the safety cable became slack and the model was in steady hovering flight. The tunnel drive motors were turned on and the airspeed began to increase. As the airspeed increased, the pitch pilot applied nose-down control and trim to tilt the model to the required attitude and the power operator adjusted the power to the model propellers in order to provide the thrust needed to balance the lift and drag of the model and to keep the model as near as possible to 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.

Hovering-flight tests were made with the same technique and setup except that the tunnel test section was not needed nor used. The tests were performed in a large enclosed area (one of the return passages of the Langley full-scale tunnel) which provided protection from random disturbances due to wind and was large enough to reduce the slipstream recirculation effects to negligible values.

Force tests.- Force tests were made to determine the static stability and control characteristics of the model for correlation with the flight-test results.

The model was secured, through an internal six-component strain-gage balance, to a portable sting and strut support system. The model and support assembly was then installed in the 30- by 60-foot test section of the Langley full-scale tunnel. The static longitudinal characteristics of the model were investigated by setting a tunnel speed and then covering a range of angles of attack from 0° to -35° at a constant model propeller speed. Normal force, axial force, and pitching moment were recorded at each test point. Such tests were made at each of several tunnel speeds in a range from 0 to 30 knots. The longitudinal characteristics were investigated for the basic configuration and for the basic configuration with horizontal-tail surfaces added at incidence angles i_t from 20° to 40°.

The static lateral characteristics of the model were investigated for angles of sideslip between 20° and -20° at angles of attack between 0° and -30°. For each angle of attack investigated, the tunnel speed was adjusted to give zero drag for an angle of sideslip of 0°. The effect of a vertical-tail surface mounted under the rear half of the rear propellers was investigated. In addition, the effect of the horizontal tail on the lateral characteristics was also determined.

No wind-tunnel corrections have been applied to the data since the model is very small in proportion to the size of the tunnel. Since conventional aerodynamic coefficients lose their significance and tend to become infinite as the airspeed approaches zero, the results of the force tests are presented in dimensional form. The model used in this investigation was constructed primarily for the flight tests and the construction techniques used were not well suited for high-power runs for extended periods of time as required in force testing. The force tests, therefore, were run at reduced model power. Except for the basic longitudinal data, the forces, moments, and velocities presented in this report have been scaled up to correspond to the flying weight of the model.

RESULTS AND DISCUSSION

Hovering Flight

In hovering flight the model had unstable oscillations in both pitch and roll (as has been the case for the models reported in references 2, 3, and 6), the rolling oscillation being somewhat more difficult to control because of its greater instability. Time histories of typical controls-fixed pitch and roll oscillations, obtained from motion-picture records of model flights, are presented in figures 5 and 6, respectively. The approximate periods and damping of these oscillations, as measured from these records, were:

	Pitch	Roll
Period, sec	5.25	3.50
Time to double amplitude, sec	1.55	0.80
Time to double amplitude, cycles	0.30	0.23

In spite of the instability of these oscillations, the model could be controlled fairly easily in hovering flight, particularly in pitch, mainly because the periods of the oscillations were fairly long and the control power was adequate. The controllability of the present model in roll was found to be better than for any of the models reported in references 2, 3, or 6. The shrouded-propeller models of references 2 and 3 were extremely difficult to control in roll without artificial stabilization because the oscillations had very short periods, were very unstable, seemed to be predominantly angular motions, and were very easily excited by translational movement or horizontal gusts. The model of reference 6, which had four unshrouded propellers, was much easier to control by remote control but did have a tendency to translate or "slide" considerably as a result of very little change in angle of roll. This tendency resulted in the model being somewhat difficult to fly steadily or to stop at an exact spot after a maneuver. The present unshrouded model was a little easier to fly in roll or to position accurately than the model of reference 6 although it still required careful pilot attention. At times, the pitch pilot could demonstrate the controllability of the model by letting the pitching oscillation build up and then apply control to stop the oscillation. The roll pilot, however, could not always stop an oscillation if he allowed it to develop.

A few hovering-flight tests were made with the tail surfaces shown in figure 3 installed on the model. There was no noticeable difference in the pitching motion of the model. In roll, however, the tails made the model a little easier to control, probably because of the increased damping and inertia of the horizontal tails.

No difficulty was experienced in controlling the model in yaw. As might be expected, the model was neutrally stable about the yaw axis in hovering and could be controlled easily for the very limited conditions covered in the tests - flight in still air and maintaining a given heading as the only task for which the yaw control was used.

Forward Flight

The basic longitudinal data from the force tests are presented in figure 7 and a summary of the model's static longitudinal characteristics is shown in figure 8. The basic lateral data from the force tests are presented in figure 9 and a summary of the model's static lateral characteristics is shown in figure 10. These data will be discussed in the following sections along with the results of the model flight tests.

Longitudinal characteristics.- The flight tests showed that as the forward speed increased, the basic model without tails required an increasing nose-down moment for pitch trim and an increasing nose-down attitude for drag trim. At 11 knots (20 knots, full scale) the model required about 11 foot-pounds of nose-down pitch trim and, as the speed increased, additional pitch trim was required at the expense of the flicker-control moment available in this direction. Finally, at a speed of about 21 knots (38 knots, full scale), the model became very difficult to control and experienced fairly rapid pitch-up divergences. The pilot believed that this condition was caused by two factors. First, the trim requirement was so great that there was only about one-half the nose-down control left to arrest the nose-up motion. Secondly, as the forward speed increased, the model seemed to have an increasing static longitudinal instability of angle of attack. To check on the reduced control factor, the available pitch trim was increased by 9 foot-pounds which again gave the pilot about the full ±17 foot-pounds of flicker control at 21 knots. With this increased control power, the model could be controlled more easily at 21 knots and flights were made to about 26 knots, but at this speed the pitch pilot again lost control of the model.

Figure 8 presents a summary of the tilt-angle α and pitching-moment variations with forward speed for the basic model and for the model with horizontal tails installed. The data for the basic model show the increasing nose-down attitude required for drag trim and the increasing pitching moment and increasing static longitudinal instability of angle of attack with forward speed. The data show that at 21 knots, the basic model required 17 foot-pounds of pitch trim and had a static attitude instability of 0.45 foot-pound per degree of angle-of-attack change. The data further show that there was no appreciable increase in pitch trim required above 21 knots and that the static longitudinal instability increased to a value of about 0.60 foot-pound per degree of angle-of-attack change at about 25 knots and stayed at this value with increasing speed.

Even though the force test data indicate no increases in the static instability or longitudinal trim above 26 knots, the model could not be flown above this speed even with the increased pitch control. The probable reason for this was that with a given level of static longitudinal instability the normal accelerations resulting from a given angular divergence became so large with increasing speed that it was too difficult to fly the model in the tunnel test section at speeds above 26 knots.

In order to improve the behavior of the model at the higher speeds, horizontal-tail surfaces (shown in fig. 3) were installed on the model. Most of the flight tests were made with a tail incidence of about 25°. With the tails installed the model motions were very smooth and the model was easy to fly up to 30 knots which was the highest speed tested. At speeds above 20 knots, the model did not exhibit the pitch-up tendencies of the basic model and the pitch trim requirements were reduced. The flight tests showed, however, that the model with tails installed did have a very mild dynamic instability. When the pilot refrained from giving control (controls fixed), the model developed a gentle unstable oscillation of fairly long period, somewhat like a phugoid oscillation.

In general, both the flight and force test results showed that horizontal tails having variable incidence would be required to obtain the optimum stability and trim throughout the speed range tested. Since the model had to cover an attitude range α of 0° to 30°, it was not possible to keep the tails unstalled and lifting in a positive direction with any one angle of incidence. For example, the data of figure 8 show that with 20° incidence the tails were probably unstalled and made the model stable over most of the tilt-wing range ($\alpha = -10^{\circ}$ to -30°), but at tilt angles greater than -20° the tails set at this incidence produced more nose-up pitching moment M_Y than the basic model. On the other hand, with 40° incidence, the tails made a greater contribution to trim but did not make the model stable with attitude except at speeds greater than 28 knots.

<u>Lateral characteristics</u>.- The most noticeable lateral characteristic of the model in forward flight was its tendency to sideslip. As the forward speed increased, the model became difficult to keep exactly alined with the wind and, if allowed to sideslip, was difficult to straighten out. The pilot felt that, at best, the model had about neutral directional stability. Since the yawing motions affected the rolling motions to some extent because of the dihedral effect of the model, this characteristic became objectionable to the pilots at forward speeds of around 15 knots (27 knots, full scale) and above.

A vertical tail, mounted under the rear half of the rear propeller as shown in figure 3, was installed on the model to improve the directional stability. This tail gave adequate directional stability and made the lateral motions very easy to control. Figure 9 gives the basic lateral data and figure 10 presents a summary of the static lateral characteristics of the model with and without the vertical and horizontal tails installed. These data show agreement with the flight-test results in that the basic model had neutral directional stability and the vertical tails gave a significant improvement. The horizontal tails gave an additional increment of directional stability at the higher forward speeds.

In roll, the basic model was about as easy to fly in forward flight as it was in hovering up to speeds of about 15 knots which was the highest speed tested without the tails installed. This result was in contrast with the results reported in reference 2 in which the ducted-propeller tandem configuration experienced an increasing dynamic instability in roll with increasing forward speed. With the vertical and horizontal tails installed, the model was fairly easy to fly in roll over the entire speed range of the tests (up to 30 knots).

The data of figure 10 show that the basic model had positive effective dihedral $-M_{X_{\beta}}$ over most of the speed range. Adding the vertical-tail surface below the rear propeller added an increment of negative effective dihedral but the further addition of the horizontal tails gave about the same results as the basic model.

CONCLUSIONS

On the basis of a static and dynamic stability and control investigation in the Langley full-scale tunnel on a model which had two unshrouded propellers in tandem that were fixed with respect to the airframe, the following conclusions were drawn:

1. In hovering, the controls-fixed pitching and rolling motions of the model were unstable oscillations. In spite of these oscillations, the model could be controlled fairly easily in hovering without artificial stabilization mainly because the periods of the oscillations were relatively long.

2. In forward flight, the basic model required an increasing nose-down attitude for drag trim as the forward speed was increased. The model experienced an increasing nose-up pitching moment and static longitudinal instability of angle of attack with increase in forward speed up to about 23 knots. No appreciable increases were experienced above this speed.

3. The basic model became very difficult to control longitudinally at speeds above 21 knots, mainly because of the static longitudinal instability with angle of attack.

4. Horizontal tails were required for reasonably satisfactory longitudinal stability and control characteristics in forward flight. Variable tail incidence was also required because of the large tilt angles experienced by the model.

5. The basic model had about neutral directional stability in forward flight and became difficult to control at speeds above 15 knots.

6. With a vertical tail installed under the rear propeller, the model had satisfactory directional stability and was easy to control over the speed range of the tests.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., June 25, 1963.

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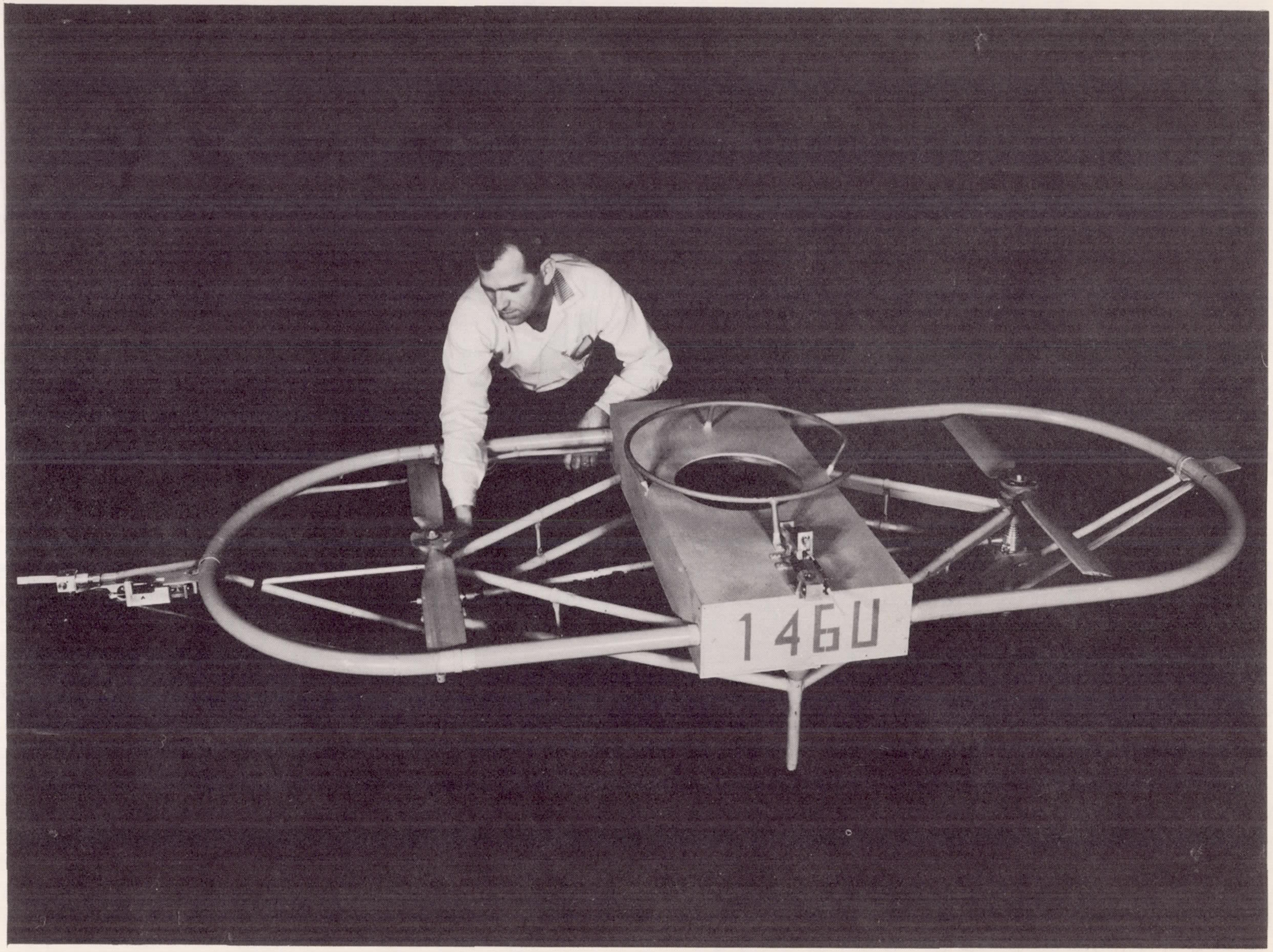
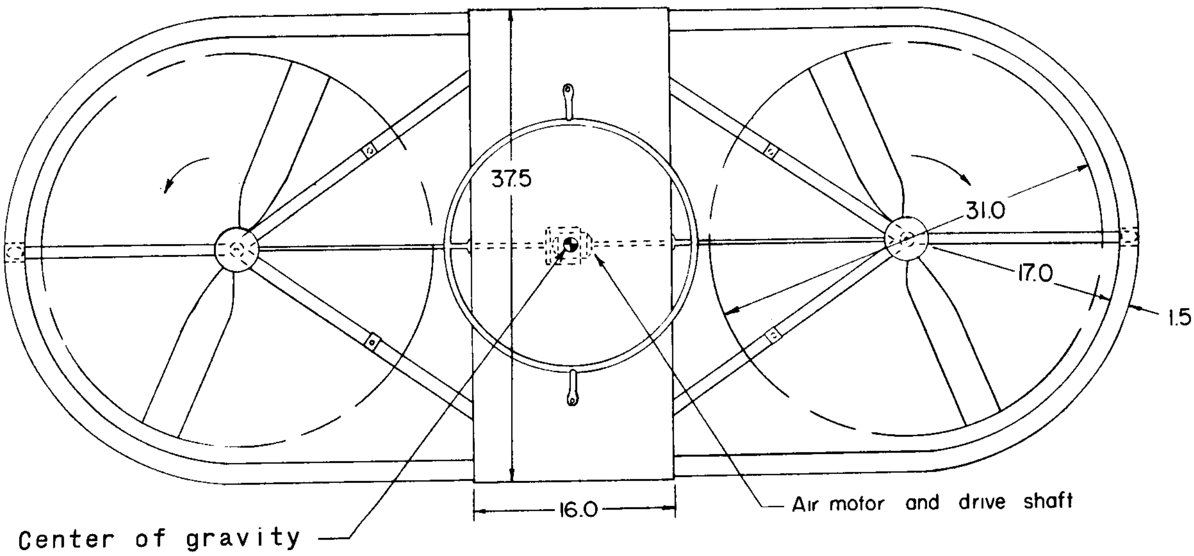


Figure 1.- Photograph of basic model. L-62-2476



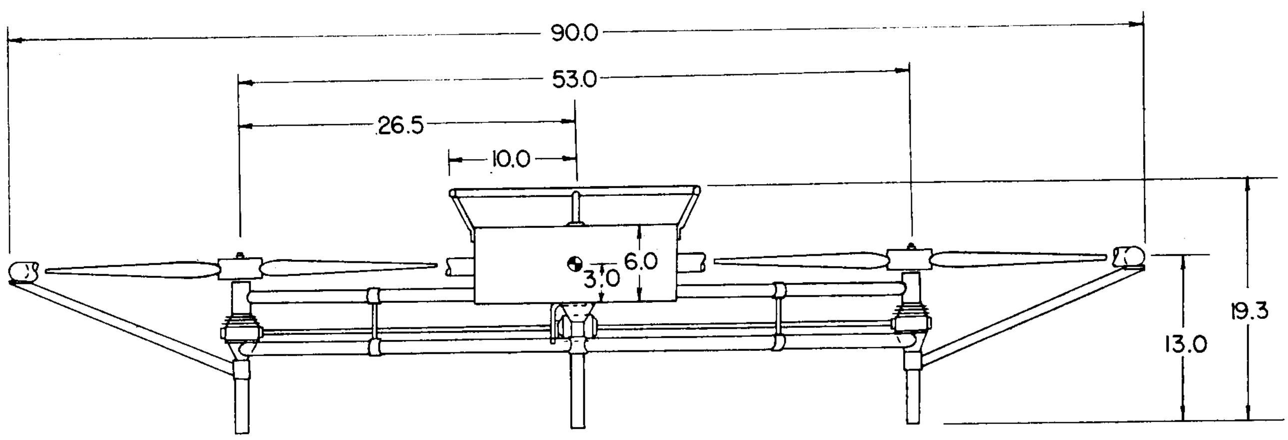


Figure 2.- Drawing of basic model. Jet reaction controls and tails not shown.
All dimensions are in inches.

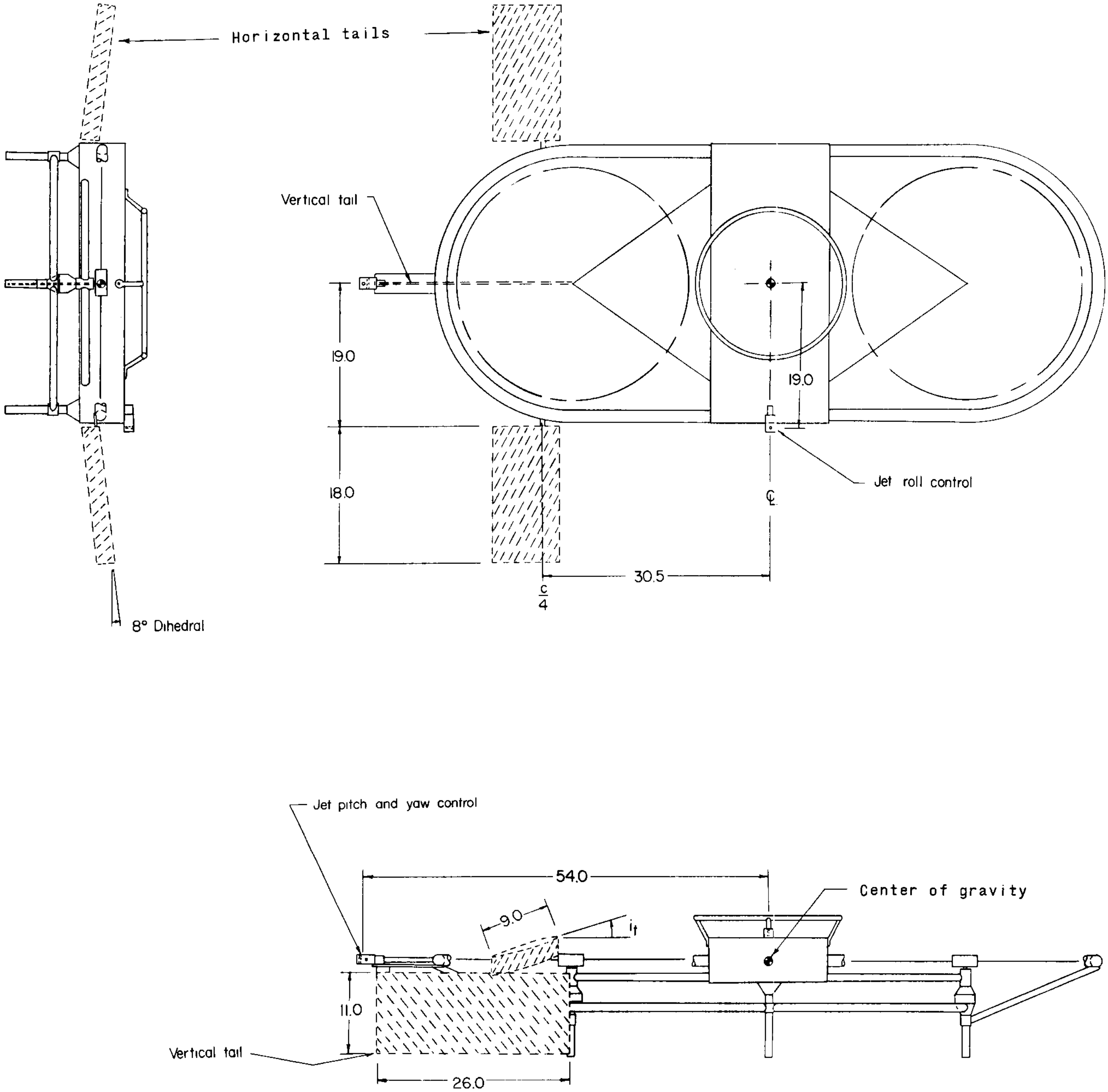
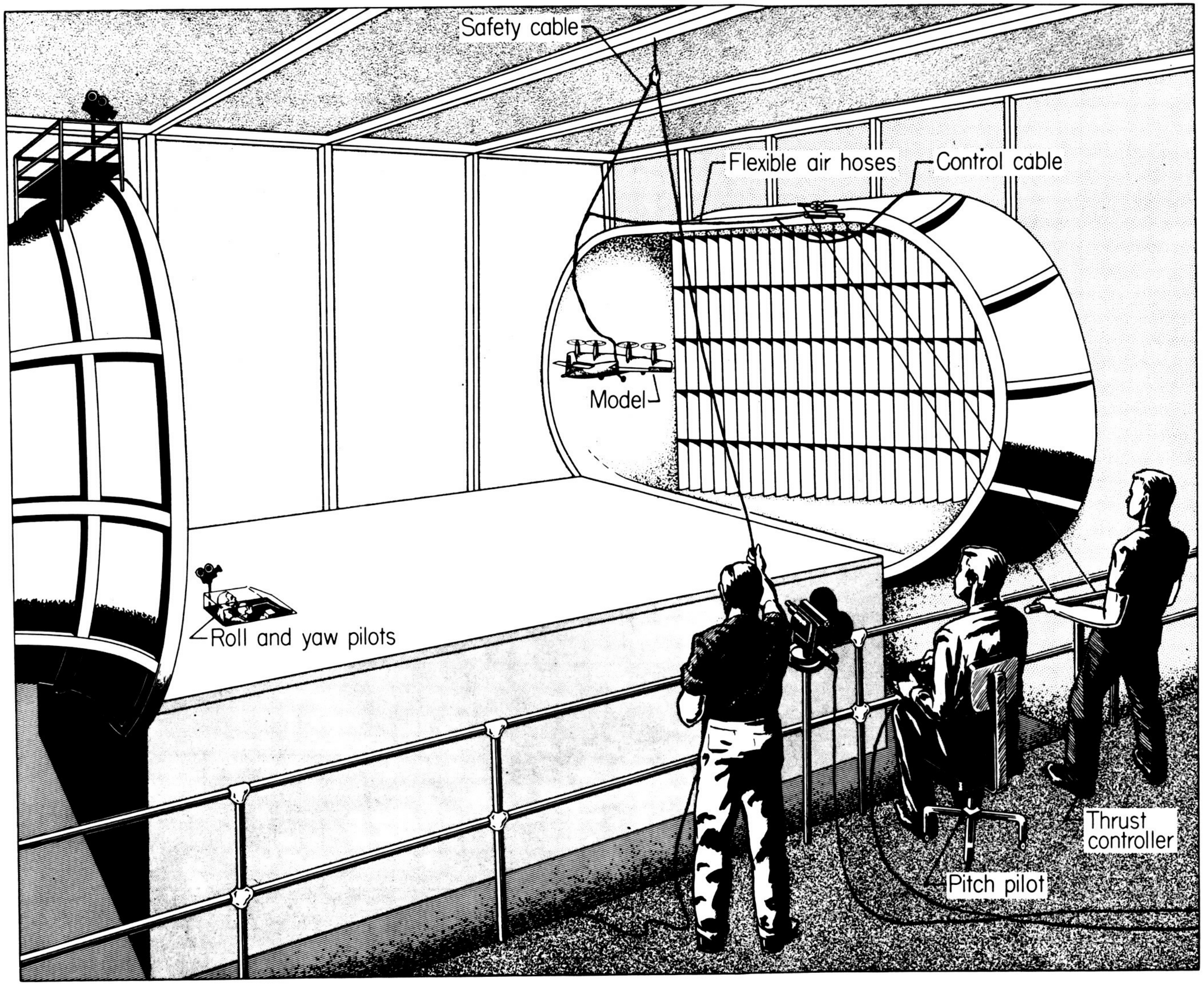


Figure 3.- Sketch of model showing jet reaction controls and vertical and horizontal tails. Tails are shown by hatching. All dimensions are in inches.



L-61-2837
Figure 4.- Typical setup used for forward-flight tests in the Langley full-scale tunnel.

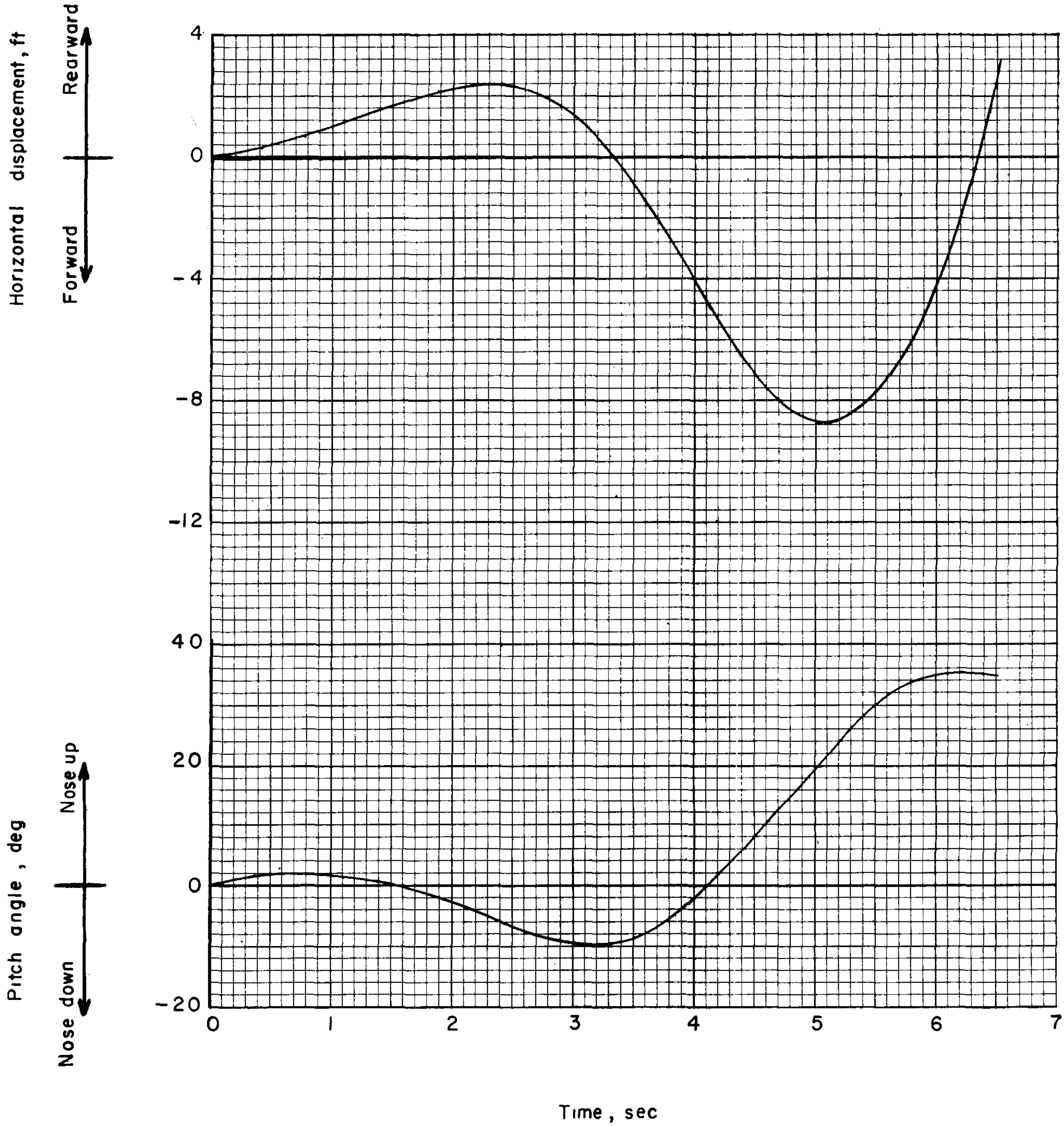


Figure 5.- Typical controls-fixed model pitching oscillations in hovering. Basic model.

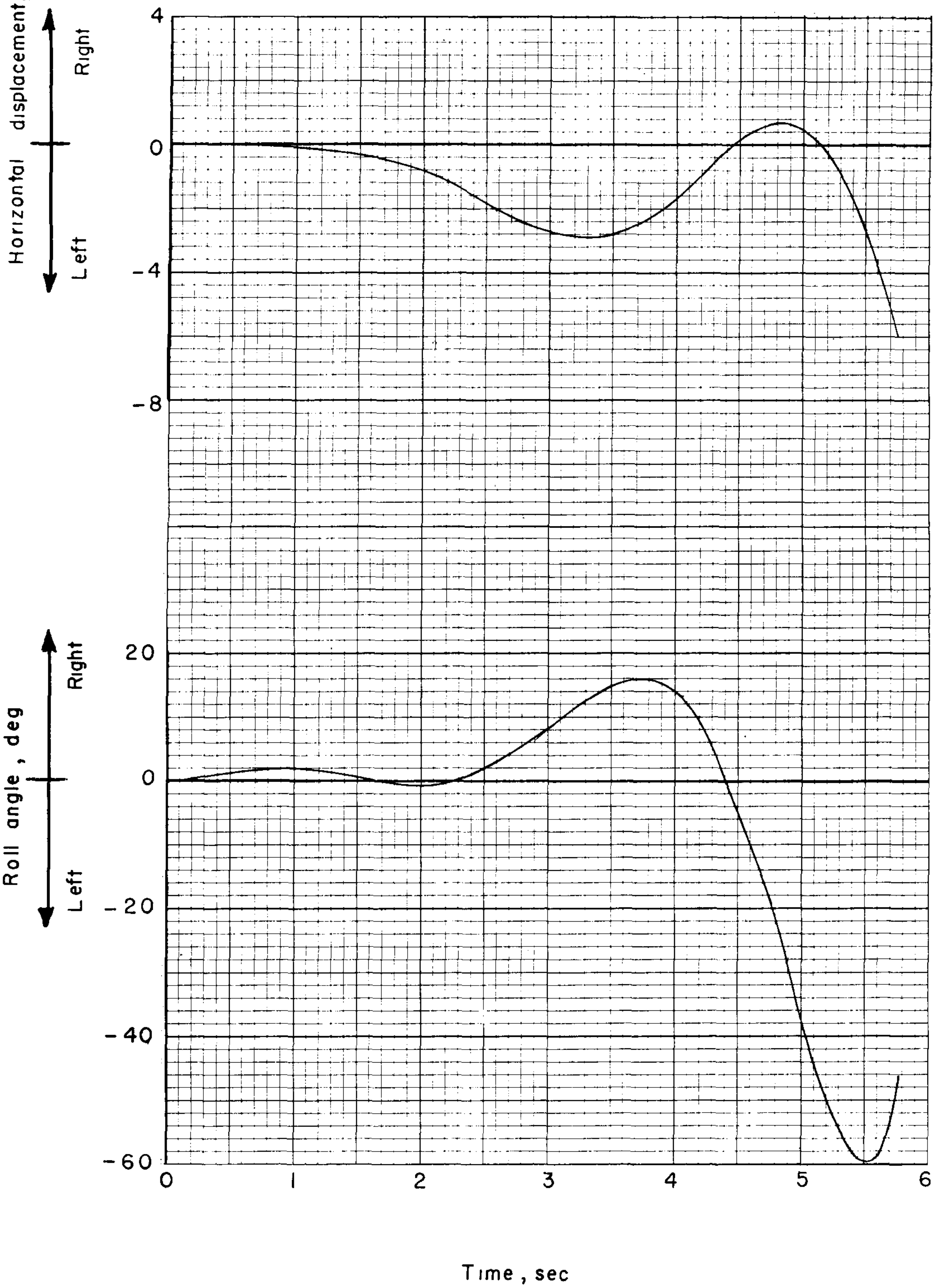
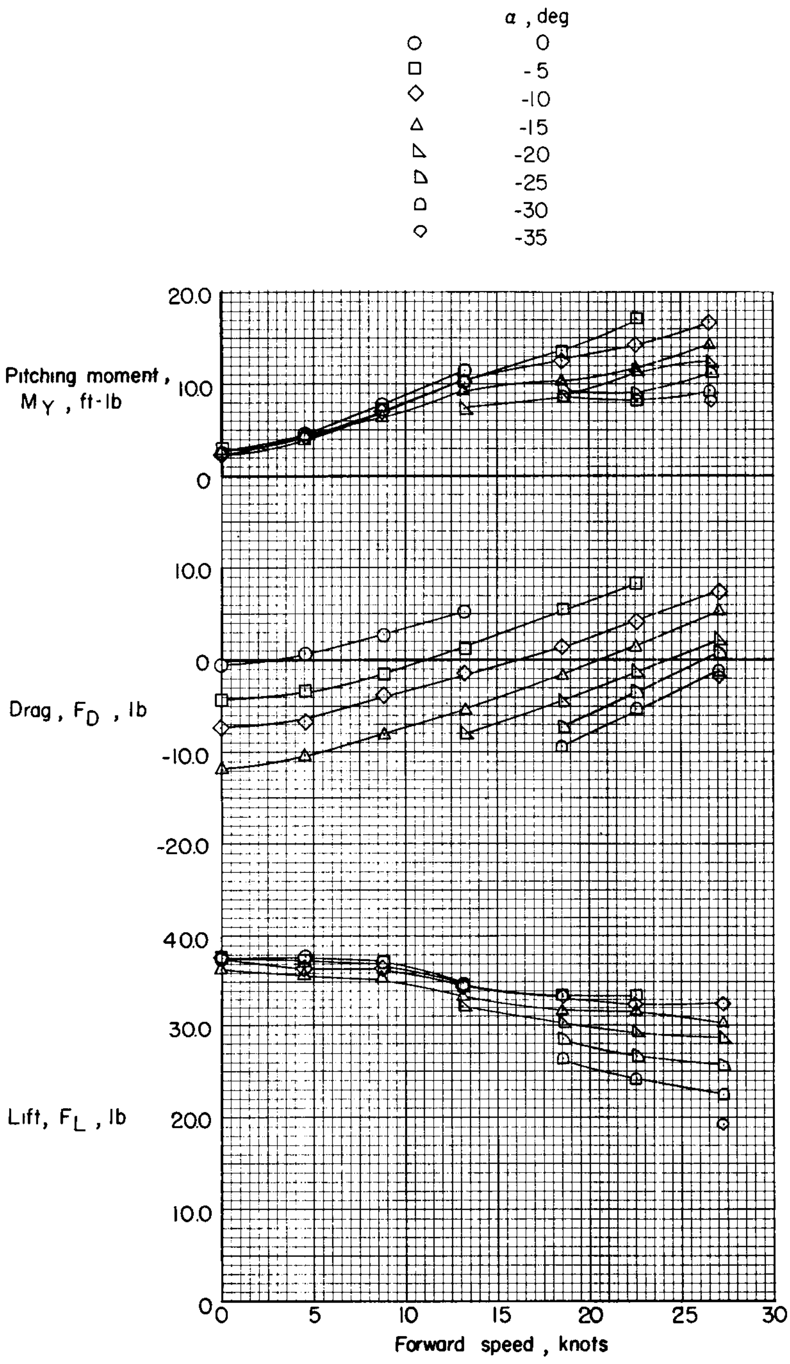
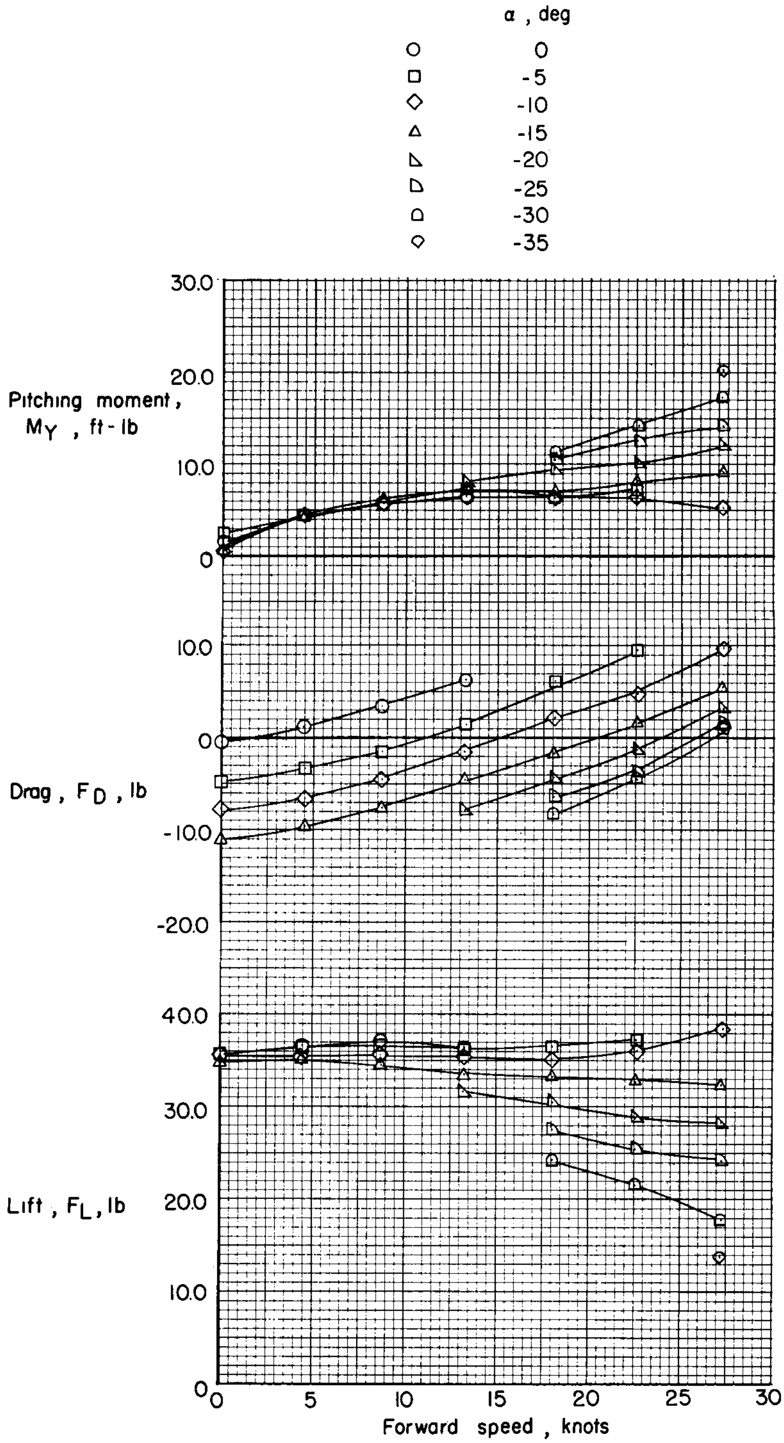


Figure 6.- Typical controls-fixed model rolling oscillations in hovering flight. Basic model.



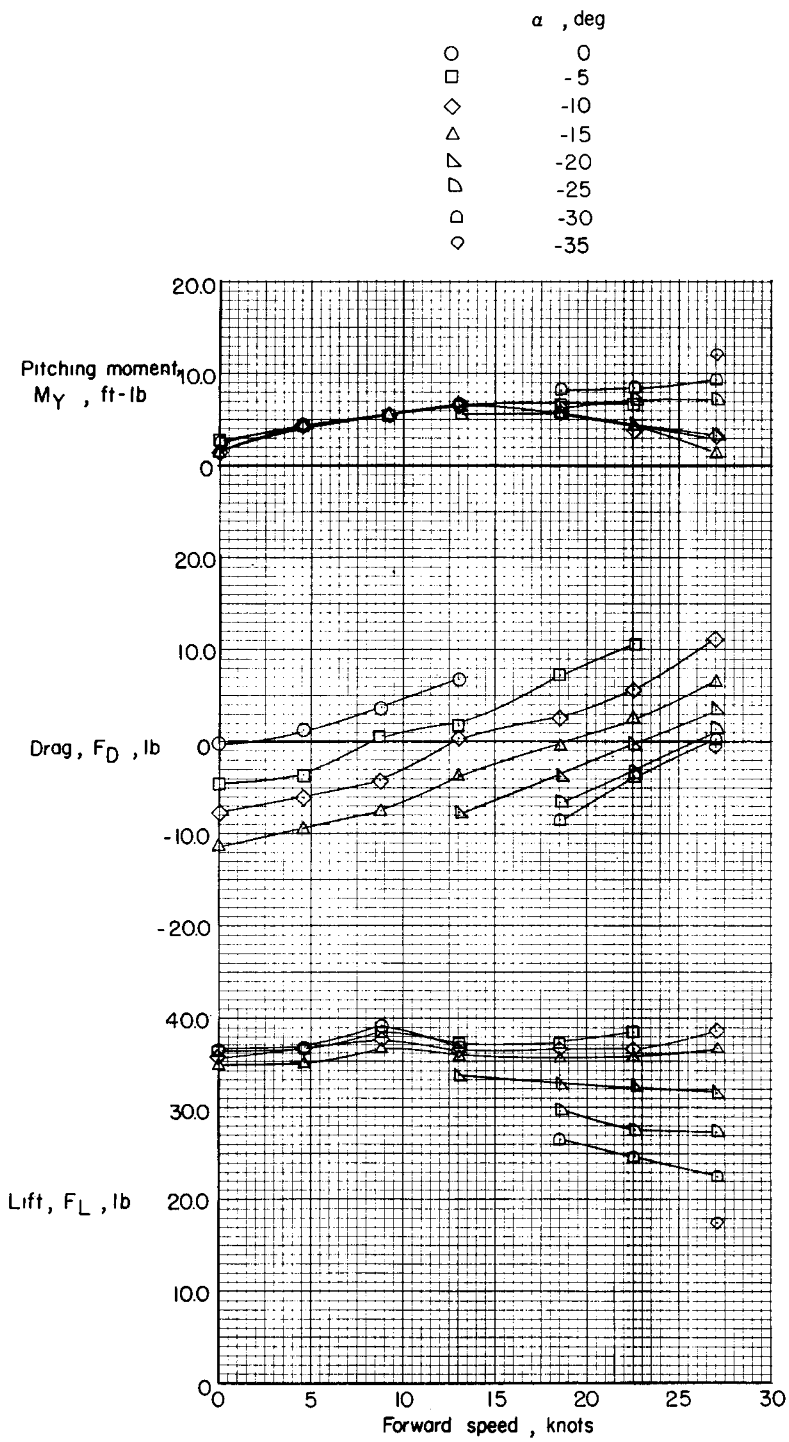
(a) No horizontal tails.

Figure 7.- Basic longitudinal data. Vertical tails on.



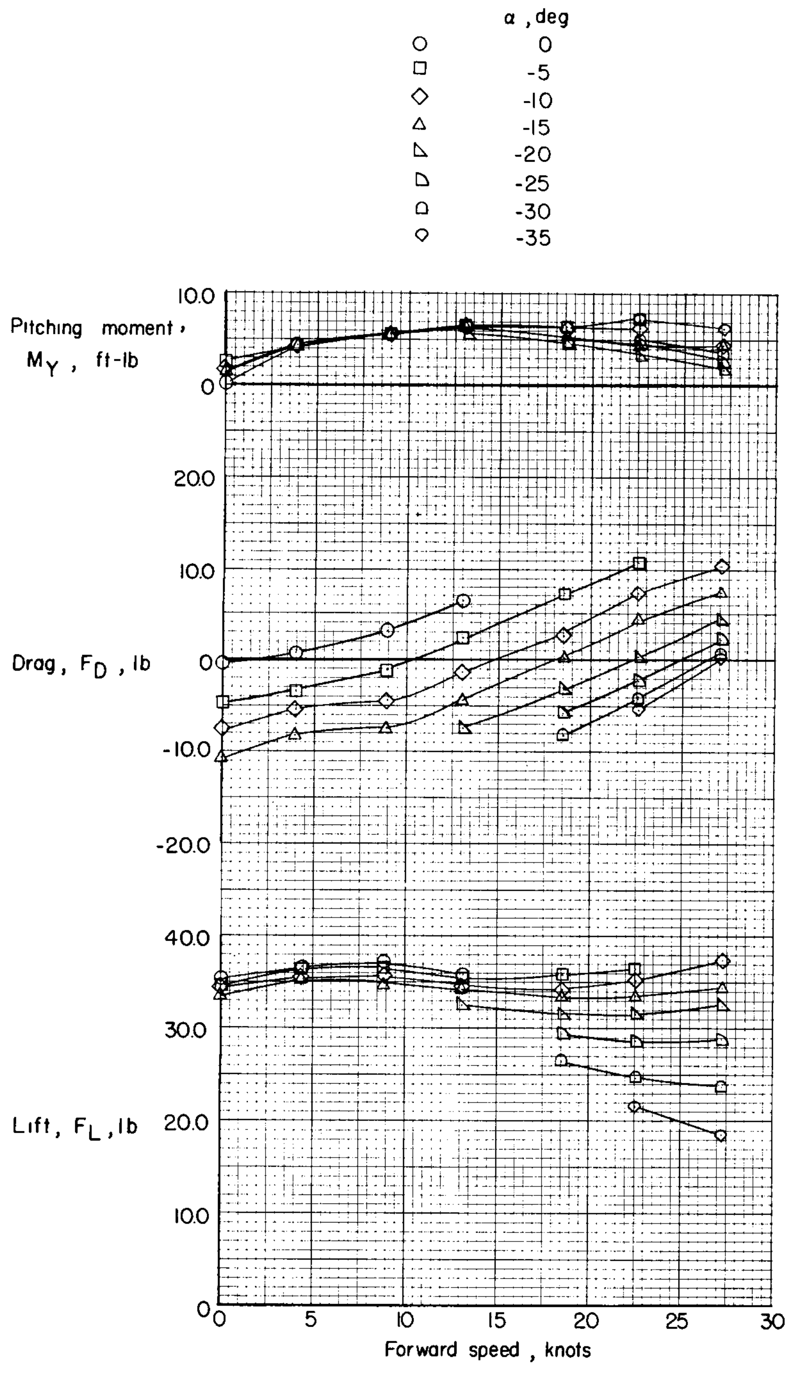
(b) Horizontal tails on; $i_t = 20^o$.

Figure 7.- Continued.



(c) Horizontal tails on; $i_t = 30^{\circ}$.

Figure 7.- Continued.



(d) Horizontal tails on; $i_t = 40^{\circ}$.

Figure 7.- Concluded.

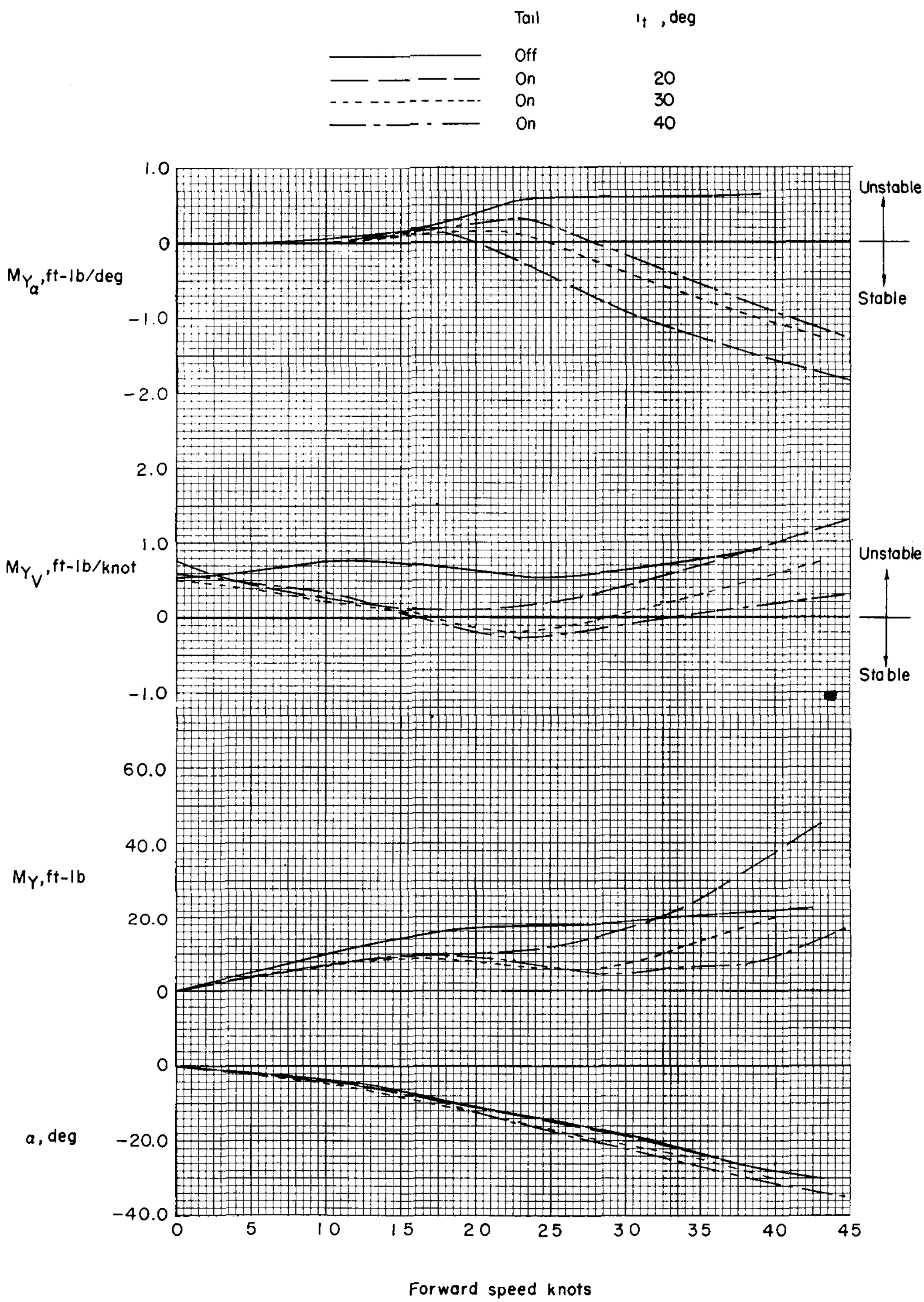
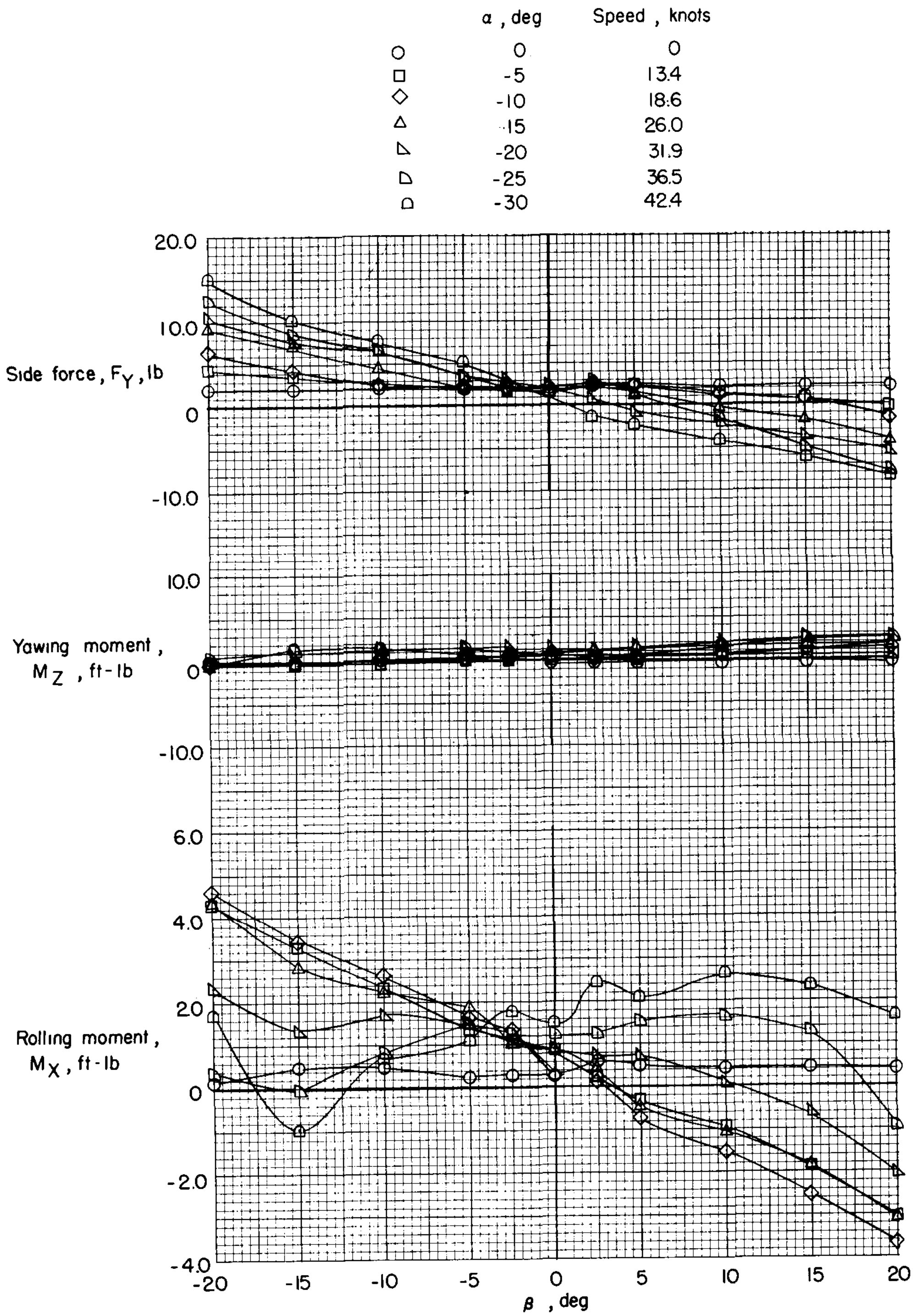
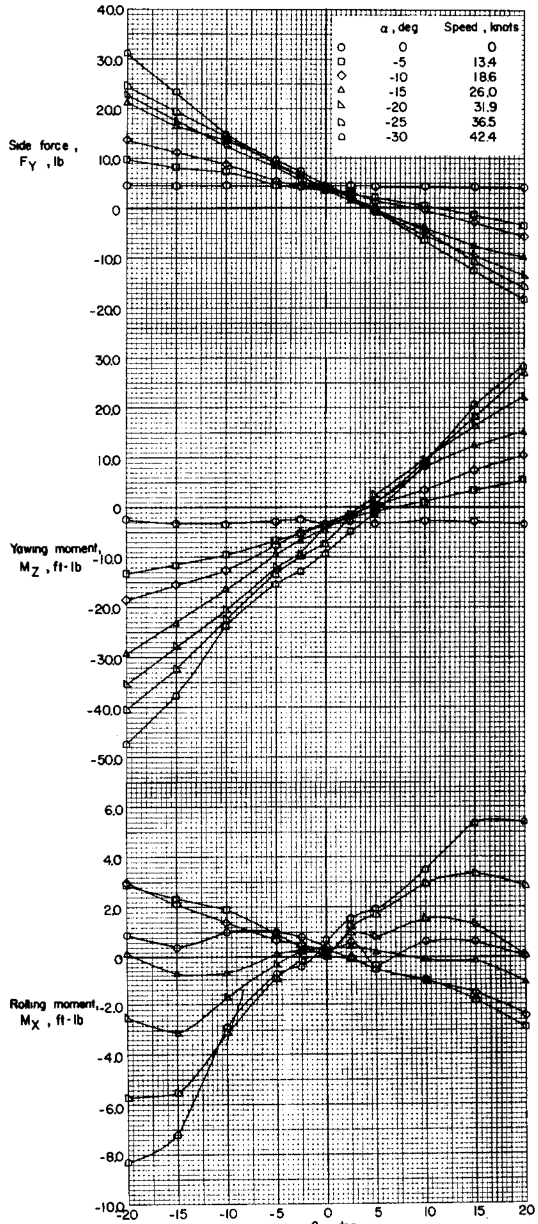


Figure 8.- Variation of longitudinal characteristics with forward speed for various tail incidences. Zero drag.



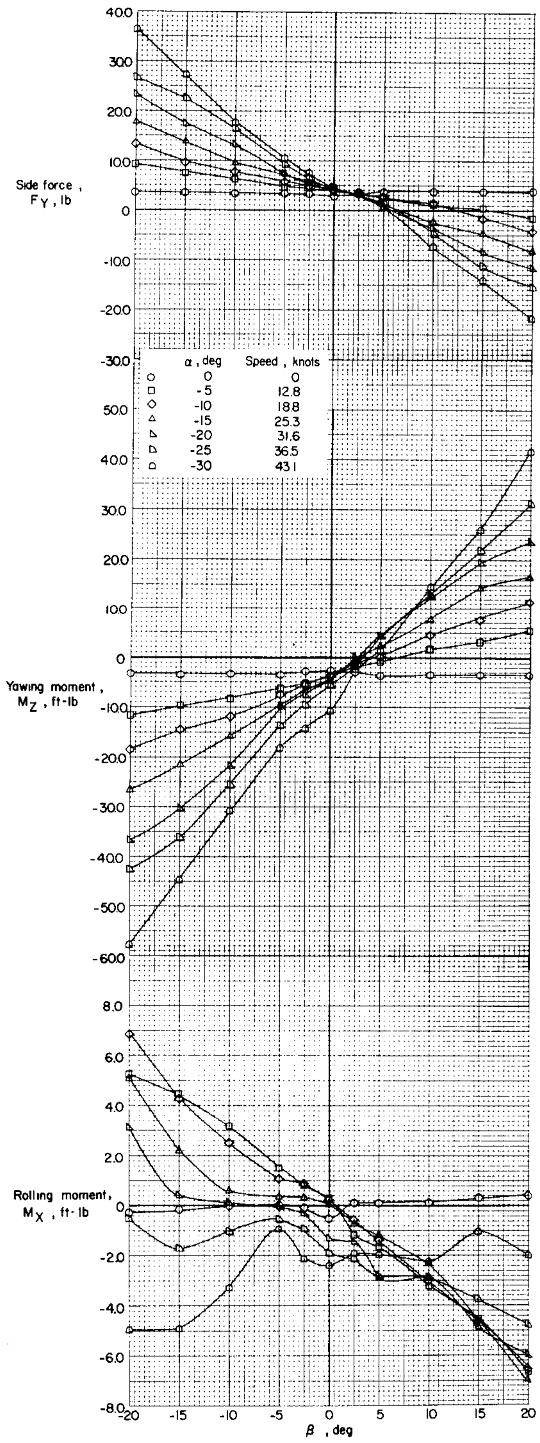
(a) No tails.

Figure 9.- Basic lateral data. Zero drag at $\beta = 0^o$.



(b) Vertical-tail on.

Figure 9.- Continued.



(c) Vertical and horizontal tails on; $i_t = 20^{\circ}$.

Figure 9.- Concluded.

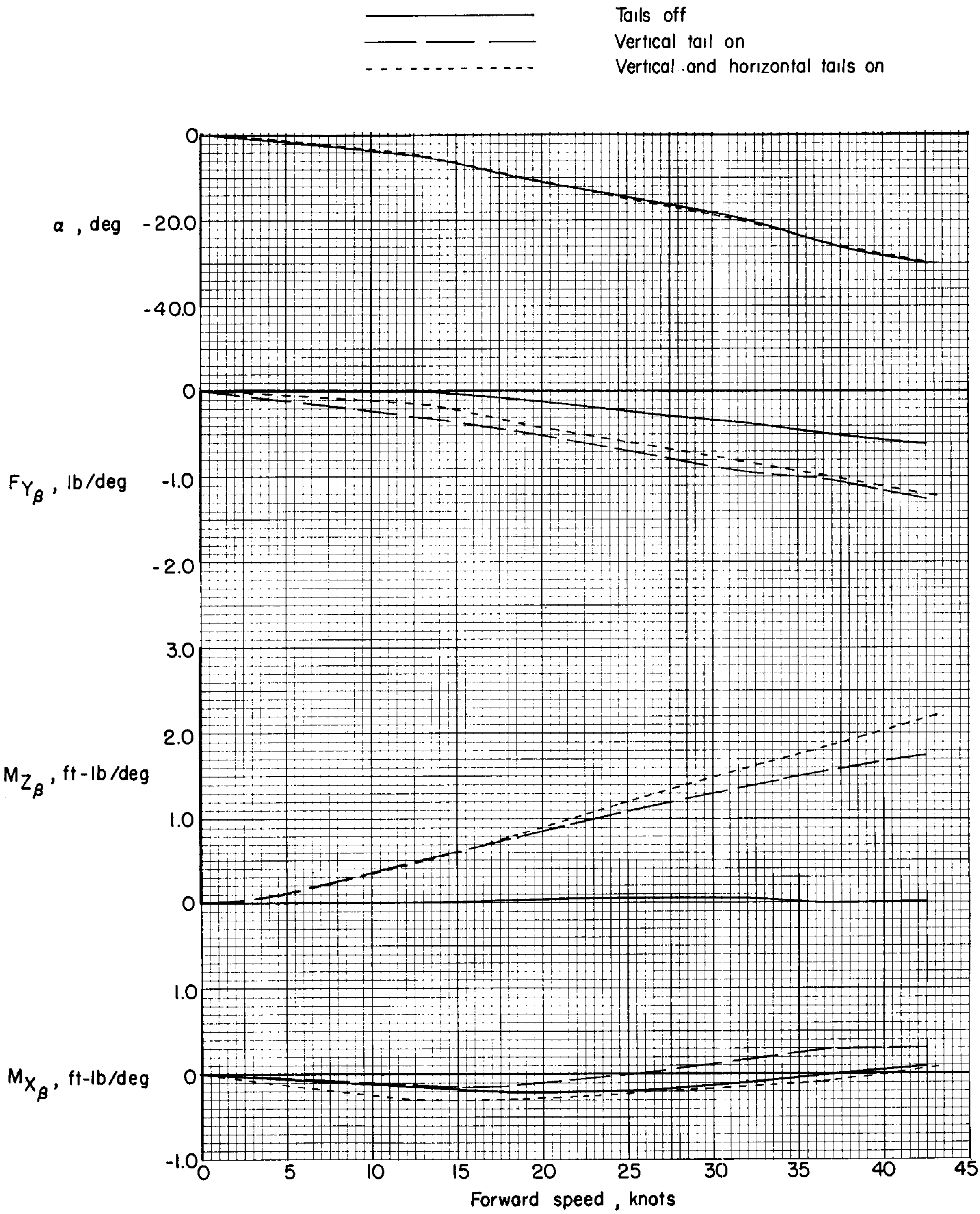


Figure 10.- Variation of lateral characteristics with forward speed with and without tails.