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EXPERIMENTAL EVALUATION OF TWO LOOP-BLADED PROPELLERS

by

Pao Chi Pien

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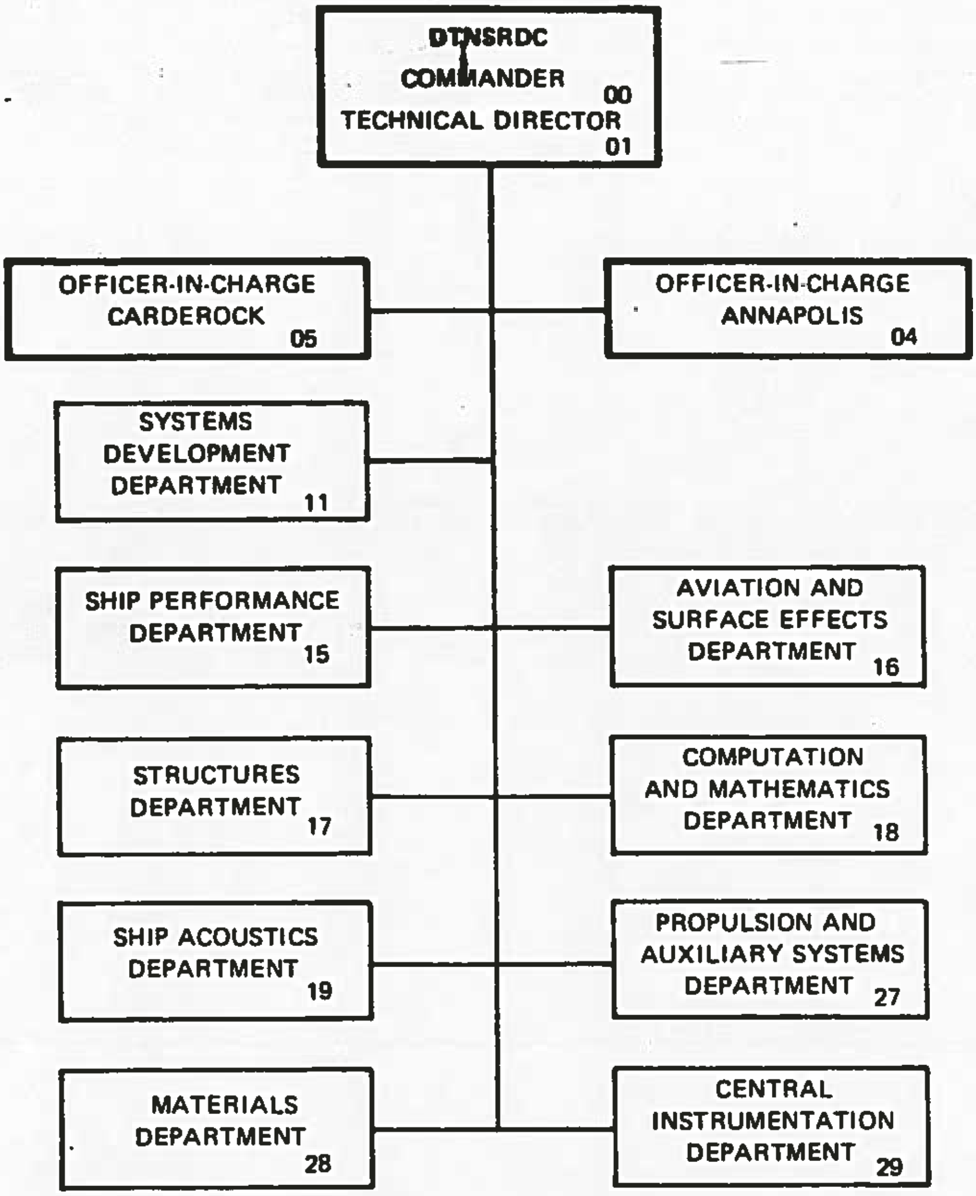

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Experimental results are given for two model propellers with new loop-bladed configurations. These results are obtained from open-water and cavitation performance performance experiments on the two propellers, and unsteady thrust and torque measurements on one of the propellers operating behind wake screens. Based on these results, potential advantages of the loop-bladed propeller configuration are stated with regard to propeller blade cavitation and propeller force fluctuation. It is recommended that research be continued on the loop bladed propeller configuration.

(Block 10)

PROGRAM ELEMENT 62543N
PROJECT F43421
TASK AREA ZF43421001
WORK UNIT NUMBER 1-1500-003-09

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NOTATION

$c_{0.7}$	Blade chord length at 0.7 radius
D	Diameter of propeller
EAR	Expanded area ratio
J	Advance coefficient, V_a/nD
J_D	Design advance coefficient
K_Q	Torque coefficient, $Q/\rho n^2 D^5$
$\tilde{K}_Q$	Unsteady torque coefficient, $\tilde{Q}/\rho n^2 D^5$
K_T	Thrust coefficient, $T/\rho n^2 D^4$
$\tilde{K}_T$	Unsteady thrust coefficient, $\tilde{T}/\rho n^2 D^4$
n	Revolutions per unit time; order of shaft frequency harmonic
Q	Mean torque
$\tilde{Q}$	Unsteady torque at n times shaft frequency
R_n	Reynolds number, $c_{0.7}\{V_a^2 + (0.7n\pi D)^2\}^{\frac{1}{2}}/\nu$
T	Mean thrust
$\tilde{T}$	Unsteady thrust at n times shaft frequency
V_a	Speed of advance
ρ	Density of water
ϕ	Phase angle of unsteady loading
ν	Kinematic viscosity

ABSTRACT

Experimental results are given for two model propellers with new loop-bladed configurations. These results are obtained from open-water and cavitation performance experiments on the two propellers, and unsteady thrust and torque measurements on one of the propellers operating behind wake screens. Based on these results, potential advantages of the loop-bladed propeller configuration are stated with regard to propeller blade cavitation and propeller force fluctuation. It is recommended that research be continued on the loop-bladed propeller configuration.

ADMINISTRATIVE INFORMATION

This work was authorized and funded by the Naval Material Command (NAVMAT Z071) and was carried out under Task Area ZF43421001, Element 62543N, at the David W. Taylor Naval Ship Research and Development Center (DTNSRDC). It is identified by DTNSRDC Work Unit Number 1-1500-103-09.

INTRODUCTION

A loop-bladed propeller is closely related hydrodynamically to a highly skewed propeller and a warped propeller. For a better understanding of the hydrodynamic characteristics of a loop-bladed propeller as well as the motivation of its development, it is appropriate to discuss briefly the highly skewed and warped propellers.

It has been found that a highly skewed propeller can be used effectively to reduce propeller-excited vibratory forces, i.e., both pressure forces transmitted through the water directly to the hull and shaft (bearing)forces transmitted through the propeller shafting, and to delay inception of leading edge and tip vortex cavitation.[1] As a further improvement, the structurally undesirable skew-induced rake associated with a highly skewed propeller can be removed without adversely influencing its performance. This leads to the concept of the warped propeller, which is achieved by moving each blade element forward a distance

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[1] References are listed on Page 10 .

corresponding to the amount of skew-induced rake. Propellers of this type are discussed in Reference 2. Of course it can also be obtained from an unskewed propeller by moving each blade element aft in the plane of the propeller without changing its axial position. A warped propeller is a great improvement over a highly skewed propeller from a structure point of view, It also has much less dimension in the axial direction and requires much less stern aperture space. It is more rigid and has less stress at blade root section, mainly due to the fact that centrifugal force of a rotating blade produces a bending moment at the root section to reduce the bending moment due to blade loading.

The end view of a warped blade resembles one half of a loop. If two warped propellers, one warped forward and one warped backward, are mounted on the same hub so that two adjacent blade tips are joined together to form a loop, the result is a loop-bladed propeller. Hence, the hydrodynamic properties of a loop-bladed propeller can be expected to be very similar to those of a warped propeller. Two loop-bladed model propellers have been designed, built, and tested for various performance characteristics. This report is intended to bring together these experimental results and to review them carefully, as well as to make some general comments and recommendations.

DESCRIPTION OF PROPELLER MODELS

The first loop-bladed propeller, identified as Propeller 4563, was designed for the same K_R value of 0.207 and J value of 1.007 as Propeller 4381 of Reference 1. Furthermore they have the same blade area ratios and similar loading distributions. The physical characteristics of Propeller 4563 are listed in Table 1 and Figure 1. Figure 1 also shows the drawing and Figure 2 shows photographs of Propeller 4563. A second loop-bladed propeller, identified as Propeller 4667, was also built for experimental purposes. Table 2 and Figure 2 lists the physical characteristics of Propeller 4667. Figure 3 also shows the drawing and Figure 4 shows photographs of Propeller 4667.

As shown by these photographs, each loop consists of two halves, the forward three halves can be viewed as a warped propeller with three blades. Similarly, the after three halves can be considered as a warped propeller in the opposite direction. Hence it is expected that a loop-bladed propeller would have similar performance characteristics to that of a warped propeller with the same amount of blade warp. Since the forward half and the after half are jointed at the tip to form a loop, it has two distinct advantages over the warped propeller. The first advantage is structural in that a loop construction has more rigidity than a curved cantilever construction. The second advantage is hydrodynamic in that there should be no vorticity concentration at the "tip."

As mentioned previously, a loop-bladed propeller is equivalent to two different warped propellers jointed together. Due to mutual interferences between them, pitch distributions and cambered surfaces of the forward halves and the after halves must be determined simultaneously. A computer program has been used to perform the complex design calculations.

Propellers 4563 and 4667 were built for model experiments to investigate the hydrodynamic properties of such a new propeller configuration. Both open-water and cavitation experiments were conducted with these propellers and unsteady force measurements were conducted with Propeller 4563 alone. Experimental procedures and results are described in the following text.

EXPERIMENTAL PROCEDURES

Open-water experiments were conducted in the deep water basin of DTNSRDC, using standard equipment and procedures. Propeller thrust and torque were measured with shaft revolutions held constant at 9 RPS, and speed of advance was varied from 3.0 to 12.0 ft. sec^{-1}. Measurements of speed of advance and shaft revolutions were determined to within 0.01 ft. sec^{-1} and 0.01 RPS respectively, while those for thrust and torque were accurate to within ± 0.2 pound or inch-pound, respectively.

Cavitation experiments were performed in the 24-inch Variable Pressure Water Tunnel (VPWT) using standard instrumentation and procedures. Tunnel water speed was calibrated using open-water thrust coefficients. Thrust was measured to within ± one pound and shaft revolutions to within ± one RPM. For each value of propeller RPS, n, corresponding to a preset value of advance coefficient, J, tunnel combing pressure was varied to cover the required range of cavitation number, σ. The tunnel water speeds used were 10 and 15 ft. sec^{-1} dependent upon propeller loading limitations for specific values of advance coefficient. Once a specific value of advance coefficient was achieved the tunnel static pressure was lowered until cavitation occurred on the propeller blades. As cavitation spread to the various propeller blade radii, static pressure was recorded to determine the cavitation number. Gas content of the tunnel water was held as closely as possible to 30 percent of atmospheric saturation.

Propeller unsteady thrust and torque values were also measured in the 24-inch VPWT using the six component unsteady force propeller dynamometer. A detailed description of this dynamometer, including analog and digital methods used for data reduction, is presented in Reference 3. Unsteady forces were excited by the use of wake screens ahead of the propeller. Both a three and a six cycle screen were used to produce a spatially varying velocity field. Table 4 lists the harmonic components generated by these screens that are significant to the experiments. The magnitudes of the harmonic components are given as a percentage of the mean velocity. With a propeller rotational speed of 15 RPS, tunnel water speed was adjusted to obtain advance coefficients of 0.6, 0.75, 0.9, 1.0, 1.1 and 1.24. These advance coefficients were determined by establishing thrust identities with the open-water results. The resulting Reynolds numbers ranged from $R_n = 8.5 \times 10^5$ to 9.4×10^5. These experiments were conducted at non-cavitating conditions. The unsteady thrust and torque were recorded in analog form on magnetic tape and data reduction were performed by a computer.

EXPERIMENTAL RESULTS

Experimental open-water and cavitation results for the two loop-bladed propellers are reported in References 4 and 5. The unsteady thrust and torque measurements are reported in Reference 6. All of these results are represented in this report for purposes of convenience.

Figures 5 and 6 show open-water characteristics of propeller 4563 in forward and backing operation, respectively. Open-water results of propeller 4381 are also shown in Figures 5 and 6 for comparison. Figure 7 shows forward open-water characteristics of propeller 4667.

Figure 8 shows photographs of propeller 4563 taken during the cavitation experiments. Curves of observed cavitation inception are given in Figure 9. These curves were obtained by plotting the radial extent of cavitation from visual observations against cavitation number for each advance coefficient. The area above any curve indicates that there was no visible cavitation of that type present at that radius for that advance coefficient. Below the curve the cavitation increases with decreasing cavitation number, σ. The cavitation inception curves were determined from cavitation observed on at least two blades. Sketches of the cavitation for each advance coefficient over the cavitation number range were also made during the experiment. Typical sketches are shown in Figure 10 for the advance coefficient, J = 0.6. These sketches were made on standard sheets for conventional propellers. Blade outlines are not those of a loop-bladed propeller. Nevertheless these sketches do show the extent of cavitation at various radii. Curves of thrust and torque loss due to cavitation are given in Figure 11. These curves were obtained by plotting K_T and K_Q at selected values of σ compared to open-water K_T and K_Q plotted against advance coefficient J. No losses occurred above σ = 5.41. At the lowest evaluated value of σ losses occurred for J 0.95.

Experimental cavitation results for propeller 4667 are shown in Figures 12 to 14. These figures were obtained in exactly the same manner as those of propeller 4563.

The unsteady thrust and torque measurements for propeller 4563 in the three cycle wake are given in Figures 15 and 16, respectively. They are presented as nondimensional coefficients K_T and K_Q over a range of advance coefficient J. As already stated the advance coefficient was obtained using a K_T identity with the open-water data. The principal unsteady component is at three times the shaft frequency with significant second, third and fourth harmonics of this frequency. The phase angles are the number of harmonic degrees by which the unsteady components of thrust and torque lead the principal harmonic component of the water velocity. Thrust in the upstream or forward direction and the corresponding torque applied by the propeller to the shaft are considered to be positive. Water velocity is positive in the downstream or aft direction. Figures 17 and 18 show the results obtained in a six-cycle wake. Here the principal unsteady component is at six times the shaft frequency and the harmonics are not as strong as in the three cycle wake. Only the harmonic at twelve times shaft frequency has a significant amplitude. Since only three and six cycle flow patterns were used in the experiment, there were no unsteady side forces or bending moments. The accuracy of magnitudes of the unsteady components is estimated to be $\pm 5\%$.

DISCUSSION OF EXPERIMENTAL RESULTS

OPEN-WATER PERFORMANCE

A comparison of the experimental performance of propeller 4563 and the predicted performance is given in Table 3. Based on this comparison, it is obvious that the design conditions have not been met. Likewise the design conditions of propeller 4667 have not been met. A computer program was developed and used for designing these two loop-bladed propellers. Since then modifications have been made to this computer program. However, no propeller has been designed and tested by using the modified computer program.

The efficiency of a loop-bladed propeller as shown in Figure 5, is comparable with that for a conventional propeller. This means that a loop-bladed propeller configuration can be an alternative propulsive device as far as efficiency is concerned.

CAVITATION PERFORMANCE

One of the outstanding features of a loop-bladed propeller is the fact that it has no tip vortex cavity. Each loop of a loop-bladed propeller can also be considered as a ring foil attached to the hub. The free vorticity is shed off smoothly along the circumference of a ring rather than concentrated in the tip region as in the case of a conventional blade. As a consequence, the undesirable tip vortex cavitation has been completely eradicated through out the entire range of cavitation tests conducted on both loop-bladed propellers.

For a conventional, a warped, or a highly skewed propeller, surface cavitation usually starts near the tip and then gradually extends toward the inner radii as the blade loading is increased or the cavitation number is reduced. In the case of a loop-bladed propeller, the surface cavitation in the tip region is totally suppressed until both advance coefficient cavitation numbersare very low, as shown in Figures 9 and 13. This is due to the fact that for each loop, the forward half of the inside surface is the suction side while the after half is the pressure side and vise versa on the outside surface. Therefore, there is strong interference at the outer radii between the forward and the after halves of each loop which essentially acts as a pressure cancelling mechanism. As a consequence, blade loading at the outer radii is greatly reduced and much less sensitive to changes in angle of attack associated with advance coefficient, etc. This situation may have an important consequence for hull vibratory forces excited by a propeller operating in the behind condition. It is known that a propeller operating under cavitating conditions excites far greater hull vibratory forces than under non-cavitating conditions. This difference is caused mainly by the large cavity volume changes as well as the high speed of cavity motion at outer radii. In the case of a loop-bladed propeller both tip vortex cavitation and surface cavitation at outer radii are absent. Hence the problem of propeller excited hull vibratory forces due to cavitation may benefit significantly with a loop-bladed propeller.

UNSTEADY THRUST AND TORQUE MEASUREMENTS

A propeller with three looped-blades operated behind a wake screen is expected to have the same characteristics as a warped or a skewed propeller with three blades and the same amount of skew. The principal unsteady forces are at three times the shaft frequency when operated behind a 3-cycle wake and six times the shaft frequency when operated behind a 6-cycle wake as shown in Figures 15 to 18. Since there is no experimental unsteady force measurement available, either for a warped or a skewed propeller with three blades, a direct comparison between unsteady forces can not be made. Nevertheless, an indirect comparison is made between the unsteady thrust coefficient data of the loop-bladed propeller 4563 with that of a five bladed propeller possessing skew at tips equal to 50 percent of the blade spanwise. Also included are data for a three and a five-bladed unskewed propeller. Since these propellers have different numbers of blades, the unsteady values presented are for appropriate fundamental blade frequency components at three and five times shaft frequency, respectively. The two unskewed propellers have unsteady thrust components of 47 percent of the mean thrust at the design condition of $K_T/J^2 = 0.204$ for the loop-bladed propeller. The unsteady thrust for both the skewed and the loop-bladed propeller is 30 percent of the mean thrust. It should be noted that the amplitude of the five cycle wake was somewhat less than that of the three cycle wake. If the results are adjusted to a 22 percent wake the unsteady thrusts for the five bladed unskewed and skewed propeller would be 57 and 36 percent of the mean thrust, respectively.

CONCLUSIONS AND RECOMMENDATIONS

1. The loop-bladed propeller is a propulsive device with comparable efficiency to conventional propellers.

2. Within the range of blade loading and cavitation number variations experimentally evaluated, both loop-bladed propellers have no visible tip vortex cavitation.

3. The loop-bladed configuration exhibits a strong pressure cancelling mechanism at the outer radii which inhibites blade cavitation in that region. This can result in a reduction of hull vibration induced by blade cavitation. It also implies that such propellers must be designed for radial load distributions which are not loaded at the outer blade radii if propulsion design conditions are to be met. This design problem, i.e., practical radial load distributions, needs further investigation.

4. The loop-bladed propeller shows a similar reduction in fluctuating thrust and torque as the warped or skewed propeller.

5. Improvements have been made to the design procedure for loop-bladed propellers and it is recommended that further propellers be designed, built and evaluated in order to establish the possible potential of these propellers.

6. It is not anticipated that loop-bladed propellers will present a strength problem but their strength evaluation is complex and requires further investigation if the concept is adopted for ship propulsion.

7. A major disadvantage of the loop-bladed propeller is the increased cost and fabrication difficulties due to its complicated blade configuration.

8. The present configuration of a loop-bladed propeller has a limitation on the number of loops and amount of skew which can be chosen. To overcome this limitation, an improved configuration as shown in Figure 20 should be used. By anchoring the forward and the after halves of each loop at different longitudinal positions as shown, a much greater freedom is obtained in choosing the number of loops as well as the amount of skew introduced to each half of a loop.

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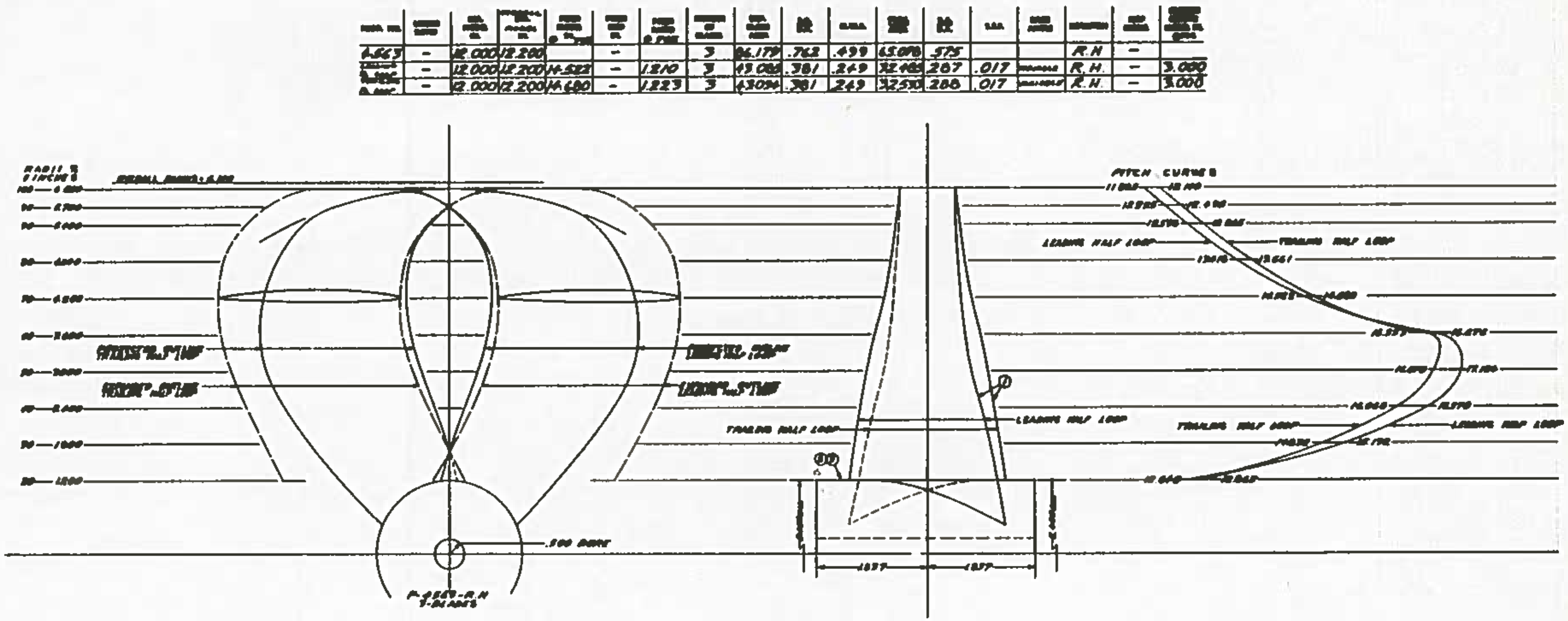


Figure 1 - Drawing of Propeller 4563

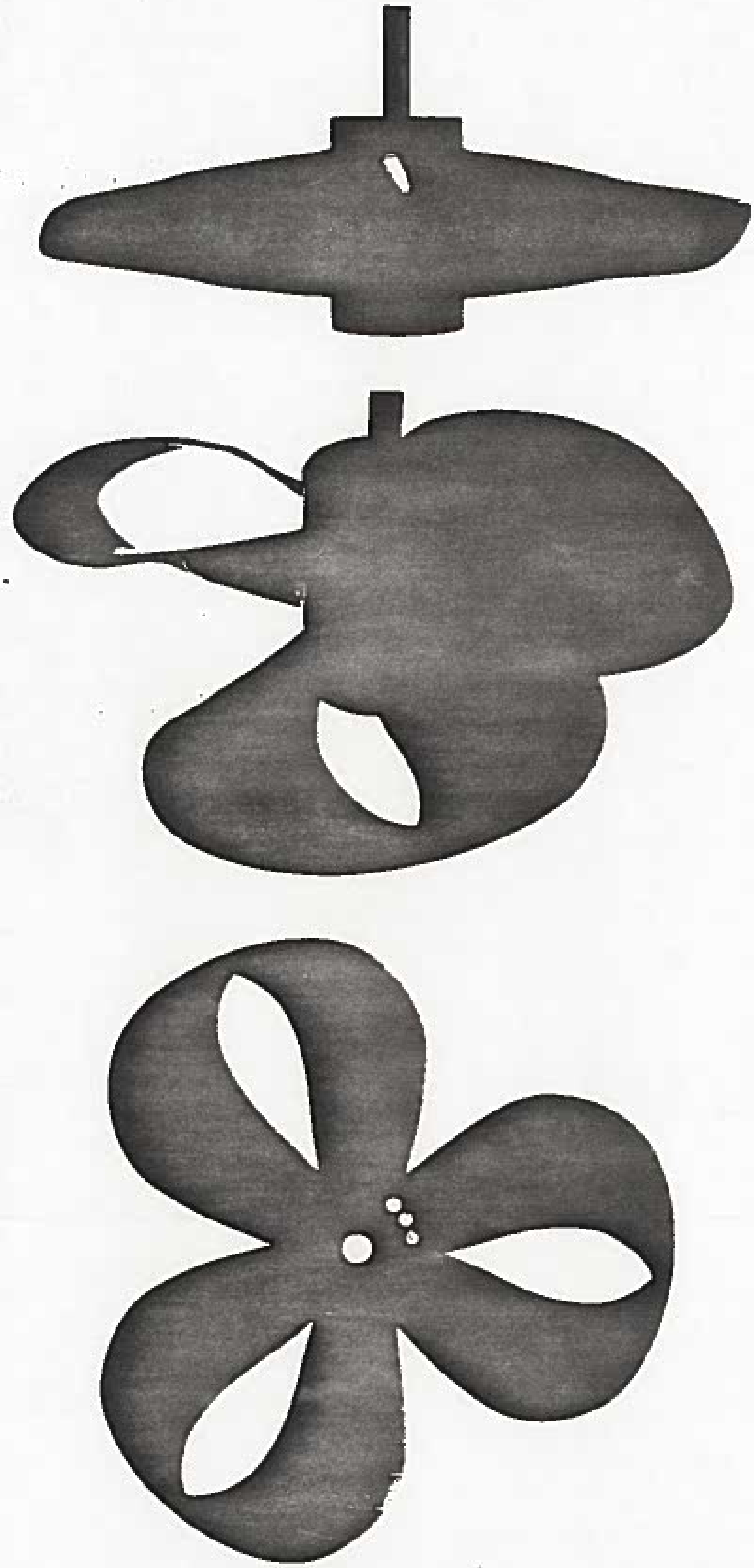


Figure 2 - Photographs of Propeller 4563

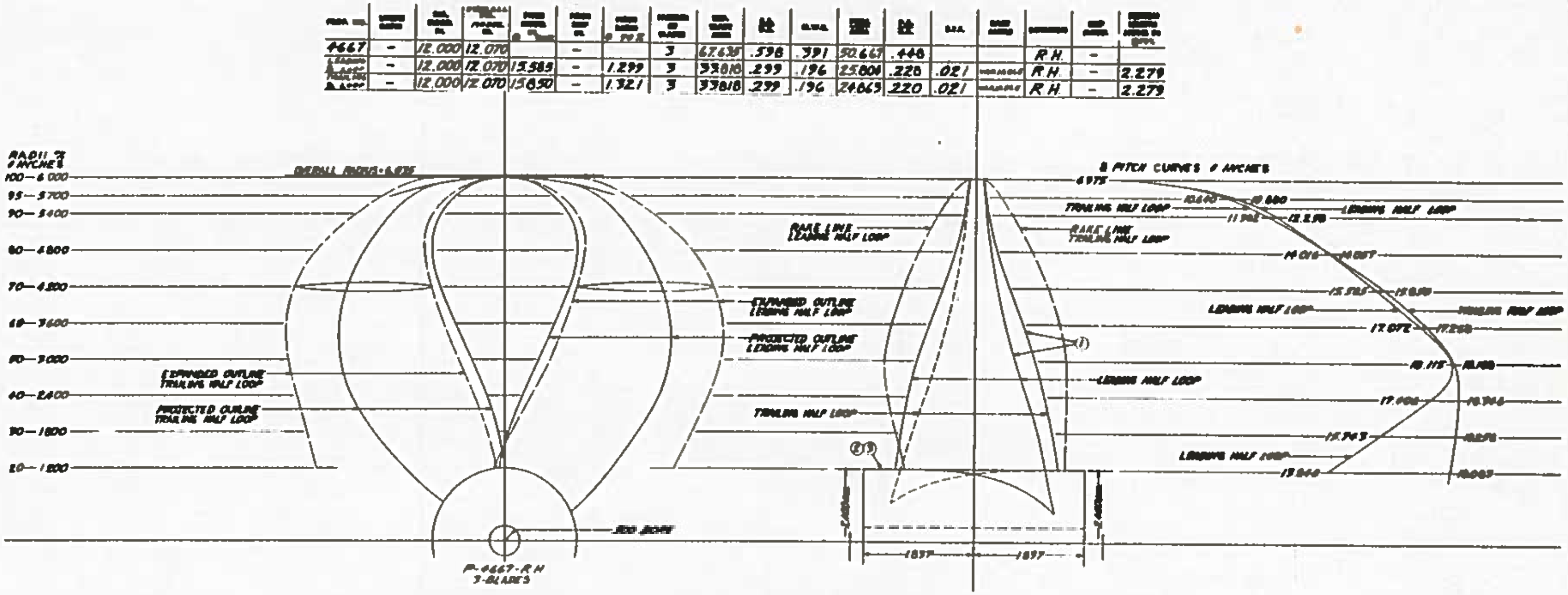


Figure 3 - Drawing of Propeller 4667

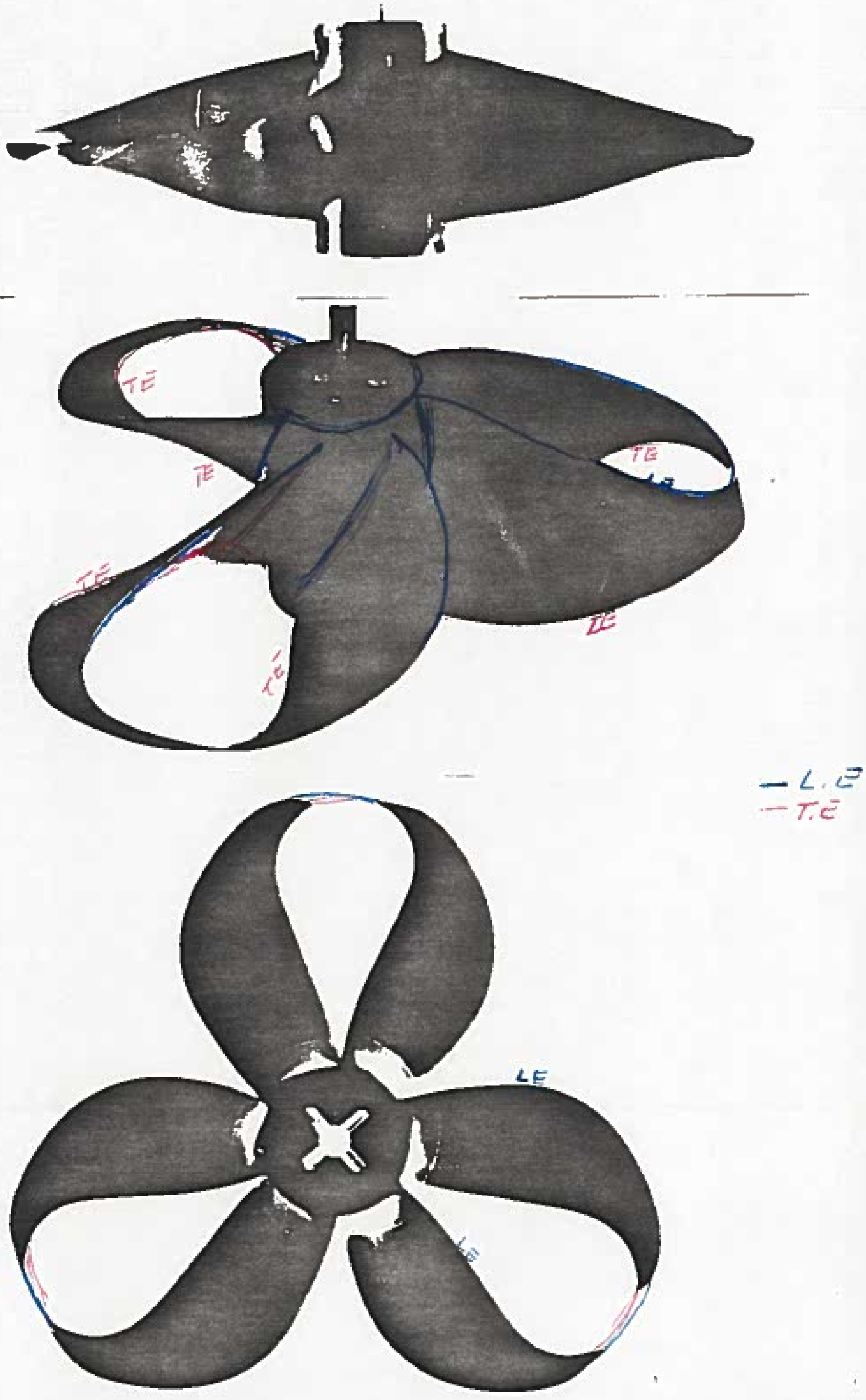


Figure 4 - Photographs of Propeller 4667

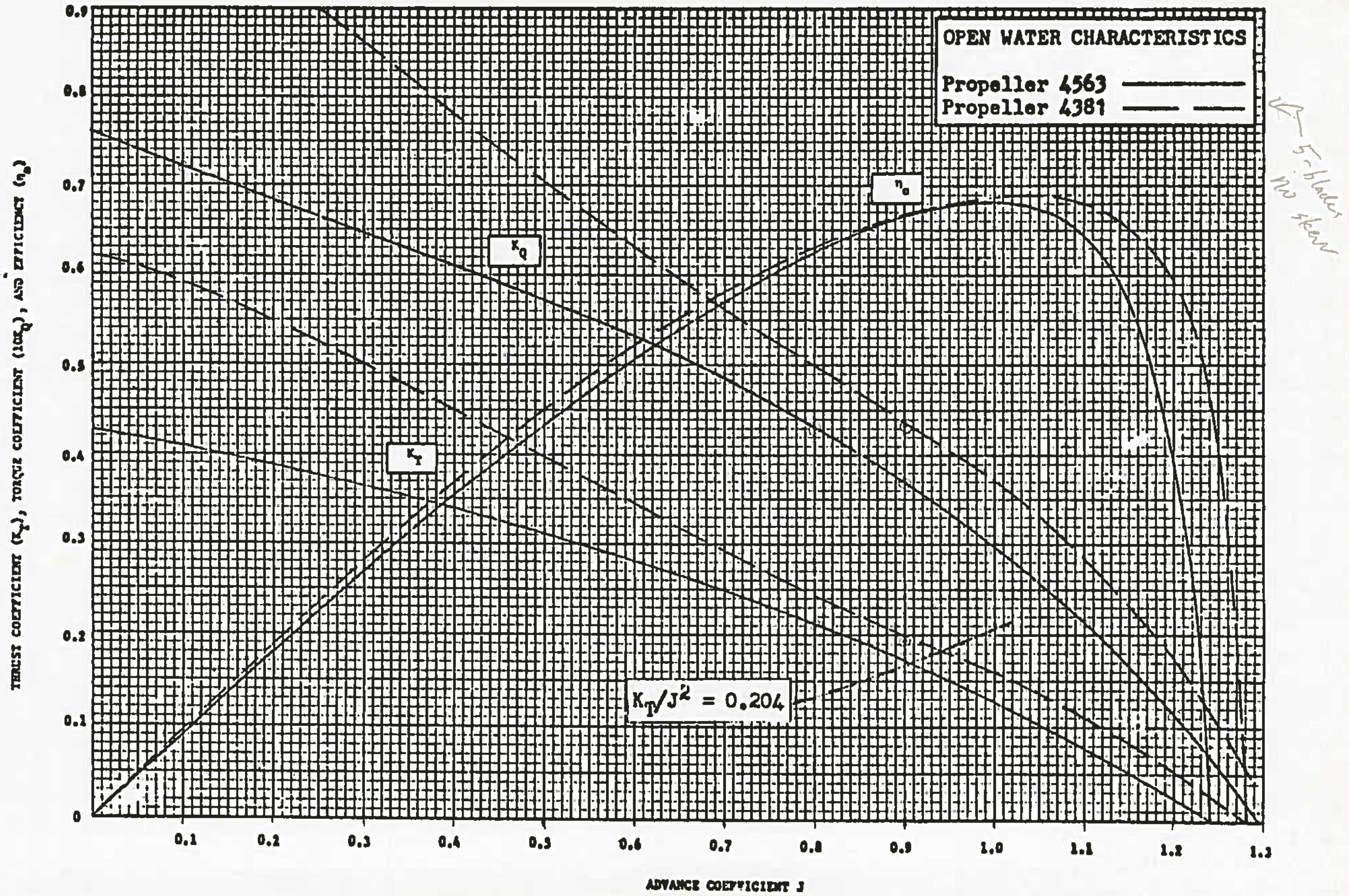


Figure 5 - Open-Water Characteristics of Propeller 4563

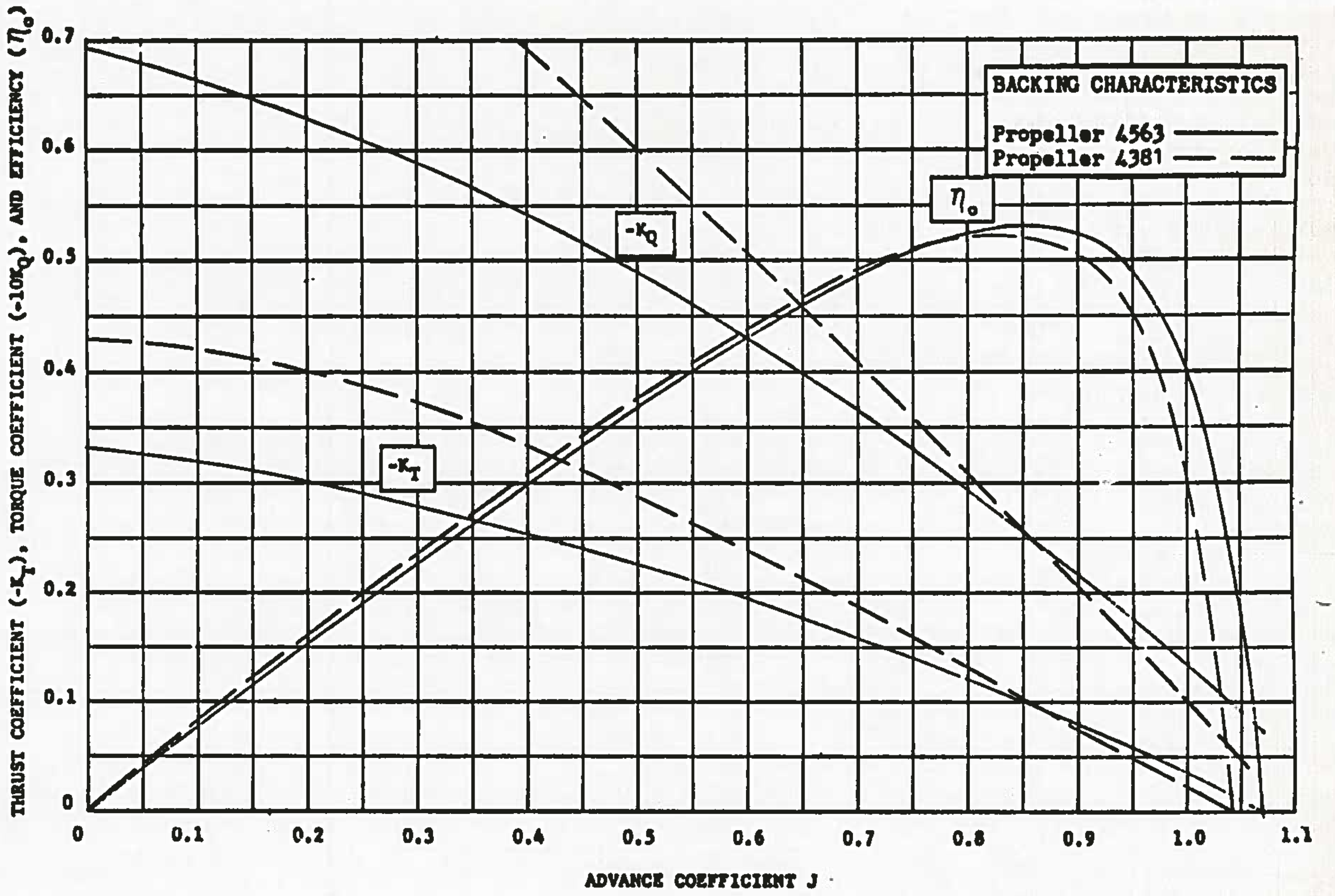


Figure 6 - Backing Characteristics of Propeller 4563

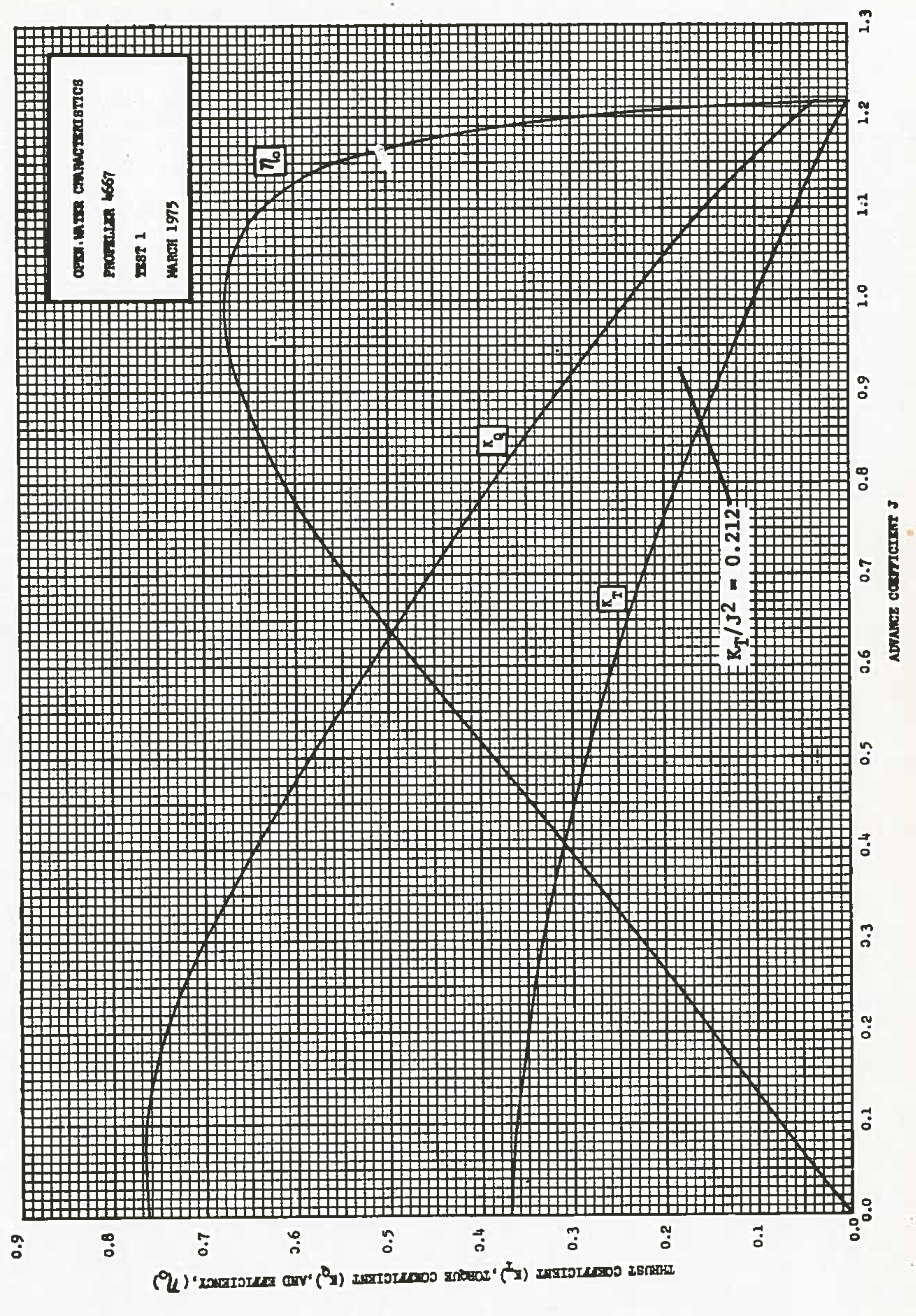
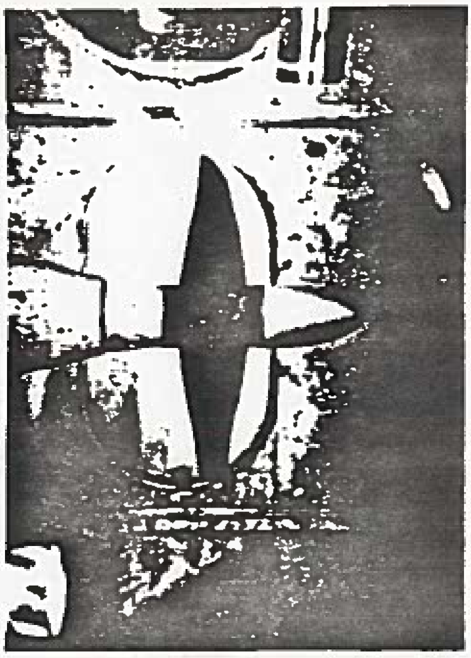
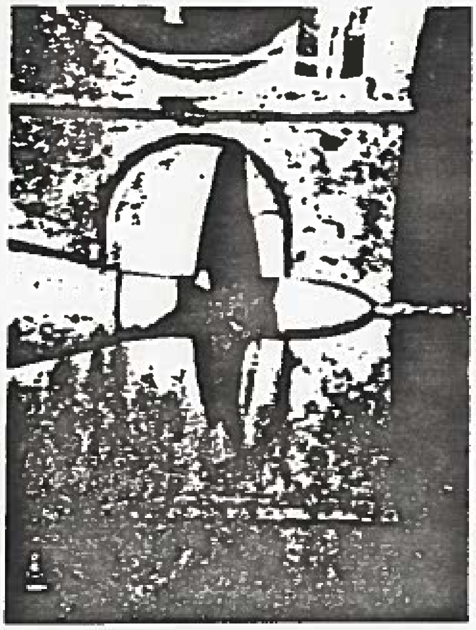


Figure 7 – Open-Water Characteristics of Propeller 4667

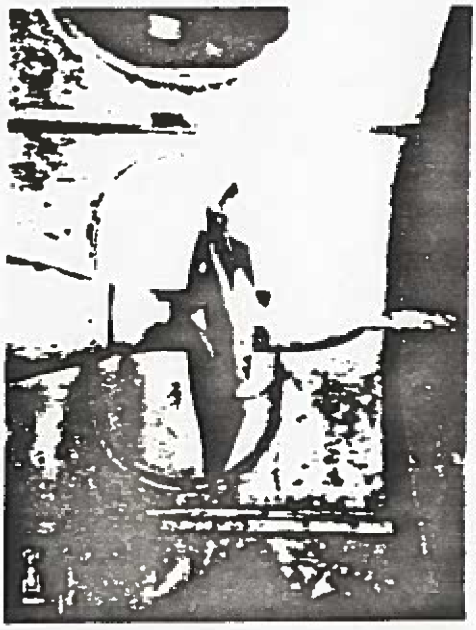


J = 1.0 σ=10.25

J = 1.0 σ=1.01



J = 0.65 σ=3.96



J = 0.65 σ=2.40

Figure 8 - Photographs of Cavitating Propeller 4563 at J = 1.0 and J = 0.65

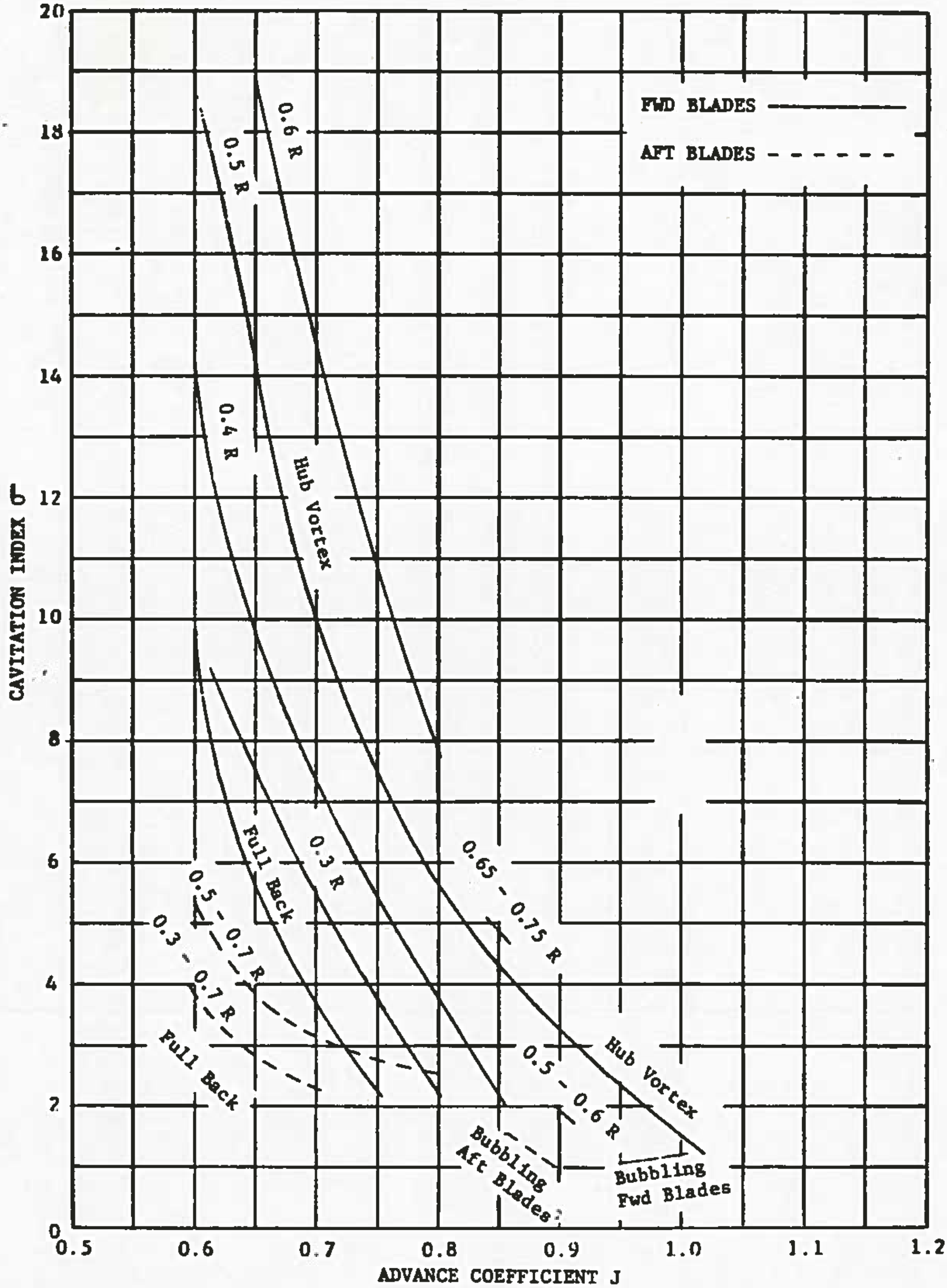


Figure 9 - Cavitation Inception Characteristics of Propeller 4563

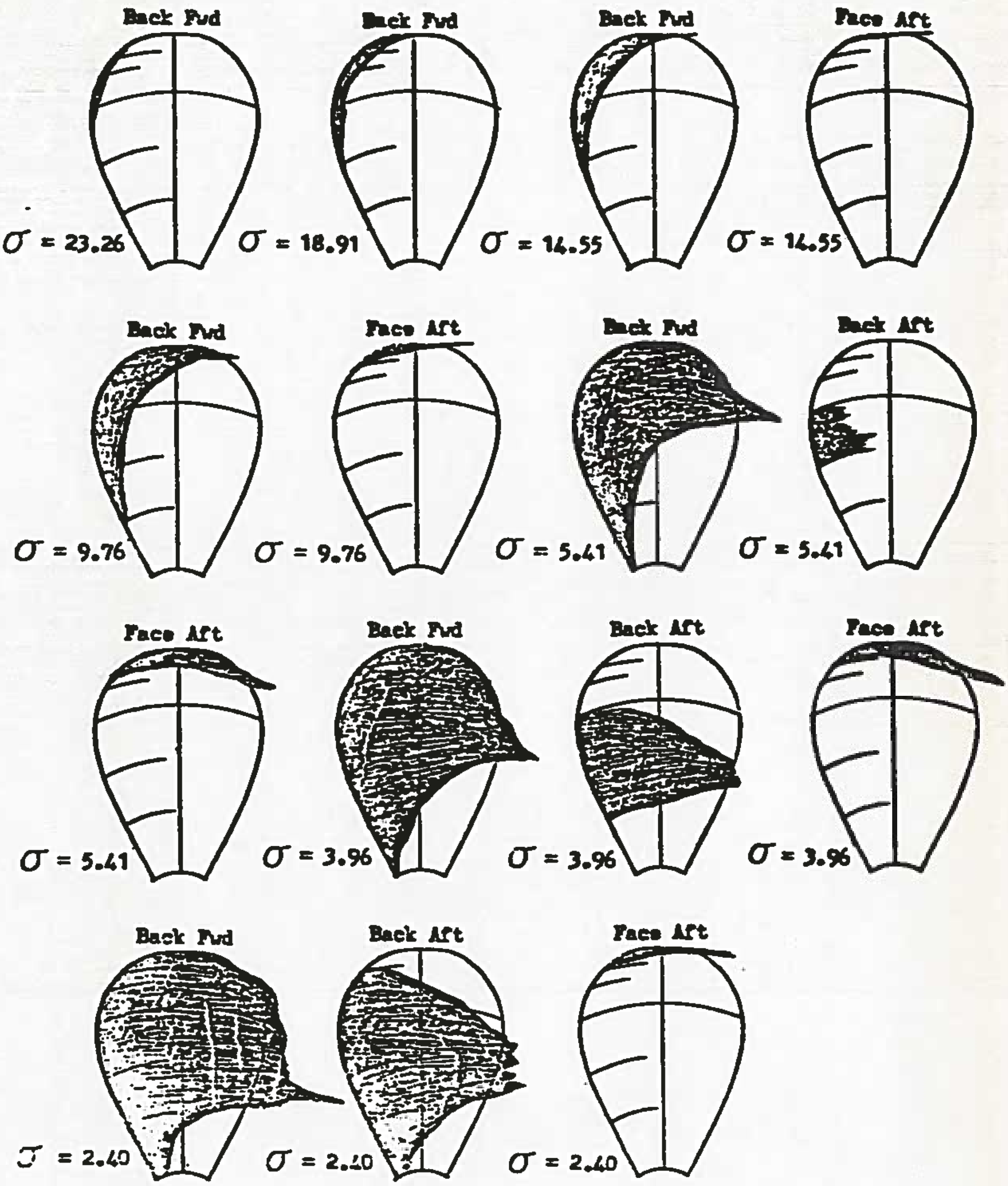


Figure 10 - Sketches of Cavitation on Propeller 4563 at J = 0.6

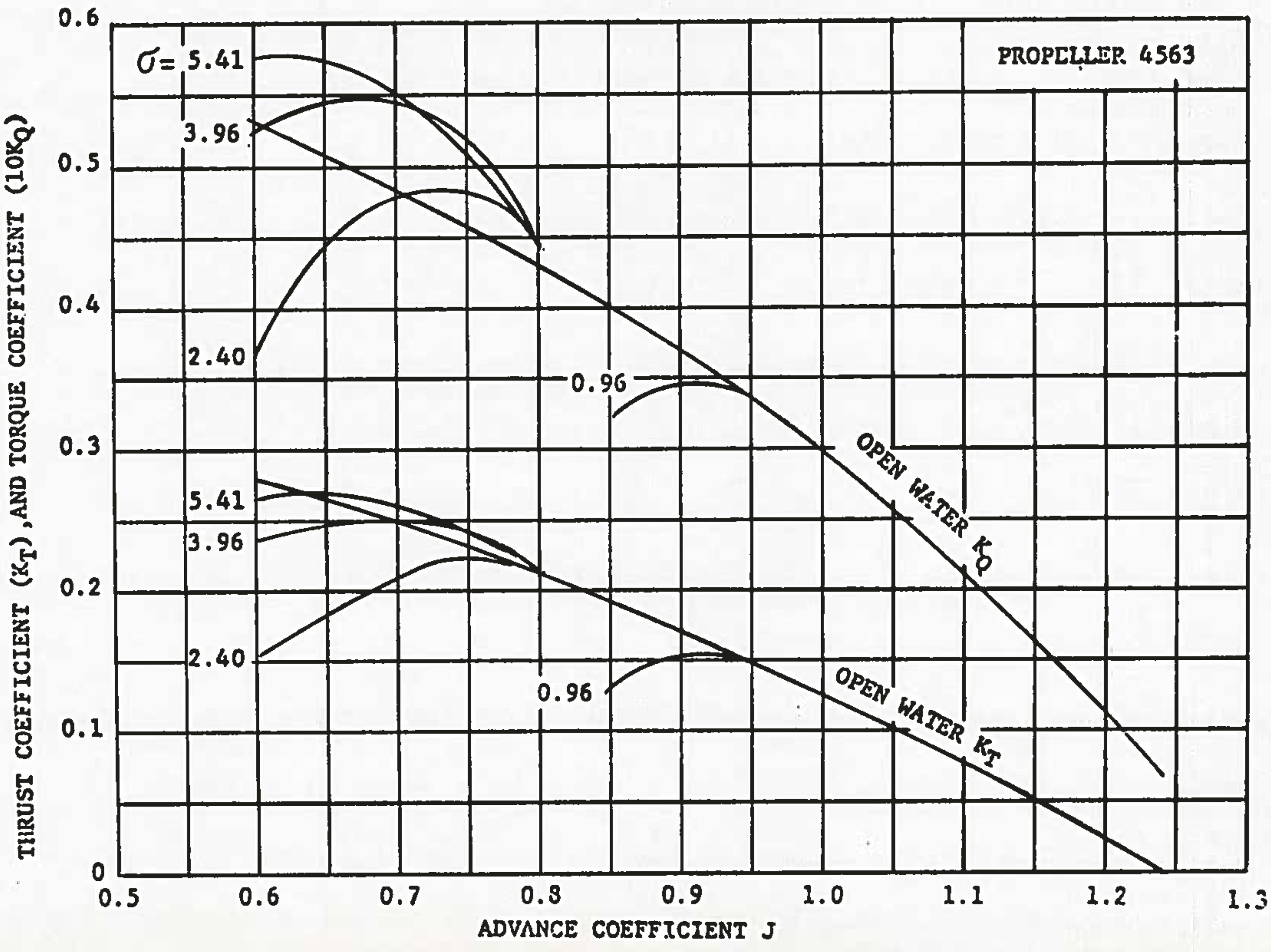
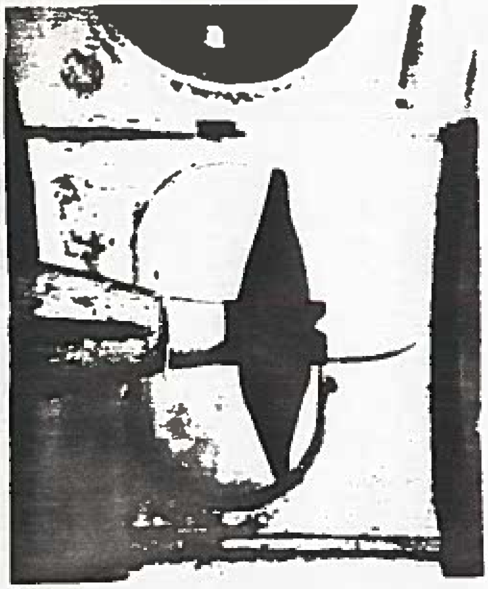
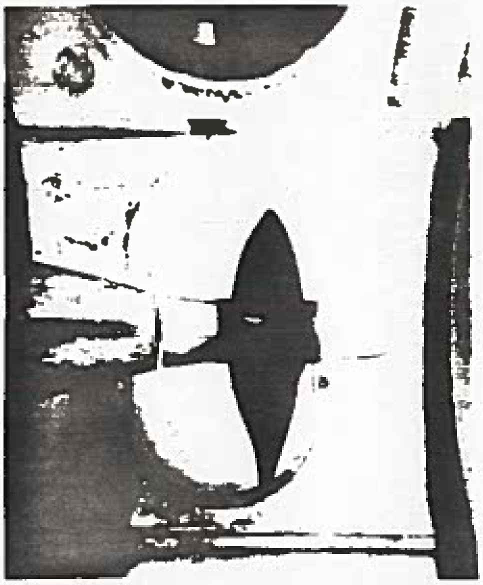


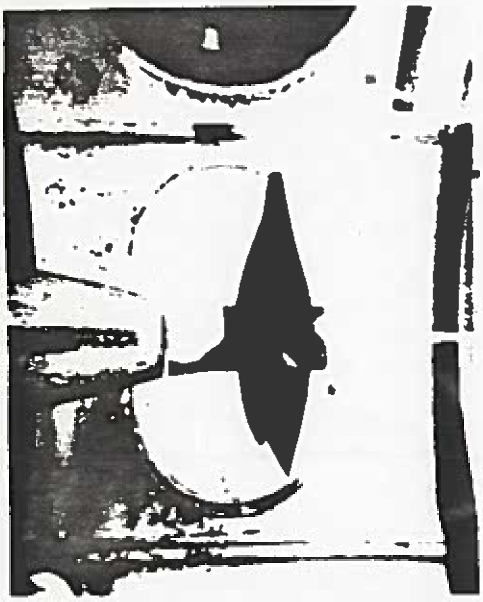
Figure 11 - Power Loss Due to Cavitation on Propeller 4563



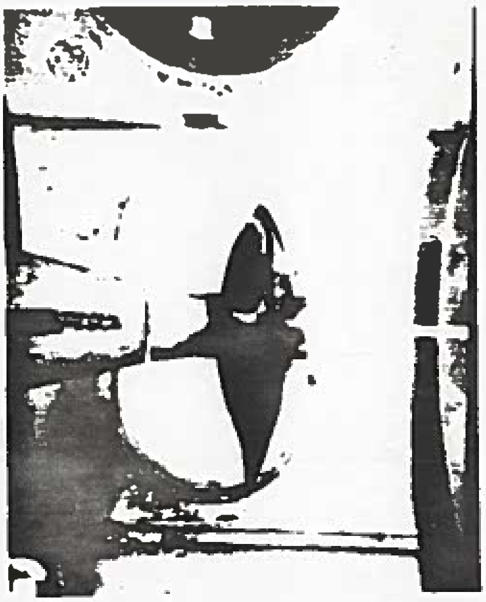
J = 0.893 σ = 7.95



J = 0.893 σ = 3.27



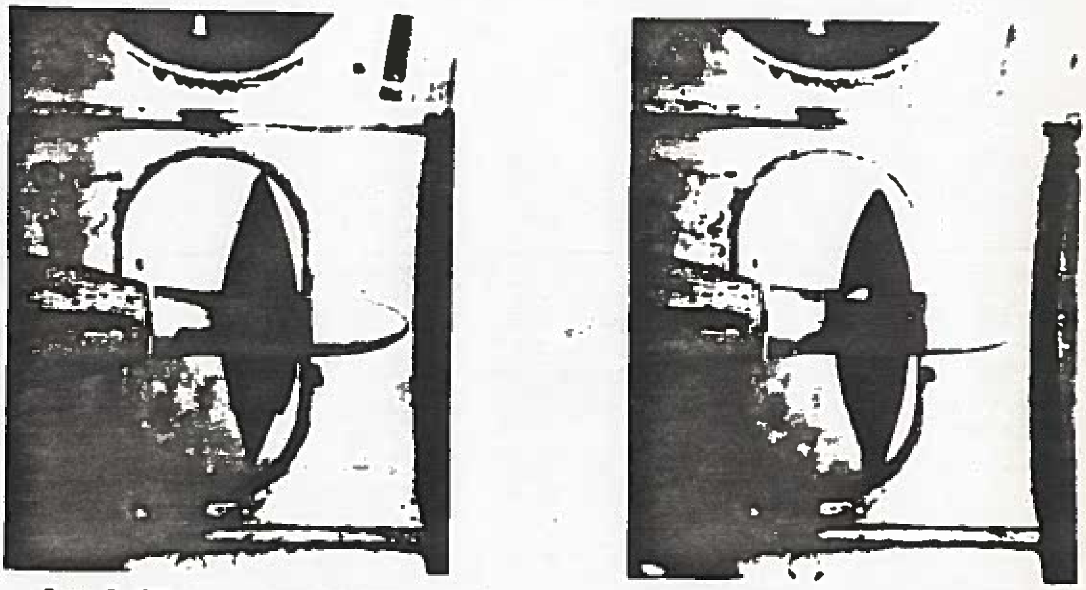
J = 0.7 σ = 10.36



J = 0.7 σ = 6.15

Figure 12. - Photographs of Cavitating Propeller 4667

Figure 12 (Continued)



J = 1.05 σ = 3.98

J = 1.05 σ = 1.71

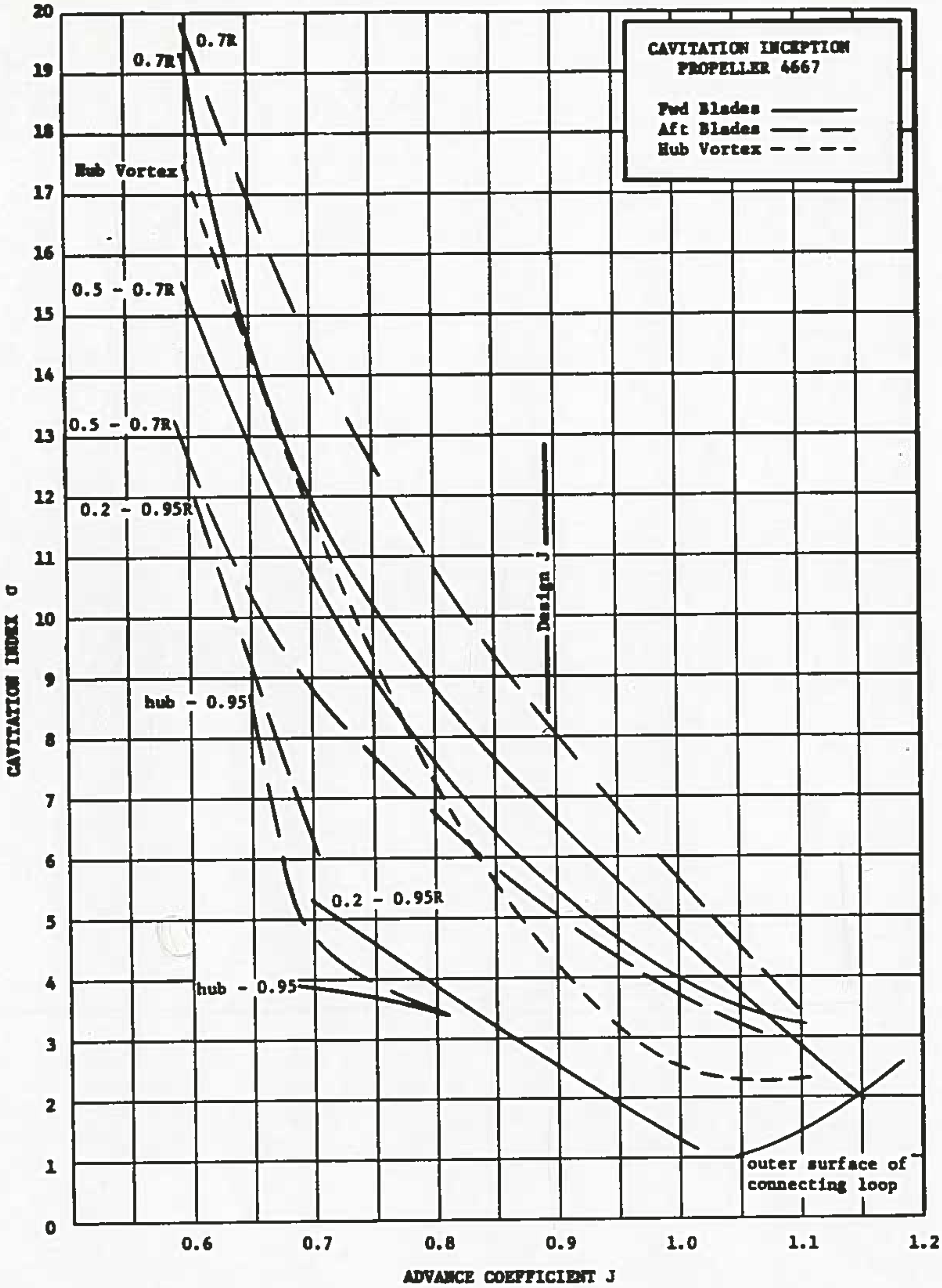


Figure 13 - Cavitation Inception Characteristics of Propeller 4667

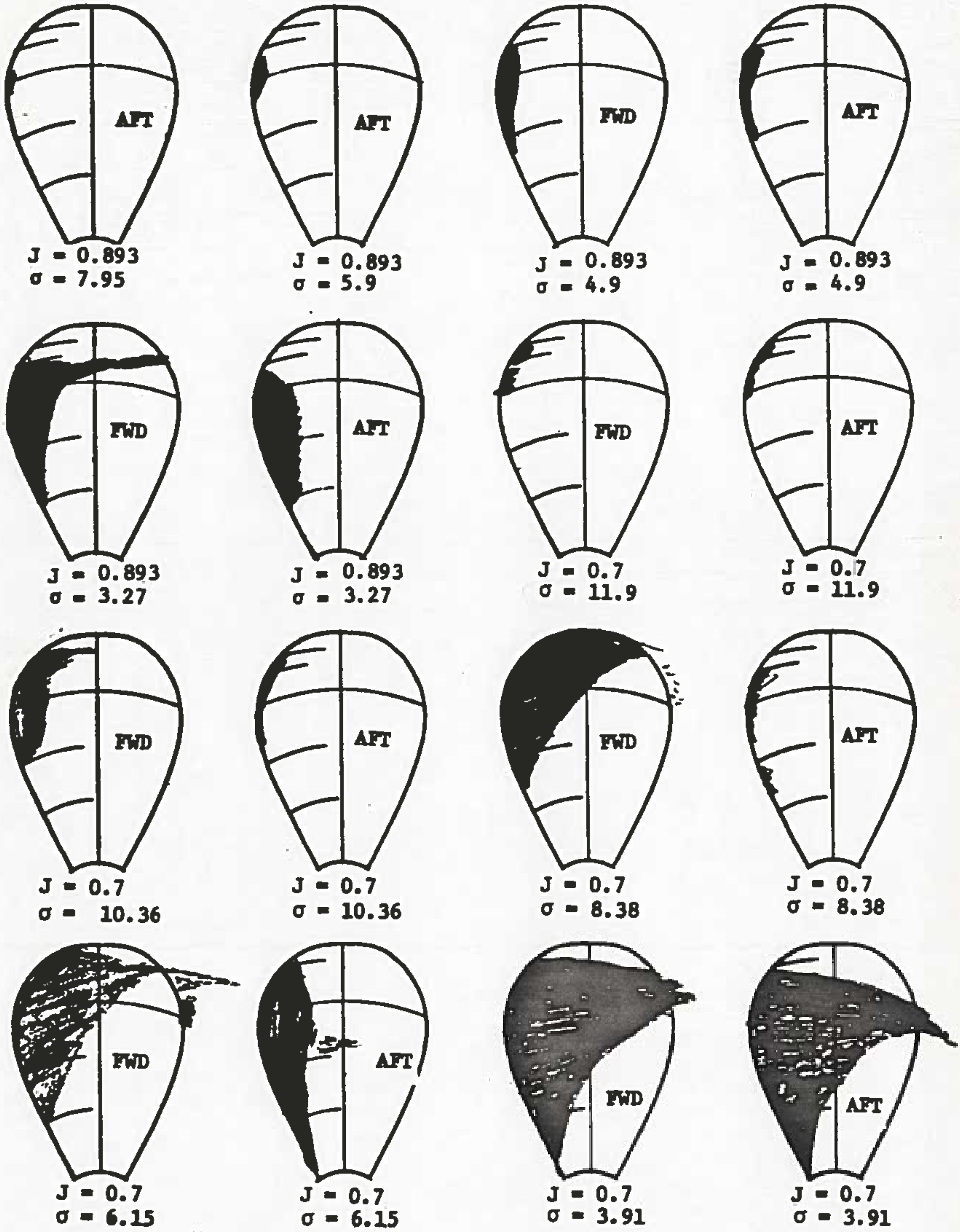
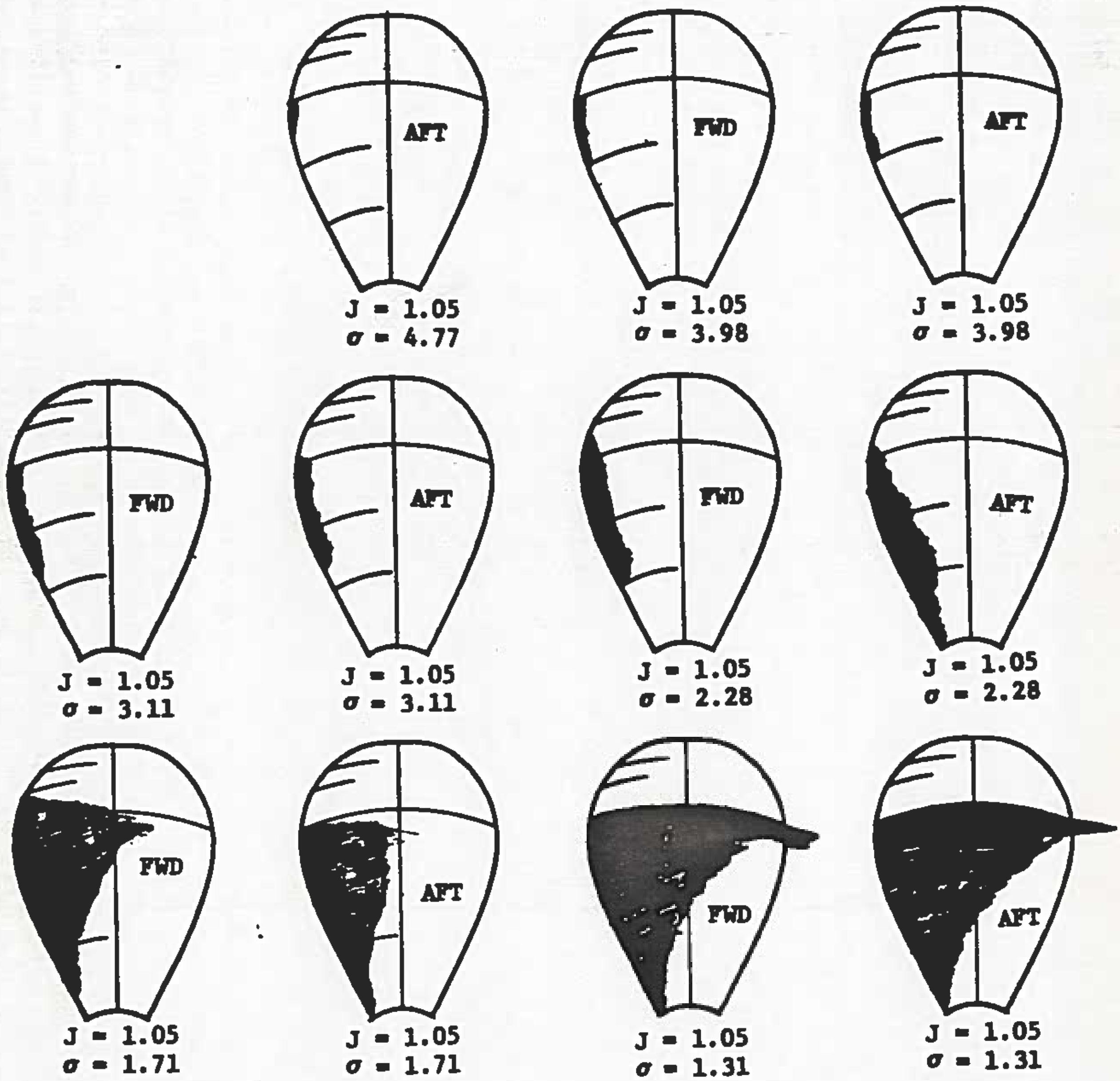


Figure 14 - Sketch of Cavitation on Propeller 4667

Figure 14 (Continued)



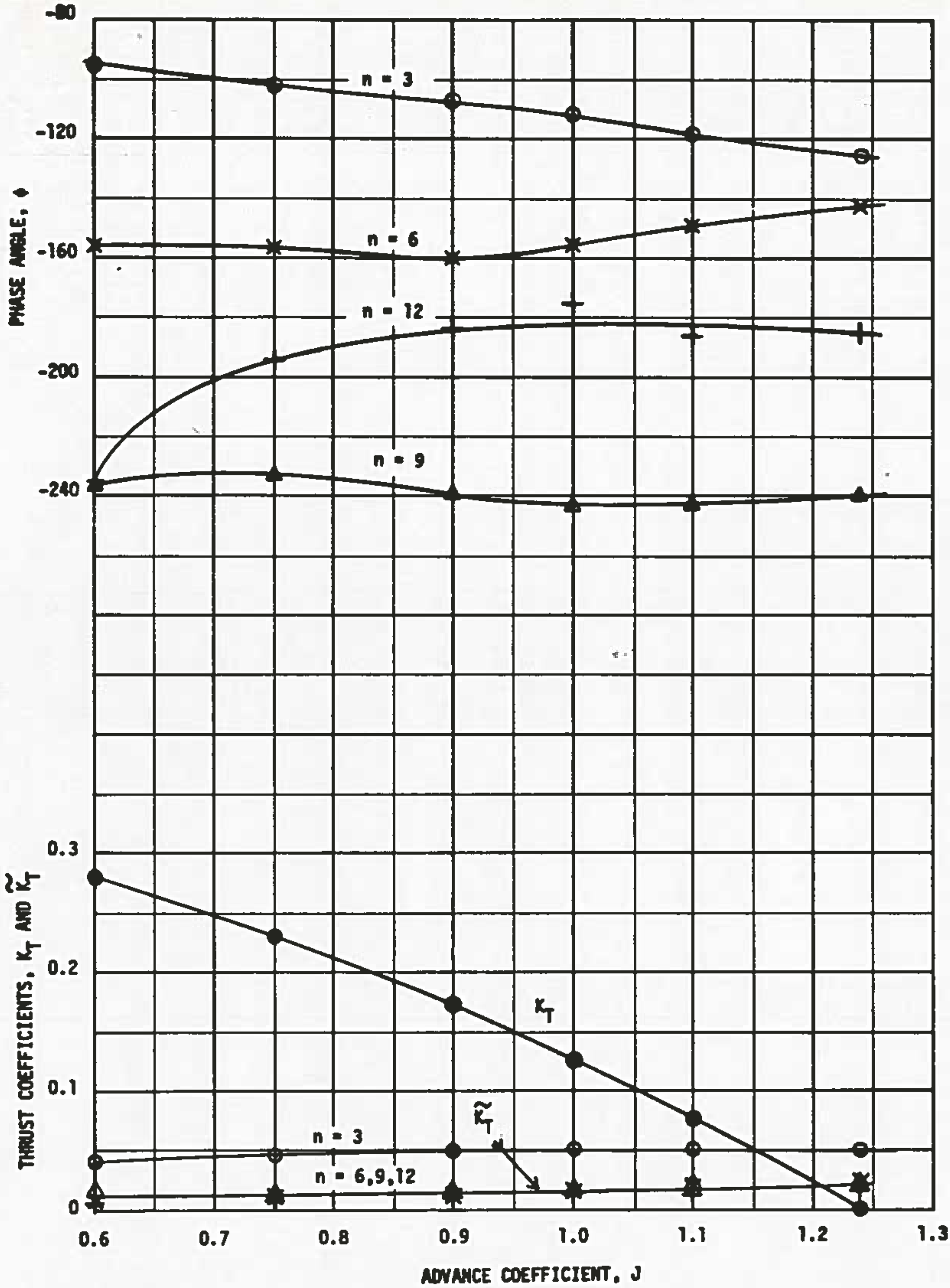


Figure 15 - Thrust Coefficients and Phase Angles of Propeller 4563 in 3-Cycle Wake

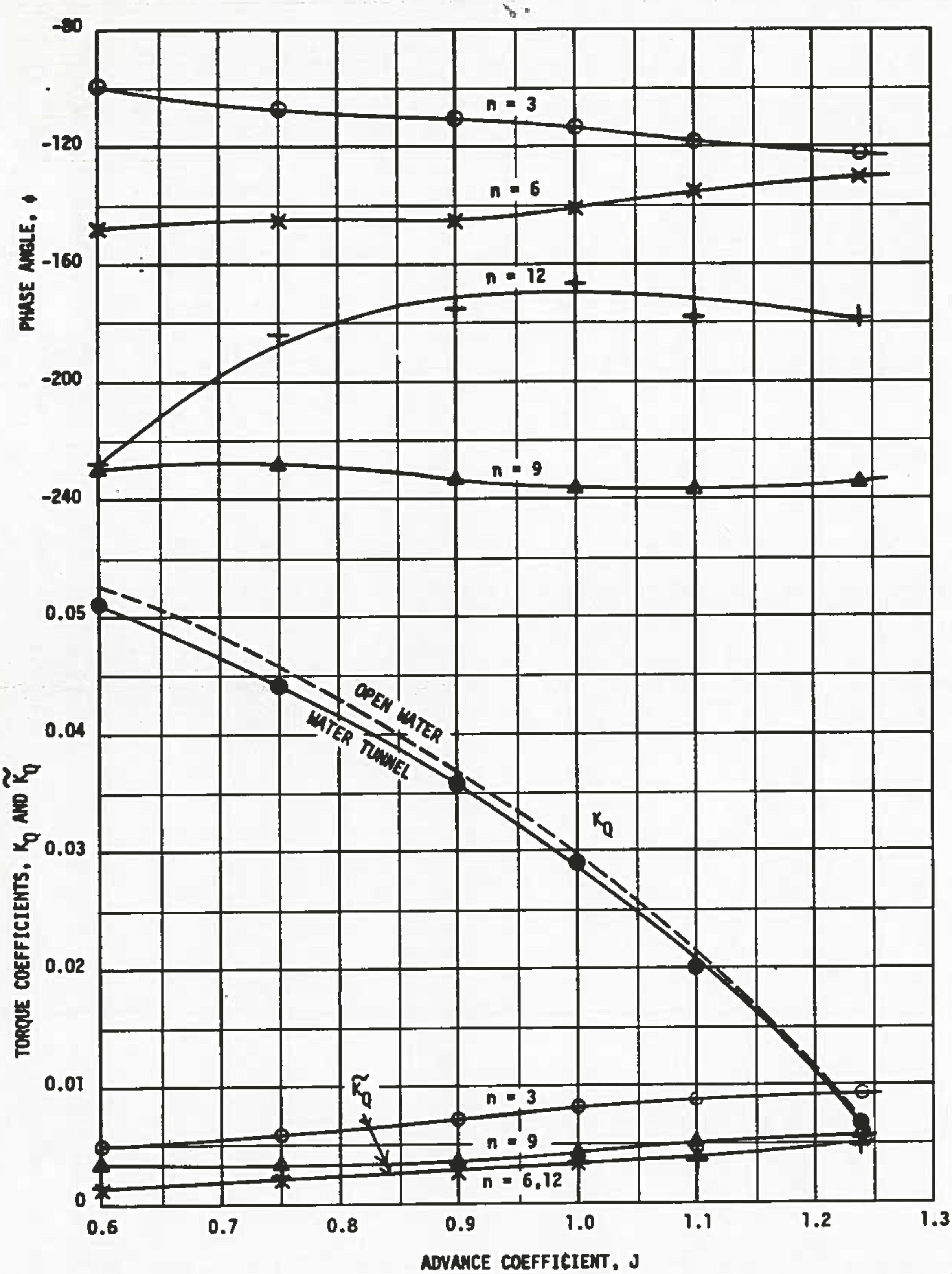


Figure 16 - Torque Coefficients and Phase Angles of Propeller 4563 in 3-Cycle Wake

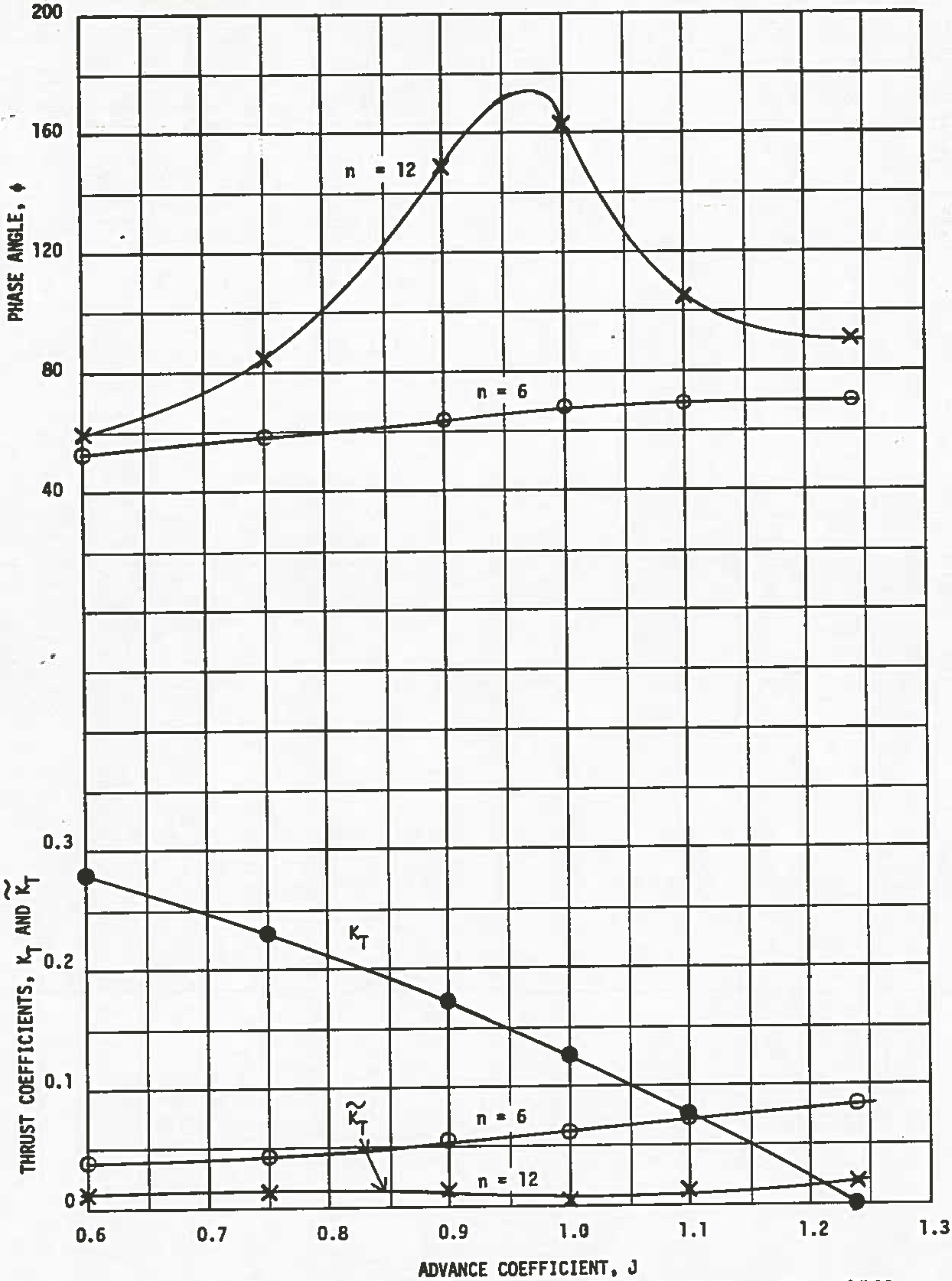


Figure 17 - Thrust Coefficients and Phase Angles of Propeller 4563 in 6-Cycle Wake

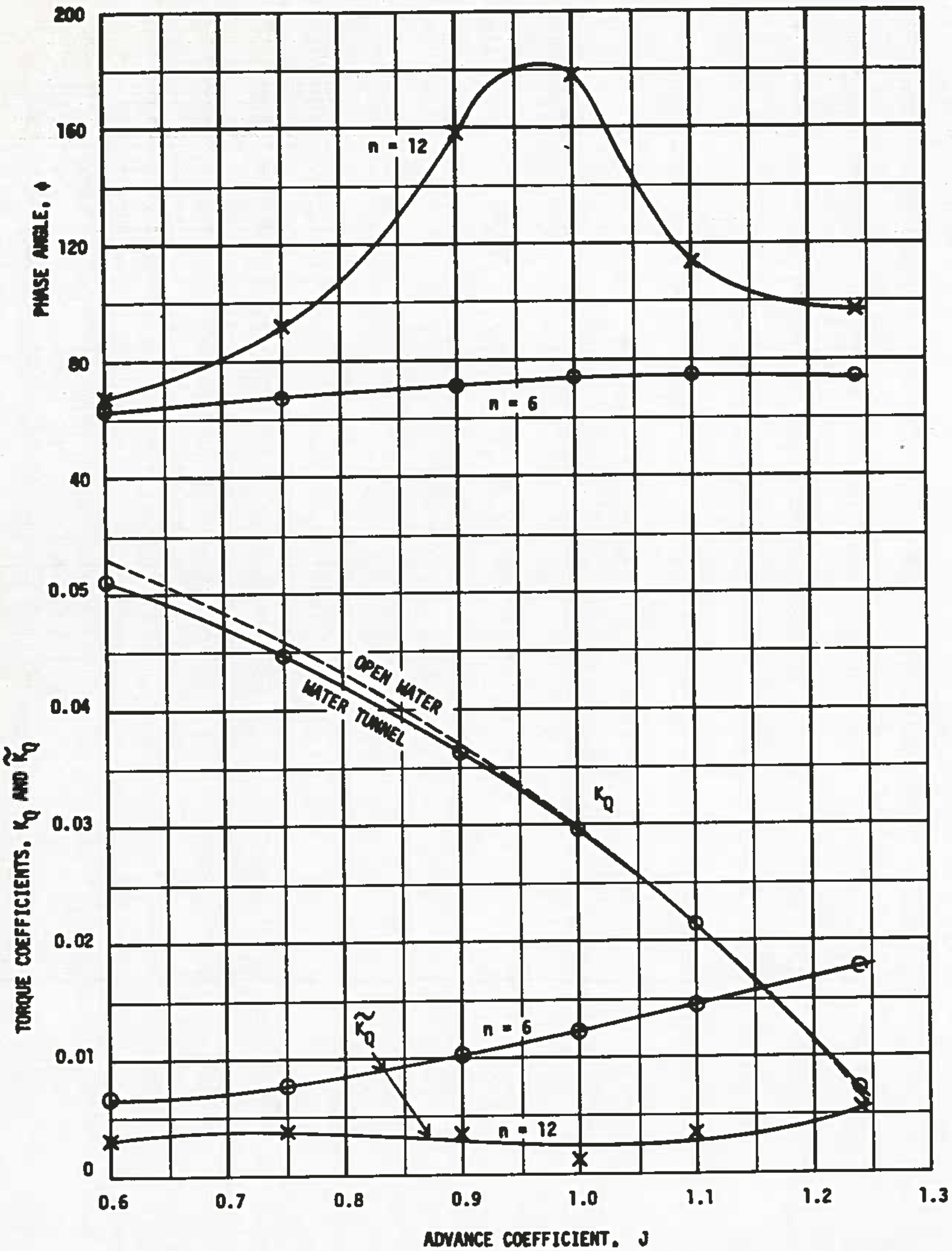


Figure 18 - Torque Coefficients and Phase Angles of Propeller 4563 in 6-Cycle Wake

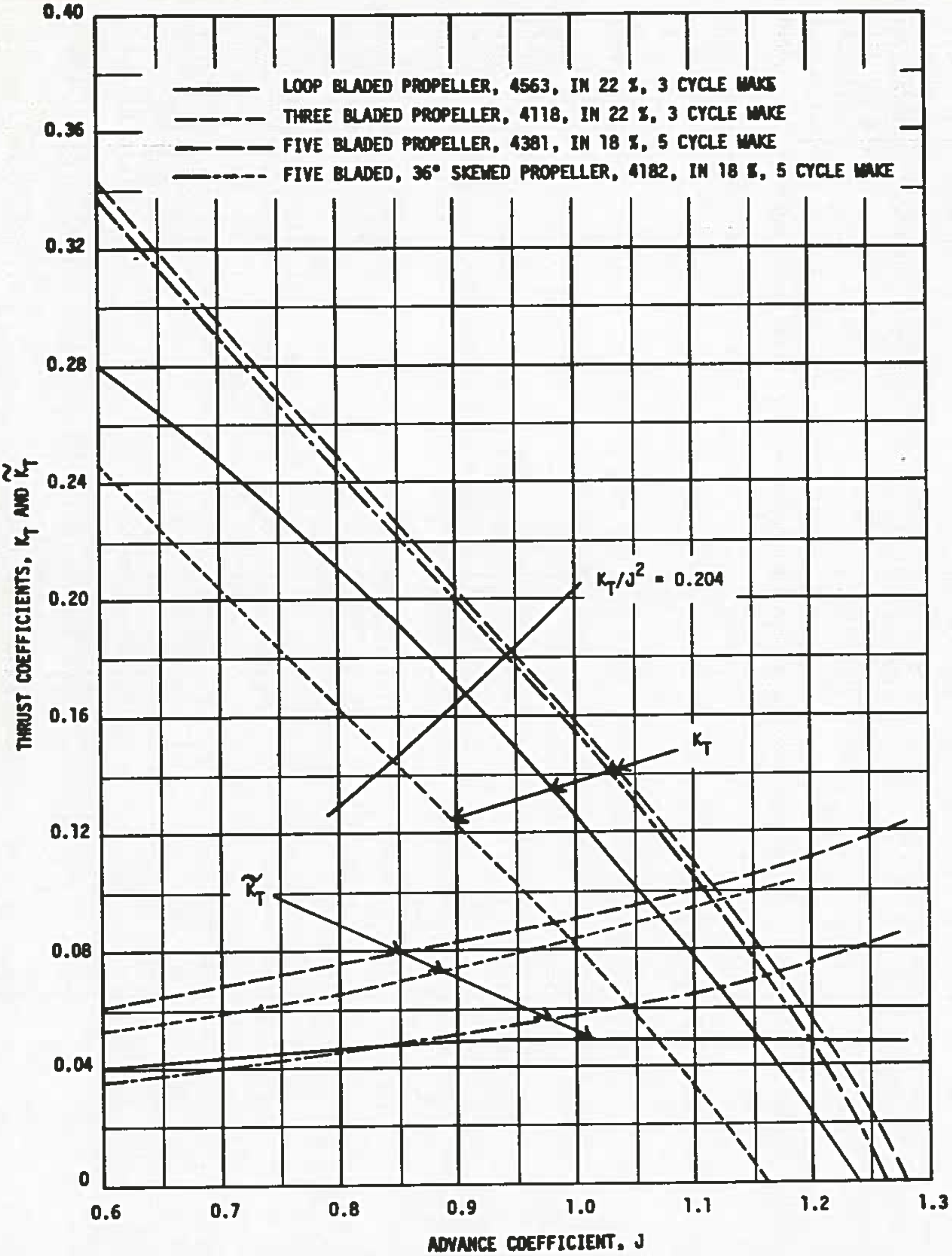


Figure 19 - Unsteady Thrust Characteristics of Propeller 4563 Compared with Other Propellers

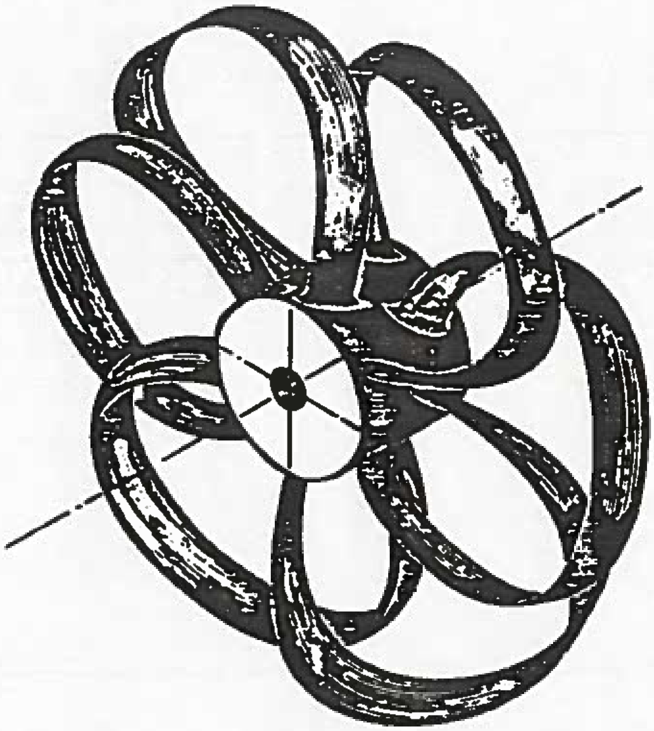


Figure 20 - An Improved Loop-Bladed Propeller Configuration

TABLE 1 - PHYSICAL CHARACTERISTICS OF PROPELLER 4563

	Leading Blade	Trailing Blade	Total
Diameter (inches)	12.00	12.00	-
Pitch-Ratio	1.210	1.223	-
E A R	-	-	0.762
M W R	-	-	0.499
B T F	-	-	0.033

TABLE 2 - PHYSICAL CHARACTERISTICS OF PROPELLER 4667

	Leading Blade	Trailing Blade	Total
Diameter (inches)	12.00	12.00	12.070
Pitch-Ratio	1.299	1.321	-
E A R	-	-	0.598
E W R	-	-	0.391
B T F	-	-	0.043

TABLE 3 - PERFORMANCE OF LOOP-BLADED PROPELLER 4563

$(K_T/J^2 = 0.204)$

	Design	Experimental	Experimental / Design
J	1.007	0.909	.903
K_T	0.207	0.169	.816
C_T	0.520	0.524	1.008

TABLE 4 - AMPLITUDE OF HARMONIC COMPONENTS IN WAKES RELATIVE TO WAKE VELOCITY

Harmonic No.	Number of Cycles in Wake Screen		
n	3	6	5
0	1	1	1
3	0.22	0.01	
6	0.02	0.17	
9	0.03	0.01	
12	0.01	0.01	
5			0.18
10			0.02