TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 677

TESTS OF A CONTRA-PROPELLER FOR AIRCRAFT

By William M. Benson
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SUMMARY

Tests of an 8-blade contra-propeller of 32-inch diameter in combination with a 4-blade, 36-inch diameter, adjustable pitch, metal propeller at pitch settings of 15°, 25°, 35°, and 45° at 0.75 R were made in the wind tunnel at Stanford University.

The tests showed a significant increase in effective thrust of the combination over that of the propeller alone for values of V/nD somewhat below those for maximum efficiency and without a corresponding increase of power absorbed. From 1/2 percent to 2-1/2 percent in propulsive efficiency was thus gained in this range. In all but one case, however, the peak propulsive efficiency of the combination was found to be from 1 to 2 percent less than that of the propeller alone.

Counter torque on the contra-propeller amounted to about 50 percent of the propeller torque.

INTRODUCTION

Investigations of the fluid motion in the wake of a propeller have shown that, in addition to an axial velocity increment, there are also tangential and radial velocity increments. The radial velocity increments are small and in this investigation have been presumed to be of negligible utility. Because of the tangential increments the fluid elements have a helical direction.

The contra-propeller of these tests consists of eight airfoil-section fixed blades, mounted back of the main propeller. Its effect is to change the direction of the slipstream elements from helical to axial, thus increasing the time rate of change of axial momentum, or thrust. If no change in direction or velocity of flow through the main propeller disk is induced by the contra-propeller, there will be no change in power absorbed or thrust developed by the main propeller and the possible addition to effective thrust is the amount of the forward force on the contra-propeller blades (reference 1).

THEORETICAL CONSIDERATIONS

A simple blade-element theory of the contra-propeller, which may be employed in the prediction of benefits to be derived, is as follows:

Consider a contra-propeller blade element (fig. 1) located in a region behind the main propeller where the angularity of the slipstream (i.e., the angle between the local direction of air flow and the axis of rotation of the main propeller) is β degrees. Let α be the angle of the contra-propeller blade element with respect to the axis of rotation. The angle of attack of the element is thus $\beta - \alpha$. With C_L as the lift coefficient of the element, C_D the corresponding drag coefficient, C_R the resultant-force coefficient, and C_t a thrust coefficient of the form T/qS, it may be seen that

$$C_t = \frac{C_L}{\cos \gamma} \sin (\beta - \gamma) \qquad (1)$$

where $\gamma = \cot^{-1} \frac{L}{D}$.

If β is greater than γ, it is evident that there will be a resultant forward force on the contra-propeller blade element. It is also evident that the magnitude of the thrust coefficient will depend largely on the value of β.

Although previous tests (reference 2) showed that the efficiency of the normal-form, well-designed air propeller might be increased about 2 percent over the full working range by the addition of fixed contra-propeller blades, it appeared desirable to determine the angle β under various conditions for the particular propellers used in this investigation as a basis for the design of the contra-propeller blades. The tests of reference 2 were made with a 4-blade contra-propeller in combination with a 2-blade wooden propeller of U.S. Navy type, 3 feet in diameter and of 3-foot geometric pitch. The purpose of the present investigation was to determine the possibilities for improved performance of the conventional metal 4-blade adjustable pitch propeller by the addition of an 8-blade contra-propeller.

By means of a cylindrical yaw head the slipstream angularity behind the propeller for each of four propeller pitch settings was observed. Measurements were made along two radial lines, 3 and 9 inches back of the propeller blade axis for several values of V/nD within the normal working range. Figure 2 shows variation in stream angularity with V/nD for five radial distances from the axis of rotation and 3 inches back of the blade axis of the 35° propeller.

Cross plots of slipstream angularity against radial distance from the axis of rotation for three values of V/nD are shown in figure 3. Corresponding curves for other propeller pitch settings were similar in form.

From a knowledge of the radial variation of slipstream angularity, it was possible to select an airfoil section and plan form for the contra-propeller blades and to make a quantitative estimate of the total thrust coefficient in the form $C_T = \frac{T}{\rho n^2 D^4}$ such blades might be expected to develop for any propeller pitch setting and at a given value of V/nD.

For the contra-propeller blades a Clark Y section was chosen. Any airfoil with a large L/D ratio would have been satisfactory; the flat lower surface of the Clark Y made the setting of the contra-propeller blades convenient and the thickness was suitable for a cantilever contra-propeller blade.

Figure 3 shows that the larger useful values of slipstream angularity β were found at the smaller radii. It was evident from equation (1) that the blade-element thrust coefficient would generally vary directly with β. It therefore appeared that, for a given area, the greatest thrust would be realized from blades of a tapered plan form with the wide end toward the propeller axis. It was also seen that little was to be gained by carrying the contra-propeller blades beyond the 16-inch radius. Beyond this point the values of β were, at V/nD of maximum efficiency, little more than for γ corresponding to the maximum L/D of the Clark Y profile. It had been planned to use a cylindrical body 8 inches in diameter behind the 3-foot diameter model propeller, as being possibly representative of an engine nacelle to which the contra-propeller blades would be fastened. As a result of the foregoing considerations, the plan form chosen was 12-inch span, 4-inch root chord, and 2-inch tip chord. The blade tips were rounded in much the same way as a conventional wing tip.

In order to determine the best orientation for the elements of contra-propeller for the present problem, the following analysis was employed. Blade-element thrust coefficients were calculated from equation (1) for various values of slipstream angularity β and of blade-element angle α. In these calculations the aerodynamic characteristics of the Clark Y given in reference 3 were used. These data were used because they were obtained at a Reynolds Number closely approximating the value that would be attainable in the Stanford University wind tunnel. Although the geometric aspect ratio of the contra-propeller blades was 4, the characteristics of an airfoil of aspect ratio 6 were used to allow for the end-plate, or tip-shield, effect of the faired body against which the blades were butted.

Figure 4 shows the calculated variation of C_t with airfoil angle α for each slipstream angularity β. A line drawn through the maxima of C_t shows that, if β varies with radius, the maximum integrated C_t for an entire contra-propeller would be realized from twisted blades. Since, however, the curves of C_t against α are relatively flat, it may reasonably be expected that nearly as beneficial results could be derived were the contra-propeller blades without twist and set at a mean optimum angle with respect to the propeller axis. Because construction was simpler, the blades were therefore made in the form of untwisted airfoils.

With knowledge of the slipstream angularity, it was possible to make a quantitative estimate of the thrust coefficient that might be expected from the contra-propeller for any propeller pitch setting and at a given V/nD. By an approximate method of integration, areas under curves of $C_t \times$ chord against radius of contra-propeller blade were determined. The integrals were converted to the form $T/\rho n^2 D^4$ for comparison with the propeller thrust coefficient.

For the specific case of the 35° propeller at V/nD 1.3 (maximum efficiency) and with contra-propeller blades set at a mean optimum angle of 1°, it was found that a thrust coefficient of about 2 percent of the propeller thrust coefficient might be realized from the contra-propeller. This value, provided that there were no change in power coefficient, would increase propulsive efficiency about 1-1/2 percent. For $V/nD = 0.7$ it appeared that an increase of 2 percent in propulsive efficiency might be expected.

Therefore, it seemed possible that an increase in propulsive efficiency of about 2 percent over the full working range might be found from the use of a contra-propeller in the proposed investigation, as it had been in reference 2.

APPARATUS

Wind tunnel.- The experimental work with the contra-propeller was done in the wind tunnel of the Daniel Guggenheim Aeronautical Laboratory at Stanford University. This tunnel is of the Eiffel type with a throat diameter of 7-1/2 feet. The maximum wind velocity is about 90 miles per hour.

Dynamometer.- The propeller dynamometer at Stanford is of the cradle type and consists essentially of a long electric motor provided with a direct-connected right-hand rotation shaft. The entire assembly is carried on thin-steel-plate knife edges below the shaft axis. Thrust is measured by the force required to balance the pull on the propeller shaft; torque is measured by the moment required to balance the torque reaction of the propeller on the dynamometer body. The dynamometer is shielded by a sheet-metal cover to protect it from the action of wind forces other than those on the propeller.

The torque of the contra-propeller was measured by restraining it from rotation by a vertical wire connected to one of the horizontal blades and leading to a sensitive pan balance located above the wind stream.

Model propeller.- The propeller used in these tests was a 3-foot diameter, 4-blade, adjustable pitch, metal model of standard U.S. Navy plan form and blade section. The nominal geometric pitch-diameter ratio was 0.7 from

0.6 R outward to the tip. It gradually decreased from 0.6R toward the hub to a value of 0.42 at 0.15 R. The plan form, sections, and pitch distribution were those of propeller E in reference 4.

Contra-propeller.- The contra-propeller consisted of eight airfoils, of Clark Y section, 12 inches long, tapering from a 4-inch to a 2-inch chord, which were mounted on the surface of a body of revolution 8 inches in diameter. The tips of the blades were thus at the 16-inch radius. The blades were fastened to the body by a single stud at about 30 percent chord, thus permitting turning to the desired angular setting.

The body was designed for mounting either on a pair of ball bearings riding on the propeller shaft, or entirely independently of the dynamometer by rigidly fastening the skirt of the body to the dynamometer shield and centering the nose by supporting wires attached to the tips of four contra-propeller blades. The wire method of support rendered the contra-propeller self-restraining; the ball-bearing method required the balancing of the turning moment by means of a vertical wire and counterweight.

A view of the propeller in combination with the complete contra-propeller is shown in figure 5.

TESTS

The following tests were conducted:

(1) Preliminary tests to determine the radial variation of slipstream angularity for various values of V/nD and each propeller pitch setting.

(2) Tests of the propeller at each pitch setting in combination with the body alone.

(3) Tests of the propeller at each pitch setting in combination with the body and 8-blade contra-propeller for contra-propeller blade angles of 0°, 2°, and 4°.

It is standard procedure at the Stanford Laboratory to obtain variation in the parameter V/nD through change in wind velocity, keeping angular velocity constant. The rotational speeds used in the tests were 2,000, 2,000, 1,500, and 1,100 r.p.m. for the 15°, 25°, 35°, and 45° pitch settings, respectively. Different rotational speeds were adopted because of the limitations as to stream velocity and to power and rotational speed available in the dynamometer. The Reynolds Numbers of the tests were thus from 0.11 to 0.06 full scale, assuming the full-scale propeller to be 9 feet in diameter and operating at 2,000 r.p.m.

The thrust and power observations were reduced to the usual coefficients

$$C_T = \frac{T}{\rho n^2 D^4}$$

$$C_P = \frac{P}{\rho n^3 D^5}$$

$$\eta = \frac{T V}{P} = \frac{C_T}{C_P} \frac{V}{nD}$$

where

T is the effective thrust.

P. power absorbed.

ρ, mass density of the air.

n, revolutions per unit time.

D, propeller diameter.

V, velocity.

The initial tests of the propeller and contra-propeller combinations showed considerable but inconsistent changes of power coefficient with introduction of contra-propeller blades and with variation of their angular settings. In these tests the body was mounted on ball bearings on the propeller shaft. Since it was evident that there might be errors in indicated torque due to side wind force upon the contra-propeller, the following test procedure was adopted:

(1) Thrust was observed with the body and contra-propeller carried by ball bearings on the propeller shaft and restrained from rotating by a single vertical wire and counterweight.

(2) Torque was observed with the body and contra-propeller supported independently of the dynamometer. With this arrangement, the torque tests indicated that, although there was some change in power coefficient due to the addition of the contra-propeller and to variation in the angle of the contra-propeller blades, these changes were small and inconsistent and might be ascribed to experimental error.

In an attempt to justify the foregoing conclusion, a survey of velocity and direction of the air stream in the plane of the main propeller-blade axis (in front of the contra-propeller blades) was made. Within the limits of measurement, no change in either direction or velocity was induced by the contra-propeller blades. Without an alteration of the air flow in the region in which the main propeller operated, there could be no change in power absorbed or thrust developed by the propeller itself.

It may be noted that a similar conclusion was reached in reference 2.

RESULTS AND DISCUSSION

The observations for tests of the propeller in combination with body alone and in combination with body and contra-propeller blades at 4° are given in coefficient form in table I.

Tests with other contra-propeller blade angles were less productive of beneficial effects. Presentation and discussion of them have therefore been omitted.

In figures 6 to 13, thrust and power coefficients and efficiency are shown graphically as functions of V/nD.

Since measurements of thrust and torque were not simultaneous, efficiencies could not be calculated for specific observations. The efficiency curves shown are derived from the faired curves of thrust and power coefficients.

Comparison of corresponding figures shows that, contrary to expectations, the contra-propeller brought about no increase in peak propulsive efficiency. There was instead, in all but for the 25° propeller, a loss. At V/nD

somewhat below that for peak efficiency, definite gains from the contra-propeller were shown. For the 15° propeller the gain was barely perceptible, but it became progressively greater as the propeller pitch was increased, reaching about 2-1/2 percent for the 45° propeller.

The failure of the contra-propeller to effect a predicted increase in thrust and, thus of efficiency near the peak, and the suspicion that this failure might be due to a difference between actual and assumed drag coefficients of the contra-propeller blades led to such investigation of the effective drag coefficients as could be made. The drag of the body alone was deducted from that of the combined body and contra-propeller blades at several angles of attack. Derived blade drag coefficients were from 30 to 60 percent greater than those of reference 3.

Some possible sources of increase in drag coefficient are as follows:

1) Localized high velocity due to the presence of the body.

2) Failure to realize accurate Clark Y profiles and smooth surfaces.

3) Interference at the junction of body and contra-propeller blades.

It may be assumed that increased drag from source 1) would not be prejudicial because it would be accompanied by a corresponding increase in lift.

With respect to 2) it may be said that the profiles were as accurate and the surfaces as smooth as commercially practicable.

Interference thus appears to have been the chief source of augmented drag in the contra-propeller blades. Interference drag might possibly be reduced by well-designed fillets. Small plasticine fillets were tried but they were ineffective toward improvement. It may be remarked that in the tests of reference 2 the body supporting the contra-propeller blades was less than half the diameter of that in the present tests. The junction of the blades and body was thus in a low-velocity wake of the propeller hub and interference was of possibly less consequence.

Whatever its source, there was evidently an increase in drag of the contra-propeller blades in the present tests over that deduced from reference 3. In order to determine the probable effect of the apparent increase, figure 4(b), similar to figure 4(a) was constructed. For this diagram, lift coefficients of reference 3 and drag coefficients as derived from the blades in combination with the body were used. Total thrust coefficients for the contra-propeller in combination with the 35° propeller were then estimated. The results were in close agreement with tests. It was also seen from this diagram that an angle of 4° for the contra-propeller blades would be nearer the mean optimum than 1° as indicated by figure 4(a). This result was also in agreement with tests.

Counter torque of the contra-propeller was observed for each propeller pitch and at each angle of the contra-propeller blades. The observations were reduced to ratios of counter torque to propeller torque and are shown in figure 14 for the 4° contra-propeller blade angle as functions of the ratio of V/nD to V/nD for maximum efficiency.

CONCLUSIONS

1. This contra-propeller does not bring about an anticipated increase in peak propulsive efficiency.

2. This contra-propeller effects a significant gain in propulsive efficiency at a V/nD equal to about one-half that corresponding to maximum efficiency.

3. The discrepancies between anticipated and experimental efficiency gain may be satisfactorily explained by a failure to realize the assumed aerodynamic characteristics of the contra-propeller blades.

4. Counter torque on the contra-propeller amounted to about 50 percent of the propeller torque for all pitch settings of the propeller and for all values of V/nD up to that corresponding to maximum efficiency.

5. Despite the generally pessimistic results of these tests, the fixed-blade contra-propeller may be useful in appreciably increasing the efficiency of airplane propulsion provided that relatively high effective lift-drag ratios can be realized from the contra-propeller blades.

6. The possible gain in propulsive efficiency through the contra-propeller is small. In order to demonstrate its existence conclusively, apparatus and experimental technique of the greatest practicable accuracy should be employed in further tests.

Daniel Guggenheim Aeronautical Laboratory,
Stanford University, Calif., April 1938.

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2. Lesley, E. P.: Experiments with a Counter-Propeller. T.N. No. 453, N.A.C.A., 1933.

3. N.A.C.A.: Aerodynamic Characteristics of Airfoils - IV. T.R. No. 244, N.A.C.A., 1928.

4. Lesley, E. P., and Reid, Elliott G.: Tests of Five Metal Model Propellers with Various Pitch Distributions in a Free Wind Stream and in Combination with a Model VE-7 Fuselage. T.R. No. 326, N.A.C.A., 1929.

TABLE I

Propeller Coefficients

15° Propeller

With body alone				With contra-propeller at 4°			
V/nD	C_T	V/nD	C_P	V/nD	C_T	V/nD	C_P
0.715	0.0152	0.714	0.0217	0.709	0.0168	0.714	0.0229
.654	.0344	.655	.0325	.657	.0334	.657	.0325
.604	.0492	.612	.0395	.605	.0480	.604	.0402
.552	.0624	.569	.0440	.566	.0574	.566	.0446
.504	.0749	.513	.0500	.507	.0736	.511	.0508
.471	.0816	.474	.0537	.472	.0816	.473	.0538
.420	.0930	.446	.0562	.427	.0931	.442	.0561
.373	.1027	.392	.0597	.386	.0999	.387	.0597
.331	.1096	.347	.0611	.348	.1077	.346	.0614
.298	.1163	.311	.0625	.309	.1145	.308	.0627
.260	.1215	.275	.0631	.261	.1237	.274	.0634

25° Propeller

With body alone				With contra-propeller at 4°			
V/nD	C_T	V/nD	C_P	V/nD	C_T	V/nD	C_P
1.085	0.0400	1.084	0.0591	1.090	0.0392	1.081	0.0588
1.030	.0578	1.031	.0718	1.033	.0575	1.030	.0724
.987	.0690	.994	.0788	.992	.0679	.988	.0808
.946	.0801	.941	.0902	.947	.0789	.940	.0902
.897	.0902	.899	.0975	.897	.0910	.897	.0969
.845	.1012	.848	.1065	.852	.1009	.846	.1060
.799	.1116	.799	.1131	.803	.1126	.799	.1114
.762	.1208	.754	.1182	.754	.1229	.762	.1172
.689	.1360	.708	.1226	.715	.1304	.712	.1217
.640	.1438	.644	.1290	.639	.1467	.647	.1274
.592	.1520	.589	.1314	.596	.1550	.596	.1304
.554	.1595	.553	.1332	.552	.1633	.538	.1334
.490	.1685	.490	.1348	.493	.1718	.497	.1339
.437	.1757	.442	.1376	.436	.1791	.447	.1367

TABLE I - Continued

Propeller Coefficients

35° Propeller

With body alone				With contra-propeller at 4°			
V/nD	C_T	V/nD	C_P	V/nD	C_T	V/nD	C_P
1.580	0.0537	1.566	0.1096	1.574	0.0509	1.559	0.1123
1.520	.0662	1.505	.1262	1.525	.0628	1.499	.1321
1.475	.0778	1.449	.1410	1.465	.0777	1.449	.1435
1.409	.0930	1.405	.1536	1.413	.0898	1.394	.1588
1.343	.1068	1.336	.1710	1.347	.1034	1.331	.1743
1.278	.1219	1.276	.1820	1.291	.1171	1.265	.1870
1.216	.1330	1.209	.1955	1.214	.1331	1.205	.1980
1.151	.1439	1.144	.2054	1.154	.1440	1.139	.2074
1.088	.1553	1.084	.2133	1.086	.1588	1.077	.2141
1.022	.1661	1.011	.2219	1.016	.1690	1.012	.2212
.930	.1731	.920	.2308	.956	.1757	.946	.2281
.866	.1752	.862	.2318	.859	.1803	.858	.2331
.790	.1768	.790	.2326	.788	.1821	.784	.2332
.700	.1776	.694	.2355	.699	.1851	.695	.2352

45° Propeller

With body alone				With contra-propeller at 4°			
V/nD	C_T	V/nD	C_P	V/nD	C_T	V/nD	C_P
2.082	0.0932	2.088	0.2387	2.057	0.0917	2.076	0.2400
1.991	.1096	1.999	.2642	1.991	.1065	2.007	.2632
1.921	.1239	1.921	.2825	1.908	.1216	1.920	.2811
1.828	.1401	1.851	.3026	1.841	.1339	1.843	.3008
1.763	.1500	1.756	.3199	1.738	.1522	1.740	.3234
1.658	.1653	1.681	.3359	1.665	.1630	1.619	.3420
1.573	.1729	1.591	.3480	1.585	.1735	1.565	.3464
1.488	.1757	1.506	.3548	1.489	.1785	1.485	.3516
1.419	.1780	1.399	.3528	1.403	.1810	1.405	.3531
1.343	.1767	1.330	.3505	1.313	.1815	1.329	.3508
1.244	.1771	1.240	.3523	1.239	.1826	1.239	.3508
1.165	.1782	1.166	.3538	1.161	.1856	1.165	.3533
1.099	.1802	1.094	.3548	1.097	.1878	1.094	.3544
1.034	.1812	1.032	.3558	1.026	.1904	1.026	.3549
.963	.1827	.955	.3581	.959	.1920	.955	.3620

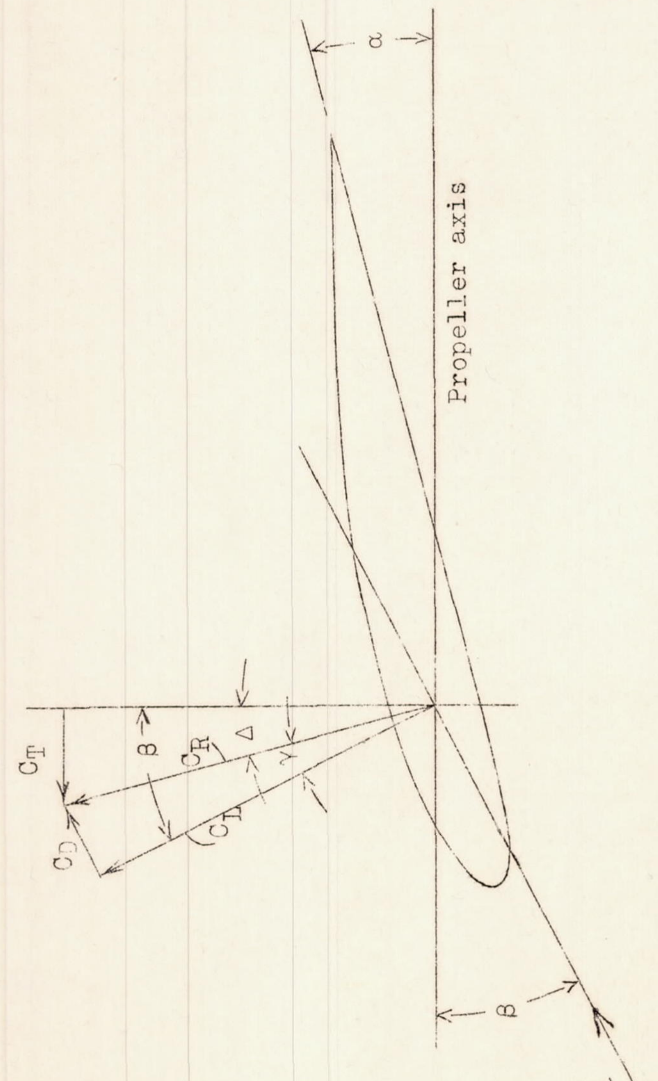

Figure 1.

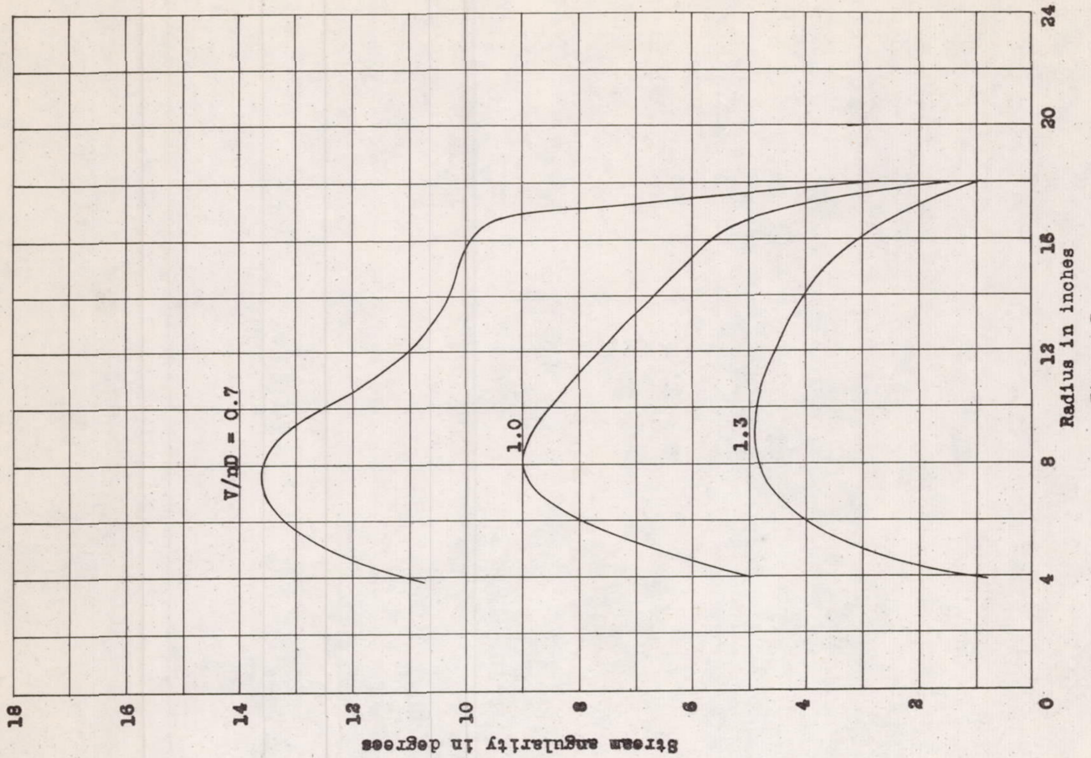

Figure 3.

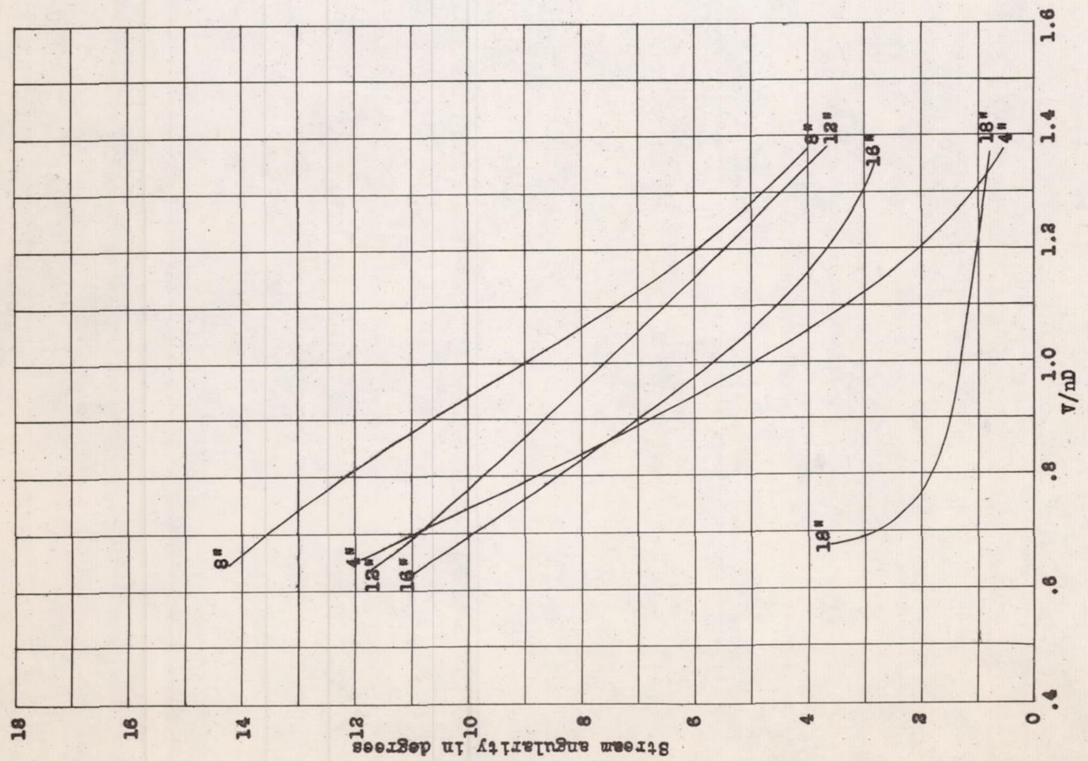

Figure 2.

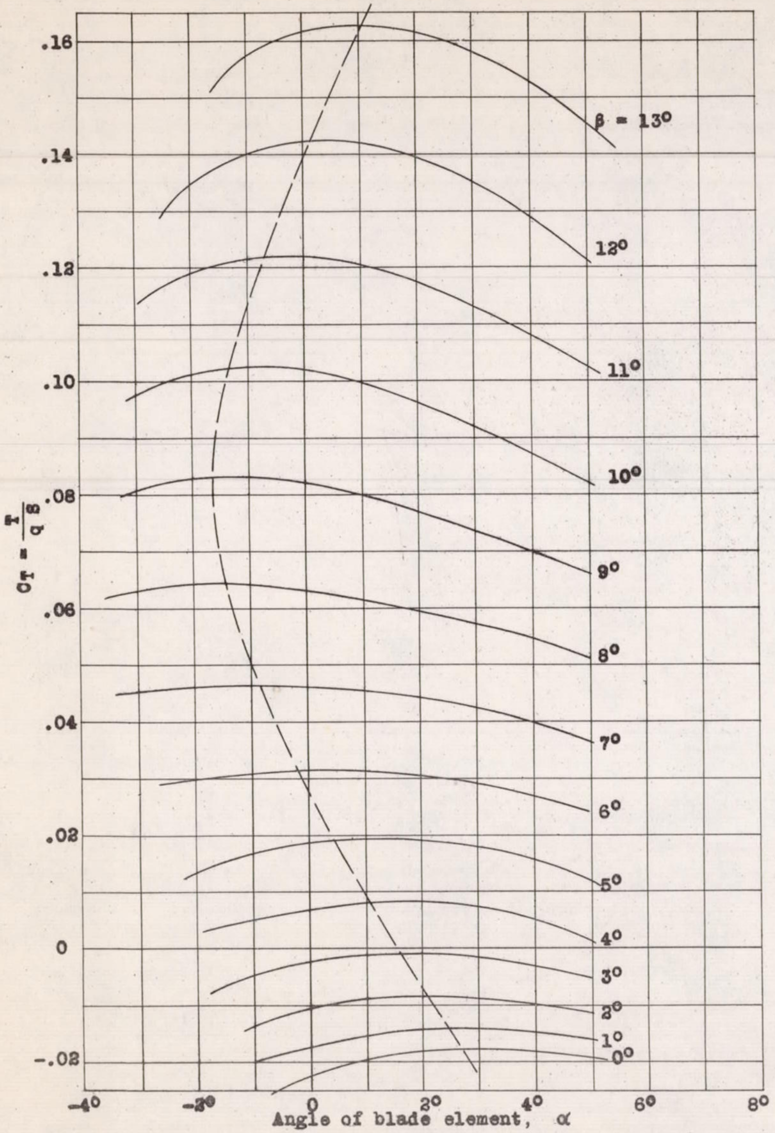

Figure 4a.- Estimated contra-propeller blade element thrust coefficient.

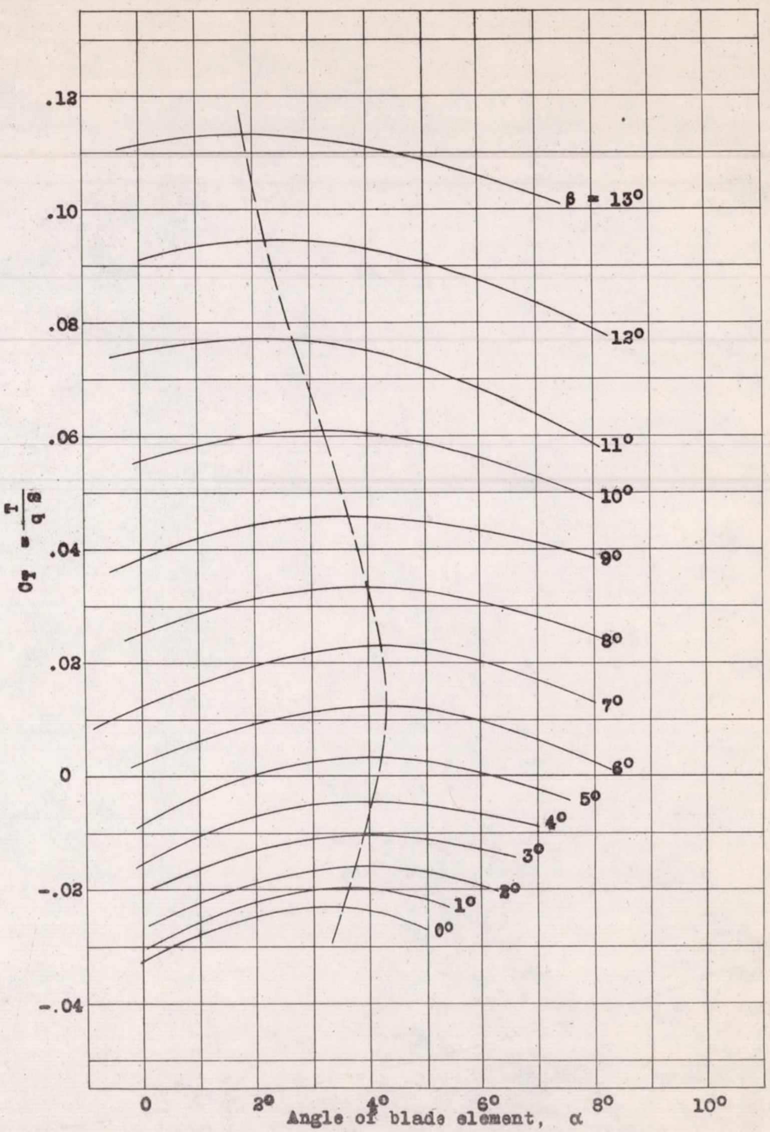

Figure 4b.- Revised contra-propeller blade element thrust coefficient.

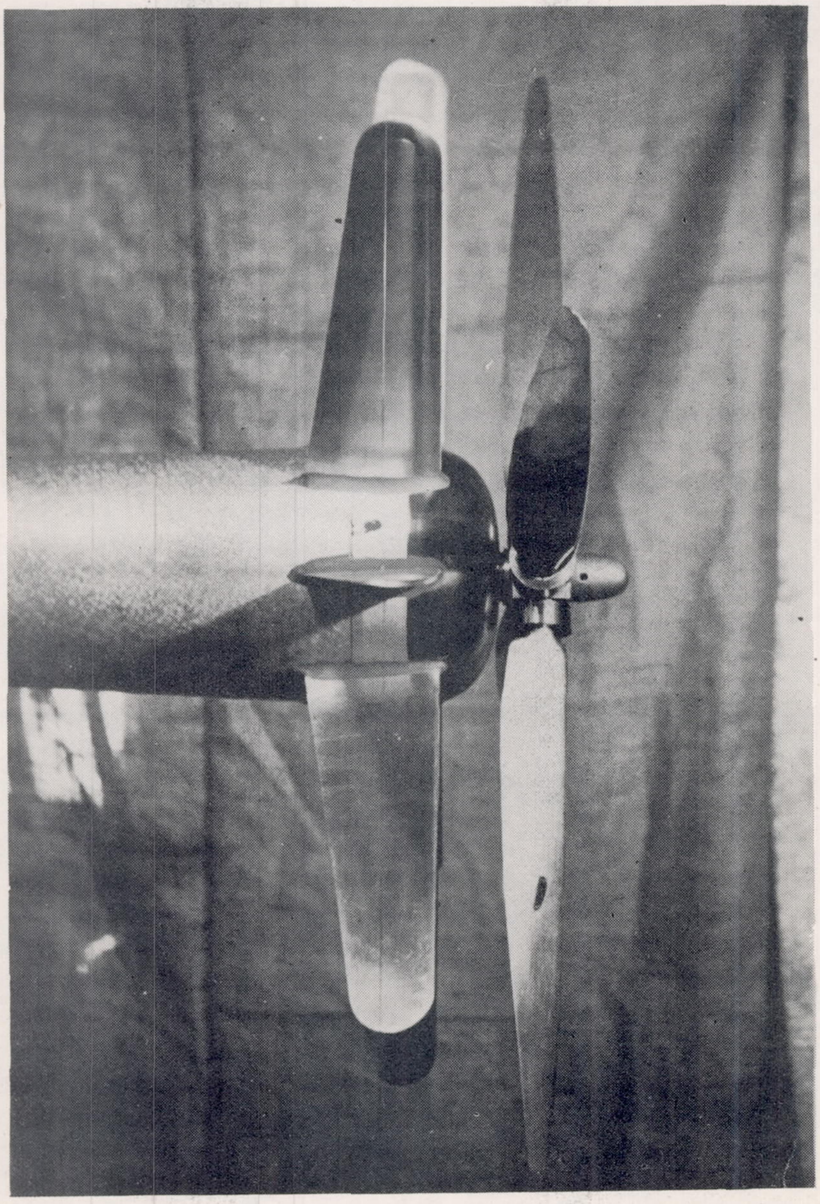

Figure 5.- Side view of contra-propeller.

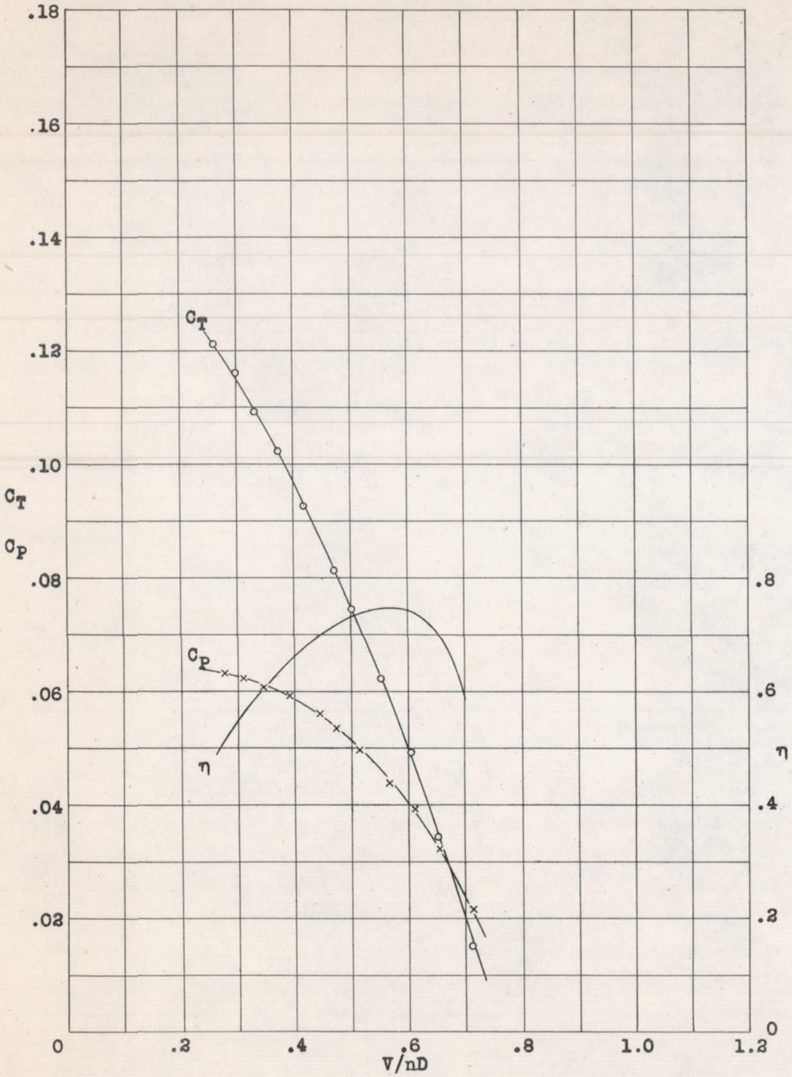

Figure 6.- 15° Propeller with body alone.

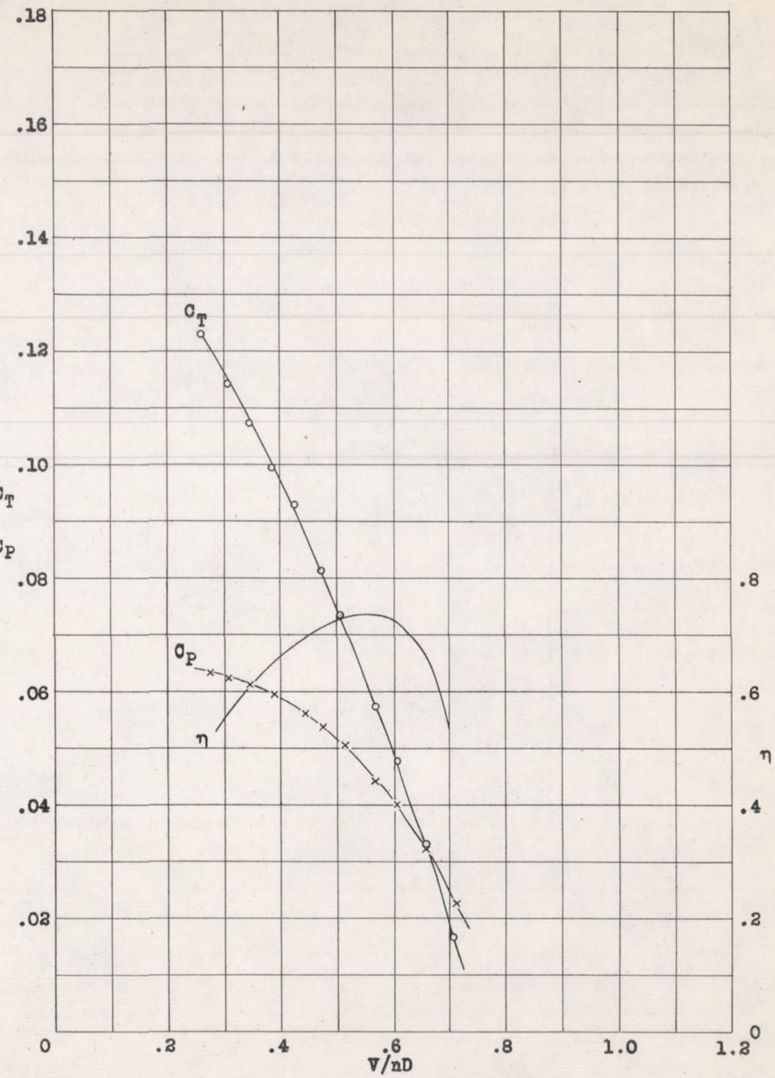

Figure 7.- 15° Propeller with contra-propeller at 4°

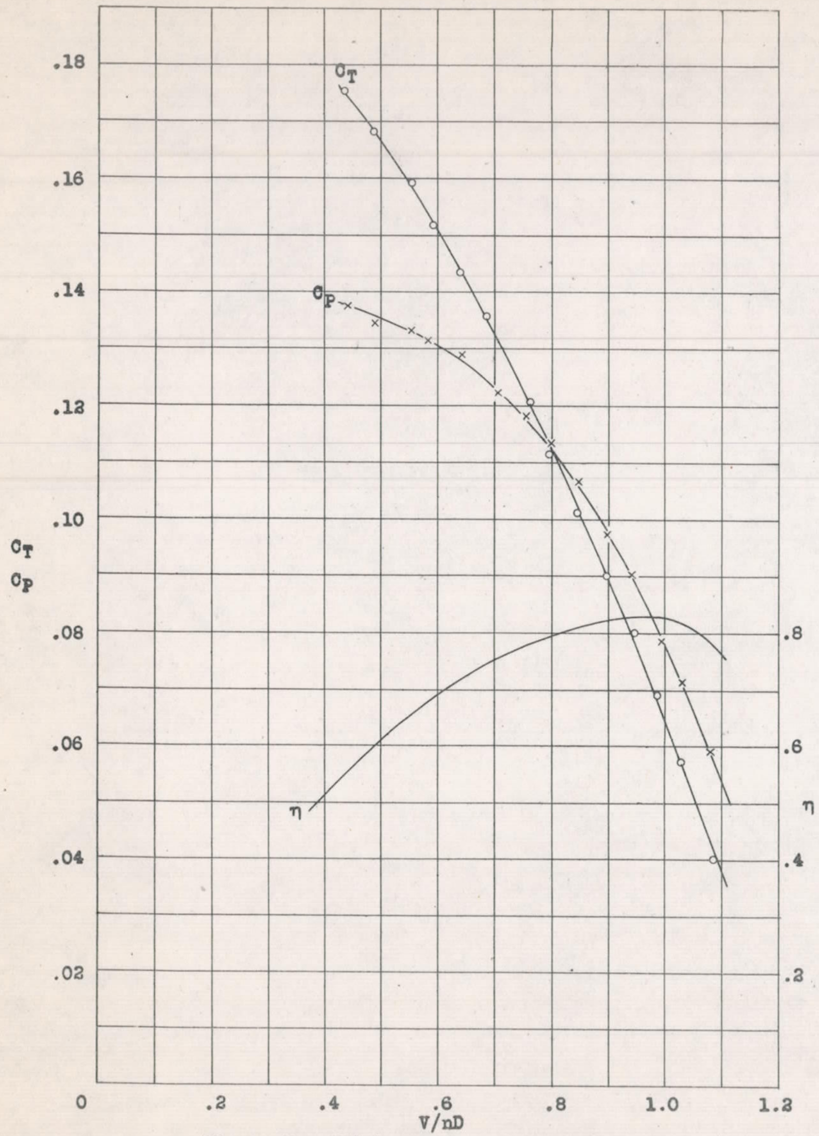

Figure 8.- 25° Propeller with body alone.

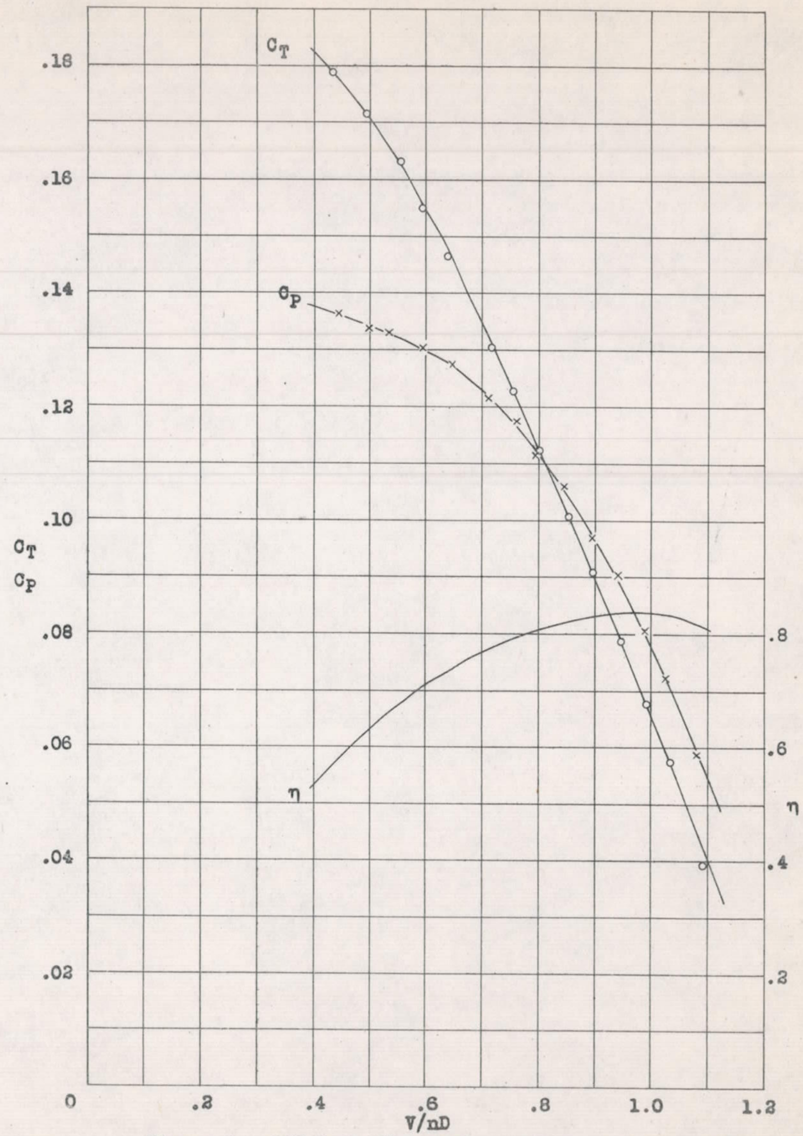

Figure 9.- 25° Propeller with contra-propeller at 4°.

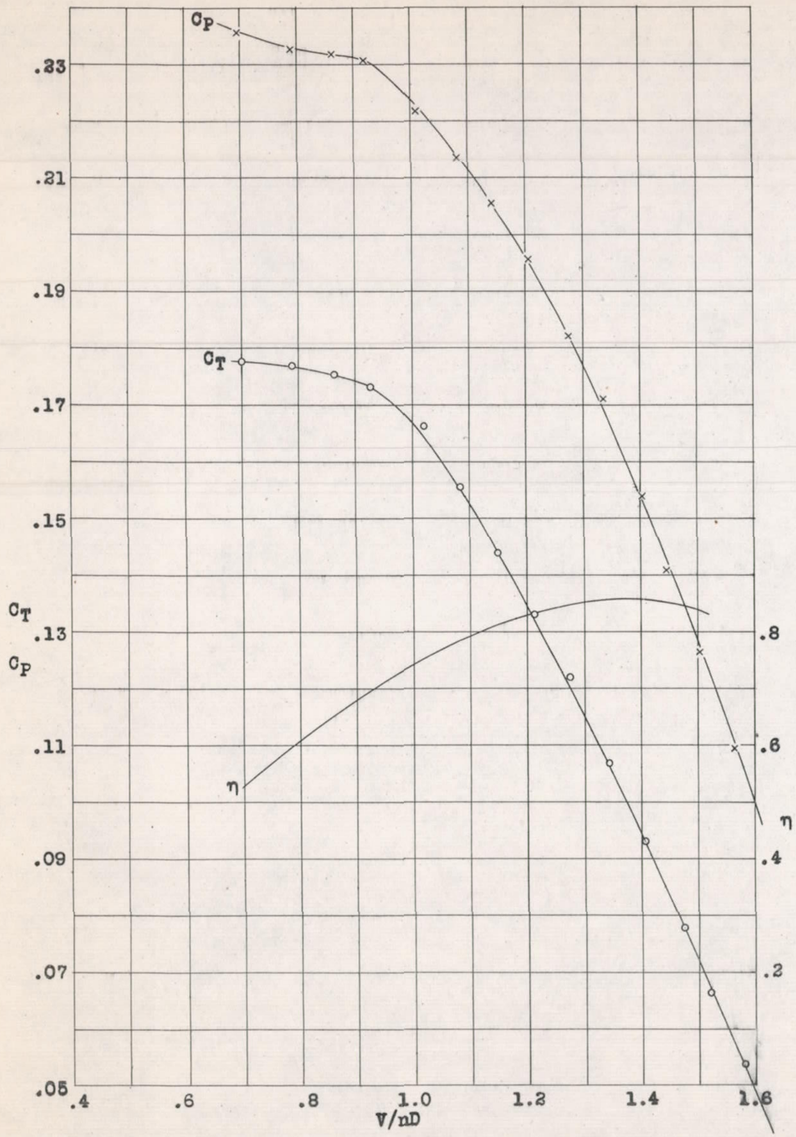

Figure 10.- 35° Propeller with body alone.

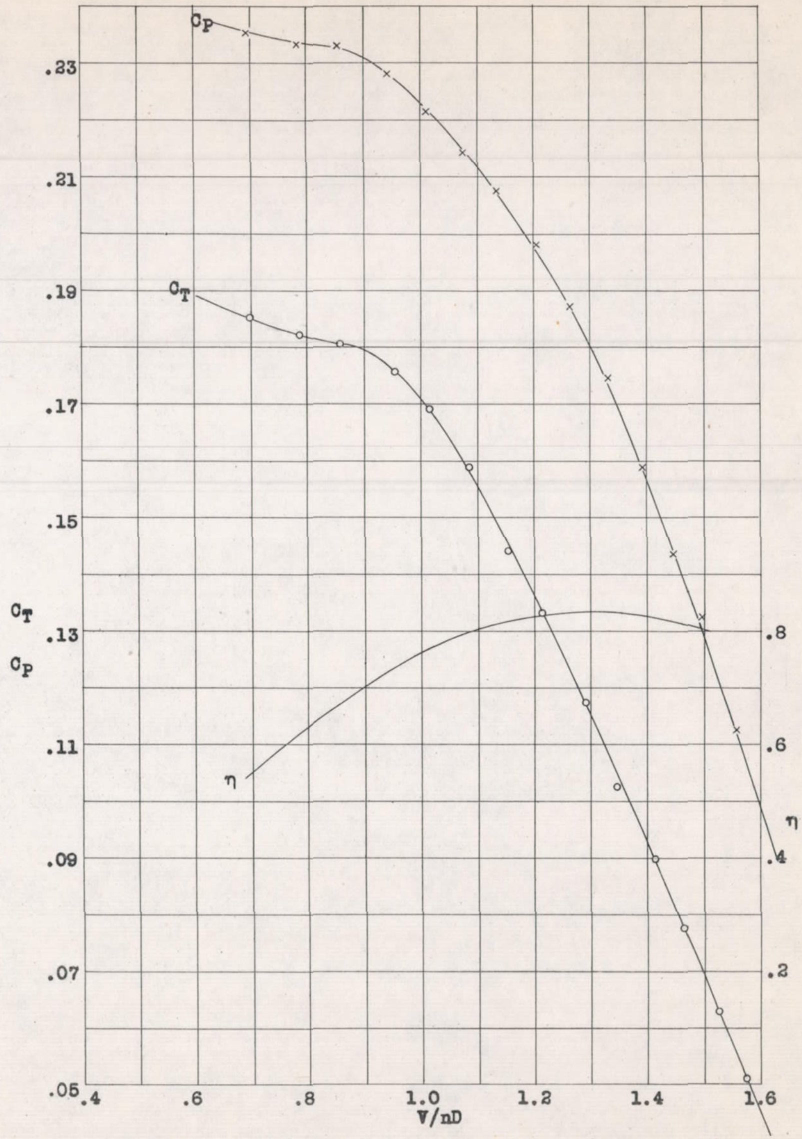

Figure 11.- 35° Propeller with contra-propeller at 4°.

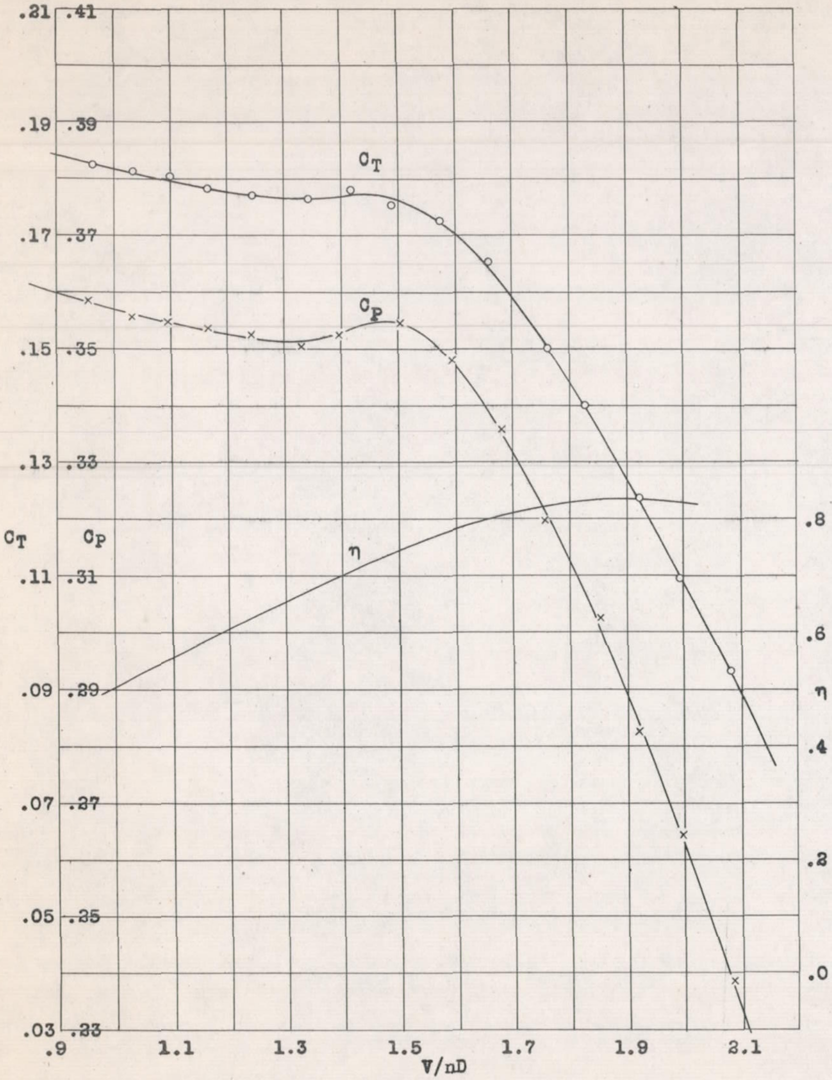

Figure 12.- 45° propeller with body alone.

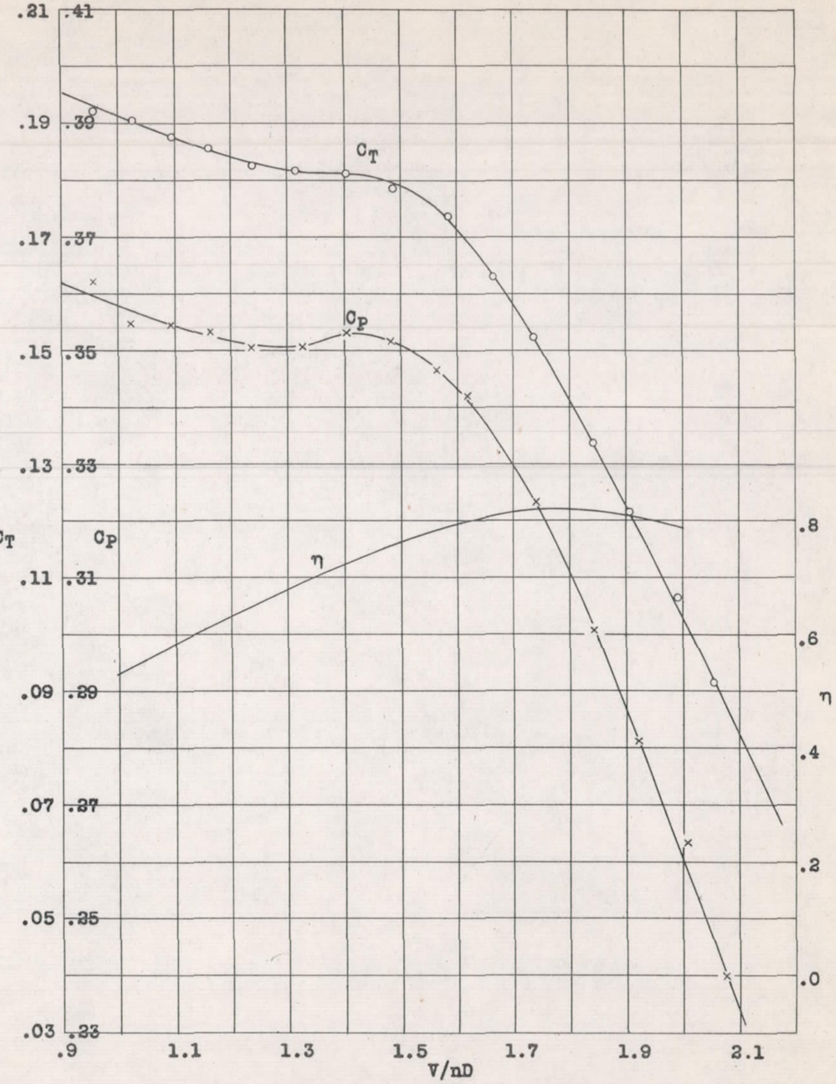

Figure 13.- 45° propeller with contra-propeller at 4°.

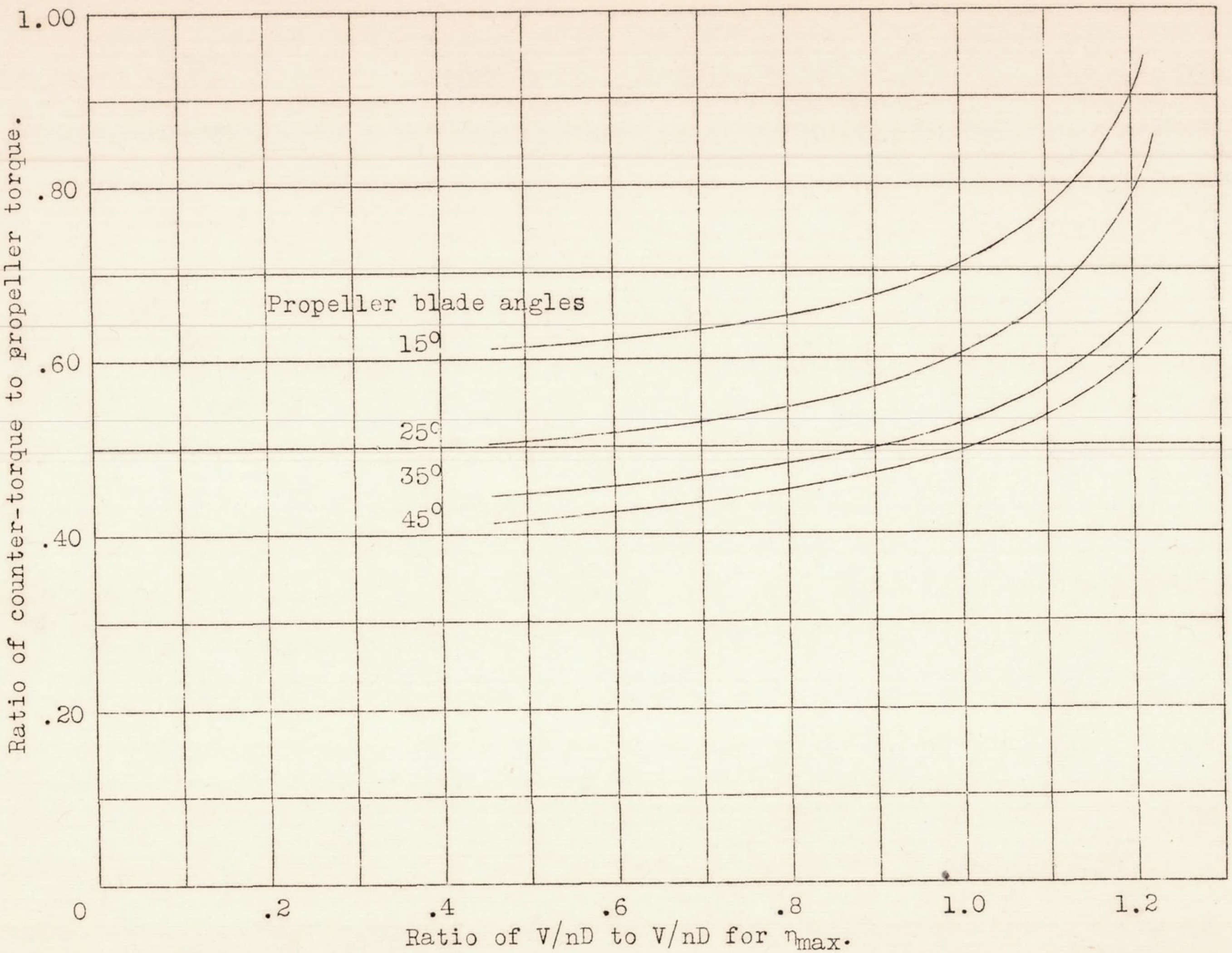

Figure 14.- Counter-torque with 4° contra-propeller blades.