NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 4190

EXPERIMENTAL INVESTIGATION OF THE LATERAL TRIM OF A WING-PROPELLER COMBINATION AT ANGLES OF ATTACK UP TO 90° WITH ALL PROPELLERS TURNING IN THE SAME DIRECTION

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SUMMARY

An experimental investigation has been made to study the feasibility, from considerations of lateral trim, of having all the propellers of a tilting-wing vertical-take-off-and-landing (VTOL) airplane rotate in the same direction since this is a desirable feature from practical considerations. The model was a wing with four propellers, the slipstream from which covered practically the entire span of the wing. Tests were made at angles of attack up to 90° for various differential flap deflections and differential blade pitch settings on the outboard propellers.

Analysis of the data indicates that it is not quite possible to obtain lateral trim of a complete tilting-wing VTOL airplane with this wing-propeller combination by using differential flap deflection and differential outboard-propeller pitch. Complete trim could be obtained, however, if the control effectiveness of the wing flaps and propellers were augmented by the use of a rudder and a jet-reaction control at the rear of the fuselage capable of producing a side force of about 1 percent of the airplane weight. Since the lateral trim of the particular configuration represented by this model is marginal, it seems likely that some airplanes of this type could be trimmed with all the propellers rotating in the same direction whereas others could not.

INTRODUCTION

On a vertical-take-off-and-landing (VTOL) airplane, as on any multiengine propeller-driven airplane, it is very desirable from practical considerations that all the propellers turn in the same direction. In order to analyze the feasibility, from the standpoint of lateral trim, of employing this design feature on a VTOL airplane, experimental data are required, since this problem cannot be analyzed by usual procedures. Inasmuch as the lateral trim characteristics might be greatly affected by the geometric and other physical characteristics of the airplane, a very extensive investigation would be required for a complete analysis of the problem. In order to provide some preliminary indication of the problems involved, however, the present investigation was conducted for a particular configuration which might be representative of possible tilting-wing VTOL airplanes. Since there are no actual airplanes of this type, the hypothetical design of references 1 and 2, which is illustrated in figure 1, was chosen to be represented in the investigation, and force tests were made with a wing-propeller model which represented this design. The model used was the model which was previously used in the investigation reported in reference 2, except that the direction of propeller rotation was altered so that all four propellers turned in the same direction. Measurements were made of the rolling moment, yawing moment, and side force at angles of attack up to 90° for various differential flap deflections and various differential propeller pitch settings of the outboard propellers.

SYMBOLS

All forces and moments are based on the stability-axis system shown in figure 2, which indicates the positive direction of forces and moments.

F_Y	side force, lb
M_X	rolling moment, ft-lb
M_Z	yawing moment, ft-lb
V	tunnel velocity, ft/sec
α	angle of attack of wing, measured from horizontal, deg
δ_f	angle of flap deflection, positive downward, deg
β	angle of propeller pitch at 0.75 radius station, deg
$\bar{c}$	mean aerodynamic chord, 9.68 in.

Subscripts:

L	left

R	right
O	outboard propeller

MODEL

The model used in the present investigation was the model used in the investigation reported in reference 2, except that the direction of propeller rotation was changed so that all the propellers rotated in the left-hand direction (counterclockwise as viewed from the rear). Sketches showing the details of the model are presented in figure 3. Figure 3(a) shows the general arrangement of the model, and figure 3(b) shows the position of the propeller relative to the wing and a typical wing section illustrating the general arrangement of the full-span slotted flap. The geometric characteristics of the model used in the investigation are as follows:

Wing:	
Sweepback (0.60-chord line), deg	0
Airfoil section	NACA 65-210
Aspect ratio	9
Tip chord, in.	7.11
Root chord (at center line), in.	11.85
Taper ratio	0.60
Area, sq in.	808
Span, in.	85.32
Mean aerodynamic chord, in.	9.68
Flap hinge line, percent chord	70
Propellers (four with two blades each):	
Diameter, in.	18
Solidity (each propeller)	0.079

Power for the two-blade propeller mounted on each gear box was supplied through connecting shafts by a 5-horsepower electric motor which was mounted at the midspan of the wing. The propellers were of the same design as those used in reference 2 but were made so that their blade angle could be adjusted. As explained in reference 2, the model was made up of components available from other investigations; therefore, it was necessary that the shafts between the motor and gear boxes be externally mounted. Because of their relatively small size, however, the effect of the shafts on the aerodynamic characteristics of the model was considered to be negligible.

TESTS

If scale models of the airplane propellers had been used in the tests, an incorrect indication of the lateral trim characteristics would have been obtained because the model propellers operating at a very low Reynolds number would have had an excessively high torque. The first problem in planning the investigation, then, was the determination of the best method for representing the aerodynamic characteristics of the propellers and, consequently, their effect on the aerodynamic characteristics of the wing. It was believed that the most important parameter to represent was the ratio of torque coefficient to thrust coefficient. Calculations indicated that for the hovering condition the hypothetical airplane of reference 1 would have a ratio of torque coefficient to thrust coefficient of about 0.067. Calibrations of the propellers which remained from the tests of reference 2 indicated that the correct simulation could be obtained with a propeller blade angle of 16° and a propeller speed of 3,000 rpm. Calculations of the torque-thrust ratio in the transition range based on the power-required data of reference 2 indicated that the ratio of torque coefficient to thrust coefficient increased from about 0.067 to 0.080 in the angle-of-attack range from 90° down to 20°. Calibration of the model propellers showed that 0.080, the ratio of torque coefficient to thrust coefficient for an angle of attack of 20°, was obtained with a blade angle of 16° and a speed of 3,000 rpm. Since this was the blade angle that gave proper simulation in the hovering condition, it was assumed that, with a blade angle of 16° and a speed of 3,000 rpm, the model propellers would give a reasonable simulation of the airplane propellers over the entire transition range of angle of attack from 20° to 90° since the propeller-calibration curves were linear throughout this range. In order to represent the ratio of torque coefficient to thrust coefficient of the airplane propellers in a cruise condition at a Mach number of 0.7 and an altitude of 35,000 feet, which corresponds to an angle of attack near 0°, a blade angle of about 45° was required.

The investigation consisted of force tests in the Langley free-flight tunnel, which has a 12-foot octagonal test section. Tests were made in the angle-of-attack range of 20° to 80° with various combinations of differential pitch of the outboard propellers and differential flap deflection, in which the flap deflections were varied from basic positions of 0°, 20°, and 40°. At each angle of attack and basic flap deflection, a tunnel speed that would give drag trim was determined; then the rolling moment, yawing moment, and side force on the model were measured for various combinations of differentially deflected flaps and differential propeller pitch on the outboard propellers. The forces and moments were measured on an electric strain-gage balance which was located below the wing immediately behind the model motor. For an angle of attack of 90°, tests were made with the left flap at 0° and the right flap deflected various amounts to determine the deflection required to trim out the torque. At an angle of attack of 0°, tests were made only with both flaps at 0° and both outboard propellers set at a pitch angle of 45°.

At the same time that the force tests were being made, a study of the flow patterns on the wing was made by using rows of tufts taped on the upper surface of the wing. Sketches were made of the type of flow over various sections of the wing throughout the angle-of-attack range for flap deflections of 0°, 20°, and 40°.

All the systematic tests were made with the propellers turning to the left. In order to make sure that the results obtained were due to the effects of the direction of propeller rotation and not to some other dissymmetry in the model, a check run was made for the complete angle-of-attack range at $\delta_f = 0^\circ$ with all the propellers turning in the right-hand direction.

RESULTS AND DISCUSSION

Basic Data

The data are presented in dimensional terms, since conventional coefficients become inadequate when the free-stream velocity is zero. The data are for drag trim and have been corrected to an arbitrarily chosen constant lift of 25 pounds as follows: At each drag-trim point a factor was determined that would bring the measured lift up to 25 pounds. The corresponding velocity was then scaled up by using the square root of the factor. The airspeeds required to give drag trim and a lift of 25 pounds for the various basic flap deflections are presented in figure 4. For convenience in analyzing the data in terms of a complete airplane configuration, the force-test results are presented with respect to the stability axes.

The data for the hovering condition are presented in figure 5, which shows the variation of rolling moment, yawing moment, and side force with deflection of the right flap. Only the right flap was deflected to trim out the torque because, with the slotted flap, the left flap could not be deflected upward. The figure shows that in the hovering condition, with all propellers at the same blade angle ($\beta = 16^\circ$), a flap deflection of less than 12° would be needed to trim the yawing moment of the model. Figures 6 to 8 present the variation of rolling moment, yawing moment, and side force with angle of attack for various differential flap deflections and differential outboard-propeller pitch settings. The figures show that with all propellers at the same angle of pitch, large rolling moments were experienced by the model in the angle-of-attack range between 30° and 70°. Calculations showed that these rolling moments, which were in the same direction as the propeller torque reaction, were as much as 3.5 times the torque produced by the propellers and as much as 5.0 times the moment caused by the sidewise shift of the propeller thrust vector. A check run was made with the propellers rotating to the right in order to make sure that the large rolling moment was caused by the direction of propeller rotation and not by some other dissymmetry in the model. The right-hand propeller rotation gave rolling moments of approximately the same magnitude but of opposite direction to those of the left-hand propeller rotation.

The tuft studies made on the model are presented in figure 9. The figure shows no consistent asymmetry in the flow patterns on the wing that would explain the large out-of-trim rolling moments measured in the force tests.

It is believed that the additional rolling moment caused by the direction of the propeller rotation results from a shift in the spanwise load distribution. One possible explanation that has been advanced is that the left-hand rotation of the propellers would tend to decrease the effect of the left tip vortex and increase the effect of the right tip vortex; this effect would result in more lift on the left wing tip and less lift on the right wing tip and thus would produce a positive rolling moment such as that shown by the data. This effective increase in lift on the left wing tip would be accompanied by an increase in drag which would result in the larger negative yawing moments shown in figures 6 to 8.

Figures 6 to 8 show that deflecting the flaps differentially had little effect on the rolling moment for angles of attack above 40° but was generally very effective in producing yawing moment over the entire angle-of-attack range. Differential propeller pitch had a powerful effect on the rolling moment but, for angles of attack above 40°, had only a slight effect on the yawing moment. It seemed, therefore, that a combination of differential flap deflection and differential outboard-propeller pitch would be required for accomplishing lateral trim throughout the complete angle-of-attack range from hovering to forward flight.

The results of the tests at an angle of attack of 0° to represent the cruise condition are not presented. The tests showed that the complete model had a small rolling moment in a direction opposite to that of propeller torque when both flaps were set at 0°. This rolling moment was taken to indicate that the small amount of twist or flap deflection which might have inadvertently been present was sufficient to trim out the propeller torque and that trim in this condition was very easy to obtain. This result would be expected, since the propeller torque for an airplane would be no greater in this condition than in hovering, whereas the high-speed airstream provided the flaps with a much greater force with which to trim the torque.

Application of Data

With the idea in mind of using the combination of differential flap deflection and differential pitch of the outboard propellers to provide trim for a tilting-wing VTOL airplane in the transition range, the data have been analyzed for two possible wing configurations of this type of airplane. The first configuration was a pure tilting-wing configuration in which the basic flap deflection was 0° throughout the range of wing incidence. The second configuration was one in which the basic flap deflection was varied as the wing incidence was varied during the transition, a feature which might be used to reduce the power required and help trim the pitching moments in the transition range. In this analysis the data have been scaled up to apply to a full-scale airplane of the size and weight shown in figure 1.

The results of the analysis for the pure tilting-wing configuration are presented in figure 10, which shows the rolling moment and yawing moment obtained by varying differential propeller pitch angles and differential flap deflection throughout the angle-of-attack range. Since the flap was not used to augment the lift of the wing in this configuration, it was assumed that a flap which could be deflected upward as well as downward was used on the airplane. It was further assumed that the effectiveness of this flap when deflected in either direction was the same as that of the slotted flap of the model in the downward direction. These assumptions amount in effect to doubling the rolling and yawing moments produced by the single flap of the model deflected only in the downward direction. The data of figure 10 show that, when the propeller pitch was adjusted to trim the rolling moments and the flaps were left at a deflection of 0°, the yawing moment remained untrimmed and at most angles of attack was made worse. The use of differential flaps (ailerons) in conjunction with the differential propeller pitch made it possible to trim the rolling moment and, except at angles of attack near 60°, the yawing moment. The data of figure 10 show that differential propeller pitch settings of as much as 9° (±4.5°) were required to trim the rolling moments and that differential flap deflections of as much as 40° (±20°) were used in trimming the yawing moments. The maximum differential flap deflection was arbitrarily limited to 40° in the analysis. The small out-of-trim yawing moment remaining when the flap deflection was limited to 40° could be further reduced on a complete airplane configuration by deflection of the rudder. A 20° deflection of the rudder of a configuration similar to that shown in figure 1 would still leave the model untrimmed by about 30,000 foot-pounds, as indicated in figure 10. The remaining moment could be trimmed by a jet-reaction control at the tail capable of producing a side force of less than 1 percent of the airplane weight. This side force is approximately one-half the force that has been found from flight tests of models of this general type to be required for adequate yaw control in hovering flight.

For the tilting-wing-with-flap configuration, the data have been analyzed for the same hypothetical VTOL airplane discussed in reference 2 (illustrated in fig. 1) in which the program of flap deflections with angles of attack was selected so that the airplane experienced essentially no change in pitch trim throughout the transition from hovering to normal unstalled forward flight. This program of flap deflections, which is shown in figure 10 of reference 2, was used in the present analysis. At each angle of attack, the model flaps were considered to be deflected differentially from the mean position indicated by reference 2 to obtain yaw trim, and the blade angles of the outboard propellers were considered to be differentially adjusted for rolling-moment trim. Figure 11 shows the results of this analysis. The large out-of-trim rolling moments encountered in the transition could be trimmed by differential pitch of the outboard propellers, and the yawing moments could be trimmed by differential flap deflection (ailerons) except for an angle-of-attack range between 40° and 70°. The yaw trim available from the rudder would not be adequate for trimming the airplane in this range, and the yawing moments would still be untrimmed by as much as 30,000 foot-pounds in the range between 40° and 70°. The addition of a jet-reaction control at the tail capable of producing a side force of about 1 percent of the airplane weight would therefore be required for trim.

From the foregoing analysis, it is obvious that the lateral trim of the tilting-wing VTOL airplanes represented by the model is marginal. Since the disk loading of the propellers of the airplanes represented by the model is in the middle of the range being considered in current design layouts, it seems likely that some airplanes of this type could be trimmed with all the propellers rotating in the same direction whereas others could not. With lighter disk loadings the ratio of torque coefficient to thrust coefficient would be greater than that of the model and the trim problem would probably be even more difficult.

CONCLUDING REMARKS

The results of the investigation of the wing-propeller combination indicate that it may be possible, from considerations of lateral trim, for a vertical-take-off-and-landing (VTOL) airplane with tilting wing and propellers of the same general configuration as the model to have all its propellers rotating in the same direction. The results indicate that it is not quite possible to obtain trim with the propellers and flaps alone, but analysis of the data indicates that lateral trim of a complete tilting-wing VTOL model with this wing-propeller combination could be obtained if the control effectiveness of the wing flaps and propellers were augmented by the use of the rudder and a jet-reaction control at the rear of the fuselage capable of producing a side force of about 1 percent of the airplane weight. Since the lateral trim of the configuration is marginal, it seems likely that some airplanes of this type could be trimmed with all the propellers rotating in the same direction whereas others could not.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., October 4, 1957.

REFERENCES

1. McKinney, M. O., Kuhn, R. E., and Hammack, J. B.: Problems in the Design of Propeller-Driven Vertical Take-Off Transport Airplanes. Aero. Eng. Rev., vol. 15, no. 4, Apr. 1956, pp. 68-75, 84.

2. Newsom, William A., Jr.: Effect of Propeller Location and Flap Deflection on the Aerodynamic Characteristics of a Wing-Propeller Combination for Angles of Attack From 0° to 80°. NACA TN 3917, 1957.

Normal gross weight, lb	60,000
Empty weight, lb	41,000
Propeller diameter, ft	20
Engine power (each engine), bhp	3,500
Tail-engine thrust, lb	3,600
Wing area, sq ft	1,000
Wing span, ft	95

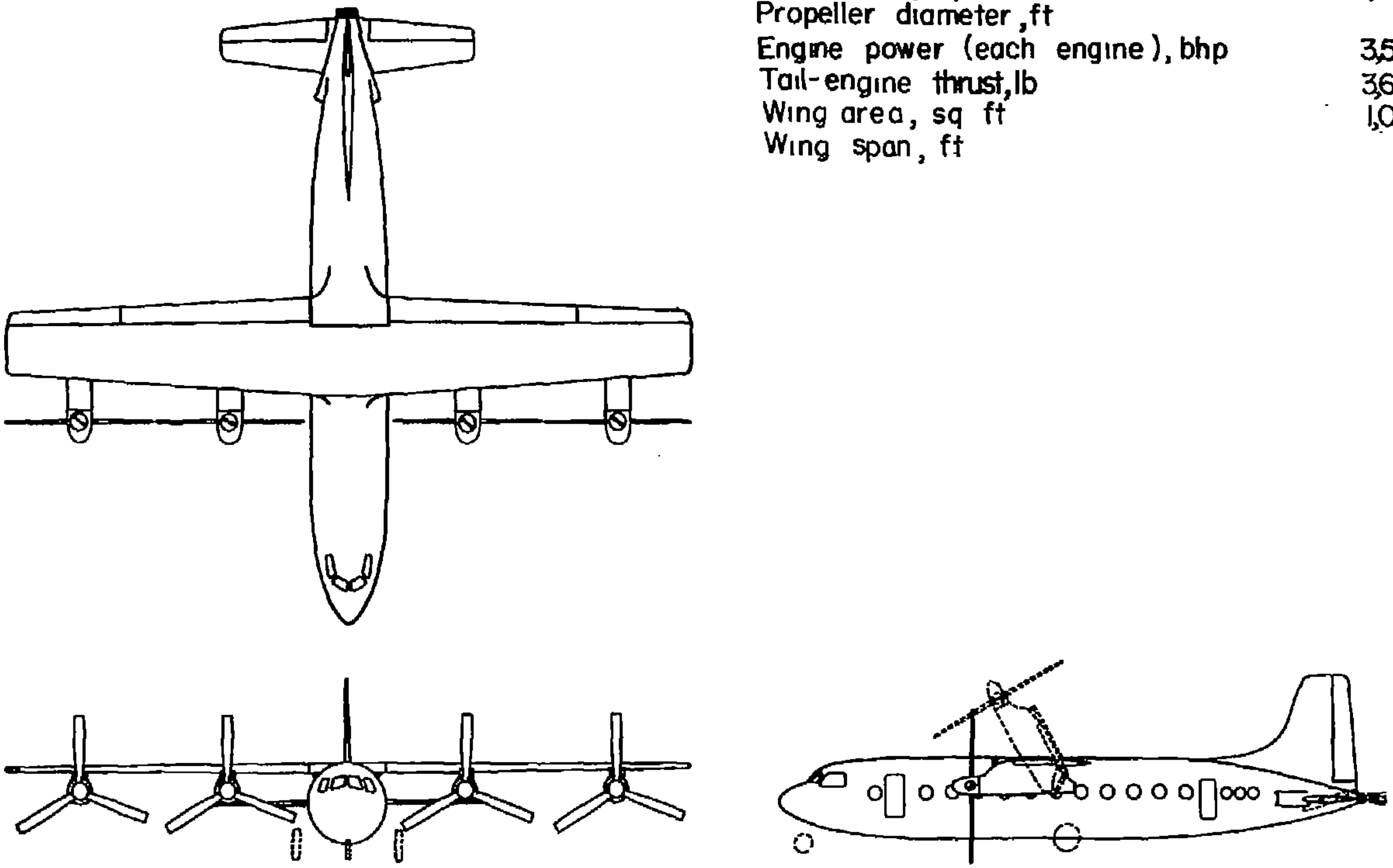


Figure 1.- Hypothetical VTOL airplane from reference 1.

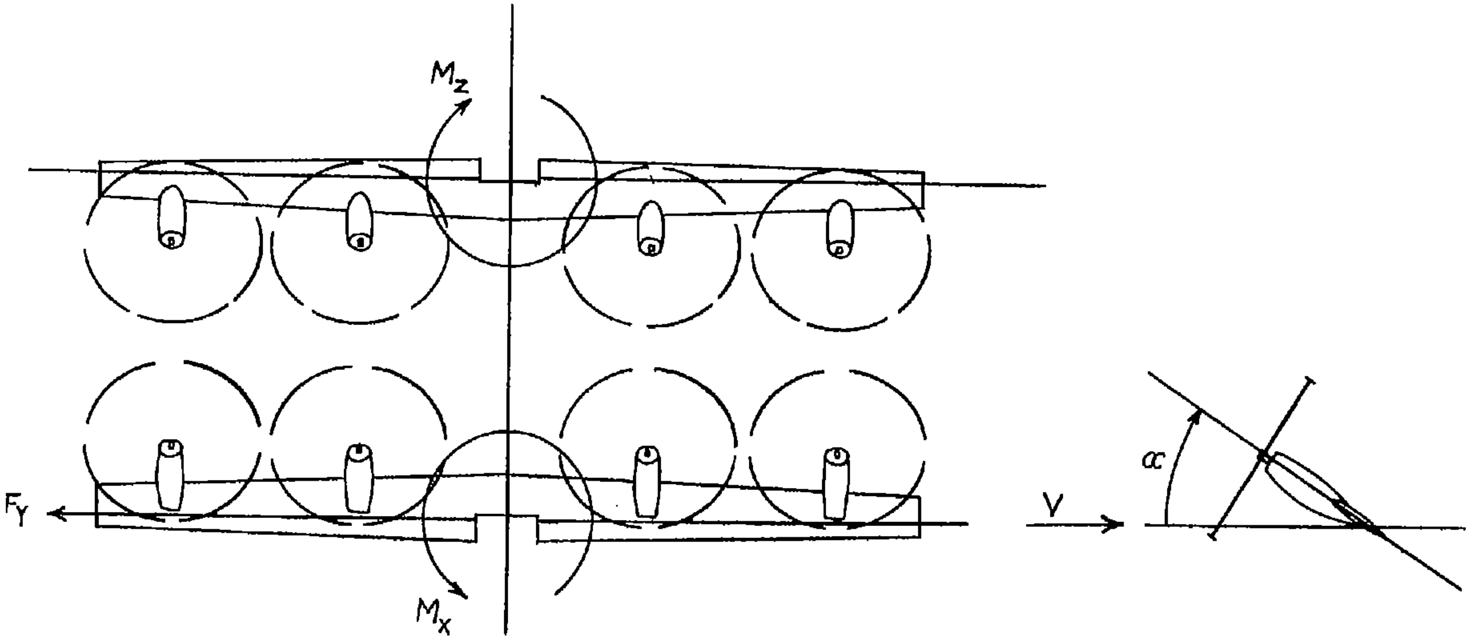
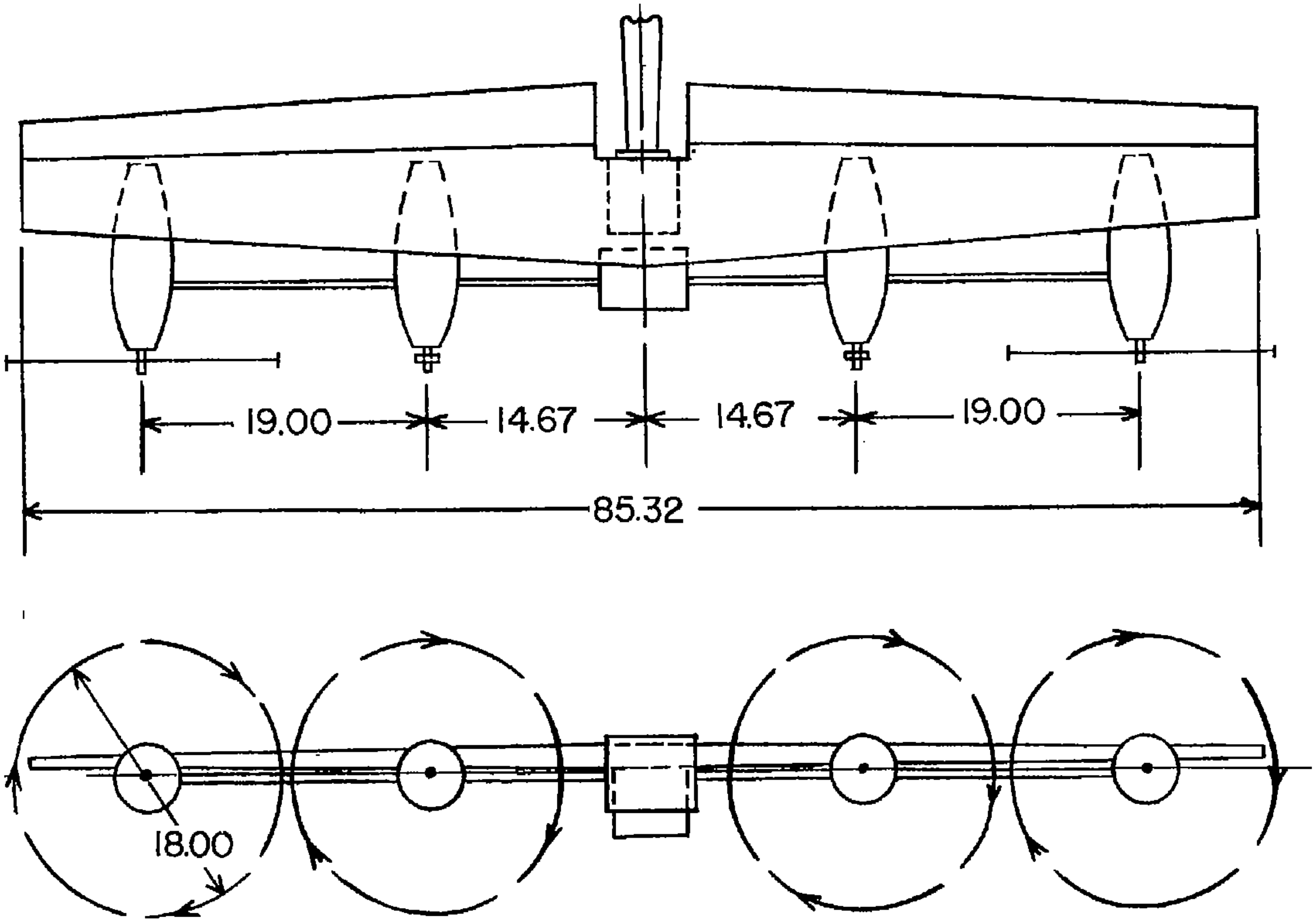
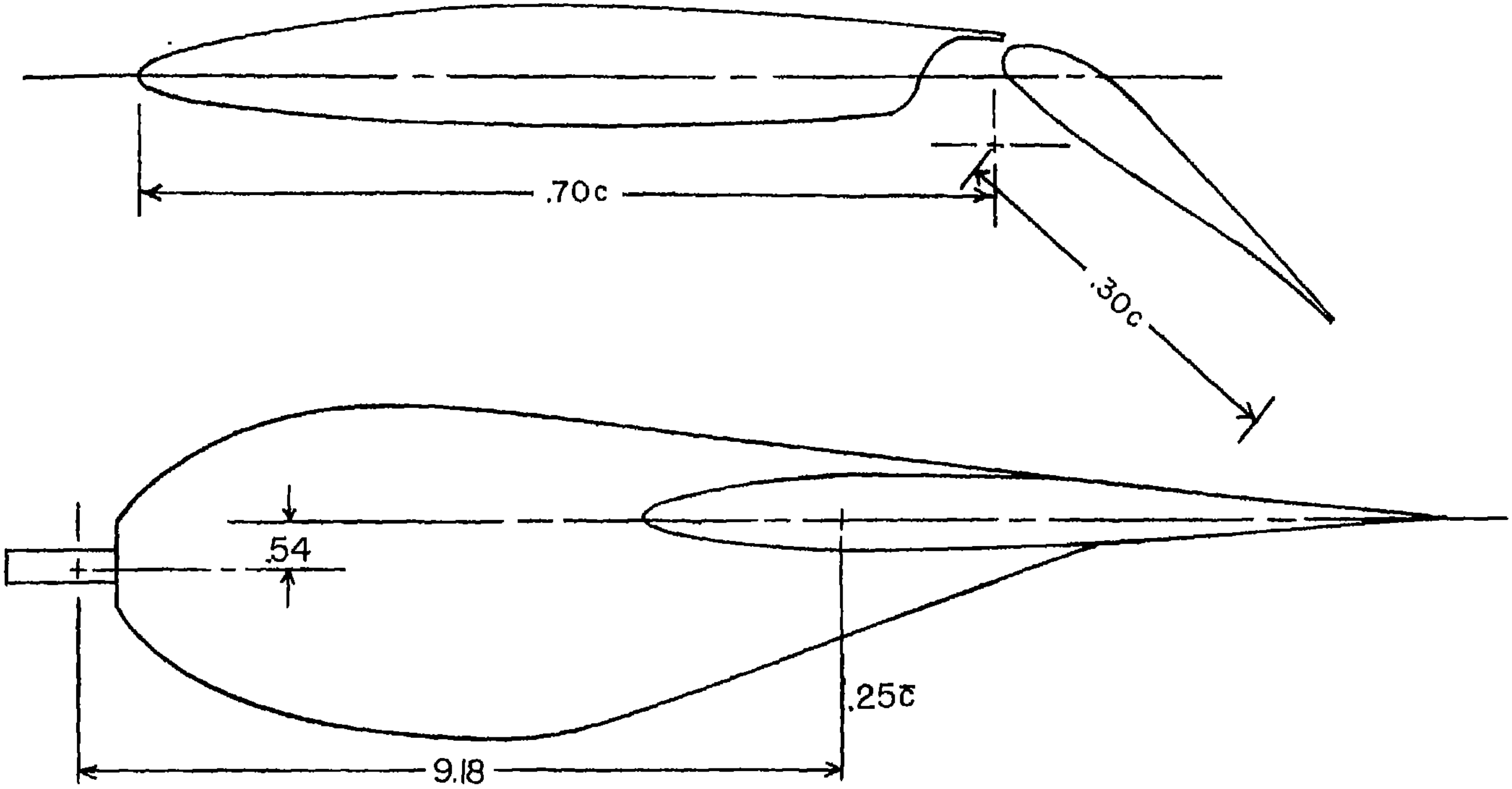


Figure 2.- Stability-axis system. Arrows indicate positive directions of forces, moments, and angular displacements.



(a) General arrangement of model. All dimensions in inches.

Figure 3.- Model of wing-propeller combination.



(b) Position of propeller relative to wing and typical wing section. All dimensions in inches except as shown.

Figure 3.- Concluded.

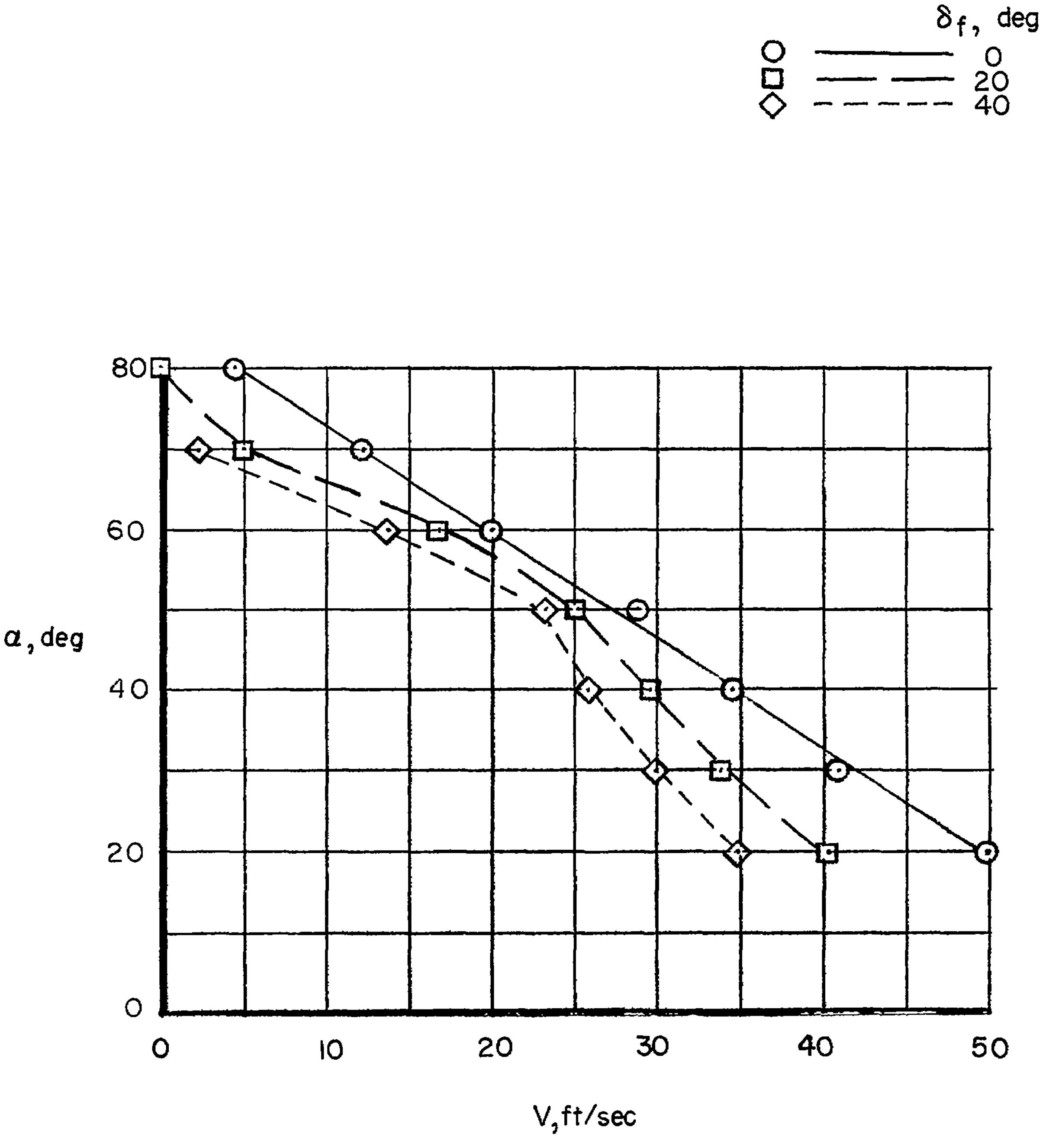


Figure 4.- Variation of airspeed to give drag trim and a lift of 25 pounds for various basic flap positions throughout angle-of-attack range.

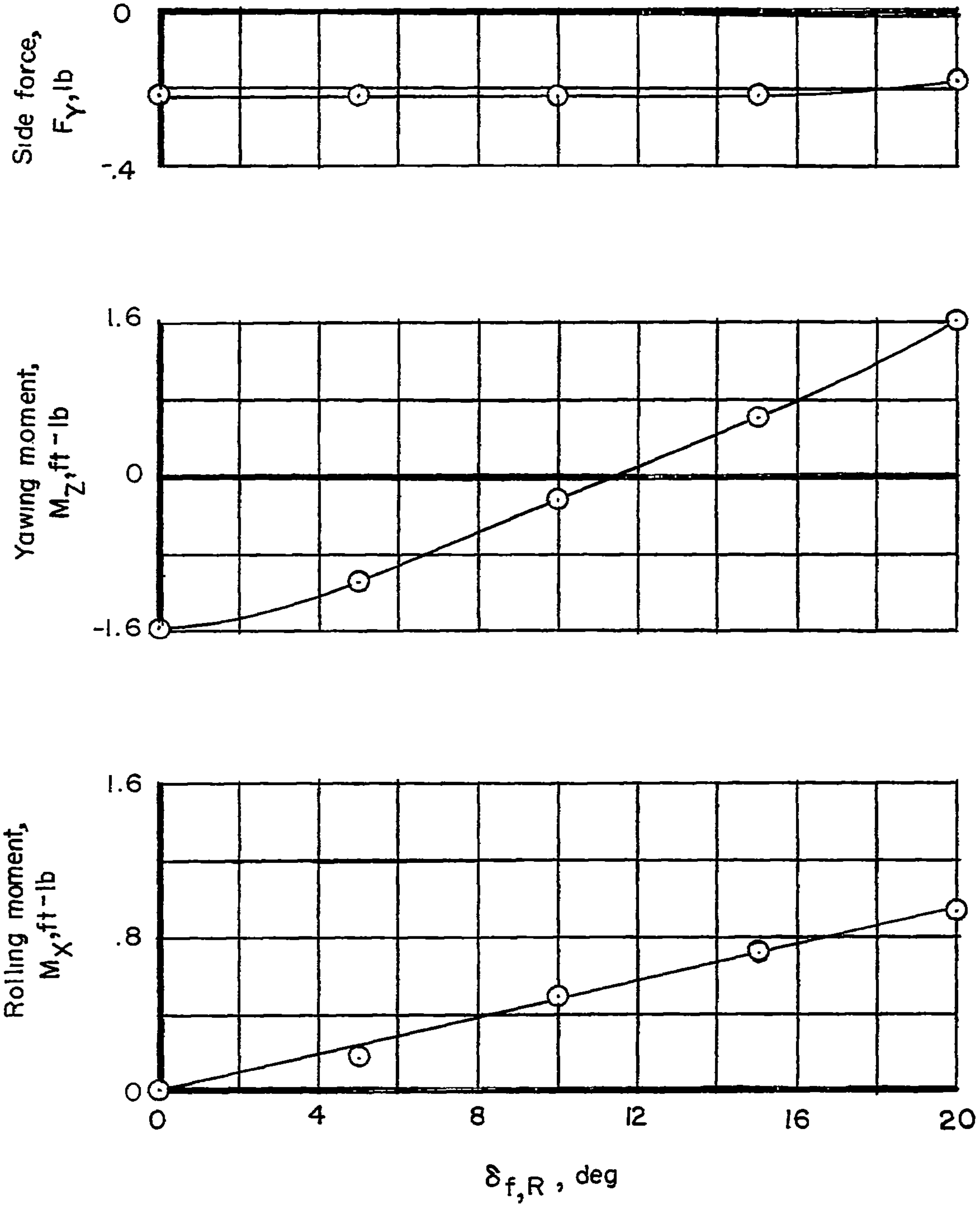
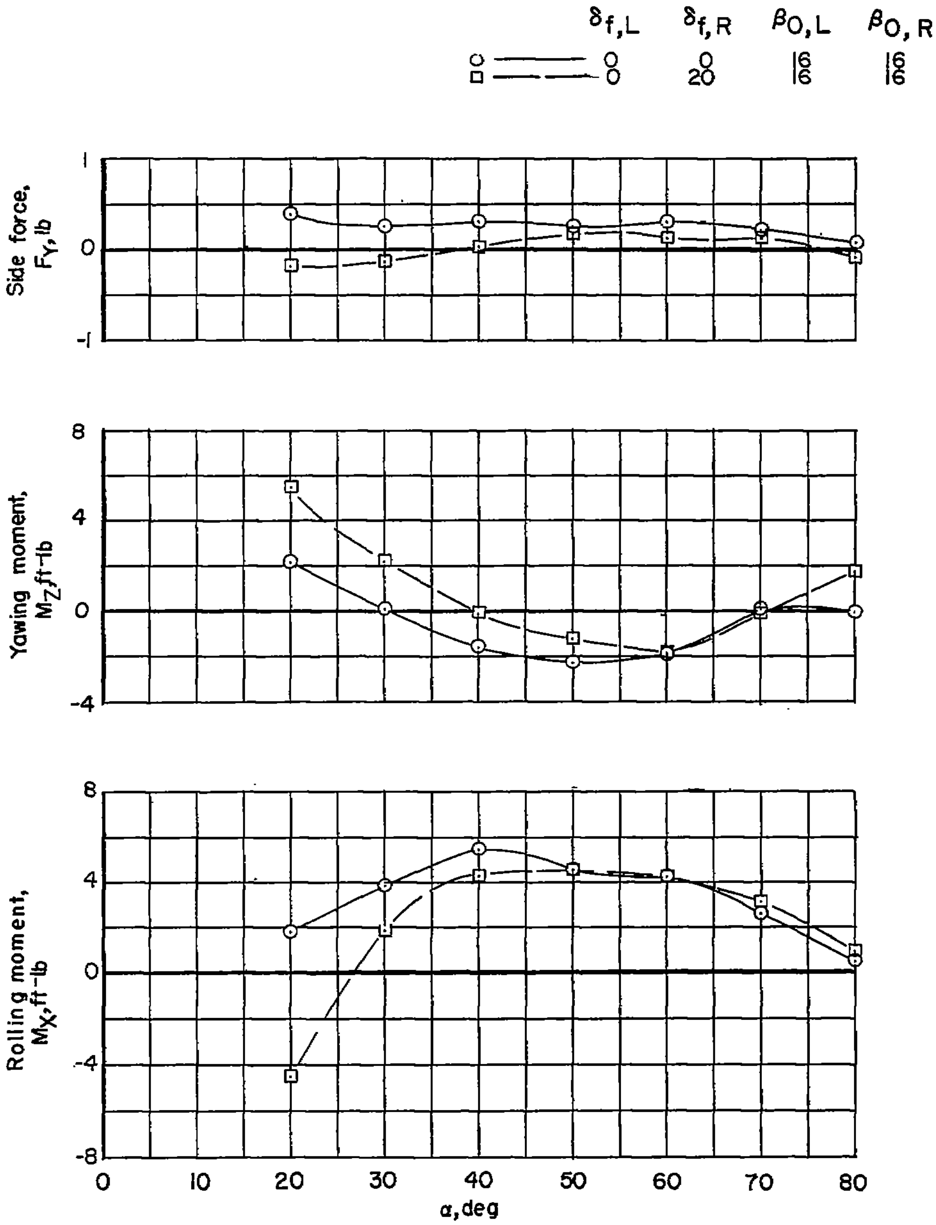
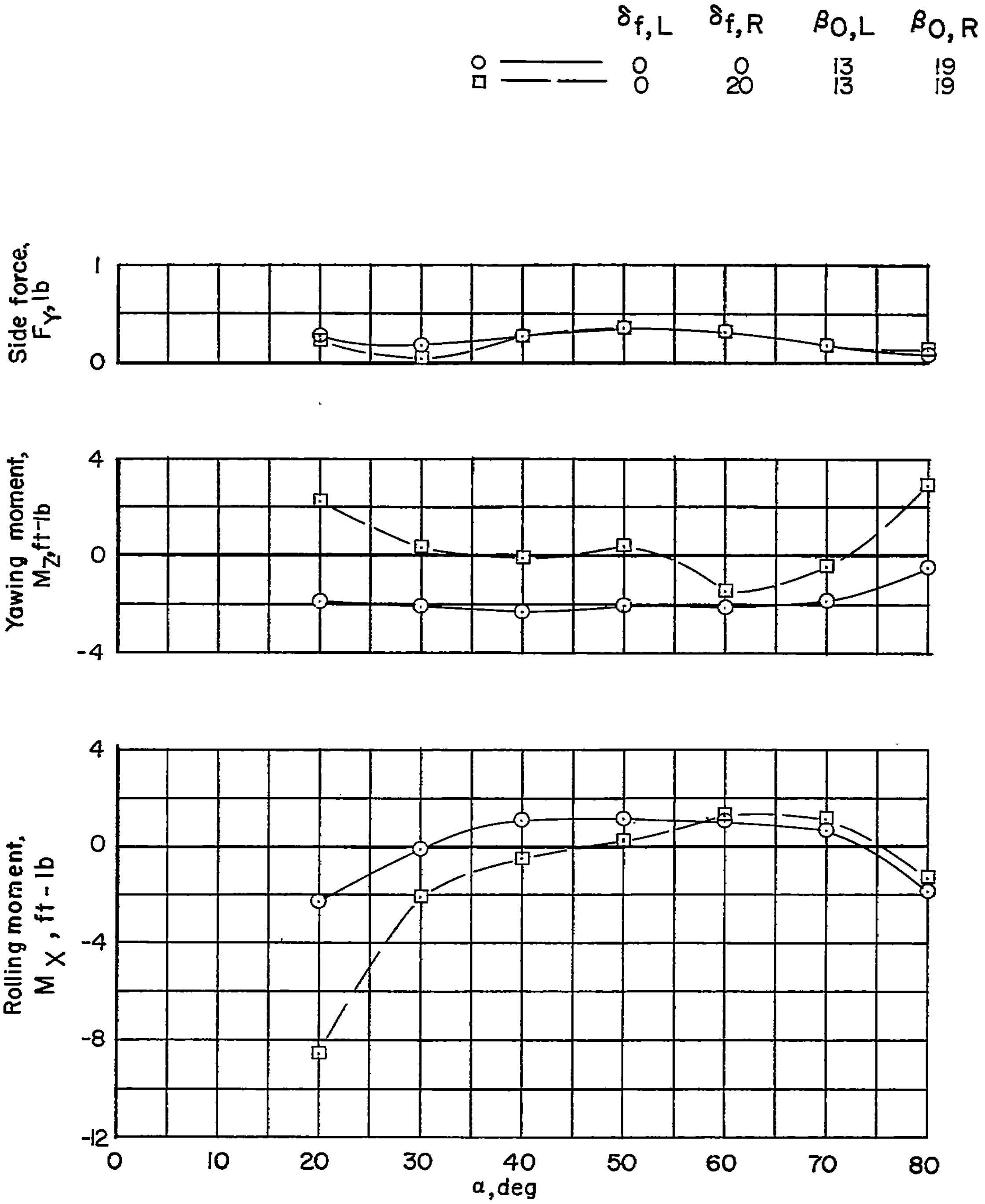


Figure 5.- Variation of rolling moment, yawing moment, and side force with deflection of right flap. $\delta_{f,L} = 0^\circ$; $\alpha = 90^\circ$; $\beta = 16^\circ$; $V = 0$.



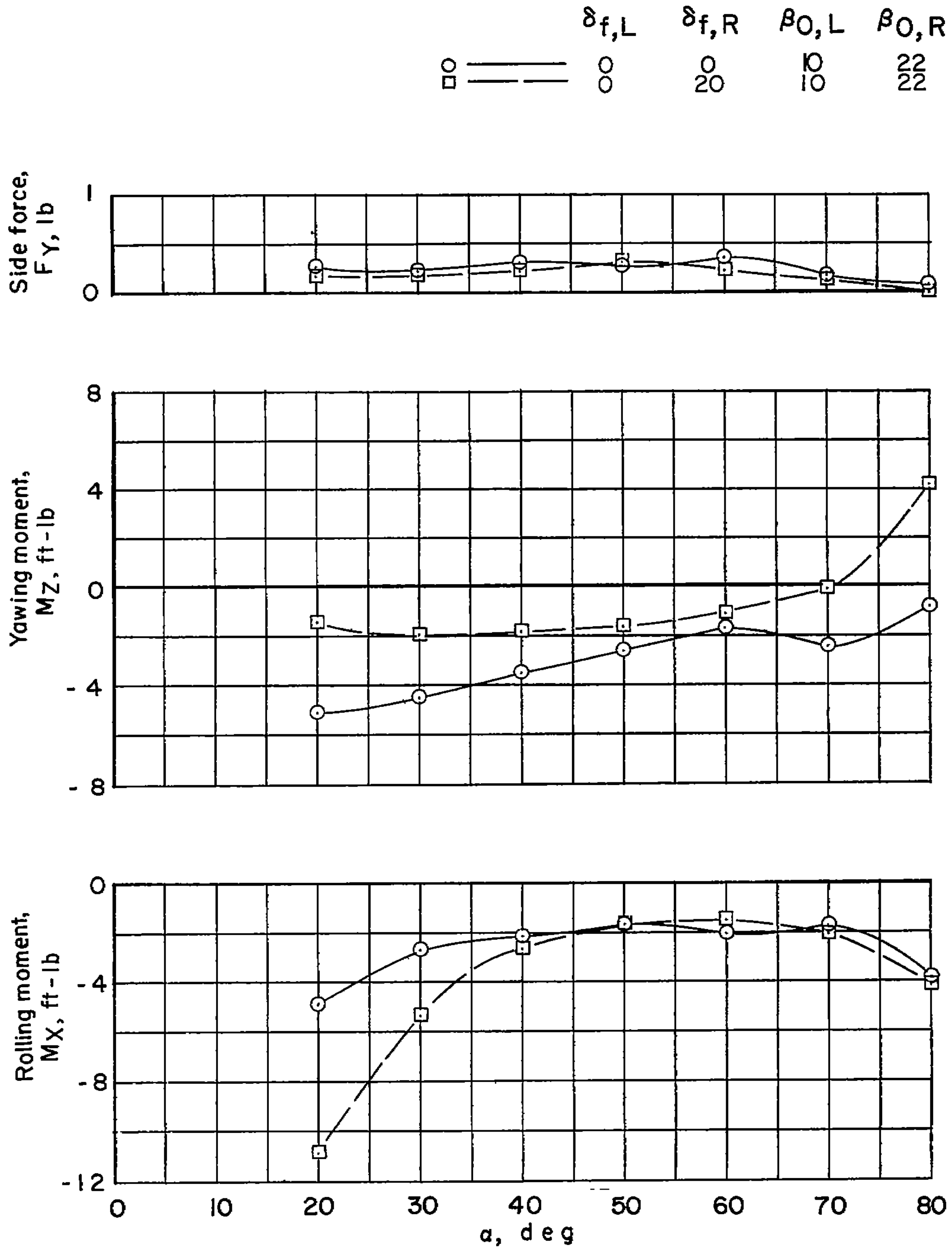
(a) $\beta_{O,R} - \beta_{O,L} = 0^\circ$.

Figure 6.- Variation of rolling moment, yawing moment, and side force with angle of attack for various differential flap deflections and differential outboard-propeller pitch settings. Basic flap position, 0°.



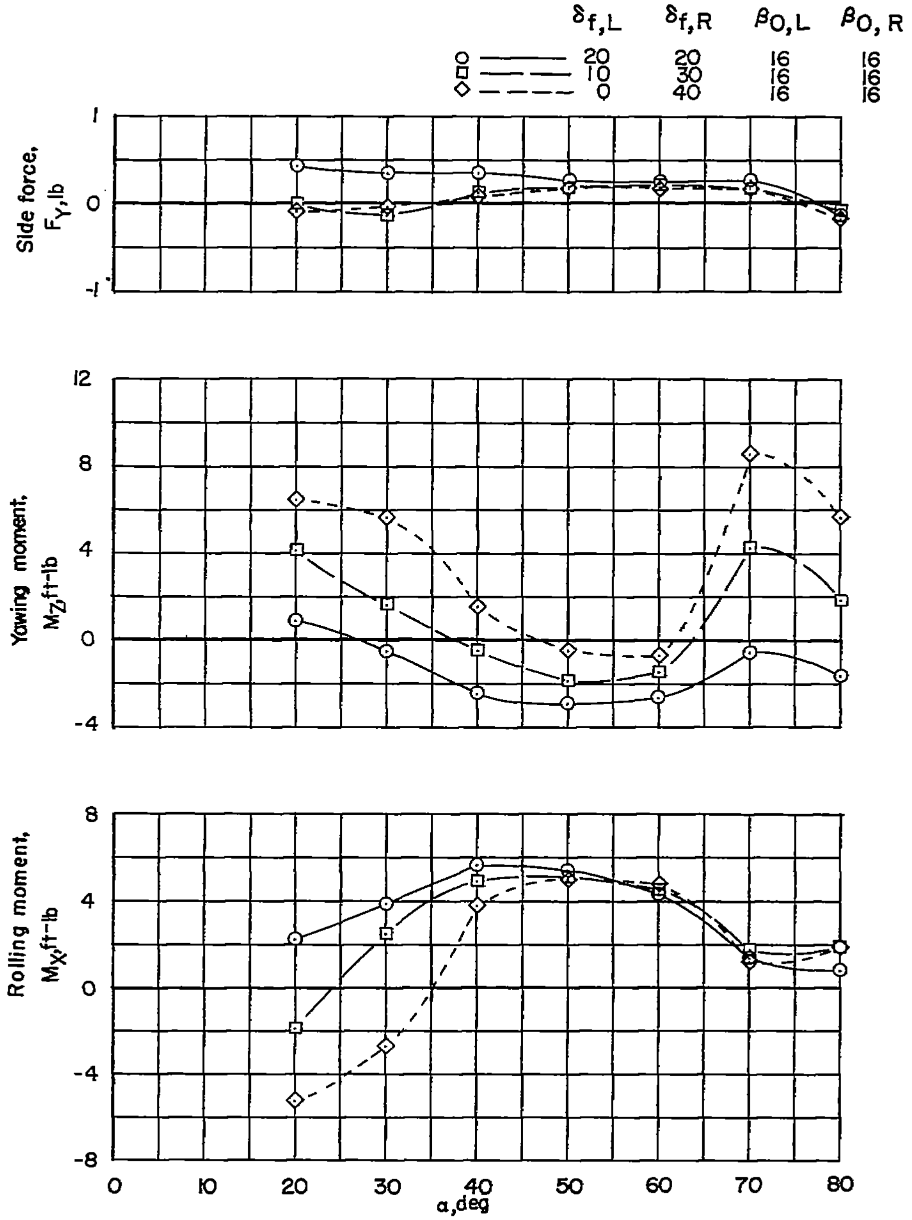
(b) $\beta_{O,R} - \beta_{O,L} = 6^\circ$.

Figure 6.- Continued.



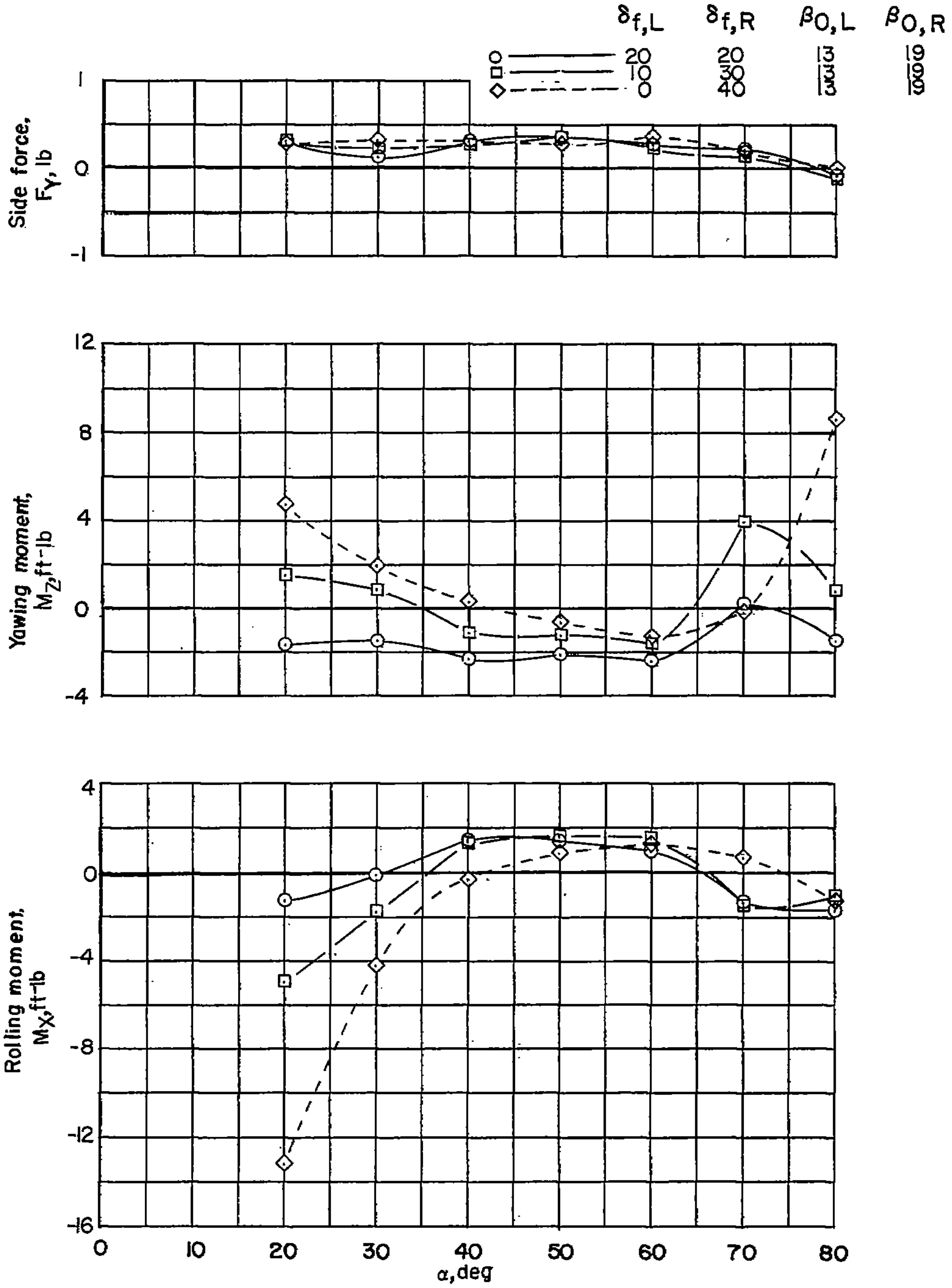
(c) $\beta_{O,R} - \beta_{O,L} = 12^{\circ}$.

Figure 6.- Concluded.



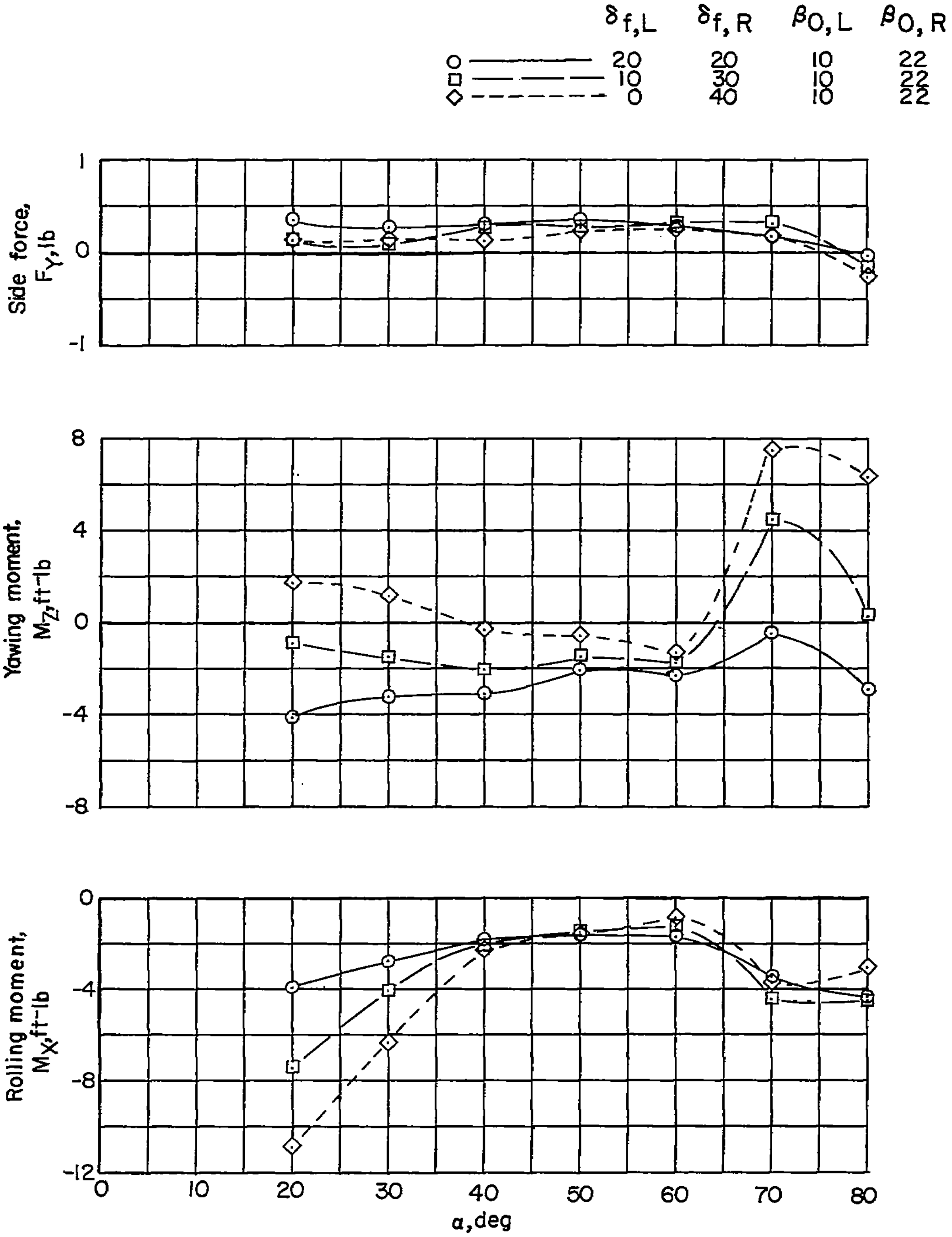
(a) $\beta_{0,R} - \beta_{0,L} = 0^{\circ}$.

Figure 7.- Variation of rolling moment, yawing moment, and side force with angle of attack for various differential flap deflections and differential outboard-propeller pitch settings. Basic flap position, 20°.



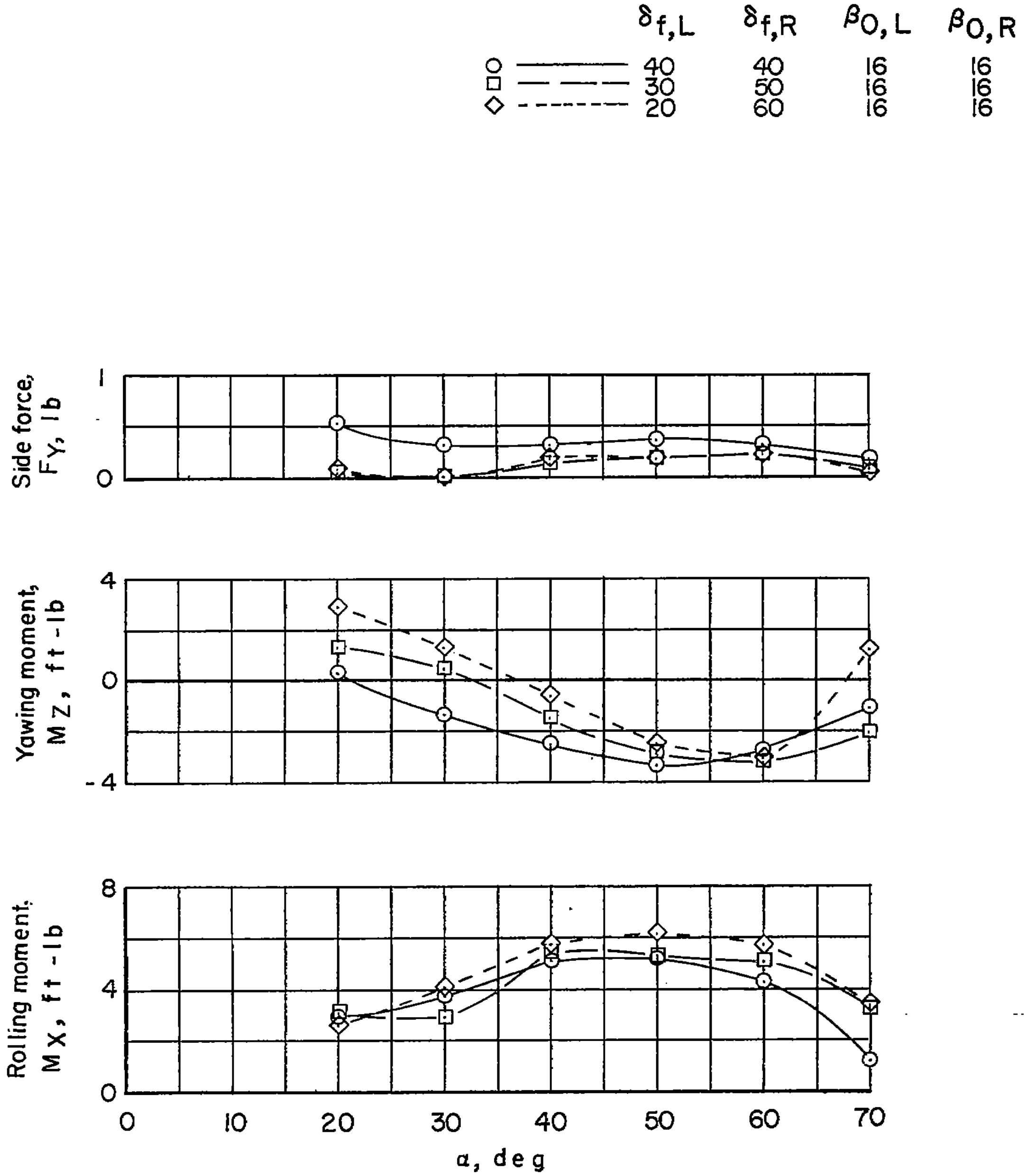
(b) $\beta_{0,R} - \beta_{0,L} = 6^\circ$.

Figure 7.- Continued.



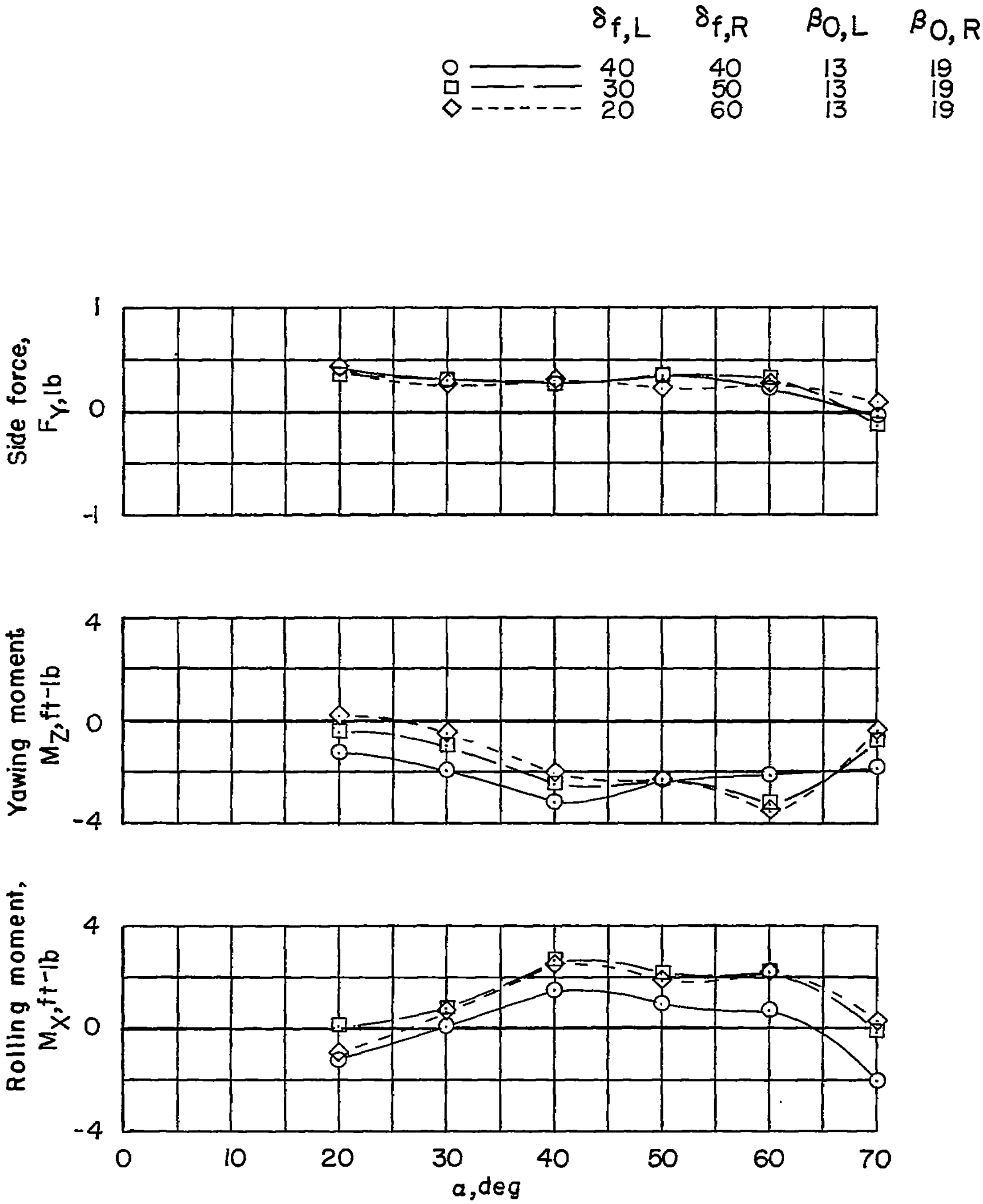
(c) $\beta_{O,R} - \beta_{O,L} = 12^{\circ}$.

Figure 7.- Concluded.



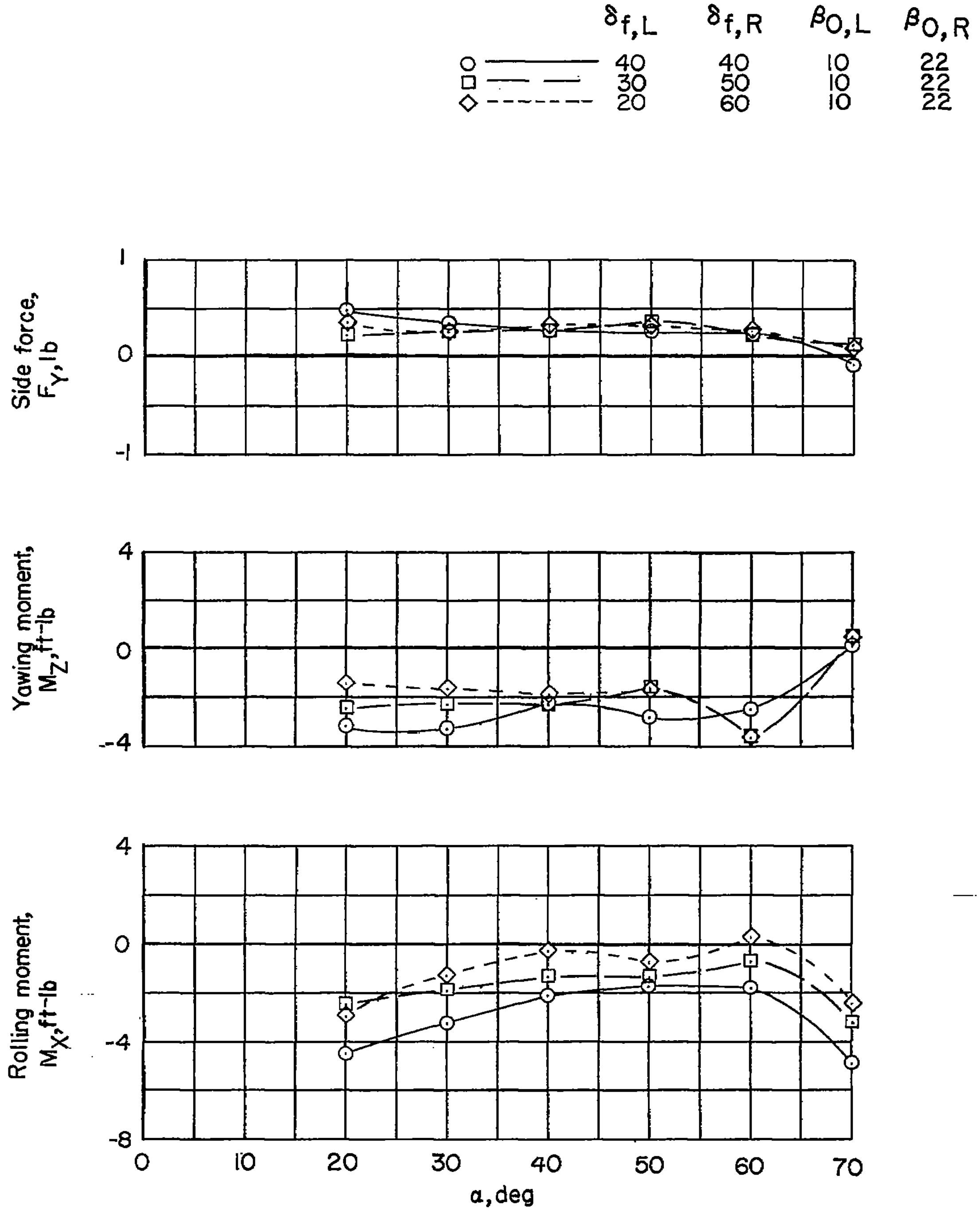
(a) $\beta_{O,R} - \beta_{O,L} = 0^{\circ}$.

Figure 8.- Variation of rolling moment, yawing moment, and side force with angle of attack for various differential flap deflections and differential outboard-propeller pitch settings. Basic flap position, 40°.



(b) $\beta_{0,R} - \beta_{0,L} = 6^{\circ}$.

Figure 8.- Continued.



(c) $\beta_{0,R} - \beta_{0,L} = 12^{\circ}$.

Figure 8.- Concluded.

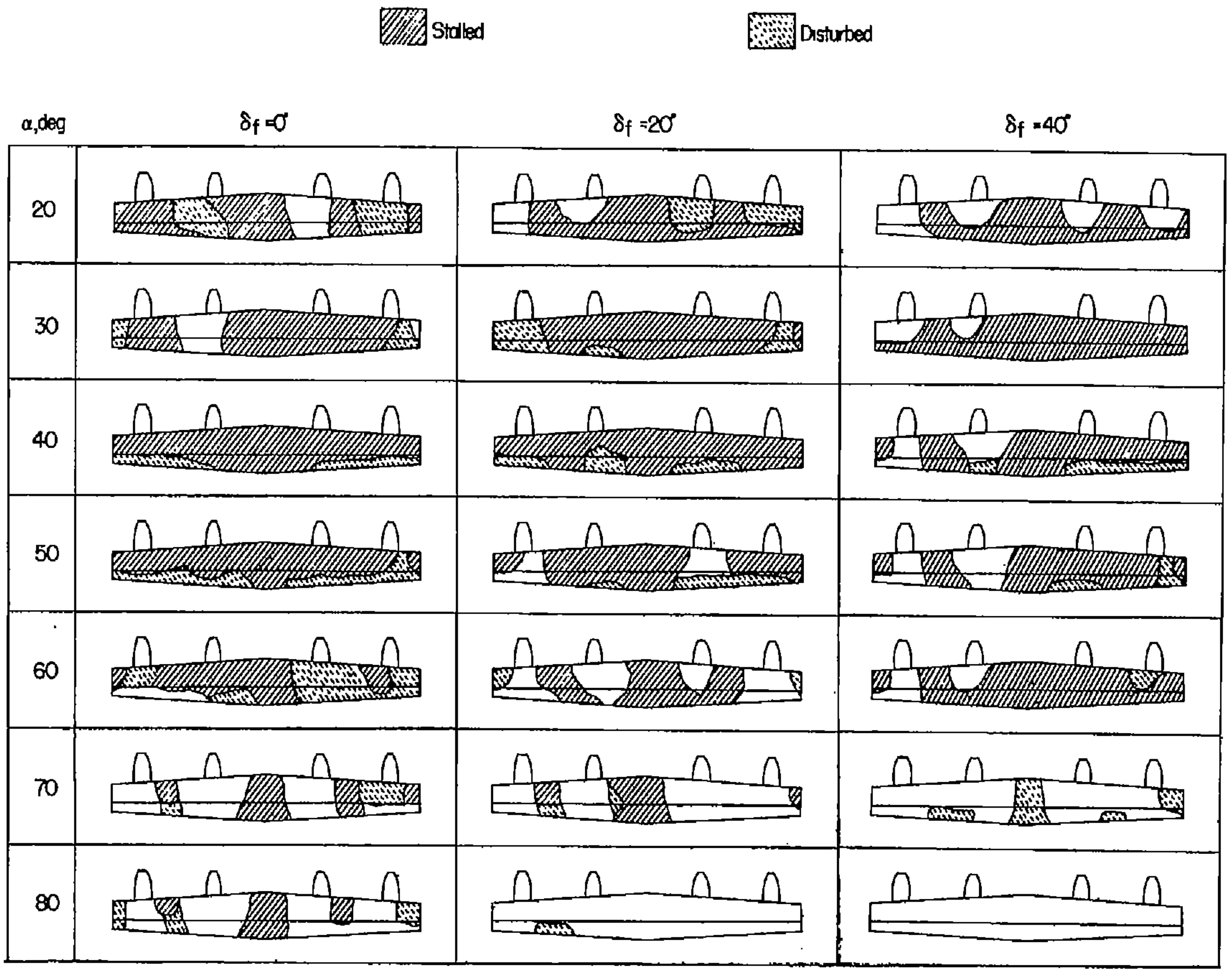


Figure 9.- Stall diagrams. Drag = 0.

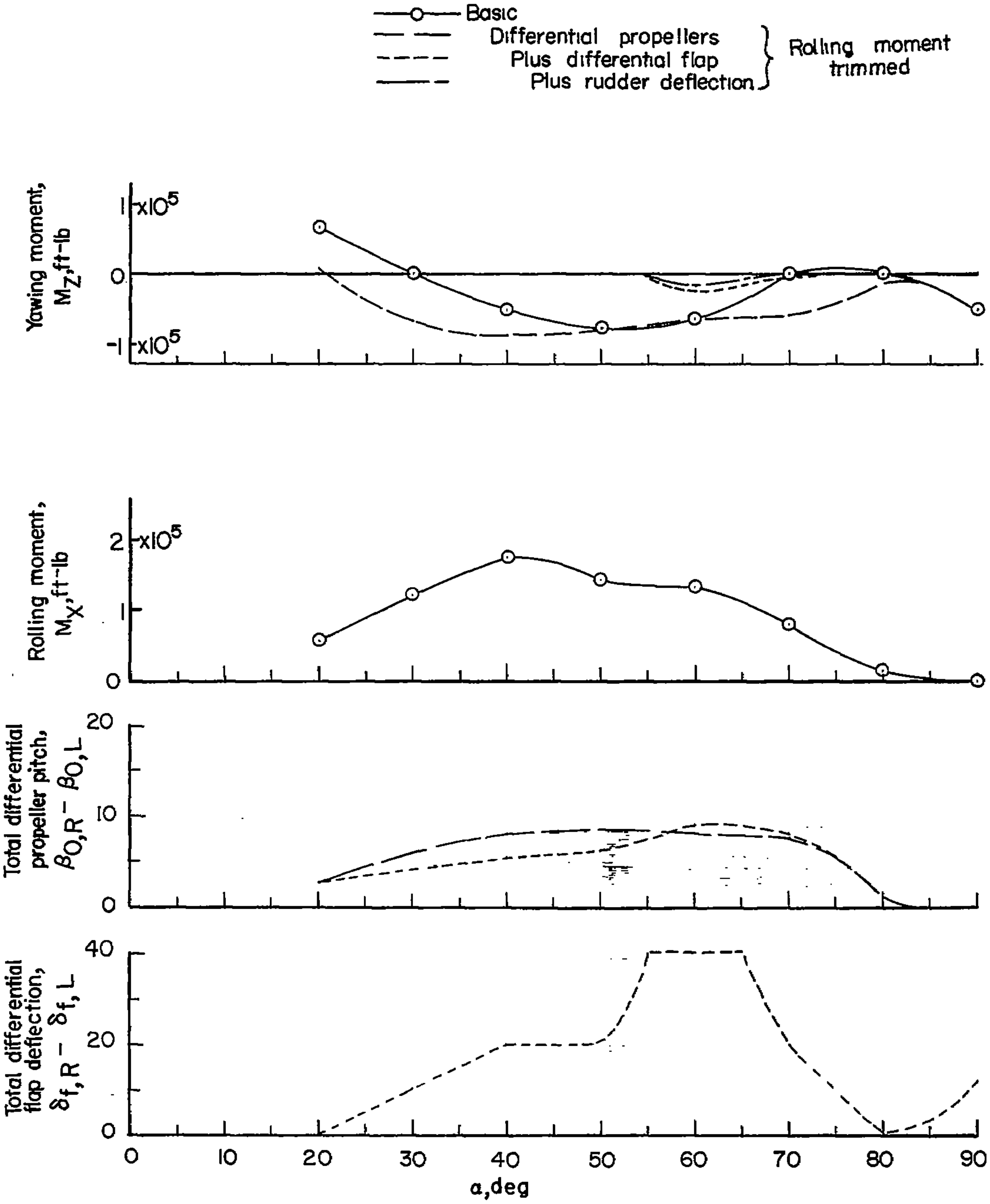


Figure 10.- Variation of rolling moment and yawing moment with angle of attack for varying differential propeller pitch angles and differential flap deflection for a pure tilting-wing VTOL airplane. Basic flap deflection, 0°.

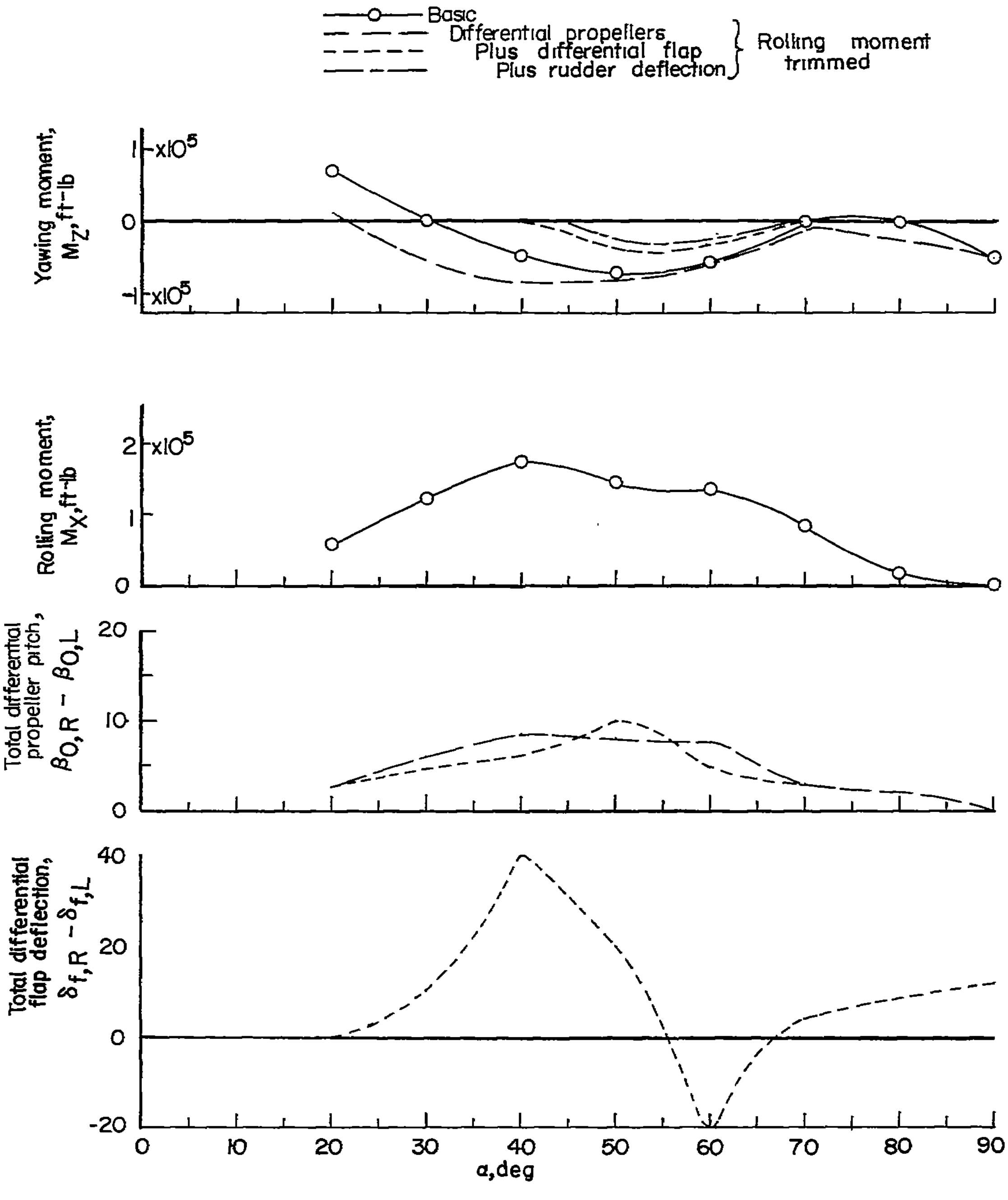


Figure 11.- Variation of rolling moment and yawing moment with angle of attack for varying differential propeller pitch angles and differential flap deflection for hypothetical airplane of reference 2.

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