To: Mr. Chas. J. McCarthy 14

66

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TANDEM AIR PROPELLERS

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SUMMARY

Tests of 2-blade, adjustable-pitch, counterrotating tandem model propellers, adjusted to absorb equal power at maximum efficiency, were made at Stanford University.

The characteristics, for 15°, 25°, 35°, and 45° pitch settings at 0.75 R of the forward propeller and for 8-1/2 percent, 15 percent and 30 percent diameter spacings, were compared with those of 2-blade and 4-blade propellers of the same blade form.

The tests showed that the efficiency of the tandem propellers was from 0.5 percent to 4 percent greater than that of a 4-blade propeller and, at the high pitch settings, not appreciably inferior to that of a 2-blade propeller.

It was found that the rear tandem propeller should be set at a pitch angle slightly less than that of the forward propeller to realize the condition of equal power at maximum efficiency. Under this condition the total power absorbed by the tandem propellers was from 3 percent to 9 percent more than that absorbed by the 4-blade propeller and about twice that absorbed by a 2-blade propeller.

INTRODUCTION

Tandem air propellers have been the subject of both experimental and theoretical investigations (references 1 to 5). The experimental studies for which data are available relate for the most part to tandem propellers separated by considerable distance, about one diameter, and with a body representing an engine nacelle between. The forward propeller was thus a tractor with interference in the rear, and rear propeller a pusher with interference forward of it.

At the request and with the financial assistance of the National Advisory Committee for Aeronautics, the present experimental study was carried out. The purpose was to determine the characteristics of tandem propellers under the condition of close spacing such as would be practicable with an engine having two concentric shafts geared together and with opposite directions of rotation.

While, in this case, the characteristics of the individual propellers of the tandem combination as well as the effect of each propeller upon the other might be of interest, the important consideration is the relation of the characteristics of the tandem combination as a whole to those of a single propeller designed to absorb the same power at the same angular velocity and speed of advance.

It is obvious that for tandem propellers of the same form, size, and angular velocity, the division of power absorbed between them would depend primarily on the relation of pitch. It seemed that an equal division of power under the usual conditions of operation might constitute an incidental advantage, since there would be no rolling moment due to propeller torque acting on the plane and the slipstream would be without twist. The condition that equal power should be absorbed by the two propellers at maximum efficiency of the combination was therefore arbitrarily chosen for determining the relation of pitch settings used for test.

APPARATUS AND TESTS

Wind tunnel.- The experiments of this investigation were carried on in the wind tunnel of the Daniel Guggenheim Aeronautical Laboratory of Stanford University. This tunnel is of the Eiffel type with open throat 7-1/2 feet in diameter. The maximum wind velocity is 90 miles per hour.

Dynamometer.- The propeller dynamometer is shown schematically in figure 1. It consists essentially of a long electric motor which is provided with a direct connected, right-hand rotation, shaft S_1, and a geared, left-hand rotation, shaft S_2. The whole assembly is mounted on knife edges below the shaft axis and is restrained from rolling by the torque arm A. The spider which carries the pinions of the bevel gear train is restrained from turning about the shaft axis by a second torque arm B.

The right-hand propeller P_1 is keyed to shaft S_1 and the left-hand propeller P_2 to shaft S_2. Any desired spacing of the propellers is obtained by moving P_1 along its shaft.

The right- and left-hand shafts are restrained from relative axial movement by thrust bearings, but the whole shaft assembly is free from longitudinal constraint. The total thrust is measured by a weighing device connected to a thrust bearing carried on shaft S_1.

The dynamometer is shielded by a sheet metal cover from wind forces other than those acting upon the propellers.

For this arrangement it can be shown that

$$Q_A = Q_{P_1} + Q_{P_2} + Q_F \tag{1}$$

and

$$Q_B = 2Q_{P_2} + Q_F \tag{2}$$

where Q_A is restraining torque acting through torque arm A.

Q_{P_1}, torque due to air forces acting on propeller P_1.

Q_{P_2}, torque due to air forces acting on propeller P_2.

Q_F, torque required to turn shafts against a combination of frictional resistances in the dynamometer bearings.

Q_B, restraining torque acting through torque arm B.

From (1) and (2)

$$Q_{P_1} - Q_{P_2} = Q_A - Q_B \tag{3}$$

and

$$Q_{P_1} + Q_{P_2} = Q_A - Q_F \tag{4}$$

If the left-hand propeller, P_2, alone is on the shaft

$$Q_A = Q_{P_2} + Q_F$$

$$Q_B = 2Q_{P_2} + Q_F$$

hence for this case

$$Q_F = 2Q_A - Q_B \qquad (5)$$

Figure 2 shows the appearance of the forward end of the dynamometer. It may be seen that the model propellers are well forward, actually one and one-half diameters, of any considerable slipstream obstruction.

Model propellers.- The propellers used in these tests were all 3-foot diameter metal models of standard U.S. Navy plan form and blade section. One was right-hand, 2-blade; another, left-hand, 2-blade; and the third, right-hand, 4-blade. Blades of all were adjustable in pitch. The geometrical pitch-diameter ratio, for a setting of 16.6° at 0.75 R, was 0.7 from 0.6 R outward to the tip. It gradually decreased from 0.6 R 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 6.

Tests.- Tests of the right- and left-hand 2-blade propellers and the 4-blade propeller were made at pitch settings for 0.75 R of 15°, 25°, 35°, and 45°.

In the tests of single propellers the torque arm B (fig. 1) and the pinions of the bevel gear train were removed. The two shafts were then locked together. The balance connected to torque arm A thus indicated the air-force torque on the propeller alone, the friction torque Q_F being eliminated.

Tests of the tandem propellers were made with the right-hand propeller in the forward position and set at pitch angles for 0.75 R of 15°, 25°, 35°, and 45°. The left-hand propeller was set at a pitch angle such that the two propellers absorbed equal power at maximum efficiency for the combination. The method of realizing this condition is shown in figure 3. With the forward propeller set at 25° and the rear propeller set first at 25° and later at 24° the differences in power coefficients of the forward and rear propellers were determined and plotted as functions of V/nD. At V/nD = 0.9, maximum efficiency of the 25° 2-blade propeller alone, the value of C_p (RH-LH) is seen to be -0.0023 for the 25° setting of the rear propeller and 0.0045 for the 24° setting. By interpolation the setting of the rear propeller that would give equal power at V/nD = 0.9 was estimated to be 24.7°. C_p (RH-LH) for the 24.7 setting of the rear propeller is also shown in figure 3. It is seen to be zero at V/nD = 0.9.

In the above test it was assumed that V/nD for maximum efficiency of the tandem combination would be the same as for a single propeller having a pitch setting equal to that of the forward propeller of the tandem pair. This assumption was later justified. (See fig. 18.)

Three spacings of the tandem propellers were used; 8-1/2 percent, 15 percent and 30 percent of propeller diameter, center to center of blade shanks. Originally it was planned that a closer spacing of 7-1/2-percent diameter would be employed, but propeller hubs and necessary bearings between them limited the minimum spacing to the 8-1/2-percent diameter used.

For the tests of the tandem propellers it was necessary to determine the friction torque Q_F in order to measure the total wind force torque $Q_{P_1} + Q_{P_2}$. Preliminary tests showed that friction torque was independent of torque load in the form of a couple with its center at the shaft axis, but that it depended primarily on rotational speed and oil viscosity, which latter was a function of temperature.

The tandem propeller tests therefore consisted of alternate runs of the left-hand rear alone and of the two propellers in tandem. From the observations of Q_A and Q_B for the single propeller runs, Q_F was computed by equation 5 and plotted against time. Values of Q_F for the intermediate runs with tandem propellers were then taken from a fair curve drawn through the plotted points. Uniform time intervals were used in corresponding operations of consecutive observations.

Following the Stanford laboratory practice a constant angular velocity was used for each test. Variation in the parameter V/nD was secured through change of the wind velocity. Because of limitations imposed by wind speed and by power and rotational speed available in the dynamometer, the rotational speeds employed were 2,000, 1,800, 1,500, and 1,100 revolutions per minute for the 15°, 25°, 35°, and 45° pitch settings, respectively. Assuming that the full-scale propeller would be nine feet in diameter and would operate at 2,000 r.p.m., the Reynolds Number of the tests was thus from 0.11 to 0.05 full scale.

The observations of the tests were reduced to the usual coefficients

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

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

$$\eta = \frac{T \times V}{P} = \frac{C_t}{C_D} \times \frac{V}{nD}$$

$$C_s = \sqrt[5]{\frac{\rho V^5}{P n^2}} = \frac{V}{nD} \sqrt[5]{\frac{1}{C_p}}$$

where T is propeller thrust.

ρ, mass density of the air.

η, revolutions per unit time.

D, propeller diameter.

P, power absorbed.

V, velocity.

RESULTS AND DISCUSSION

The propeller coefficients derived from the observations of these tests are given in table I. For the tandem propellers, C_p and C_s are coefficients computed for the total power of the tandem pair as is C_t a coefficient computed for the total thrust. C_p (RH-LH) is the difference between the power coefficients of the forward (right-hand) and rear (left-hand) propellers. The coefficients C_t, C_p, and η are shown graphically as functions of V/nD in figures 4 to 8. In addition, working charts for design selection of 2-blade, 4-blade, and tandem propellers are included in figures 9 to 11. The method of using these charts is described in reference 7, and a curve of C_p has been included for convenience in calculation of the thrust of automatic propellers at low air speeds. The final figure 12 compares a selected tandem-propeller combination with the 4-blade propeller.

From figures 4 and 5 it may be seen that the results of tests of the right-hand and left-hand 2-blade propellers at the same pitch settings are not identical. The right-hand propellers appear to absorb slightly smaller power and to have somewhat greater peak efficiency, particularly for the lower pitch settings. Micrometer measurements revealed that the right-hand blades were appreciably thinner than the left-hand, possibly enough to account for the difference in power coefficients found. The results for right-hand and left-hand propellers are, however, probably as nearly the same as could be expected from blades produced by the best commercial practice. For all practical purposes the right- and left-hand propellers may be regarded as identical.

To realize the condition of equal power at maximum efficiency in tandem propellers it was found in all cases except that of the 15° setting the rear propeller should be set at the smaller pitch angle. Eiffel's tests (reference 5) gave similar results. These present tests show that the difference in pitch setting required is a function of pitch itself. For the 15° setting no difference was found, while for 25°, 35°, and 45°, the differences were 0.3°, 0.6°, and 1.1°, respectively. In some cases it was found impracticable to realize, exactly, the condition of equal power at maximum efficiency. It was attained, however, within the limitations imposed by minimum observable change in blade angles, about 0.1°, and by probable error in difference of torque, about 0.02 lb. ft.

The data of figure 8 show that the spacing of tandem propellers has little effect upon the characteristics of the combination. With respect to efficiency the 15-percent diameter spacing appears somewhat better than the closer spacing of 8-1/2-percent diameter. The 30-percent spacing is but little, if any, better than 15 percent. It may be noted that thrust developed and power absorbed by the tandem propellers increase slightly with the spacing. This may be accounted for by the increase in pitch setting of the rear propeller required to maintain the condition of equal power at maximum efficiency as spacing is increased.

Effects of spacing, practically identical to the above, were observed for the tandem propellers at 35° pitch setting of the forward propeller. Since the 15-percent diameter spacing appeared definitely better than 8-1/2 percent and not appreciably worse than 30 percent for these two cases, only the 15-percent spacing was investigated for the forward propeller at 15° and 45°.

One incidental effect of close spacing was observed. At 8-1/2 percent the tandem propellers were extremely noisy. At 15 percent the sound was noticeably more than that produced by a 4-blade propeller of the same pitch, while at 30 percent it was, to the ear, but little louder than for a 4-blade propeller.

For corresponding pitch settings of 2-blade propellers and the forward blades of the tandem propellers, (compare, for example, figs. 4 and 7, and figs. 9 and 11) tandem propellers are generally less efficient than 2-blade propellers. The difference in maximum efficiency varies inversely with the pitch setting. It is about 4 percent at 15° and 0.5 percent at 35°. For 45° the tandem propellers appear to have a maximum efficiency about 0.5 percent greater than the 2-blade. In the climbing range, taken arbitrarily at 0.75 V/nD for maximum efficiency, the tandem propellers show about 5 percent less efficiency than the 2-blade propellers for the 15° setting but about 2.5 percent greater efficiency than the 2-blade propellers for the 45° setting.

At maximum efficiency, the power absorbed by the tandem propellers is from 1.87 to 1.97 times that absorbed by a 2-blade propeller. In the climbing range, the ratios are from 1.97 to 2.09. In each case the smaller ratio applies to the lower setting.

Comparison of the efficiency curves of the tandem and 4-blade propellers (fig. 12) shows that under practically all conditions of operation the former are somewhat more efficient. At maximum efficiency, the difference in favor of the tandem propellers is from 0.5 to 1.5 percent. In the climbing condition it becomes 2.5 percent for the 45° pitch setting.

At maximum efficiency the tandem propellers absorb from 3 to 5 percent more power than the 4-blade propellers. In the climbing condition the difference is from 4 to 9 percent. In both cases the high pitch propellers show the greater difference.

The above comparisons of power and efficiency are made at equal values of V/nD. Since the tandem propellers absorb greater power than 4-blade propellers however, a more significant basis for comparison of efficiency is at equal values of the speed power coefficient C_s. Figure 13 shows the efficiencies of the 45° 4-blade and 45°-43.9° tandem propellers as functions of the speed-power coefficient C_s. It may be seen that for all values of C_s throughout the working range the efficiency of the tandem propellers is appreciably greater. The maximum difference is about 4 percent. The gain in efficiency for this case is the largest found. For smaller pitch settings it becomes progressively less and is negligible, about 0.5 percent, at 15°.

CONCLUSIONS

These tests have shown that identical, counterrotating, 2-blade, close-spaced, tandem propellers, adjusted in pitch to absorb equal power at maximum efficiency, have from 0.5 percent to 4 percent greater efficiency than that of 4-blade propellers of the same blade form and designed to absorb the same total power.

Tandem propellers are inferior in efficiency to single 2-blade propellers for pitch settings at 0.75 R of less than 35°. For higher pitch settings, the tandem propellers have an appreciable advantage.

Tandem propellers absorb from 3 percent to 9 percent more power than 4-blade propellers and about twice the power of 2-blade propellers of equal diameter.

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Daniel Guggenheim Aeronautical Laboratory,
Stanford University, July 14, 1937.

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TABLE I

PROPELLER COEFFICIENTS

Two-Blade Right-Hand Propeller

15° at 0.75 R

V/nD	C_t	C_p	C_s	η
0.740	0.0040	0.0103	1.848	0.291
.716	.0085	.0126	1.717	.482
.681	.0153	.0160	1.557	.653
.646	.0206	.0186	1.433	.718
.626	.0248	.0204	1.364	.760
.600	.0290	.0226	1.280	.771
.568	.0334	.0241	1.197	.787
.529	.0395	.0265	1.094	.789
.509	.0423	.0276	1.043	.780
.478	.0463	.0285	.974	.775
.449	.0499	.0294	.909	.761
.420	.0537	.0305	.845	.740
.390	.0571	.0312	.780	.713
.348	.0622	.0323	.692	.672
.302	.0673	.0329	.598	.617
.222	.0754	.0330	.439	.507

TABLE I - Continued

Two-Blade Right-Hand Propeller

25° at 0.75 R

V/nD	C_t	C_p	C_s	η
1.181	0.0033	0.0160	2.700	0.240
1.140	.0110	.0218	2.451	.577
1.086	.0192	.0289	2.207	.720
1.040	.0275	.0361	2.022	.792
.994	.0350	.0418	1.877	.832
.944	.0409	.0464	1.745	.830
.898	.0479	.0515	1.626	.836
.854	.0536	.0548	1.527	.835
.803	.0604	.0586	1.417	.828
.767	.0641	.0609	1.342	.807
.718	.0699	.0632	1.248	.794
.667	.0776	.0662	1.148	.782
.612	.0823	.0673	1.050	.748
.540	.0898	.0684	.924	.709
.500	.0927	.0682	.855	.680
.430	.0962	.0705	.731	.586
.328	.0966	.0718	.556	.442
.233	.0947	.0751	.391	.294

TABLE I - Continued

Two-Blade Right-Hand Propeller

35° at 0.75 R

V/nD	C_t	C_p	C_s	η
1.620	0.0219	0.0555	2.889	0.638
1.571	.0275	.0616	2.744	.700
1.518	.0352	.0705	2.580	.758
1.454	.0439	.0799	2.411	.794
1.395	.0514	.0879	2.268	.816
1.335	.0589	.0950	2.137	.826
1.255	.0666	.1018	1.984	.822
1.205	.0726	.1070	1.884	.817
1.141	.0805	.1124	1.767	.814
1.067	.0851	.1163	1.641	.780
1.009	.0894	.1191	1.544	.757
.940	.0910	.1209	1.435	.708
.874	.0932	.1210	1.333	.674
.817	.0930	.1220	1.244	.623
.739	.0939	.1225	1.126	.566
.675	.0952	.1246	1.024	.516
.600	.0962	.1272	.907	.454
.529	.0984	.1299	.796	.401
.440	.0991	.1345	.657	.324
.314	.1025	.1395	.466	.230

TABLE I - Continued

Two-Blade Right-Hand Propeller

45° at 0.75 R

V/nD	C_t	C_p	C_s	η
2.254	0.0286	0.1034	3.550	0.623
2.170	.0375	.1170	3.335	.696
2.103	.0448	.1282	3.173	.735
2.040	.0521	.1387	3.027	.759
1.959	.0596	.1493	2.867	.782
1.888	.0662	.1574	2.732	.794
1.813	.0737	.1665	2.595	.802
1.740	.0804	.1745	2.469	.802
1.656	.0864	.1818	2.329	.787
1.577	.0888	.1858	2.210	.754
1.492	.0910	.1863	2.089	.729
1.408	.0891	.1840	1.977	.682
1.321	.0899	.1835	1.855	.648
1.227	.0914	.1837	1.723	.611
1.136	.0928	.1846	1.593	.571
1.044	.0933	.1856	1.462	.525
.923	.0941	.1906	1.285	.456
.824	.0944	.1934	1.145	.403
.713	.0944	.1970	.987	.342
.559	.0984	.2075	.766	.265

TABLE I - Continued

Two-Blade Left-Hand Propeller

15° at 0.75 R

V/nD	C_t	C_p	C_s	η
0.757	0.0007	0.0080	1.988	0.071
.717	.0089	.0126	1.719	.507
.674	.0165	.0167	1.528	.666
.630	.0239	.0204	1.372	.737
.599	.0294	.0230	1.274	.766
.565	.0347	.0253	1.178	.774
.544	.0376	.0263	1.126	.776
.510	.0429	.0280	1.043	.781
.478	.0479	.0297	.967	.770
.444	.0531	.0313	.888	.752
.416	.0561	.0322	.827	.724
.368	.0617	.0332	.727	.684
.326	.0668	.0336	.643	.648
.282	.0707	.0341	.554	.584
.224	.0757	.0342	.440	.497
.129	.0844	.0330	.255	.331

TABLE I - Continued **B**

Two-Blade Left-Hand Propeller

25° at 0.75 R

V/nD	C_t	C_p	C_s	η
1.178	0.0042	0.0182	2.624	0.272
1.129	.0143	.0271	2.323	.595
1.081	.0232	.0350	2.113	.714
1.027	.0317	.0416	1.940	.786
.974	.0390	.0466	1.798	.816
.914	.0470	.0519	1.653	.827
.858	.0545	.0562	1.527	.832
.796	.0621	.0605	1.394	.817
.732	.0696	.0637	1.269	.799
.674	.0776	.0674	1.156	.776
.592	.0861	.0688	1.012	.741
.519	.0932	.0693	.886	.698
.457	.0946	.0706	.776	.614
.405	.0922	.0740	.682	.505
.329	.0928	.0753	.552	.404
.238	.0948	.0774	.397	.293

TABLE I - Continued

Two-Blade Left-Hand Propeller

35° at 0.75 R

V/nD	C_t	C_p	C_s	η
1.601	0.0252	0.0597	2.813	0.675
1.550	.0323	.0681	2.654	.735
1.503	.0390	.0747	2.526	.784
1.431	.0476	.0847	2.345	.805
1.380	.0535	.0904	2.230	.816
1.322	.0614	.0980	2.105	.829
1.265	.0664	.1023	1.996	.822
1.198	.0739	.1077	1.871	.822
1.121	.0819	.1123	1.735	.817
1.046	.0878	.1156	1.610	.795
.993	.0898	.1187	1.523	.751
.912	.0882	.1202	1.393	.669
.818	.0900	.1216	1.247	.605
.713	.0924	.1230	1.085	.536
.681	.0938	.1240	1.033	.515
.604	.0962	.1260	.914	.461
.491	.0996	.1308	.737	.374
.412	.1016	.1341	.616	.312

TABLE I - Continued

Two-Blade Left-Hand Propeller

45° at 0.75 R

V/nD	C_t	C_p	C_s	η
2.205	0.0340	0.1114	3.422	0.674
2.156	.0400	.1215	3.287	.710
2.060	.0499	.1381	3.061	.744
1.984	.0576	.1496	2.900	.765
1.912	.0644	.1570	2.769	.784
1.819	.0732	.1664	2.605	.800
1.713	.0820	.1756	2.427	.799
1.642	.0869	.1810	2.312	.789
1.546	.0885	.1837	2.170	.745
1.467	.0887	.1817	2.063	.721
1.442	.0890	.1813	2.028	.708
1.357	.0885	.1820	1.908	.660
1.265	.0900	.1818	1.778	.626
1.178	.0913	.1811	1.657	.594
1.087	.0920	.1811	1.530	.552
.973	.0936	.1835	1.365	.496
.841	.0976	.1861	1.175	.436
.709	.1002	.1940	.984	.366
.551	.1022	.2003	.760	.281

TABLE I - Continued

Four-Blade Propeller

15° at 0.75 R

V/nD	C_t	C_p	C_s	η
0.744	0.0020	0.0155	1.713	0.095
.713	.0137	.0220	1.532	.445
.679	.0244	.0278	1.391	.597
.646	.0353	.0334	1.275	.684
.627	.0405	.0359	1.221	.708
.595	.0494	.0403	1.132	.730
.553	.0600	.0449	1.029	.741
.525	.0680	.0480	.964	.743
.493	.0758	.0512	.893	.731
.467	.0825	.0535	.839	.720
.445	.0861	.0548	.796	.698
.406	.0958	.0576	.719	.677
.381	.1004	.0594	.670	.646
.335	.1086	.0610	.586	.596
.300	.1148	.0624	.523	.552
.263	.1206	.0632	.457	.502
.227	.1258	.0634	.394	.451

TABLE I - Continued C

Four-Blade Propeller

25° at 0.75 R

V/nD	C_t	C_p	C_s	η
1.171	0.0062	0.0327	2.320	0.222
1.128	.0209	.0458	2.090	.515
1.078	.0381	.0594	1.897	.692
1.046	.0488	.0685	1.788	.745
.998	.0613	.0785	1.661	.779
.960	.0719	.0864	1.567	.799
.906	.0824	.0936	1.455	.798
.883	.0888	.0979	1.405	.801
.853	.0978	.1038	1.342	.803
.823	.1041	.1084	1.283	.791
.786	.1126	.1130	1.216	.783
.735	.1221	.1174	1.128	.765
.687	.1331	.1226	1.045	.748
.640	.1429	.1265	.968	.722
.583	.1545	.1300	.877	.693
.523	.1633	.1313	.785	.650
.465	.1736	.1341	.695	.603
.409	.1780	.1368	.609	.532
.333	.1753	.1411	.493	.406
.267	.1771	.1430	.394	.331

TABLE I - Continued

Four-Blade Propeller

35° at 0.75 R

V/nD	C_t	C_p	C_s	η
1.597	0.0409	0.1032	2.515	0.632
1.544	.0545	.1189	2.364	.708
1.484	.0684	.1347	2.217	.754
1.440	.0796	.1476	2.112	.776
1.406	.0873	.1550	2.042	.790
1.374	.0956	.1641	1.972	.801
1.336	.1031	.1704	1.905	.808
1.274	.1153	.1816	1.792	.808
1.206	.1312	.1954	1.672	.810
1.138	.1451	.2065	1.561	.799
1.078	.1565	.2146	1.467	.786
1.006	.1661	.2213	1.362	.757
.938	.1669	.2268	1.263	.691
.877	.1695	.2275	1.179	.653
.820	.1700	.2265	1.104	.616
.750	.1724	.2298	1.006	.563
.670	.1757	.2352	.895	.501
.584	.1812	.2410	.776	.439
.482	.1843	.2440	.638	.364
.352	.1884	.2534	.463	.262

TABLE I - Continued

Four-Blade Propeller

45° at 0.75 R

V/nD	C_t	C_p	C_s	η
2.184	0.0661	0.2135	2.978	0.676
2.085	.0865	.2418	2.772	.746
2.020	.0990	.2619	2.640	.764
1.930	.1160	.2856	2.480	.784
1.848	.1289	.3022	2.350	.790
1.807	.1364	.3100	2.283	.796
1.710	.1522	.3290	2.136	.791
1.626	.1635	.3447	2.013	.772
1.542	.1679	.3502	1.902	.739
1.448	.1704	.3500	1.786	.706
1.349	.1716	.3505	1.664	.661
1.258	.1722	.3502	1.552	.619
1.134	.1756	.3510	1.398	.567
1.052	.1779	.3530	1.295	.530
.958	.1815	.3571	1.177	.487
.821	.1830	.3614	1.007	.415
.660	.1876	.3725	.804	.332
.532	.1910	.3828	.644	.265

TABLE I. - Continued

Tandem Propellers

Right-Hand (Forward) 15° at 0.75 R
Left-Hand (Rear) 15° at 0.75 R

15 Percent Diameter Spacing

V/nD	C_t	C_p	C_p(RH-LH)	C_s	η
0.749	0.0023	0.0166	0.0009	1.700	0.102
.715	.0143	.0232	.0006	1.518	.440
.675	.0271	.0297	.0007	1.363	.625
.639	.0382	.0353	.0006	1.247	.690
.602	.0494	.0408	.0005	1.142	.729
.568	.0595	.0452	.0003	1.056	.747
.550	.0636	.0468	.0002	1.015	.748
.520	.0718	.0495	-.0003	.949	.754
.491	.0795	.0528	-.0004	.885	.739
.441	.0920	.0573	-.0006	.781	.708
.408	.0990	.0601	-.0004	.716	.672
.362	.1078	.0619	-.0011	.632	.631
.308	.1203	.0654	-.0011	.532	.567
.242	.1318	.0663	-.0019	.416	.480

D

TABLE I - Continued

Right-Hand (Forward) 25° at 0.75 R
Left-Hand (Rear) 24.7° at 0.75 R

15 Percent Diameter Spacing

V/nD	C_t	C_p	C_p(RH-LH)	C_s	η
1.185	0.0038	0.0288	0.0042	2.410	0.157
1.125	.0258	.0484	.0028	2.064	.600
1.051	.0493	.0683	.0016	1.798	.759
.969	.0731	.0871	.0006	1.578	.813
.912	.0878	.0982	.0001	1.450	.815
.830	.1084	.1123	-.0005	1.286	.801
.732	.1309	.1251	-.0013	1.110	.766
.668	.1455	.1320	-.0021	1.002	.736
.600	.1600	.1372	-.0027	.893	.700
.519	.1755	.1408	-.0042	.768	.647
.437	.1889	.1455	-.0060	.643	.567
.333	.1955	.1515	-.0088	.486	.428
.247	.1987	.1566	-.0110	.358	.313

TABLE 1 - Continued

Tandem Propellers

Right-Hand (Forward) 35° at 0.75 R
Left-Hand (Rear) 34.4° at 0.75 R

15 Percent Diameter Spacing

V/nD	C_t	C_p	C_p(RH-LH)	C_s	η
1.611	0.0385	0.1019	0.0060	2.543	0.610
1.547	.0576	.1238	.0045	2.350	.720
1.489	.0728	.1405	.0019	2.207	.766
1.442	.0837	.1530	.0016	2.100	.789
1.377	.1003	.1710	.0005	1.960	.808
1.310	.1161	.1870	-.0005	1.830	.813
1.244	.1297	.1986	-.0011	1.722	.812
1.182	.1447	.2110	-.0023	1.614	.810
1.105	.1606	.2220	-.0036	1.494	.800
1.042	.1718	.2310	-.0041	1.397	.784
.969	.1851	.2386	-.0055	1.294	.751
.889	.1925	.2476	-.0066	1.178	.691
.816	.1975	.2554	-.0074	1.075	.631
.732	.1988	.2570	-.0093	.962	.566
.662	.2016	.2590	-.0104	.868	.515
.597	.2056	.2635	-.0115	.779	.466
.493	.2112	.2705	-.0121	.639	.385
.349	.2196	.2840	-.0135	.449	.269

TABLE I - Continued

Tandem Propellers

Right-Hand (Forward) 45° at 0.75 R
Left-Hand (Rear) 43.9° at 0.75 R

15 Percent Diameter Spacing

V/nD	C_t	C_p	C_p(RH-LH)	C_s	η
2.250	0.0557	0.2011	0.0123	3.100	0.623
2.150	.0744	.2270	.0099	2.892	.705
2.074	.0923	.2533	.0068	2.730	.755
1.995	.1082	.2757	.0048	2.582	.784
1.919	.1253	.2968	.0014	2.447	.810
1.849	.1390	.3176	.0009	2.327	.809
1.762	.1546	.3357	-.0014	2.192	.811
1.682	.1680	.3517	-.0021	2.072	.803
1.598	.1804	.3653	-.0023	1.954	.790
1.506	.1895	.3762	-.0074	1.832	.759
1.410	.1933	.3822	-.0134	1.698	.713
1.314	.1949	.3830	-.0197	1.592	.668
1.230	.1976	.3843	-.0194	1.488	.632
1.132	.2011	.3845	-.0184	1.370	.592
1.016	.2047	.3867	-.0178	1.229	.538
.883	.2084	.3930	-.0185	1.064	.460
.756	.2115	.4028	-.0195	.907	.397
.613	.2136	.4125	-.0216	.731	.317

TABLE I - Continued

Tandem Propellers

Right-Hand (Forward) 25° at 0.75 R
Left-Hand (Rear) 24.5° at 0.75 R

8-1/2 Percent Diameter Spacing

V/nD	c_t	c_p	c_p(RH-LH)	c_s	η
1.177	0.0055	0.0307	0.0058	2.363	0.211
1.127	.0230	.0475	.0049	2.072	.546
1.080	.0391	.0605	.0038	1.891	.698
1.029	.0549	.0742	.0023	1.733	.762
.970	.0720	.0870	.0010	1.581	.803
.918	.0854	.0970	.0004	1.465	.808
.858	.0997	.1070	-.0001	1.343	.799
.790	.1151	.1159	-.0007	1.216	.784
.728	.1295	.1238	-.0013	1.107	.760
.666	.1445	.1306	-.0020	1.001	.737
.598	.1585	.1360	-.0031	.892	.697
.521	.1735	.1400	-.0039	.772	.646
.449	.1852	.1410	-.0043	.664	.589
.352	.1961	.1469	-.0060	.517	.470
.245	.2000	.1535	-.0080	.356	.319

TABLE I - Continued

Tandem Propellers

Right-Hand (Forward) 25° at 0.75 R
Left-Hand (Rear) 24.8° at 0.75 R

30 Percent Diameter Spacing

V/nD	c_t	c_p	c_p(RH-LH)	c_s	η
1.187	0.0059	0.0318	0.0007	2.365	0.222
1.140	.0234	.0474	.0005	2.100	.563
1.096	.0385	.0602	.0004	1.923	.697
1.045	.0551	.0744	.0001	1.758	.774
.990	.0695	.0858	0	1.619	.802
.944	.0811	.0941	0	1.514	.812
.896	.0944	.1036	-.0002	1.410	.816
.855	.1055	.1107	-.0005	1.328	.815
.784	.1230	.1216	-.0010	1.195	.793
.756	.1290	.1253	-.0014	1.145	.778
.704	.1406	.1302	-.0016	1.060	.760
.655	.1511	.1347	-.0018	.978	.734
.607	.1626	.1390	-.0026	.901	.710
.540	.1755	.1416	-.0035	.798	.669
.469	.1871	.1445	-.0058	.691	.607
.415	.1939	.1493	-.0070	.607	.539
.346	.1970	.1544	-.0098	.503	.441
.240	.1976	.1595	-.0120	.346	.297

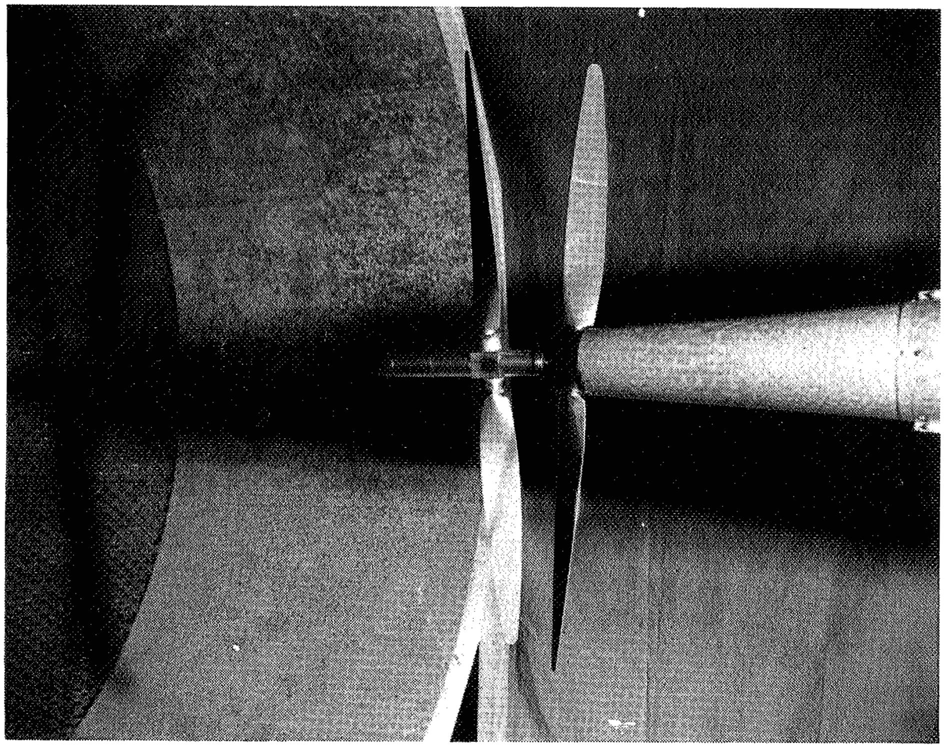

Figure 2.- Forward end of propeller dynamometer with tandem propellers at 15 percent diameter spacing.

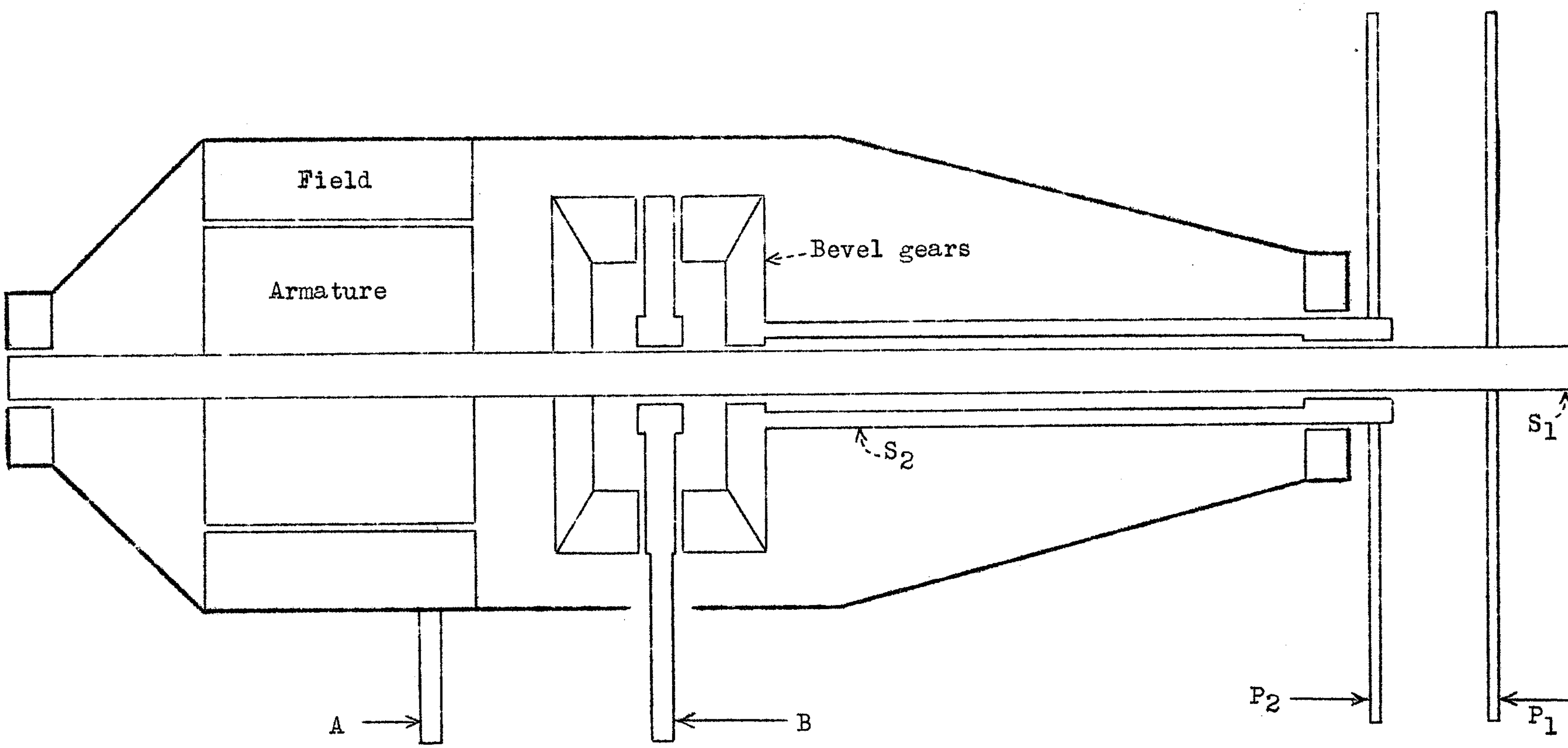

Figure 1.- Schematic section of propeller dynamometer.

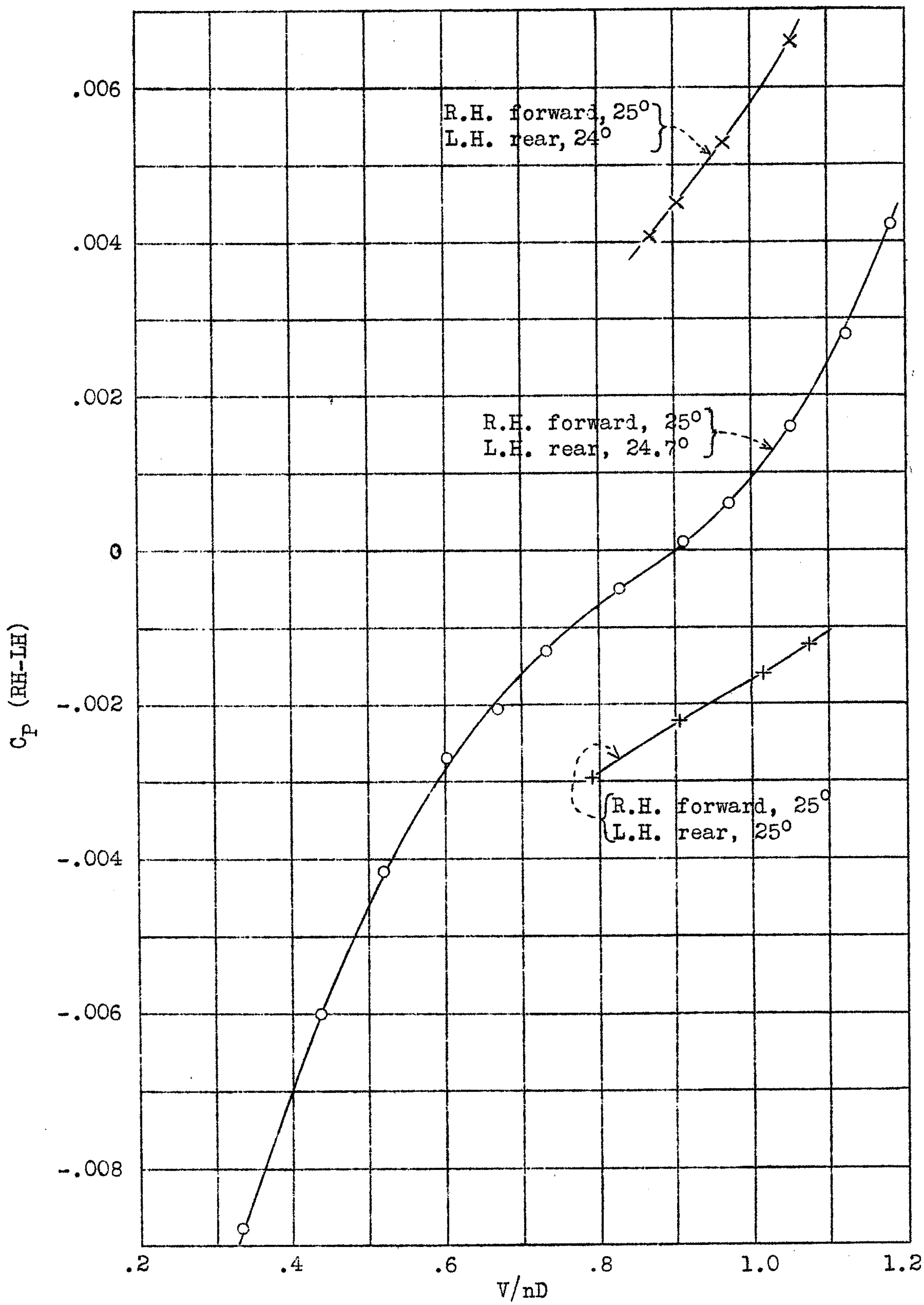

Figure 3.- Difference in power coefficients as affected by change in rear propeller pitch setting.

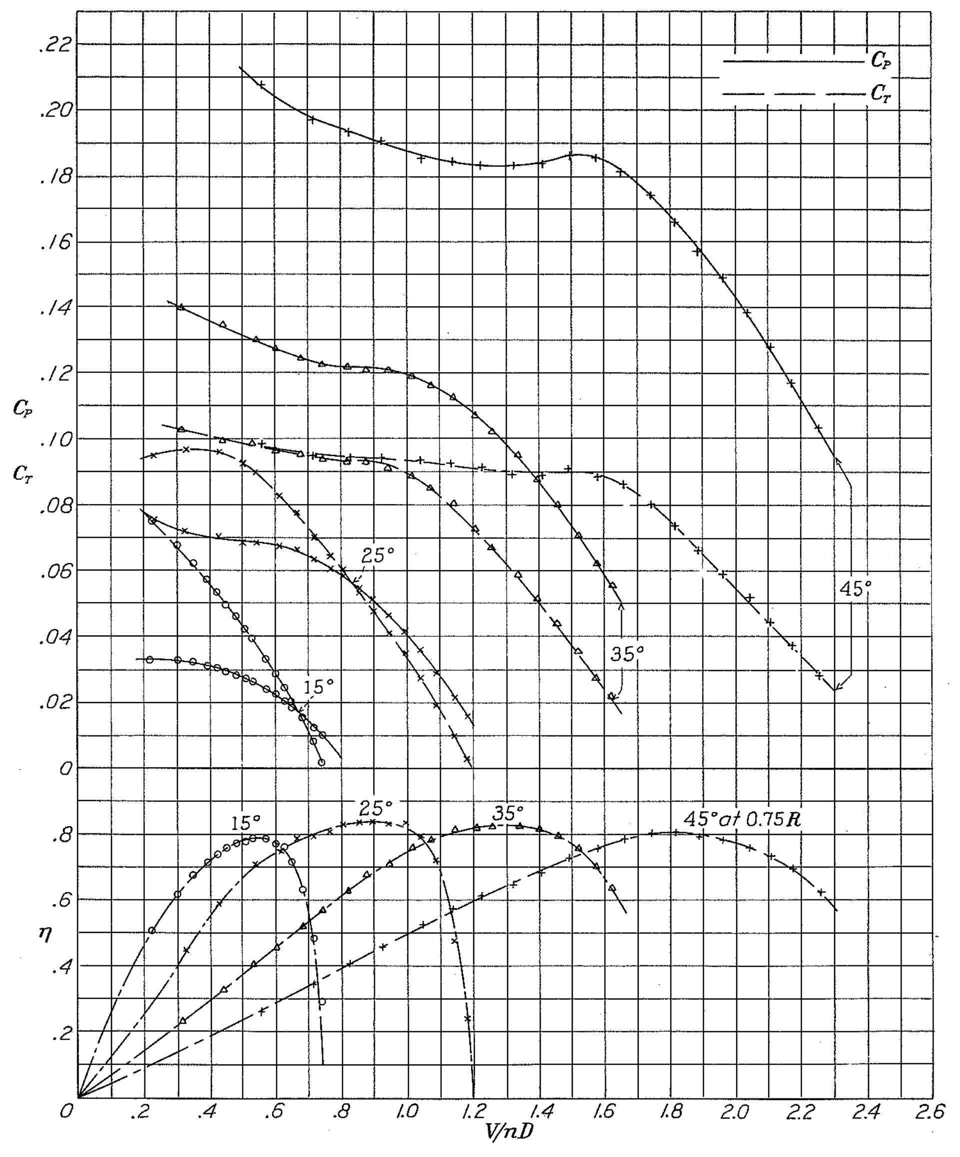

Figure 4.- Power, thrust, and efficiency. Two blade right-hand propeller.

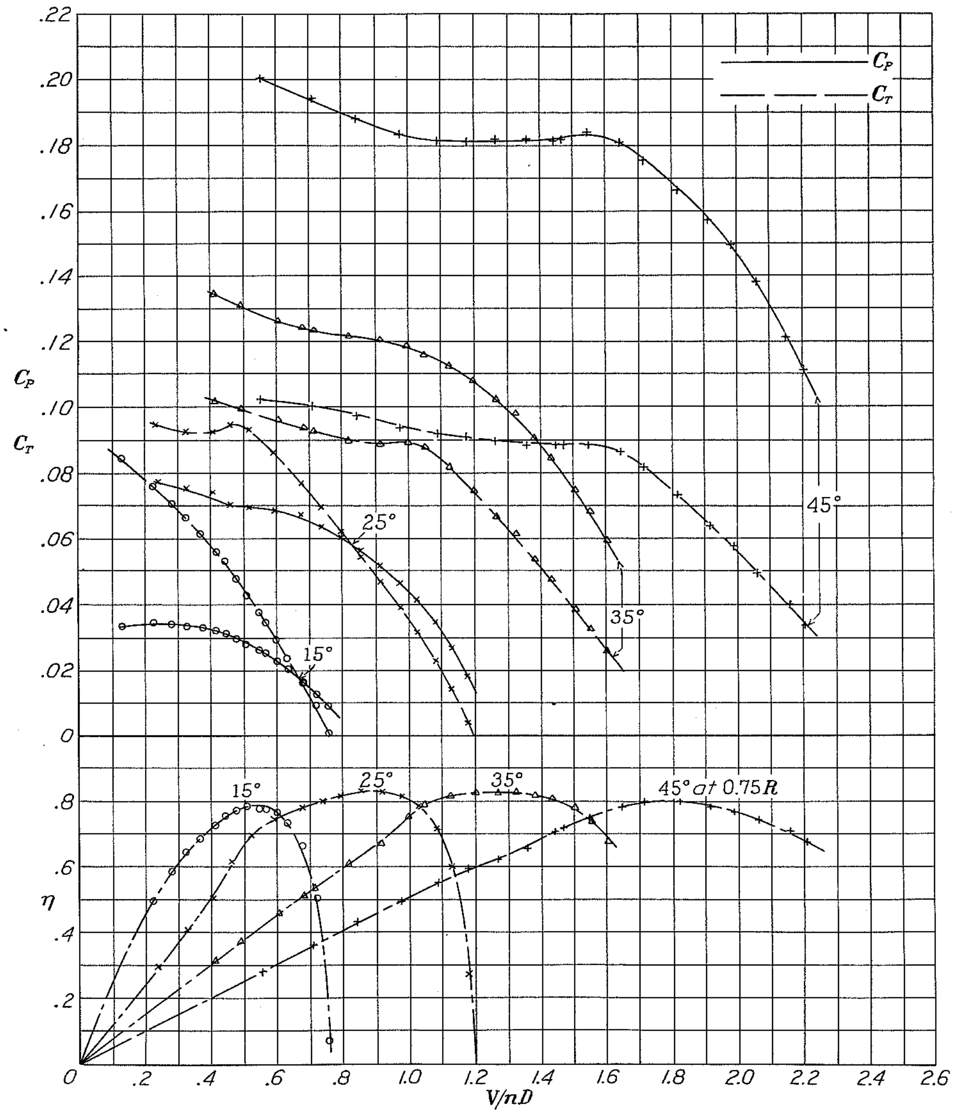

Figure 5.- Power, thrust, and efficiency. Two blade left-hand propeller.

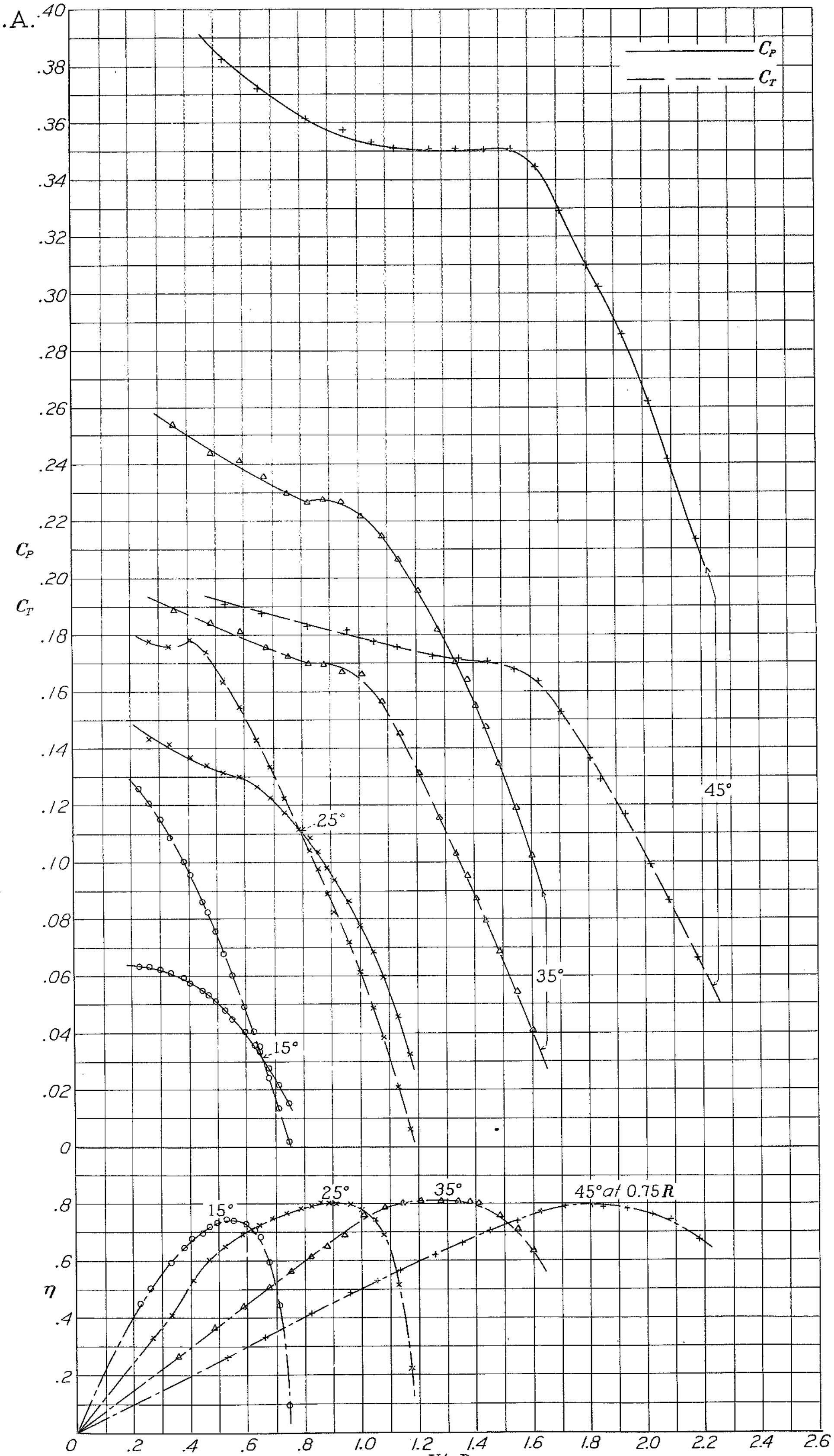

Figure 6.- Power, thrust, and efficiency. Four blade right-hand propeller.

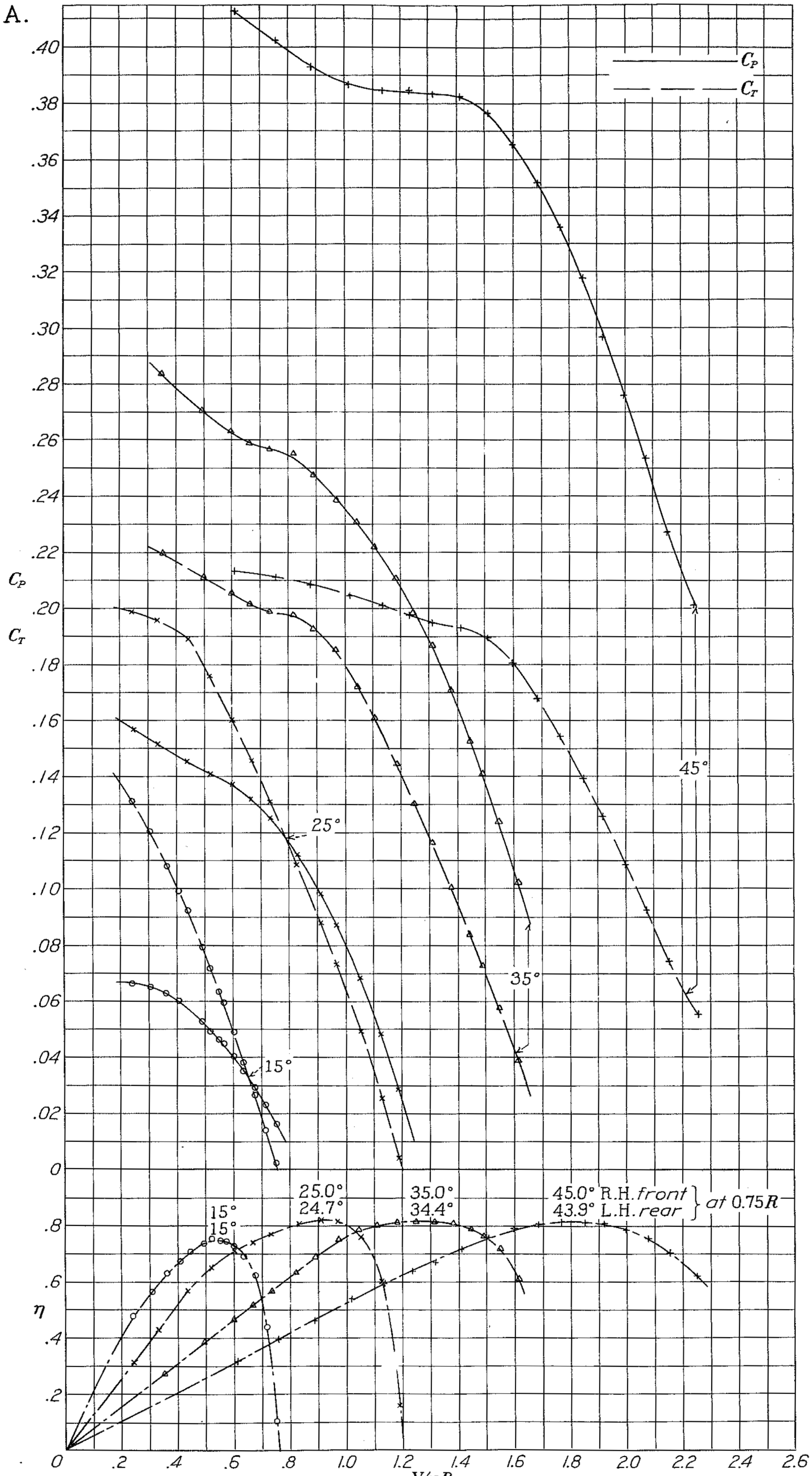

Figure 7.- Power, thrust, and efficiency. Two blade tandem R.H. (forward) and L.H. (rear) propellers with 15% diameter spacing.

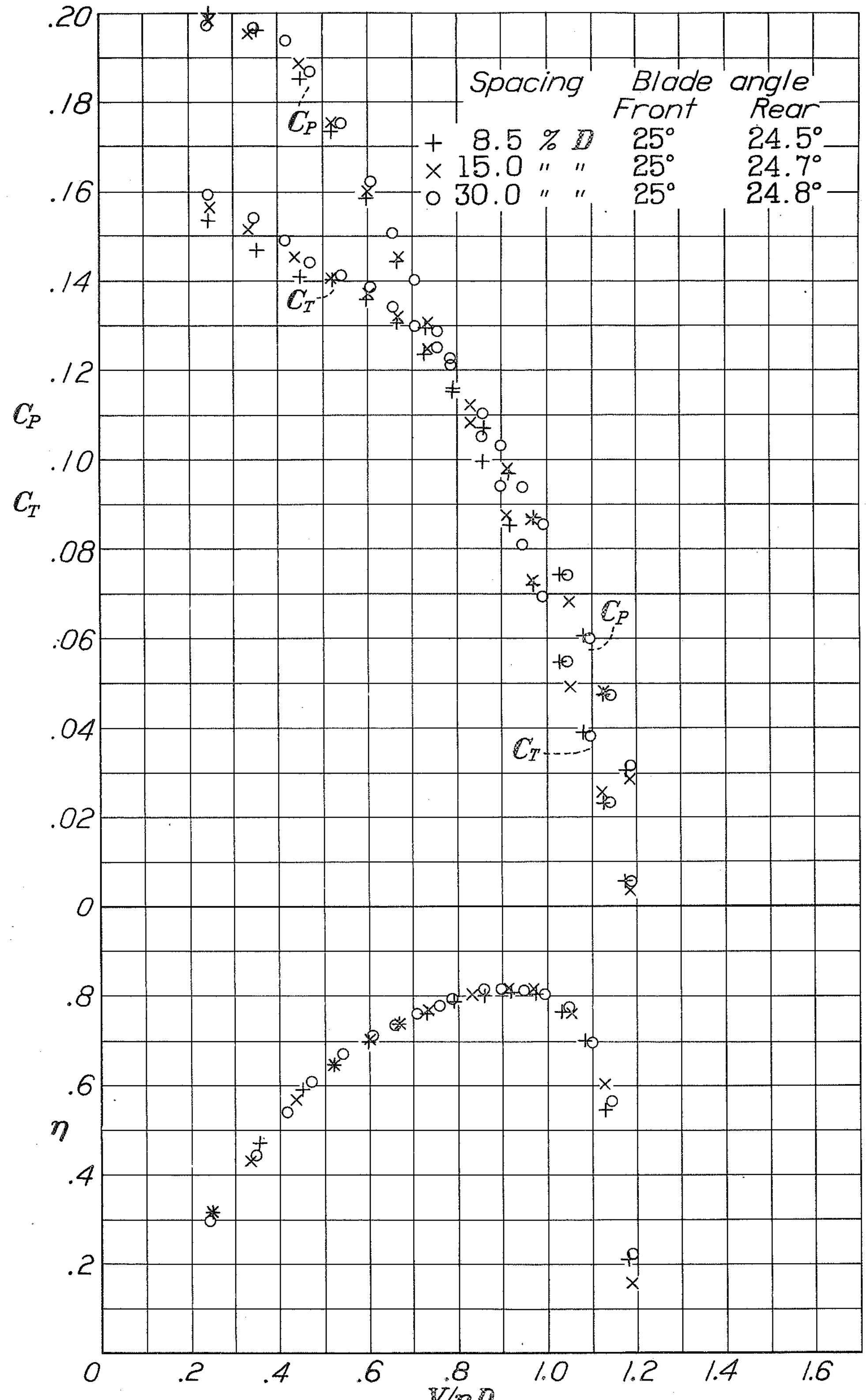

Figure 8.- Power, thrust, and efficiency. Two-blade tandem R.H. (front) and L.H. (rear) propellers with 25° blade angle and various axial spacings.

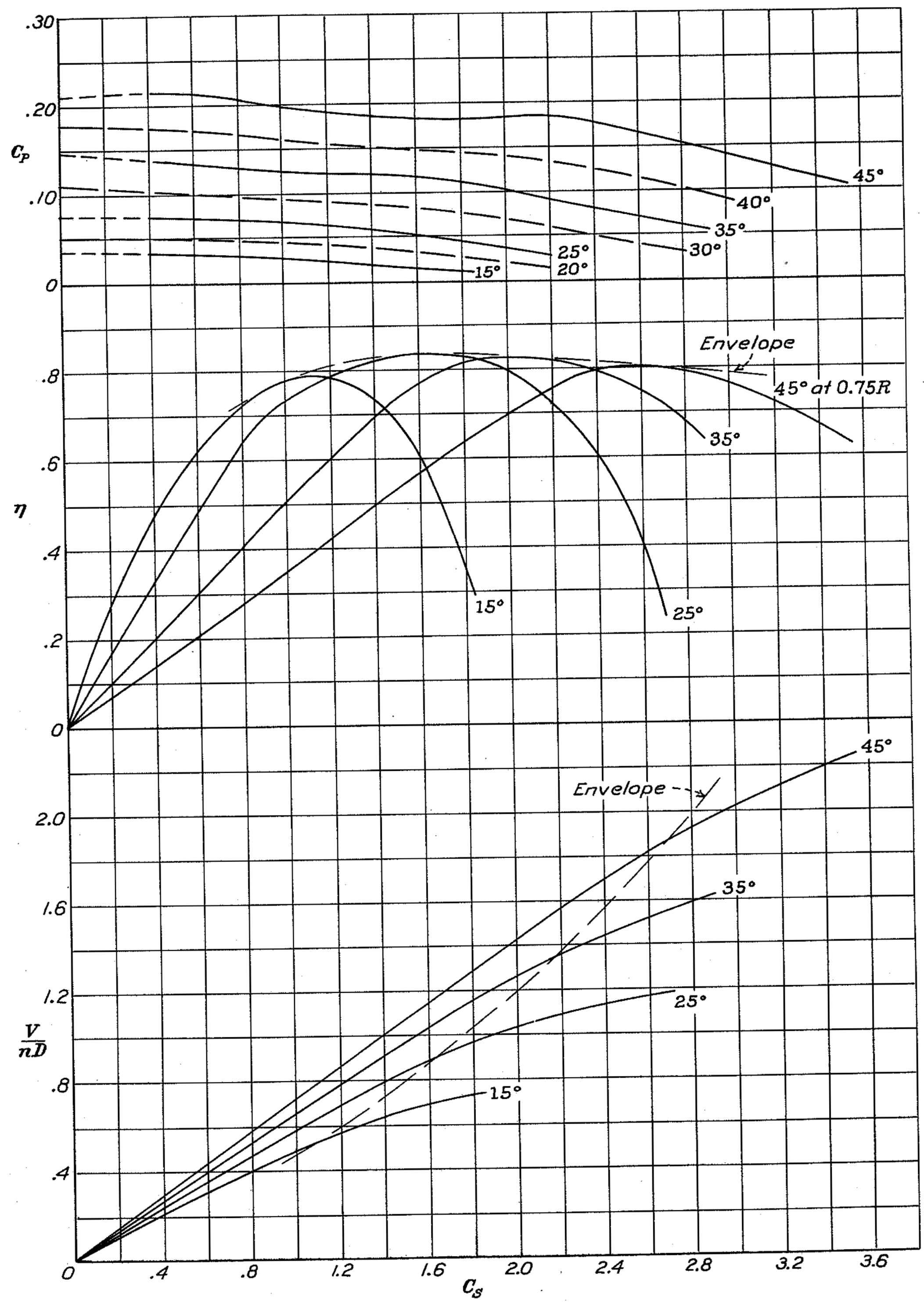

Figure 9.- Working chart. Two blade right-hand propeller

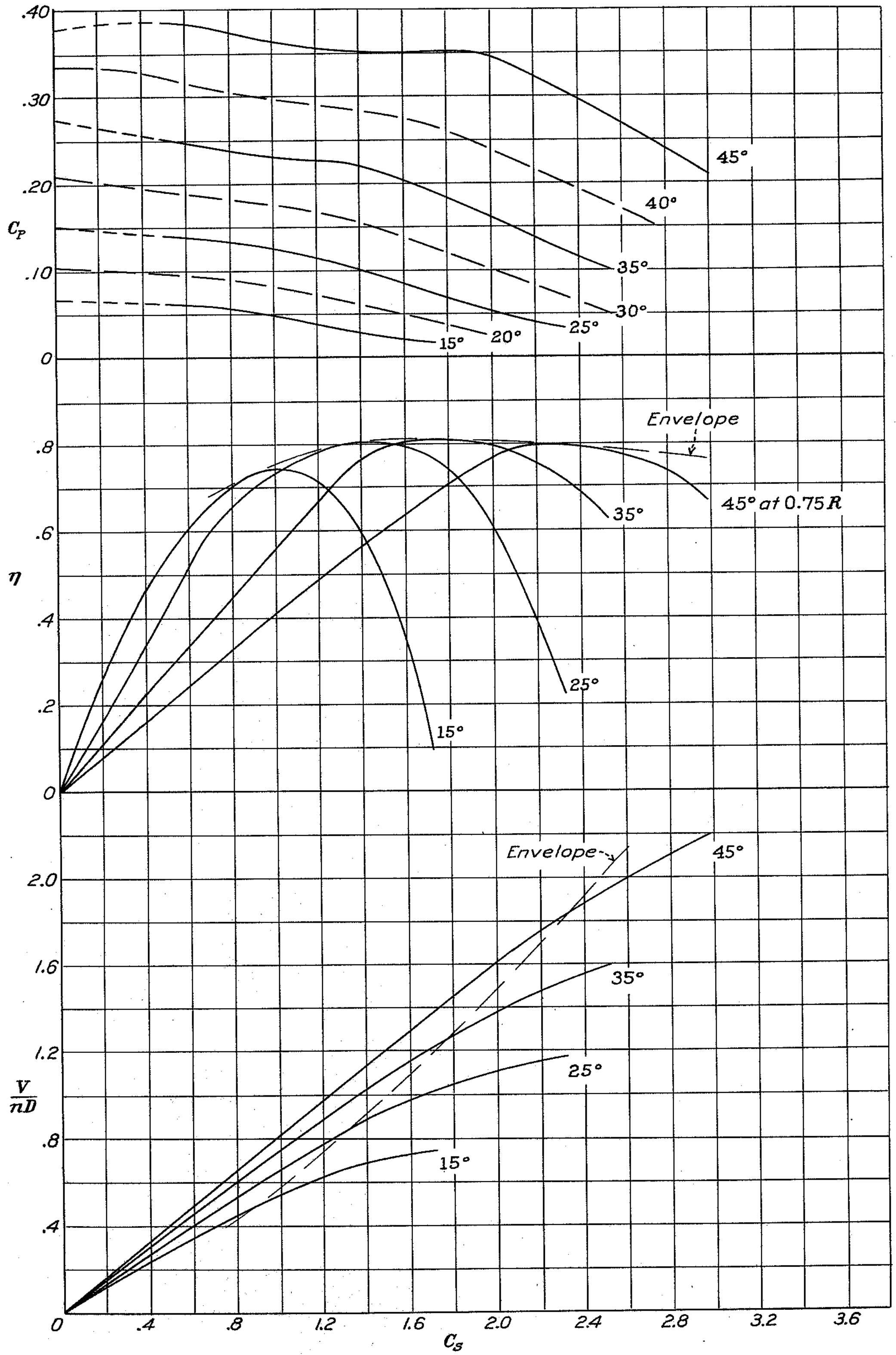

Figure 10.- Working chart. Four blade right-hand propeller.

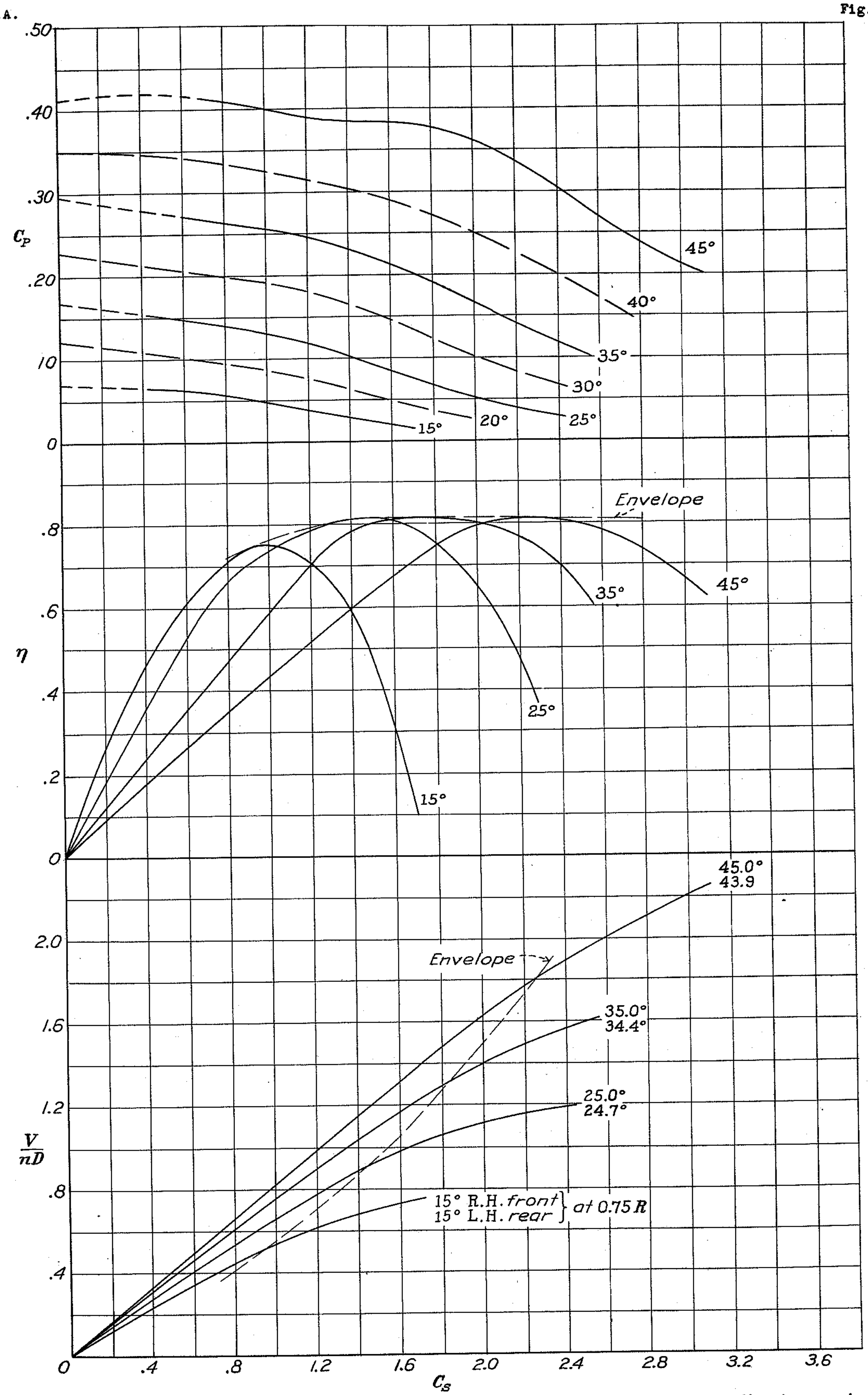

Figure 11.- Working chart. Two blade R.H. (front) and L.H. (rear) propeller with 15 percent diameter spacing

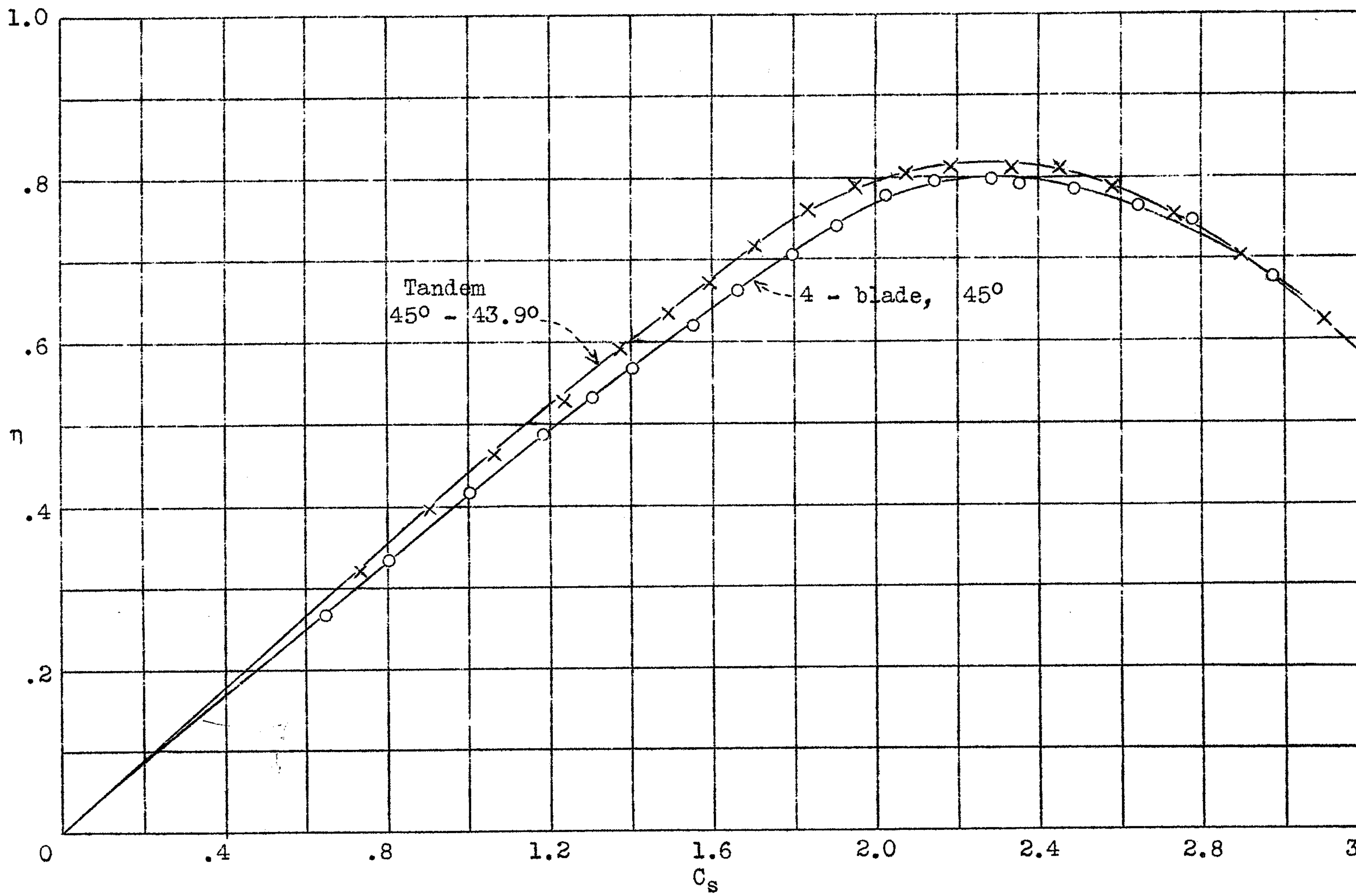

Figure 12.- Comparison of efficiency for 45° 4-blade propellers and 45° - 43.9° tandem propellers at same values of C_s.