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TECHNICAL NOTES

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No. 453

EXPERIMENTS WITH A COUNTER-PROPELLER

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SUMMARY

This note describes tests made at Stanford University on a four-blade fixed counter-propeller in combination with a two-blade rotating propeller. It is shown that the efficiency of the normal form, well-designed air propeller can be increased about two per cent over the full working range by the addition of fixed counter-propeller blades.

PROGRAM OF TESTS

The following tests were conducted:

A - Preliminary test to determine the rotation in the slipstream of a model propeller, the observed data to serve as a basis for a counter-propeller design.

B - Test of the model propeller alone in the usual manner.

C - Test of the model propeller in combination with the counter-propeller.

Test A.- The propeller selected for the investigation was the U.S. Navy type model F, three-foot diameter and three-foot geometrical pitch. It is completely described in N.A.C.A. Technical Report No. 237 entitled "Tests on Thirteen Navy Type Model Propellers." by W. F. Durand.

This pitch ratio was chosen because preliminary trials showed that for the same thrust and velocity of advance, the helix angles of the slipstream elements, as measured from the axial direction, vary directly with the pitch ratio. Since any gain with a counter-propeller must result from recovering some part of the rotational energy of the slipstream, it appeared that a high-pitch propeller would offer the greater opportunity for improvement.

The direction of the slipstream elements was measured with a cylindrical yaw head. Observations were made along two radial lines, one about one-half inch from the trailing edge of the propeller and the other three inches farther to the rear. The general wind velocity was about 60 feet per second. Propeller rotative speeds were adjusted to give 8 pounds, 16 pounds and 27 pounds thrust, thus providing three points in the range of v/nD through which the propeller would normally operate. Slipstream directions were observed for each of the three thrusts. The angularity of the elements, relative to the axial direction is shown in Figure 1. Close to the trailing edge it is somewhat greater than at points three inches to the rear. It varies inversely as the radius and directly as the thrust. It should be noted that the angles measured take no account of any radial velocity, but only of the tangential and axial components.

To determine the best direction for the elements of a counter-propeller, placed in a slipstream of this nature, the following analysis was employed.

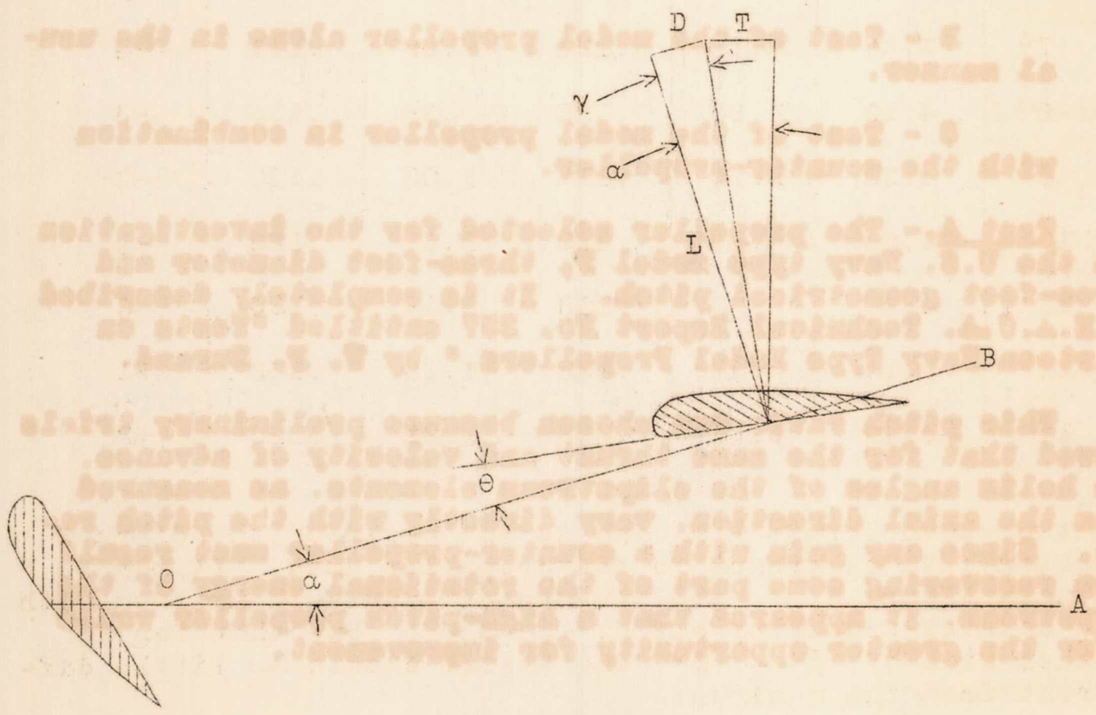

Figure 2.

Let OA (fig. 2) represent the axial direction. OB making an angle α with OA is the direction of the slipstream element. An airfoil element, at an angle of attack θ, would experience a lift L and a drag D. Let $\gamma = \cot^{-1}\frac{L}{D}$.

The thrust component $T = L \sec\gamma \sin(\alpha - \gamma)$. Since γ will generally be small and $\sec\gamma$ therefore nearly equal to one, we may write $T = L \sin(\alpha - \gamma)$.

The airfoil contour selected for the counter-propeller was the Clark Y. For the largest value of α (about 11° fig. 1), the thrust component, in coefficient form, was calculated for various angles of attack as follows:

$\alpha = 11°$

θ	γ	$\alpha - \gamma$	$\sin(\alpha-\gamma)$	C_L	C_T	β
4°	3.25°	7.75	.135	.69	.093	-7°
5°	3.40°	7.60	.132	.76	.100	-6°
6°	3.60	7.40	.129	.83	.107	-5°
7°	3.85	7.15	.124	.90	.111	-4
8°	4.10	6.90	.120	.96	.115	-3
9°	4.30	6.70	.117	1.03	.120	-2
10°	4.55	6.45	.112	1.09	.122	-1
11°	4.80	6.20	.108	1.14	.123	0
12°	5.10	5.90	.103	1.18	.122	+1
13	5.40	5.60	.098	1.21	.118	+2

In the above $\beta = \theta - \alpha$ and is the angle of the Clark Y section with reference to the propeller axis. It may be seen that for $\alpha = 11°$ the thrust would be maximum with the counter-propeller set at $\beta = 0°$, but that for 2° either side of $\beta = 0°$ the thrust should be little different from the maximum.

Similar computations for $\alpha = 8^\circ$ and $\alpha = 5^\circ$ also showed the optimum angle of the counter-propeller to be about 0°, with little difference in thrust for a change of 2° either way. It was evident from the foregoing that counter-propeller blades, without twist, and set at from +2 to -2° to the propeller axis, should yield nearly the maximum thrust throughout the full working range of model propeller F, full working range being understood as covered by the conditions of test A.

For $\alpha = 2.9^\circ$ or less, it would not be possible to realize thrust from a counter-propeller having a Clark Y section, since the minimum value of γ is 2.9° for the Clark Y and $T = L \sin (\alpha - \gamma)$. It was thus evident from Figure 1 that counter-propeller blades with Clark Y sections should not extend beyond a radius of about 15 in. At greater radii, the values of α were, even in the case of 27 pounds thrust, but little more than the 2.9° minimum value of γ.

Four airfoils, Clark Y section, 13 inches long, tapered from four to two inch chord, were arranged for attachment to a fixture as shown in Figure 3. The fixture was 3.5 inches in diameter so that the tips of the counter-propeller blades were at the 14.75-inch radius. The fastening was with a single stud at about 30 per cent chord. The airfoils could thus be turned upon the studs to adjust the angle of attack as desired.

The propeller dynamometer at Stanford is of the cradle type. The thrust is measured by the force necessary to balance the pull on the propeller shaft. The turning moment or torque is measured by the moment required to balance the torque reaction of the propeller on the dynamometer body; the latter, with driving motor, being carried on thin steel-plate knife-edges.

The counter-propeller fixture was arranged for mounting either on a ball bearing attached to the propeller shaft, or on the dynamometer body. In the former case, a forward axial force on the fixture and on the counter-propeller was added to the propeller thrust. The turning moment of the counter-propeller was balanced by a lever and counterweight, no counter-propeller torque being communicated to the dynamometer except the negligible friction torque of the ball bearing.

When the fixture was mounted on the dynamometer body, the thrust force of the propeller only was transmitted to the shaft. The turning moment, as indicated by the dynamometer, was the algebraic sum of the torque reaction against the propeller and the torque of the counter-propeller.

Test B.- For the test of the model propeller alone, the counter-propeller fixture, without the blades, was mounted on the propeller shaft; the purpose being to determine the net thrust of the propeller and fixture for later comparison with net thrust of propeller, fixture and counter-propeller. The observations and deduced coefficients for this test are given in Table I. Thrust and power coefficients and efficiency, as functions of v/nD, are plotted in Figure 4.

Test C.- Table II shows the observations and deduced coefficients with the four counter-propeller blades attached to the fixture, the blades being set at -2° to the propeller axis. The coefficients are plotted in Figure 5.

Comparison of Figures 4 and 5 shows that the counter-propeller produces an increase in efficiency of about two per cent over the full working range. This is due mainly to increase in thrust, but at the smaller values of v/nD there seems to be, due to the presence of the counter-propeller, a slight reduction in power absorbed. Tests with the counter-propeller blades set at 0°, -1° and -4° to the propeller axis gave results similar to those for -2°. The latter, however, appeared to show the greatest over-all improvement.

One further test was made. This was with the counter-propeller blades set at -2°, but with the fixture attached to the dynamometer body. Derived thrust and apparent power coefficients are given in Table III and are shown graphically in Figure 6.

The thrust of this test is the axial force on the propeller only, but in the presence of the counter-propeller. The thrust coefficient of Figure 5 is little different from that of Figure 6, thus indicating a very small axial force upon the counter-propeller and fixture. No actual measurements of fixture drag or counter-propeller thrust in the presence of the propeller could be made with the test method employed, but, for a propeller thrust of 27 pounds, the counter-propeller thrust has been calculated to be possibly

0.36 pound, and the drag of the fixture a somewhat less amount, so that the small difference in thrust coefficients of Figures 5 and 6 seems reasonable. On the other hand, Figures 4 and 5 show, at small V/nD, a thrust coefficient for the propeller, counter-propeller and fixture, about 2 per cent greater than for the propeller and fixture. This indicates, at 27 pounds thrust, a forward axial force on the counter-propeller blades of about 0.54 pound, or 50 per cent more than computed as possible. The computed possible counter-propeller thrust of 0.36 pound was derived, however, with the assumption of steady stream directions as shown in Figure 1, and these are mean directions as indicated by a cylindrical yaw head. The actual directions no doubt fluctuate with the passage of every propeller blade and in considerable amounts either side of the mean. In a stream of this nature it is known that an airfoil may have a much reduced or even negative drag (Katzmayr effect). The values of γ $(\cot^{-1} \frac{L}{D})$ may be thus much smaller than allowed for, and the thrust $L \sin (\alpha - \gamma)$ greater than calculated.

Since the counter-propeller blades should act in the direction of inducing smaller angles of attack for the propeller elements, it would appear that the thrust of the propeller itself should be reduced in the presence of the counter-propeller. The slightly smaller power coefficient in the presence of the counter-propeller, as shown by Figures 4 and 5, seems to be logical.

While these tests indicate that there is little probability the propulsive efficiency for airplanes can be considerably increased by the use of the counter-propeller, they show that some improvement can be effected. Figure 1 shows that slipstream rotation, from which any benefit with a counter-propeller must be derived, increases, for a given propeller, with disk loading. The modern high-speed and high-power aviation engine often requires a conventional two-blade propeller operating at tip speed near the velocity of sound and with consequent poor efficiency. It is suggested that with smaller diameter, the same r.p.m., lowered tip speed, increased disk loading through more or wider blades, and with a counter-propeller, efficiencies possibly greater than now practicable may be attained, and with considerably less of the noise nuisance.

An incidental advantage from a counter-propeller may lie in partial compensation of torque reaction upon the airplane. The apparent power coefficients in Figure 6 are but one-half to two-thirds of those in Figure 5. The difference represents the torque of the counter-propeller. Smaller differences in rigging of the two sides of an airplane, or smaller control-stick forces, are thus required to overcome propeller torque when a counter-propeller is used.

In any event it appears that further experimental investigation of the counter-propeller should be interesting and may be profitable.

TABLE I. TEST OF MODEL PROPELLER F ALONE

Velocity ft./sec.	r.p.s.	Thrust lb.	Torque ft-lb.	Air density ρ	v/nD	C_T $\frac{T}{\rho n^2 D^4}$	C_P $\frac{P}{\rho n^3 D^5}$	η efficiency
57.2	22.59	6	2.97	.00223	.844	.0652	.0678	.812
57.4	24.42	8	3.72	.00223	.783	.0745	.0726	.803
57.6	26.05	10	4.44	.00222	.737	.0819	.0763	.791
57.9	27.63	12	5.14	.00222	.698	.0874	.0785	.777
58.0	29.10	14	5.81	.00222	.664	.0921	.0801	.763
59.1	31.30	17	6.84	.00222	.629	.0966	.0814	.747
60.3	33.97	21	8.20	.00222	.591	.1014	.0830	.722
60.9	37.35	27	10.08	.00222	.543	.1079	.0844	.694
62.6	41.45	35	12.60	.00222	.503	.1130	.0857	.666

TABLE II. TEST OF MODEL PROPELLER F WITH COUNTER-PROPELLER ON SHAFT - BLADES AT -2° TO PROPELLER AXIS

Velocity ft./sec.	r.p.s.	Thrust lb.	Torque ft-lb.	Air density ρ	v/nD	C_T $\frac{T}{\rho n^2 D^4}$	C_P $\frac{P}{\rho n^3 D^5}$	η efficiency
55.7	22.10	6	2.89	.00226	.840	.0672	.0679	.831
55.8	23.96	8	3.65	.00226	.776	.0764	.0730	.812
56.1	25.62	10	4.36	.00226	.729	.0835	.0763	.798
56.6	27.21	12	5.05	.00226	.693	.0888	.0783	.786
56.8	28.68	14	5.70	.00226	.660	.0934	.0797	.773
57.4	30.71	17	6.64	.00226	.623	.0988	.0809	.761
58.4	33.21	21	7.91	.00225	.586	.1045	.0817	.750
61.2	36 85	27	9.86	.00225	.553	.1092	.0836	.723
62.0	40.74	35	12.30	.00225	.507	.1157	.0852	.688

TABLE III TEST OF MODEL PROPELLER F WITH COUNTER-PROPELLER ATTACHED TO DYNAMOMETER BODY - BLADES AT -2° TO PROPELLER AXIS

Velocity ft./sec.	r.p.s.	Thrust lb.	Apparent torque ft-lb.	Air density ρ	v/nD	C_T $\frac{T}{\rho n^2 D^4}$	Apparent C_P $\frac{P}{\rho n^3 D^5}$
56.5	22.26	6	1.53	.00224	.844	.0670	.0358
57.9	24.32	8	2.10	.00224	.794	.0749	.0418
58.3	26.09	10	2.63	.00224	.745	.0812	.0448
59.1	27.72	12	3.14	.00224	.710	.0866	.0475
59.7	29.30	14	3.66	.00223	.678	.0903	.0495
60.5	31.37	17	4.40	.00223	.643	.0961	.0520
61.7	34.00	21	5.34	.00223	.605	.1008	.0537
64.6	37.71	27	6.77	.00222	.571	.1055	.0555
66.1	41.71	35	8.62	.00222	.528	.1120	.0577

TABLE FOR CONSTRUCTION OF FIGURE 1.

Observed Angularity in Slipstream of Model Propeller F

Radial line 1/2 inch from trailing edge

Radius

Thrust	5 in.		8 in.		11 in.		14 in.		17 in.	
lb.	deg.	min.	deg.	min.	deg.	min.	deg.	min.	deg.	min.
8	6	35	6	25	4	25	3	0	1	05
16	9	10	8	05	5	40	3	45	1	40
27	11	25	9	55	7	35	5	15	3	0

Radial line 3-1/2 inches from trailing edge

Radius

Thrust	5 in.		8 in.		11 in.		14 in.		17 in.	
lb.	deg.	min.	deg.	min.	deg.	min.	deg.	min.	deg.	min.
8	5	30	5	30	3	30	2	[illegible]0	0	45
16	8	40	7	35	5	25	3	35	1	30
27	11	0	9	25	7	0	4	40	2	35

Stanford University,
Stanford University, Calif., February 20, 1933.

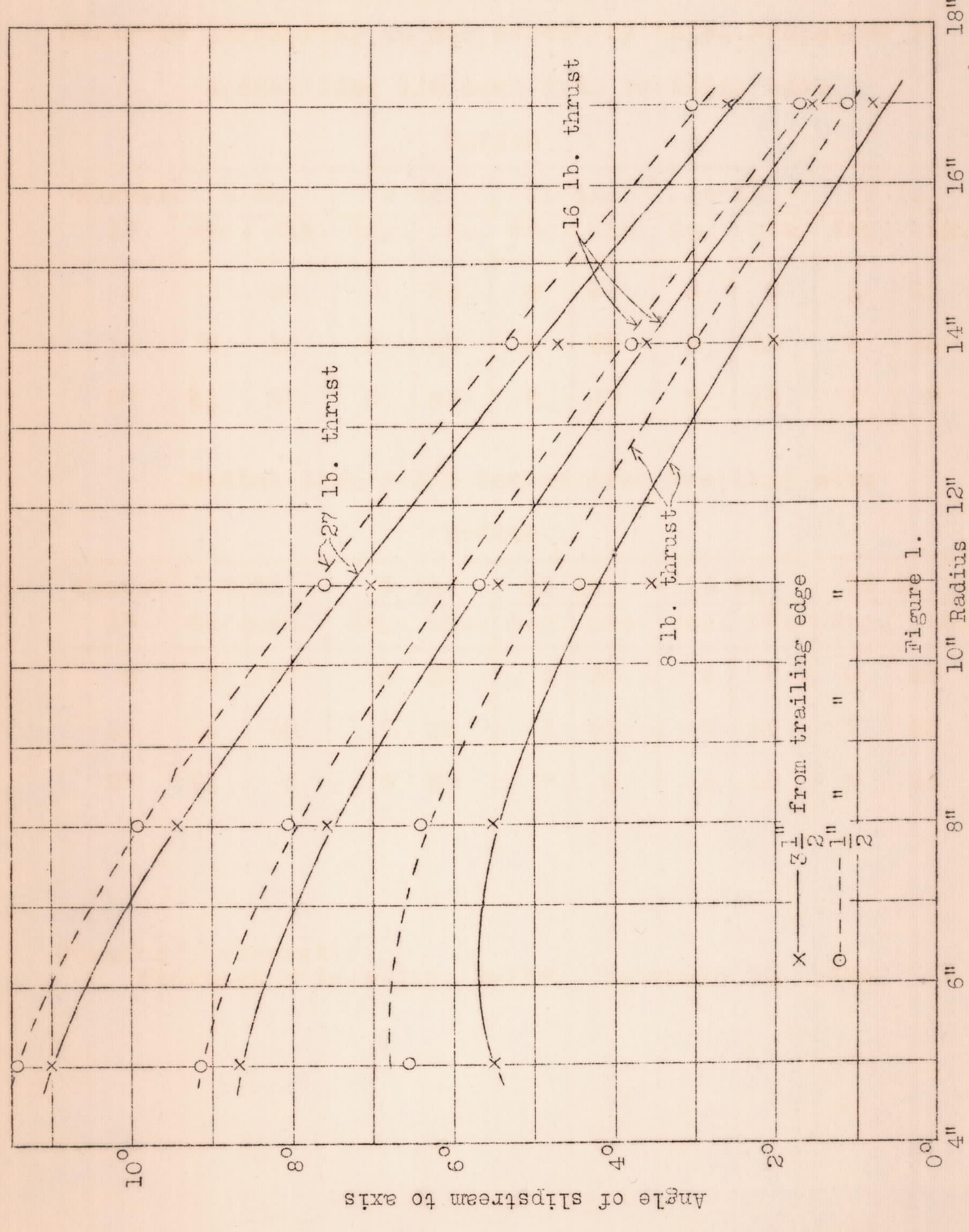
27 lb. thrust
16 lb. thrust
8 lb. thrust
× —— $3\frac{1}{2}$" from trailing edge
○ – – – $\frac{1}{2}$" " " "
Angle of slipstream to axis
Radius
0°
2°
4°
6°
8°
10°
4"
6"
8"
10"
12"
14"
16"
18"

Figure 1.

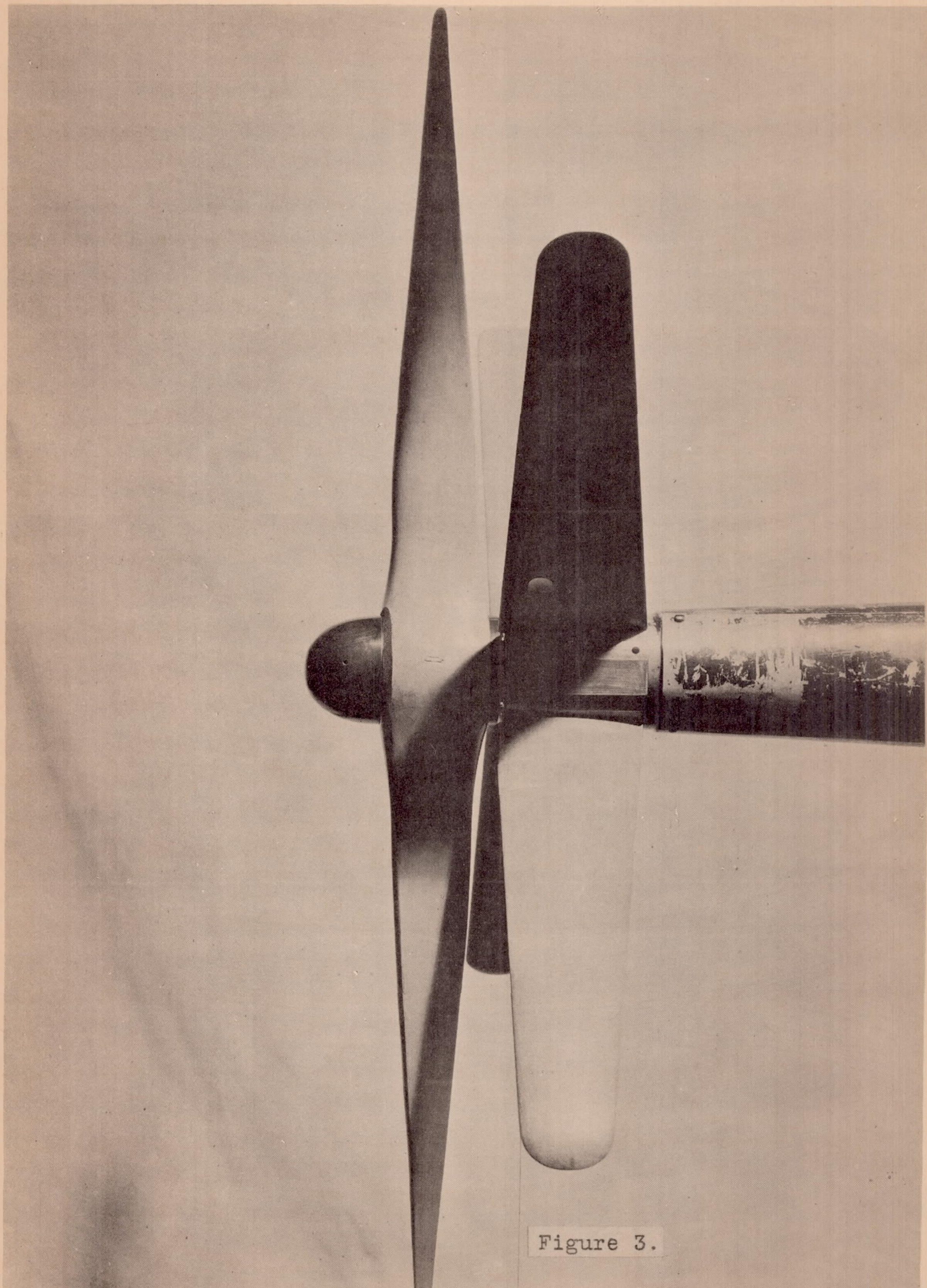

Figure 3.

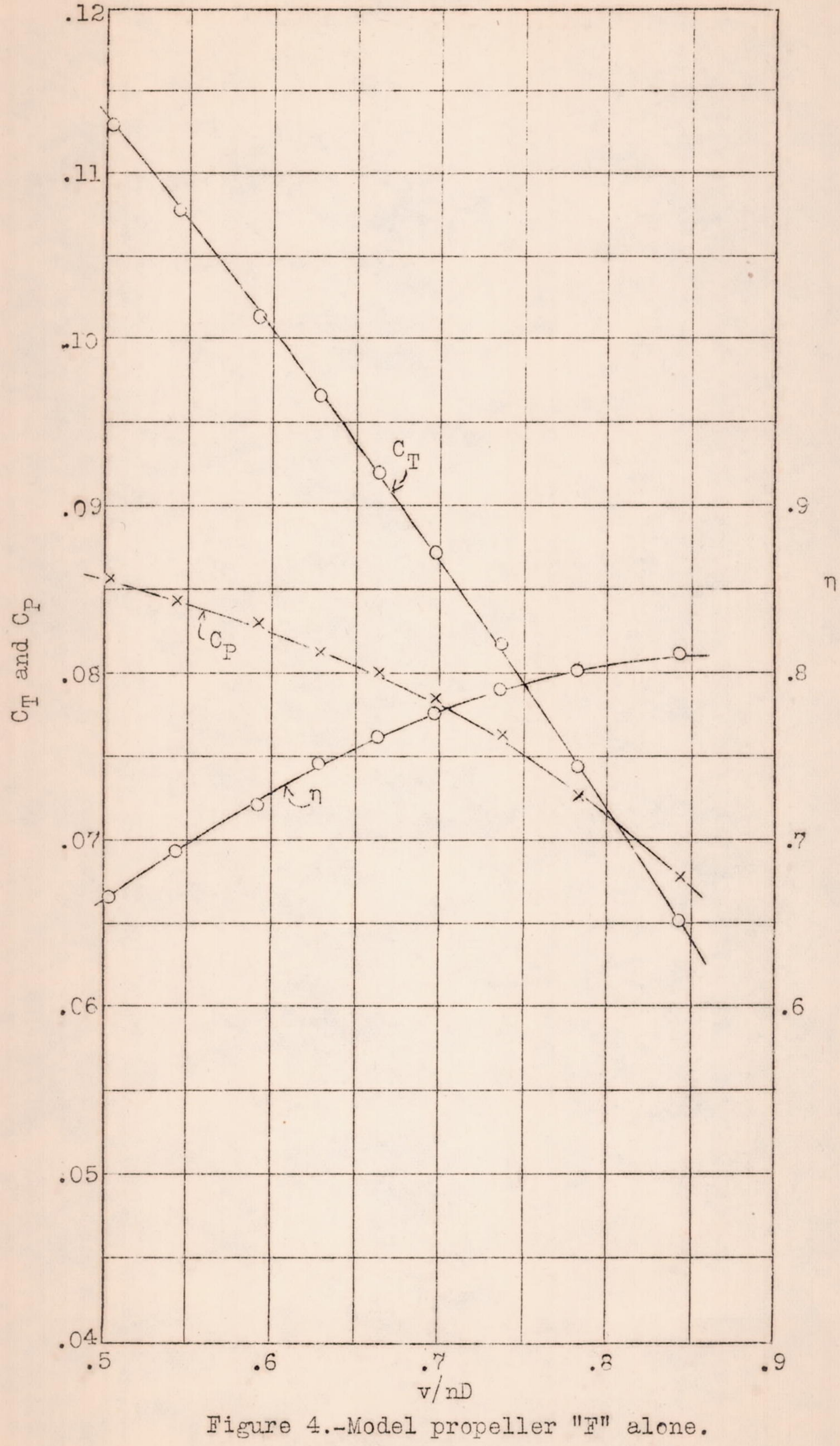

Figure 4.-Model propeller "F" alone.

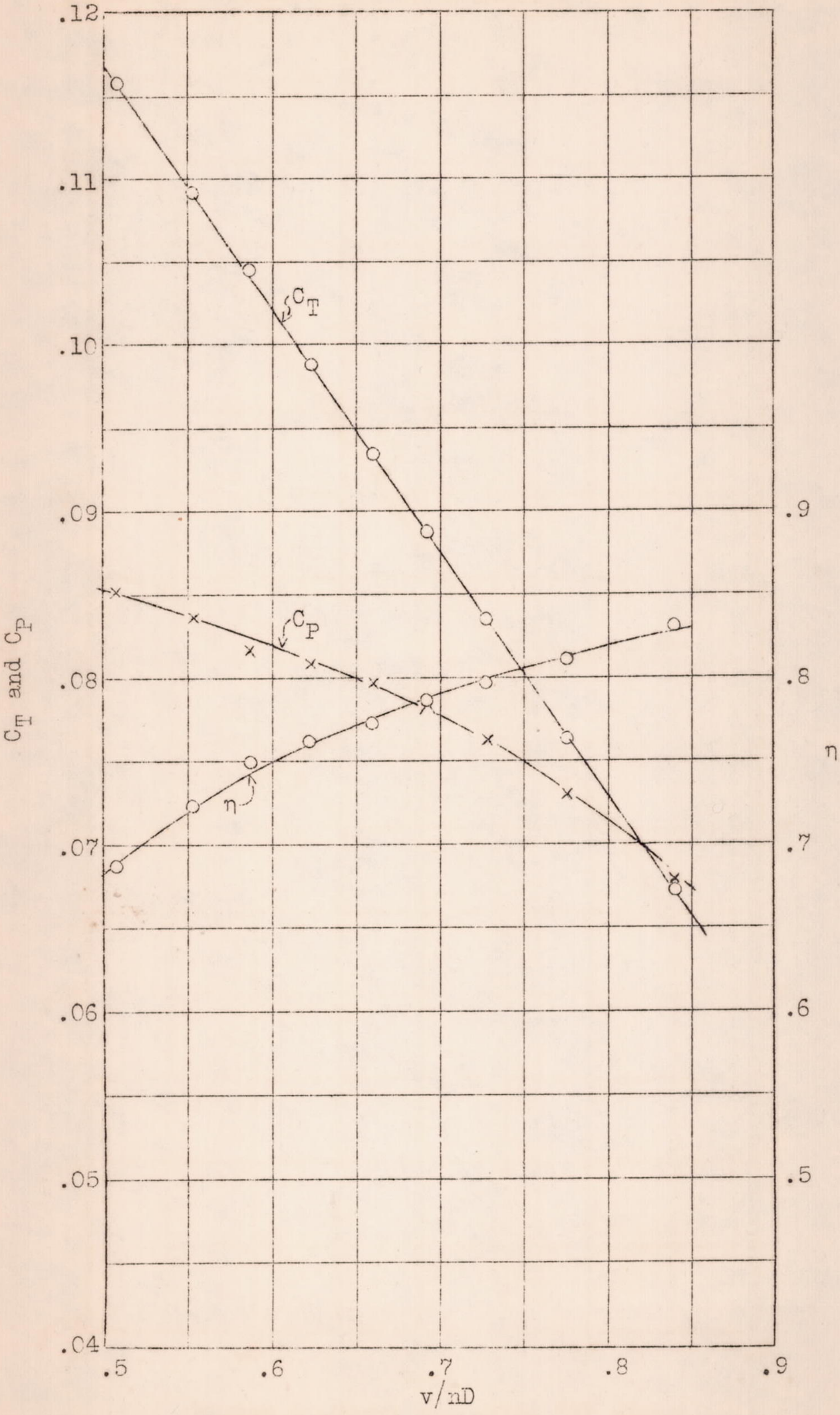

Figure 5.-Model propeller "F" with counter-propeller on shaft.

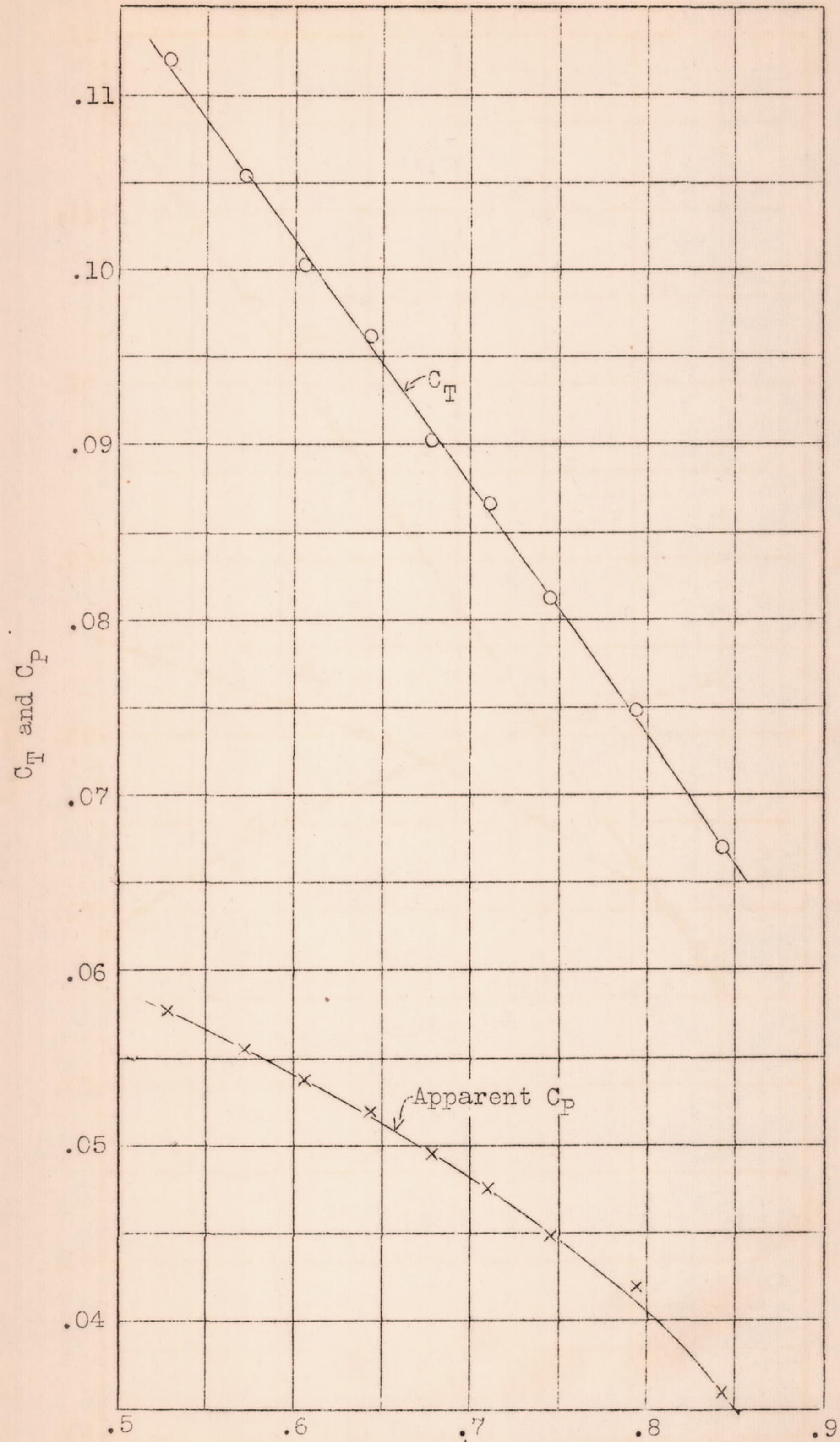

Figure 6.-Model propeller "F" with counter-propeller on dynamometer body.