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SUMMARY

The static and propulsive performance characteristics of the ducted fan were defined for a wide range of fan advance ratios by varying the fan rotational speed from 1800 to 4800 rpm and the free-stream velocity from 0 to 140 knots. These characteristics were examined for fan blade angles from 11° to 43°.

The static efficiency (figure of merit) at blade angles from 11° to 20° was essentially constant at about 78 percent, but at higher angles it decreased rapidly. A maximum propulsive efficiency of about 58 percent was achieved at an advance ratio of 0.6 and a blade angle of 23°. For a more comprehensive means of evaluating performance over the entire velocity range, the thrust to horsepower ratio was examined as a function of free-stream velocity. The results indicated that the performance was reasonably good for free-stream velocities from 0 to 100 knots. At higher velocities, performance deteriorated rapidly because the ducted fan was designed primarily for good static performance. Evaluation of another ducted fan design indicated that if higher velocities are specifically considered in the design, good high speed performance can be achieved.

INTRODUCTION

A 4-foot-diameter ducted fan mounted on a wing tip was tested previously to obtain aerodynamic data for a wide range of operating conditions (refs. 1 to 3). Most of those tests were performed at a single blade angle; hence the effect of blade angle on propulsive performance was not determined. Data are presented here for the same model at 0° angle of attack but for several blade angles. The objectives of this report are to present the thrust and power results and to evaluate the static and propulsive performance.

NOTATION

A_e net exit area, (shroud exit area)-(centerbody area at exit), sq ft

b fan blade chord, in.

c duct chord, ft

c_{l_i} blade-section design lift coefficient, $\frac{\text{section design lift}}{qb}$

C_f flat-plate friction drag coefficient, $\frac{\text{friction drag}}{(\text{wetted area})q}$

C_P power coefficient, $\frac{550\ \text{SHP}}{\rho n^3 d^5}$

C_T thrust coefficient, $\frac{T}{\rho n^2 d^4}$

d fan diameter, ft

d_e duct exit diameter, ft

FM figure of merit, $50 \frac{d}{\sqrt{A_e}} \frac{{C_T}^{3/2}}{C_P}$, percent

h fan blade thickness, in.

J fan advance ratio, $\frac{V}{nd}$

n fan rotational speed, rps

q free-stream dynamic pressure, psf

r radial distance from duct center line, ft

R fan radius, ft

SHP input power, hp

T thrust, lb

T_c thrust coefficient, $\frac{T}{qcd_e}$

V free-stream velocity, fps

V_e computed velocity at duct exit, fps

V_∞ free-stream velocity, knots

β fan blade angle measured at tip (unless otherwise noted), deg

η propulsive efficiency, $J \frac{C_T}{C_P} 100$, percent

ρ mass density of air, slugs/cu ft

MODEL AND APPARATUS

Characteristics

The ducted fan and the semispan wing panel upon which the fan was mounted were the same as those of reference 1. The general arrangement for testing in the wind tunnel is shown in figure 1, and the dimensions of the fan and the wing are presented in figure 2 and tables I and II. It should be noted that the shroud and stators were designed primarily for good static performance rather than optimum cruise performance. The fan blade form curves are shown in figure 3.

Instrumentation

Forces and moments on the ducted fan were measured independently of those on the wing and support structure by strain gages which were mounted on the duct-trunnion support tube.

The power to the motor for driving the fan was recorded on a polyphase wattmeter and the meter readings were corrected for motor efficiency. No corrections were made for gear box losses because they were estimated to be much less than the indicated input power accuracy.

TESTS

For the tests the fan blade angle was set and the fan advance ratio was varied from 0 to 1.8 by combining fan rotational speeds ranging from 1800 to 4800 rpm with free-stream velocities from 0 to 140 knots.

REDUCTION OF DATA

Duct-Trunnion Strain Gage Data

The thrust gages were directly calibrated in pounds of force and required no corrections.

Accuracy of Measuring Devices

The various measuring devices were accurate within the following limits. The values include errors involved in reading and reducing the data as well as the accuracy of the device itself.

Thrust	±10 lb
Fan rotational speed	±0.5 rps
Shaft horsepower	±20 hp
Free-stream dynamic pressure	±0.1 psf for values $\leq$ 20 psf ±1/2 percent for values $\geq$ 20 psf
Fan blade angle	±0.5°

RESULTS AND DISCUSSION

Basic Thrust and Power Characteristics

These characteristics are shown in figures 4 and 5 for fan blade angles from 11° to 43°. The $\beta = 15^\circ$ and 23° performance results of reference 1 have been added to the $\beta = 15^\circ$ and 23° results of the subject tests. The scatter evident in figure 4 is due to the results obtained at lower rotational speeds where the measurement error of the thrust and power is a greater percentage of the value measured. For the range of rotational speeds and free-stream velocities tested, these coefficients were found to be only a function of fan advance ratio and blade angle. It is apparent from the results presented in figure 4(a) that the variations in thrust coefficient are regular for blade angles from 11° through 35°, but at 43° the blades stalled at zero advance ratio and remained stalled until the advance ratio exceeded about 1.0. So that the results of this report can be used conveniently with those of reference 1 in predicting flight performance of tilting ducted fan vehicles, the thrust coefficient curves of figure 4(a) are presented in figure 5 referenced to free-stream dynamic pressure and duct projected area (chord times exit diameter).[1]

Efficiency

The static efficiency and propulsive efficiency computed from the faired curves of figure 4 are presented in figure 6. The static efficiency is shown in figure 6(a) by presenting the figure of merit (based on net exit area) as a function of blade angle. It is apparent from these results that the figure of merit is nearly constant at about 78 percent for blade angles from 11° to 20°. As blade angle is increased beyond 20° the figure of merit decreases. The

[1]The thrust coefficient in figure 5 is equal to $-C_{D_d}$ at zero angle of attack in reference 1.

propulsive efficiency, which is indicative of the high speed performance, is presented in figure 6(b). It is apparent from this figure that the propulsive efficiency has a maximum value of 58 percent at an advance ratio of 0.6 and a blade angle of 23°. However, the efficiency curves have a reasonably flat envelope so that over 55-percent efficiency is available for a range of advance ratios from about 0.4 to 1.1.

Evaluation of the Performance

Comparison with theory.- From the results of figure 4, the T/SHP was determined as a function of free-stream velocity for an input power which was held constant at the design value for zero free-stream velocity (420 hp). The blade angle and rotational speed were adjusted as free-stream velocity was increased to give the best thrust. The results are presented in figure 7. Along with these results the theoretical performance is presented for comparison. This performance was computed by means of "simple momentum ducted fan theory" and with the assumption that 90 percent of the input power was delivered to the air stream for producing thrust. In addition, a simple flat-plate drag coefficient was used for estimating the reduction in T/SHP due to shroud friction drag, and the estimate was subtracted from the computed results. The resulting curve is considered to be representative of the performance possible with a very good ducted fan design with the same power loading and shroud dimensions. It is apparent from figure 7 that the T/SHP of the present ducted fan was good for velocities from 0 to about 100 knots, but at greater velocities it deteriorated very rapidly from the theoretical value.

If an estimated zero-power fan drag is subtracted from the zero-power drag which can be obtained from figure 4, the drag of the shroud, centerbody, vanes, etc., can be estimated. This estimate shows that the reduction in performance is largely due to this drag. Also, if this drag is added to the experimental T/SHP curve, the result would indicate that the fan efficiency is relatively constant over a large range of free-stream velocities (about 100 to 300 or 400 knots) as is usually the case for propellers and ducted propellers.

Since this fan was designed for static performance rather than cruise performance, its shroud has a relatively high thickness ratio and a large diffusion ratio, and its stator vanes are set for optimum static performance. To determine the extent to which T/SHP might be increased if the drag were reduced and to determine whether the theoretical curve is reasonable, the next section presents a comparison with the ducted fan of reference 4. This ducted fan had two shroud configurations: one designed expressly for good high speed performance and the other for good static performance.

Comparison with the ducted fan of reference 4.- The T/SHP ratio for the ducted fan of reference 4 for the same exit area power loading (SHP/A_e = 28.2 hp/ft^2) and best thrust producing conditions is presented in figure 7. It is apparent that with the shroud designed for cruise, performance at free-stream velocities greater than 100 knots did not decrease from the theoretical value as did that of the ducted fan reported herein. In fact, the performance is very close to the computed curve for this velocity range.[2] Hence the reduction in performance of the ducted fan of reference 4 due to shroud drag is relatively small and indicates that high speed performance comparable to that computed theoretically can be obtained.

For free-stream velocities less than 100 knots the performance of the cruise shroud of reference 4 is poor because the flow separates at the inlet lip. The static performance of the shroud configuration which had a large bell mouth is very good; however, it is only slightly better than that of the ducted fan of this report. Hence it can be concluded that the shroud design of this ducted fan was very good for static performance.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif., Sept. 14, 1965

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1. Mort, Kenneth W.; and Yaggy, Paul F.: Aerodynamic Characteristics of a 4-Foot-Diameter Ducted Fan Mounted on the Tip of a Semispan Wing. NASA TN D-1301, 1962.

2. Yaggy, Paul F.; and Mort, Kenneth W.: A Wind-Tunnel Investigation of a 4-Foot-Diameter Ducted Fan Mounted on the Tip of a Semispan Wing. NASA TN D-776, 1961.

3. Yaggy, Paul F.; and Goodson, Kenneth W.: Aerodynamics of a Tilting Ducted Fan Configuration. NASA TN D-785, 1961.

4. Grose, Ronald M.: Wind-Tunnel Tests of Shrouded Propellers at Mach Numbers From 0 to 0.60. WADC TR 58-604, United Aircraft Corp., 1958.

[2]The computed shroud drag increment for the shroud of reference 4 would be about 3/4 of that of the subject ducted fan shroud.

TABLE I.- BASIC DIMENSIONS OF DUCTED FAN AND WING

Duct	
Inside diameter	4 ft
Outside diameter	4 ft 10.5 in.
Chord	2 ft 9 in.
Exit diameter	4 ft 6.3 in.
Diffuser angle	11°
Exit area	14.9 ft^2
Inlet guide vanes	
Chord	3 in.
Number of vanes	7
Airfoil section	NACA 65A010
Position of vane c/4, percent of duct chord	14.5 percent
Twist	0°
Fan	
Plan-form curves	see fig. 3
Number of blades	8
Hub to tip diameter ratio	0.333
Position of hub center line, percent of duct chord	29.3 percent
Design static thrust disc loading	150 psf
Blade angle control	fixed pitch
Blade angle at tip	15°
Approximate blade tip clearance	0.030 in.
Stators	
Position of stator c/4, percent of duct chord	49.4 percent
Twist, centerbody to tip	15°
8 stators with 6-inch chord	
Airfoil	NACA 0008.4
Mean line	a = 0.4
Additional 9-inch chord stator which housed fan drive shaft	
Airfoil	NACA 0017
Mean line	a = 0.4
Wing	
Airfoil section	NACA 2418
Area	48 ft^2
Semispan	8 ft
Mean aerodynamic chord	6.09 ft
Taper ratio	0.675

TABLE II.- SHROUD AND CENTERBODY COORDINATES

Shroud coordinates tabulated in percent of shroud chord (33.00 in.)			Centerbody coordinates tabulated in percent of centerbody length (71.5 in.)	
Chordwise length	Outside radius	Inside radius	Length	Radius
0	81.5	81.5	0	0
.5	83.4	79.6	.5	2.07
.75	83.8	79.0	1.25	3.20
1.25	84.4	78.4	2.50	4.46
2.5	85.4	77.2	5.0	6.17
5.0	86.4	75.8	7.5	7.40
7.5	87.1	74.9	10	8.31
10.0	87.6	74.2	15	9.68
15.0	88.2	73.3	20	10.54
20.0	88.6	72.9	25	11.01
25.0	88.6	72.7	25.875[a]	11.06
30.0	88.6	72.7	30	11.19
35.0	88.6	72.7	32.57[b]	11.19
40.0	88.6	72.7	40	11.19
45.0	88.6	72.7	50	11.19
50.0	88.6	72.7	60	11.19
55.0	88.6	73.2	70	10.49
60.0	88.6	74.1	72.05[c]	10.14
65.0	88.0	75.1	80	7.97
70.0	87.4	76.1	83.20	6.77
75.0	86.8	77.1	90	4.03
80.0	85.9	78.1	95	2.01
85.0	85.2	79.1	100	0
90.0	84.3	80.1		
95.0	83.3	81.1		
100	82.2	82.0		

[a]Shroud leading-edge position.

[b]Inlet guide vane c/4 line position.

[c]Shroud trailing-edge position.

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Figure 1.- Ducted fan model mounted in the Ames 40- by 80-Foot Wind Tunnel.

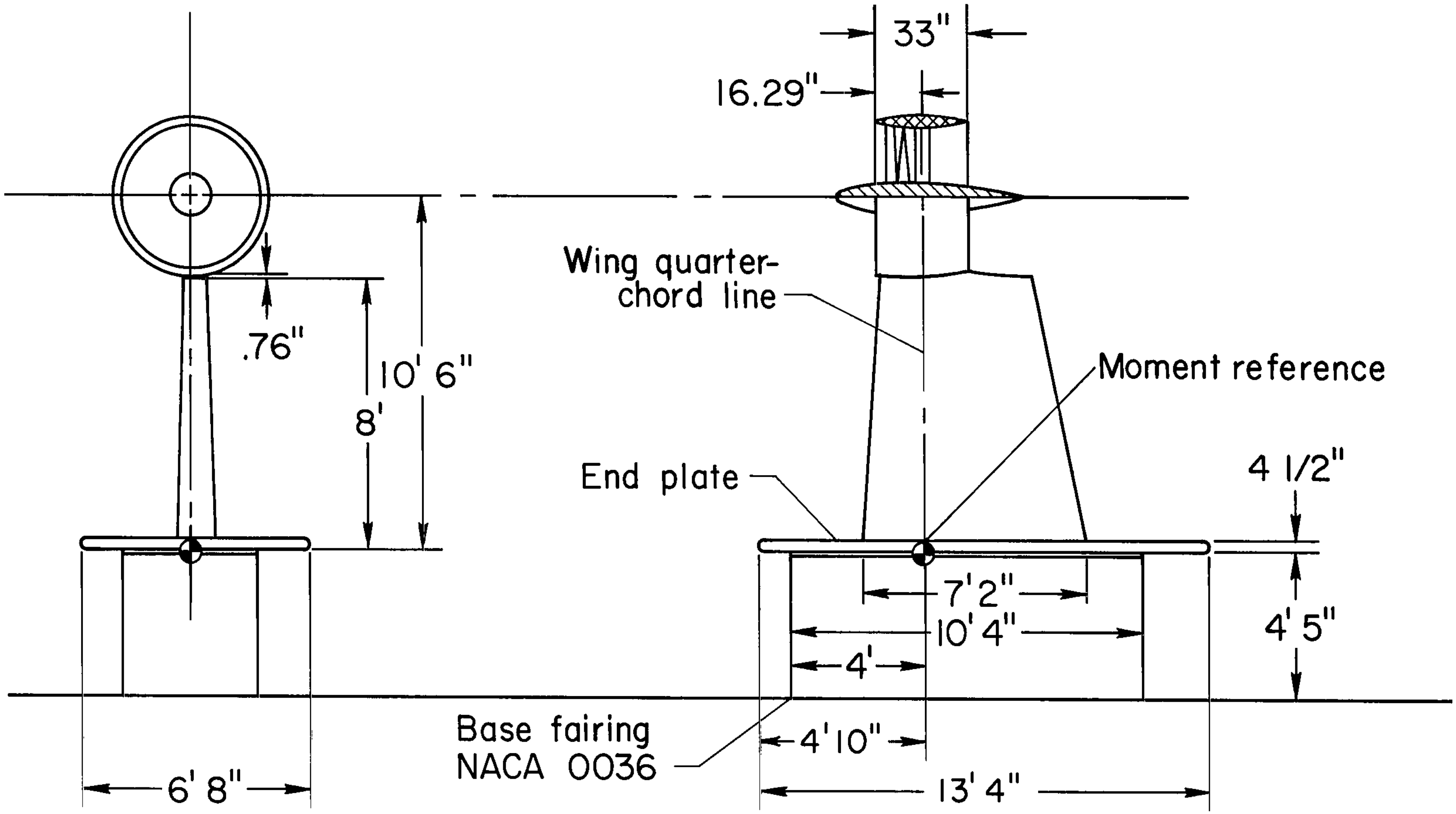


Figure 2.- Basic model dimensions.

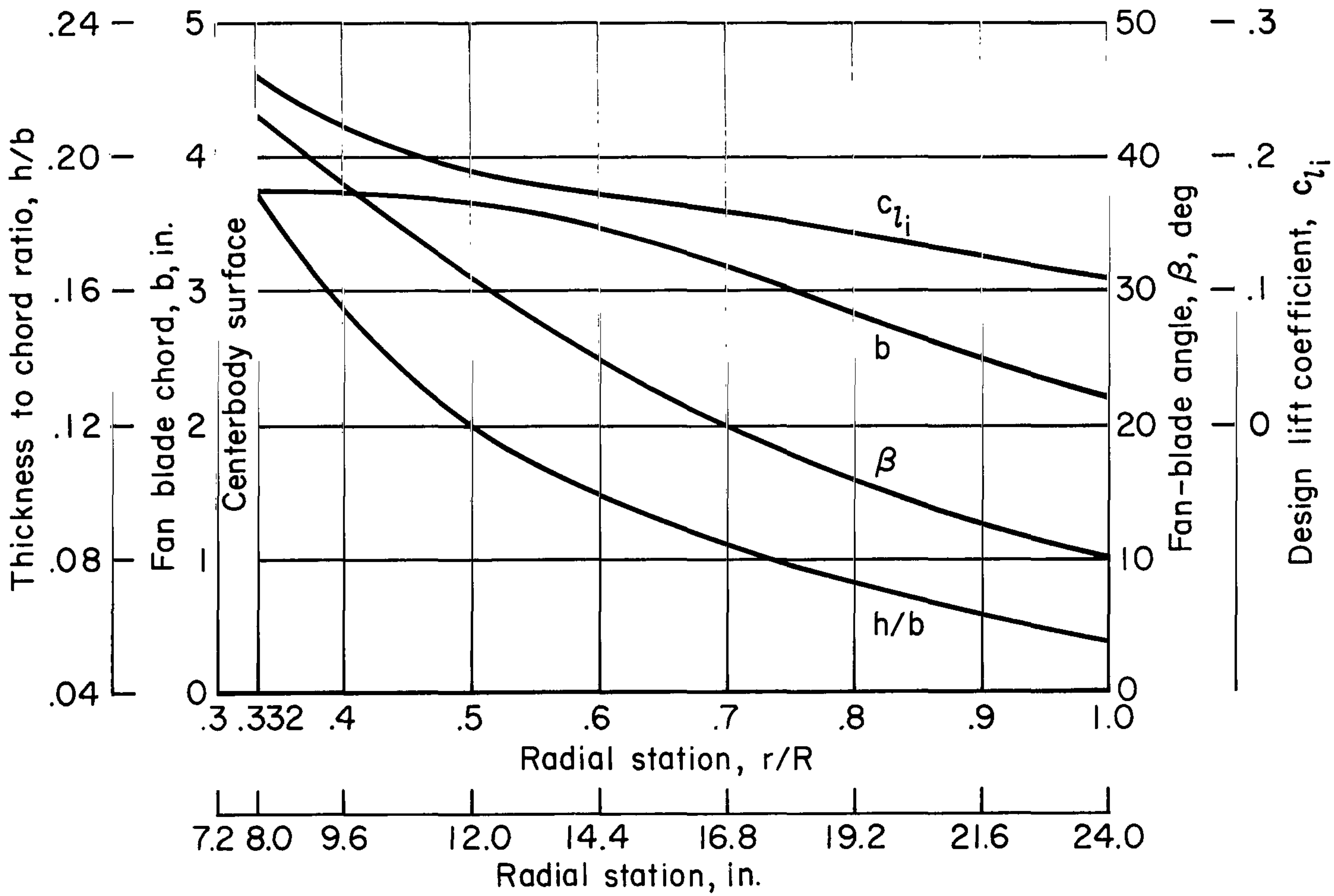
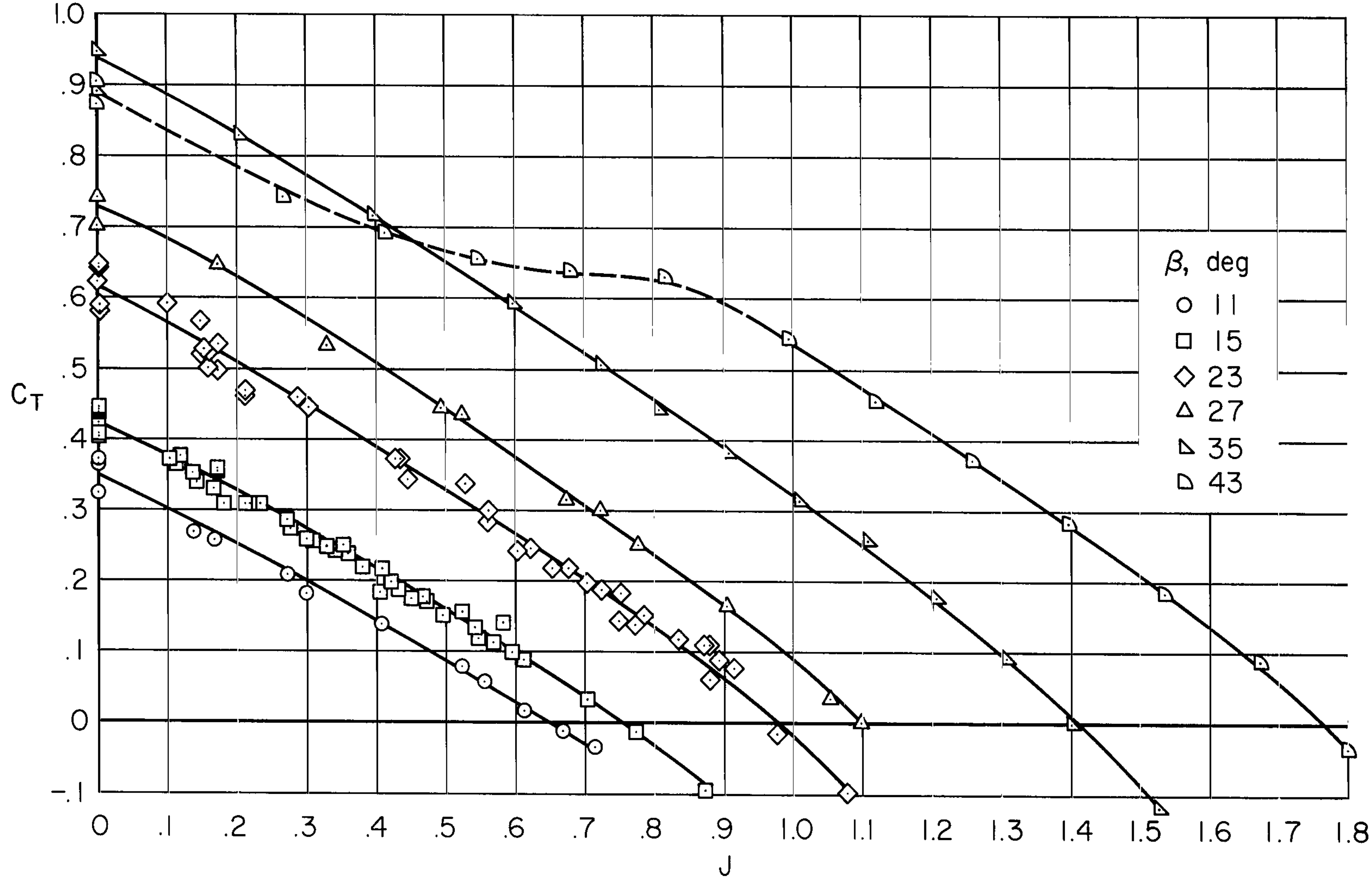
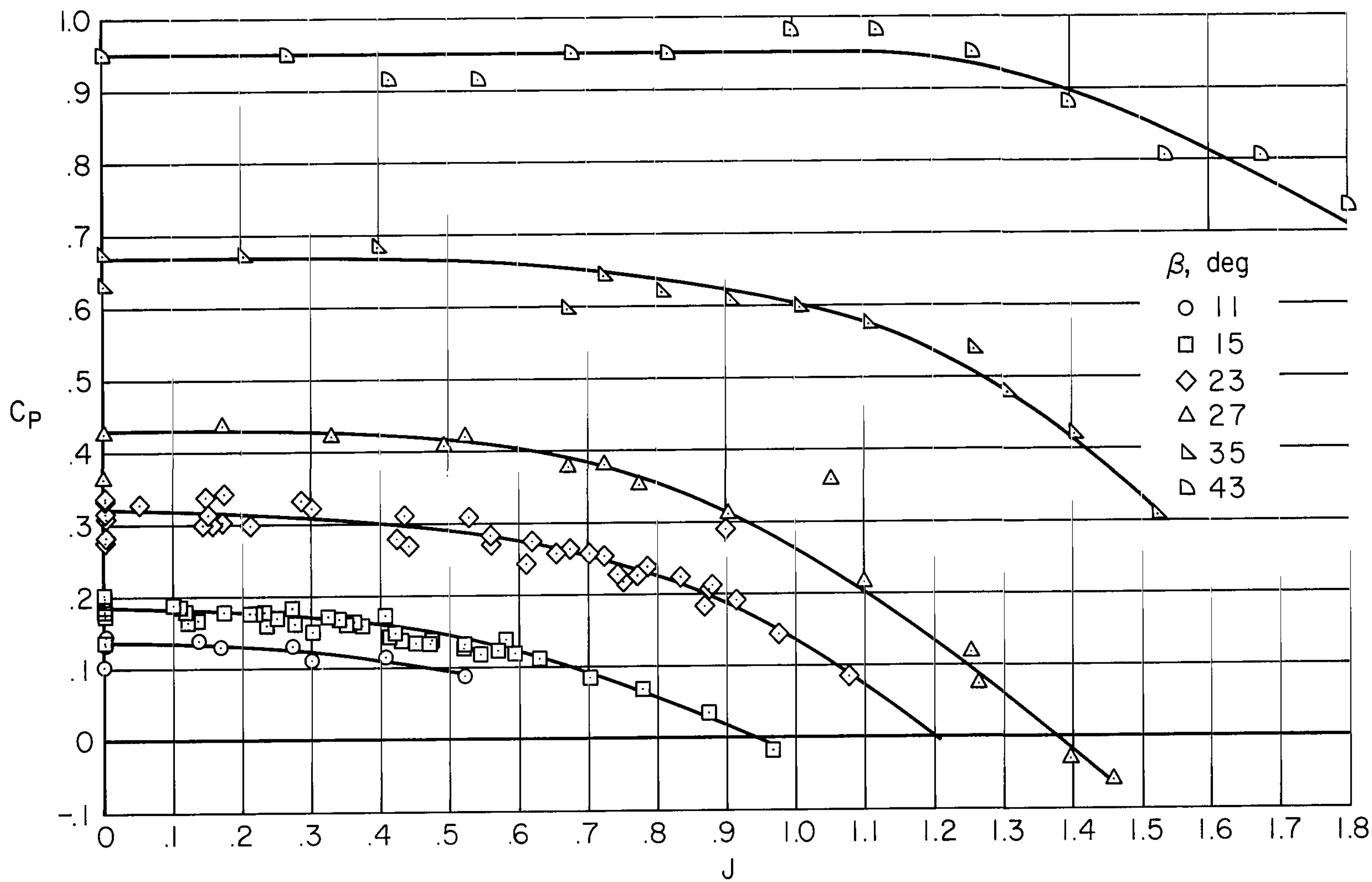


Figure 3.- Fan blade-form curves with the design lift coefficient, blade chord, blade angle, and blade thickness to chord ratio as functions of the radial distance from the duct center.



(a) Thrust coefficient as a function of advance ratio.

Figure 4.- Performance characteristics for several blade angles.



(b) Power coefficient as a function of advance ratio.

Figure 4.- Concluded.

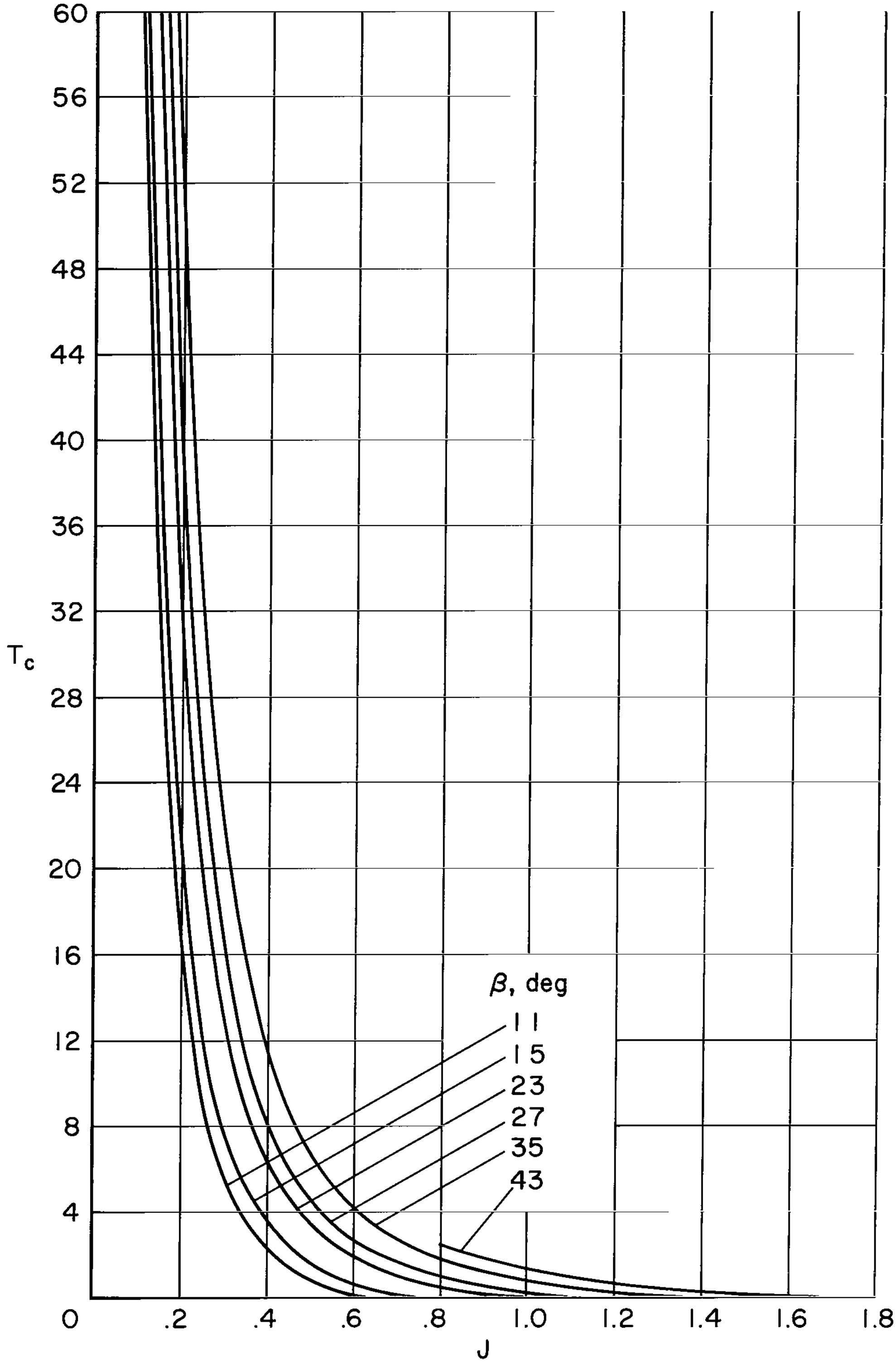
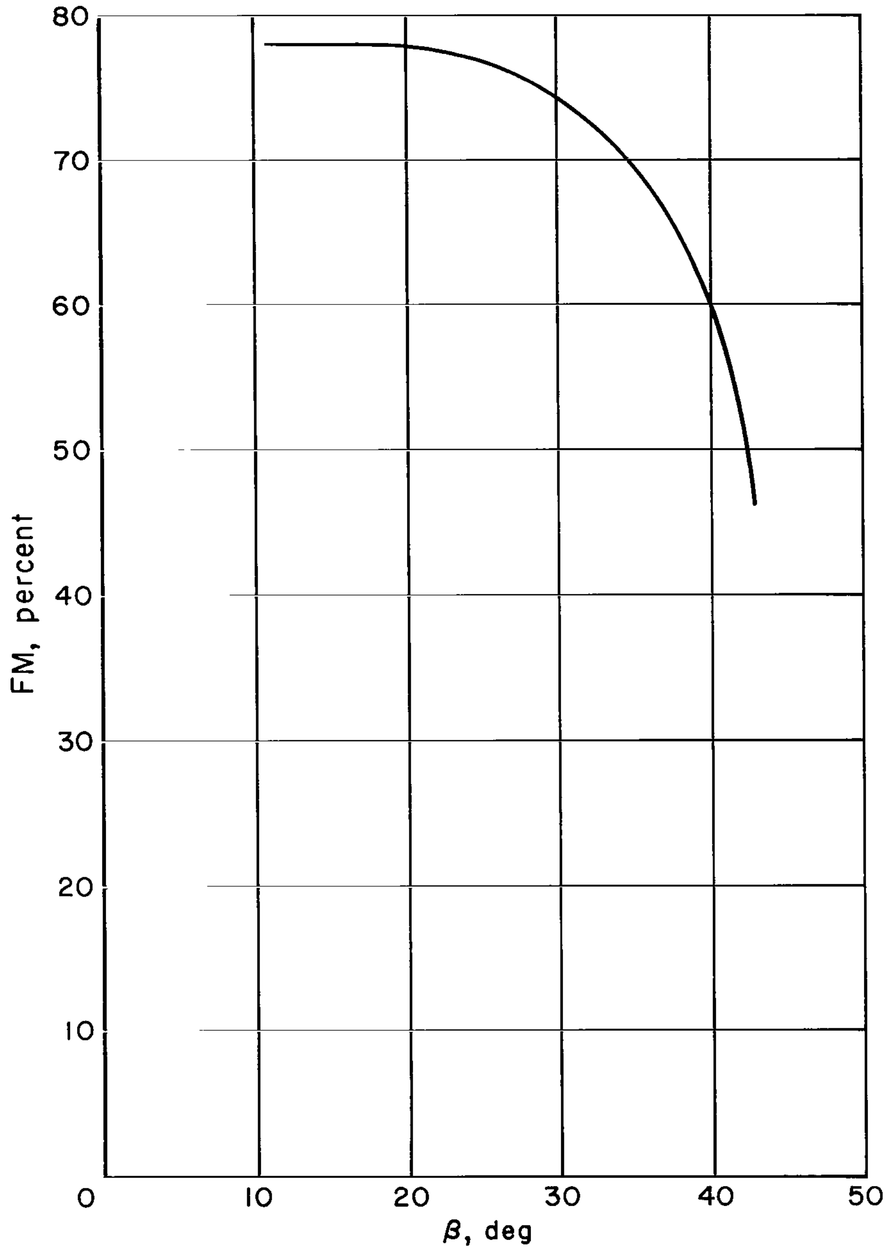
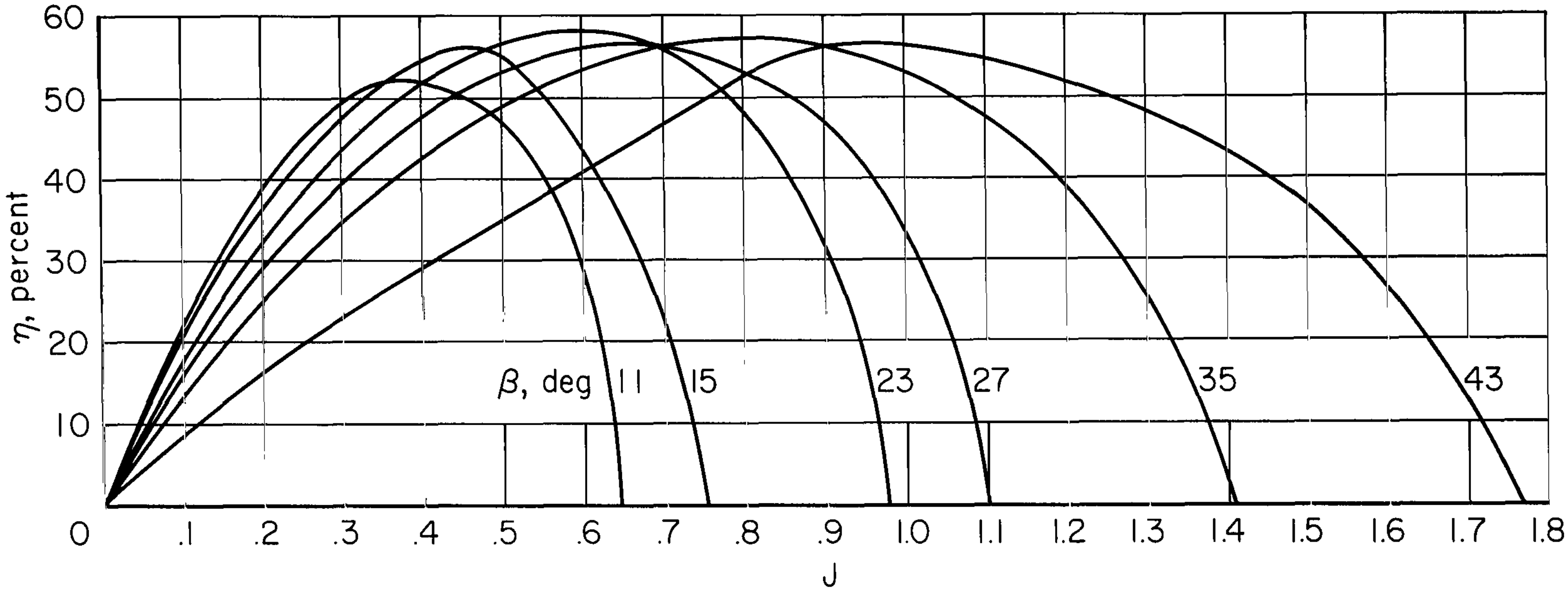


Figure 5.- Thrust coefficient referred to free-stream dynamic pressure as a function of advance ratio.



(a) Figure of merit as a function of blade angle.

Figure 6.- Figure of merit and propulsive efficiency computed from the curves of figure 4.



(b) Propulsive efficiency as a function of advance ratio for several blade angles.

Figure 6.- Concluded.

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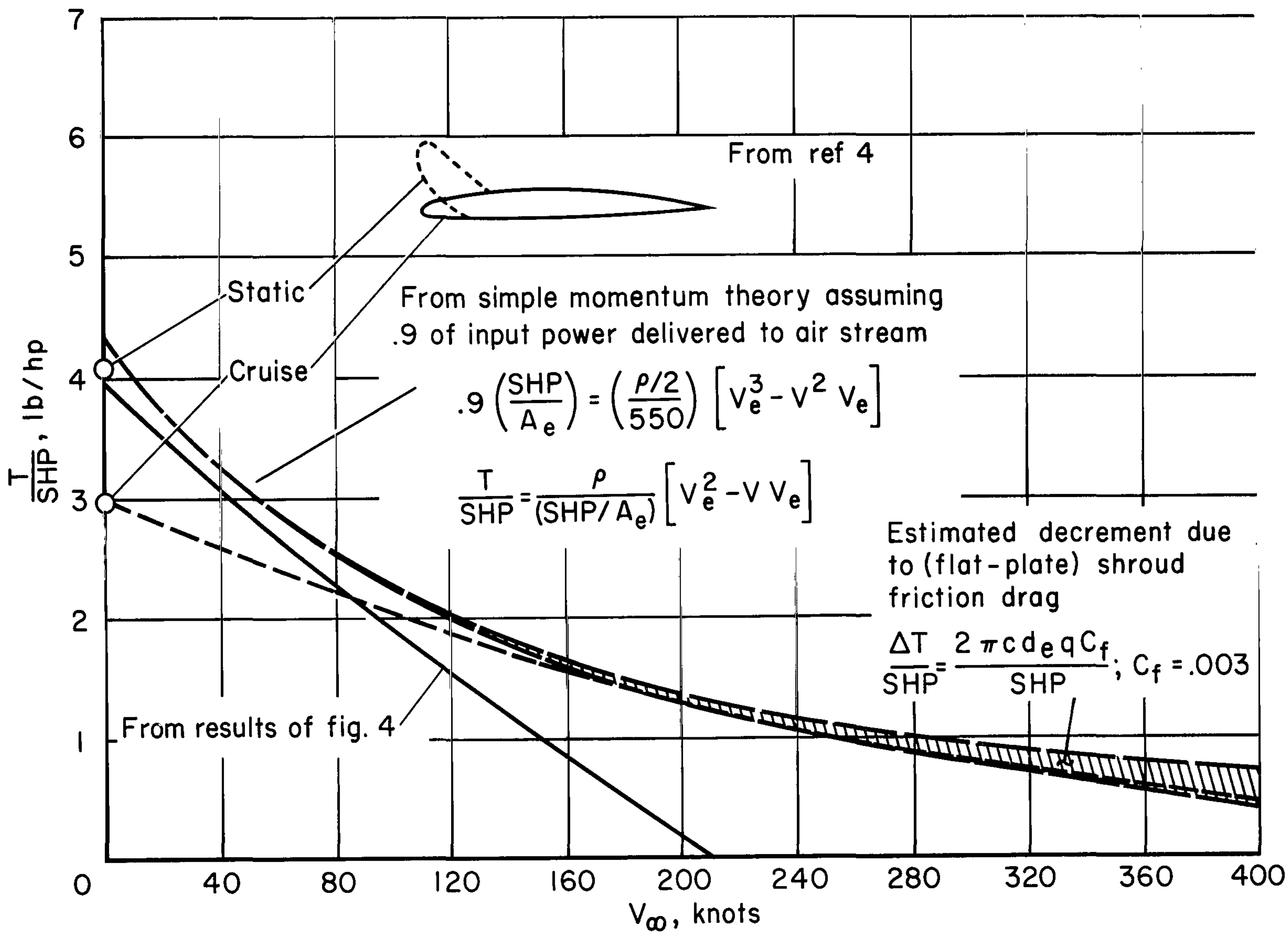

Figure 7.- Thrust to horsepower ratio as a function of free-stream velocity for an exit area power loading of 28.2 hp/ft^2.

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