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PERFORMANCE CHARACTERISTICS OF THREE PROPELLERS WITH VARYING PITCH DISTRIBUTIONS ON AN INCLINED SHAFT

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Naval Ship Research and Development Center

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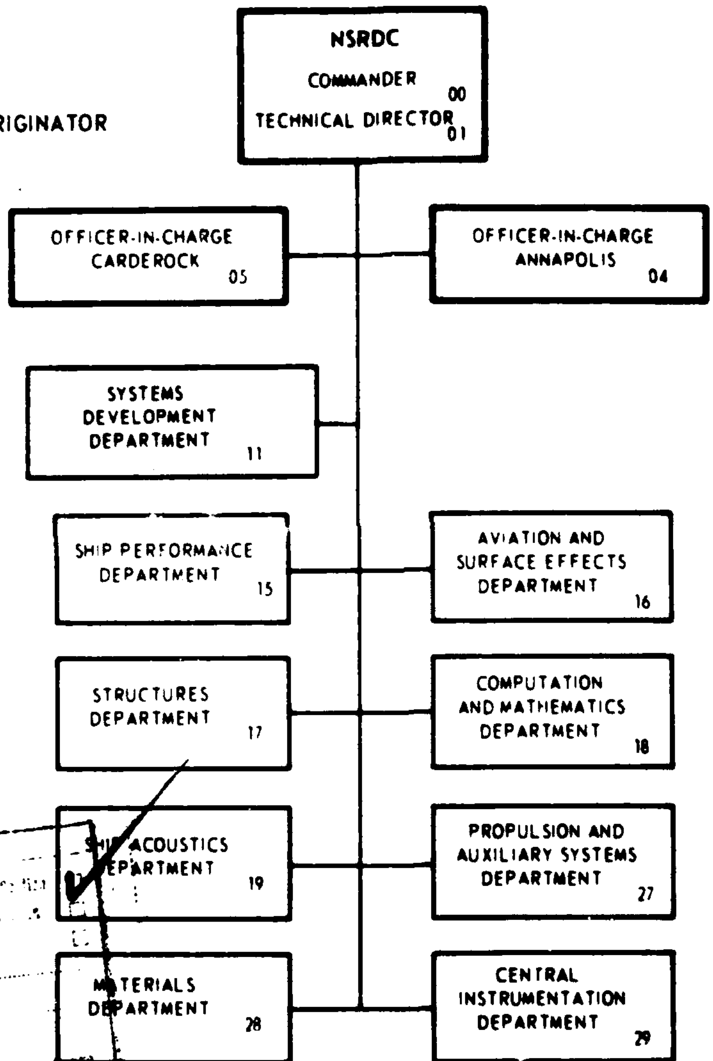

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A series of three commercial propellers with systematic pitch reductions at the hub were characterized at zero and 15 degrees shaft angle, over a range of cavitation numbers and advance coefficients. In addition to the usual thrust and torque forces, horizontal and vertical side forces were measured. These experiments showed that varying the pitch distribution of these propellers changed the type of cavitation on the propellers without significantly affecting the performance of the propeller.

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NOTATION

BF_{ang}	Bearing force angle, measured from the vertical $BF_{ang} = \arctan F_H/F_V$ [deg]
$c_{0.7}$	Blade-section length at 0.7 radius [ft]
D	Propeller diameter [ft]
F_H	Horizontal force, measured perpendicular to the shaft [lb]
F_V	"Vertical" force, measured perpendicular to the shaft [lb]
F_{BF}	Bearing force $F_{BF} = \sqrt{F_H^2 + F_V^2}$ [lb]
J	Advance coefficient $J = V/nD$
K_{BF}	Bearing-force coefficient $K_{BF} = F_{BF}/\rho n^2 D^4$
K_L	Lift coefficient $K_L = L/\rho n^2 D^4$
K_Q	Torque coefficient $K_Q = Q/\rho n^2 D^5$
K_T	Thrust coefficient $K_T = T/\rho n^2 D^4$
L	Lift force $L = T' \sin\alpha + F_V \cos\alpha$ [lb]
n	Revolutions per second of unit time
p_∞	Ambient static pressure [lb/ft^2]
p_v	Ambient vapor pressure [lb/ft^2]
Q	Torque [ft-lb]
T	Thrust in the horizontal plane $T = T' \cos\alpha - F_V \sin\alpha$ [lb]
T′	Thrust measured on the shaft [lb]
V	Speed of advance [ft/sec]
α	Angle of shaft inclination [deg]
η	Efficiency $\eta = TV/2\pi Qn$
ρ	Mass density of water [lb – sec^2/ft^4]
σ	Cavitation number $\sigma = \dfrac{p_\infty - p_v}{1/2\, \rho V^2}$

ABSTRACT

A series of three commercial propellers with sysyematic pitch reductions at the hub were characterized at zero and 15 degrees shaft angle, over a range of cavitation numbers and advance coefficients. In addition to the usual thrust and torque forces, horizontal and vertical side forces were measured. These experiments showed that varying the pitch distribution of these propellers changed the type of cavitation on the propeller without significantly affecting the performance of that propeller.

ADMINISTRATIVE INFORMATION

This work was funded by the Naval Sea Systems Command, sponsored by PMS 300 under Funding Code 49501, Work Unit 1532-242.

INTRODUCTION

One of the most persistent problems which high-performance, small craft have encountered is propeller cavitation erosion in the blade root area. This problem was also observed on a series of constant pitch commercial propellers which were characterized on inclined shafts at the Naval Ship Research and Development Center (NSRDC).[1] The Naval Sea Systems Command (NAVSEA) requested that NSRDC investigate the effect of reducing propeller pitch at the hub on propeller blade root cavitation.

Two propellers were purchased with specific pitch reductions at 0.2R of 80 percent and 90 percent of the pitch at 0.7R. The design

[1]Peck, J. G. and D. H. Moore, "Inclined-Shaft Propeller Performance Characteristics," NSRDC Report 4127 (Apr 1974)

pitch distribution of these propellers and of a constant pitch propeller from a series characterized earlier[1] are shown in Figure 1. The pitch of each blade of the three propellers was measured at several radial stations. An averaged value for the four blades of each propeller was calculated. These values are given in Table 1, and are presented as percent of pitch at 0.7 radius in Figure 1.

EXPERIMENTAL PROCEDURE AND FACILITIES

Propeller open-water characteristics were obtained in the deep-water towing basin using a propeller boat with zero degrees shaft inclination. All three propellers were characterized in open water over a range of advance coefficients (J) from zero velocity to zero thrust loading. Reynolds number for the open-water tests ranged from 6.8×10^5 to 7.4×10^5.

Cavitation characteristics of the propellers were obtained in the 36-inch variable pressure water tunnel using the right-angle shaft dynamometer. Cavitation experiments were conducted with a strut and shaft system upstream of the propellers simulating a typical full-scale environment. Tunnel water velocities for each propeller were established by setting thrust values at zero degrees shaft inclination equal to the thrust values obtained from the open-water characteristics tests at the same propeller advance coefficient. A water speed of 20 fps was used for all of the experiments. Reynolds number for the cavitation experiments ranged from 1.5×10^6 to 2.2×10^6.

All three propellers were characterized at cavitation number values from 0.5 to 14.7 over a range of advance coefficients from zero thrust loading to maximum torque of the dynamometer. Characterizations were made at zero and 15 degrees shaft inclination. In addition to thrust and torque, forces perpendicular to the shaft in the vertical plane and in the horizontal plane were measured. Cavitation observations and sketches were made throughout the entire program.

PRESENTATION OF DATA AND DISCUSSION

The open-water characteristics data of the propellers were reduced to the usual nondimensional coefficients of thrust and torque. The characteristic curves of these propellers are presented in Figure 2. These curves show that, except when lightly loaded, the propellers with radially varying pitch distribution increasing toward the tip produce more thrust at the same advance coefficient but are less efficient than the constant pitch propellers.

During the cavitation characteristic experiments, forces perpendicular to the shaft and thrust and torque forces in the shaft were measured. In order to present the results in the usual coordinate system, the thrust and side forces were resolved into horizontal and vertical components as shown in Figure 3. The resultant thrust and torque data from the cavitation experiments were reduced to the usual nondimensional coefficients, K_T and K_Q, for each propeller. The lift coefficient K_L, bearing force coefficient K_{BF}, and bearing force angle BF_{ang}, were also computed from measured data. Efficiencies, K_T/J^2 and K_Q/J^3 were computed from the faired values of K_T and K_Q. All force coefficients are given in Tables 2 through 7.

The cavitation characteristics of the three propellers are shown in Figures 4 through 15. Figures 4 through 8 show the performance characteristics of each propeller for various cavitation numbers at zero shaft inclination and 15 degrees shaft inclination. Cavitation inception curves for the three propellers at 15 degrees shaft inclination are given in Figures 10 through 12. The cavitation inception curves represent the limiting values of sigma for cavitation at the section r/R under consideration; i.e., the area above the curves indicates there is no cavitation present at the given radius r/R. At a given

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advance coefficient and cavitation number, the type and location of propeller cavitation will be determined by the curves above this point on the chart. These curves clearly demonstrate the effect of pitch reduction at the hub on face cavitation. The pitch reduction causes face cavitation from the hub to 0.3 radius, at much higher cavitation numbers than on the constant pitch propeller.

Figures 13 through 15 show propeller efficiency versus propeller loading for each propeller at various cavitation numbers. These curves indicate the propeller efficiency which might be expected for a given propeller loading at a specific cavitation number.

Photographs of the constant pitch propeller and one of the reduced pitch propeller are shown in Figure 16. These photographs show that, for the same operating conditions, the constant pitch propeller has back cavitation over a larger extent of the blades, whereas the reduced pitch propeller has heavier face cavitation from 0.45 radius to the hub. Figure 17 presents sketches of the cavitation present on the three propellers at 15 degrees shaft inclination for two propeller loadings. These sketches illustrate the decrease in back cavitation and increase in face cavitation on a propeller with pitch reduction at the hub compared to a constant pitch propeller with the same pitch at 0.7 radius.

CONCLUSIONS AND RECOMMENDATIONS

These experiments show the changes in propeller cavitation which may be made by varying the radial pitch distribution of propellers having the same pitch at 0.7 radius. Reducing the pitch at the hub decreases back cavitation in that area but increases face cavitation.

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The erosion damage caused by the different types of cavitation cannot be determined by the experiments. The performance of these propellers was not greatly affected by the pitch distribution. It is therefore recommended that constant pitch propellers continue to be used on high-performance small craft.

REFERENCES

1. Peck, J. G. and D. H. Moore, "Inclined-Shaft Propeller Performance Characteristics," NSRDC Report 4127 (Apr 1974)

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Table 1

Pitch Distribution of Propeller Series

Propeller	4529	4615	4614
r/R	Averaged Measured Pitch Ins	Averaged Measured Pitch Ins	Averaged Measured Pitch Ins
0.2	-	7.637	7.360
0.3	10.117	8.300	9.120
0.5	10.104	9.588	9.565
0.7	10.175	10.217	10.144
0.9	10.289	10.776	10.505

Table 2 - Performance Characteristics of Propeller 4529 at Zero Shaft Inclination

INCLINATION ANGLE = 0.000 PITCH RATIO = 1.000 SIGMA = 14.700

J	KTOUT	10KQOUT	EFFIC	KT/J2	KQ/J3	KL	KBF	HFANG
.6500	.2226	.3756	.6132	.5269	.1368	.0012	.0024	60.5474
.7000	.1998	.3478	.6401	.4078	.1014	.0013	.0027	62.3387
.7500	.1774	.3192	.6634	.3154	.0757	.0013	.0030	65.0422
.8000	.1551	.2916	.6769	.2424	.0570	.0013	.0035	67.2665
.8500	.1326	.2644	.6785	.1835	.0431	.0015	.0040	63.4799
.9000	.1093	.2342	.6684	.1349	.0321	.0017	.0046	68.8037
.9500	.0868	.1983	.6461	.0939	.0231	.0018	.0051	68.8050
1.0000	.0591	.1558	.6035	.0591	.0156	.0019	.0054	69.2896
1.0500	.0330	.1090	.5055	.0299	.0094	.0019	.0059	71.0952
1.1000	.0079	.0649	.2125	.0065	.0049	.0019	.0071	74.8843

INCLINATION ANGLE = 0.000 PITCH RATIO = 1.000 SIGMA = 3.000

J	KTOUT	10KQOUT	EFFIC	KT/J2	KQ/J3	KL	KBF	HFANG
.6500	.2200	.3716	.6124	.5207	.1353	.0010	.0029	69.6555
.7000	.2020	.3457	.6511	.4123	.1008	.0007	.0030	75.7671
.7500	.1817	.3176	.6810	.3222	.0753	.0005	.0032	80.7575
.8000	.1581	.2889	.6967	.2470	.0564	.0006	.0035	79.8802
.8500	.1333	.2584	.6979	.1845	.0421	.0011	.0039	74.4612
.9000	.1076	.2241	.6878	.1329	.0307	.0016	.0044	68.9103
.9500	.0816	.1845	.6641	.0905	.0215	.0018	.0050	67.7328
1.0000	.0557	.1394	.6355	.0557	.0139	.0016	.0057	72.5410
1.0500	.0296	.0921	.5372	.0268	.0080	.0014	.0065	79.0656
1.1000	.0027	.0498	.0935	.0022	.0037	.0019	.0070	74.1673

INCLINATION ANGLE = 0.000 PITCH RATIO = 1.000 SIGMA = 1.500

J	KTOUT	10KQOUT	EFFIC	KT/J2	KQ/J3	KL	KBF	HFANG
.6500	.1562	.2864	.5640	.3696	.1043	.0005	.0034	81.0644
.7000	.1658	.2992	.6173	.3384	.0872	.0006	.0040	81.7123
.7500	.1635	.2975	.6560	.2906	.0705	.0006	.0041	80.8255
.8000	.1518	.2819	.6857	.2372	.0551	.0008	.0041	77.9572
.8500	.1331	.2546	.7072	.1843	.0415	.0012	.0042	74.0192
.9000	.1095	.2188	.7169	.1352	.0300	.0015	.0046	70.5337
.9500	.0828	.1778	.7044	.0918	.0207	.0019	.0054	68.8866
1.0000	.0551	.1355	.6470	.0551	.0136	.0022	.0064	69.5798
1.0500	.0282	.0954	.4949	.0256	.0082	.0024	.0074	71.4841
1.1000	.0045	.0603	.1310	.0037	.0045	.0027	.0082	71.0915

INCLINATION ANGLE = 0.000 PITCH RATIO = 1.000 SIGMA = .750

J	KTOUT	10KQOUT	EFFIC	KT/J2	KQ/J3	KL	KBF	BFANG
.6500	.0754	.1670	.4672	.1785	.0608	-.0002	.0032	*00.4547
.7000	.0841	.1828	.5127	.1717	.0533	-.0002	.0034	-46.5191
.7500	.0917	.1959	.5586	.1630	.0464	.0002	.0040	37.3538
.8000	.0963	.2071	.5917	.1504	.0405	.0009	.0046	87.7723
.8500	.0955	.2123	.6085	.1322	.0346	.0016	.0051	92.7012
.9000	.0870	.2048	.6082	.1074	.0281	.0021	.0058	71.1846
.9500	.0692	.1793	.5838	.0767	.0209	.0025	.0065	53.0690
1.0000	.0426	.1350	.5027	.0426	.0135	.0030	.0075	58.7266
1.0500	.0101	.0788	.2135	.0091	.0068	.0038	.0085	78.7778
1.1000	-.0221	.0290	-1.3333	-.0183	.0022	.0052	.0094	53.8147

INCLINATION ANGLE = 0.000 PITCH RATIO = 1.000 SIGMA = .500

J	KTOUT	10KQOUT	EFFIC	KT/J2	KQ/J3	KL	KBF	BFANG
.6500	.0392	.1008	.4021	.0927	.0367	.0009	.0031	83.7098
.7000	.0491	.1182	.4630	.1003	.0345	-.0001	.0040	37.2028
.7500	.0554	.1300	.5089	.0985	.0308	-.0003	.0045	-33.8817
.8000	.0604	.1450	.5298	.0943	.0283	-.0001	.0050	-46.7173
.8500	.0617	.1571	.5311	.0854	.0256	.0007	.0058	1.7039
.9000	.0552	.1534	.5155	.0682	.0210	.0019	.0070	69.2888
.9500	.0375	.1233	.4597	.0416	.0144	.0035	.0085	103.5606
1.0000	.0086	.0675	.2040	.0086	.0067	.0050	.0097	76.3755
1.0500	-.0251	.0062	-6.7184	-.0228	.0005	.0059	.0099	18.6609
1.1000	-.0485	-.0113	7.5260	-.0401	-.0008	.0052	.0079	55.0316

Table 3 - Performance Characteristics of Propeller 4615 at Zero Shaft Inclination

INCLINATION ANGLE = 0.000 PITCH RATIO = 1.000 SIGMA = 14.700

J	KTOUT	10KQOUT	EFFIC	KT/J2	KQ/J3	KL	KBF	BFANG
.6500	.2270	.3681	.6381	.5374	.1340	.0012	.0035	69.3566
.7000	.2027	.3380	.6681	.4136	.0985	.0010	.0038	73.0760
.7500	.1794	.3086	.6939	.3189	.0731	.0011	.0039	73.2014
.8000	.1565	.2769	.7197	.2446	.0541	.0014	.0043	71.1506
.8500	.1330	.2423	.7426	.1841	.0395	.0018	.0049	69.1542
.9000	.1079	.2055	.7524	.1332	.0282	.0020	.0057	69.2358
.9500	.0809	.1669	.7330	.0896	.0195	.0020	.0066	72.1917
1.0000	.0523	.1252	.6648	.0523	.0125	.0017	.0074	76.5710
1.0500	.0238	.0763	.5207	.0216	.0066	.0018	.0081	77.6556
1.1000	-.0016	.0111	-.2498	-.0013	.0008	.0031	.0088	66.4400

INCLINATION ANGLE = 0.000 PITCH RATIO = 1.000 SIGMA = 3.000

J	KTOUT	10KQOUT	EFFIC	KT/J2	KQ/J3	KL	KBF	BFANG
.6500	.2239	.3796	.6103	.5300	.1382	.0007	.0028	75.4496
.7000	.2039	.3519	.6456	.4162	.1026	.0008	.0029	74.1267
.7500	.1797	.3186	.6731	.3194	.0755	.0011	.0031	69.4587
.8000	.1546	.2837	.6936	.2415	.0554	.0015	.0035	65.4841
.8500	.1295	.2484	.7050	.1792	.0405	.0018	.0040	64.2982
.9000	.1037	.21[illegible]8	.7010	.1280	.0291	.0019	.0047	65.9371
.9500	.0762	.1726	.6674	.0844	.0201	.0019	.0057	69.6126
1.0000	.0468	.1298	.5736	.0468	.0130	.0019	.0066	73.1461
1.0500	.0173	.0846	.3420	.0157	.0073	.0020	.0071	73.7539
1.1000	-.0073	.0410	-.3103	-.0060	.0031	.0025	.0068	68.2906

INCLINATION ANGLE = 0.000 PITCH RATIO = 1.000 SIGMA = 1.500

J	KTOUT	10KQOUT	EFFIC	KT/J2	KQ/J3	KL	KBF	BFANG
.6500	.1676	.3088	.5615	.3968	.1125	.0005	.0033	81.4845
.7000	.1719	.3181	.6022	.3509	.0927	.0005	.0034	81.6400
.7500	.1661	.3110	.6375	.2953	.0737	.0007	.0033	77.8019
.8000	.1510	.2919	.6587	.2359	.0570	.0011	.0035	71.3416
.8500	.1288	.2638	.6604	.1782	.0429	.0017	.0040	55.1661
.9000	.1020	.2288	.6387	.1259	.0314	.0022	.0048	52.1385
.9500	.0730	.1880	.5868	.0809	.0219	.0024	.0056	63.4995
1.0000	.0426	.1415	.4790	.0426	.0142	.0025	.0054	67.2883
1.0500	.0096	.0881	.1825	.0087	.0076	.0030	.0073	66.7631
1.1000	-.0302	.0255	-2.0761	-.0250	.0019	.0051	.0086	48.8228

INCLINATION ANGLE = 0.000 PITCH RATIO = 1.000 SIGMA = .750

J	KTOUT	10KQOUT	EFFIC	KT/J2	KQ/J3	KL	KBF	BFANG
.6500	.0999	.1948	.5301	.2363	.0710	-.0005	.0018	-86.1424
.7000	.1025	.2026	.5634	.2091	.0591	-.0002	.0022	-12.0605
.7500	.1013	.2076	.5823	.1801	.0492	.0005	.0032	60.4590
.8000	.0982	.2098	.5959	.1534	.0410	.0014	.0041	99.6356
.8500	.0915	.2050	.6041	.1267	.0334	.0023	.0050	77.5663
.9000	.0781	.1874	.5972	.0964	.0257	.0032	.0057	49.8148
.9500	.0551	.1518	.5493	.0611	.0177	.0043	.0067	34.9996
1.0000	.0220	.0958	.3654	.0220	.0096	.0054	.0077	44.3829
1.0500	-.0178	.0221	-1.3404	-.0161	.0019	.0066	.0086	51.4588
1.1000	-.0545	-.0593	1.6097	-.0450	-.0045	.0072	.0067	-28.4576

INCLINATION ANGLE = 0.000 PITCH RATIO = 1.000 SIGMA = .500

J	KTOUT	10KQOUT	EFFIC	KT/J2	KQ/J3	KL	KBF	BFANG
.6500	.0598	.1420	.4358	.1416	.0517	-.0000	.0026	-24.5531
.7000	.0676	.1550	.[illegible]	.1379	.0452	-.0004	.0025	-44.2589
.7500	.0662	.1539	.[illegible]132	.1177	.0365	-.0002	.0029	-15.1510
.8000	.0580	.1488	.4960	.0905	.0291	.0007	.0039	47.5079
.8500	.0441	.1384	.4310	.0610	.0225	.0018	.0055	87.8570
.9000	.0255	.1173	.3112	.0315	.0161	.0024	.0071	97.7087
.9500	.0032	.0822	.0586	.0035	.0096	.0020	.0082	84.8195
1.0000	-.0209	.0391	-.8490	-.0209	.0039	.0004	.0078	61.1614
1.0500	-.0432	.0094	-7.2693	-.0392	.0009	-.0018	.0051	31.1928
1.1000	-.0584	.0394	-2.5935	-.0483	.0030	-.0032	-.0010	-19.8701

Table 4 - Performance Characteristics of Propeller 4616 at Zero Shaft Inclination

INCLINATION ANGLE = 0.000 PITCH RATIO = 1.000 SIGMA = 14.700

J	KTOUT	10KQOUT	EFFIC	KT/J2	KQ/J3	KL	KBF	BFANG
.6500	.2239	.3668	.6316	.5300	.1336	.0017	.0028	53.4108
.7000	.2006	.3406	.6560	.4093	.0993	.0017	.0031	57.5566
.7500	.1781	.3132	.6790	.3167	.0742	.0017	.0035	60.7193
.8000	.1549	.2799	.7048	.2421	.0547	.0018	.0039	62.7819
.8500	.1305	.2423	.7286	.1806	.0394	.0019	.0043	63.9353
.9000	.1048	.2040	.7361	.1294	.0280	.0020	.0046	64.5143
.9500	.0783	.1680	.7051	.0868	.0196	.0022	.0052	64.8348
1.0000	.0511	.1328	.6117	.0511	.0133	.0025	.0060	65.0301
1.0500	.0224	.0897	.4179	.0203	.0077	.0029	.0069	64.8883
1.1000	-.0092	.0187	-.8661	-.0076	.0014	.0035	.0078	63.6885

INCLINATION ANGLE = 0.000 PITCH RATIO = 1.000 SIGMA = 3.000

J	KTOUT	10KQOUT	EFFIC	KT/J2	KQ/J3	KL	KBF	BFANG
.6500	.2241	.3792	.6113	.5304	.1381	.0008	.0025	70.3770
.7000	.2040	.3532	.6433	.4163	.1030	.0008	.0030	74.3377
.7500	.1803	.3224	.6674	.3205	.0764	.0007	.0034	78.6387
.8000	.1555	.2897	.6832	.2429	.0566	.0007	.0038	79.6128
.8500	.1301	.2565	.6861	.1800	.0418	.0009	.0040	77.5858
.9000	.1036	.2226	.6668	.1279	.0305	.0011	.0043	74.9620
.9500	.0755	.1870	.6103	.0836	.0218	.0012	.0048	74.3102
1.0000	.0455	.1475	.4912	.0455	.0148	.0013	.0055	76.4501
1.0500	.0151	.1014	.2485	.0137	.0088	.0014	.0063	78.5378
1.1000	-.0124	.0453	-.4779	-.0102	.0034	.0017	.0070	72.1520

INCLINATION ANGLE = 0.000 PITCH RATIO = 1.000 SIGMA = .750

J	KTOUT	10KQOUT	EFFIC	KT/J2	KQ/J3	KL	KBF	BFANG
.6500	.0933	.1879	.5139	.2209	.0684	-.0005	.0031	*13.7666
.7000	.0962	.1969	.5444	.1964	.0574	-.0003	.0038	-80.0924
.7500	.0955	.2031	.5609	.1697	.0482	-.0001	.0045	-4.0161
.8000	.0938	.2067	.5777	.1465	.0404	.0002	.0051	59.8923
.8500	.0890	.2022	.5956	.1232	.0329	.0005	.0055	90.8262
.9000	.0770	.1829	.6028	.0950	.0251	.0010	.0060	91.1750
.9500	.0542	.1445	.5666	.0600	.0169	.0019	.0065	75.9572
1.0000	.0205	.0890	.3667	.0205	.0089	.0029	.0072	62.2532
1.0500	-.0177	.0288	-1.0271	-.0161	.0025	.0038	.0076	58.6377
1.1000	-.0453	-.0096	8.2429	-.0374	-.0007	.0040	.0073	54.6130

INCLINATION ANGLE = 0.000 PITCH RATIO = 1.000 SIGMA = 1.500

J	KTOUT	10KQOUT	EFFIC	KT/J2	KQ/J3	KL	KBF	BFANG
.6500	.1670	.2973	.5810	.3952	.1083	-.0007	.0035	-69.9498
.7000	.1734	.3107	.6217	.3539	.0906	-.0008	.0044	-80.6324
.7500	.1676	.3069	.6518	.2979	.0727	-.0007	.0050	-95.8818
.8000	.1515	.2865	.6731	.2367	.0560	-.0004	.0051	-79.6970
.8500	.1279	.2541	.6809	.1770	.0414	.0002	.0055	-19.2312
.9000	.0998	.2152	.6643	.1232	.0295	.0013	.0069	64.2581
.9500	.0697	.1744	.6045	.0772	.0203	.0028	.0089	104.4582
1.0000	.0391	.1328	.4682	.0391	.0133	.0042	.0093	-20.9486
1.0500	.0076	.0860	.1476	.0069	.0074	.0044	.0029	*01.2360
1.1000	-.0273	.0214	-2.2317	-.0226	.0016	.0017	-.0193	*03.5837

INCLINATION ANGLE = 0.000 PITCH RATIO = 1.000 SIGMA = .500

J	KTOUT	10KQOUT	EFFIC	KT/J2	KQ/J3	KL	KBF	BFANG
.6500	.0601	.1411	.4403	.1422	.0514	.0005	.0030	81.0092
.7000	.0654	.1523	.4784	.1335	.0444	.0004	.0032	82.2089
.7500	.0667	.1596	.4992	.1187	.0378	.0005	.0032	81.3843
.8000	.0638	.1617	.5023	.0997	.0316	.0005	.0032	80.2353
.8500	.0563	.1557	.4887	.0779	.0254	.0006	.0034	79.2654
.9000	.0427	.1373	.4456	.0527	.0188	.0008	.0038	78.2373
.9500	.0195	.1014	.2910	.0216	.0118	.0011	.0045	76.6286
1.0000	-.0205	.0422	-.7744	-.0205	.0042	.0015	.0053	74.0876
1.0500	-.0891	-.0460	3.2352	-.0808	-.0040	.0020	.0062	70.8892
1.1000	-.2038	-.1687	2.1153	-.1684	.0127	.0025	.0069	68.3903

Table 5 - Performance Characteristics of Propeller 4529 at 15 Degrees Shaft Inclination

INCLINATION ANGLE = 15.000 PITCH RATIO = 1.000 SIGMA = 14.780

J	KTOUT	10KQOUT	EFFIC	KT/J2	KQ/J3	KL	KBF	BFANG
.6500	.2191	.3855	.5879	.5185	.1404	.0809	.0227	-13.6048
.7000	.1977	.3595	.6129	.4036	.1048	.0770	.0241	-12.7635
.7500	.1775	.3349	.6327	.3156	.0794	.0737	.0251	-11.5613
.8000	.1578	.3103	.6477	.2466	.0606	.0708	.0275	-10.3901
.8500	.1379	.2841	.6565	.1908	.0463	.0680	.0310	-9.4135
.9000	.1168	.2553	.6555	.1442	.0350	.0651	.0339	-8.6528
.9500	.0940	.2230	.6376	.1042	.0260	.0619	.0356	-8.0720
1.0000	.0693	.1872	.5891	.0693	.0187	.0584	.0371	-7.6640
1.0500	.0429	.1484	.4828	.0389	.0128	.0546	.0436	-7.5361
1.1000	.0160	.1084	.2581	.0132	.0081	.0507	.0654	-7.9951

INCLINATION ANGLE = 15.000 PITCH RATIO = 1.000 SIGMA = 3.000

J	KTOUT	10KQOUT	EFFIC	KT/J2	KQ/J3	KL	KBF	BFANG
.6500	.2107	.3884	.5612	.4986	.1414	.0795	.0225	-7.6808
.7000	.1970	.3666	.5987	.4020	.1069	.0774	.0241	-9.8460
.7500	.1786	.3408	.6254	.3175	.0808	.0740	.0257	-10.7821
.8000	.1583	.3139	.6421	.2474	.0613	.0704	.027[illegible]	-10.7347
.8500	.1371	.2861	.6480	.1897	.0466	.0668	.029[illegible]	-10.0354
.9000	.1146	.2565	.6401	.1415	.0352	.0634	.0319	-9.0544
.9500	.0905	.2238	.6110	.1002	.0261	.0599	.0348	-8.1532
1.0000	.0644	.1876	.5465	.0644	.0188	.0561	.0379	-7.6373
1.0500	.0377	.1492	.4226	.0342	.0129	.0522	.0410	-7.7088
1.1000	.0137	.1128	.2123	.0113	.0085	.0484	.0436	-8.4192

INCLINATION ANGLE = 15.000 PITCH RATIO = 1.000 SIGMA = 1.500

J	KTOUT	10KQOUT	EFFIC	KT/J2	KQ/J3	KL	KBF	BFANG
.6500	.1450	.2785	.5384	.3431	.1014	.0538	.0147	10.7725
.7000	.1525	.2886	.5889	.3113	.0841	.0608	.0193	5.2480
.7500	.1554	.2943	.6301	.2762	.0698	.0659	.0234	-.9895
.8000	.1507	.2872	.6681	.2355	.0561	.0681	.0269	-5.7514
.8500	.1381	.2666	.7009	.1912	.0434	.0676	.0298	-8.3353
.9000	.1189	.2367	.7193	.1467	.0325	.0650	.0324	-9.0767
.9500	.0950	.2029	.7080	.1053	.0237	.0613	.0351	-8.9008
1.0000	.0690	.1687	.6510	.0690	.0169	.0574	.0381	-8.8743
1.0500	.0429	.1325	.5406	.0389	.0114	0537	.0414	-9.7574
1.1000	.0173	.0836	.3631	.0143	.0063	1499	.0449	-11.5552

INCLINATION ANGLE = 15.000 PITCH RATIO = 1.000 SIGMA = .750

J	KTOUT	10KQOUT	EFFIC	KT/J2	KQ/J3	KL	KBF	BFANG
.6500	.0759	.1888	.4158	.1796	.06[illegible]	.0256	.0054	17.6763
.7000	.0814	.2026	.4474	.1660	.0591	.0300	.0083	16.4611
.7500	.0866	.2144	.4820	.1539	.0508	.0348	.0116	15.3385
.8000	.0900	.2231	.5138	.1407	.0436	.0400	.0156	11.8499
.8500	.0894	.2258	.5354	.1237	.0368	.0449	.0204	5.9127
.9000	.0823	.2193	.5376	.1016	.0301	.0486	.0257	-1.1174
.9500	.0675	.2013	.5069	.0748	.0235	.0501	.0312	-7.3837
1.0000	.0452	.1717	.4192	.0452	.0172	.0490	.0363	-11.4660
1.0500	.0185	.1339	.2304	.0168	.0116	.0457	.0406	-13.3180
1.1000	-.0064	.0962	-.1166	-.0053	.0072	.0420	.0437	-15.2050

INCLINATION ANGLE = 15.000 PITCH RATIO = 1.000 SIGMA = .500

J	KTOUT	10KQOUT	EFFIC	KT/J2	KQ/J3	KL	KBF	BFANG
.6500	.0397	.1149	.3576	.0940	.0418	.0160	.0054	19.1620
.7000	.0443	.1255	.3928	.0903	.0366	.0172	.0053	14.8735
.7500	.0516	.1438	.4280	.0916	.0341	.0204	.0066	13.0623
.8000	.0562	.1572	.4549	.0878	.0307	.0240	.0088	11.7246
.8500	.0557	.1619	.4655	.0771	.0264	.0274	.0122	9.4117
.9000	.0499	.1589	.4498	.0616	.0218	.0307	.0168	5.3980
.9500	.0397	.1511	.3970	.0440	.0176	.0339	.0226	-.1502
1.0000	.0262	.1394	.2989	.0262	.0139	.0366	.0288	-6.0073
1.0500	.0098	.1195	.1377	.0089	.0103	.0369	.0335	-9.7192
1.1000	-.0105	.0784	-.2351	-.0087	.0059	.0312	.0332	-7.4358

Table 6 - Performance Characteristics of Propeller 4615 at 15 Degrees Shaft Inclination

INCLINATION ANGLE = 15.000 PITCH RATIO = 1.000 SIGMA = 14.700

J	KTOUT	10KQOUT	EFFIC	KT/J2	KQ/J3	KL	KBF	BFANG
.6500	.2223	.3977	.5783	.5262	.1448	.0819	.0225	-15.7900
.7000	.1998	.3717	.5988	.4078	.1084	.0777	.0241	-14.5626
.7500	.1790	.3482	.6136	.3182	.0825	.0743	.0261	-13.0000
.8000	.1583	.3221	.6257	.2473	.0629	.0709	.0281	-11.5607
.8500	.1363	.2929	.6295	.1886	.0477	.0674	.0304	-10.4115
.9000	.1120	.2622	.6120	.1383	.0360	.0636	.0329	-9.5514
.9500	.0853	.2313	.5575	.0945	.0270	.0593	.0356	-8.9350
1.0000	.0567	.1982	.4553	.0567	.0198	.0548	.0387	-8.5965
1.0500	.0281	.1556	.3016	.0255	.0134	.0504	.0419	-8.7734
1.1000	.0027	.0880	.0529	.0022	.0066	.0464	.0448	-10.0298

INCLINATION ANGLE = 15.000 PITCH RATIO = 1.000 SIGMA = 3.000

J	KTOUT	10KQOUT	EFFIC	KT/J2	KQ/J3	KL	KBF	BFANG
.6500	.2163	.3900	.5737	.5119	.1420	.0808	.0222	-4.8659
.7000	.2014	.3717	.6039	.4111	.1084	.0791	.0245	-8.7217
.7500	.1824	.3451	.6308	.3242	.0818	.0758	.0265	-10.5810
.8000	.1610	.3156	.6494	.2515	.0616	.0719	.0282	-10.7729
.8500	.1380	.2851	.6548	.1910	.0464	.0676	.0301	-9.9346
.9000	.1136	.2535	.6421	.1403	.0348	.0634	.0322	-8.8145
.9500	.0878	.2193	.6052	.0972	.0256	.0590	.0347	-8.0742
1.0000	.0606	.1807	.5339	.0606	.0181	.0547	.0375	-8.0912
1.0500	.0333	.1370	.4062	.0302	.0118	.0505	.0407	-8.7612
1.1000	.0081	.0889	.1591	.0067	.0067	.0469	.0437	-9.3008

INCLINATION ANGLE = 15.000 PITCH RATIO = 1.000 SIGMA = 1.500

J	KTOUT	10KQOUT	EFFIC	KT/J2	KQ/J3	KL	KBF	BFANG
.6500	.1607	.2983	.5574	.3804	.1086	.0604	.0172	13.4653
.7000	.1657	.3082	.5989	.3381	.0898	.0655	.0206	8.0264
.7500	.1643	.3075	.6379	.2921	.0729	.0690	.0241	1.6228
.8000	.1556	.2945	.6726	.2431	.0575	.0701	.0275	-3.8633
.8500	.1399	.2707	.6993	.1937	.0441	.0688	.0305	-7.6473
.9000	.1187	.2392	.7111	.1466	.0328	.0656	.0331	-9.7678
.9500	.0937	.2028	.6986	.1038	.0237	.0614	.0358	-10.8117
1.0000	.0663	.1627	.6482	.0663	.0163	.0569	.0386	-11.6402
1.0500	.0369	.1163	.5302	.0335	.0100	.0522	.0419	-13.1143
1.1000	.0045	.0557	.1428	.0038	.0042	.0470	.0462	-15.8200

INCLINATION ANGLE = 15.000 PITCH RATIO = 1.000 SIGMA = .750

J	KTOUT	10KQOUT	EFFIC	KT/J2	KQ/J3	KL	KBF	BFANG
.6500	.0808	.1708	.4893	.1912	.0622	.0278	.0063	19.4317
.7000	.0897	.1882	.5312	.1831	.0549	.0341	.0100	12.7222
.7500	.0940	.1985	.5649	.1670	.0471	.0389	.0134	6.9270
.8000	.0933	.2004	.5929	.1458	.0391	.0422	.0166	2.1074
.8500	.0873	.1928	.6121	.1208	.0314	.0440	.0199	-2.1944
.9000	.0753	.1755	.6144	.0929	.0241	.0446	.0237	-6.5619
.9500	.0575	.1488	.5839	.0637	.0174	.0442	.0284	-11.3102
1.0000	.0349	.1140	.4874	.0349	.0114	.0427	.0335	-16.0917
1.0500	.0102	.0734	.2320	.0092	.0063	.0398	.0379	-19.5026
1.1000	-.0122	.0302	-.7089	-.0101	.0023	.0344	.0390	-18.6884

INCLINATION ANGLE = 15.000 PITCH RATIO = 1.000 SIGMA = .500

J	KTOUT	10KQOUT	EFFIC	KT/J2	KQ/J3	KL	KBF	BFANG
.6500	.0514	.1345	.3953	.1217	.0490	.0188	.0058	18.3419
.7000	.0584	.1552	.4193	.1192	.0452	.0227	.0068	10.8549
.7500	.0633	.1725	.4378	.1125	.0409	.0277	.0098	4.7211
.8000	.0658	.1821	.4600	.1028	.0356	.0314	.0132	.9603
.8500	.0622	.1817	.4630	.0861	.0296	.0328	.0163	-.8112
.9000	.0487	.1714	.4068	.0601	.0235	.0320	.0190	-1.6174
.9500	.0246	.1527	.2431	.0272	.0178	.0295	.0215	-2.3599
1.0000	-.0044	.1287	-.0541	-.0044	.0129	.0258	.0233	-3.0555
1.0500	-.0226	.1031	-.3659	-.0205	.0089	.0207	.0232	-2.0725
1.1000	-.0014	.0801	-.0312	-.0012	.0060	.0129	.0189	4.6314

Table 7 - Performance Characteristics of Propeller 4616 at 15 Degrees Shaft Inclination

INCLINATION ANGLE = 15.000 PITCH RATIO = 1.000 SIGMA = 14.700

J	KTOUT	10KQOUT	EFFIC	KT/J2	KQ/J3	KL	KBF	BFANG
.6500	.2189	.3884	.5830	.5181	.1414	.0810	.02 2	-13.5094
.7000	.1971	.3639	.6035	.4023	.1061	.0772	.0241	-12.3259
.7500	.1774	.3429	.6176	.3154	.0813	.0740	.0260	-10.7703
.8000	.1572	.3191	.6272	.2456	.0623	.0708	.0280	-9.3467
.8500	.1353	.2907	.6294	.1872	.0473	.0672	.0302	-8.3020
.9000	.1113	.2583	.6173	.1374	.0354	.0633	.0326	-7.6955
.9500	.0856	.2234	.5797	.0949	.0261	.0592	.0353	-7.4679
1.0000	.0588	.1867	.5009	.0588	.0187	.0550	.0383	-7.5112
1.0500	.0309	.1465	.3531	.0281	.0127	.0509	.0416	-7.7373
1.1000	.0019	.0965	.0341	.0016	.0073	.0469	.0453	-8.1480

INCLINATION ANGLE = 15.000 PITCH RATIO = 1.000 SIGMA = 3.000

J	KTOUT	10KQOUT	EFFIC	KT/J2	KQ/J3	KL	KBF	BFANG
.6500	.2159	.3776	.5916	.5111	.1375	.0810	.0225	-6.6045
.7000	.1995	.3542	.6275	.4071	.1033	.0788	.0248	-9.6279
.7500	.1803	.3264	.6594	.3206	.0774	.0755	.0267	-10.5978
.8000	.1596	.2977	.6827	.2494	.0581	.0718	.0285	-10.2386
.8500	.1375	.2690	.6918	.1904	.0438	.0679	.0304	-9.2993
.9000	.1138	.2394	.6807	.1404	.0328	.0639	.0327	-8.4377
.9500	.0879	.2066	.6430	.0974	.0241	.0598	.0354	-8.1061
1.0000	.0598	.1670	.5698	.0598	.0167	.0555	.0385	-8.4360
1.0500	.0302	.1160	.4349	.0274	.0100	.0508	.0418	-9.1231
1.1000	.0009	.0483	.0311	.0007	.0036	.0458	.0446	-9.3124

INCLINATION ANGLE = 15.000 PITCH RATIO = 1.000 SIGMA = 1.500

J	KTOUT	10KQOUT	EFFIC	KT/J2	KQ/J3	KL	KBF	BFANG
.6500	.1596	.3110	.5308	.3777	.1132	.0597	.0167	13.4178
.7000	.1657	.3230	.5716	.3381	.0942	.0660	.0210	5.3333
.7500	.1654	.3253	.6070	.2941	.0771	.0702	.0251	-2.1391
.8000	.1562	.3153	.6308	.2440	.0616	.0710	.0284	-7.0964
.8500	.1385	.2930	.6396	.1918	.0477	.0689	.0310	-9.4678
.9000	.1149	.2610	.6307	.1419	.0358	.0649	.0335	-10.2548
.9500	.0883	.2227	.5995	.0979	.0260	.0607	.0365	-10.7713
1.0000	.0606	.1817	.5312	.0606	.0182	.0570	.0402	-11.8831
1.0500	.0316	.1405	.3764	.0287	.0121	.0530	.0441	-13.2488
1.1000	-.0027	.0997	-.0472	-.0022	.0075	.0458	.0464	-12.5591

INCLINATION ANGLE = 15.000 PITCH RATIO = 1.000 SIGMA = .750

J	KTOUT	10KQOUT	EFFIC	KT/J2	KQ/J3	KL	KBF	BFANG
.6500	.0879	.2015	.4513	.2081	.0734	.0309	.0074	16.3909
.7000	.0939	.2174	.4814	.1917	.0634	.0361	.0109	13.6581
.7500	.0985	.2296	.5122	.1751	.0544	.0411	.0144	9.7134
.8000	.0999	.2380	.5342	.1560	.0465	.0454	.0181	4.1701
.8500	.0958	.2401	.5398	.1326	.0391	.0486	.0222	-2.1941
.9000	.0846	.2326	.5210	.1045	.0319	.0502	.0269	-8.1039
.9500	.0656	.2127	.4660	.0726	.0248	.0499	.0319	-12.4520
1.0000	.0396	.1796	.3510	.0396	.0180	.0475	.0369	-14.9654
1.0500	.0100	.1353	.1231	.0090	.0117	.0434	.0412	-16.8716
1.1000	-.0172	.0866	-.3469	-.0142	.0065	.0387	.0439	-21.5646

INCLINATION ANGLE = 15.000 PITCH RATIO = 1.000 SIGMA = .500

J	KTOUT	10KQOUT	EFFIC	KT/J2	KQ/J3	KL	KBF	BFANG
.6500	.0638	.1750	.3773	.1511	.0637	.0221	.0051	18.2236
.7000	.0742	.1979	.4177	.1514	.0577	.0284	.0085	14.8623
.7500	.0803	.2155	.4450	.1428	.0511	.0337	.0119	11.0062
.8000	.0811	.2256	.4578	.1267	.0441	.0373	.0151	5.8148
.8500	.0757	.2269	.4512	.1047	.0369	.0394	.0185	-.2497
.9000	.0637	.2189	.4170	.0787	.0300	.0403	.0226	-6.0688
.9500	.0455	.2016	.3410	.0504	.0235	.0404	.0277	-10.5140
1.0000	.0219	.1753	.1985	.0219	.0175	.0394	.0332	-13.0932
1.0500	-.0055	.1401	-.0651	-.0050	.0121	.0360	.0375	-14.5972
1.1000	-.0340	.0955	-.6229	-.0281	.0072	.0280	.0374	-17.7461

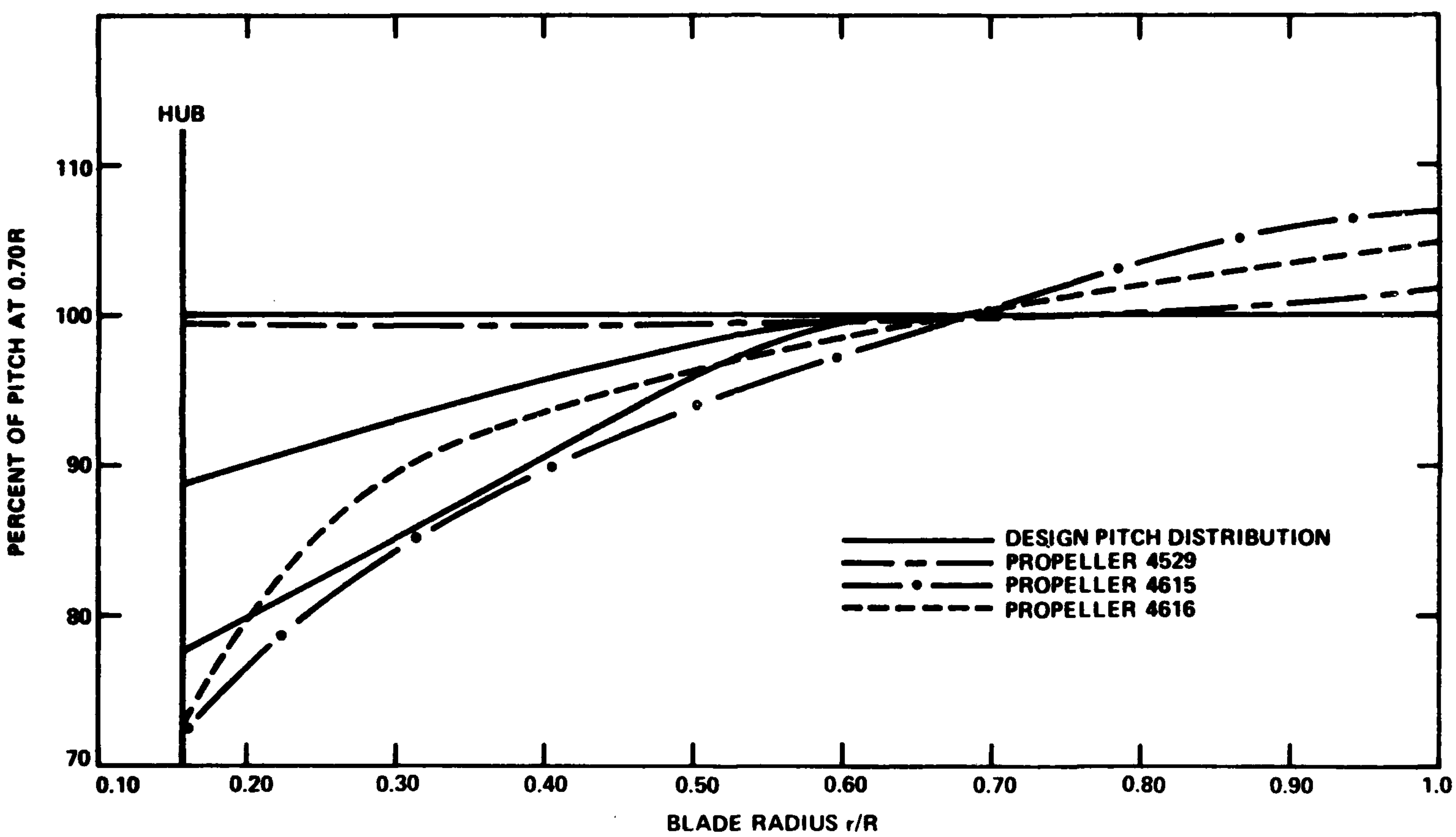


Figure 1 - Pitch Distribution on Propellers 4529, 4615, and 4616

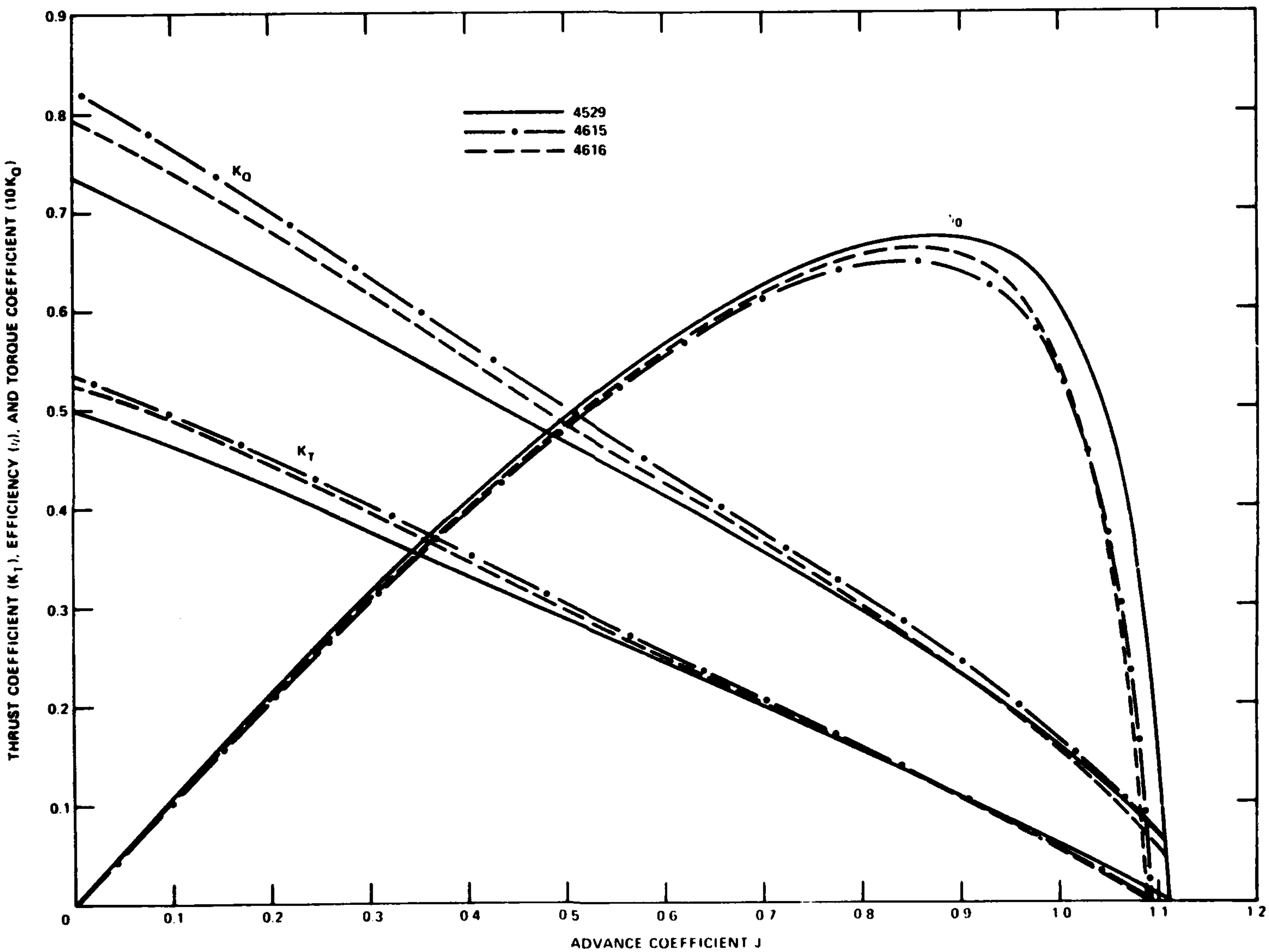


Figure 2 - Open Water Characteristics of Propellers 4529, 4615, and 4616

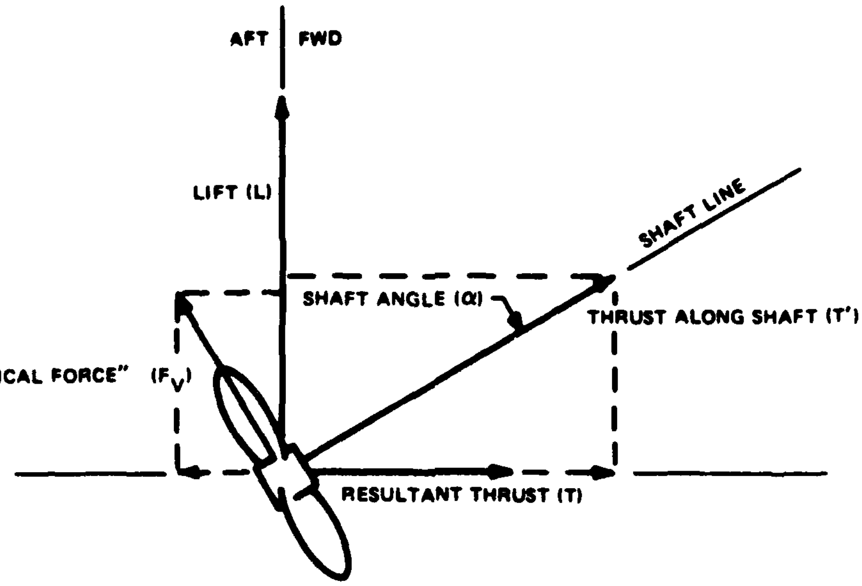


Figure 1a – Side View

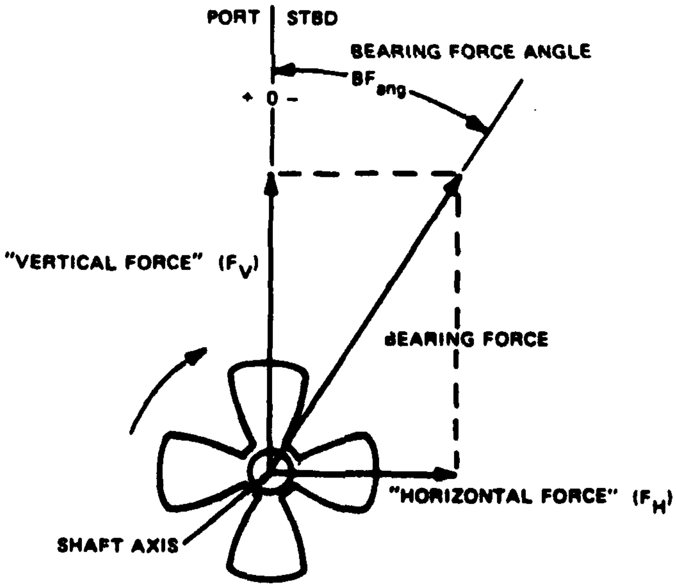


Figure 1b – End View

Figure 3 - Force Diagram for Side Force Measurements

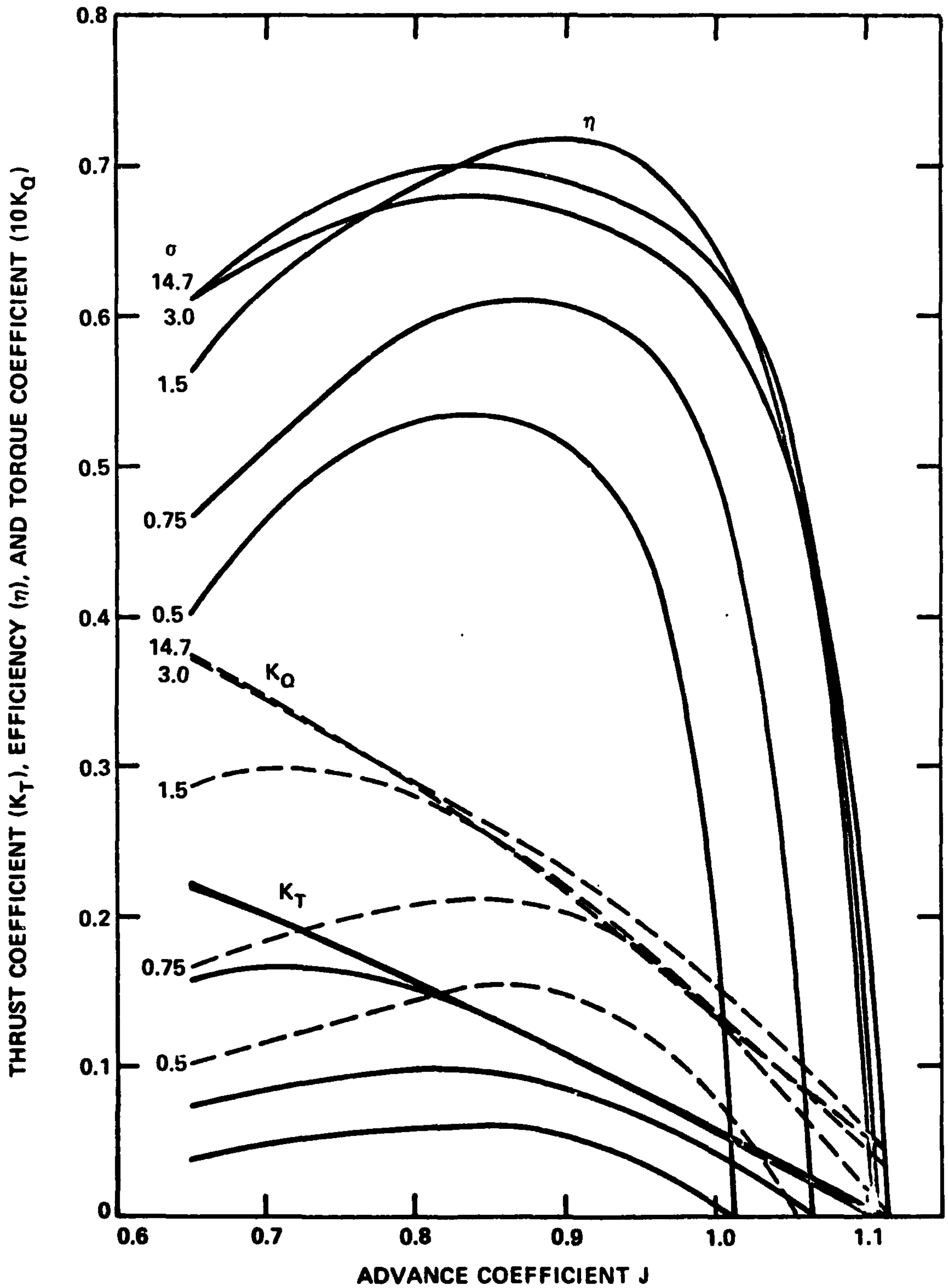


Figure 4 - Cavitation Characteristics of Propeller 4529 at Zero Shaft Inclination

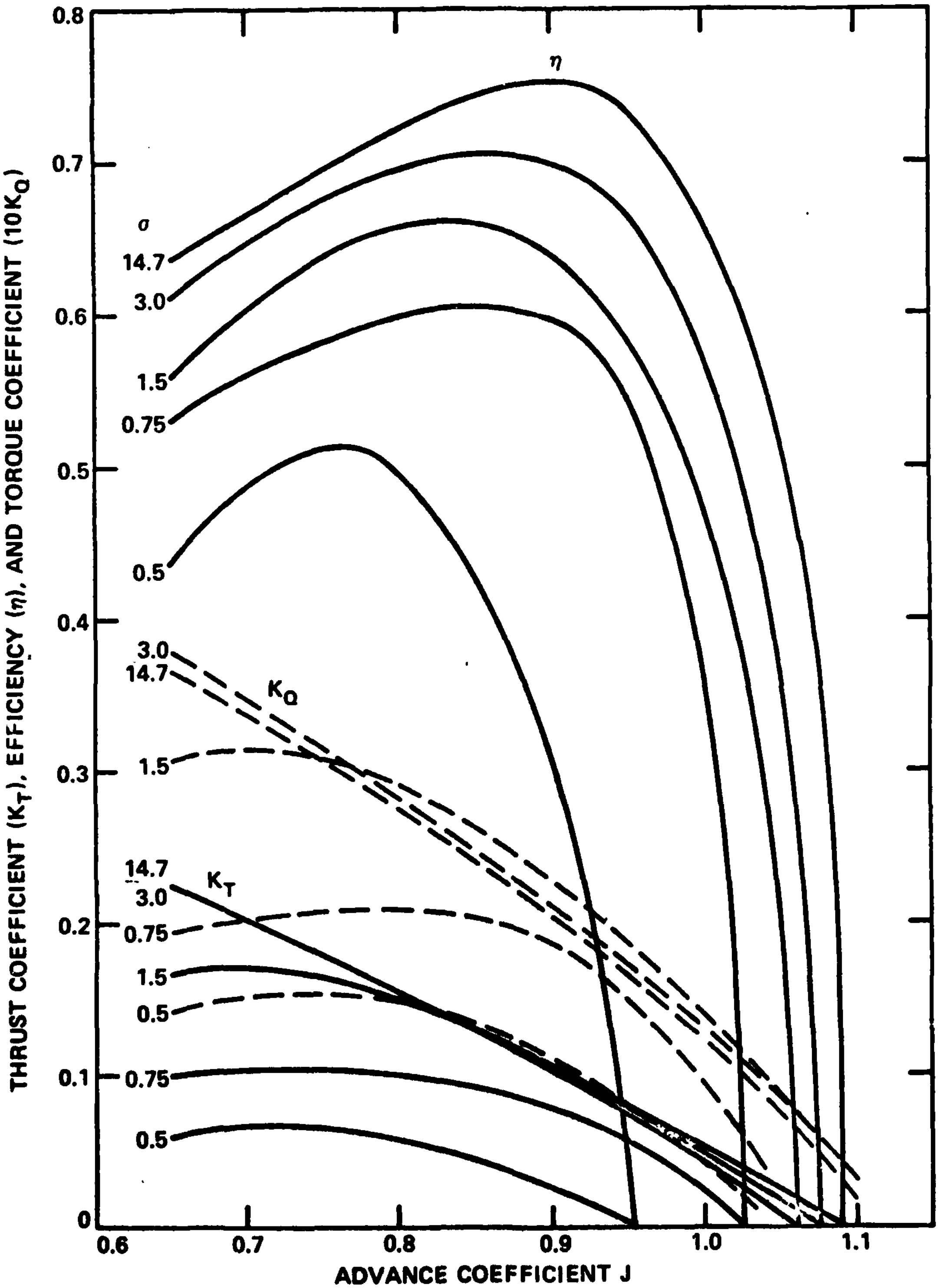


Figure 5 - Cavitation Characteristics of Propeller 4615 at Zero Shaft Inclination

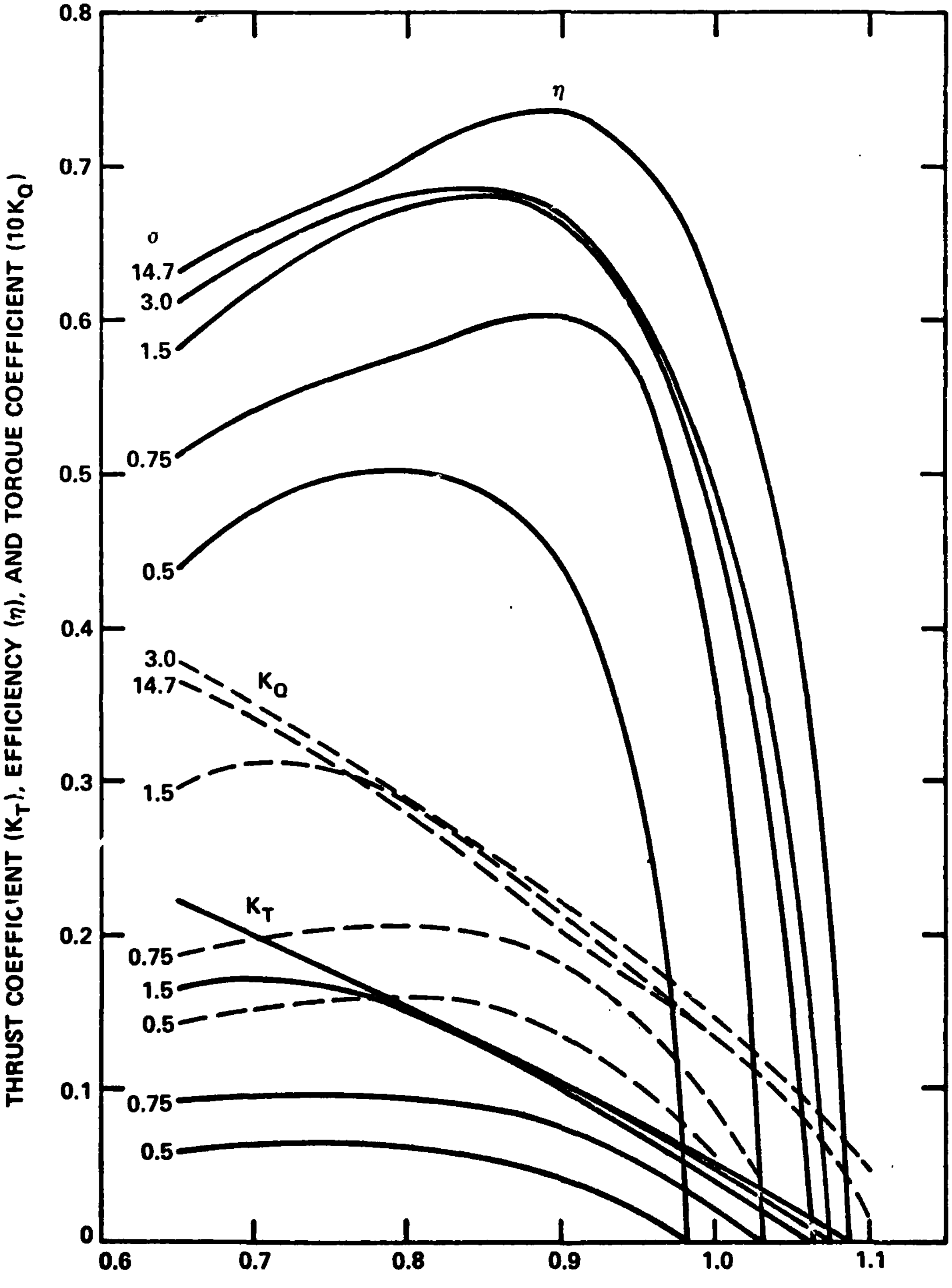


Figure 6 - Cavitation Characteristics of Propeller 4616 at Zero Shaft Inclination

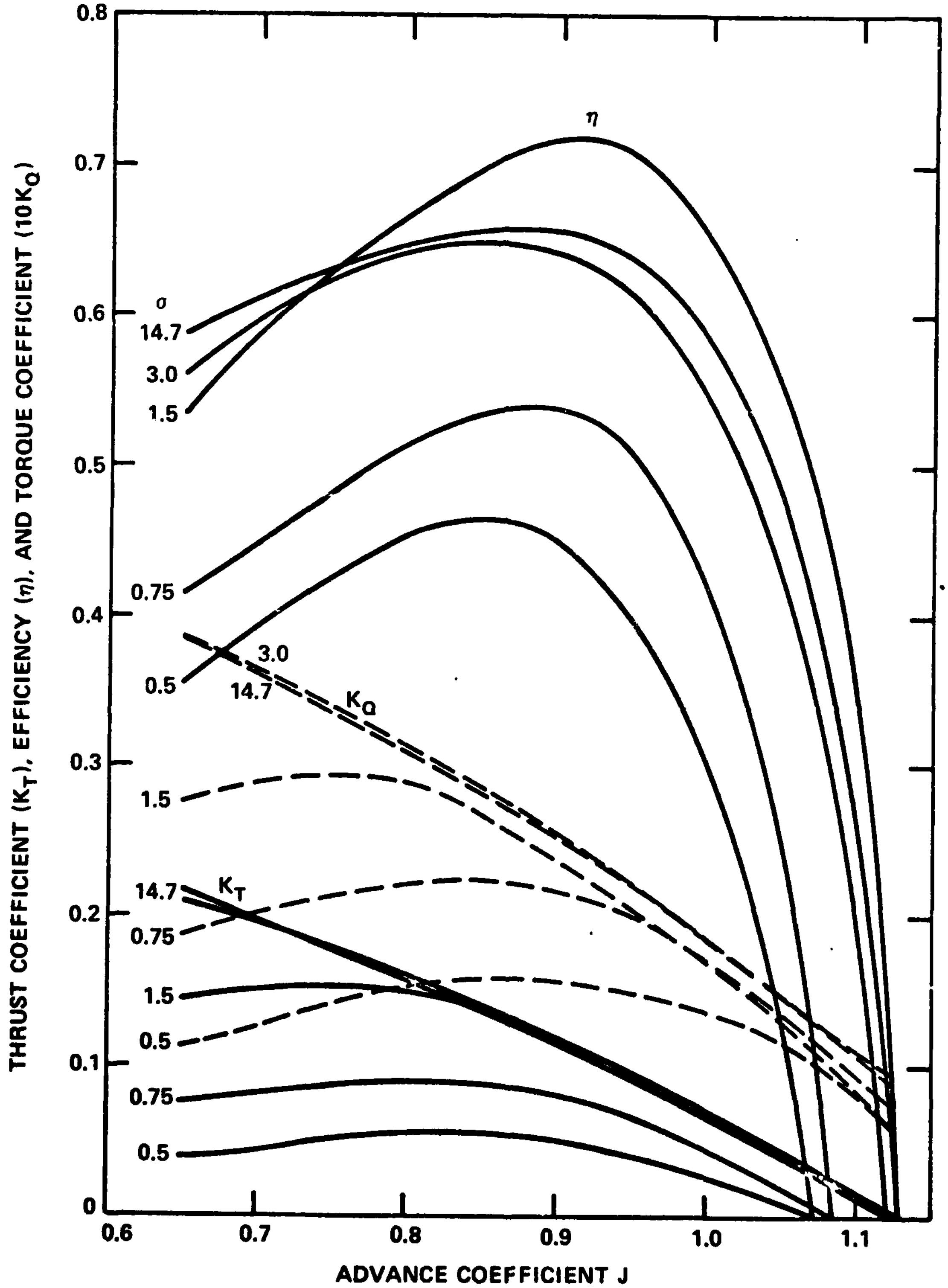


Figure 7 - Cavitation Characteristics of Propeller 4529 at 15 Degrees Shaft Inclination

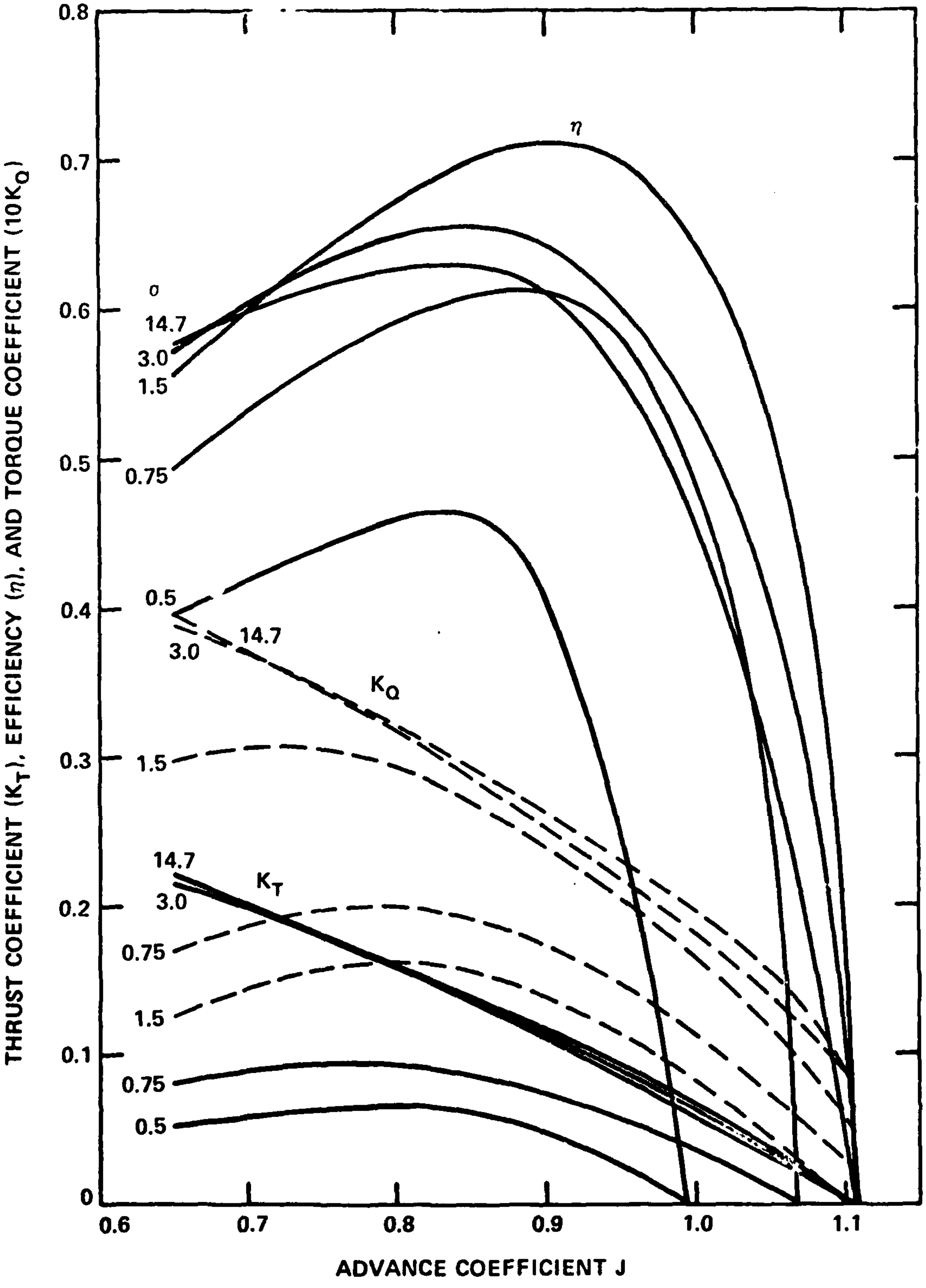


Figure 8 - Cavitation Characteristics of Propeller 4615 at 15 Degrees Shaft Inclination

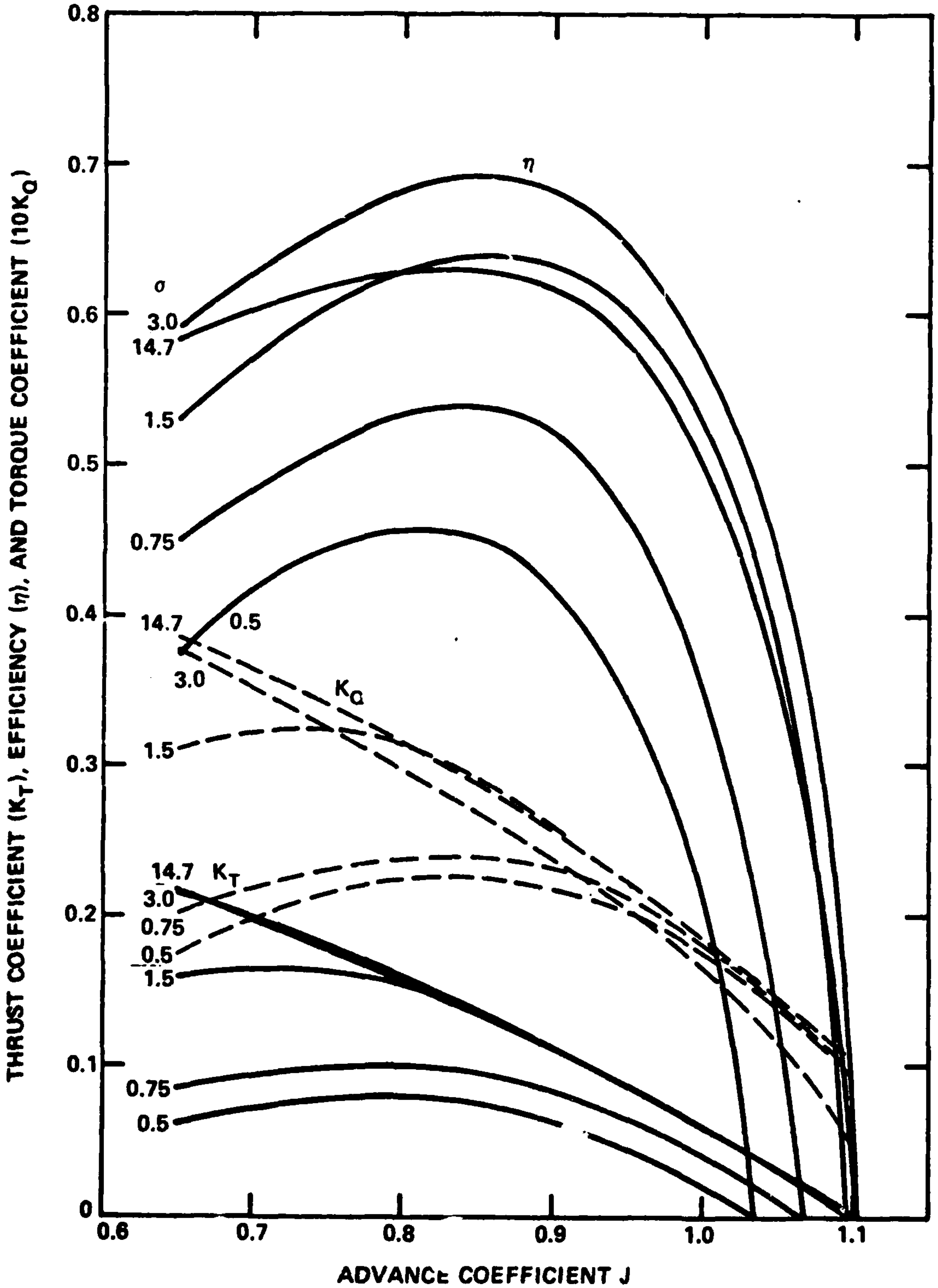


Figure 9 - Cavitation Characteristics of Propeller 4616 at 15 Degrees Shaft Inclination

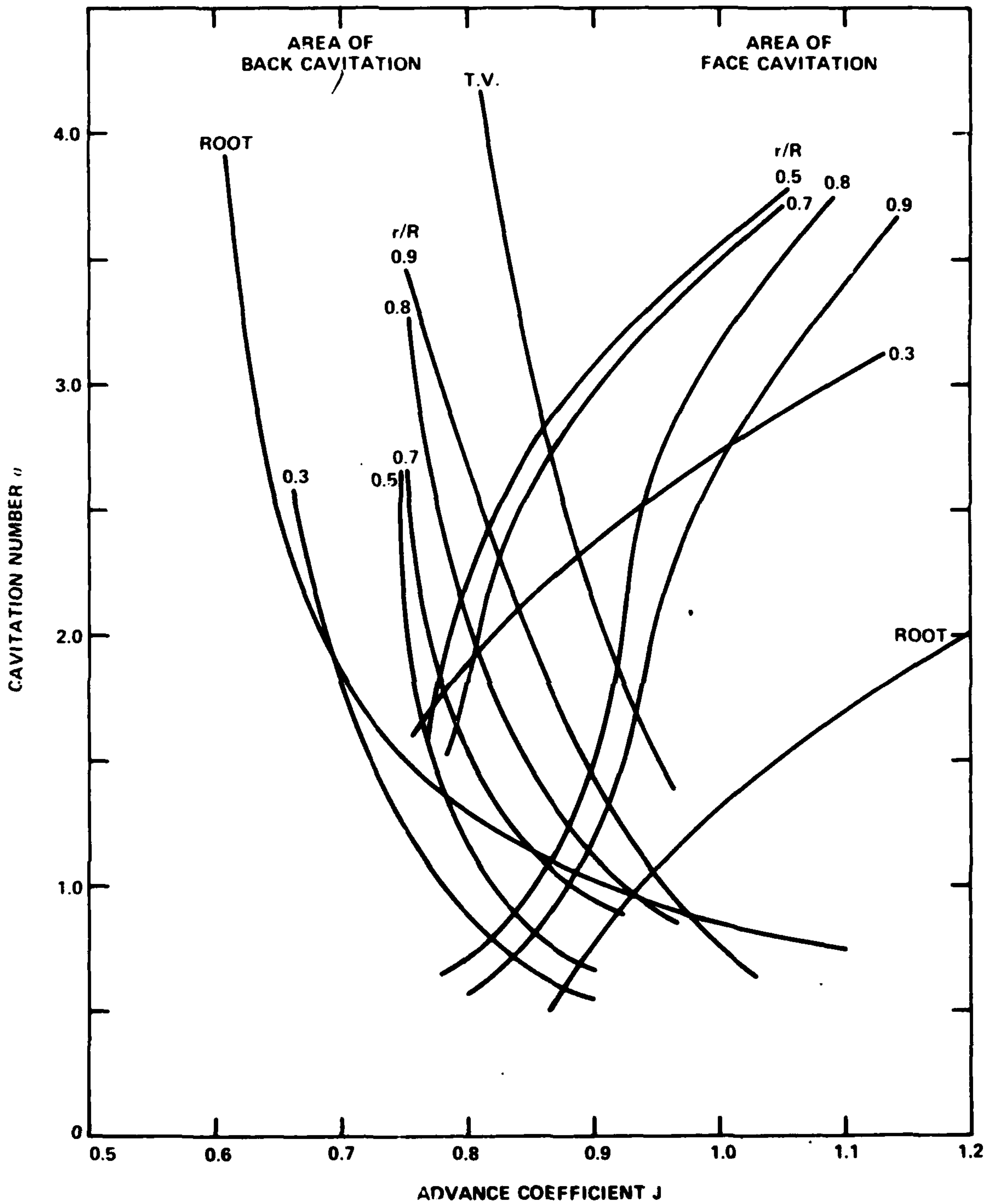


Figure 10 - Cavitation Inception Curves for Propeller 4529 at 15 Degrees Shaft Inclination

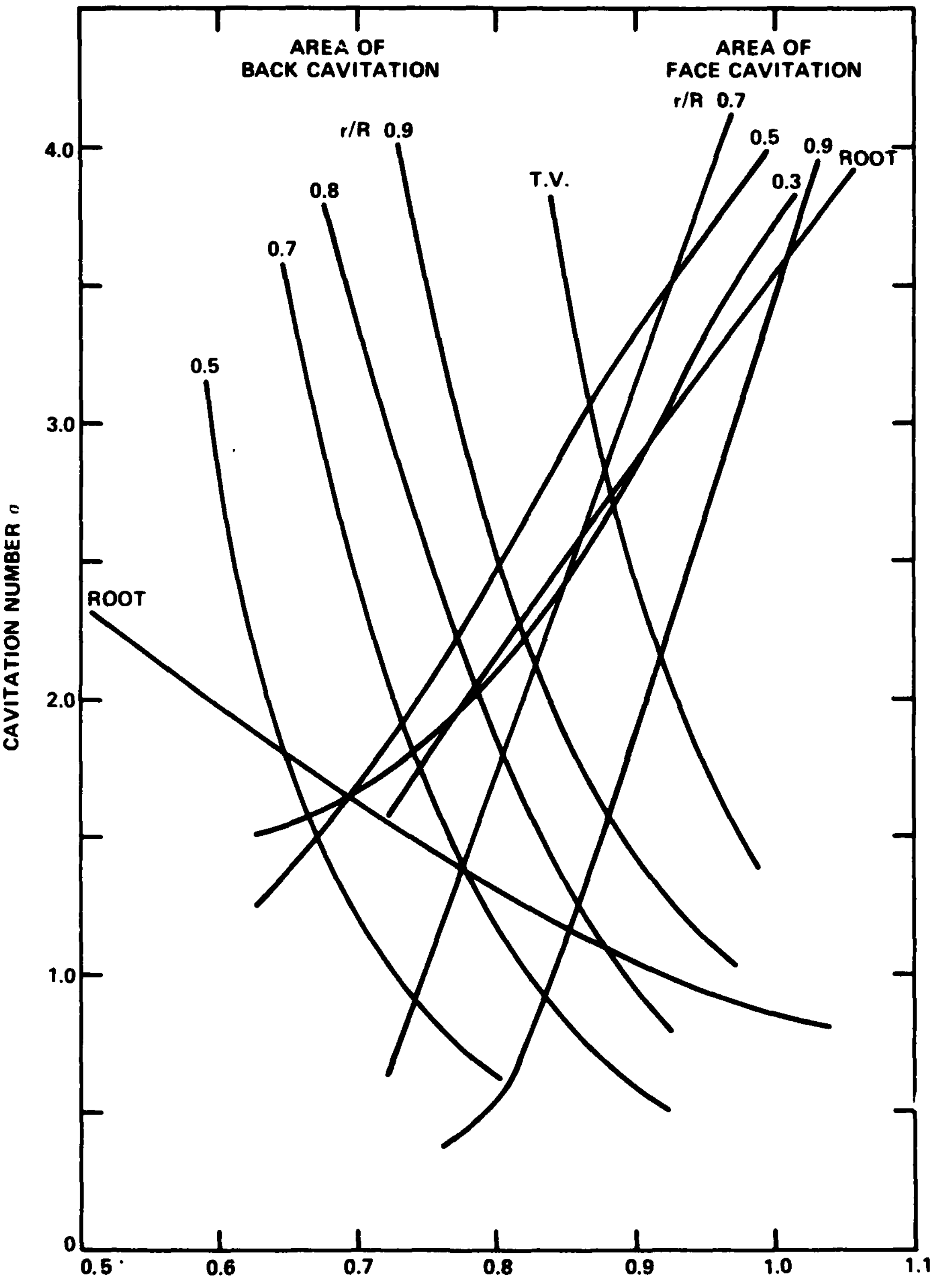


Figure 11 - Cavitation Inception Curves for Propeller 4615 at 15 Degrees Shaft Inclination

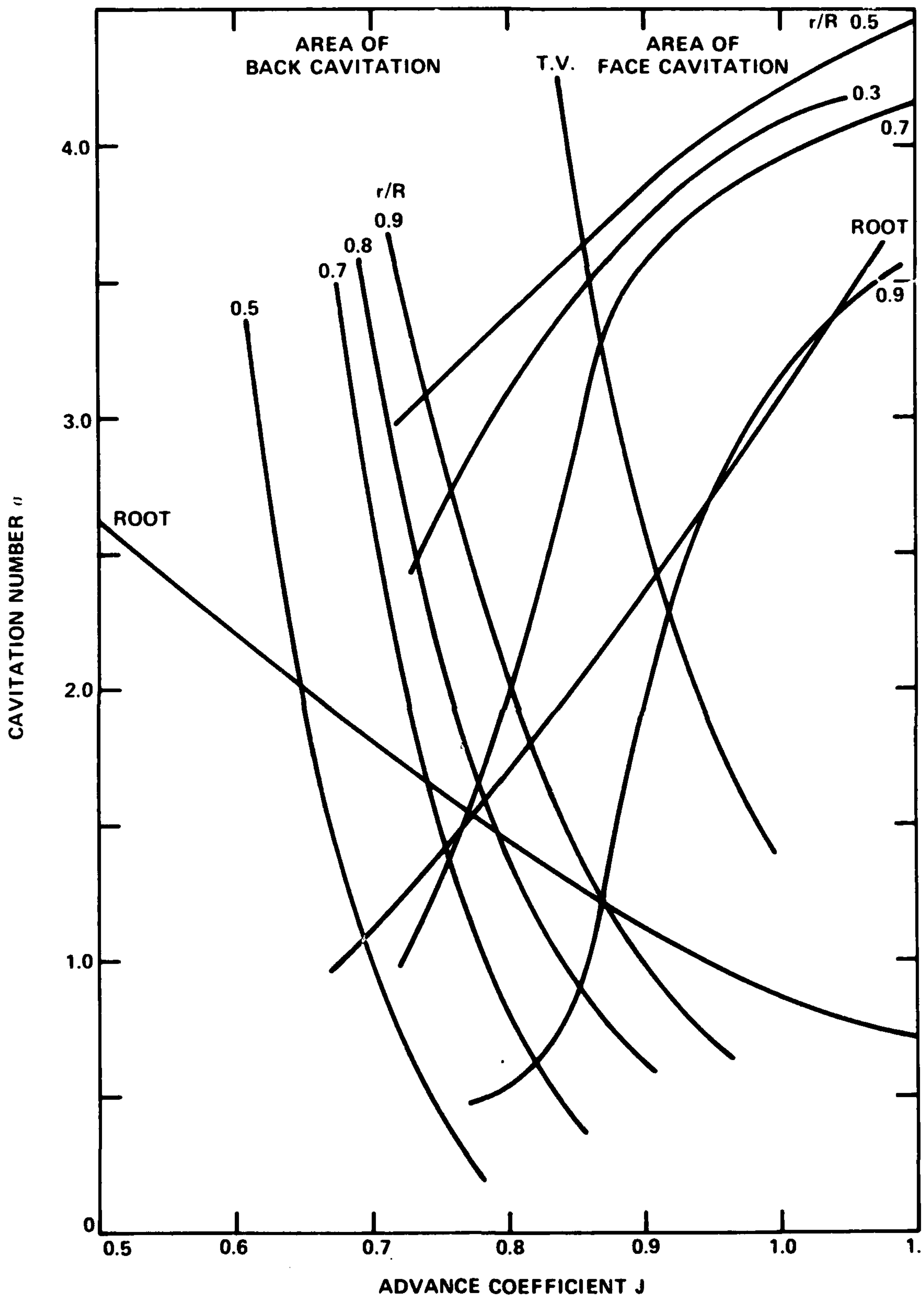


Figure 12 - Cavitation Inception Curves for Propeller 4616 at 15 Degrees Shaft Inclination

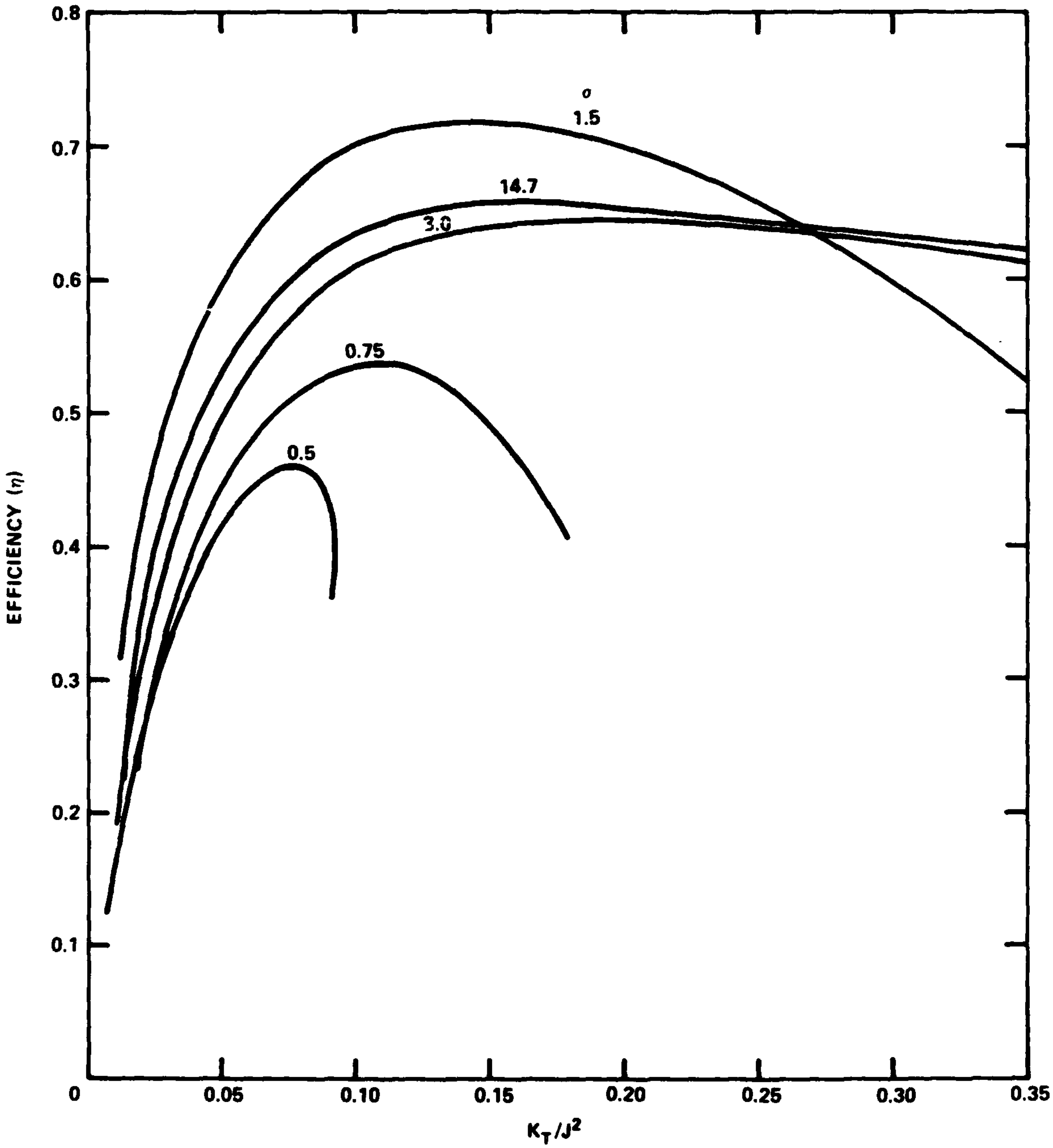


Figure 13 - Propeller 4529 Efficiencies versus K_T/J^2 for Various Cavitation Numbers at 15 Degrees Shaft Inclination

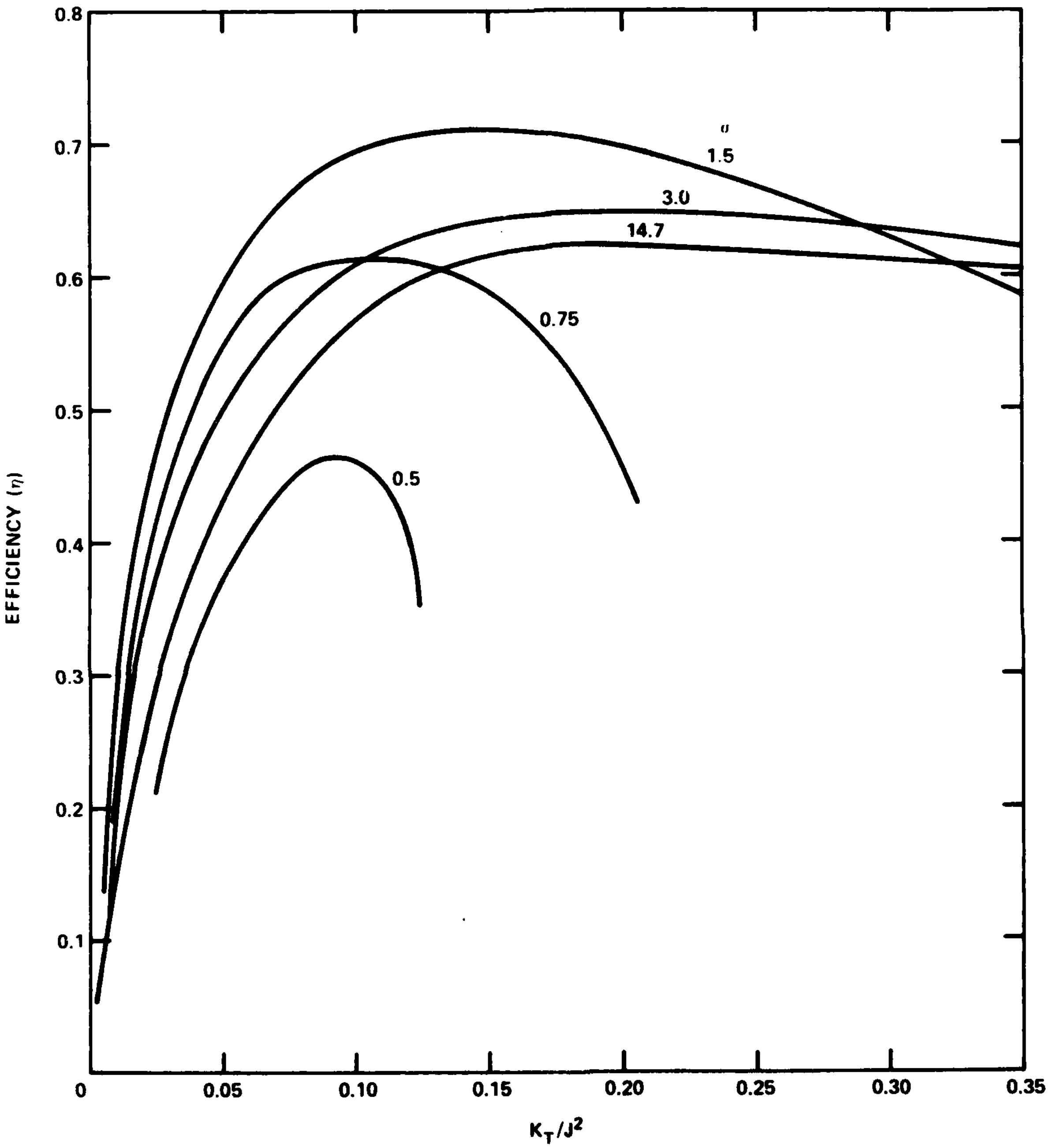


Figure 14 - Propeller 4615 Efficiencies versus K_T/J^2 for Various Cavitation Numbers at 15 Degrees Shaft Inclination

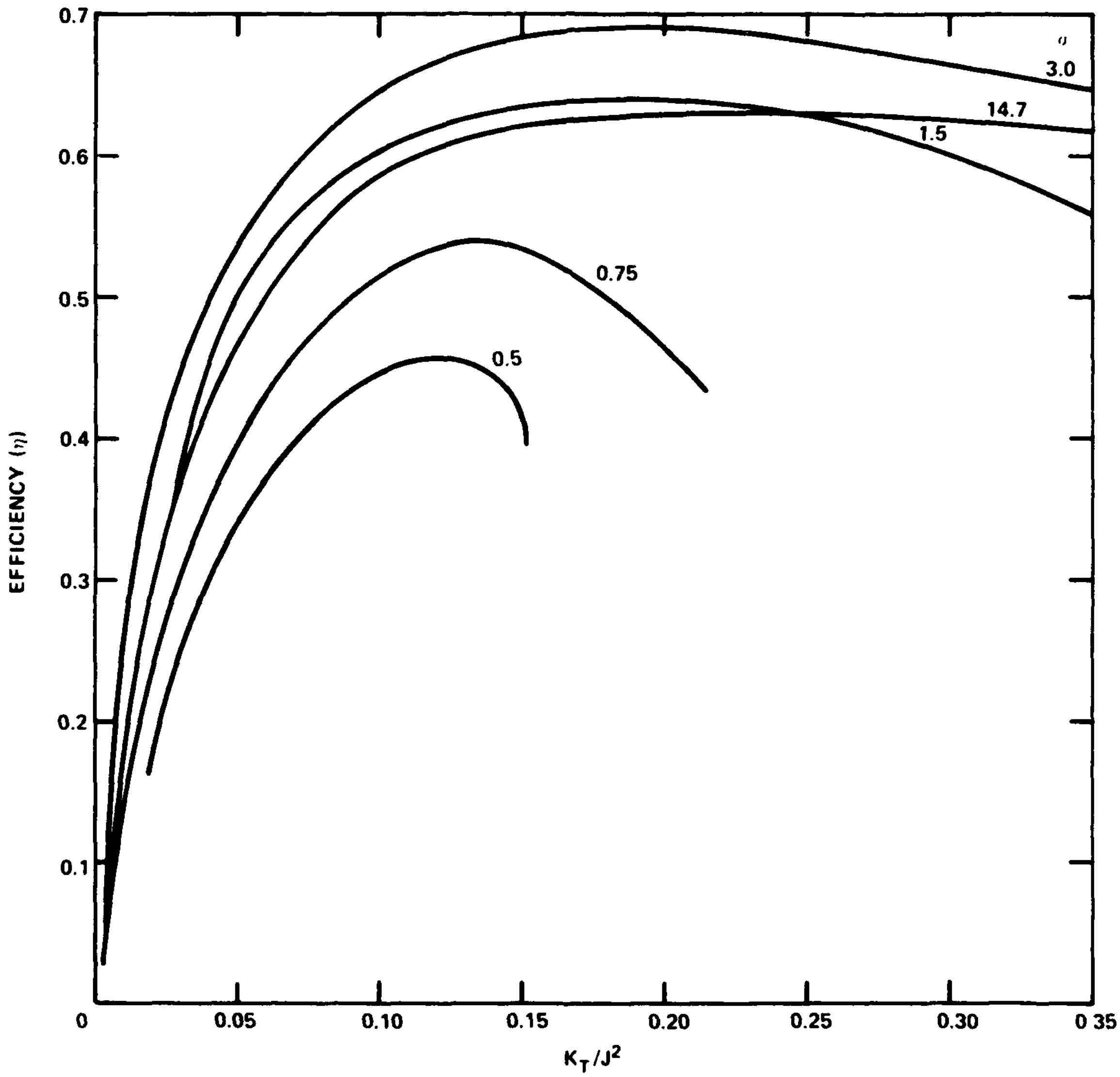
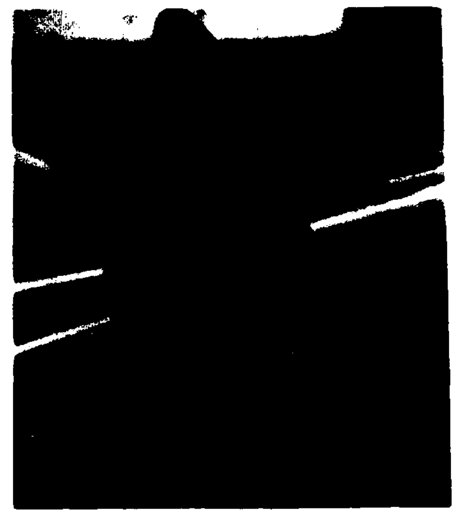


Figure 15 - Propeller 4616 Efficiencies versus K_T/J^2 for various Cavitation Numbers at 15 Degrees Shaft Inclination

Propeller 4529 Constant Pitch Distribution



Propeller 4616 Reduced Pitch at the Hub

Figure 16 - Comparison of Cavitation on Propellers 4529 and 4616 at $J = 0.9$, $\sigma = 0.75$, and 15 Degrees Shaft Inclination

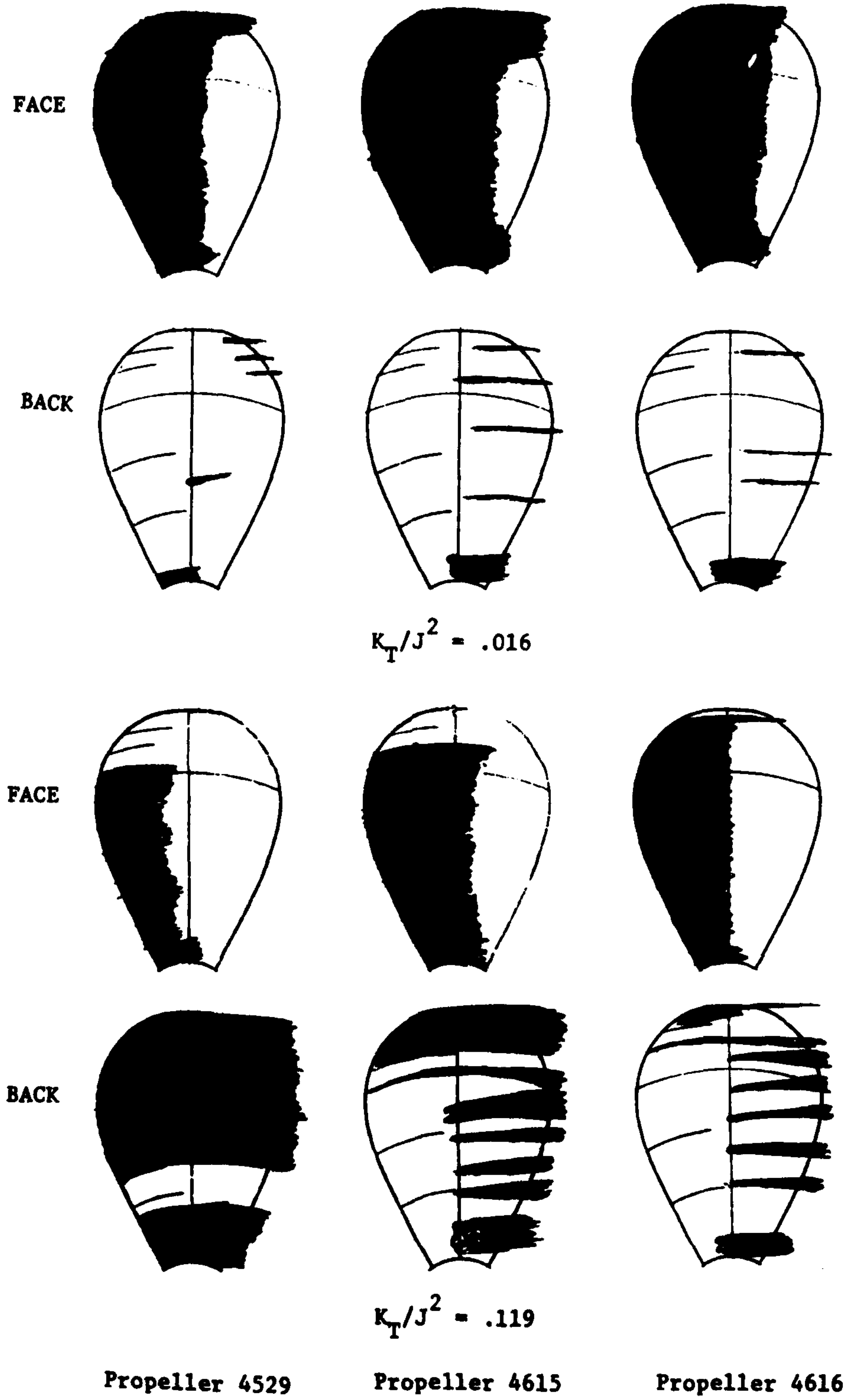


Figure 17 - Sketching of Cavitation Present on Propellers at 15 Degrees Shaft Inclination, σ = 0.75, and Two Thrust Loadings