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AERODYNAMIC CHARACTERISTICS OF A LARGE-SCALE V/STOL TRANSPORT MODEL WITH TANDEM LIFT FANS MOUNTED AT MID-SEMISPAN OF THE WING

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16. Abstract

The low-speed aerodynamic characteristics of a large-scale V/STOL transport model powered by tip-turbine-driven fans were investigated. The model had four fans, tandem mounted in pods, fore and aft of the wing at mid-semispan. The high mounted wing had an aspect ratio of 5.8, was swept back 35° at the quarter-chord line, and had a taper ratio of 0.3.

The results showed a large increase in lift with forward speed in spite of the unloading of the wing induced by front fan operation. Longitudinal characteristics with four fans operating appear to be similar to the characteristics of conventional aircraft. A comparison of test results, past and present, indicates that a configuration with the front fans at wing mid-semispan and the aft fans inboard near the wing root may have good induced lift characteristics.

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NOTATION

A	fan exit area, sq ft, or wing aspect ratio
b	wing span, ft
c	wing chord parallel to plane of symmetry, ft
$\bar{c}$	mean aerodynamic chord, $\frac{2}{S}\int_0^{b/2} c^2\,dy$, ft
C_D	drag coefficient, $\frac{D}{qS}$
C_l	rolling-moment coefficient, $\frac{l}{qSb}$
C_L	lift coefficient, $\frac{L}{qS}$
C_m	pitching-moment coefficient, $\frac{M}{qS\bar{c}}$
C_n	yawing-moment coefficient, $\frac{N}{qSb}$
C_Y	side-force coefficient, $\frac{Y}{qS}$
D	drag, lb
D_e	effective diameter of the fan, ft
D_f	diameter of the fan, ft
i_t	horizontal-tail incidence angle, deg
l	rolling moment, ft-lb, or length, ft
L	total lift on model, lb
M	pitching moment, ft-lb
N	yawing moment, ft-lb
p_o	standard atmospheric pressure, 2116 lb/sq ft

p_s	free-stream static pressure, lb/sq ft
q	free-stream dynamic pressure, lb/sq ft
RPM	corrected fan rotational speed, $\frac{\text{fan speed}}{\sqrt{\theta}}$
ΔRPM	difference in RPM between fore and aft fans or right and left fans, RPM
S	wing area, sq ft
T	complete ducted thrust in the lift direction with $\alpha = 0°$ and $\beta_V = 0°$, $\rho A v_j^2$, lb
v	air velocity, ft/sec
V	free-stream air velocity, knots or ft/sec
$\bar{V}$	tail volume coefficient, $\frac{S_t l_t}{S\bar{c}}$
Y	side force, lb
α	angle of attack of the wing chord plane, deg
β	angle of sideslip, deg
β_V	fan exit-vane deflection angle from the fan axis, deg
$\Delta\beta_V$	difference in exit-vane angle between the left and right fans, $\beta_L - \beta_R$, deg
δ	relative static pressure, $\frac{p_s}{p_o}$
δ_f	trailing-edge flap deflection measured normal to the hinge line, deg
θ	ratio of ambient temperature to standard temperature (519° R)
ϵ	average downwash at the horizontal tail, deg
η	fraction of wing semispan, $\frac{2y}{b}$
μ	tip-speed ratio, $\frac{2V}{\omega D_f}$

ρ density, lb-sec^2/ft^4

ω fan rotational speed, radians/sec

Subscripts

c corrected

j fan exit

i induced

s static condition

T tare

u uncorrected

w wing

t tail

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SUMMARY

The low-speed aerodynamic characteristics of a large-scale V/STOL transport model powered by tip-turbine-driven fans were investigated. The model had four fans, tandem mounted in pods, fore and aft of the wing at mid-semispan. The high mounted wing had an aspect ratio of 5.8, was swept back 35° at the quarter-chord line, and had a taper ratio of 0.3.

The results showed a large increase in lift with forward speed in spite of the unloading of the wing induced by front fan operation. Longitudinal characteristics with four fans operating appear to be similar to the characteristics of conventional aircraft. A comparison of test results, past and present, indicates that a configuration with the front fans at wing mid-semispan and the aft fans inboard near the wing root may have good induced lift characteristics.

INTRODUCTION

Ames Research Center is studying the low-speed aerodynamic characteristics of large-scale V/STOL transport configurations with lift and cruise fans. Wind-tunnel tests of fan-in-wing models (refs. 1 to 3) focused attention on problems related to fan operations such as pitching moment associated with high induced lift, loss in flap effectiveness by the flow turning prematurely ahead of the flap, and the structural disadvantage of mounting fans in the wing. Tandem lift fan configurations (ref. 4) have evolved to circumvent some of these problems.

This report presents results from a model with four lift fans, tandem mounted in pods, located at the wing mid-semispan. The purpose of the investigation, conducted in the Ames 40- by 80-Foot Wind Tunnel, was to study the effect of the interference between the fan flow and the wing flow field on lift and moment. Fan performance and longitudinal aerodynamic characteristics of the model are shown for various configurations with two front, two aft, and four fan operation. Limited lateral-directional characteristics are presented.

MODEL AND APPARATUS

Model

The model is shown installed in the test section of the Ames 40- by 80-Foot Wind Tunnel in figure 1. Figure 2 is a sketch of the model with pertinent dimensions.

Wing geometry— The high mounted wing had an aspect ratio of 5.8, a taper ratio of 0.3, and was swept back 35° at the quarter-chord line. An NACA 65-412 airfoil section was basic for the wing. Pods (fig. 2(b)) containing the propulsion system were located under the wing at 50-percent semispan.

Details of the 22-percent chord single-slotted flap are shown in figure 2(c). The flap extended from 15.9- to 37.5-percent semispan. Flap deflections of 0° and 45° were tested.

The 15-percent-chord leading-edge slat extended the full span of the wing except the area enclosed by the propulsion system pods ($\eta = 0.383$ to 0.631), (see fig. 2(b)). Unless noted, the data presented were taken with this slat.

Fuselage— The fuselage was slab sided with rounded corners. Overall it was 6.5 feet high, 5.8 feet wide, and 44.0 feet long.

Tail— The geometry and location of the all movable horizontal tail are shown in figure 2(a). The tail was pivoted about the quarter chord and had a range from -10° to 20° incidence. For the tests with "tail off" only the horizontal tail was removed.

Propulsion System

For these studies, the four 3-foot-diameter G.E. X-376 tip-turbine-driven fans (see ref. 4) were powered by individual T-58 gas generators. Each T-58 was located within the pod of its respective fan. (See fig. 2(a).)

Fan installation— Details of the tandem lift fan pods are shown in figure 2(b). The fans were completely enclosed within the pods fore and aft of the wing.

A cascade of fourteen 4.06-inch-chord exit vanes was mounted downstream of the lift fan pods. These vanes extended across the tip-turbine exhaust and were used both to direct the fan flow and as a lower surface pod closure ($\beta_V = 90°$) for power-off testing.

TESTING AND PROCEDURE

Longitudinal force and moment data were obtained through an angle-of-attack range from -3° to 24°; lateral-directional data were obtained through an angle-of-sideslip range of -14° to +2° at an angle of attack of 0° and 10°.

Test at Zero Angle of Attack

At 0° angle of attack, fan speed and wind-tunnel velocity were varied independently. Data were obtained at several exit vane angles, two flap deflections, tail on and tail off.

Tests With Variable Angle of Attack

When angle of attack was varied, fan RPM and tunnel forward speed were held essentially constant. Results were obtained for several fan speeds and tunnel airspeeds. Model variables were the same as those mentioned above.

CORRECTIONS

Force and moment data obtained without the fans operating (power off) have been corrected for the effects of wind-tunnel wall interference in the following manner:

$$\alpha = \alpha_u + 0.488\ C_{L_u}$$

$$C_D = C_{D_u} + 0.0085\ C_L{}^2$$

$$C_m = C_{m_u} + 0.02027\ C_{L_u} \text{ (tail on only)}$$

The entire program was conducted without a fairing around the tail strut. Appropriate tare corrections have been applied to drag and pitching moment to account for this influence.

According to the data of reference 5 the model to wind-tunnel size ratio of the current tests was sufficiently small that no wind-tunnel wall corrections need be applied to the fans-operating data.

RESULTS

Lift fan tip-speed ratio will be used as the independent parameter in the presentation of results unless otherwise stated. The relationship between tip-speed ratio and free stream to fan velocity ratio is shown in figure 3.

Table 1 is an index to the figures. The results will be presented in the following order: lift fan characteristics, longitudinal characteristics at zero angle of attack, longitudinal characteristics with angle of attack, and stability and control.

Lift Fan Characteristics

The performance of individual fans at zero airspeed is shown in figure 4. Figure 4(a) shows the forces and moments as a function of $(RPM)^2$. The effect of exit-vane deflection on forces and moments at 3300 fan RPM is presented in figure 4(b). Figure 5 presents the variation in fan thrust with forward speed for the left front and rear fans as measured with equal-area momentum rakes.

Aerodynamic Characteristics

Zero angle of attack– Figure 6(a) shows the variation of lift, drag, and pitching-moment to static-thrust ratio with tip-speed ratio for combinations of two forward and two aft fans operating. Similar data for four fans operating (two forward plus two aft) at two different flap deflections with horizontal tail on and off are presented in figure 6(b).

Results in figures 7 through 12 show the variation of lift, drag, and pitching-moment coefficient with tip-speed ratio for exit vane deflections from -5° to 50°. Figures 7 and 8 present data for two fans forward and two fans aft, respectively. Figures 9 through 12 are for four fans operating at two flap deflections, tail on and off, and slats on and off.

The variation in average downwash at the horizontal tail is shown in figure 13. Results were computed from tail-on and tail-off data in figures 9 through 12.

Variable angle of attack– The variation in longitudinal characteristics with angle of attack is shown in figures 14 through 19. The data for speeds up to 30 knots are presented as forces and moments while the results for higher speeds are in coefficient form. Power-off data at two flap deflections with the horizontal tail on and off are shown in figure 14. Results with two fans forward, two fans aft, and four fans with the tail off are shown in figures 15 through 17. Figures 18 and 19 show the four-fan arrangement with the horizontal tail on.

Stability and control– The variation of pitching moment with fan operation and forward speed is shown in figure 20. The variation of longitudinal characteristics with four fans operating at different fan RPM (fore and aft) is shown in figure 21. Horizontal-tail effectiveness is presented in figure 22.

The variation in lateral-directional characteristics with sideslip angle at 0° and 10° angle of attack is shown in figures 23 through 25. Low-speed data are shown as forces and moments. With four fans operating the effectiveness of differential fan RPM for roll control is shown in figure 26, and differential exit louver deflection for yaw control in figure 27.

DISCUSSION

Fan Performance

Performance of the lift fans was measured statically and with forward speed. Static measurements were obtained from the force balance while the variation in thrust with forward speed was measured with pressure rakes mounted beneath the two fans on the left-hand wing.

At zero forward speed, measured fan thrust was nearly the same for all four fans (fig. 4), but shows a loss of 12 percent when compared to the static thrust data of reference 4. Some thrust loss was expected since installing deeper partial inlets to fair the pods into the wing required a reduction of inlet area at the fan face.

The variations of velocity ratio (V/V_j) or fan thrust with forward speed (tip-speed ratio) are presented in figures 3 and 5. The different inlet designs of the front and rear fans caused forward velocity to have marked different effects on fan performance. Front fan thrust decreased continually with increased forward speed while the aft fan thrust remained fairly constant. (See fig. 2 for fan inlet details.)

Aerodynamic Characteristics

Induced effects from fan operation– To determine the induced effects of fan operation on the wing lift, data were obtained with the two front fans then with the two aft fans operating before the complete four-fan configuration was studied. The variation of total model lift, fan thrust, and power-off lift are shown in figure 28 as a function of free stream to fan velocity ratio for flaps up and tail off. Comparison of the difference between fan thrust plus power-off lift and total measured lift will show the dependence of induced lift on fan location. Figure 28(a) shows the effect of fans operating in front of the wing at a mid-semispan location. As the velocity ratio (V/V_j) increases from 0 to 0.34 power-off lift and fan thrust are augmented by induced lift. At velocity ratios greater than 0.34, the induced effect of front fan operation was detrimental to total lift.

The effect of aft fan operation on the wing lift (fig. 28(b)) was an induced lift of 66 percent of static thrust at a velocity ratio of 0.34. For the complete configuration (fig. 28(c)) a net induced lift of 17 percent of static thrust was obtained. If front and rear induced effects were additive, induced lift would be about 0.33 L/T_S; thus about 50 percent of the induced lift derived from aft fans is negated by the front fans when all four fans are operating in tandem pairs.

The variations of induced lift with velocity ratio for these results (fig. 28), and similar data from reference 4, are shown in figure 29. When both configurations are compared at a velocity ratio of 0.34, the induced lift from forward fans located at $\eta = 0.5$ was 0 and for $\eta = 0.29$ a value of -0.2 is shown. The outboard location significantly reduced the adverse effect of front fan operation on wing lift. With the aft fans at $\eta = 0.5$ the induced lift was approximately 79 percent of that with the fans at $\eta = 0.29$. For the complete configurations (four fans) with the outboard fan at $\eta = 0.5$, the induced lift was slightly more than 50 percent of that with the fans at $\eta = 0.29$. From these results it can be surmised that for high induced lift, the front fans should be located at mid-semispan and the aft fans should be located inboard near the wing root.

Flap effectiveness– The power-off flap lift coefficient indicated in figure 14 is 75 percent of that estimated in reference 6. Only flap deflections of 0° and 45° were tested and no attempt was made to optimize the flaps for maximum effectiveness. Figures 10 and 11 show that for $\mu = 0.10$ ($V/V_j = 0.18$) with $\beta_v = 0°$ flap effectiveness approached the theoretical value with the aid of the flow induced by fan operation. Figure 30 presents the variation of total lift, fan thrust, and power-off lift with velocity ratio for flap deflections of 0° and 45°. For $V/V_j = 0.25$, $\delta_f = 45°$, the difference between total lift and fan thrust plus power-off lift is 38 percent more than for the flaps up configuration because of the increased flap effectiveness with aft fan operation. These results are similar to those of reference 1.

Stability and Control

Longitudinal stability and control– Longitudinal stability characteristics are shown in figures 14 through 19. For the complete configuration, static longitudinal stability varied from neutral to $\partial C_m/\partial C_L = -0.19$ over the transition speed range. The pitching moment was fairly linear up to stall, where pitch-up occurred.

From figure 17 $\partial C_m/\partial C_L$ and $\partial C_L/\partial\alpha$ are independent of power and exit louver angle, and when compared to figures 19(c) through (e) C_m/C_L tail on is the same. Then for tip-speed ratios between 0.12 and 0.24 downwash was little affected by power.

Figure 21 presents the longitudinal characteristics with differential fan RPM, fore and aft, to determine the effectiveness of lift fans as a low-speed pitch control. At a tip-speed ratio of 0.06 with flaps deflected 45° a 20° change in horizontal-tail incidence would be required to produce a pitching moment equal to 280 ΔRPM.

The effectiveness of the horizontal tail to trim at various airspeeds is shown in figure 22. The horizontal-tail incidence required for trim varied from -7.5° at $\mu = 0.06$ to 0° at $\mu = 0.24$. With these incidences and the downwash data from figure 13 it is seen that the horizontal tail is far from stall.

Figure 31 presents a comparison of pitching-moment variations with velocity ratio for various lift fan configurations from the references. Figure 5 shows an increasing difference in fan thrust, between the fore and aft fans, with increasing tip-speed ratio. The thrust difference introduces a pitch-down moment. If T/T_s is assumed equal for all fans and pitching moment is corrected, the slope of the curve is significantly changed. Figure 31 shows the moment variation with speed adjusted to equal thrust. The moment variation more nearly resembles that of fan-in-wing types, but is still less.

Lateral-directional stability and control– The lateral-directional characteristics with angle of sideslip (figs. 23 through 25) show side force and rolling moment to be large and a function of airspeed, but stable. The variation of yawing moment with sideslip while stable over most of the speed range becomes neutrally stable at low speed. Figure 26 presents the lateral and longitudinal characteristics with differential RPM, left and right, for producing positive roll. Since drag was trimmed with exit vanes at ΔRPM = 0, some positive yaw was produced as power was varied with β_v constant. In figure 27 the lateral and longitudinal characteristics are shown for several tip-speed ratios with various differentially deflected exit vane angles, left and right, for producing positive yaw. Drag was trimmed with the exit vanes and $\Delta\beta_v$ taken about the trim point. The data show that $\Delta\beta_v$ at constant power would cause an adverse roll-yaw couple which would have to be offset by power modulation.

SUMMARY OF RESULTS

Wind-tunnel tests of a large-scale V/STOL transport model with lift fans tandem mounted in pods show that wing unloading induced by forward fan operation was significantly reduced when the fans were located at mid-semispan as opposed to wing root. However, the induced lift derived from aft fan operation was 21 percent less when the fans were located at mid-semispan than at $\eta = 0.29$.

The pitching-moment variation with airspeed for tandem fans was less than with fan-in-wing types; thus the pitch trim requirements with airspeed are less than for fan-in-wing configurations. Fan operation did not change longitudinal stability significantly. Power modulation for pitch and roll control was acceptable, but differential exit louver operation at constant power for yaw control caused adverse yaw-roll coupling when the louvers were deflected about a β_V setting for $C_D = 0$.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif., 94035, Sept. 3, 1970

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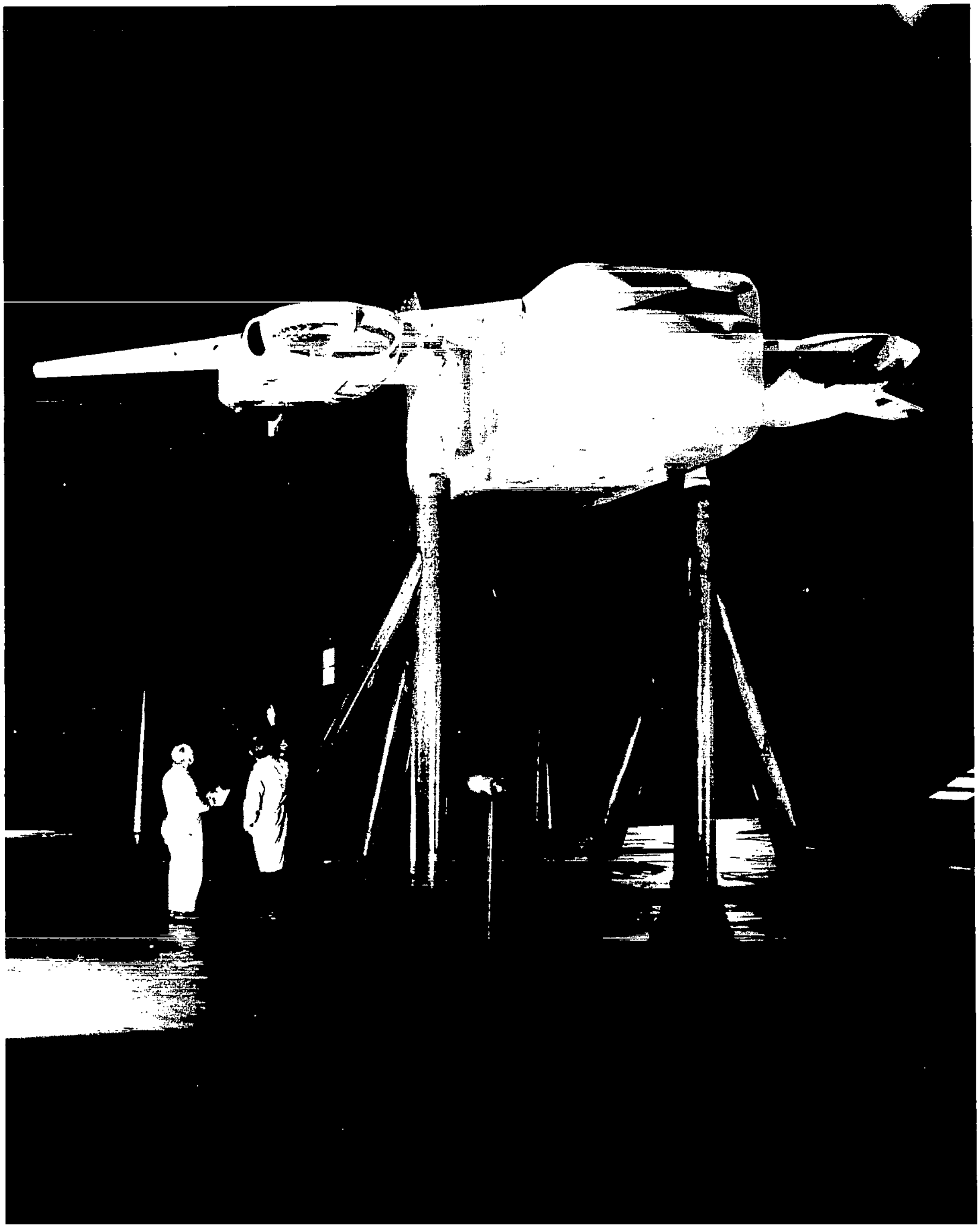
TABLE 1.– INDEX TO FIGURES

Figure	α, deg	β, deg	β_V, deg	i_t, deg	V, knots	δ_f, deg	Remarks
				Fan characteristics			
3	0	0	0	0	Variable	45	Relationship of μ to V_o/V_j
4(a)			↓		0		Lift fan performance
(b)			Variable		↓		
5	↓	↓	0	↓	Variable	↓	Effect of forward speed on fan thrust
				Longitudinal data at zero angle of attack			
6(a)	0	0	0	Off	Variable	0	Two fans operating
(b)			↓				Four fans operating
7(a)			Variable				Forward fans only
(b)							
8(a)							Aft fans only
(b)							
9(a)							Four fans operating
(b)				↓			
10(a)				0			Complete configuration (four fans)
(b)						↓	
11(a)						45	
(b)							
12(a)							Four fans, slats off
(b)						↓	
13	↓	↓	↓	↓	↓	0	Average downwash at the horizontal tail
				Longitudinal data at variable angle of attack			
14	Variable	0	90	0,Off	80	45,0	Power off, slats on and off
15			Variable	Off	Variable	45	Forward fans only
16							Aft fans only
17			↓	↓			Four lift fans
18			0	0	↓		Complete configuration
19(a)			Variable	↓	20		Complete configuration, four fans
(b)				-7.5	30		
(c)				-2.5	40		
(d)				0	60		
(e)	↓	↓	↓	↓	80	↓	
				Stability and control			
20(a)	0	0	0	Off	Variable	0	Variation in pitching moment with forward speed 2 and 4 fans operating
(b)			↓	0,Off		0,45	
21	↓		Variable	0		45	Pitch control with ΔRPM
22	0,10	↓	↓	Variable	↓	45,0	Horizontal tail effectiveness
23	↓	2 to -14	90	0	80	45	Power off
24(a)	0		Variable		60,80		Complete configuration, four fans
(b)	↓				20,30,40		
25	10	↓			↓		
26(a)	0	0			Variable		Roll control with ΔRPM
(b)							
27(a)							Yaw-roll with $\Delta\beta_V$
(b)	↓	↓	↓	↓	↓	↓	
				Summary			
28(a)	0	0	0	Off	Variable	0	Effect of forward speed on lift, front fans
(b)							Effect of forward speed on lift, aft fans
(c)							Effect of forward speed on lift, four fans
29				↓		↓	Effect of fan location on induced lift
30				0		0,45	
31	↓	↓	↓	Off	↓	0	Variation of pitching moment with airspeed for various lift fan configurations



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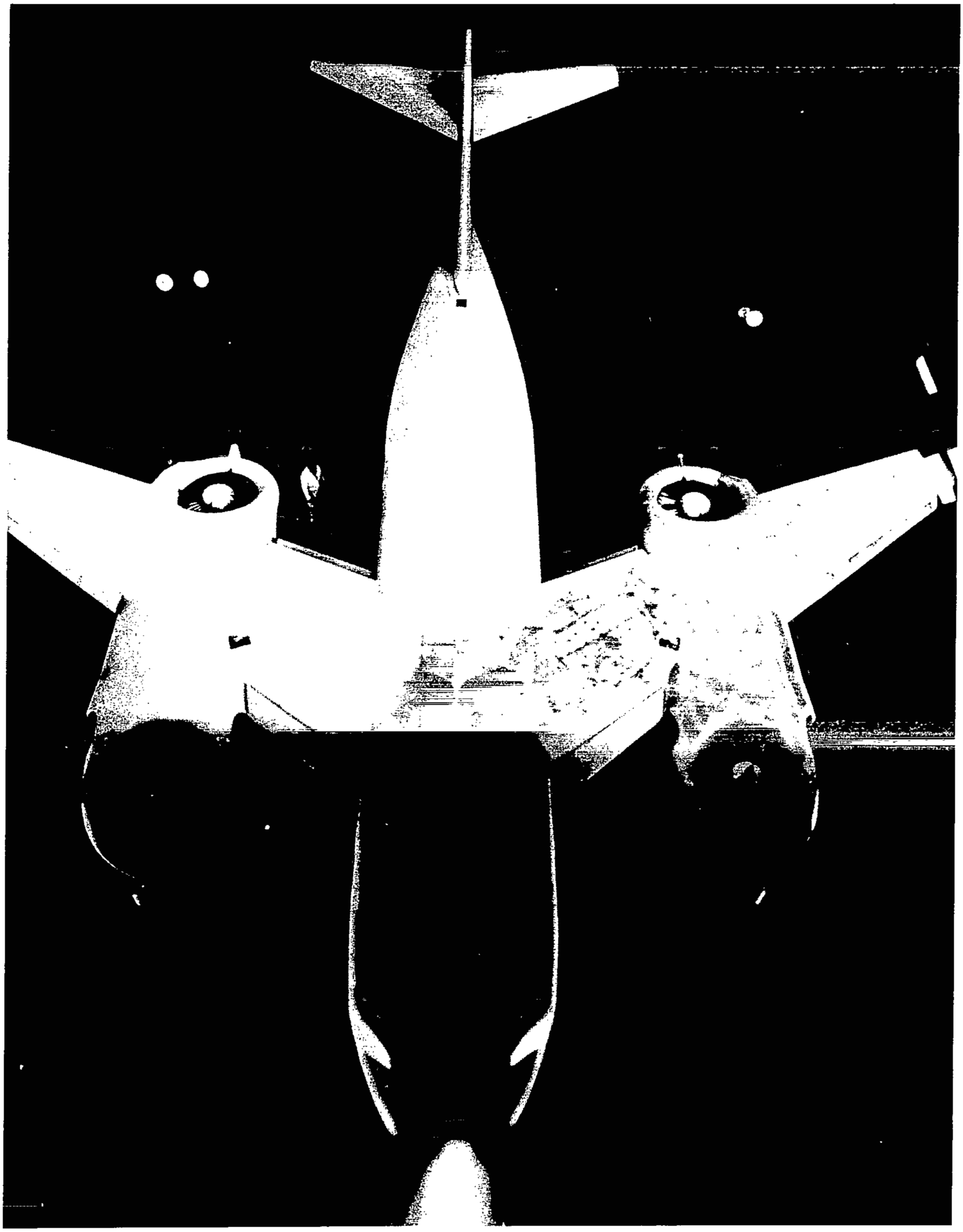
(a) Three-quarter front view.

Figure 1.– Model mounted in Ames 40- by 80-Foot Wind Tunnel.



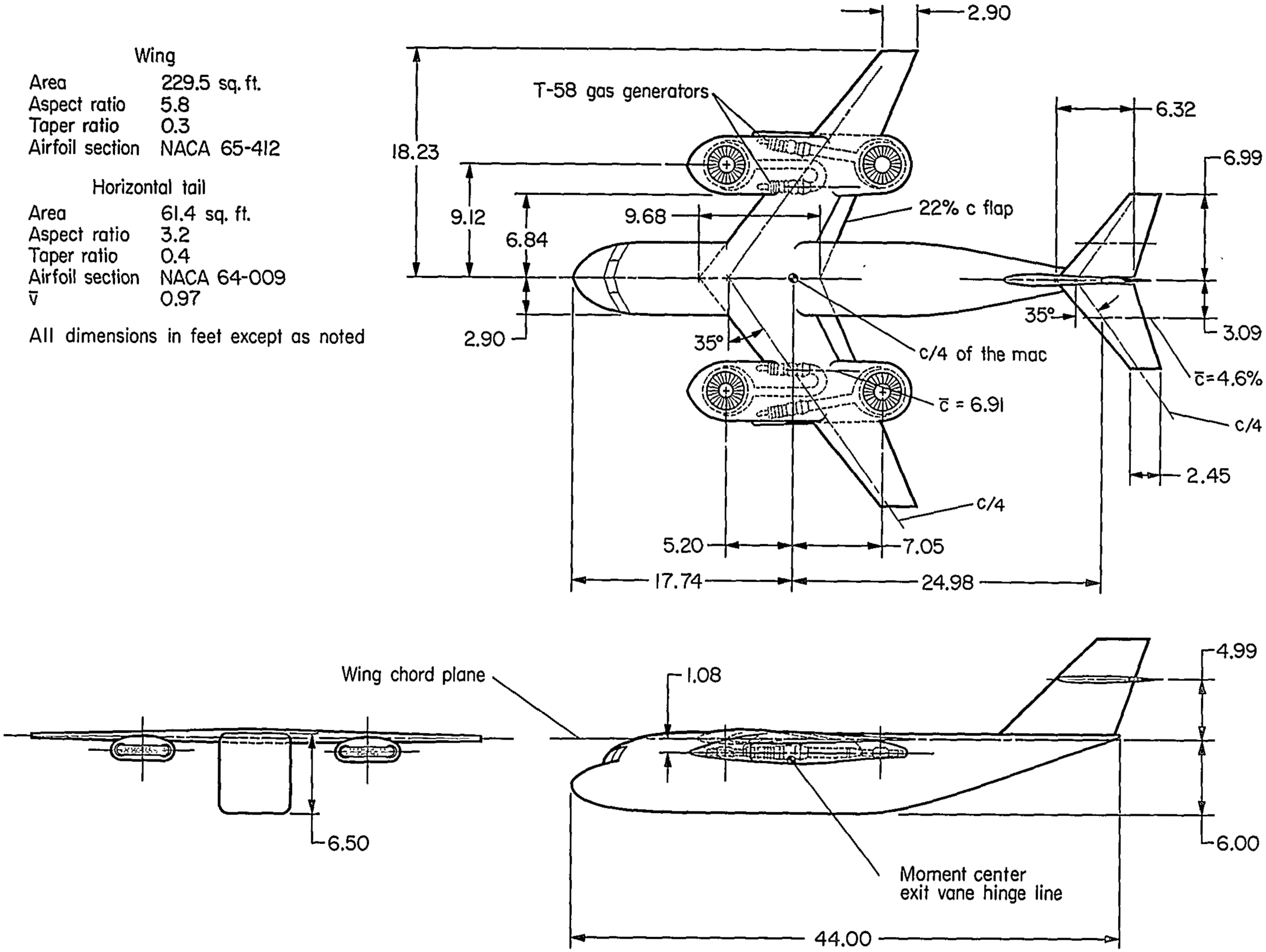
A-40223

(b) Top view.

Figure 1.— Concluded.

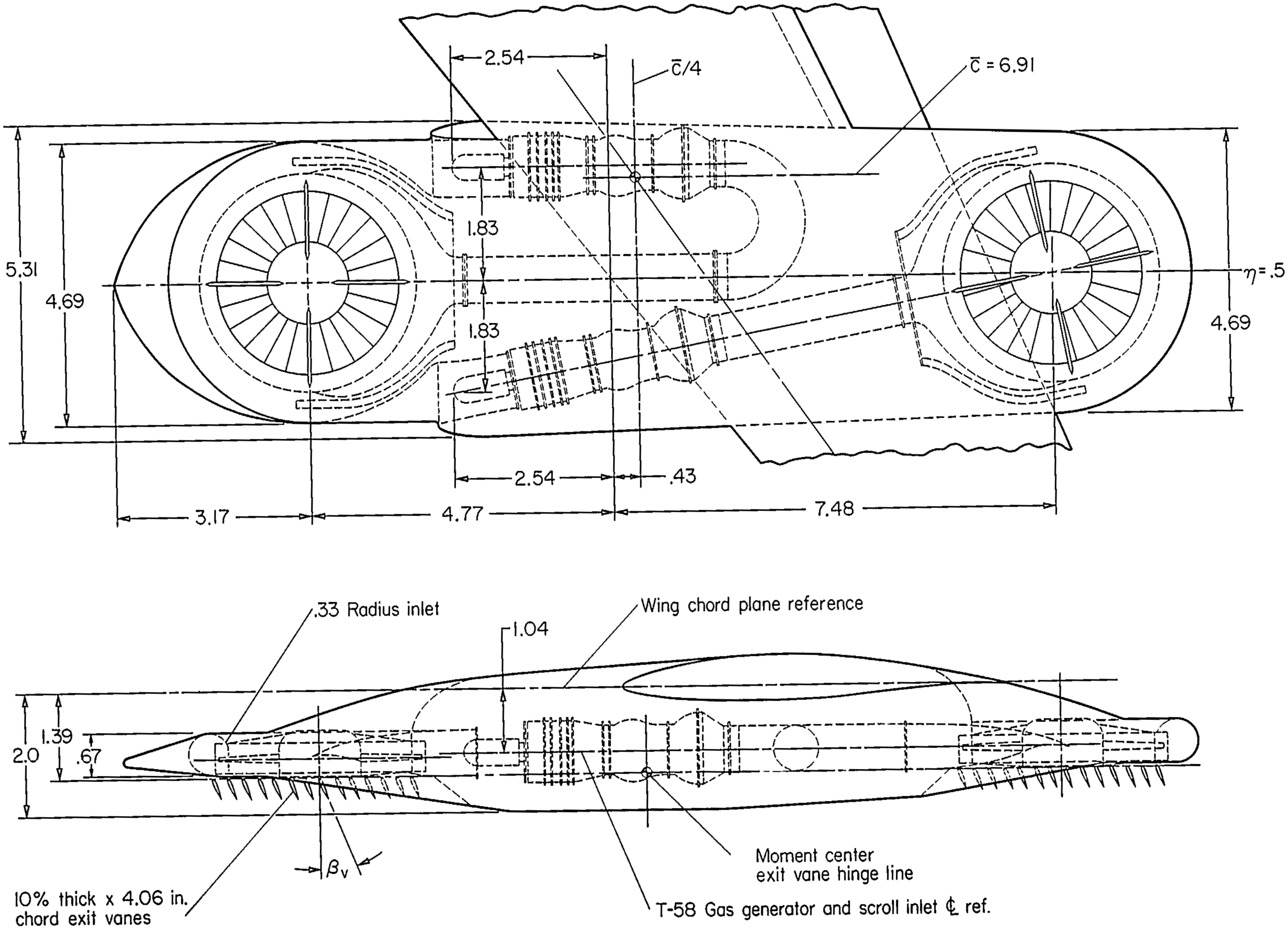
Wing	
Area	229.5 sq. ft.
Aspect ratio	5.8
Taper ratio	0.3
Airfoil section	NACA 65-412
Horizontal tail	
Area	61.4 sq. ft.
Aspect ratio	3.2
Taper ratio	0.4
Airfoil section	NACA 64-009
$\bar{V}$	0.97

All dimensions in feet except as noted



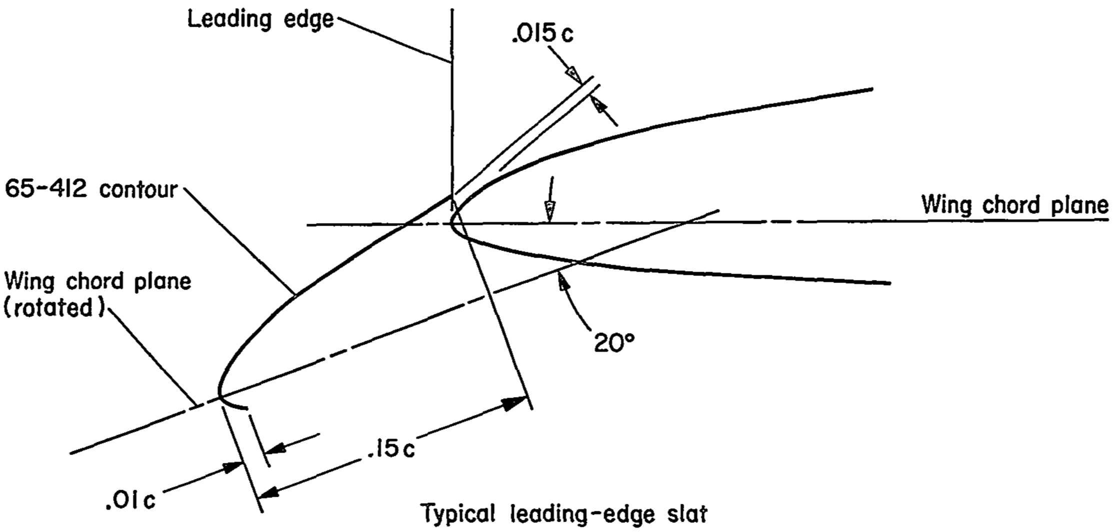
(a) Model geometry.

Figure 2.– Geometric details of the V/STOL transport model.

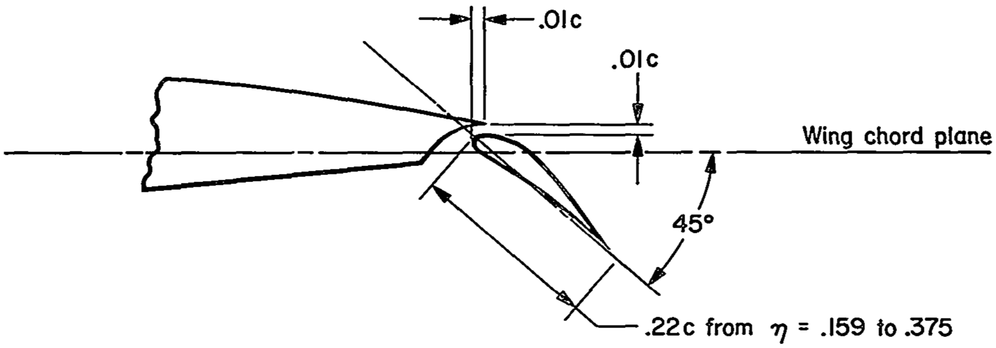


(b) Details of tandem lift fan pods.

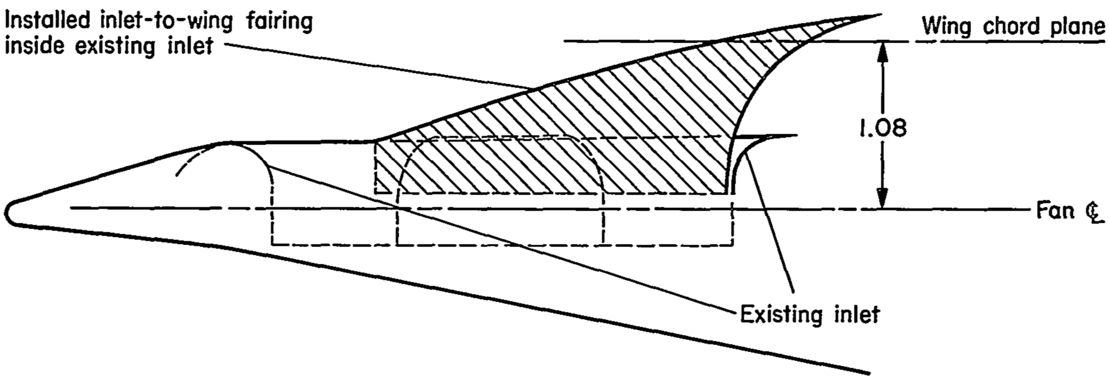
Figure 2.– Continued.



Typical leading-edge slat



Typical trailing-edge flap



Typical inlet-to-wing fairing

(c) Details of trailing-edge flap, leading-edge slat, and fan inlet-to-wing fairing.

Figure 2.– Concluded.

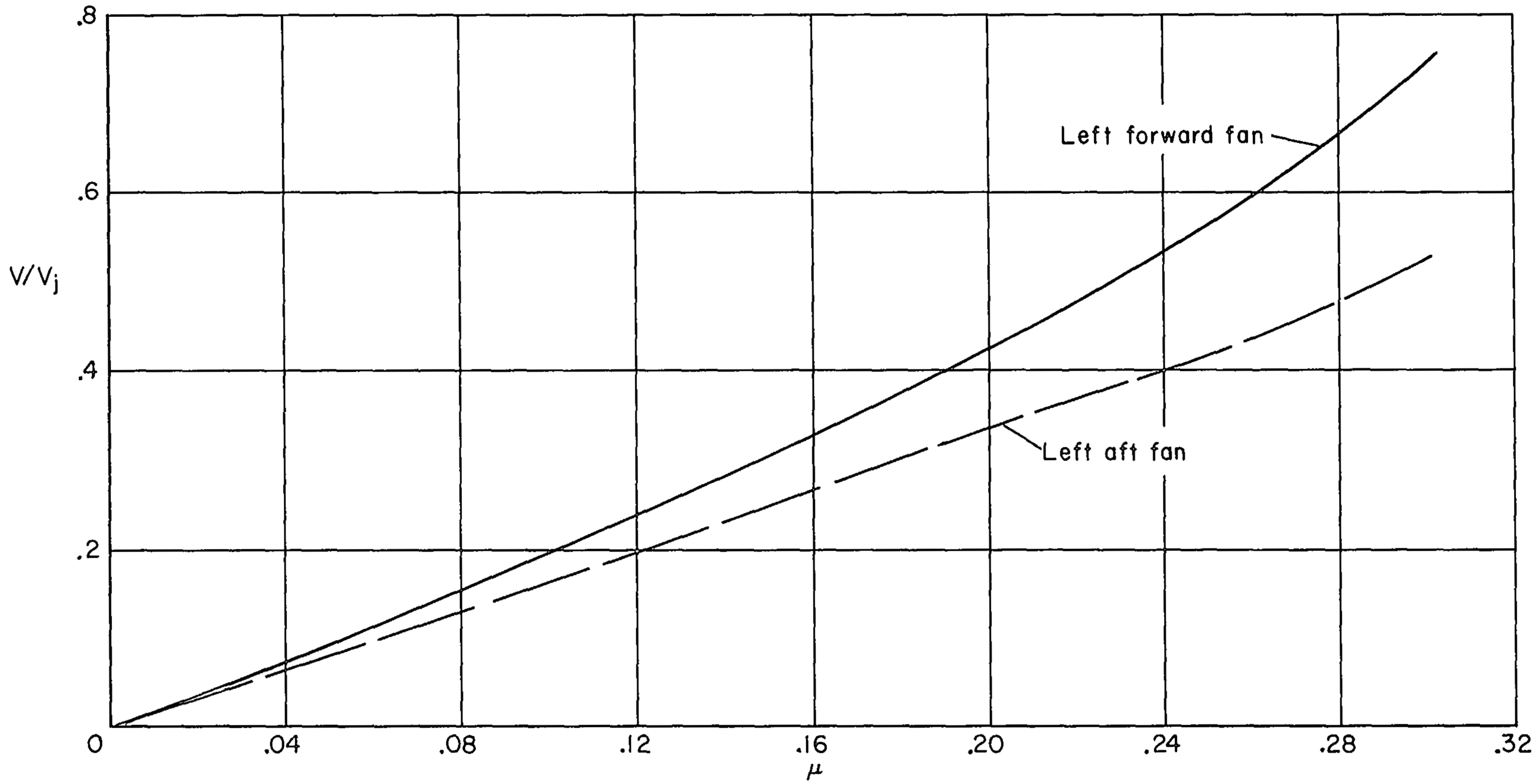
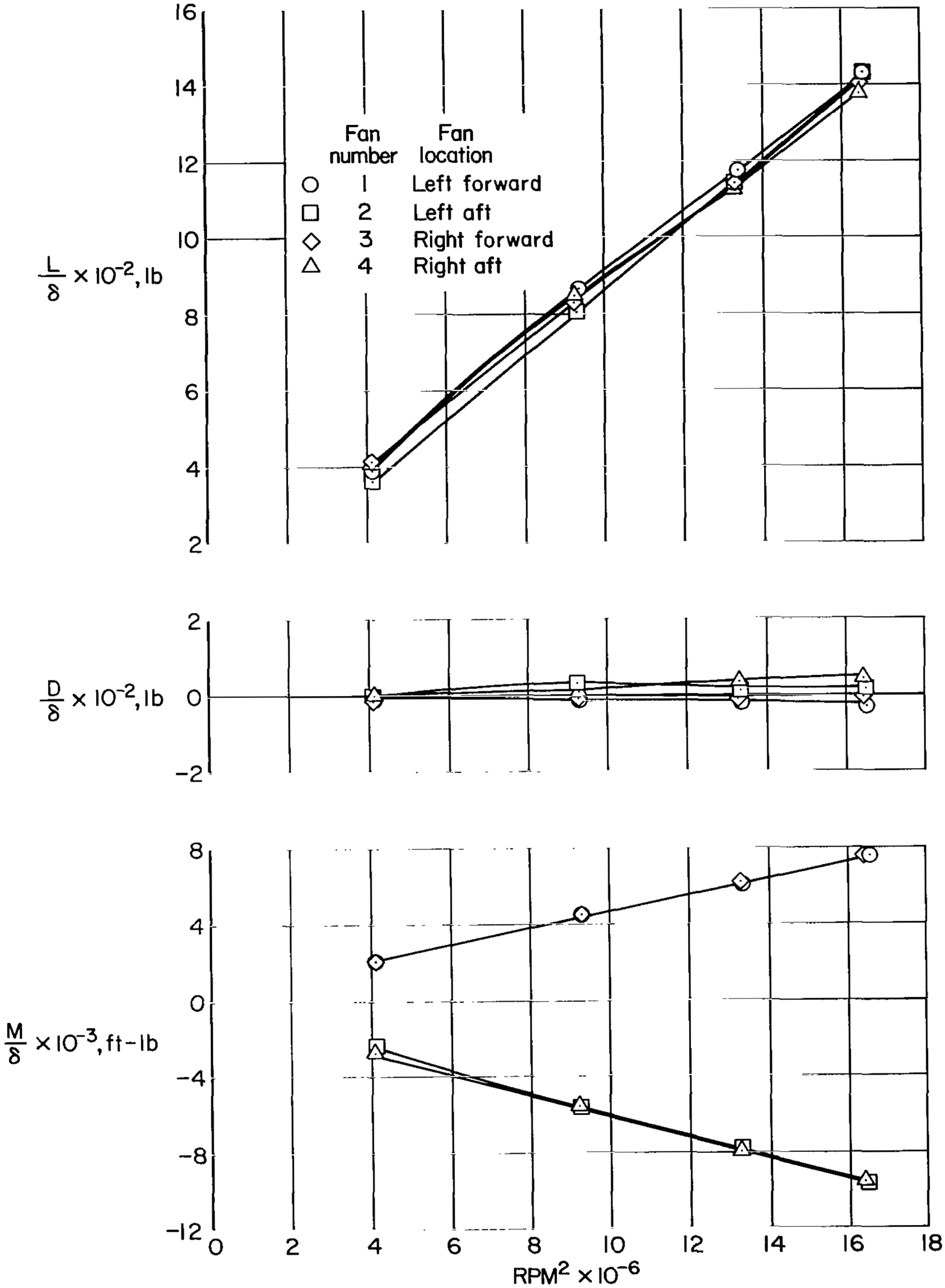
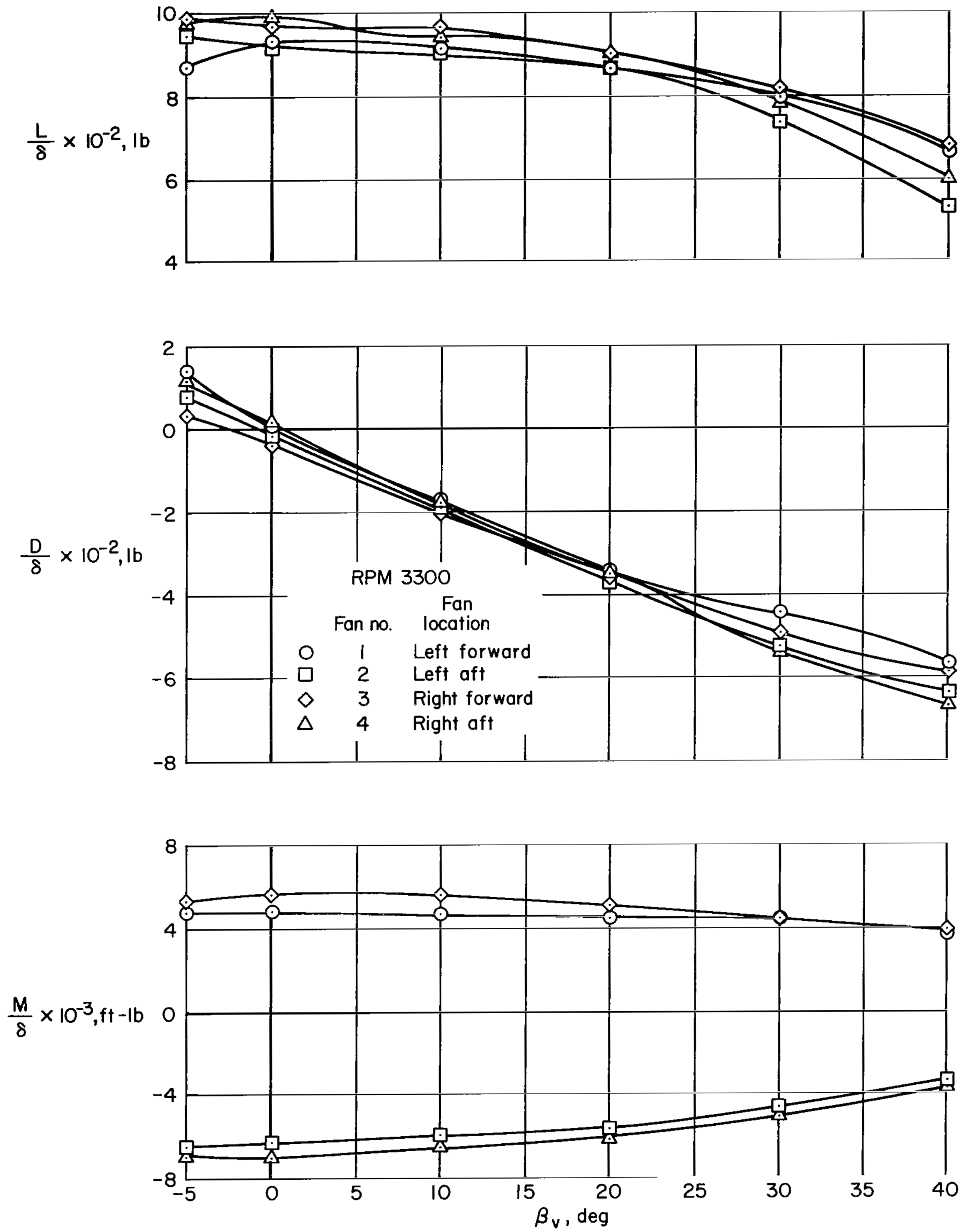


Figure 3.– Variation of velocity ratio with tip-speed ratio; $\beta_V = 0°$.



(a) Variation with RPM^2, tail on, $i_{t_o} = 0°$.

Figure 4.– Zero airspeed characteristics; $\delta_f = 45°$, $\alpha = 0°$, $\beta_v = 0°$.



(b) Variation with exit vanes, tail off.

Figure 4.– Concluded.

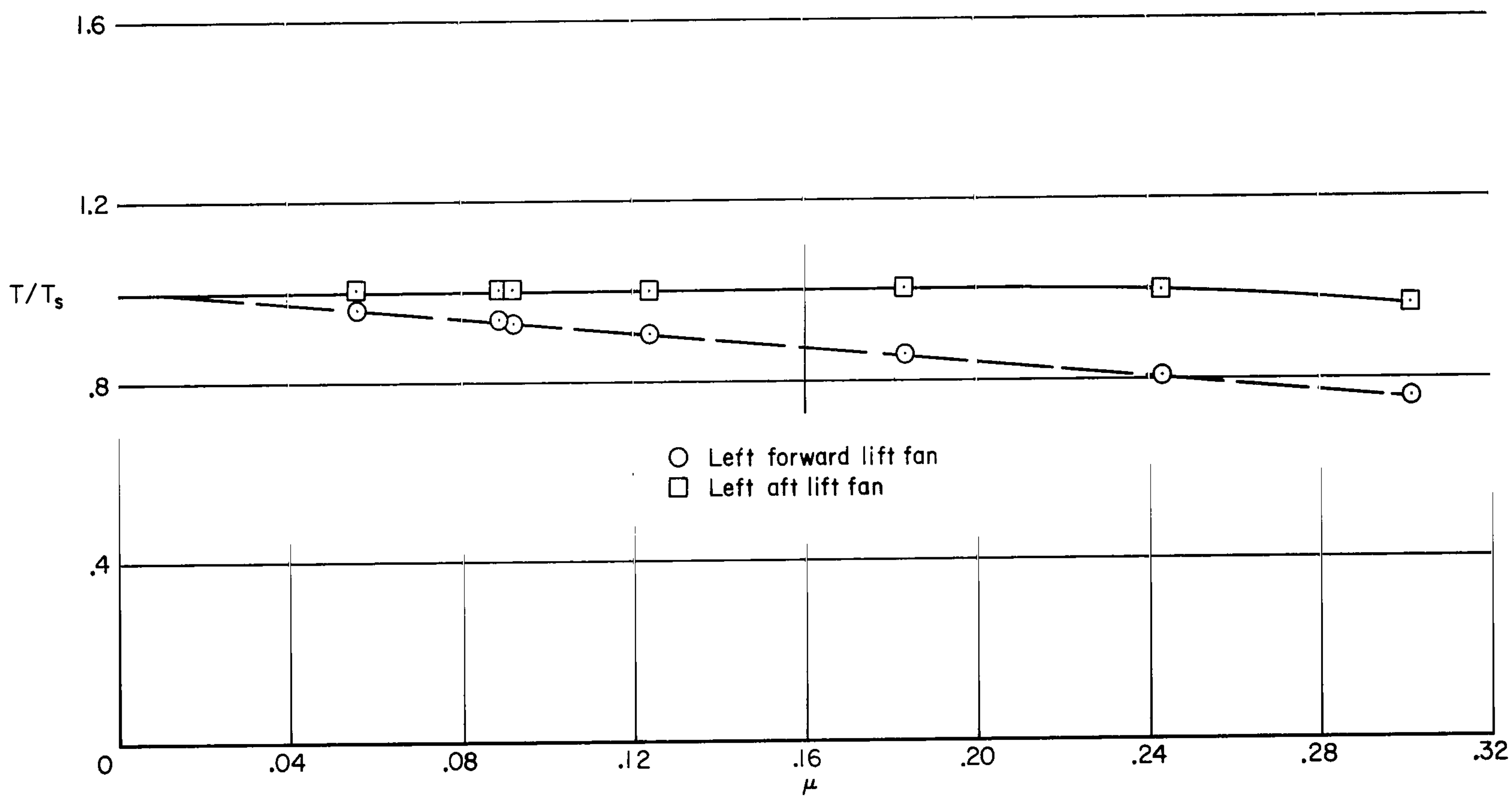
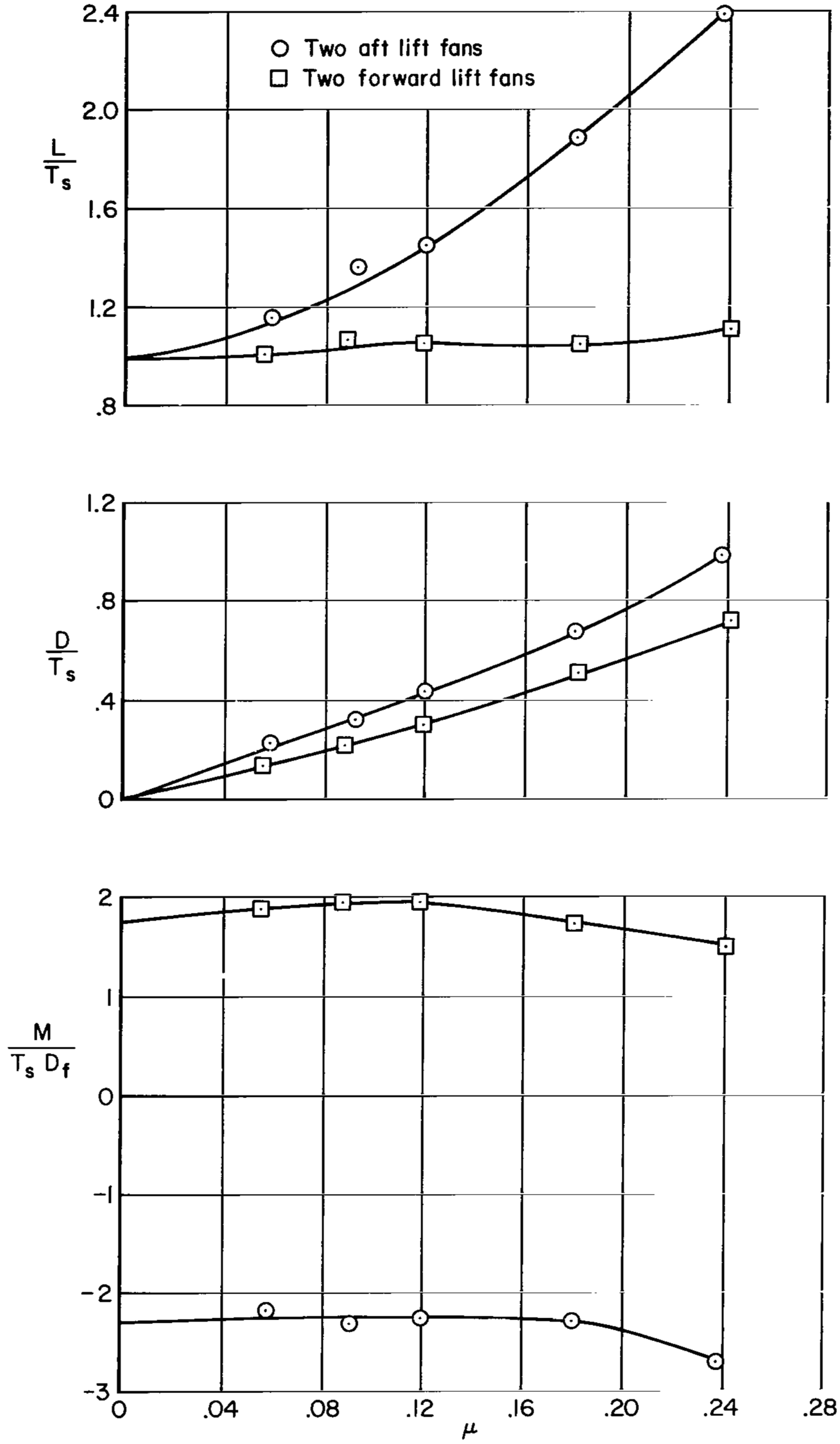
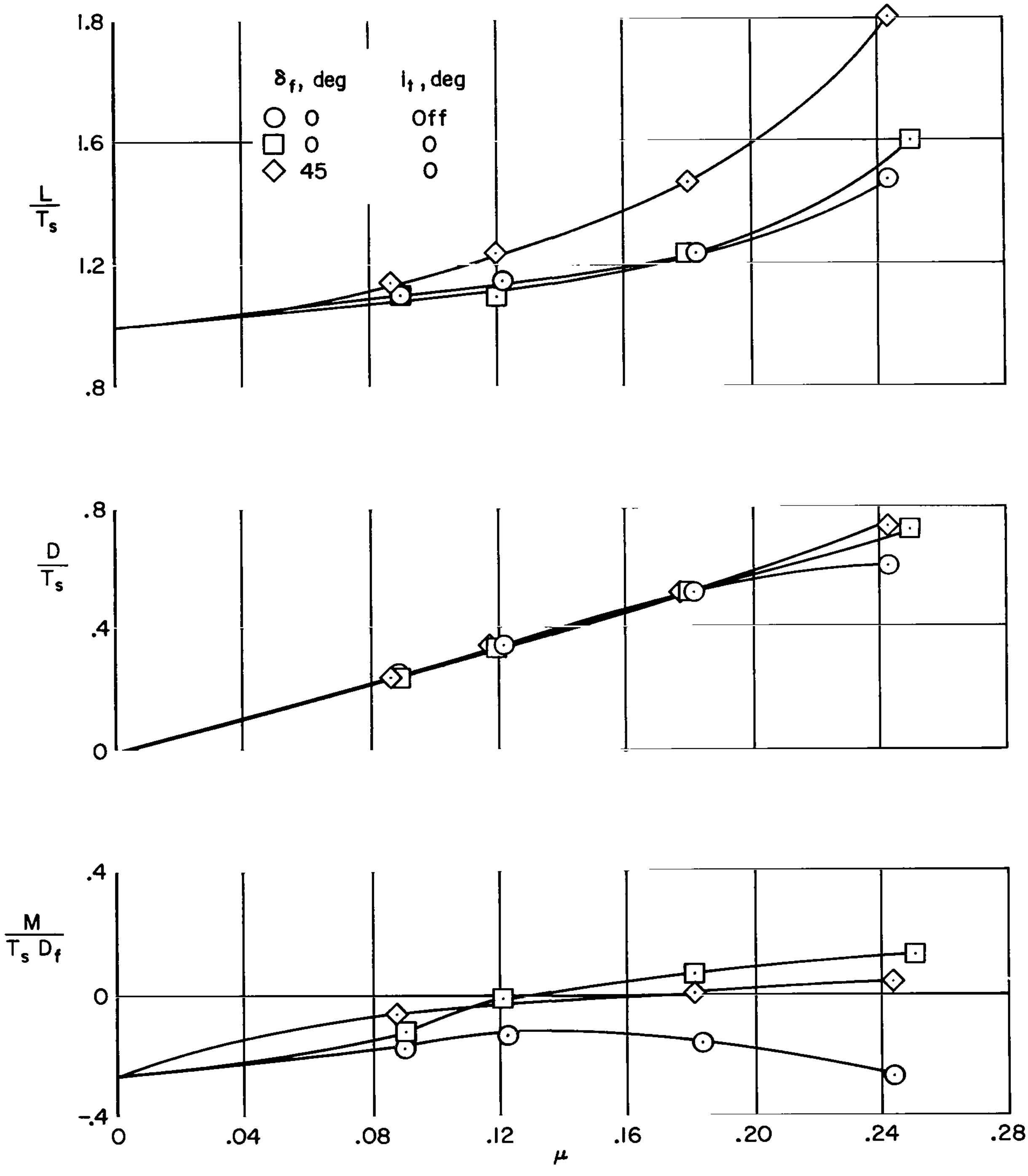


Figure 5.– The effect of forward speed (tip-speed ratio) on average fan thrust; $\alpha = 0°$, $\beta_V = 0°$, RPM = 3300.



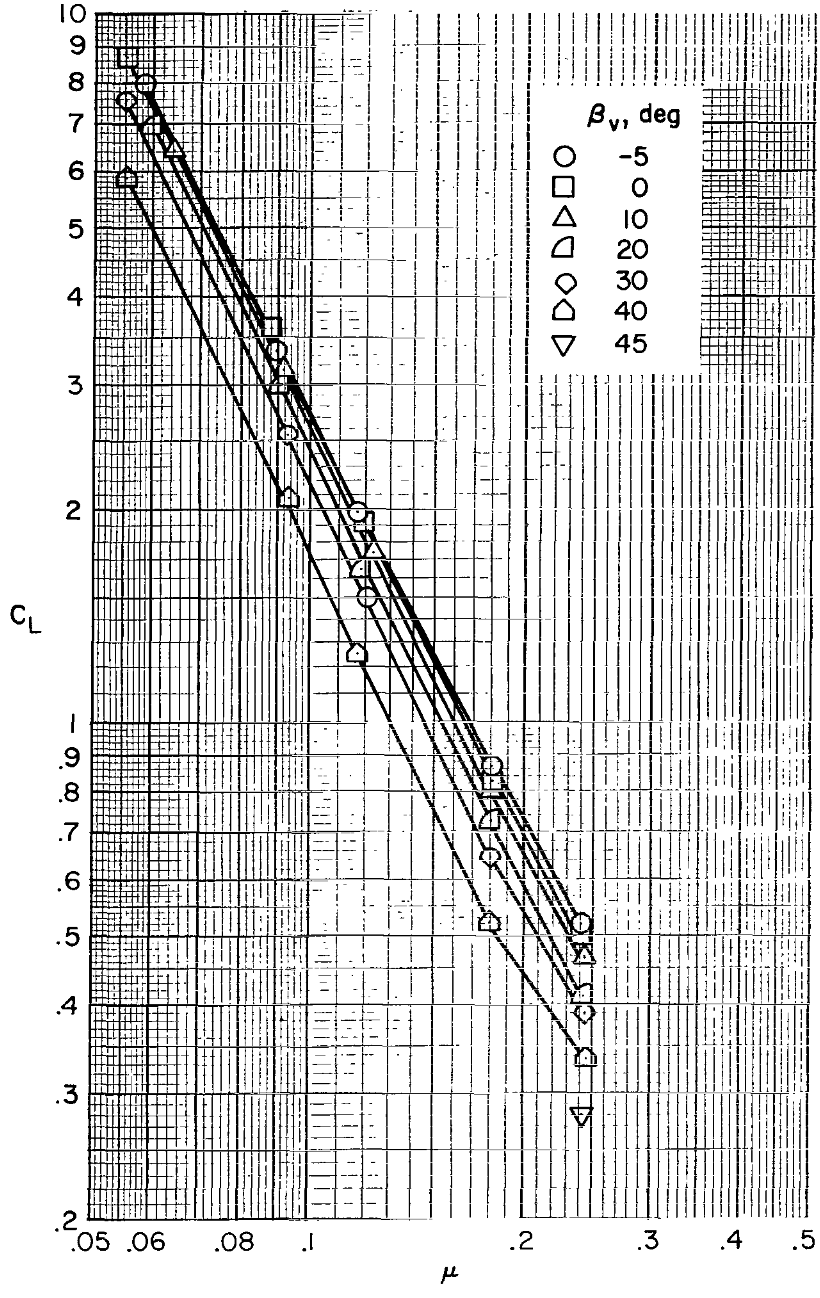
(a) Two lift fans, $\delta_f = 0°$, tail off.

Figure 6.– The variation of longitudinal characteristics with tip-speed ratio; $\alpha = 0°$, $\beta_V = 0°$, RPM = 3300.



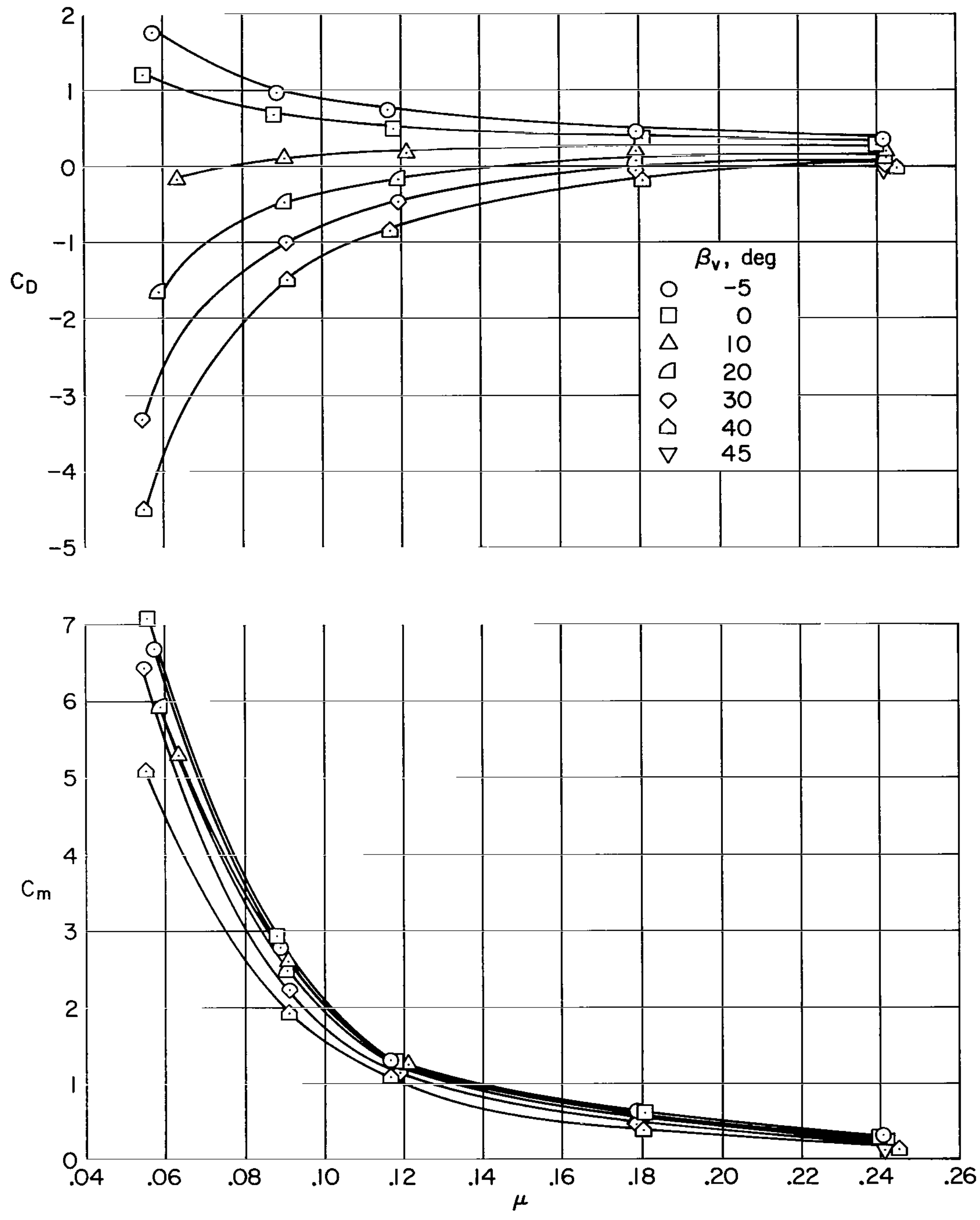
(b) Four fans.

Figure 6.– Concluded.



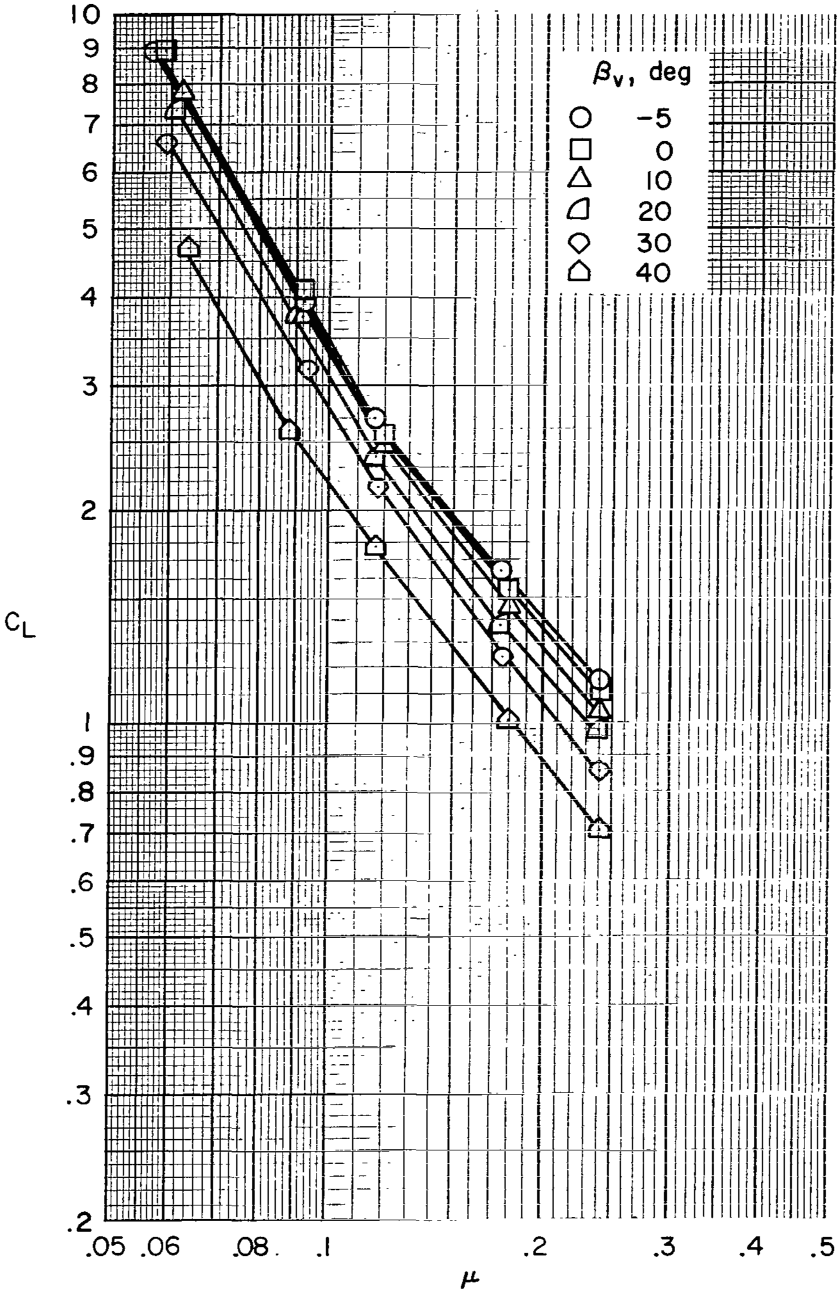
(a) C_L versus tip-speed ratio.

Figure 7.– Variation of longitudinal characteristics with tip-speed ratio, two front fans; $\alpha = 0°$, $\delta_f = 0°$, tail off, RPM = 3300, aft fans sealed.



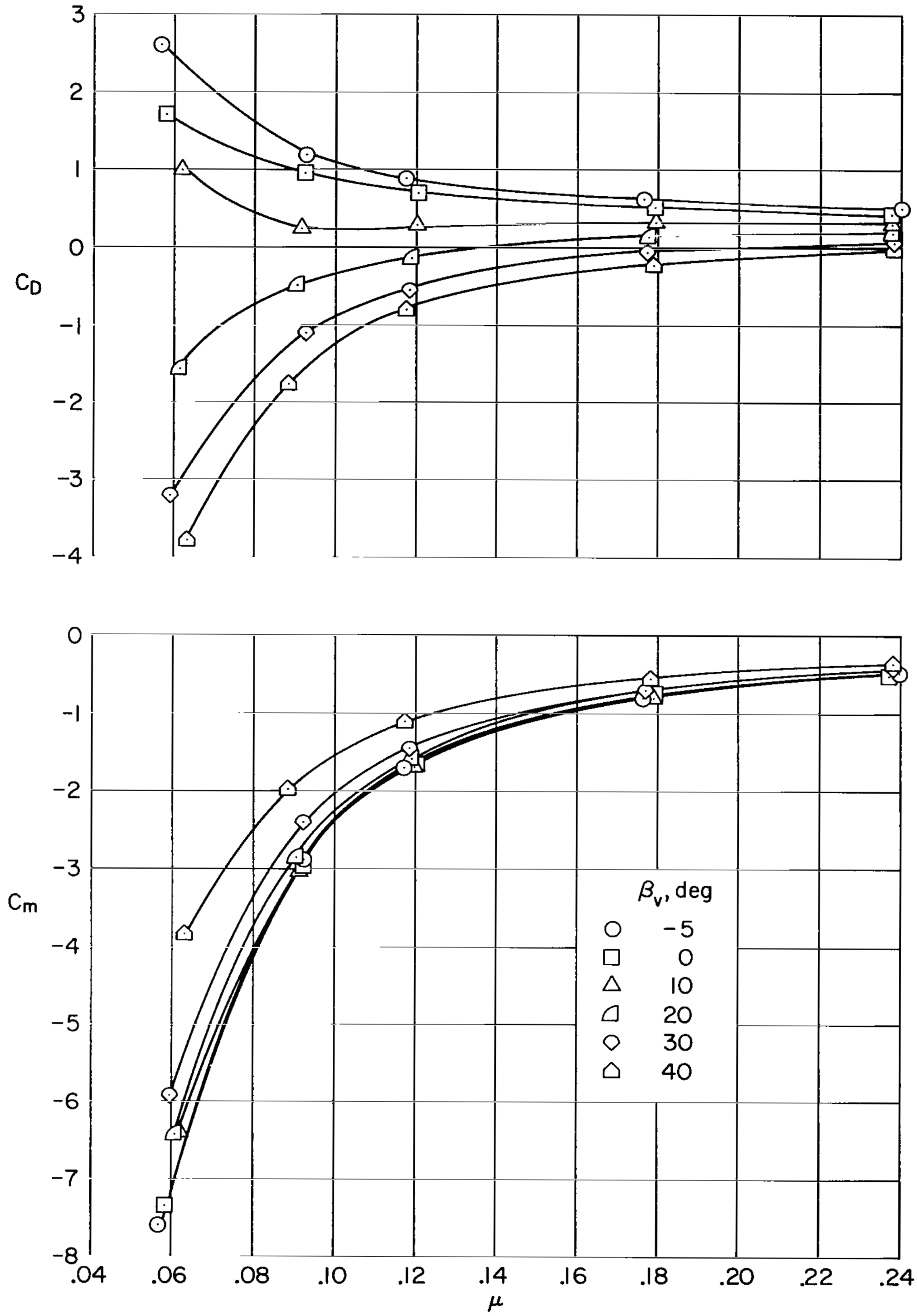
(b) C_D, C_m versus tip-speed ratio.

Figure 7.– Concluded.



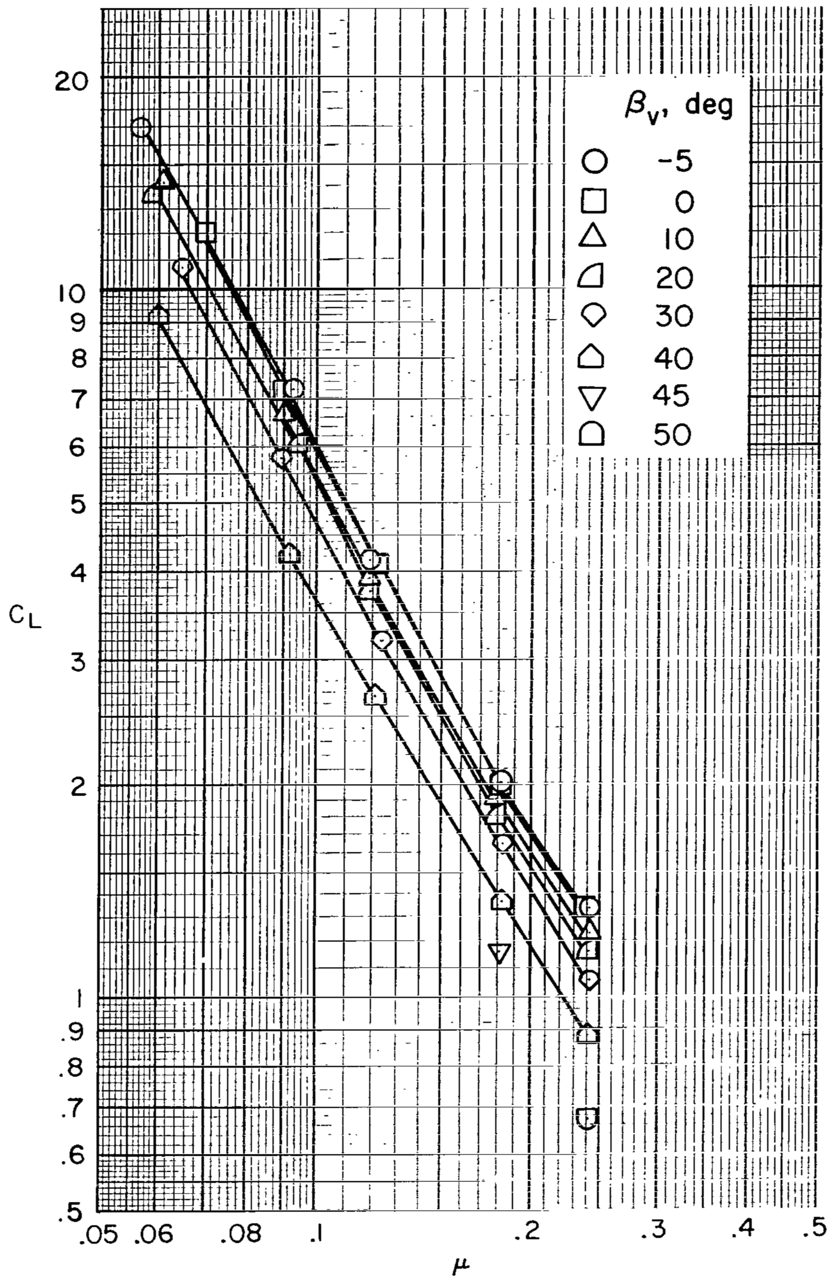
(a) C_L versus tip-speed ratio.

Figure 8.– Variation of longitudinal characteristics with tip-speed ratio, two aft fans; $\alpha = 0°$, $\delta_f = 0°$, tail off, RPM = 3300, front fans sealed.



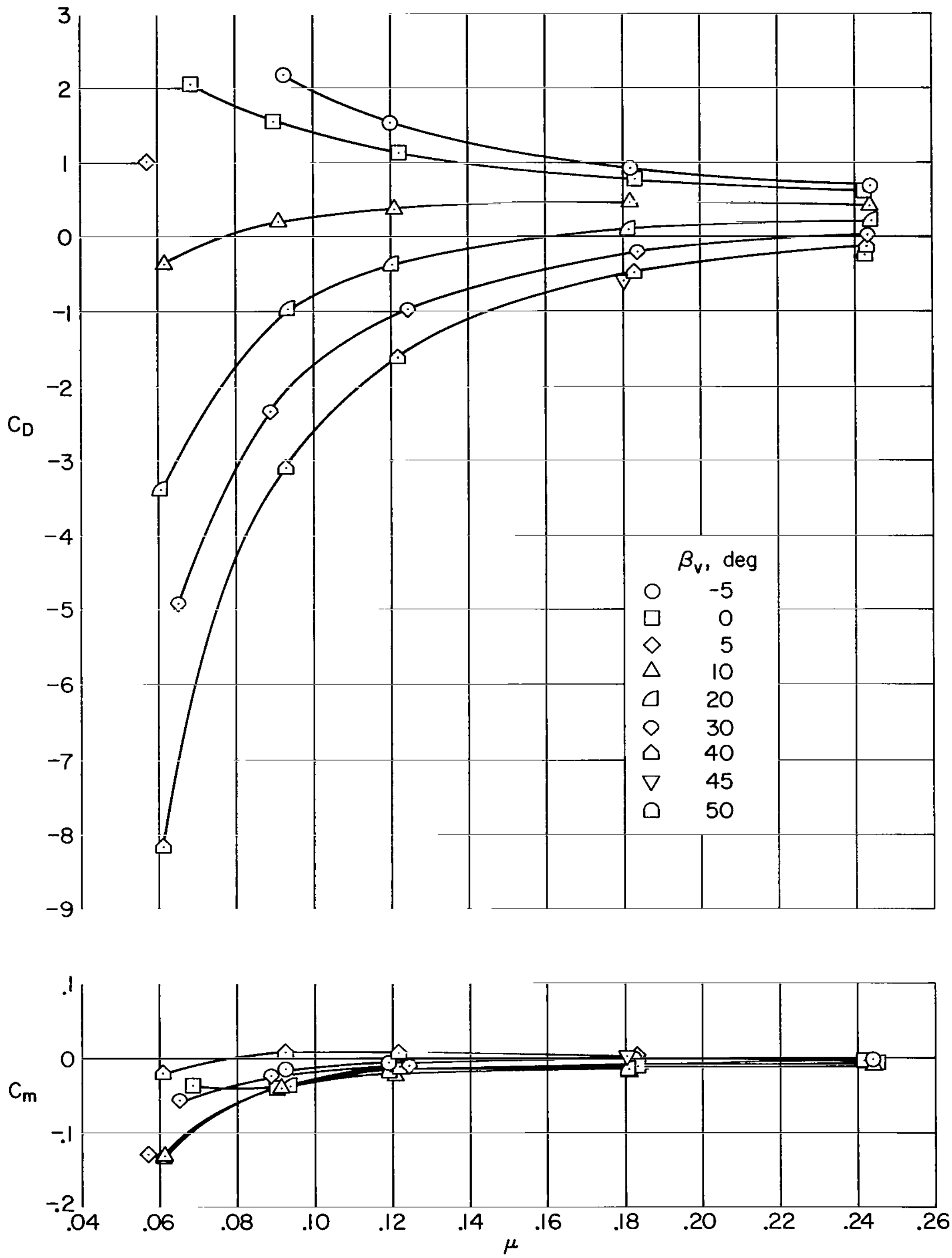
(b) C_D, C_m versus tip-speed ratio.

Figure 8.– Concluded.



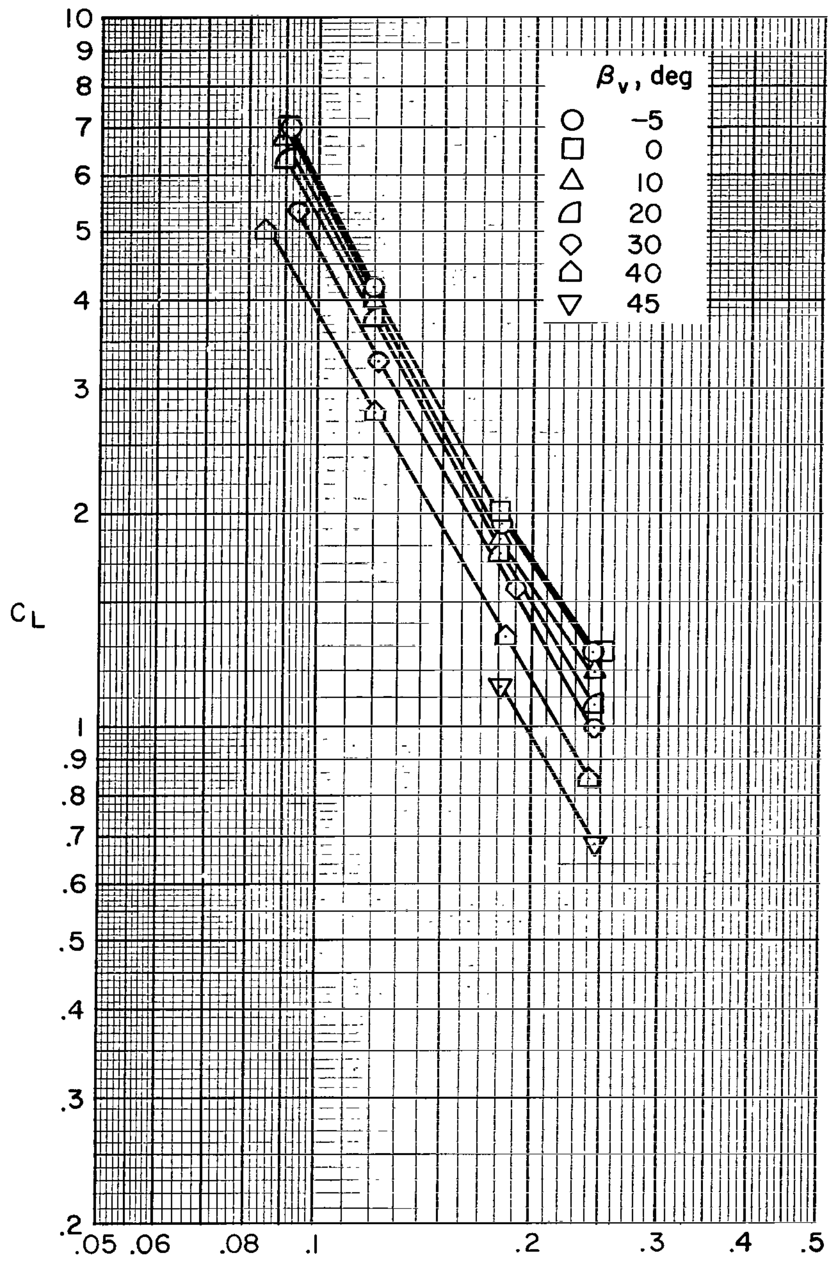
(a) C_L versus tip-speed ratio.

Figure 9.— Variation of longitudinal characteristics with tip-speed ratio, four fans; $\alpha = 0°$, $\delta_f = 0°$, tail off, RPM = 3300.



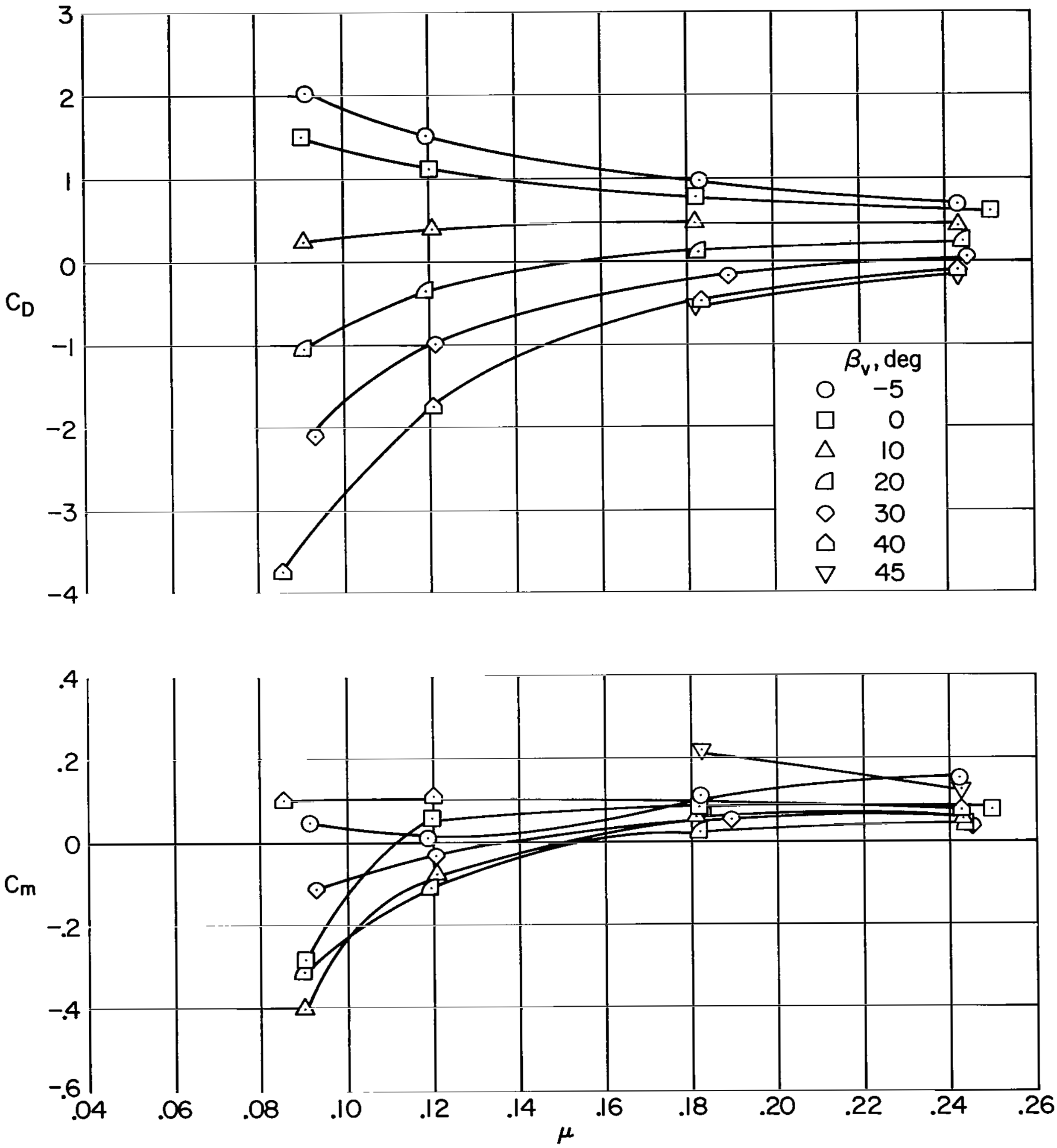
(b) C_D, C_m versus tip-speed ratio.

Figure 9.— Concluded.



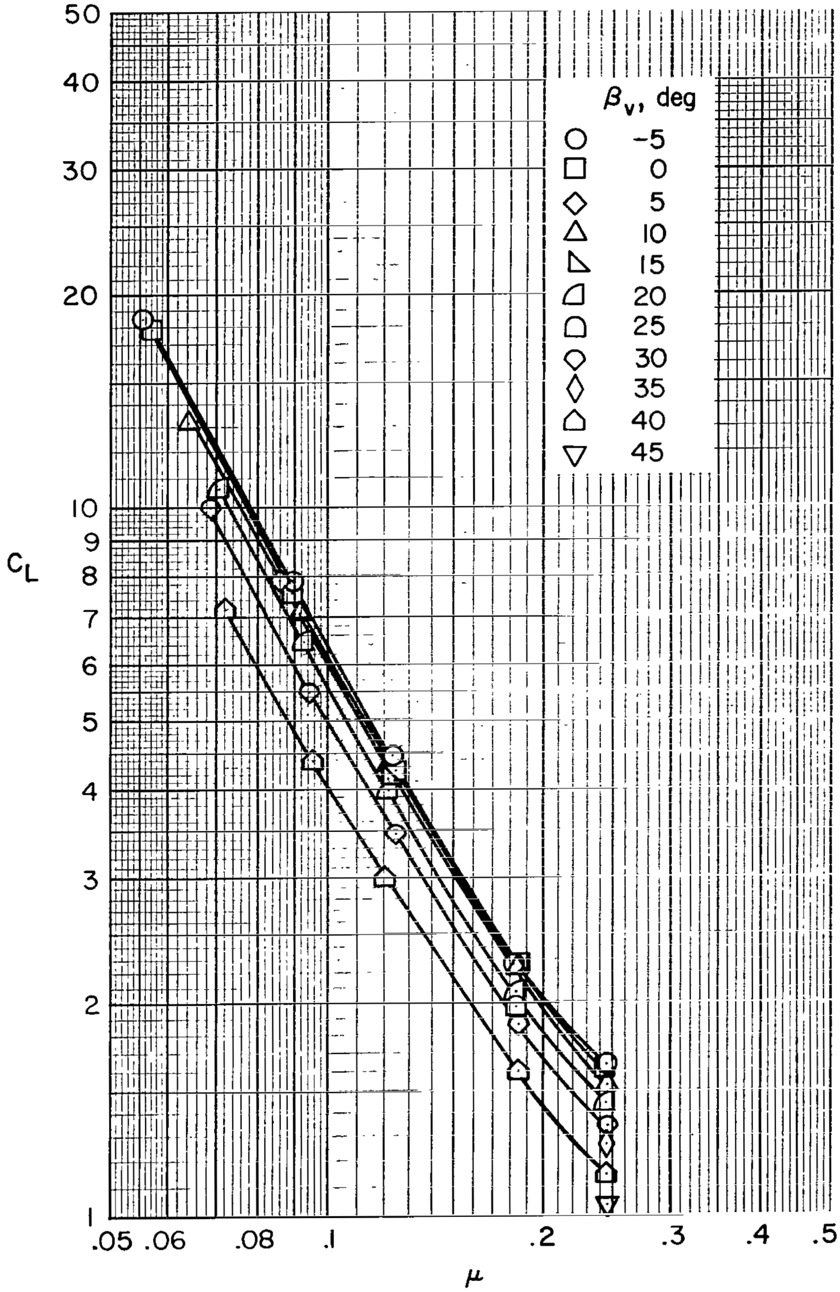
(a) C_L versus tip-speed ratio.

Figure 10.– Variation of longitudinal characteristics with tip-speed ratio, four fans; $\alpha = 0°$, $i_t = 0°$, $\delta_f = 0°$, RPM = 3300.



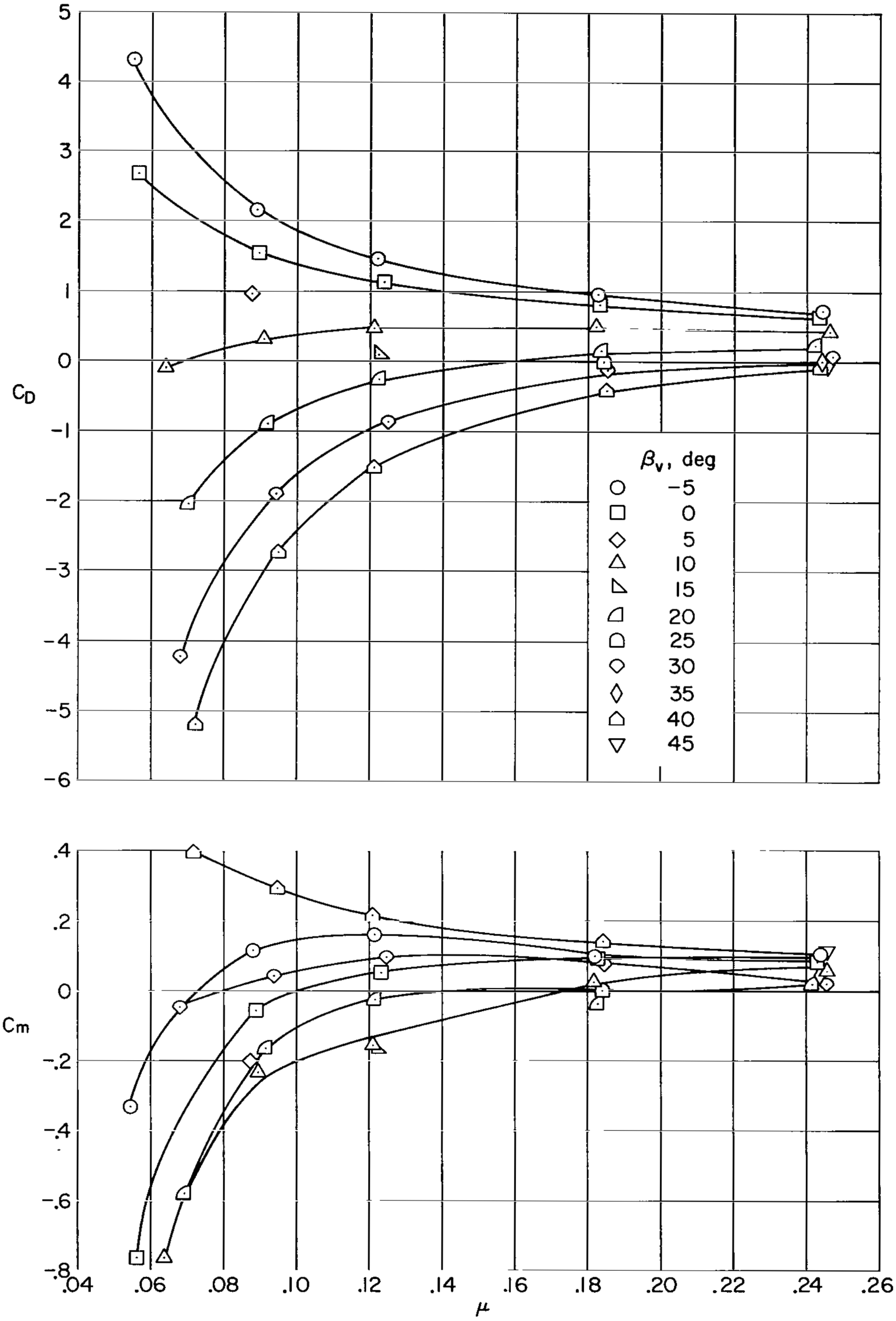
(b) C_D, C_m versus tip-speed ratio.

Figure 10.– Concluded.



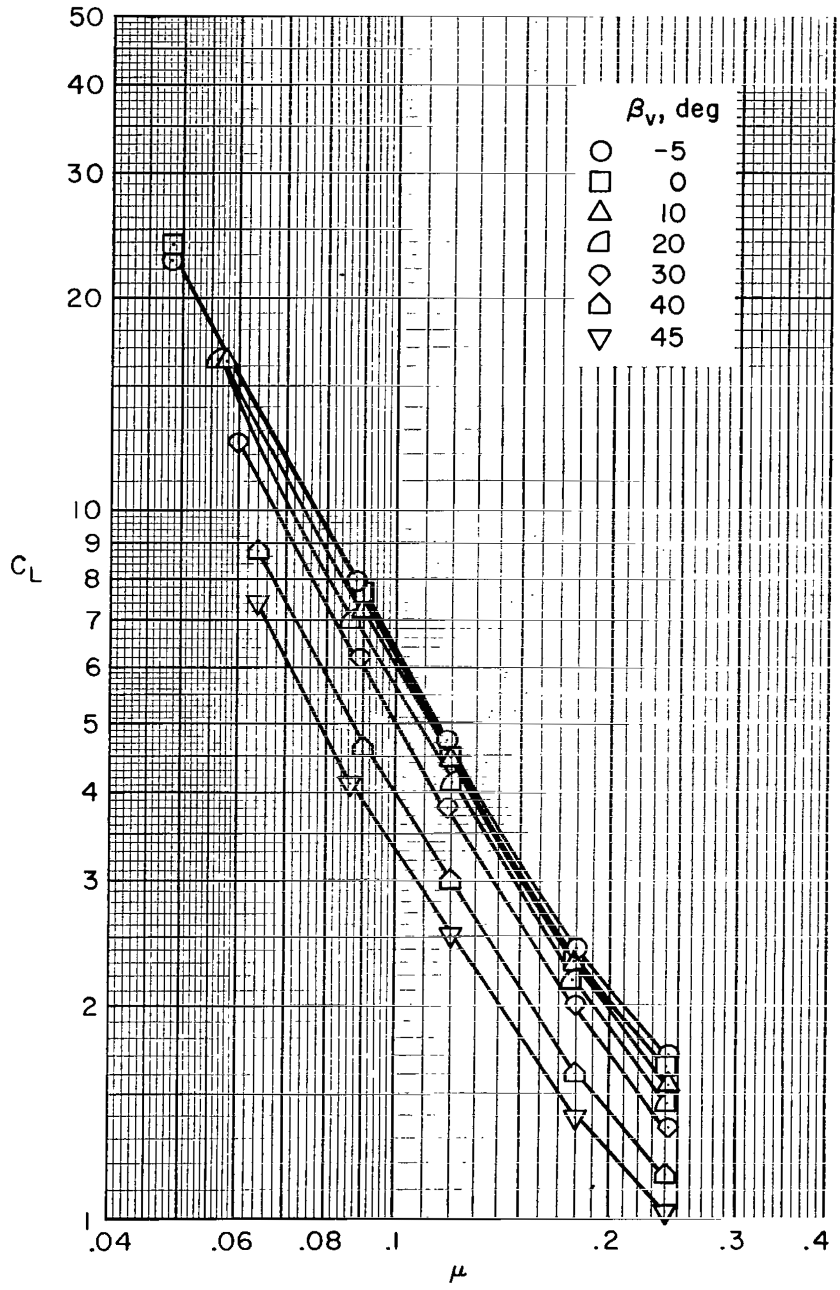
(a) C_L versus tip-speed ratio.

Figure 11.– Variation of longitudinal characteristics with tip-speed ratio, four fans; $\alpha = 0°$, $\delta_f = 45°$, $i_t = 0°$, RPM = 3300.



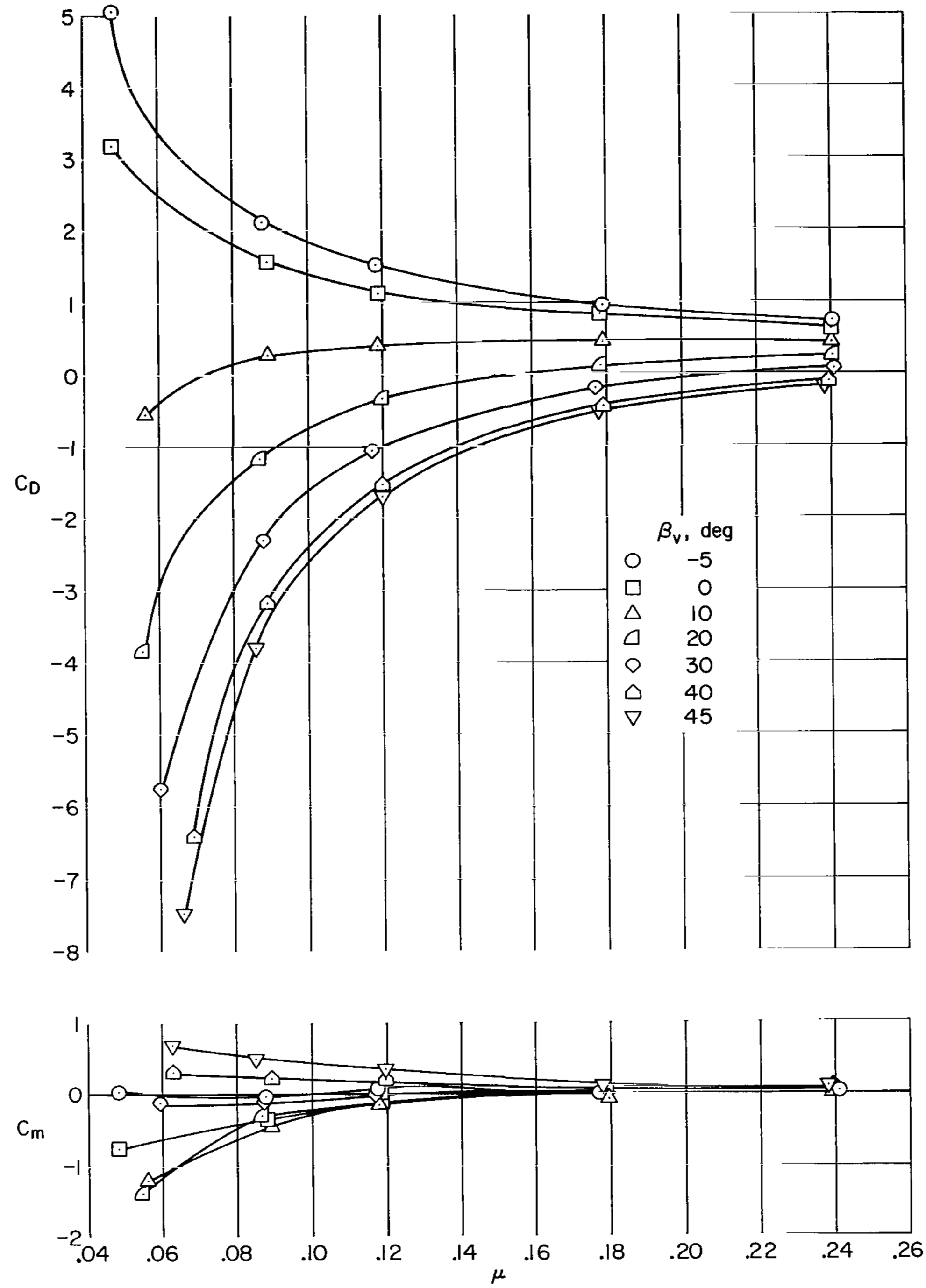
(b) C_D, C_m versus tip-speed ratio.

Figure 11.– Concluded.



(a) C_L versus tip-speed ratio

Figure 12.– Variation of longitudinal characteristics with tip-speed ratio; four fans; $\alpha = 0°$, $\delta_f = 45°$, $i_t = 0°$, slats off, RPM = 3300.



(b) C_D, C_m versus tip-speed ratio.

Figure 12.– Concluded.

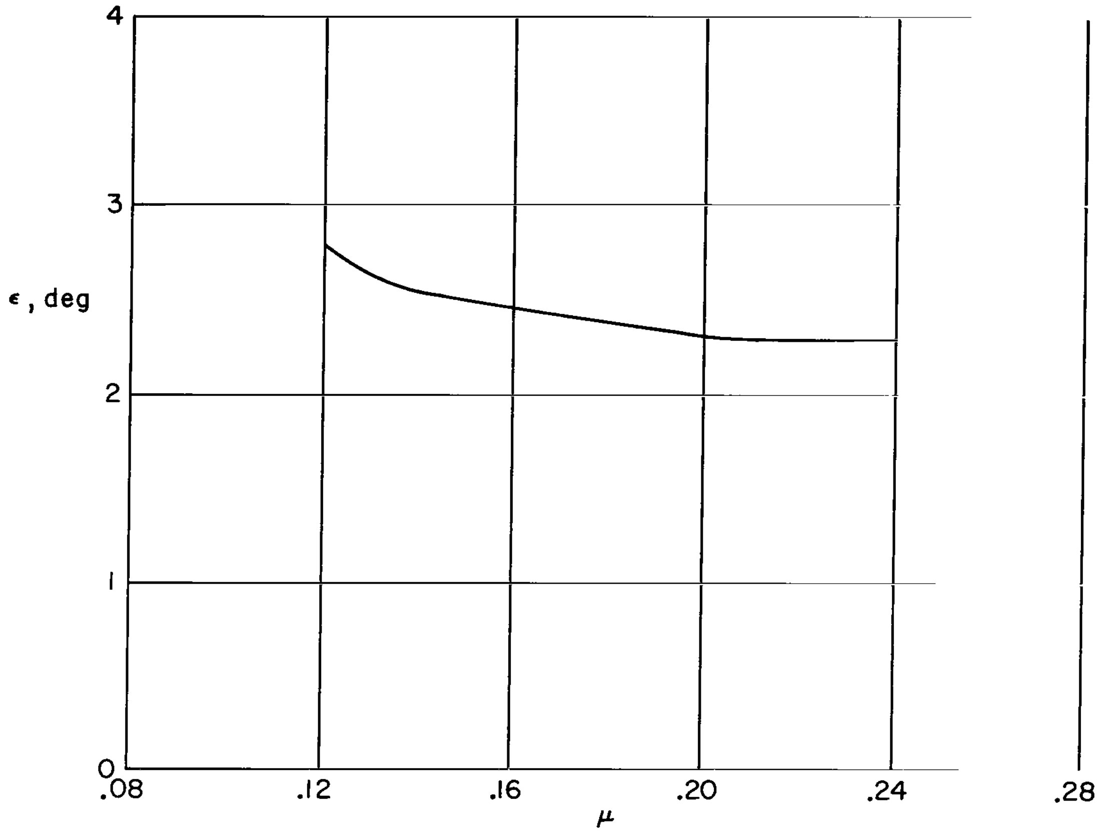


Figure 13.– Variation of average downwash at the horizontal tail for the complete tandem lift fan configuration; α = 0°, δ_f = 0°, β_v = 0°, RPM = 3300.

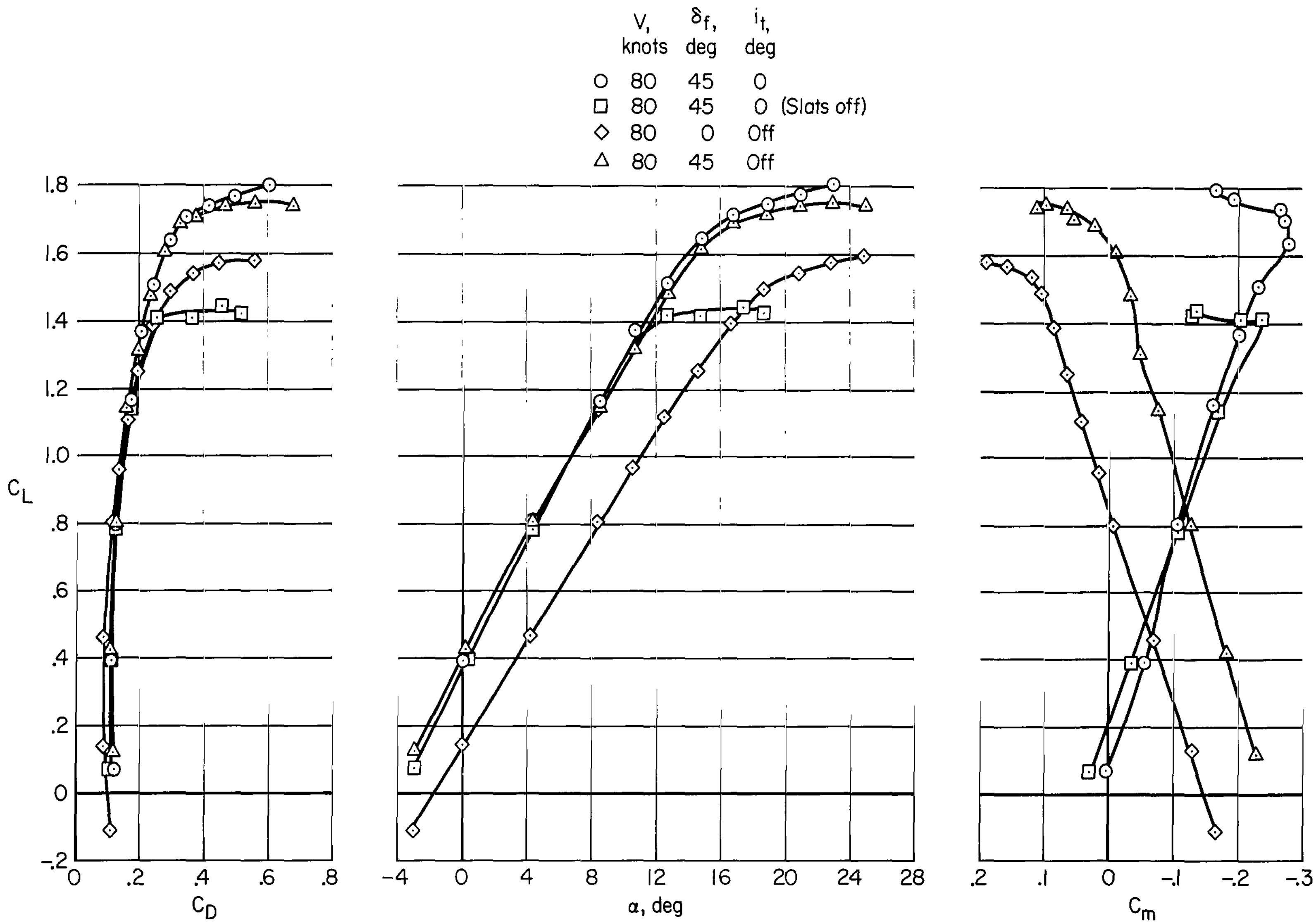


Figure 14.– Longitudinal characteristics with power off; $\beta_V = 90°$, fan inlets sealed.

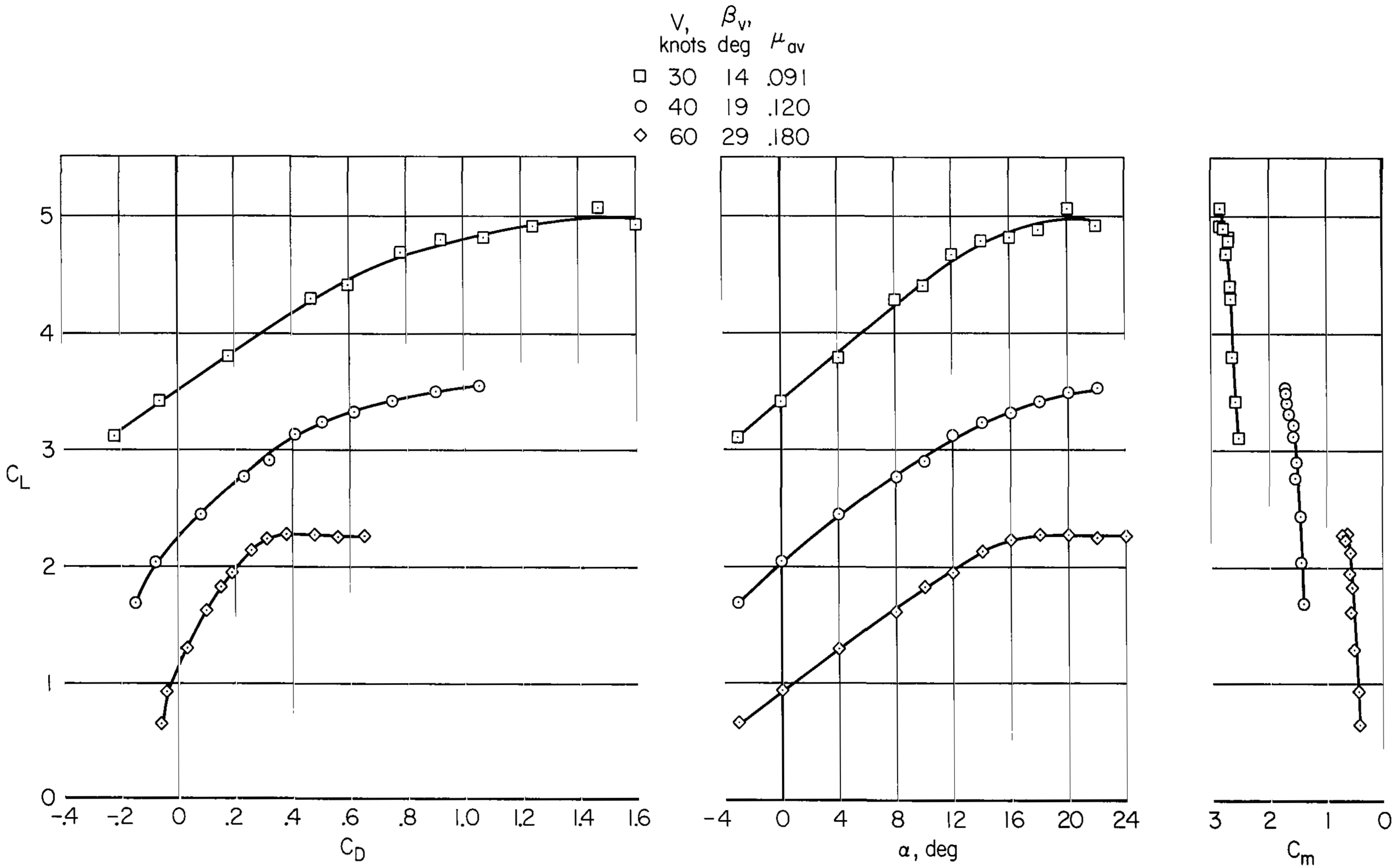


Figure 15.– Longitudinal characteristics with two front fans; $\delta_f = 45°$ tail off, RPM = 3300, aft fan inlets sealed.

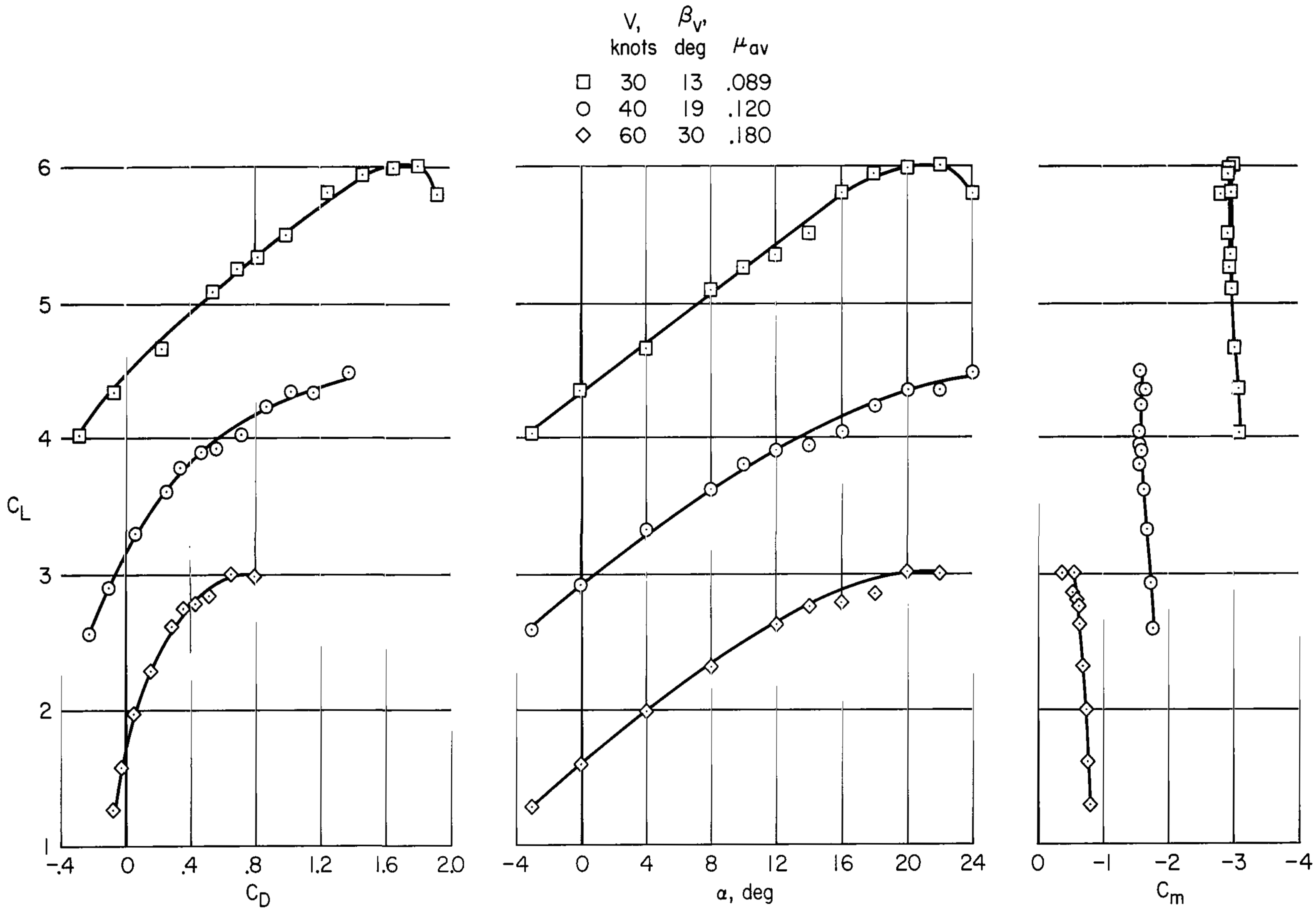


Figure 16.– Longitudinal characteristics with two aft fans; tail off $\delta_f = 45°$, RPM = 3300, front fan inlets sealed.

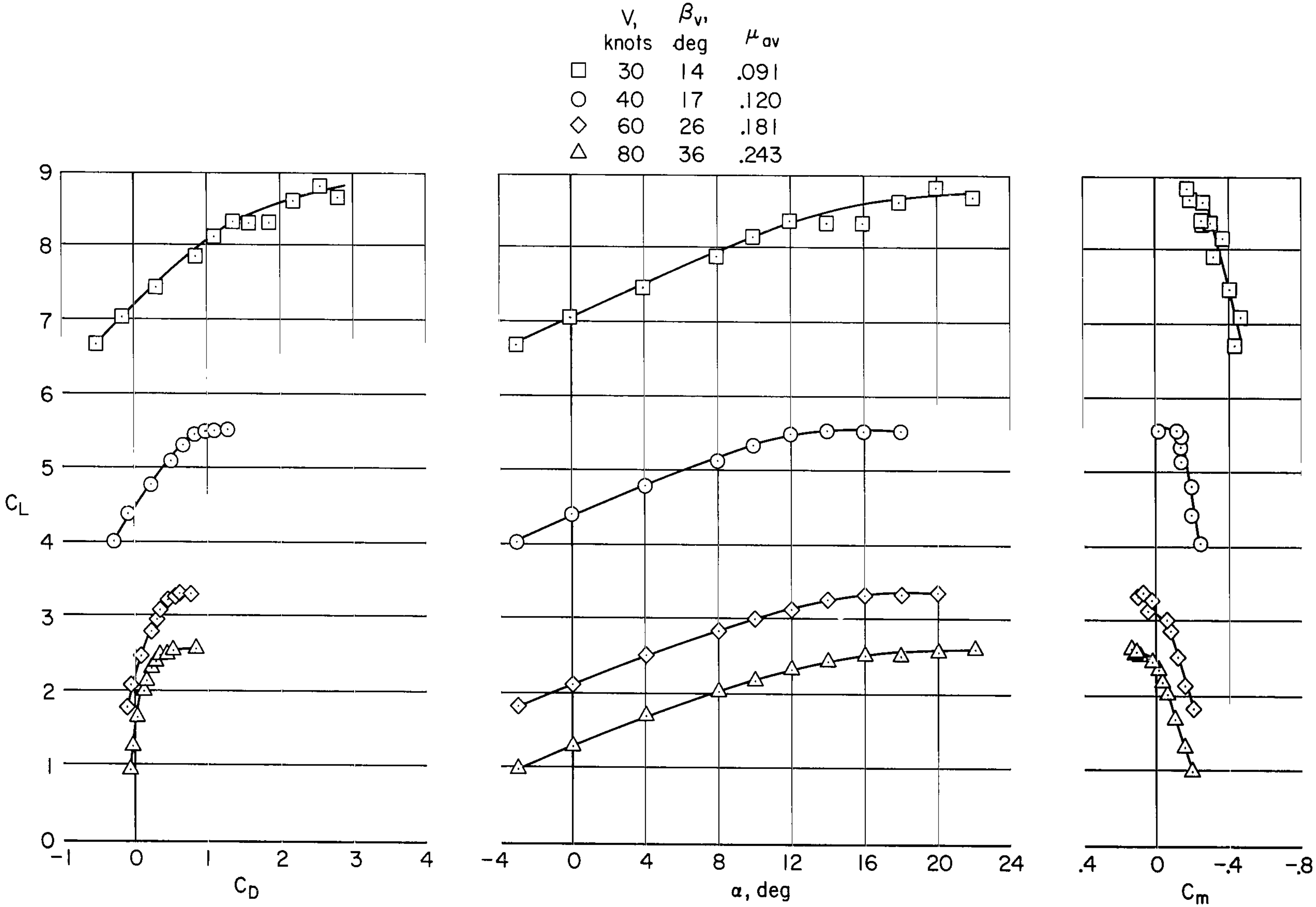


Figure 17.– Longitudinal characteristics with four fans; tail off, $\delta_f = 45°$, RPM = 3300.

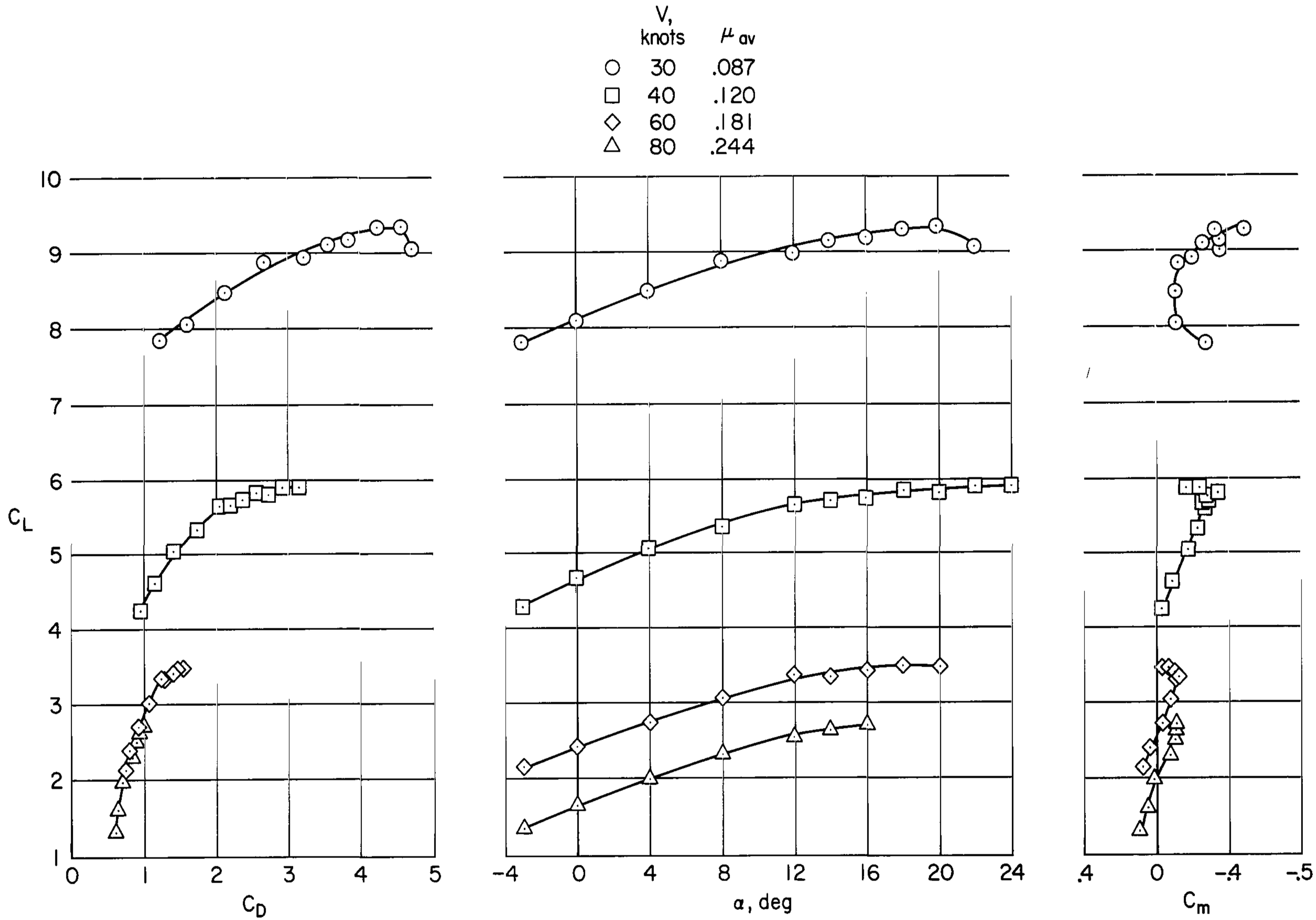
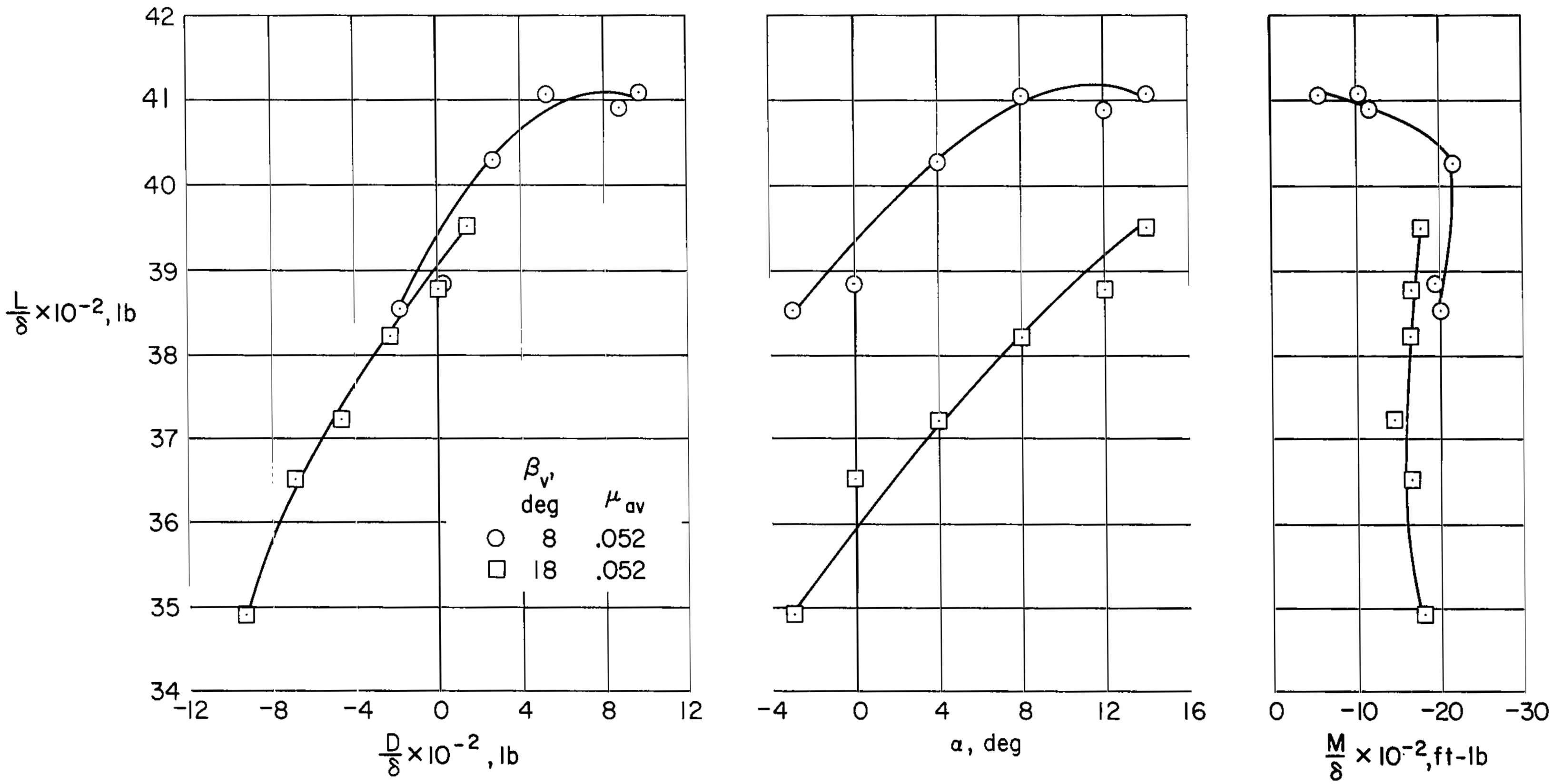
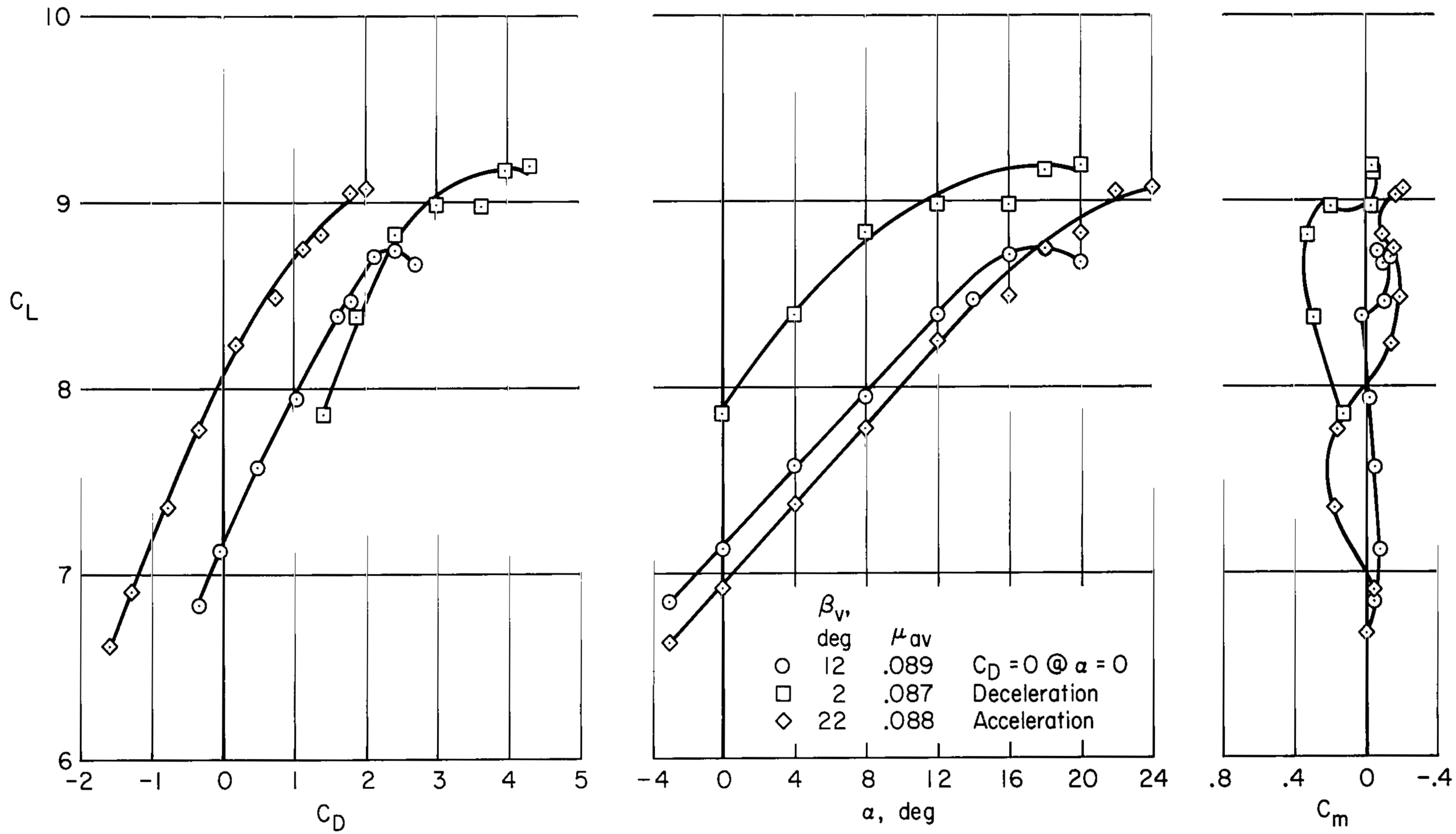


Figure 18.– Longitudinal characteristics with four fans; $\delta_f = 45°$, $\beta_v = 0°$, tail on, $i_t = 0°$, RPM = 3300.



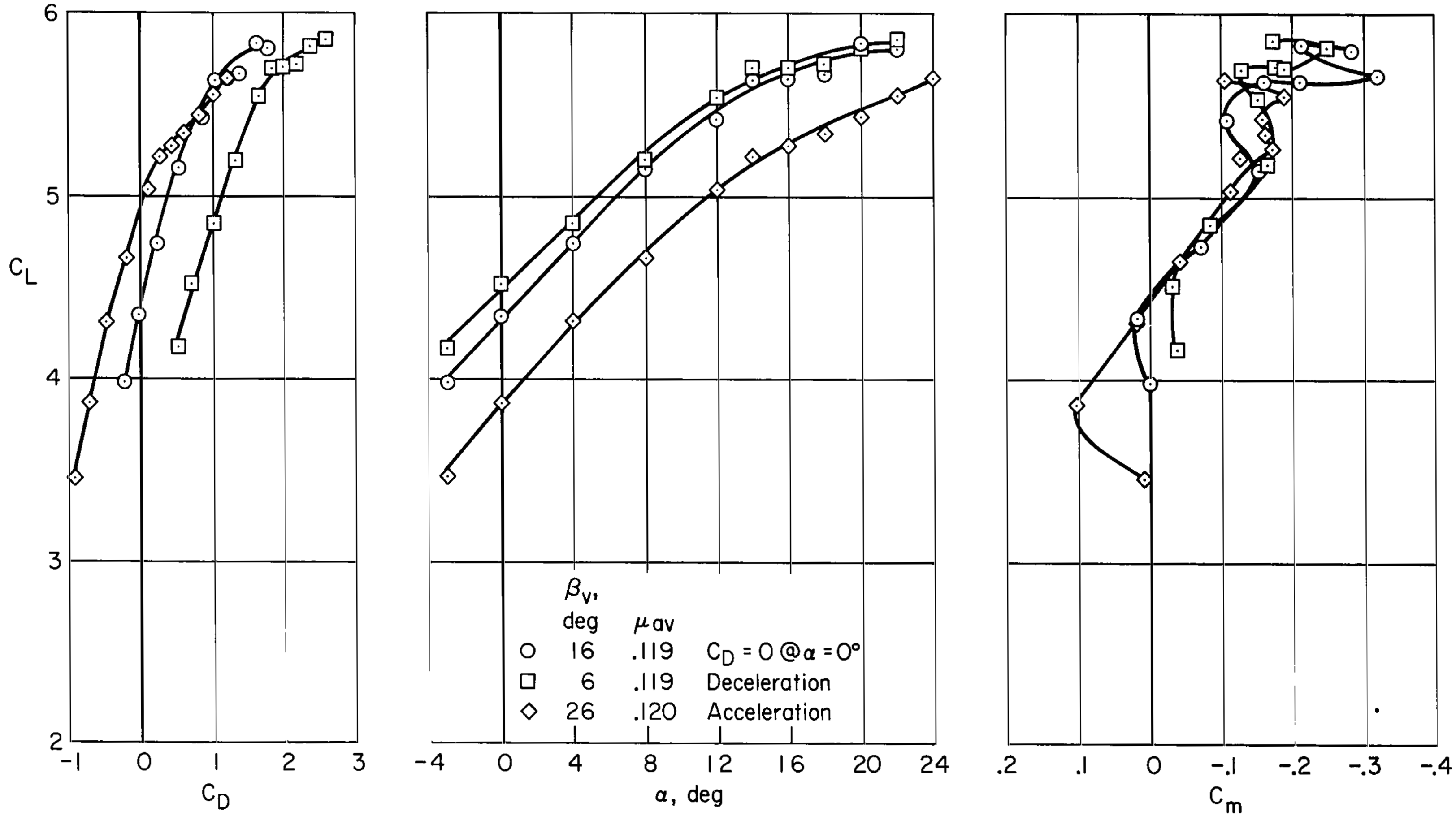
(a) $i_t = 0°$, V = 20 knots.

Figure 19.– Longitudinal characteristics with four fans; $\delta_f = 45°$, RPM = 3300.



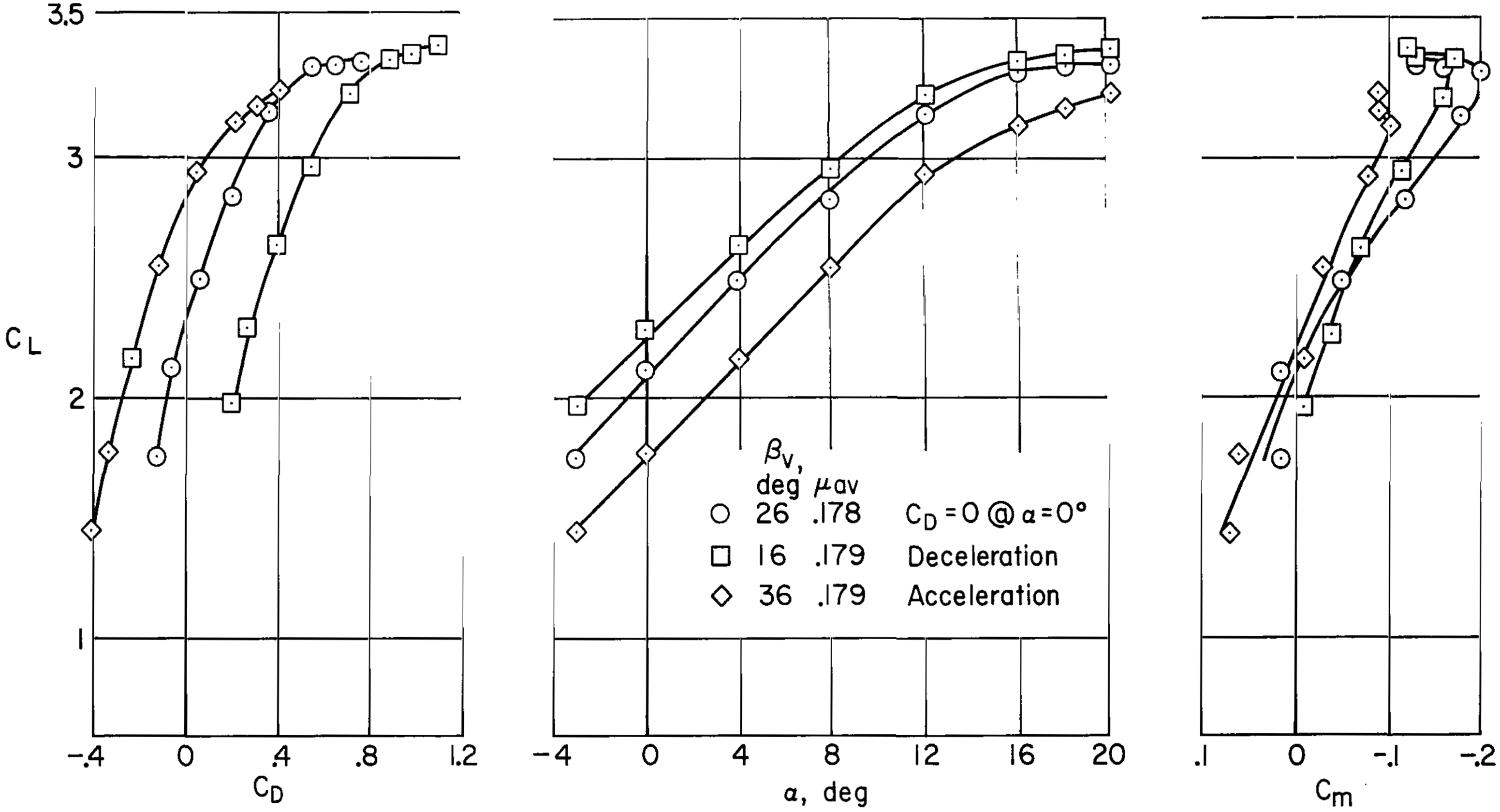
(b) i_t = -7.5°, V = 30 knots.

Figure 19.– Continued.



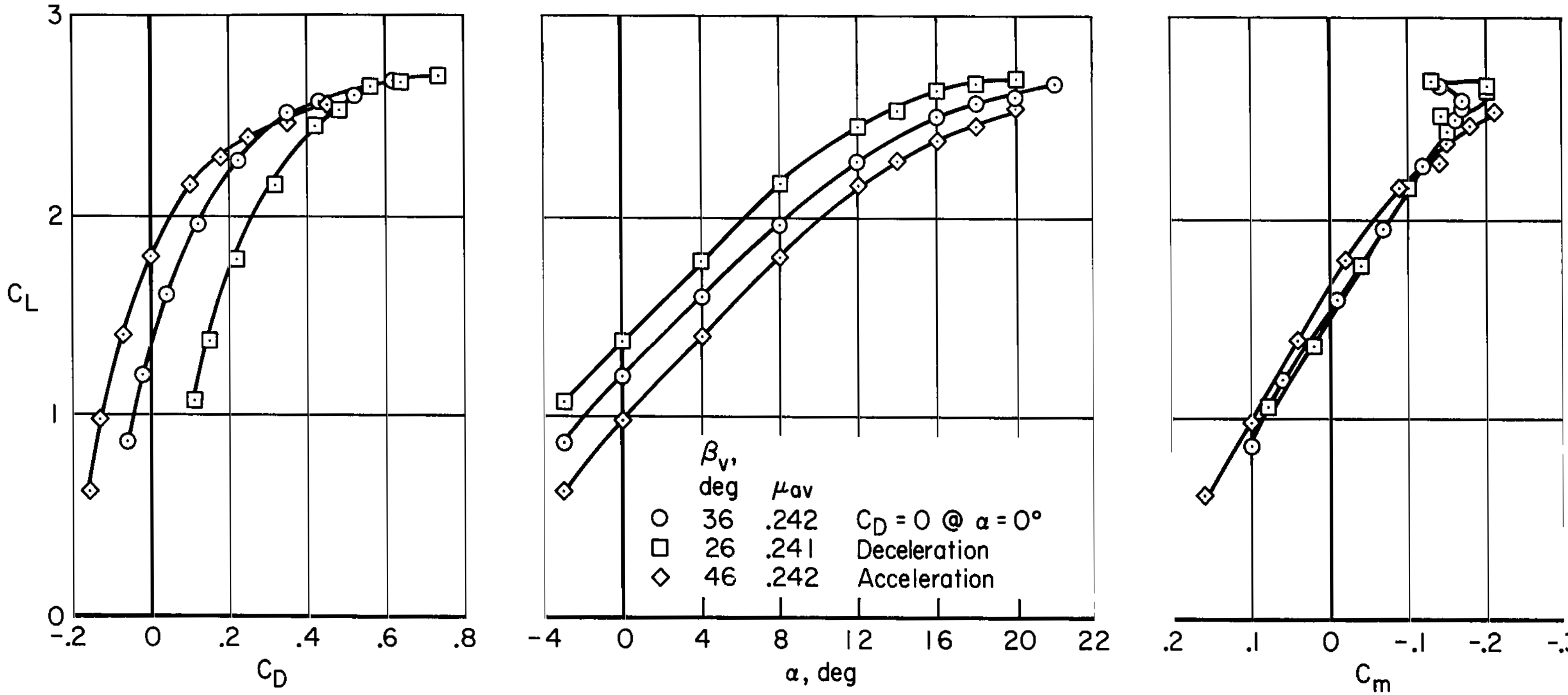
(c) $i_t = -2.5°$, V = 40 knots.

Figure 19.– Continued.



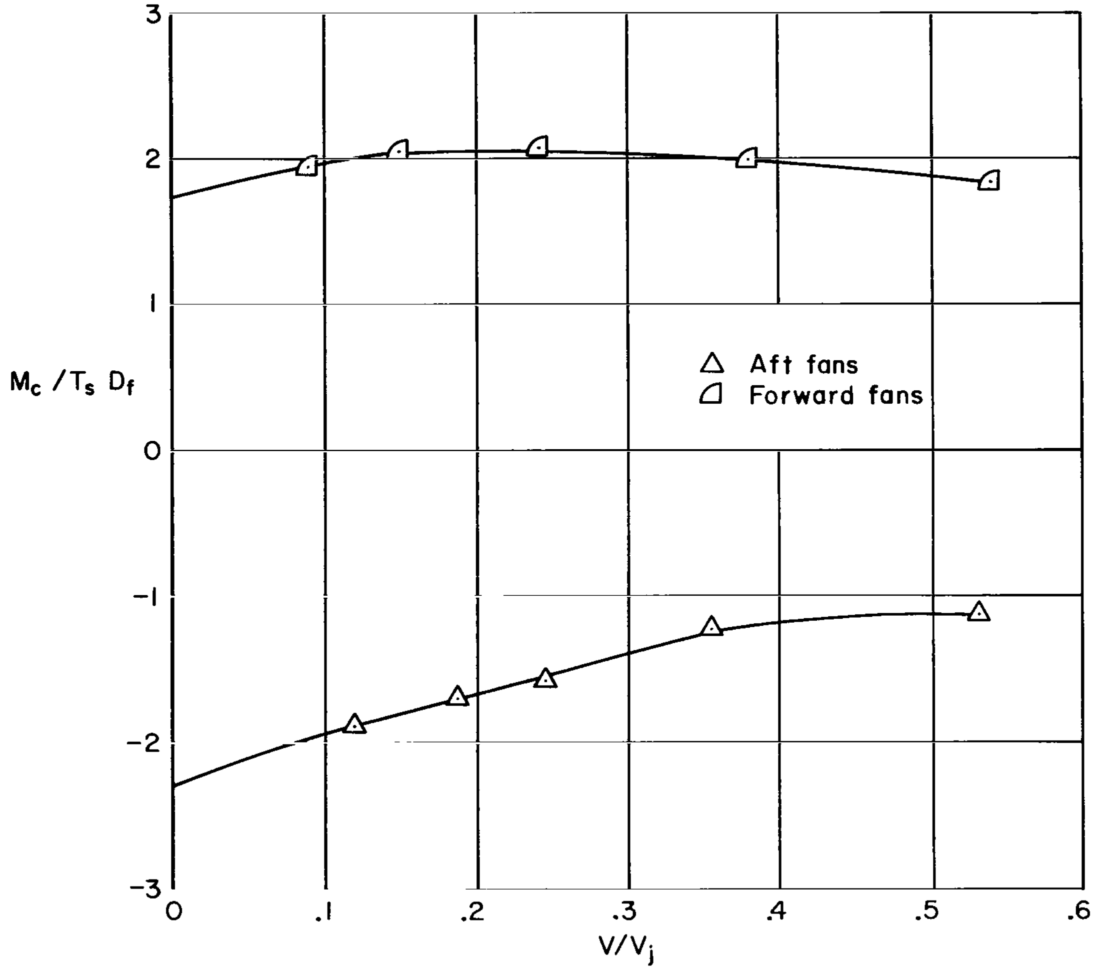
(d) $i_t = 0°$, V = 60 knots.

Figure 19.– Continued.



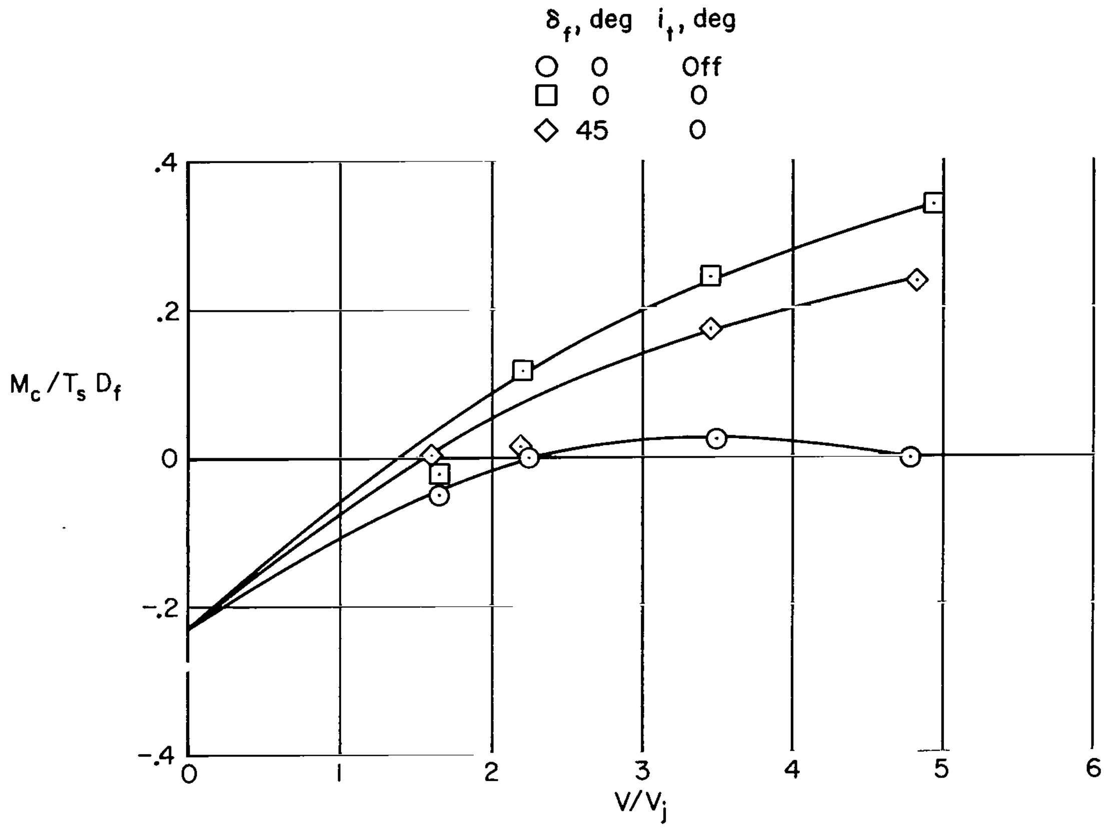
(e) i_t = 0°, V = 80 knots.

Figure 19.– Concluded.



(a) Two lift fans, $\delta_f = 0°$, tail off.

Figure 20.– Effect of fan operation and forward speed on pitching moment; $\alpha = 0°$, $\beta_V = 0°$, constant RPM.



(b) Four lift fans.

Figure 20.– Concluded.

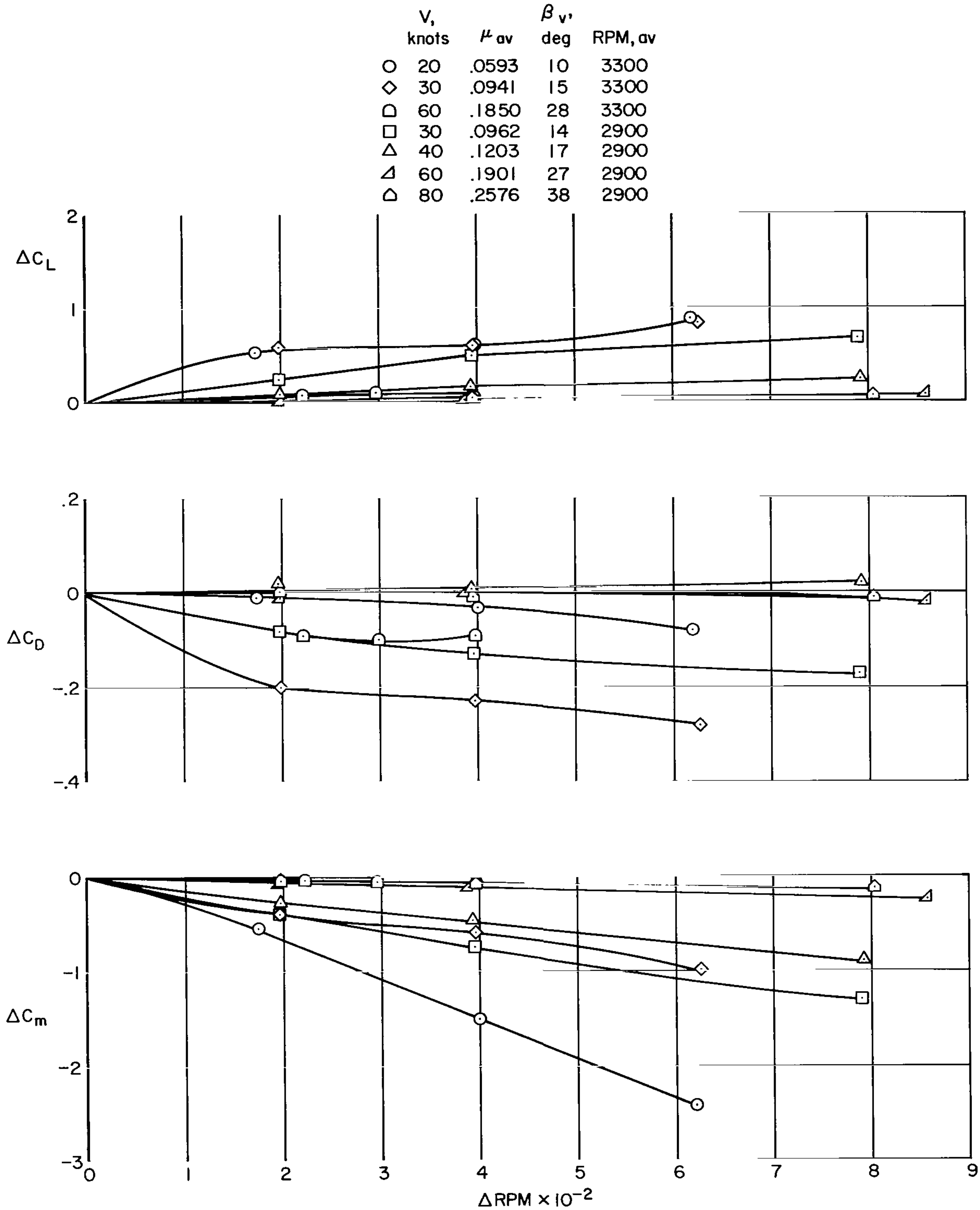


Figure 21.– Effect of differential lift fan RPM, fore and aft, on longitudinal characteristics; four fans operating, $\alpha = 0°$, $\delta_f = 45°$, $i_t = 0°$, $C_D = 0$ at Δ RPM = 0.

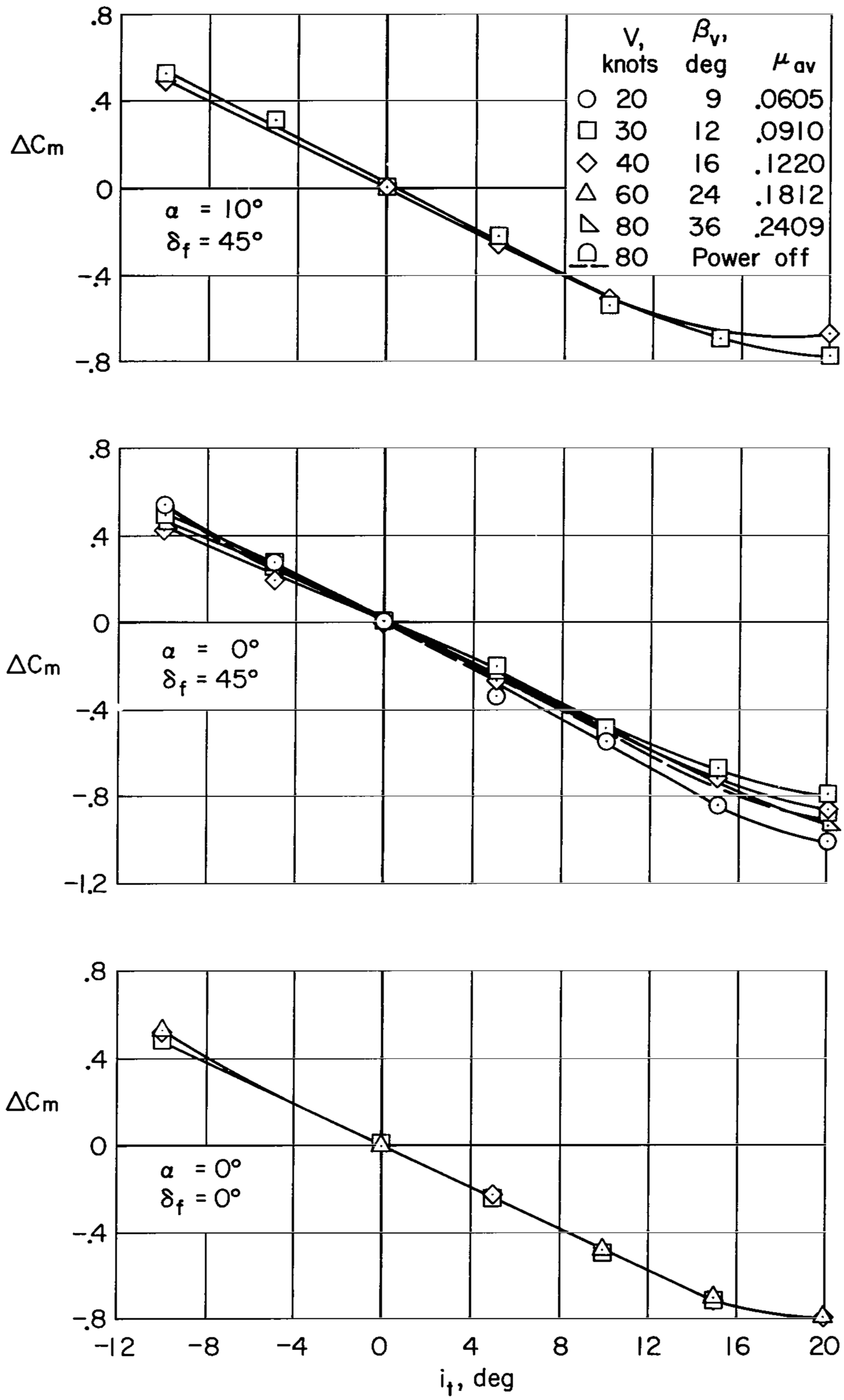


Figure 22.– Horizontal tail effectiveness; RPM = 3300.

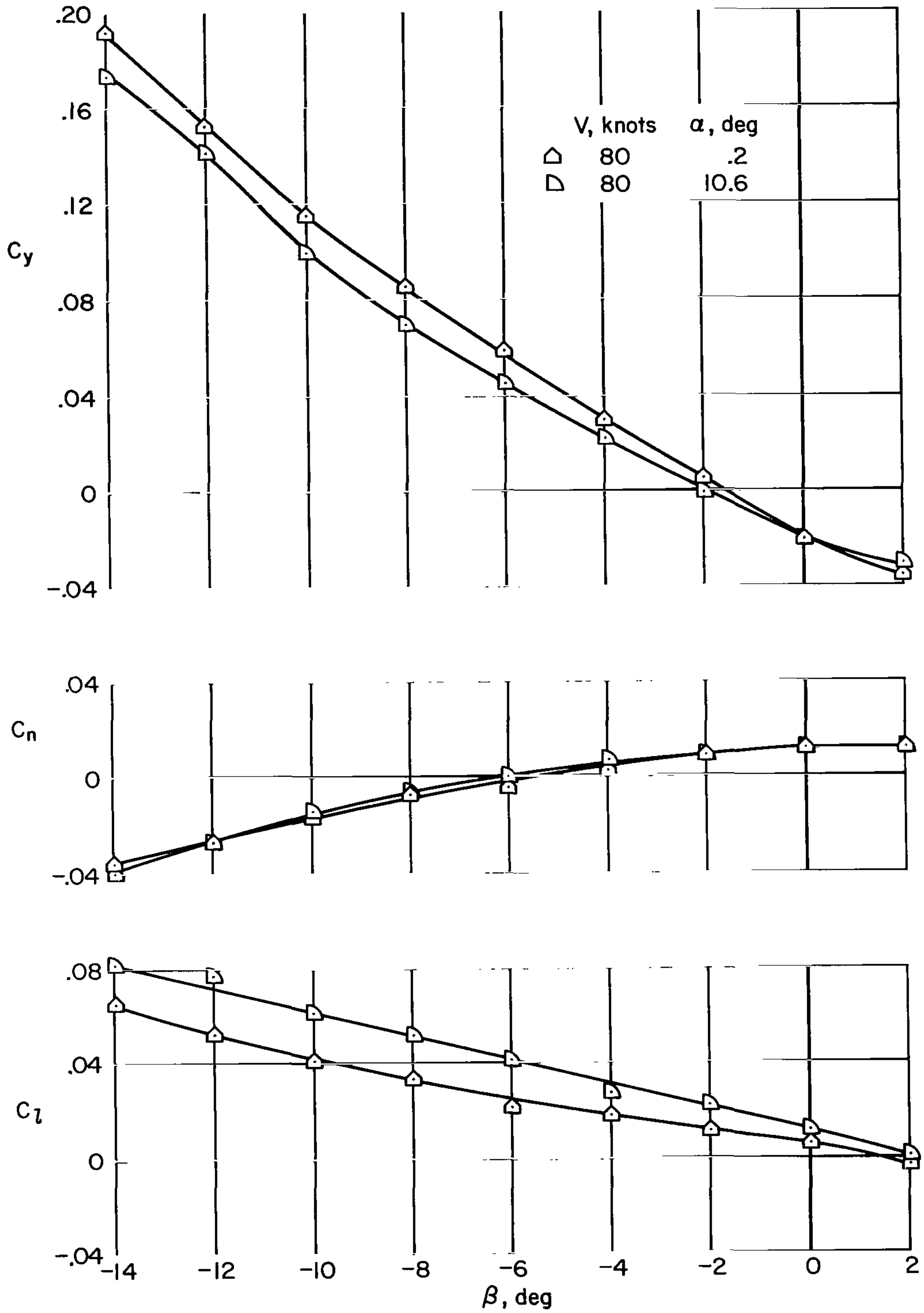
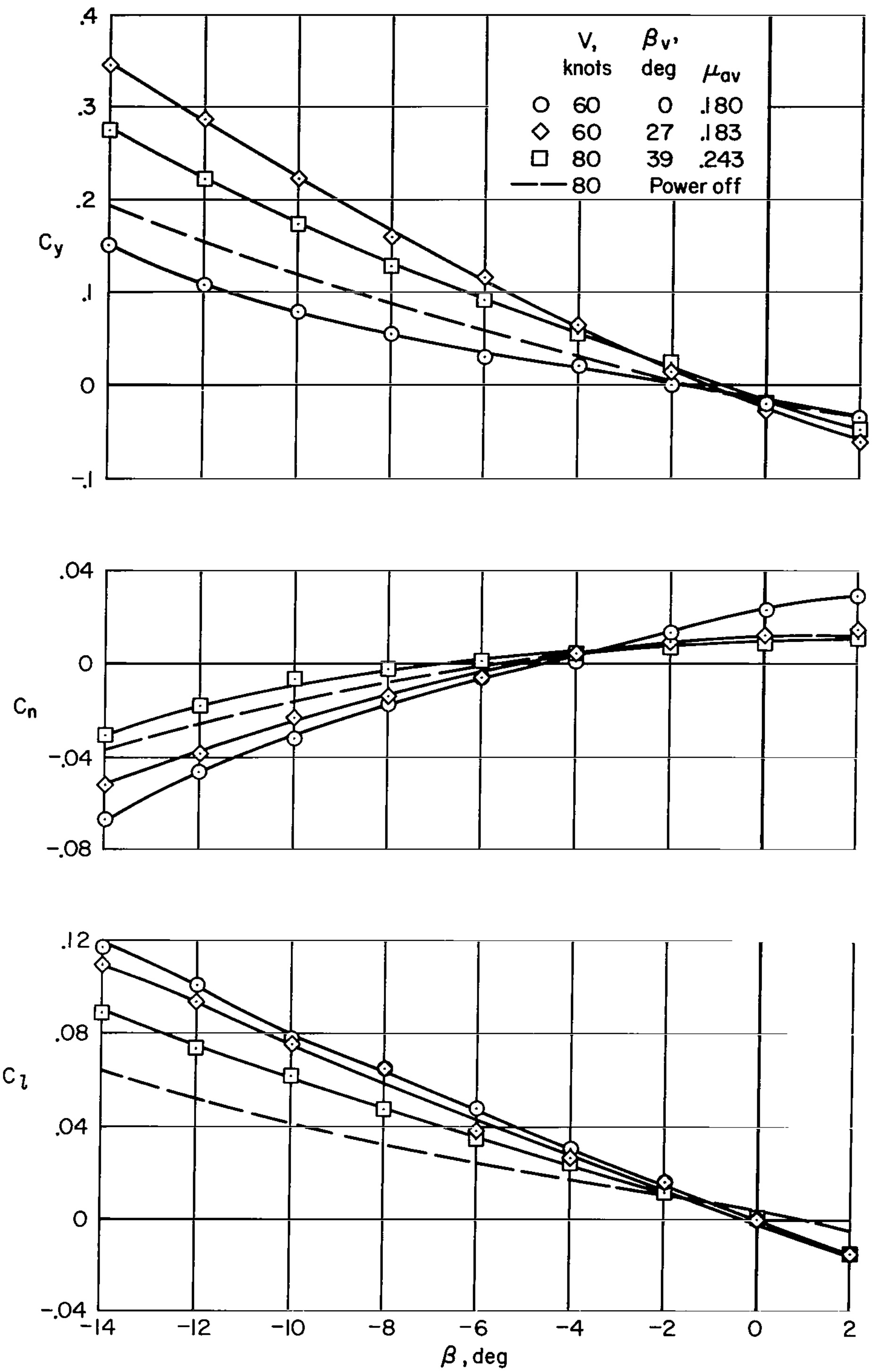
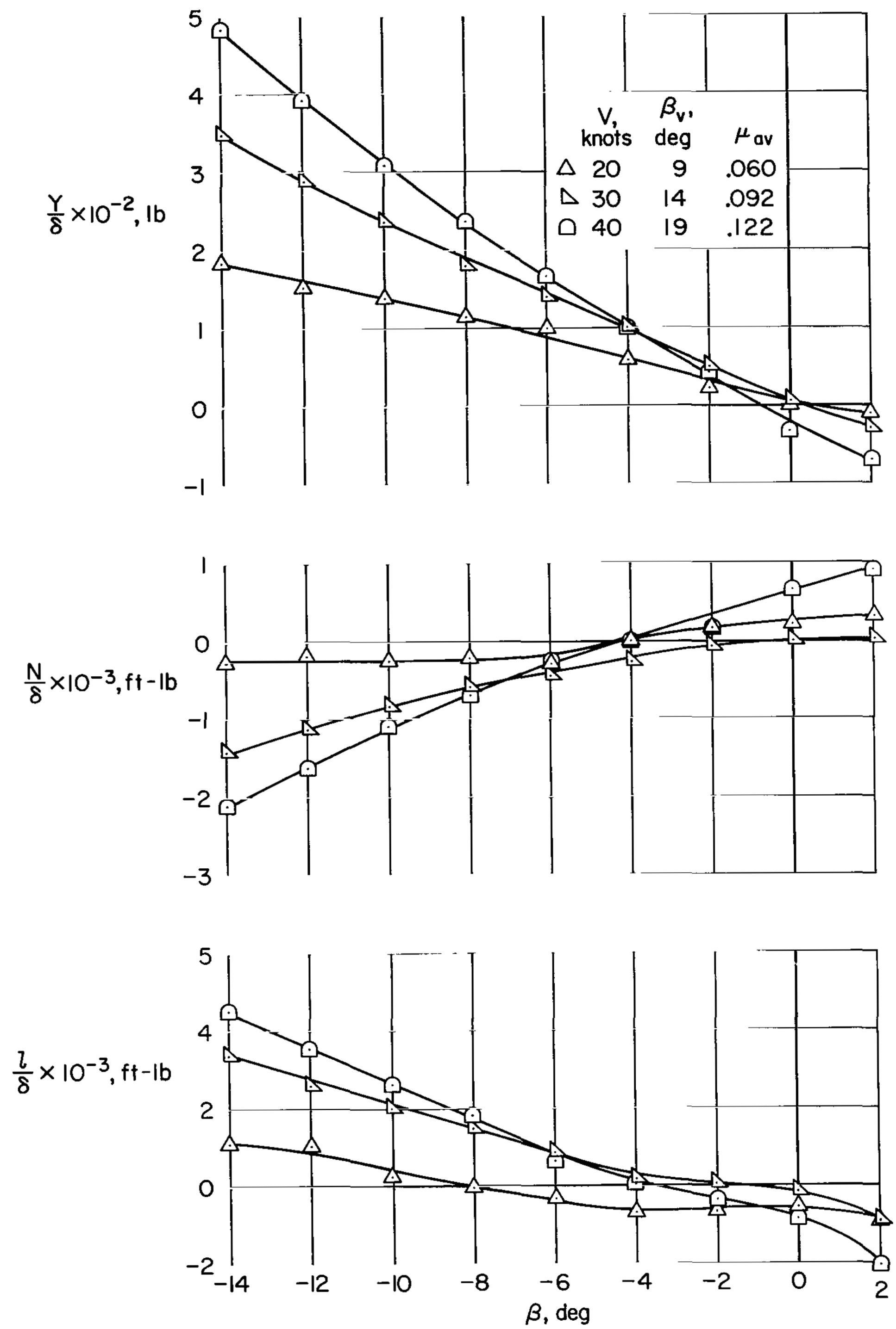


Figure 23.– Lateral-directional characteristics with power off; $\delta_f = 45°$, tail on, $i_t = 0°$, $\beta_v = 90°$, fan inlets sealed.



(a) C_y, C_n, C_l, versus sideslip.

Figure 24.— Lateral-directional characteristics with four fans, $\alpha = 0°$, tail on, $i_t = 0°$, $\delta_f = 45°$, RPM = 3300.



(b) Forces and moments versus sideslip.

Figure 24.– Concluded.

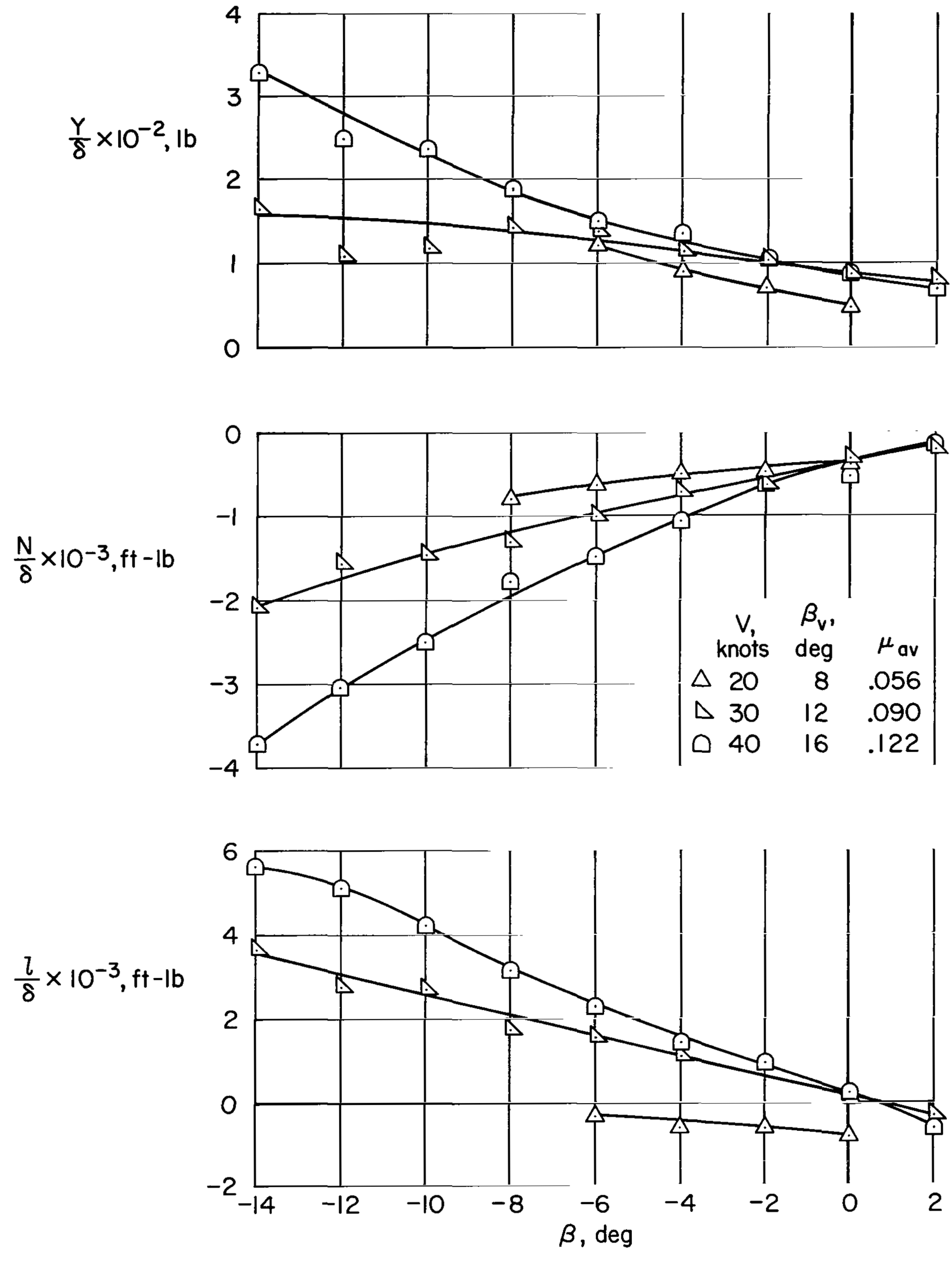
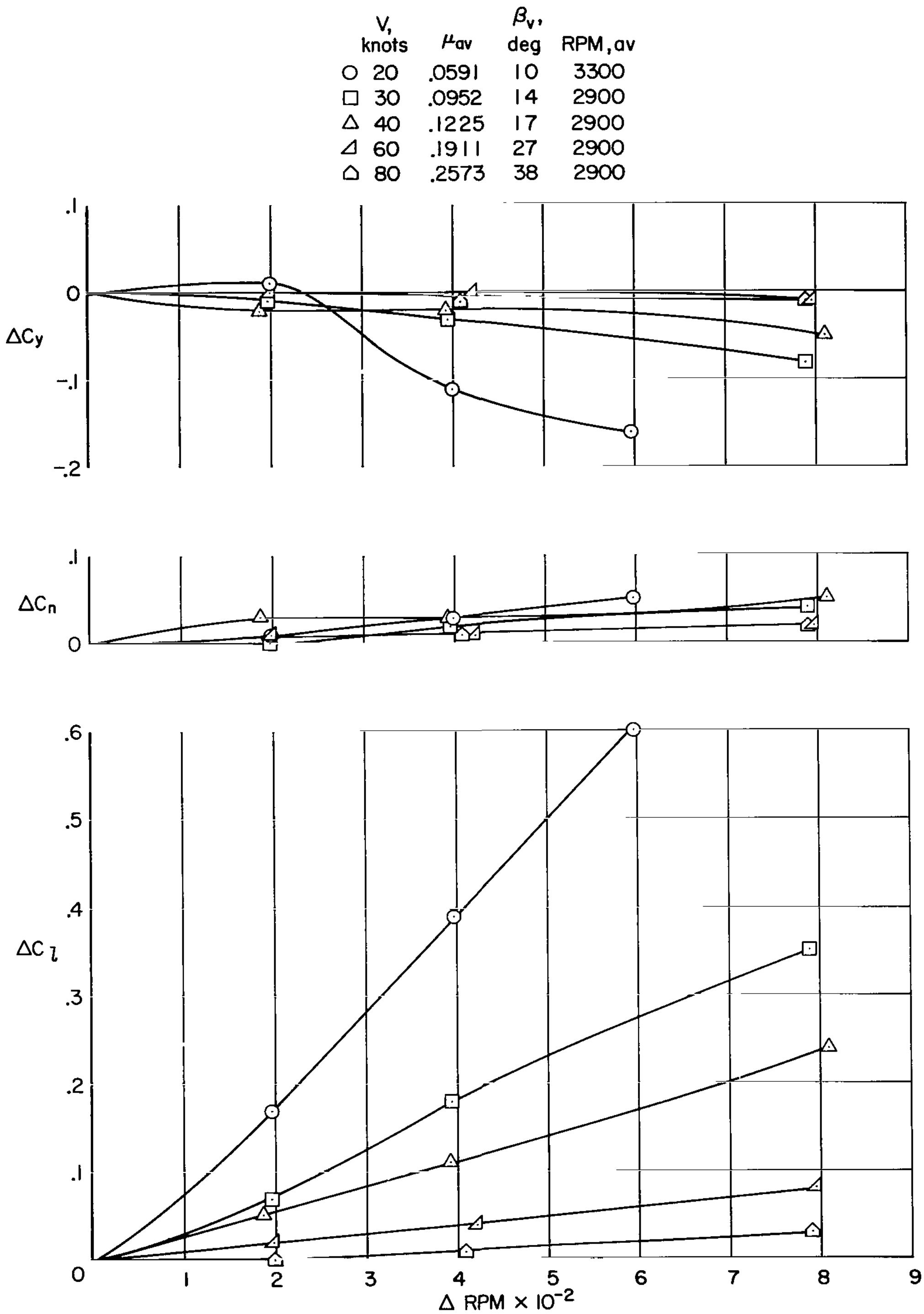
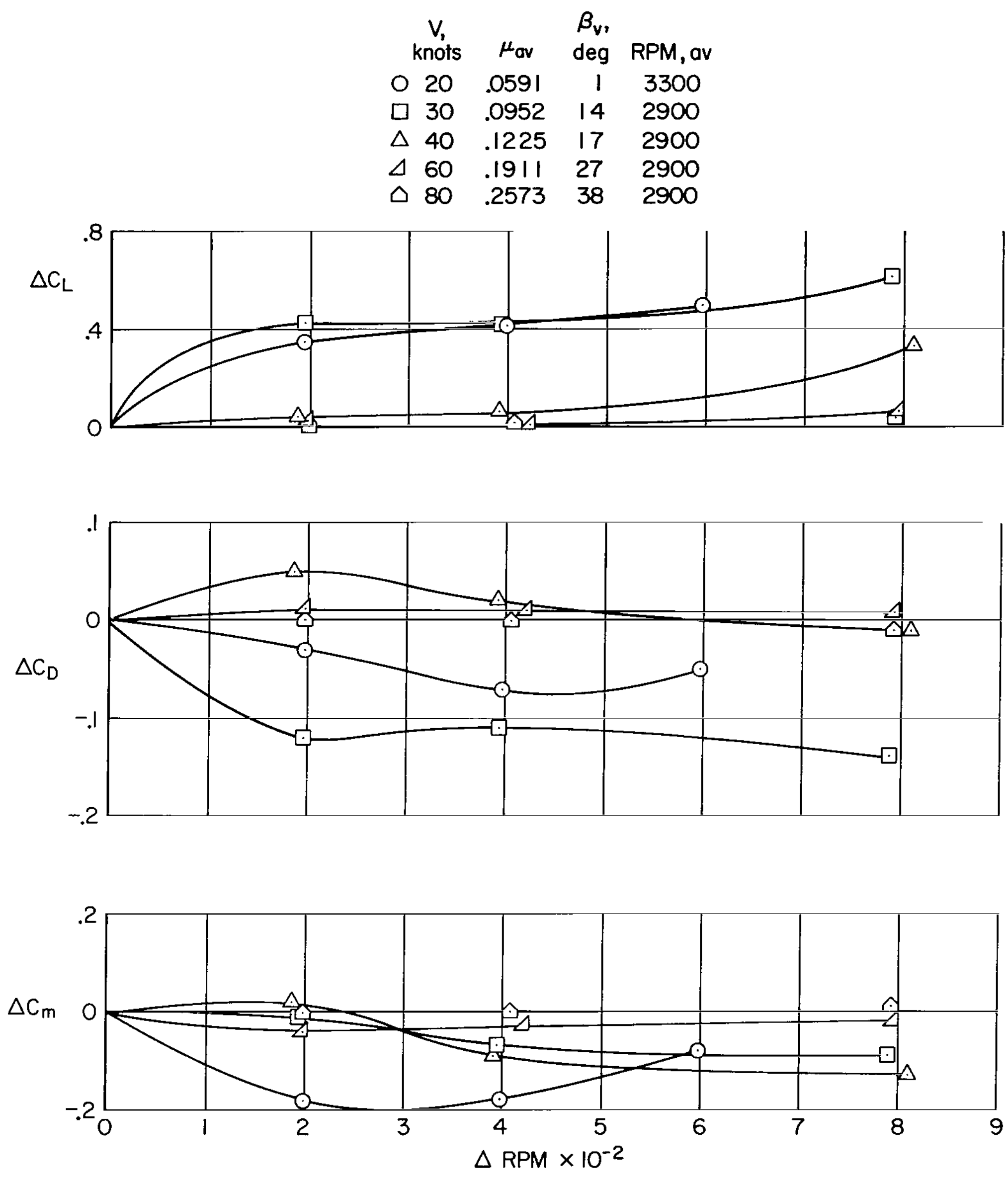


Figure 25.– Lateral-directional characteristics with sideslip, four fans; $\alpha = 10°$, $\delta_f = 45°$, tail on, $i_t = 0°$, RPM = 3300.



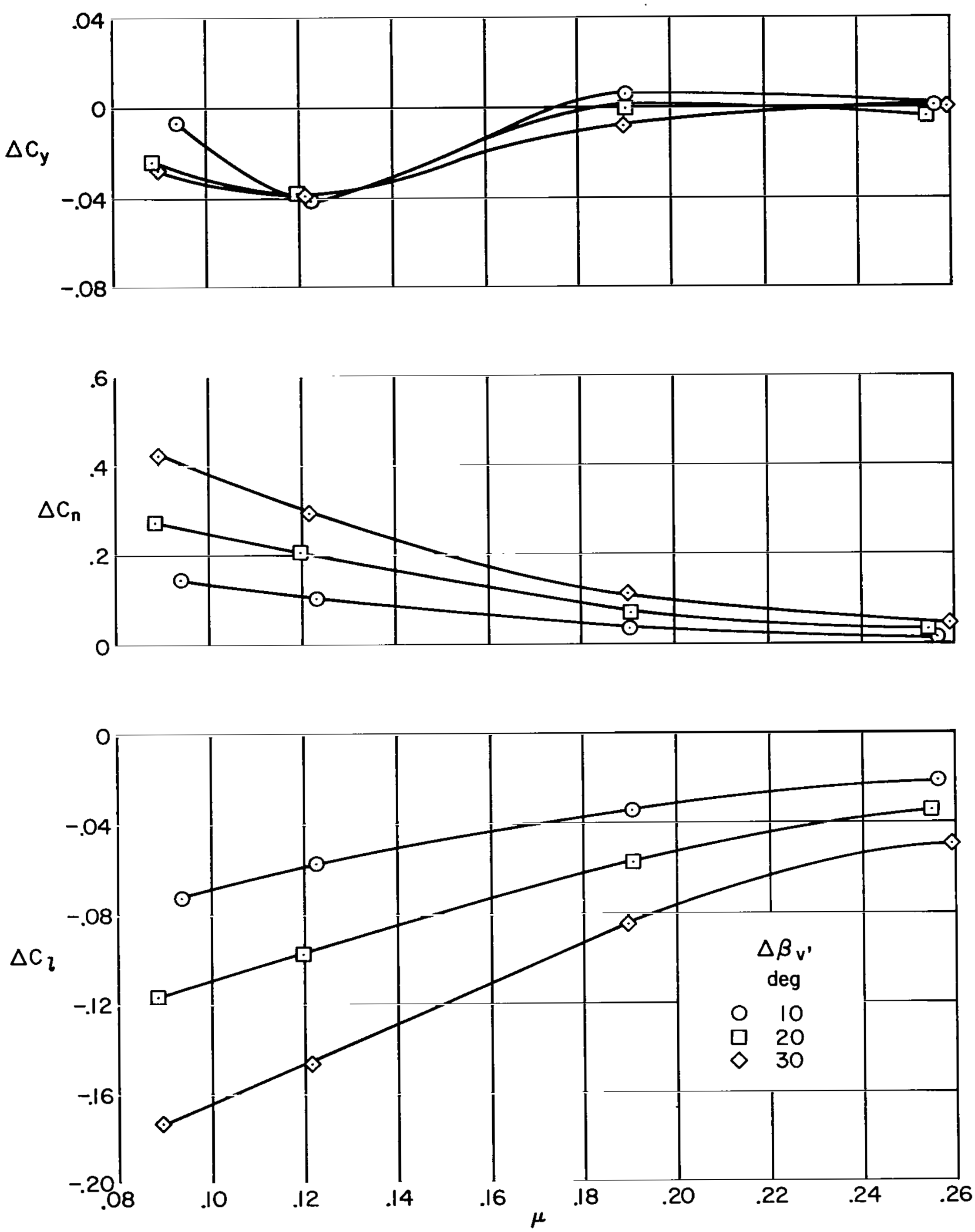
(a) Lateral characteristics.

Figure 26.– Effect of differential fan speed, right and left; four fans operating, $\delta_f = 45°$, $\alpha = 0°$, $i_t = 0°$, $C_D = 0$ at Δ RPM = 0.



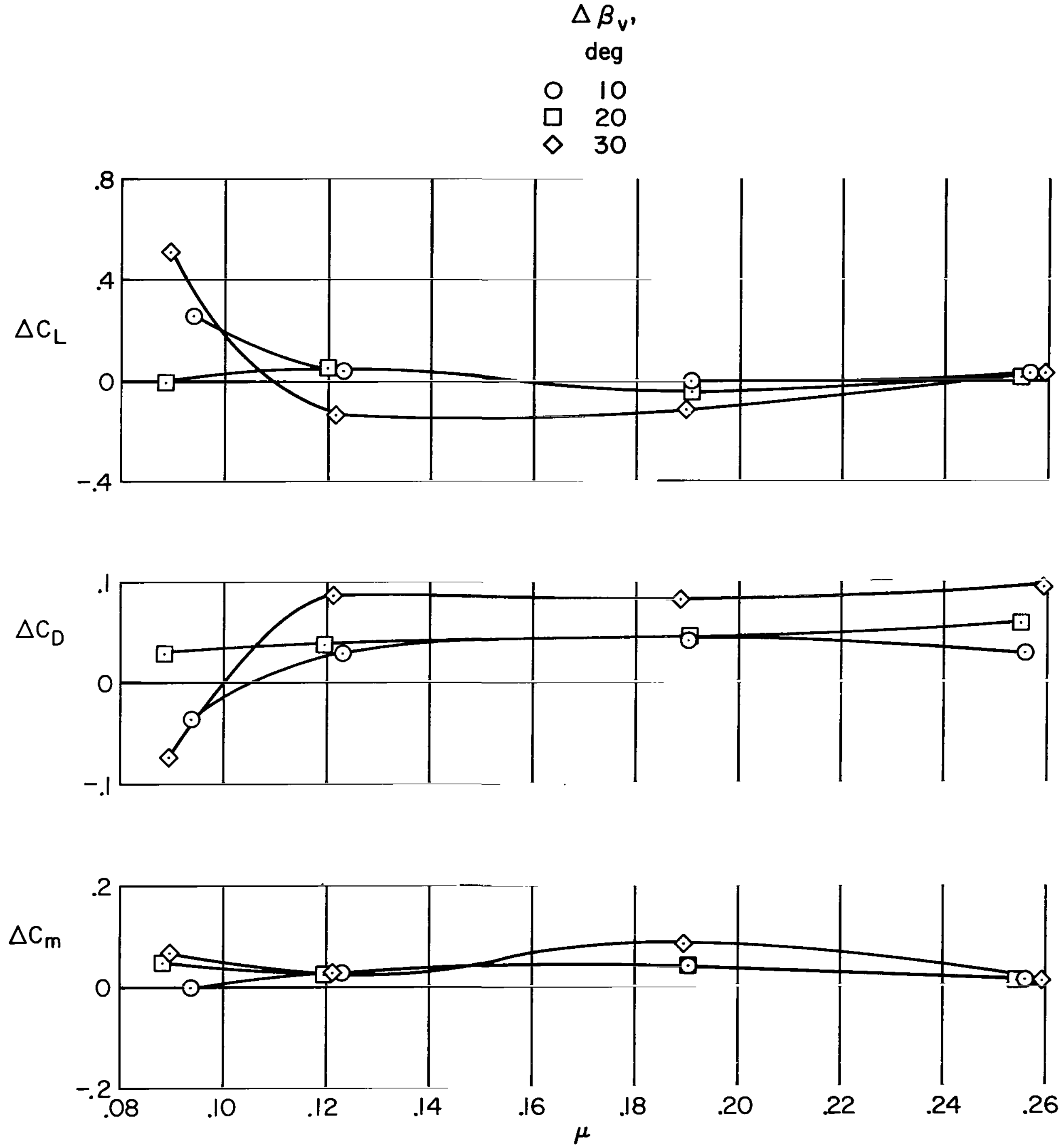
(b) Longitudinal characteristics.

Figure 26.– Concluded.



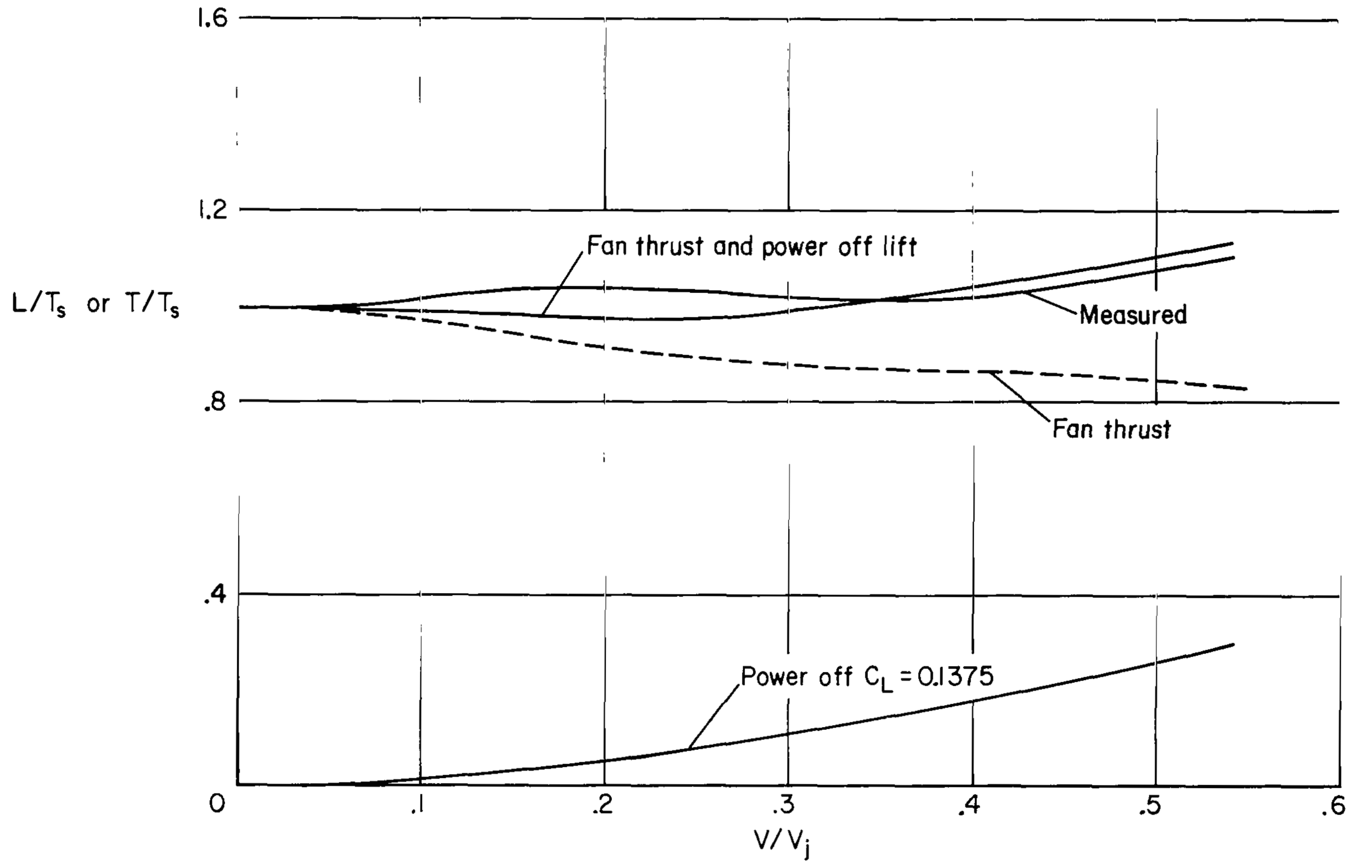
(a) Lateral characteristics.

Figure 27.– Effect of differential exit vane deflection, right and left, with four fans operating; $\delta_f = 45°$, $\alpha = 0°$, $i_t = 0°$, RPM = 2900.



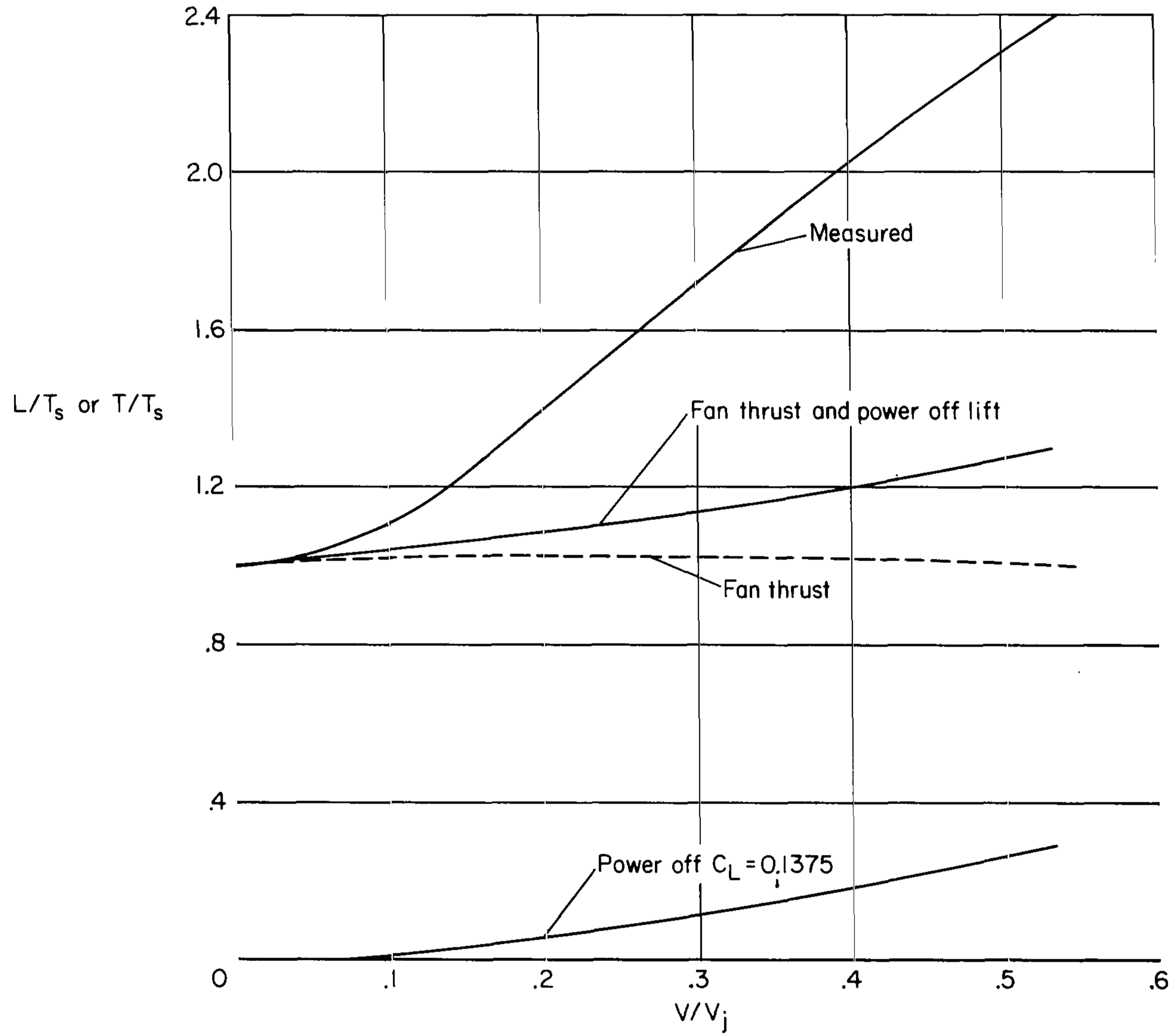
(b) Longitudinal characteristics.

Figure 27.– Concluded.



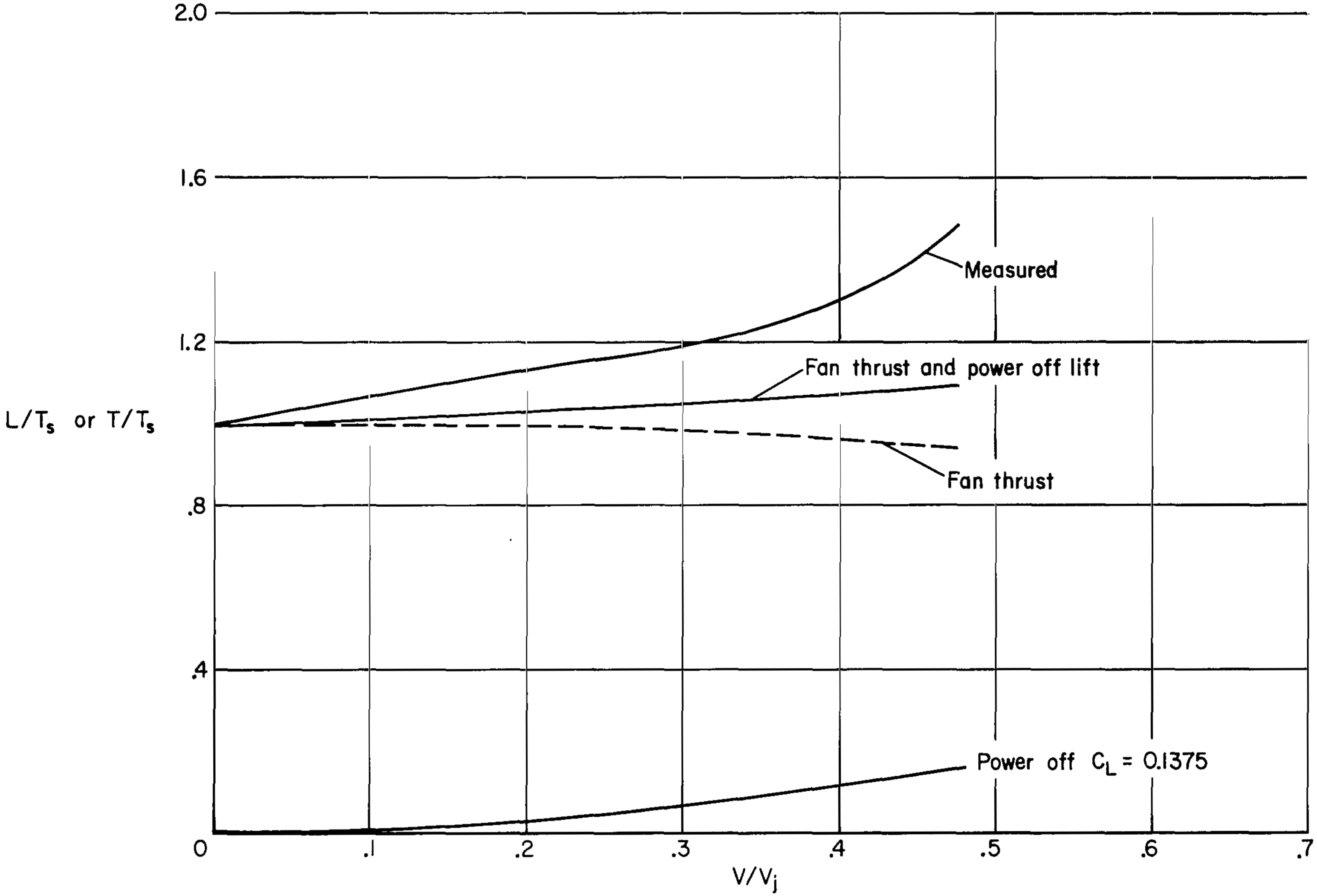
(a) Front lift fans, aft fans sealed.

Figure 28.– Effect of fan operation and forward speed on lift at constant RPM; $\alpha = 0°$, $\delta_f = 0°$, $\beta_v = 0°$, tail off.



(b) Aft lift fans, front fans sealed.

Figure 28.– Continued.



(c) Four lift fans.

Figure 28.– Concluded.

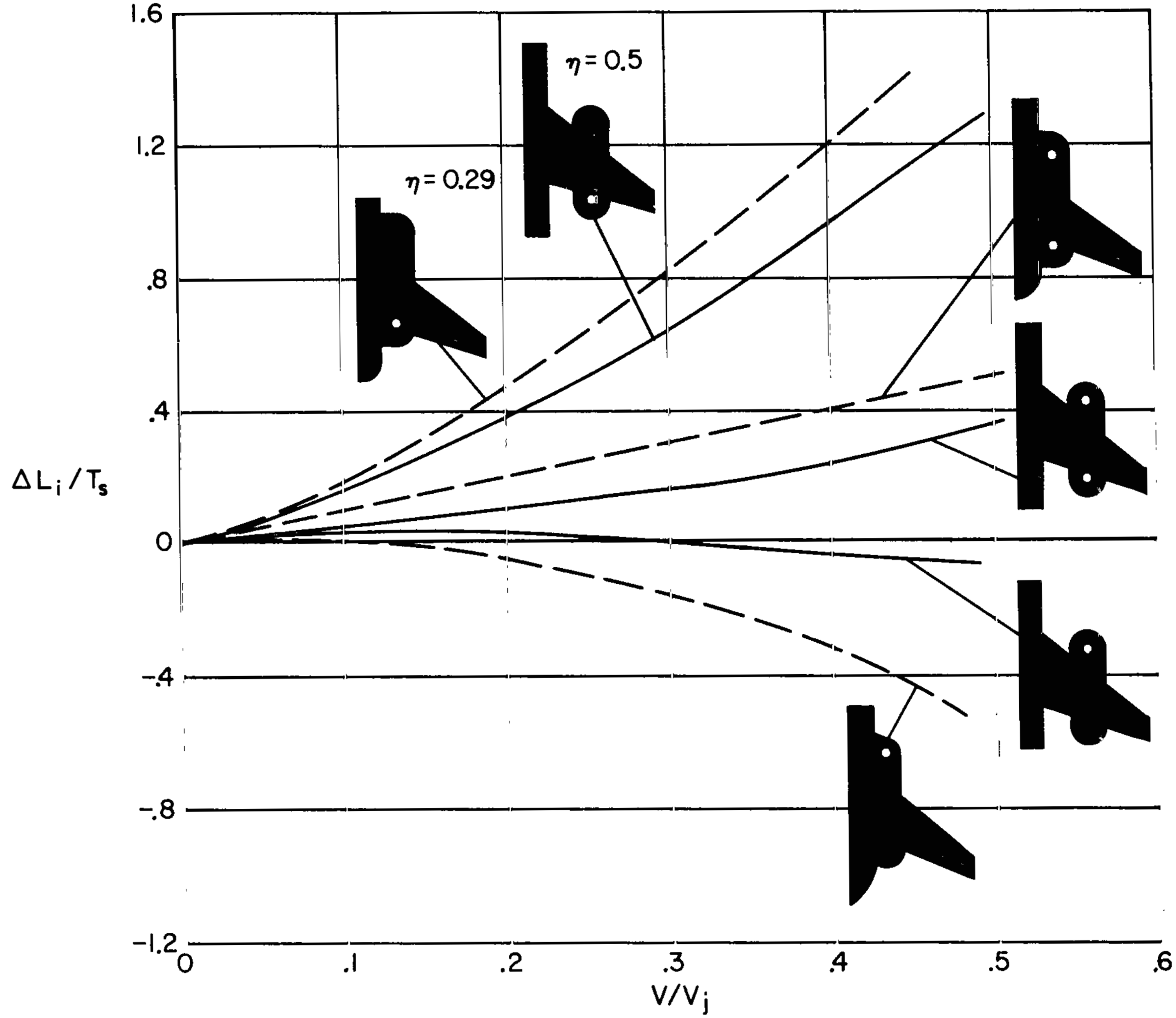


Figure 29.– Effect of fan location on induced lift; $\alpha = 0°$, $\delta_f = 0°$, $\beta_v = 0°$, tail off, constant RPM.

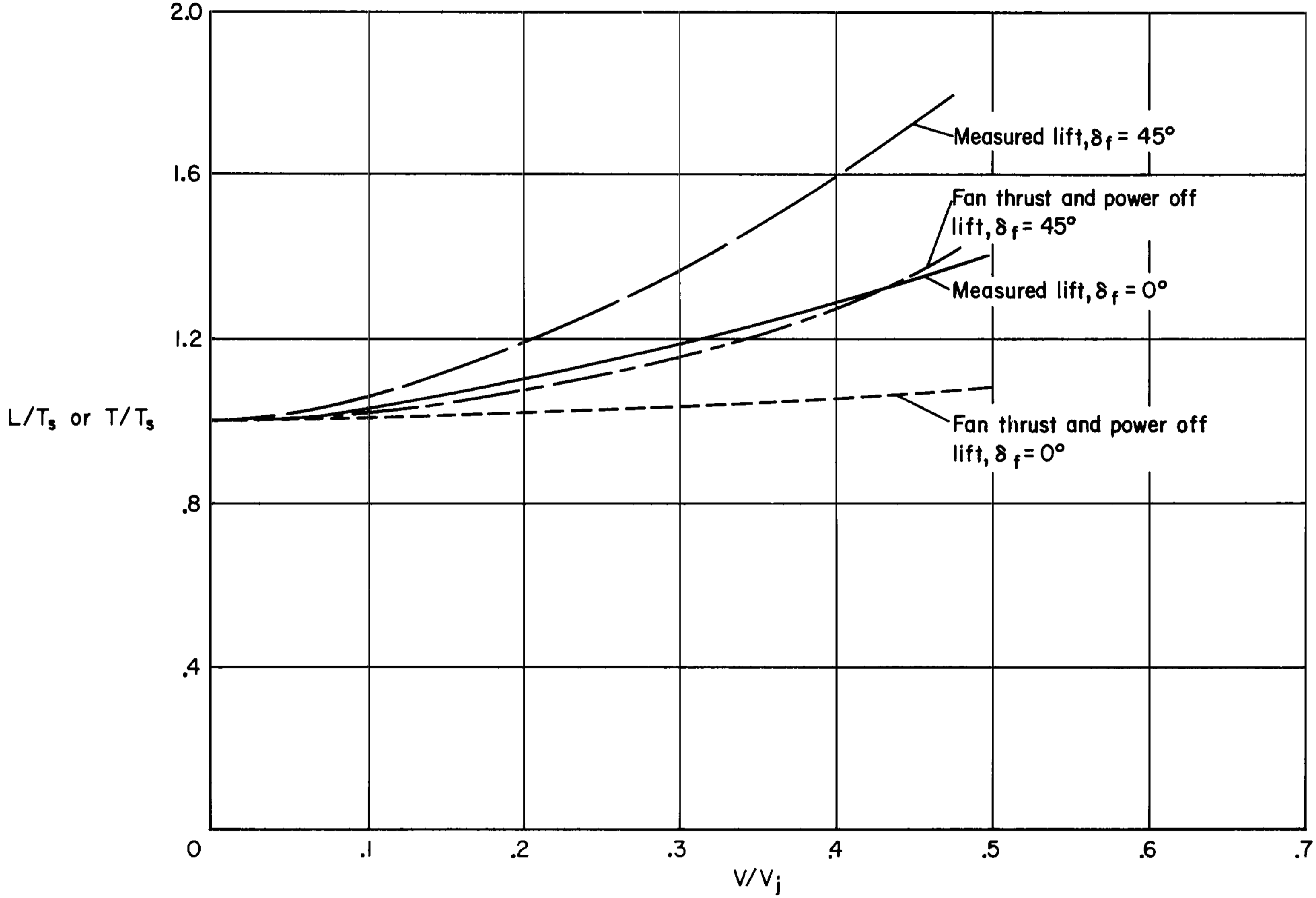


Figure 30.– Effect of fan operation and forward speed on lift with four lift fans; $\alpha = 0°$, $\beta_V = 0°$, tail on, $i_t = 0°$, constant RPM.

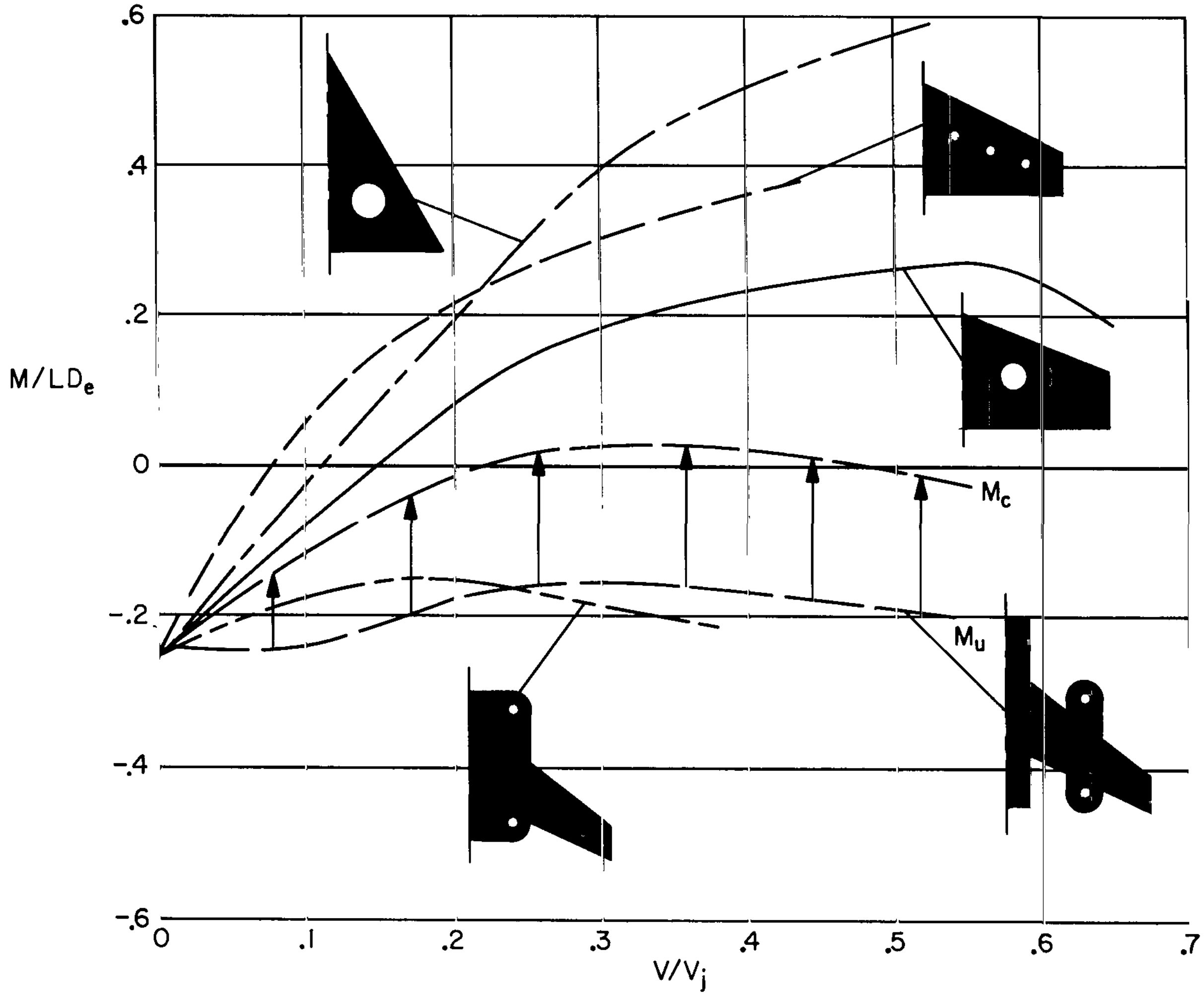


Figure 31.– The variation of pitching-moment with forward speed for various lift fan configurations; $\alpha = 0°$, $\delta_f = 0°$, $\beta_v = 0°$, constant RPM.

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