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TECHNICAL NOTE

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WIND-TUNNEL INVESTIGATION OF A SMALL-SCALE MODEL OF AN AERIAL VEHICLE SUPPORTED BY DUCTED FANS

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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SUMMARY

A wind-tunnel investigation has been made to study the longitudinal-stability and pitching-moment characteristics and the power requirements of a simplified model of an aerial vehicle supported by ducted fans. The model had two ducted fans which were fixed with respect to the airframe so that their axes of revolution were vertical for hovering flight. Tests performed on the basic model in the tandem and side-by-side configurations indicated that the pitching moment and tilt angle required for trim at forward speeds were of such magnitude as to limit seriously the usefulness of a machine of this type. The pitching moment and the tilt angle were found to be greater for the side-by-side arrangement than for the tandem arrangement at any given forward speed, but the power required for the side-by-side configuration was somewhat less. A system of turning vanes beneath the forward duct of the tandem configuration to turn the propeller slipstream rearward caused reductions in both trim pitching moment and tilt angle required in forward flight, but vane deflections large enough to produce any appreciable beneficial effects on pitching moment and tilt angle apparently entail a power penalty which may be unacceptably high. The model possessed stability with speed and instability with angle of attack for all configurations tested.

INTRODUCTION

Considerable interest has been shown in the development of a general-purpose vertical-take-off-and-landing aircraft to serve as a light-transport and reconnaissance aerial vehicle. As orginally visualized, this vehicle would be able to hover or fly forward at speeds up to about 50 knots and would carry a payload of about 1,000 pounds. The overall dimensions of the machine would permit four to be loaded for transport in a 10- by 10- by 20-foot cargo space, and the slipstream velocity would be such that when the machine operated near the ground the dust disturbance would not be prohibitively large. The proposed vehicle would be simpler in construction, lower in silhouette, and easier to operate and maintain than a small helicopter.

In view of the apparent necessity for minimizing both the rotor diameter and slipstream velocity for a given static thrust and for providing protection of nearby personnel and the rotors themselves, it appeared reasonable to assume that ducted fans might be incorporated in the design of the proposed vehicle. In an effort to provide some basic information on the stability and control characteristics of aircraft utilizing groups of ducted fans, the National Aeronautics and Space Administration has undertaken a program of free-flight and static force tests on simplified models of about 1/3 scale generally representing two- and four-duct vehicles. Reference 1 presents a discussion, based in part on some of these tests, of stability and control problems to be anticipated with this type of vehicle.

The free-flight-model tests discussed in reference 1 brought to light some rather serious problems which seem inherent in any simple ducted-fan configuration in forward flight. Two of these problems are an undesirably large forward tilt angle required for trim at the higher speeds and a noseup pitching moment which increases rapidly with forward speed. These problems are of such magnitude that their solution is considered to be almost imperative to the practical operation of the ducted-fan vehicles originally visualized.

This paper presents the results of some static force tests made to obtain quantitative data on the forces and moments associated with the forward flight of a two-duct configuration and the evaluation of a system of turning vanes in the slipstream as a solution to the two previously mentioned problems.

SYMBOLS

D — net drag, lb

M_{α} — slope of curve of pitching moment plotted against angle of attack, taken at point where drag is zero, ft-lb/deg

α — angle of attack (tilt angle), negative when nose is down, deg

δ — deflection of downstream half of vane, deg

θ — deflection of upstream half of vane, deg

MODEL AND APPARATUS

A sketch of the model is presented as figure 1. The model was not meant to represent any specific full-scale machine, but was intended to be simply a research vehicle which might yield test results generally applicable to a number of proposed two-duct designs.

The model fans were of laminated-wood construction and had a fixed blade angle of 20° at 0.75 radius. For all the tests, the fans were driven, through gearboxes and interconnecting shafting, by an induction motor which was connected to a variable-frequency power supply.

The slipstream turning vanes shown in figure 1 were hinged along their midchord line and were linked together so that the deflection of the downstream half of the vane, relative to the fan axis, was twice the deflection of the upstream half. The vane deflections referred to elsewhere in this paper are for the downstream half, but in all cases the upstream half was deflected just half as much. These vanes were installed under only one of the two ducts, the forward duct for the tandem configurations. The vanes were removable and were installed only for the test specifically concerned with slipstream deflection.

The model was secured, through an internal strain-gage balance, to a portable sting and strut support system. The whole model and support assembly was then installed in the test section of the Langley full-scale tunnel. The aerodynamic forces and moments acting on the model during tests were indicated by the balance, and motor torque was indicated by a separate strain-gage balance, also internally mounted. These measurements of motor torque give an indication of the power required in the various test conditions, but include the power absorbed by the drive system as well as by the propellers.

The error in the strain-gage balance and its readout system under static loads is approximately 1 percent. The torque-indicating system, however, was found to be less reliable and might have been subject to as much as 10-percent error.

TESTS

The tests were made by first setting a tunnel speed and then covering a range of angle of attack from 0° to -40° at model fan speeds of 1,875 and 2,250 rpm. Normal and axial force, pitching moment, and motor torque readings were made at each test point. Such tests were made at each of several tunnel speeds in a range from 2 to 18 knots for both tandem and side-by-side arrangements. (See figs. 2 and 3.) Tests generally similar to these were also made for the tandem configuration with the slipstream vanes installed and deflected at angles of 15°, 30°, and 45°. (See fig. 4.)

RESULTS AND DISCUSSION

Precision of Data

As mentioned previously the precision of the balance and its read- L
out system in response to a static load is of a fairly high order. How- 8
ever, other sources of error in the test setup act to reduce appreciably 3
the precision of the values as plotted in the final curves. The flexi- 8
bility of the model and its support system was detrimental to precision as the model tended to develop, under some conditions, an angular oscillation about its longitudinal or lateral axis which produced relatively large and erratic fluctuations in the moment readings. Precision suffered also from the difficulty of measuring the free-stream wind velocity at the very low speeds and from the virtual impossibility of keeping the low velocities constant. The several sources of inaccuracy might have combined to produce a total error of as much as 10 percent in the final curves.

The magnitude of the Reynolds number effect is unknown. No corrections have been applied for it, but it has been minimized by basing the final curves, as far as possible, on data from tests at the higher disk loadings (about 7 pounds per square foot).

Basic Data

The basic data from the tests are presented in figures 2 to 4. In this paper, drag is to be construed as the net force acting on the model along a line through its center of gravity and parallel to the free-stream velocity. Lift is the net force acting through the center of gravity perpendicular to the relative wind and in the longitudinal plane of symmetry of the model. No attempt has been made to nondimensionalize the data because of the difficulty involved in formulating a basis for coefficients which would be meaningful in both the hovering and forward-flight conditions. The use of tip speed, for instance, as the nondimensionalizing velocity parameter would be unsatisfactory because the model fans are not considered representative of the fans likely to be used in a machine of this type. The forces, moments, and velocities from the drag equilibrium points in figures 2 to 4 have been scaled up in the preparation of figures 5 to 11 so that in cases in which zero net drag is indicated the lift equals 75 pounds, the approximate flying weight of the model. At this weight the model represented a 1/3-scale model of a 2,000-pound machine.

Pitching-Moment Characteristics

Figure 5 shows a comparison of the variation of pitching moment and tilt angle with forward speed for the side-by-side and tandem configurations. These data show that the tandem configuration produces smaller moments and requires somewhat smaller forward tilt angles for trim at nearly any given speed. This result might be explained as follows in terms of downwash and interference effects. In the tandem configuration, the rear duct and fan assembly operates in a downwash induced by the forward assembly, and the incoming air is therefore more nearly alined with the duct axis than in the case of the forward duct. If the forces on each duct assembly are considered as being resolved into an axial force acting along the axis of fan rotation, a normal force perpendicular to this and through the center of gravity of the whole model, and a pitching moment about the intersection of these two force vectors, then the rear duct assembly of this configuration, operating in the downwash field of the front duct, would experience less axial force, normal force, and pitching moment than would the forward assembly. The difference in axial forces between the front and rear assemblies would produce a noseup pitching moment about the center of gravity of the whole model, but the pitching moment of the rear duct about its own center would be less than that of the ducts of the side-by-side arrangement, where neither duct is in such a downwash field. Since the total pitching moment of the tandem model about its center of gravity is the sum of the moments produced by the axial forces and the moments acting about the center of each duct, it is evident that the reduction in duct pitching moment more than offsets the effect of the difference in axial forces and results in less net noseup pitching moment for the tandem configuration. Similarly, because of the effect of the downwash of the front duct on the rear one, the sum of the normal forces is less for the tandem configuration; therefore the drag, and consequently the tilt angle, was somewhat less than for the side-by-side arrangement at any given forward speed. It will be noted that this explanation of the downwash effect on the pitching moment is different from the analysis presented in reference 1, where only the effect of downwash on propeller thrust is considered and the conclusion is drawn that the noseup pitching moment would be greater for the tandem than for the side-by-side configuration.

The curves of figure 5 indicate that even in the tandem configuration the large magnitudes of forward tilt angle and perhaps also the large pitching moment could impose serious limitations on the top speed of a full-scale machine of the general type represented by the model. Primarily in an effort to alleviate the tilt-angle problem, a system of turning vanes was installed in the slipstream of the forward duct of the tandem configuration. These vanes were intended to produce a force which would have a large horizontal component in the direction of flight and would thereby increase the forward speed for a given tilt angle. To minimize the noseup moment produced by this component, its moment arm was kept relatively small by mounting the vanes as high on the model as was structurally possible. There would also be a downward vertical component of the vane force which, with the relatively long moment arm resulting from its forward location, would have the additional beneficial effect of producing a nosedown moment. No vanes were installed beneath the rear duct because the downward forces acting on them would have produced a strong noseup pitching moment that would offset the nosedown moment caused by the downward force on the forward vanes.

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Figure 6 shows the curves of pitching moment required for trim resulting from longitudinal tests of the model in the tandem configuration with the vanes installed and deflected to three different positions. The solid lines are lines of constant vane deflection, whereas the dashed lines connect points of equal tilt angle.

The dashed lines indicated that increasing vane deflection at any given tilt angle did indeed have the desired effect of increasing the speed for steady level flight for that angle. The data also show that increasing vane deflection in the lower part of the vane-angle range resulted in an increased noseup pitching moment for a given tilt angle. Apparently, the increase in moment was not due primarily to the moment produced by the vane force, but was mainly the result of the larger moment produced by the ducts and fans at the increased trim speed afforded by the vanes. It is likely, however, that under some conditions the vane force did produce a small noseup contribution to the pitching moment. This would occur if the resultant vector of the vane force passed below the center of gravity of the model. That this condition actually existed is evidenced in figure 6 by the fact that at zero forward speed the pitching moment is less for a vane deflection of 15° than it is for a deflection of 30°. Had the vanes been located farther below the center of gravity of the model, this adverse effect might have been even more pronounced. At the greater vane deflection angles the situation seems to be more straightforward in that the vane resultant vector was then apparently rotated far enough to pass above the center of gravity; increasing vane deflection in this range produced not only an increase in speed but also a definite nosedown moment. That the vane force must have produced the nosedown moment is indicated by a consideration of the basic data as presented in figure 2, which show that for the model in the tandem configuration, without vanes, increased speed at any constant tilt angle resulted in increased pitching moment through the entire ranges of speeds and tilt angles tested. Any reduction in pitching moment with increased forward speed at a constant tilt angle with vanes installed must therefore have been due to the moment produced by the vane force. Figure 6 also indicates that, with the vanes deflected, there may exist more than one steady level flight speed for some of the tilt angles. For instance, with the vanes deflected 30°, the noseup angle required at zero forward speed is seen to be 10°, which is also the angle required for a forward speed of 3.1 knots.

The beneficial effects of the vanes in reducing the tilt angle and pitching moment required for trim in forward flight are obtained at the expense of an increase in the power required. This fact is not documented in the present paper, but was observed qualitatively in flight tests and in some force tests that did not result in sufficient accuracy to warrant publication.

Stability Characteristics

All of the basic-data figures (figs. 2, 3, and 4) incorporate pitching-moment curves which show that the model possesses a definite speed stability; that is, as forward speed increases, the pitching moment increases in the direction to reduce the tilt angle and thereby tends to resist the increase in speed. A pronounced instability of pitching moment with angle of attack is indicated, however, by figures 7, 8, and 9, which present the variation of pitching moment with angle of attack at constant forward speeds for the tandem configuration with and without vanes and the side-by-side configuration. A plot of M_α against model speed for the several configurations is presented as figure 10. This plot indicates that for all configurations the instability increased with increasing speed. The data also indicate that all these configurations possessed about the same amount of angle-of-attack instability. The configuration with vanes installed and deflected 45° was the most unstable of the group.

Power Requirements

For steady level flight with pitching moment untrimmed, the power requirements are reduced in going from the hovering condition to a forward speed of about 15 knots. At higher speeds the power required increases with increasing forward speed.

The curves of figure 11 also indicate that less power is required by the side-by-side configuration than for the tandem at any given forward speed. This same general effect has been previously noted for helicopters in connection with the power required for side-by-side and tandem rotor arrangements. This result may be attributed to the downwash effect which, in the tandem configuration, causes an unequal load distribution between the two ducts. The lift on the rearward duct assembly is reduced somewhat while that on the forward assembly must be increased by the same amount to maintain a constant total lift. Since, from momentum relationships, the power absorbed by each fan is proportional to the 3/2 power of the thrust, the decrement in power absorbed by the rear fan is more than offset by the increase in power of the forward fan, with the net result that more total power is required than for the case in which the two duct assemblies carry equal lift loads, as they do in the side-by-side arrangement.

CONCLUSIONS

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On the basis of static force tests of a simplified model with two ducted propellers in both the tandem and side-by-side configurations, the following conclusions are drawn:

1. The tandem arrangement exhibits less noseup pitching moment and requires a slightly smaller tilt angle for a given forward speed than the side-by-side arrangement in the range from 0 to 25 knots, but the side-by-side arrangement requires appreciably less power than the tandem in the same speed range.

2. Both the trim pitching moment and tilt angle required for forward flight of the tandem configuration may be reduced by turning vanes judiciously placed in the slipstream of the forward duct. However, as observed qualitatively in flight tests and in some force tests, the power penalty associated with such an installation may be unacceptably high.

3. The model possesses pitching-moment stability with speed and instability with angle of attack. Instability with angle of attack is relatively insensitive to the changes in model configuration made during these tests.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Field, Va., February 8, 1960.

REFERENCE

1. McKinney, M. O.: Stability and Control of the Aerial Jeep. Preprint No. 10S, SAE Annual Meeting (Detroit, Mich.), Jan. 1959.

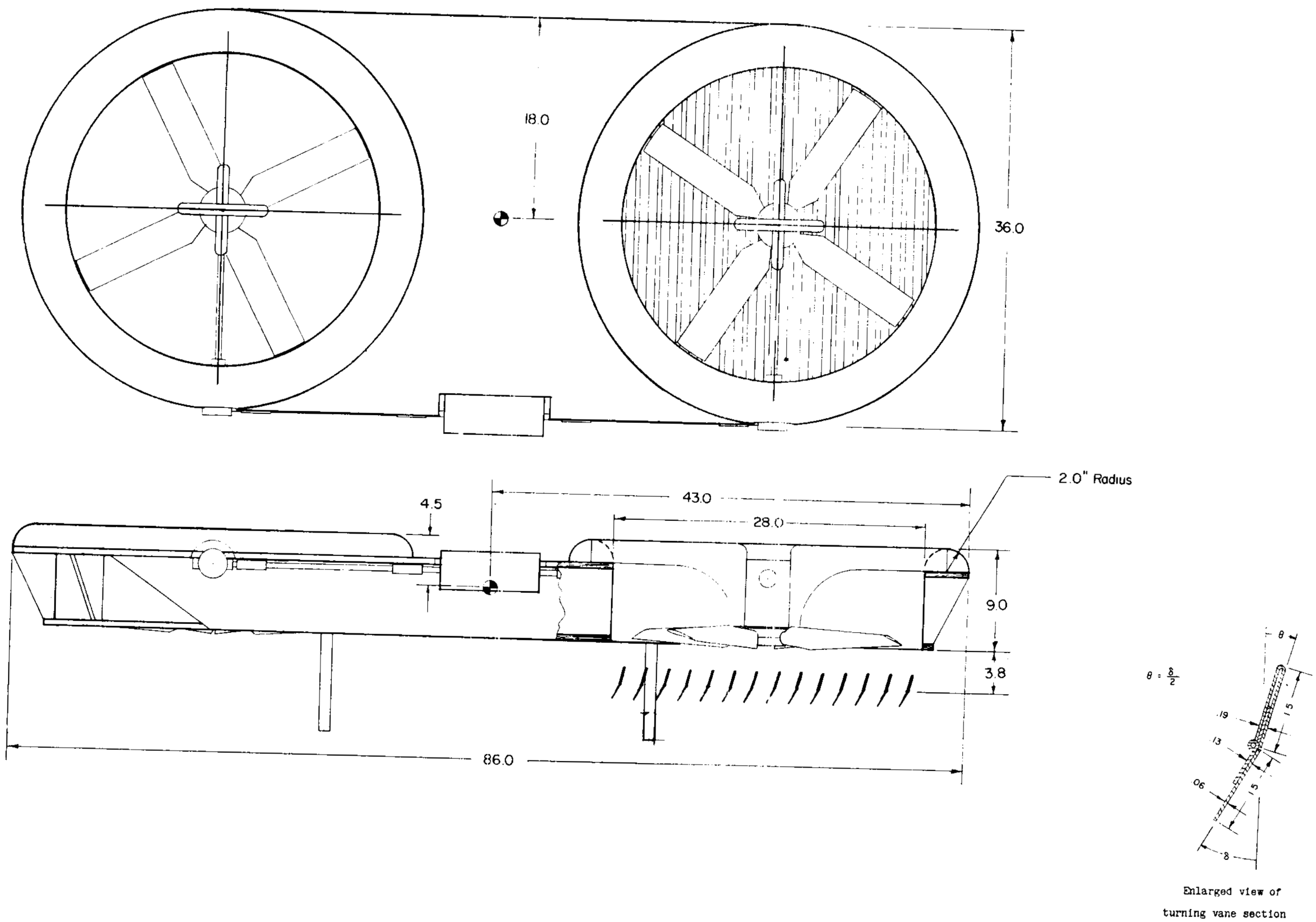

Figure 1.- Sketch of model. All dimensions are in inches.

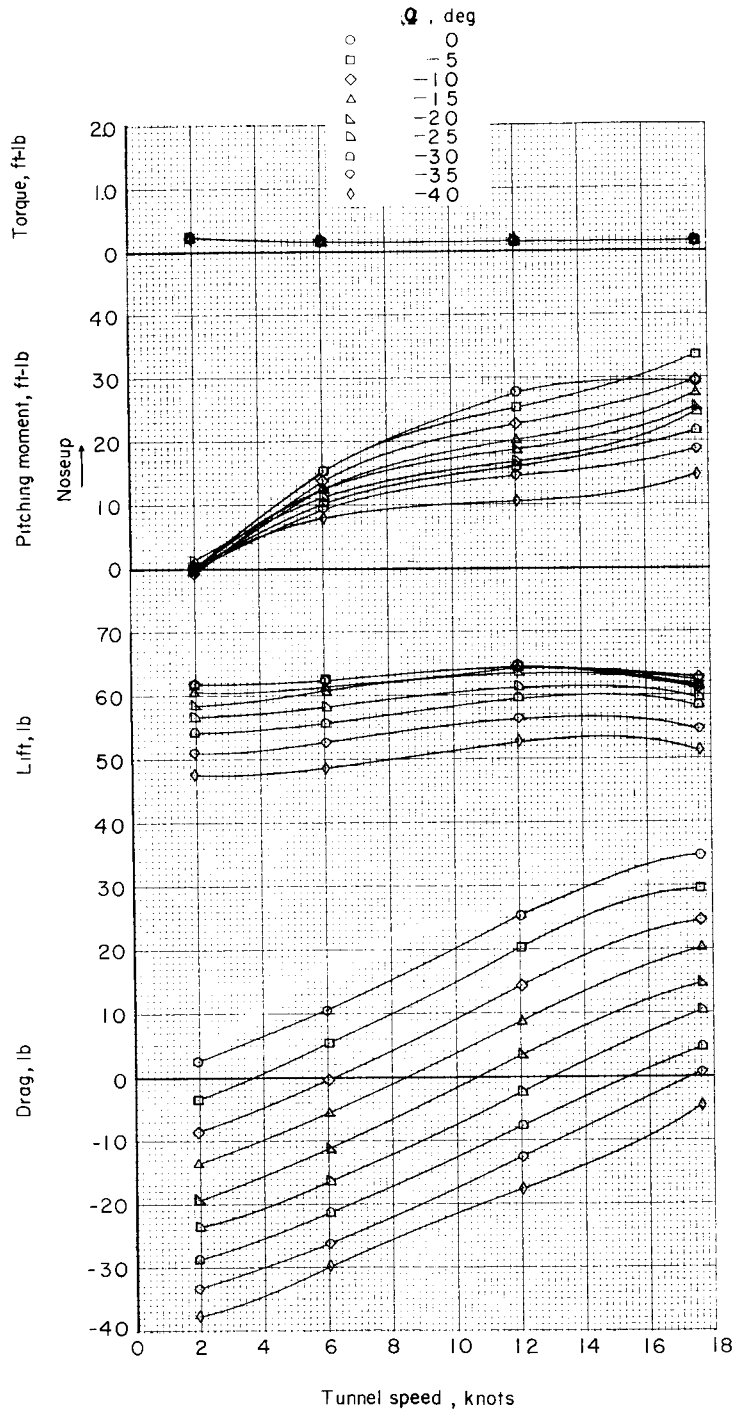

Figure 2.- Basic data for model in tandem configuration, without vanes. Model fan speed, 2,250 rpm.

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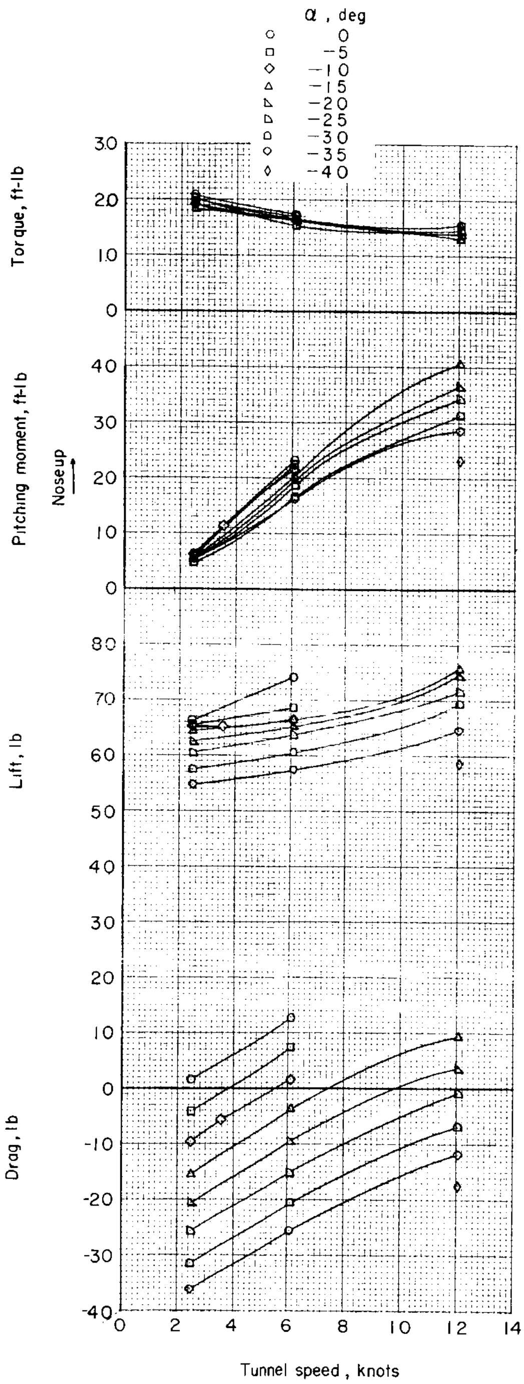
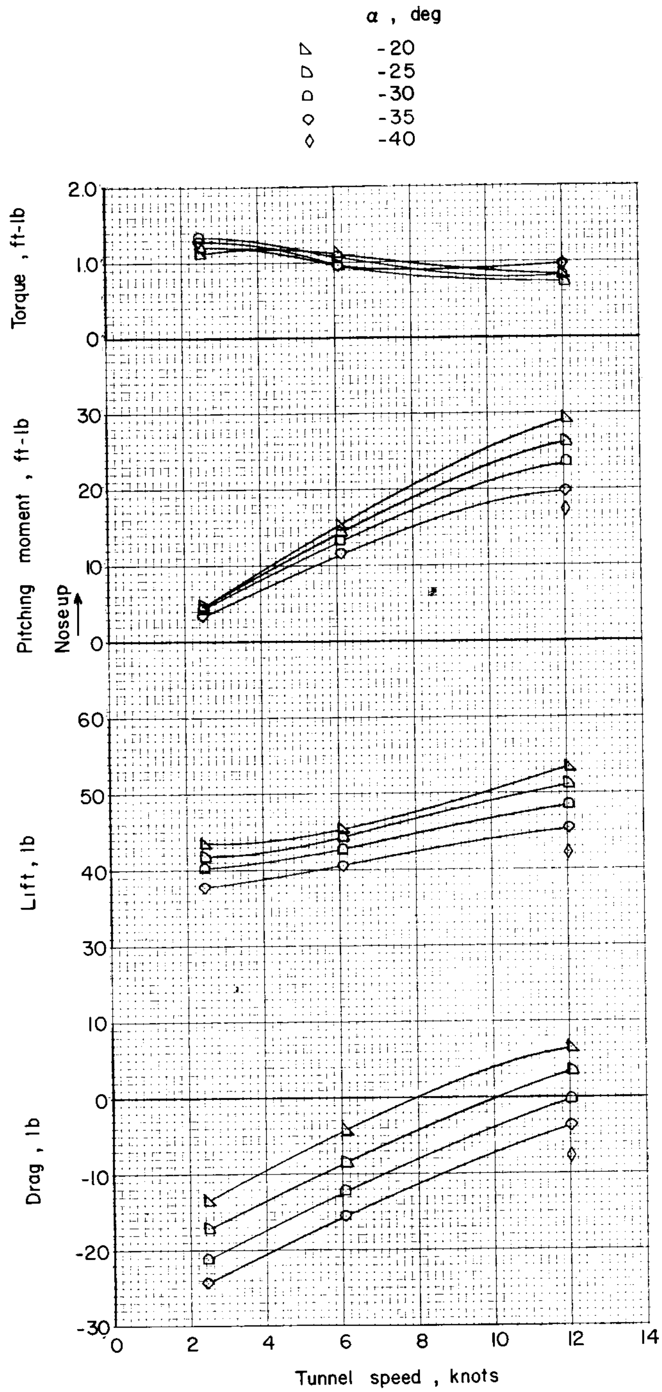


(a) Model fan speed, 2,250 rpm.

Figure 3.- Basic data for model in side-by-side configuration.



(b) Model fan speed, 1,875 rpm.

Figure 3.- Concluded.

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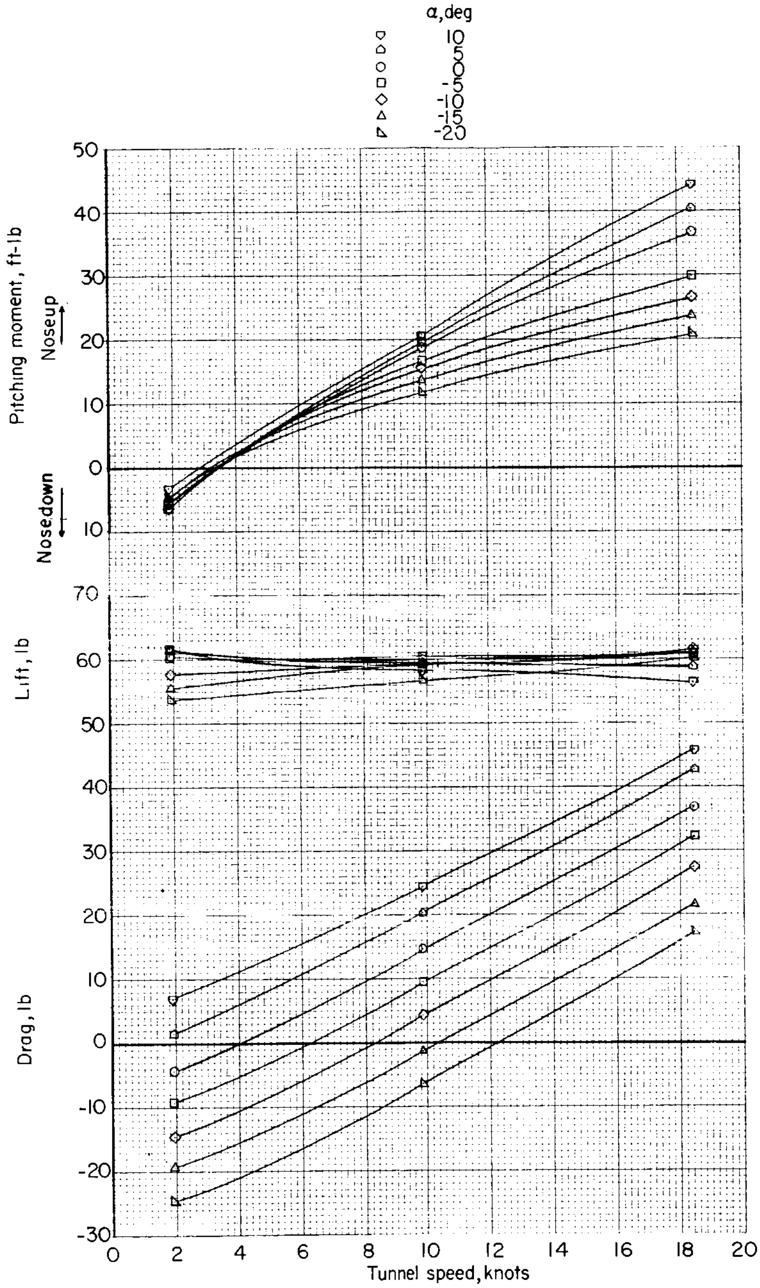
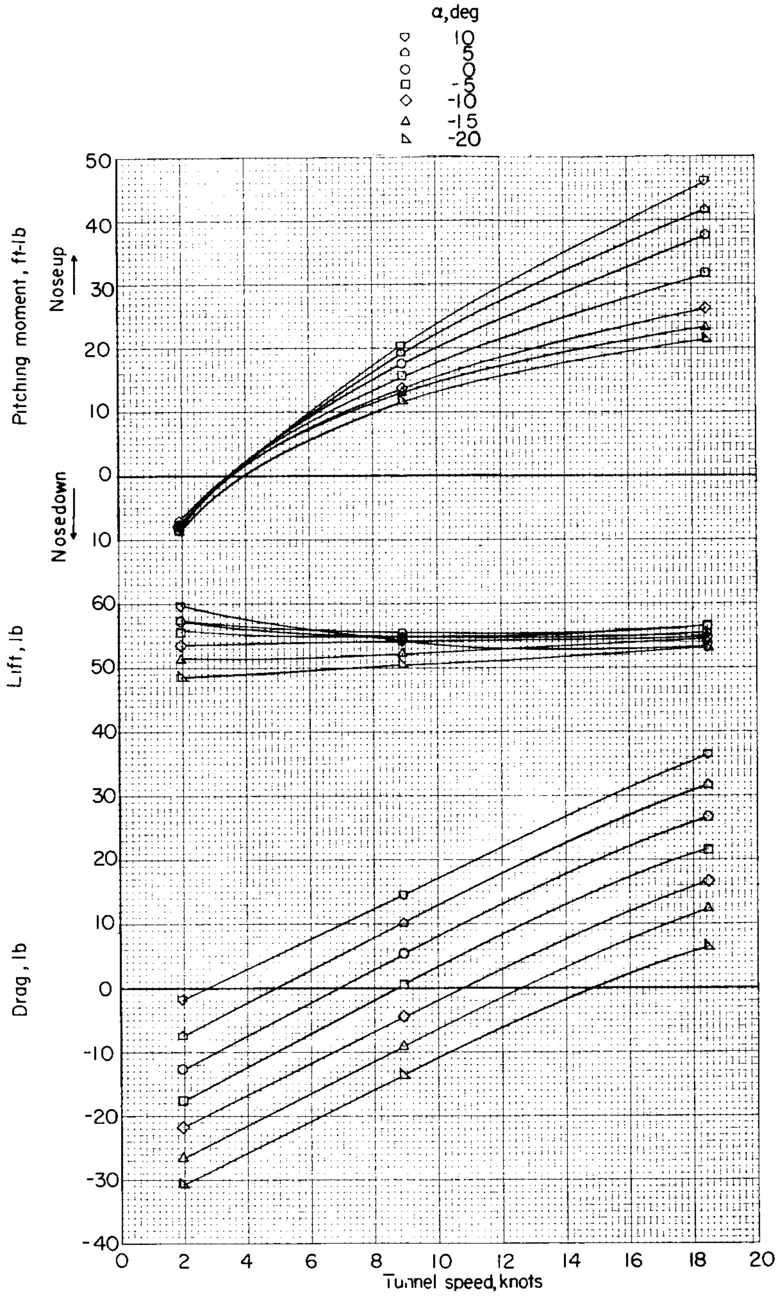


(a) Vane deflection, $\delta = 15^{\circ}$.

Figure 4.- Basic data for tandem model with vanes installed.



(b) Vane deflection, δ = 30°.

Figure 4.- Continued.

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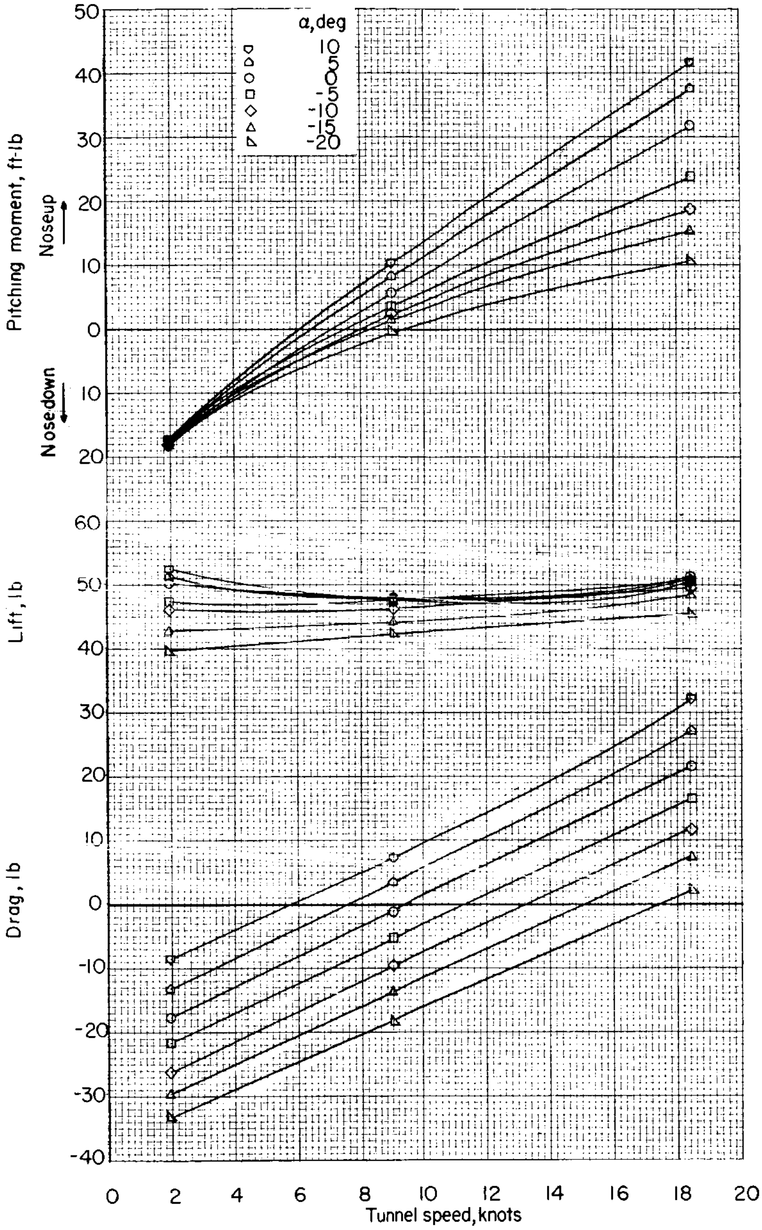

(c) Vane deflection, $\delta = 45^{\circ}$.

Figure 4.- Concluded.

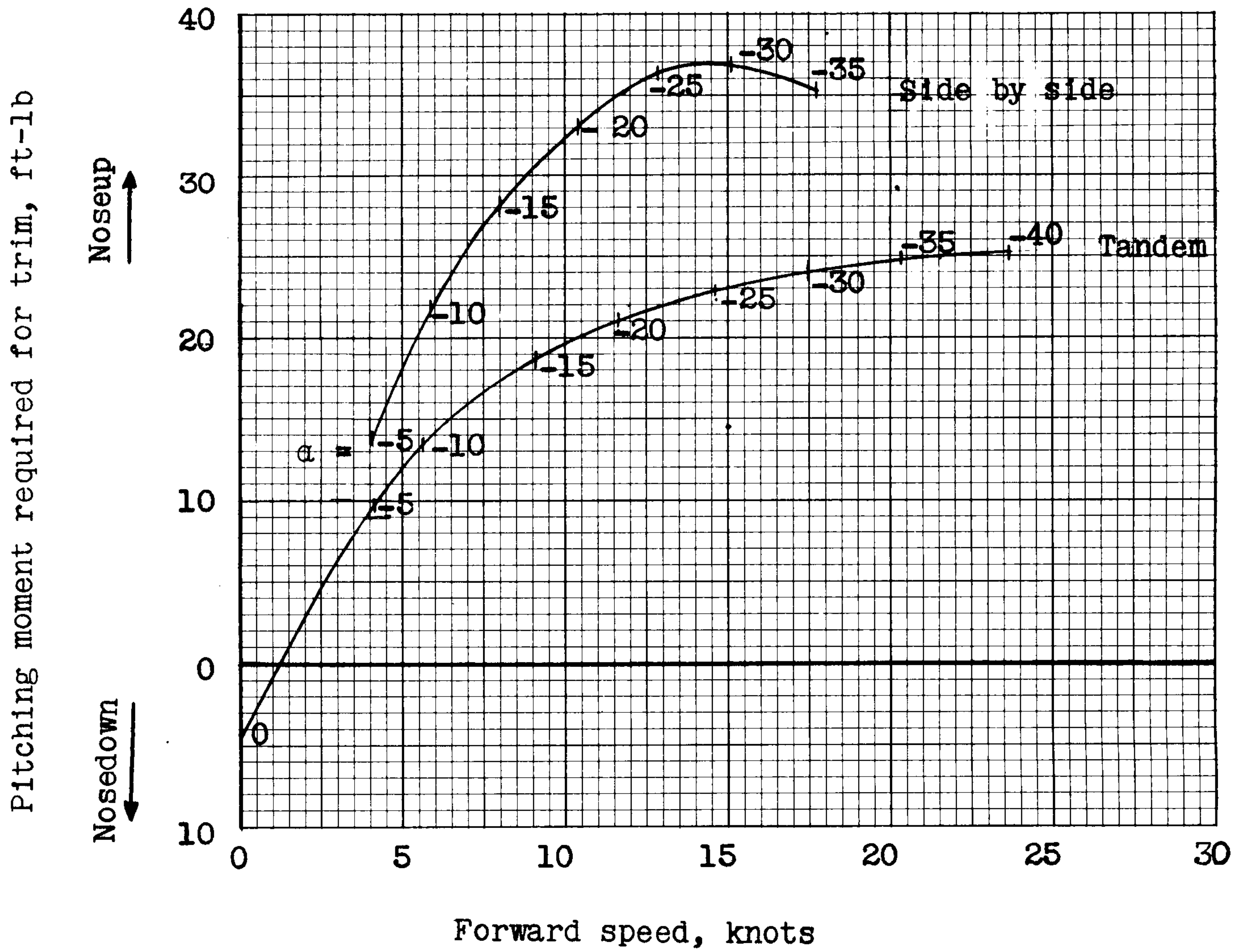

Figure 5.- Variation of pitching moment and tilt angle required for trim with forward speed for the side-by-side and tandem configurations.

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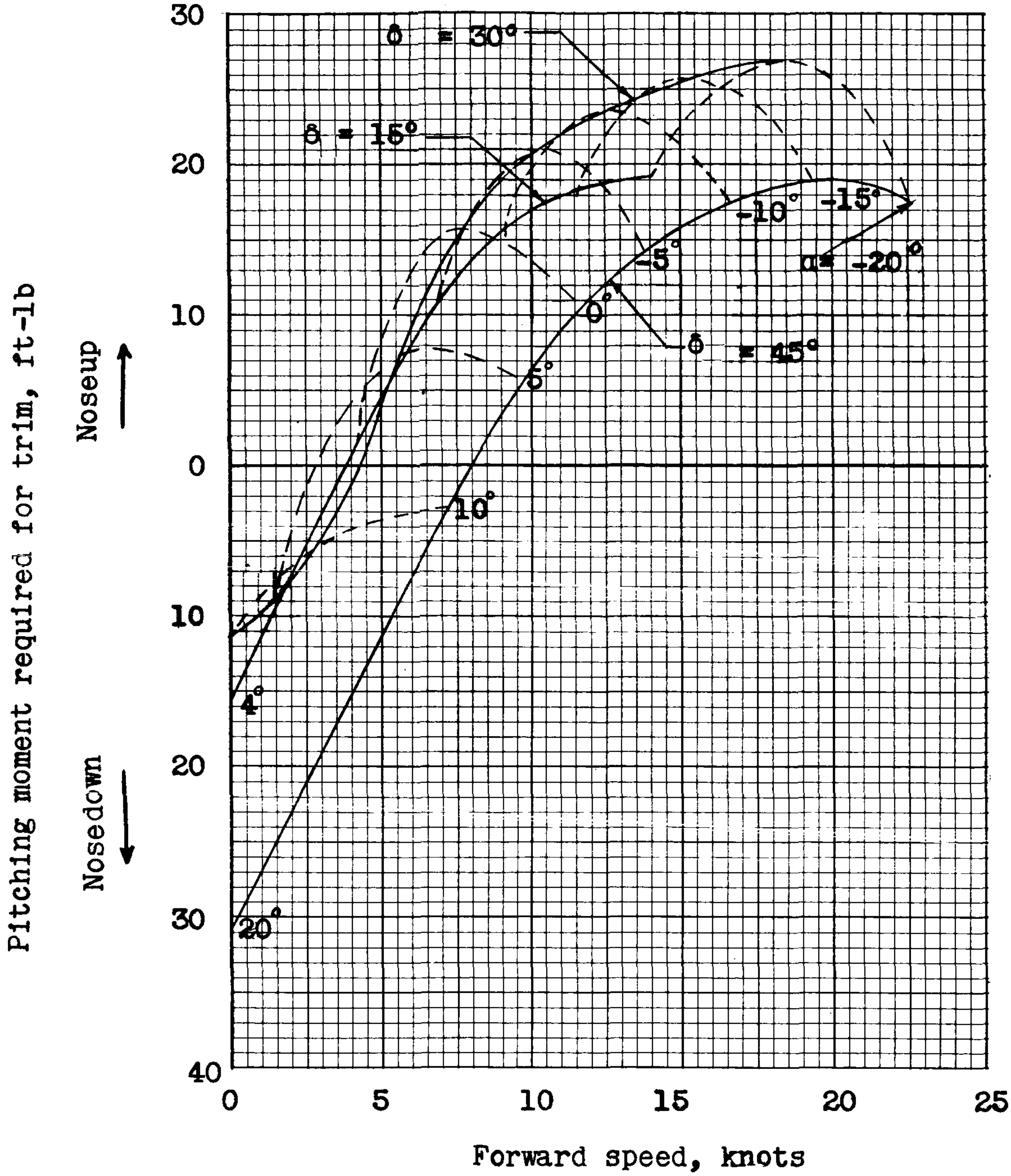

Figure 6.- Variation of pitching moment and tilt angle required for trim with forward speed for the tandem configuration with vanes installed and deflected. The solid lines indicate constant vane deflection, whereas the dashed lines connect points of equal tilt angle.

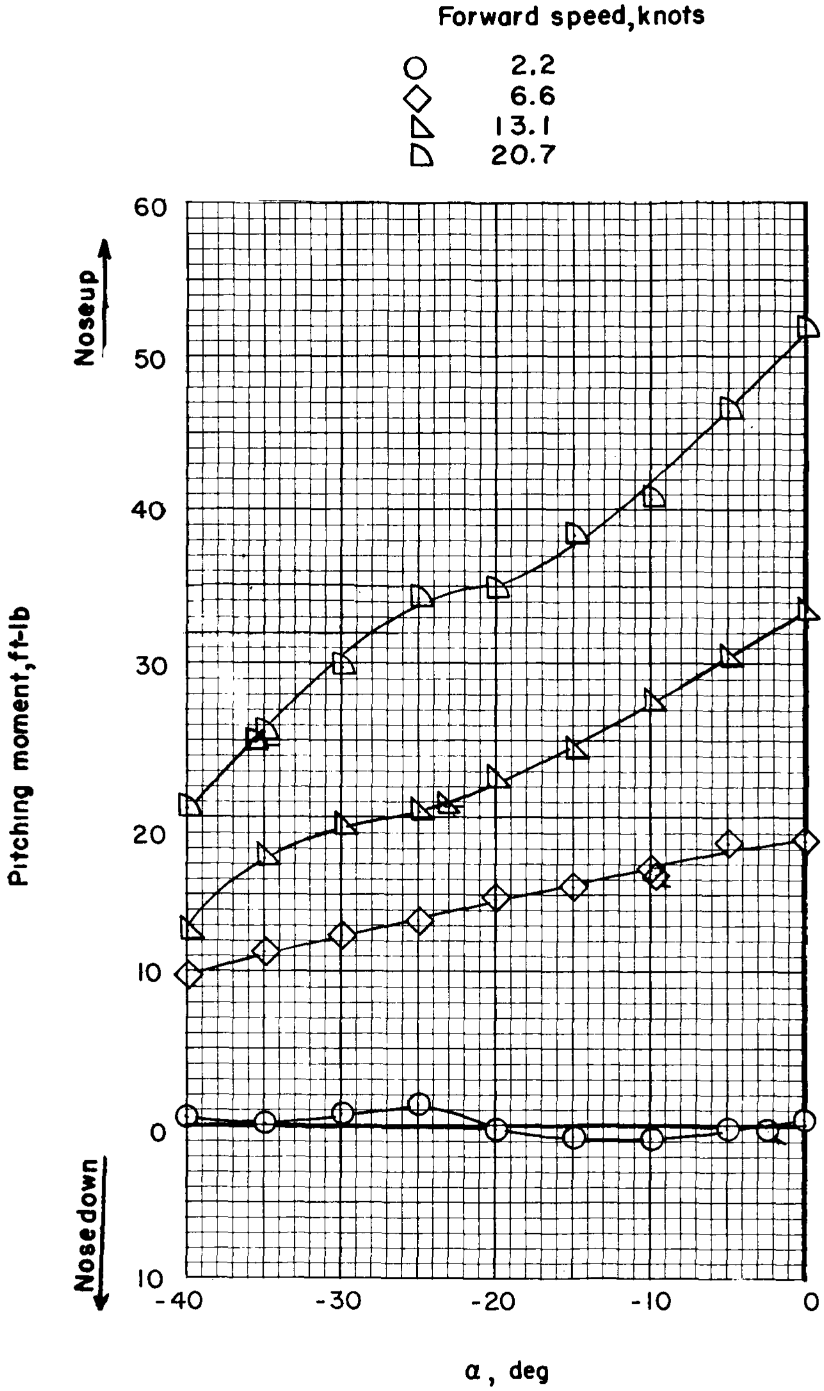

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Figure 7.- Variation of pitching moment with angle of attack for basic model in tandem configuration. Flagged symbols indicate points at which D = 0.

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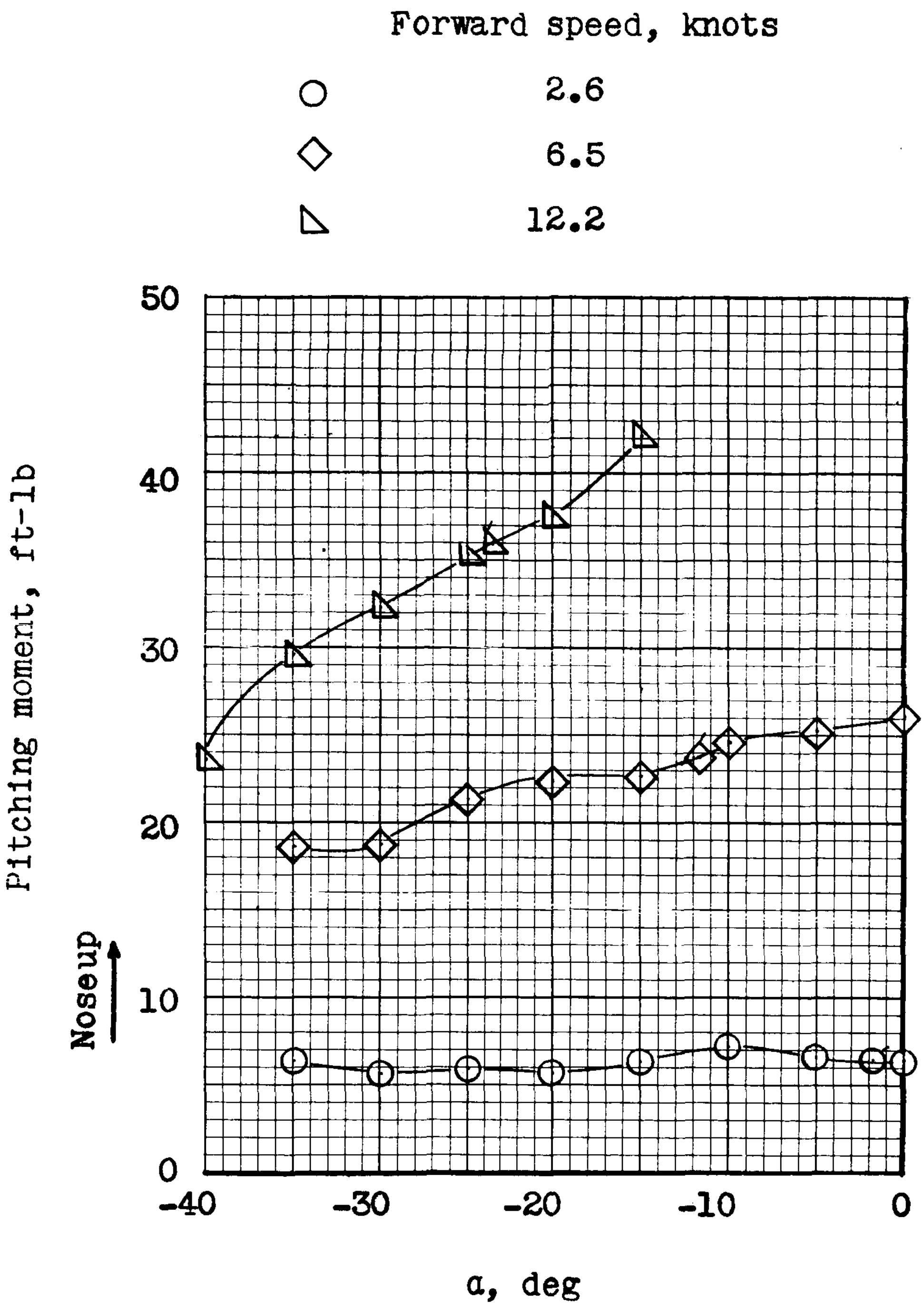
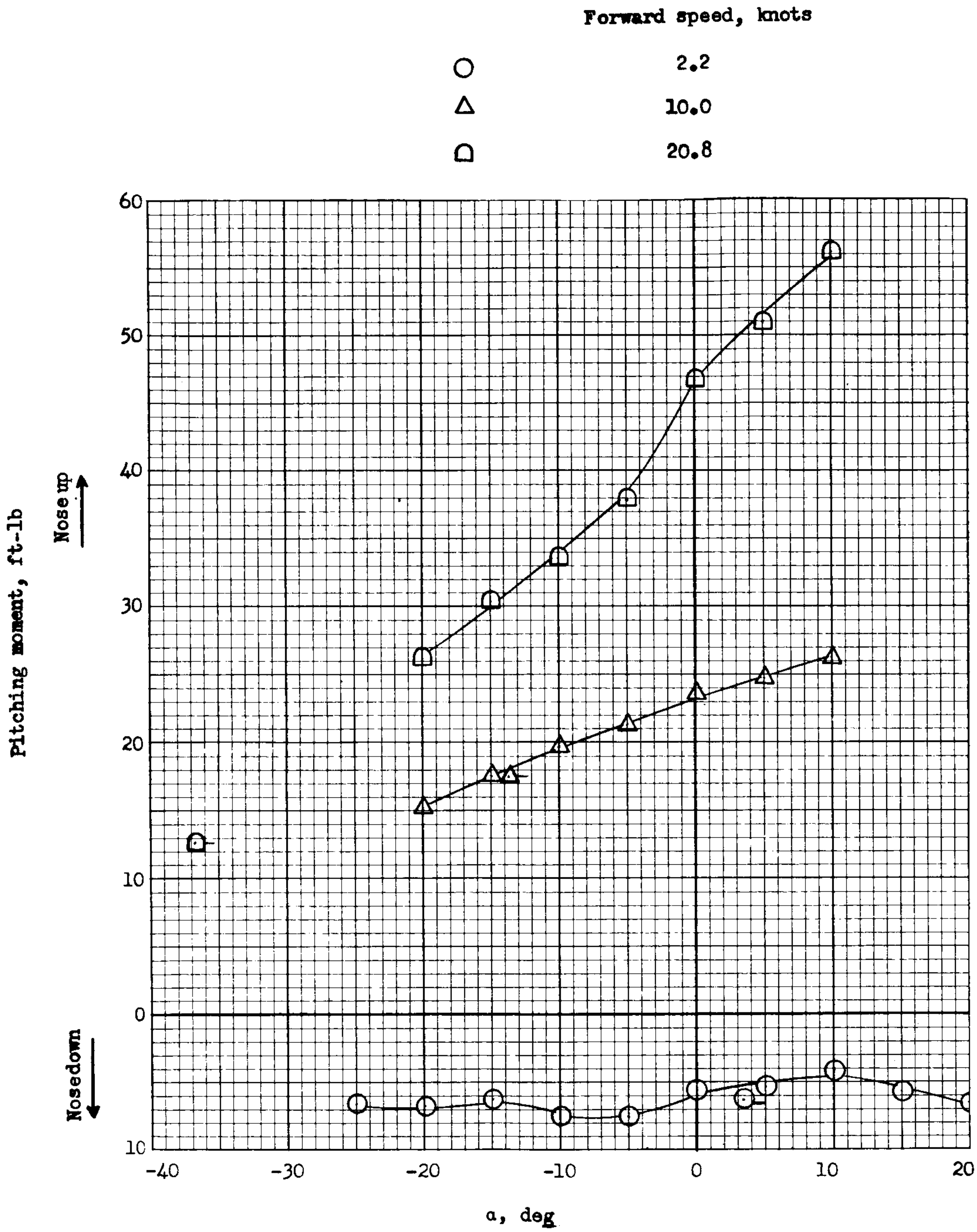


Figure 8.- Variation of pitching moment with angle of attack for basic model in side-by-side configuration. Flagged symbols indicate points at which D = 0.



(a) Vane deflection, $\delta = 15^{\circ}$.

Figure 9.- Variation of pitching moment with angle of attack for tandem configuration with vanes installed. Flagged symbols indicate points at which D = 0.

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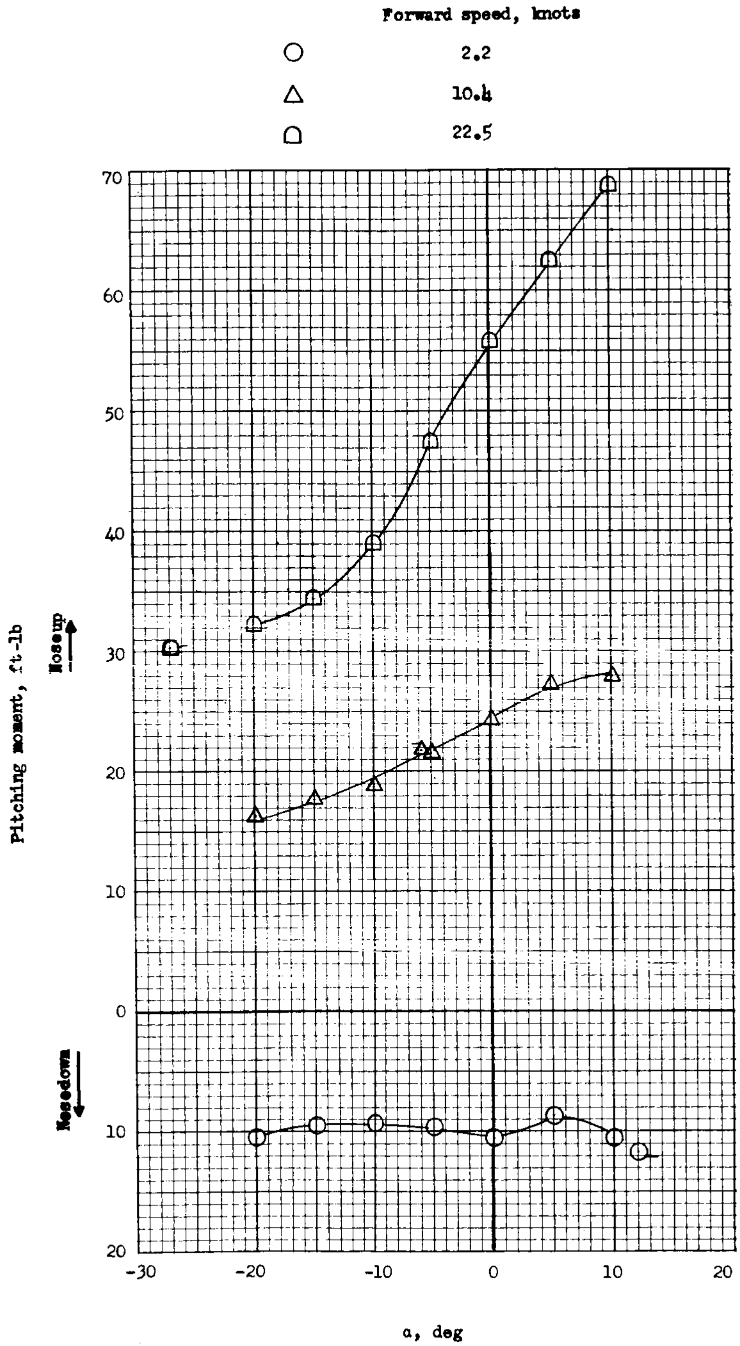
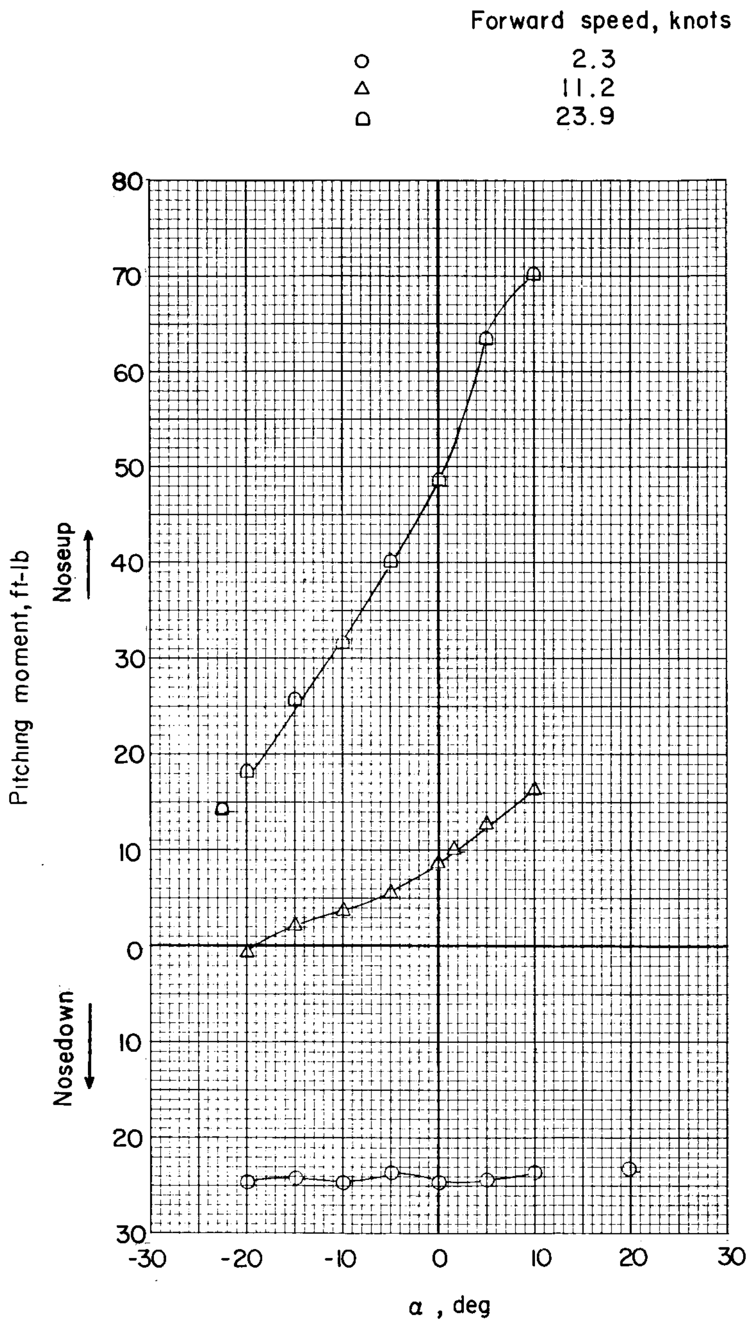


(b) Vane deflection, $\delta = 30^{\circ}$.

Figure 9.- Continued.



(c) Vane deflection, $\delta = 45^{\circ}$.

Figure 9.- Concluded.

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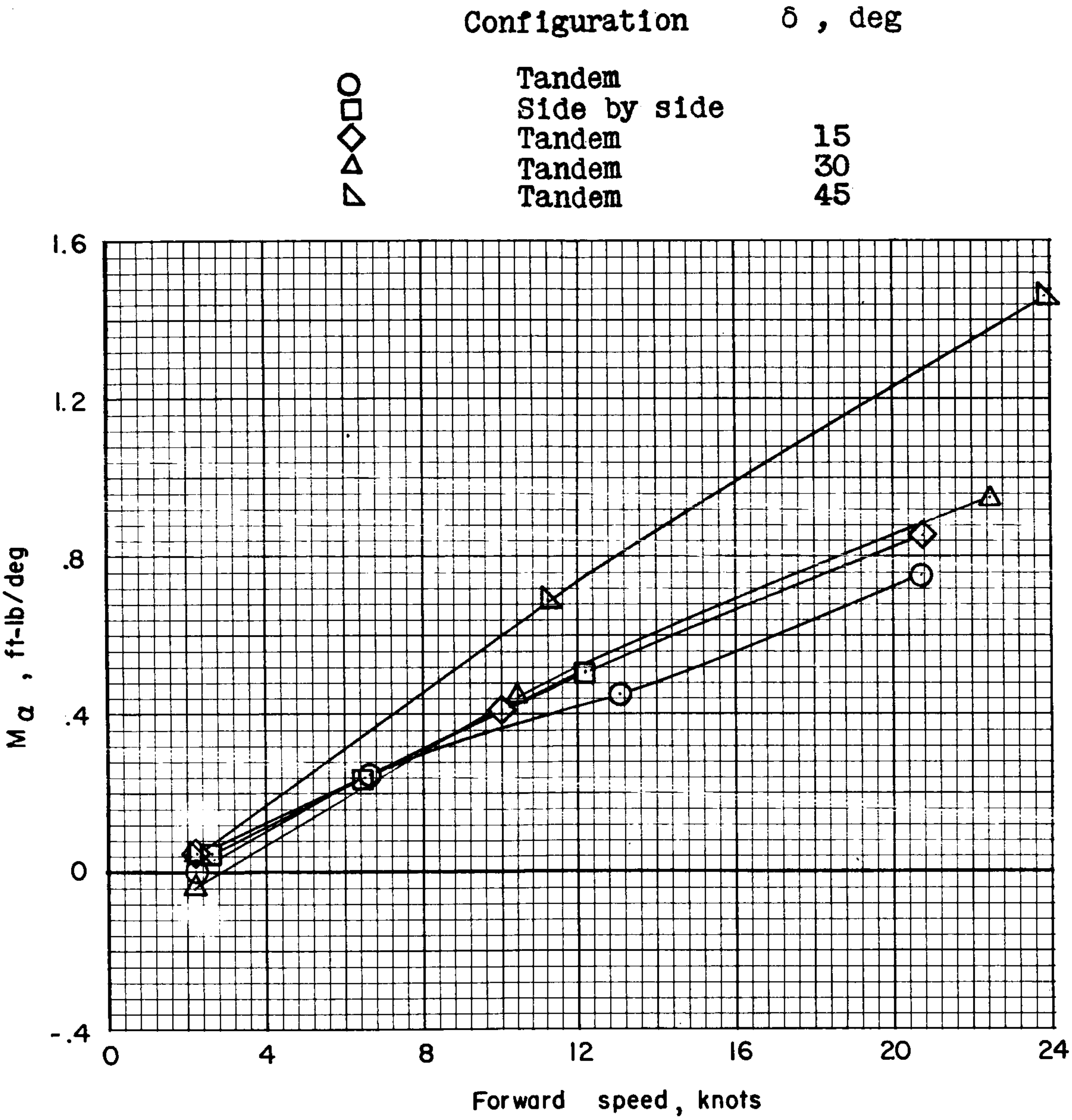

Figure 10.- Variation of M_α with forward speed for the side-by-side configuration and the tandem configuration with and without vanes.

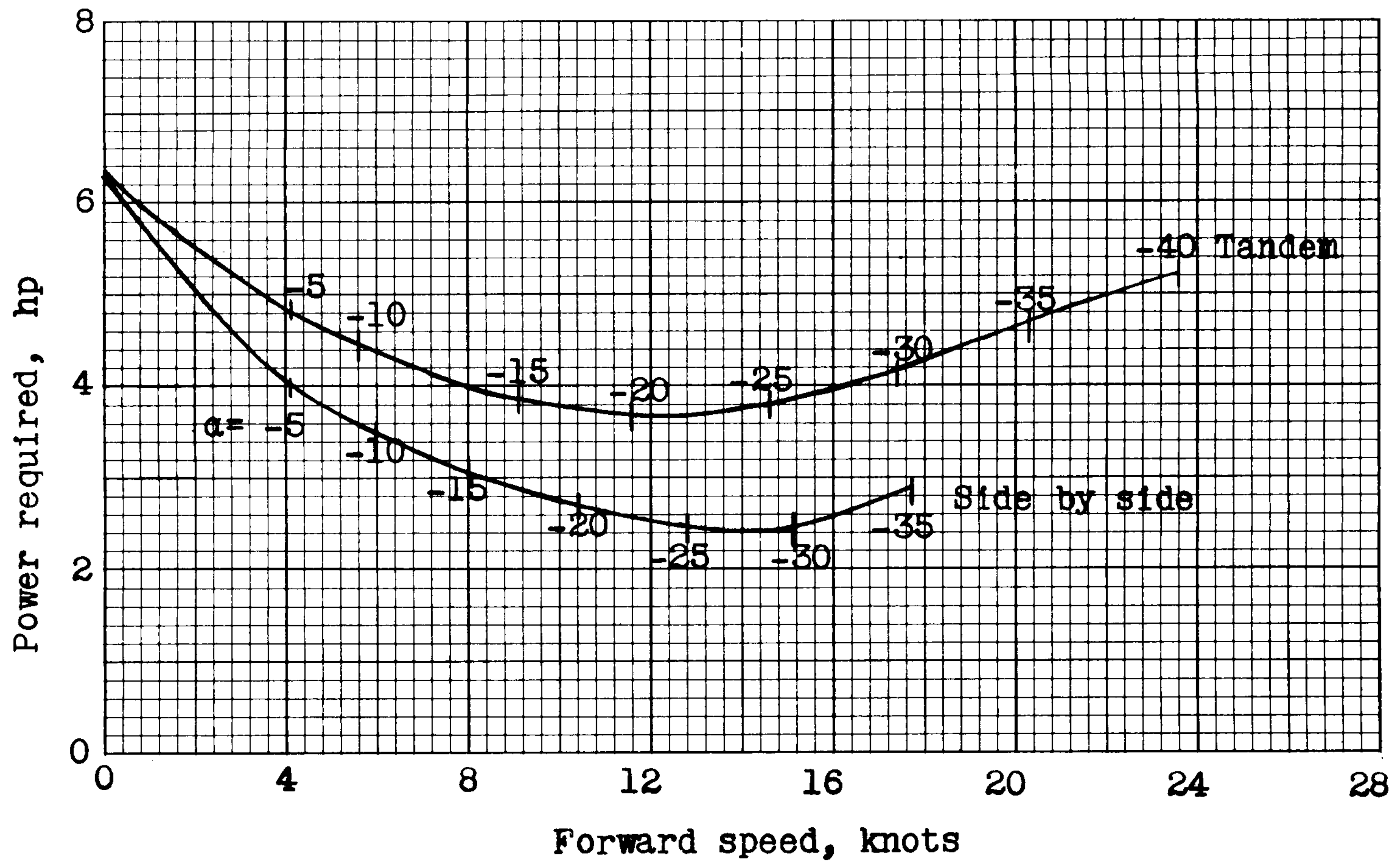

Figure 11.- Power required for basic model in tandem and side-by-side configurations for steady level flight with pitching moments untrimmed. (See fig. 5.)