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Experimental Determination of Unsteady Forces on Contrarotating Propellers in Uniform Flow

David W Taylor Naval Ship R & D Center, Bethesda, Md.

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DAVID W. TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Bethesda, Md. 20084

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EXPERIMENTAL DETERMINATION OF UNSTEADY FORCES ON CONTRAROTATING PROPELLERS IN UNIFORM FLOW

by

Marlin L. Miller

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MARCH 1976

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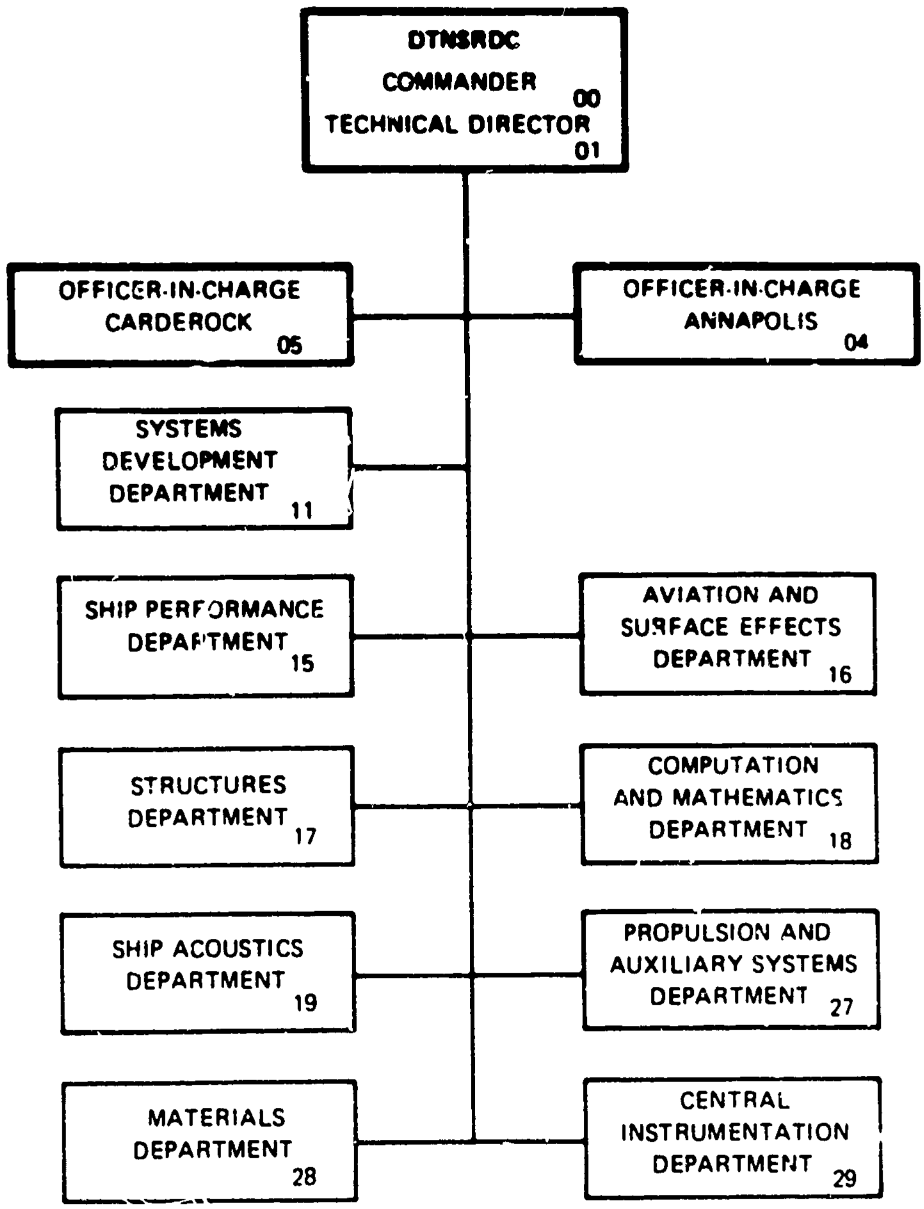

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This report reviews the development of equipment and procedures for the measurement of unsteady forces and moments on contrarotating propellers in the 24-inch water tunnel and presents the results from 4 x 4 and 4 x 5 bladed propeller sets in uniform flow. A serious problem encountered was that of maintaining the two propellers in a constant phase relationship. This problem has not been completely solved.

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NOTATION

A_N	Fourier cosine coefficient of unsteady loading
B_N	Fourier sine coefficient of unsteady loading
$C_{0.7}$	Chord length at 0.7R
D	Forward propeller diameter
$\tilde{F}_H$	Amplitude of unsteady horizontal side force
$\tilde{F}_V$	Amplitude of unsteady vertical side force
J	Advance coefficient, V_a/nD
$\tilde{K}_F$	Unsteady side force coefficient, $\tilde{F}/\rho n^2 D^4$
$\tilde{K}_M$	Unsteady bending moment coefficient, $\tilde{M}/\rho n^2 D^5$
K_Q	Steady torque coefficient, $Q/\rho n^2 D^5$
$\tilde{K}_Q$	Unsteady torque coefficient, $\tilde{Q}/\rho n^2 D^5$
K_T	Steady thrust coefficient, $T/\rho n^2 D^4$
$\tilde{K}_T$	Unsteady thrust coefficient, $\tilde{T}/\rho n^2 D^4$
$\tilde{M}_H$	Amplitude of unsteady horizontal bending moment
$\tilde{M}_V$	Amplitude of unsteady vertical bending moment
n	Rotational speed of propeller
N	Order of shaft frequency harmonic
Q	Steady component of torque
$\tilde{Q}$	Amplitude of unsteady component of torque
r	Radial coordinate
R	Radius of propeller
R_N	Reynolds number at 0.7R, $C_{0.7}[V_a^{\ 2} + (0.7\pi nD)^2]^{1/2}/\nu$

T	Steady component of thrust
$\tilde{T}$	Amplitude of unsteady component of thrust
V_a	Speed of advance
η	Propeller efficiency
θ	Angular position of propeller from upward vertical measured in the direction of propeller rotation
ν	Kinematic viscosity of the fluid
ρ	Mass density of the fluid
ϕ	Phase angle, arctan B_N/A_N

ABSTRACT

This report reviews the development of equipment and procedures for the measurement of unsteady forces and moments on contrarotating propellers in the 24-inch water tunnel and presents the results from 4 x 4 and 4 x 5 bladed propeller sets in uniform flow. A serious problem encountered was that of maintaining the two propellers in a constant phase relationship. This problem has not been completely solved.

The unsteady thrust and torque measured on a 4 x 4 propeller set and the unsteady side forces and bending moments measured on a 4 x 5 set in both cases were larger on the forward propeller. This result was not expected. A recently developed program for computing unsteady loading on contrarotating propellers was used to calculate values for the experimental conditions. Calculated values were in fair agreement with experimental values for the forward propellers but the calculated values for the aft propellers were much greater than the experimental values and greater than the calculated values for the forward propeller.

ADMINISTRATIVE INFORMATION

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INTRODUCTION

When a marine propeller operates in a nonuniform flow such as the wake of a ship or torpedo, it experiences an unsteady loading at multiples of shaft frequency. With contrarotating propellers, each one can experience unsteady loading due to the wake and, additionally each propeller can cause an unsteady loading on the other. These unsteady loadings can cause a serious amount of vibration and it is important to be able to predict them before selecting a propeller design for a given application. These predictions can be made by calculations based on propeller theory or from the results of experimental measurements made with model propellers.

Although it is more convenient to calculate unsteady forces, it is necessary to have good experimental results in order to be able to evaluate the calculation methods until they have been developed to the point where complete confidence in their results has been established.

A six-component propeller dynamometer for use in the 24-inch water tunnel was developed and successfully used to measure unsteady propeller bearing forces and moments on single propellers operating in wakes produced by screens.[1] The success of this dynamometer led to the decision to develop a system for measuring unsteady loading on the propellers of a contrarotating set.

Two methods for obtaining measurements from the second propeller were available. One was to construct a complete second system for the upstream tunnel shaft complete with additional signal conditioning and recording equipment. The other was to make measurements on one propeller at a time by shifting the dynamometer from one shaft to the other. The second method was selected although the only advantage was a considerable reduction in cost. Only a new upstream drive shaft and supporting struts were required and these could be used if it were later decided to build a complete system for the second shaft. With two complete systems measurements on the two propellers could be made simultaneously so that the experimental conditions would be identical for the two propellers and the time required for the experiment would be reduced.

UNSTEADY FORCE MEASUREMENTS

The first measurements were made with the six-component dynamometer on the upstream shaft and with the aft propeller driven by the regular downstream shaft and dynamometer of the tunnel. The experiments were conducted in uniform flow so that the unsteady forces would be due only to the interaction of the two propellers of the set. Since this was to be principally an evaluation of the system and development of experimental techniques, existing sets of contrarotating propellers were used. Propellers 3686 and 3687A were a 4 x 4 set from a series used to study the effect of propeller spacing.[2] Propeller 3849 was a 5 bladed aft propeller designed to form a 4 x 5 set with propeller 3686. The forward propeller of these sets was 12.017 inches (0.3052 m) in diameter. Design details of these propellers are shown in Tables 1, 2, and 3 and their open water characteristics are shown in Figures 1 and 2.

Both propellers were run at a constant rotational speed of 12 rps and the water speed varied to obtain a range of loadings from zero thrust to a total thrust coefficient of approximately 0.5. Water speed was determined by using a thrust identity between the total steady thrust and the total open water thrust. The Reynolds number was between 5.1 and 5.8 times 10^5. The axial spacing between the propeller centerlines was 1.70 inches (0.0432 m).

At the beginning of the experiments, it was immediately apparent that although the speed control of the propeller shafts would have been considered excellent for a single propeller on either shaft, it was entirely inadequate for these measurements. If the rpm of the two propellers are not exactly equal there will be a continuously varying phase relationship between the blade frequency signals and the angular position of either propeller. With this changing phase, the usual signal averaging and data analysis by computer could not be used. However, since these experiments were being conducted in uniform flow, the amplitudes of the signals were constant and on-the-spot measurements were made using a wave analyzer. In order to obtain on-the-spot phase measurements an oscilloscope was used to display the phase relationship of the two shafts to the tunnel operator so that he could attempt to maintain the proper relationship. The phase still changed so rapidly that no readings could be made.

Such random variations in rotational speed are probably characteristic of all applications of contrarotating propellers except where the propellers are geared together. However, when experimental investigations are being made it is necessary to have known conditions that can be held long enough to obtain a good data sample.

Before the next measurements were attempted some improvements in the instrumentation were developed. In order to improve the speed control of the two shafts the system was modified so that a common reference voltage could be used for both. Also, a very fine speed control was added for one shaft. Since it was believed that even this would not assure obtaining a continuous sequence of 100 or more in-phase revolutions for computer averaging, an additional means was developed for obtaining good data. The six component dynamometer generates a pulse to mark the beginning of each revolution as the reference blade passes the top center position. For single propellers, the computer uses these pulses to divide the data into a series of one revolution segments which are then averaged to enhance the shaft frequency signal and its harmonics. With contrarotating propellers the average should include only those revolutions where the second propeller is at a fixed position when a pulse is generated by the first propeller. In order to select these in-phase revolutions a pulse generator was attached to the second propeller shaft so that a pulse is formed each revolution when the propeller is at a selected angular position. The pulses from the two shafts are fed into an electronic circuit that generates an output pulse when the input pulses are in coincidence. This pulse is recorded on magnetic tape along with the six channels of data. It also flashes a lamp and drives a counter to indicate how much in-phase data is being accumulated. The computer is programmed to use only the data from revolutions marked by a pulse and followed by a marked revolution.

After these changes were made, unsteady force and moment measurements were made on both four- and five-bladed aft propellers while counterrotating with the four bladed forward propeller. Although the speed control was improved, it was extremely difficult to hold the speed steady enough to obtain on-the-spot phase measurements. Computer analysis of the data indicated that the phase variations were too great to obtain good average values.

The measurements on the aft propeller were repeated after some additional improvements were made. The propeller-shaft speed controls were tuned for optimum performance at the speed used for the experiments and the pulse coincidence detector was modified to permit less tolerance from true coincidence. Data was collected only for revolutions starting with a blade of each propeller within ± 0.6 degrees of the upward vertical position. After the results from the measurements on the aft propellers were analyzed and found to be satisfactory, the dynamometer was installed on the upstream shaft and measurements of unsteady forces and moments were obtained for the four-bladed forward propeller with both four- and five-bladed aft propellers.

RESULTS

Figure 3 shows the unsteady thrust coefficient amplitudes and phase angles for the 4 x 4 contrarotating set at blade passing frequency (eight times shaft frequency).

If the unsteady thrust is expressed as,

$$\tilde{T} = A_N \cos N\theta + B_N \sin N\theta$$

then

$$\tilde{K}_T = (A_N^2 + B_N^2)^{1/2} / \rho n^2 D^4$$

and

$$\phi = \arctan B_N / A_N$$

In this case the order of the shaft harmonic N is eight. The total values are the vector sums of the forward and after values and were computed using total values of the coefficients A and B, i.e.,

$$A_{Total} = A_{Forward} + A_{After}$$

and

$$B_{Total} = B_{Forward} + B_{After}$$

Angles are measured in the direction of propeller rotation from the upward vertical position shown as the vector F_V in Figure 4. This figure also shows the directions for the positive values of the forces and moments. The curves are drawn through the values obtained by computer analysis of the data recorded during the final series of experiments. On-the-spot values are also shown including those obtained during the first series of experiments. Figure 5 presents similar results for torque. The unsteady thrust and torque contained a strong second harmonic of blade passing frequency. These results are shown on Figures 6 and 7. It is seen that the unsteady thrust and torque on the forward propeller was considerably greater than on the after propeller. This result was not expected and has not been explained.

When the two propellers have equal numbers of blades there is no net side force or bending moment transmitted to the shaft. In order to observe side forces and bending moments a five-bladed after propeller was used with the same four-bladed forward propeller. This combination produced side forces and bending moments at nine times shaft frequencey. A discussion of the frequencies of the alternating forces due to interactions of contrarotating propellers is given in Reference 3.

Figures 8,9,10, and 11 show the vertical and horizontal side forces and bending moments and their phase angles for the 4 x 5 set of propellers. Since side forces and bending moments could not be obtained from the on-the-spot readings when phase angles could not be read, only the results from the computer analysis of the final series of experiments is shown. No significant amplitudes of side force or bending moment were observed at any other frequencies. Like thrust and torque, the forward propeller showed considerably greater forces and moments except at low values of advance coefficient.

DISCUSSION OF RESULTS

This report has reviewed the development of the equipment and experimental techniques for measuring unsteady forces and moments on contrarotating propellers and has presented the results of measurements on a 4 x 4 and a 4 x 5 set in uniform flow. Since the computer-averaged results obtained from the final series of experiments is in good agreement with the on-the-spot readings of thrust and torque it is evident that the method used to select only good propeller revolutions for analysis was satisfactory.

The 4 x 4 set of propellers produced unsteady thrust and torque at blade passing frequency with a strong second harmonic. No side forces or bending moments were observed as is to be expected in uniform flow where the unsteady loading is due only to the interaction between the two propellers. The much greater amplitudes on the forward propeller were contrary to what was expected and have not been explained. For the 4 x 5 set only side forces and bending moments at nine times shaft frequency were observed with those on the forward propeller again being greater in magnitude. No other experimental results for uniform flow are available for comparison. Experimental results for a 4 x 5 set of contrarotating propellers in the wake of a ship model[4] do not indicate any side force or bending moment component at nine times shaft frequency. However, a bending moment component due to propeller interaction at forty times shaft frequency is reported in Reference 4.

A program for calculating steady and unsteady loading on contra-rotating propellers has been developed from a theoretical analysis.[5,6]

Results calculated with this program are compared with the experimental results in Tables I and II taken from Reference 5. While the experimental results showed considerably greater unsteady loading on the forward propeller the opposite is true of the calculated values with the greatest differences being in the values for the aft propeller.

The fact that the unsteady thrust and torque values repeated well for the two experiments and that the data and calculations were carefully checked indicate the difference between experiment and theory is due to some fault in the experimental set up or in the theory. One possible cause is that, as shown in Figure 12, the somewhat bulky dynamometer was downstream of the propellers when the after propeller forces were measured and upstream for the forward propeller measurements.

FUTURE PLANS

A new series of experiments with the propellers operating in a four cycle wake is being started. For these experiments a fairing similar to the dynamometer will be placed around the other shaft so that flow conditions will be more nearly the same for the measurements on the two propellers. Before the wake is introduced some of the uniform flow conditions will be repeated to determine whether the use of this fairing will change the relationship between the forward and after loadings. Other aspects of the experiment will also be carefully examined.

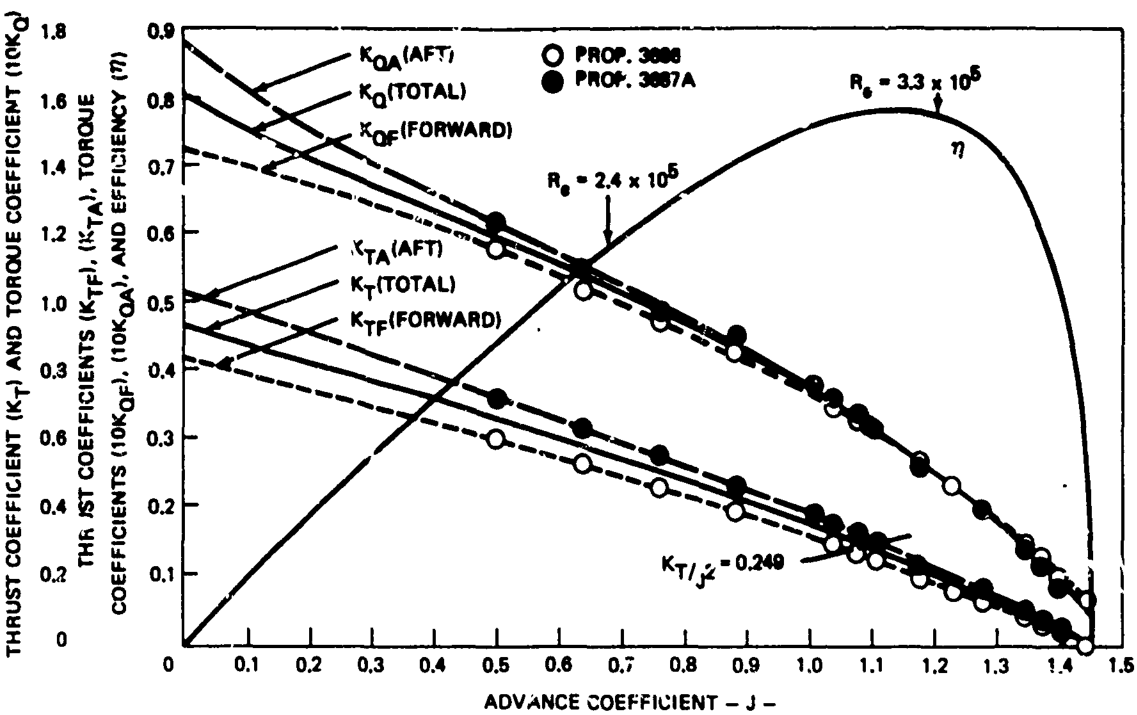


Figure 1 – Open Water Characteristics of Propellers 3686-87A

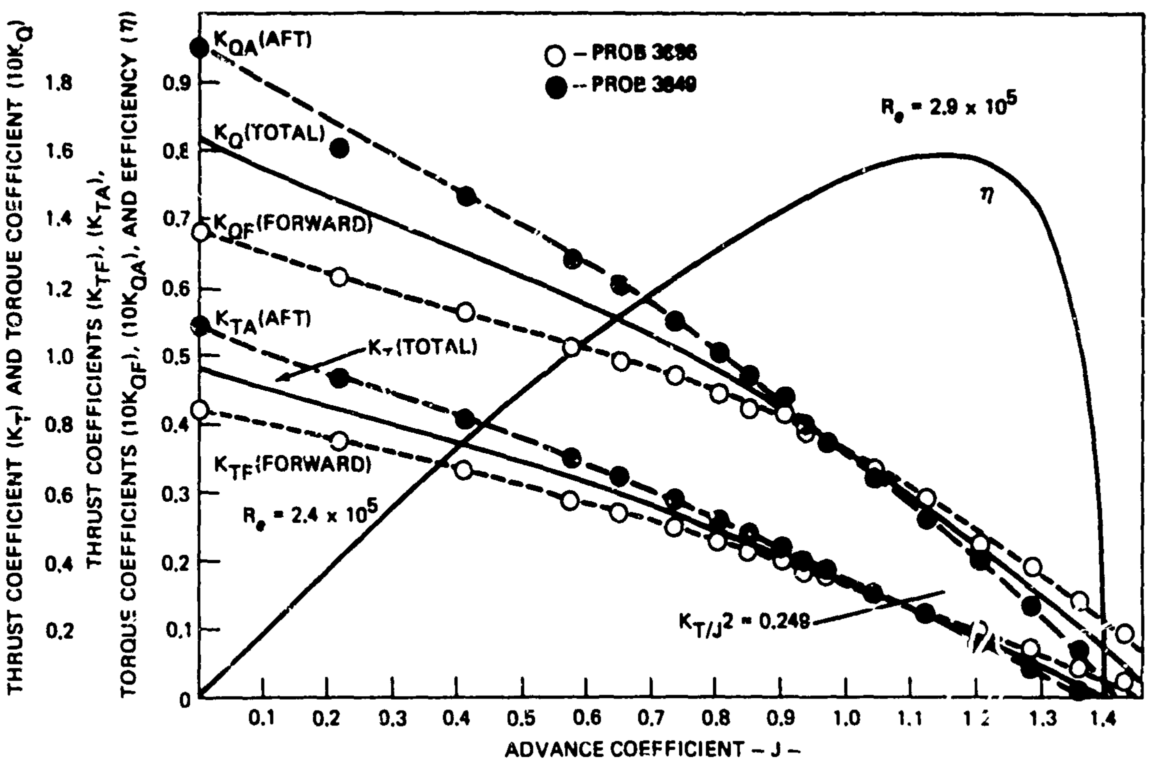


Figure 2 Open Water Characteristics of Propellers 3686-3849

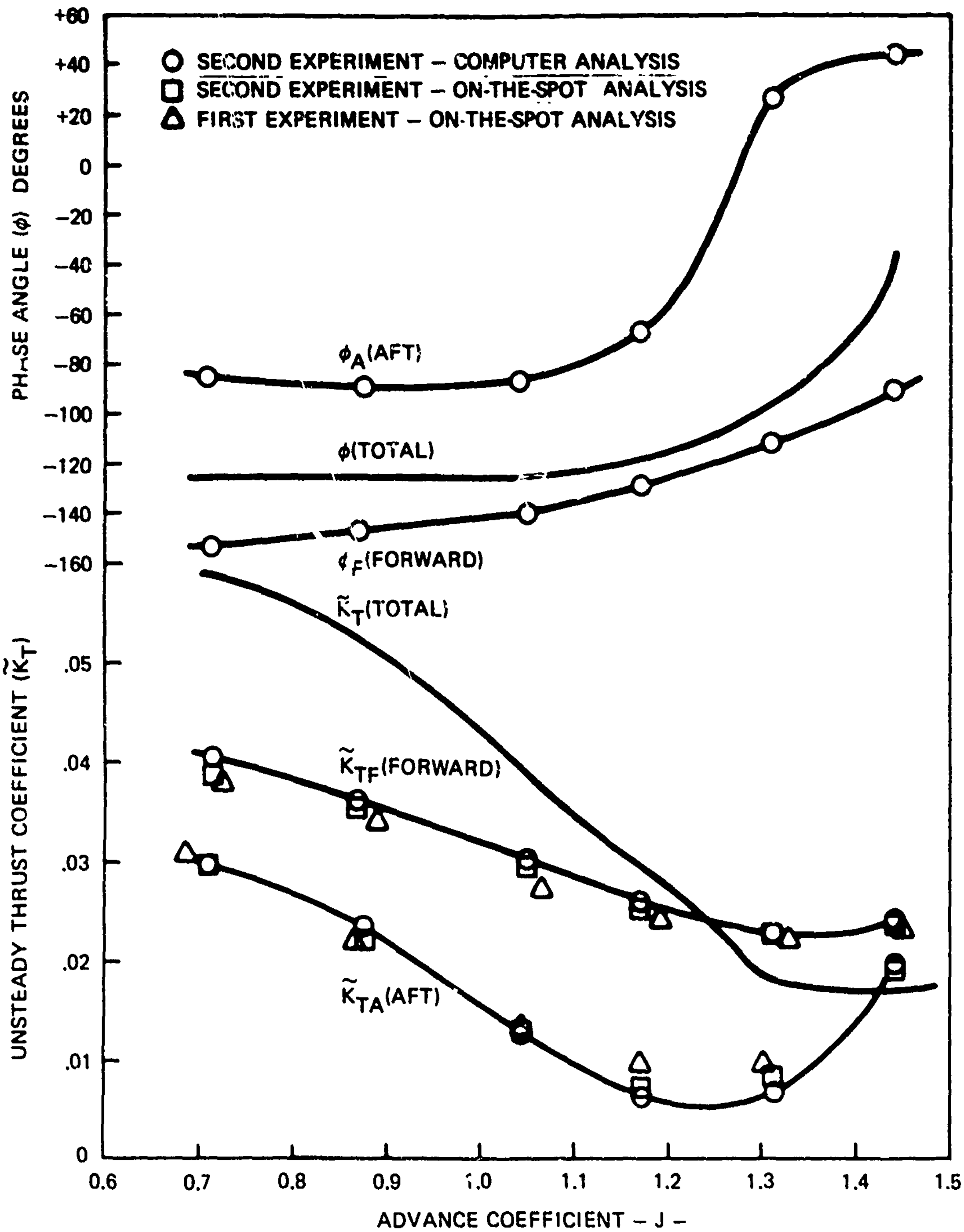


Figure 3 Unsteady Thrust on 4 X 4 Set at Eight Times Shaft Frequency

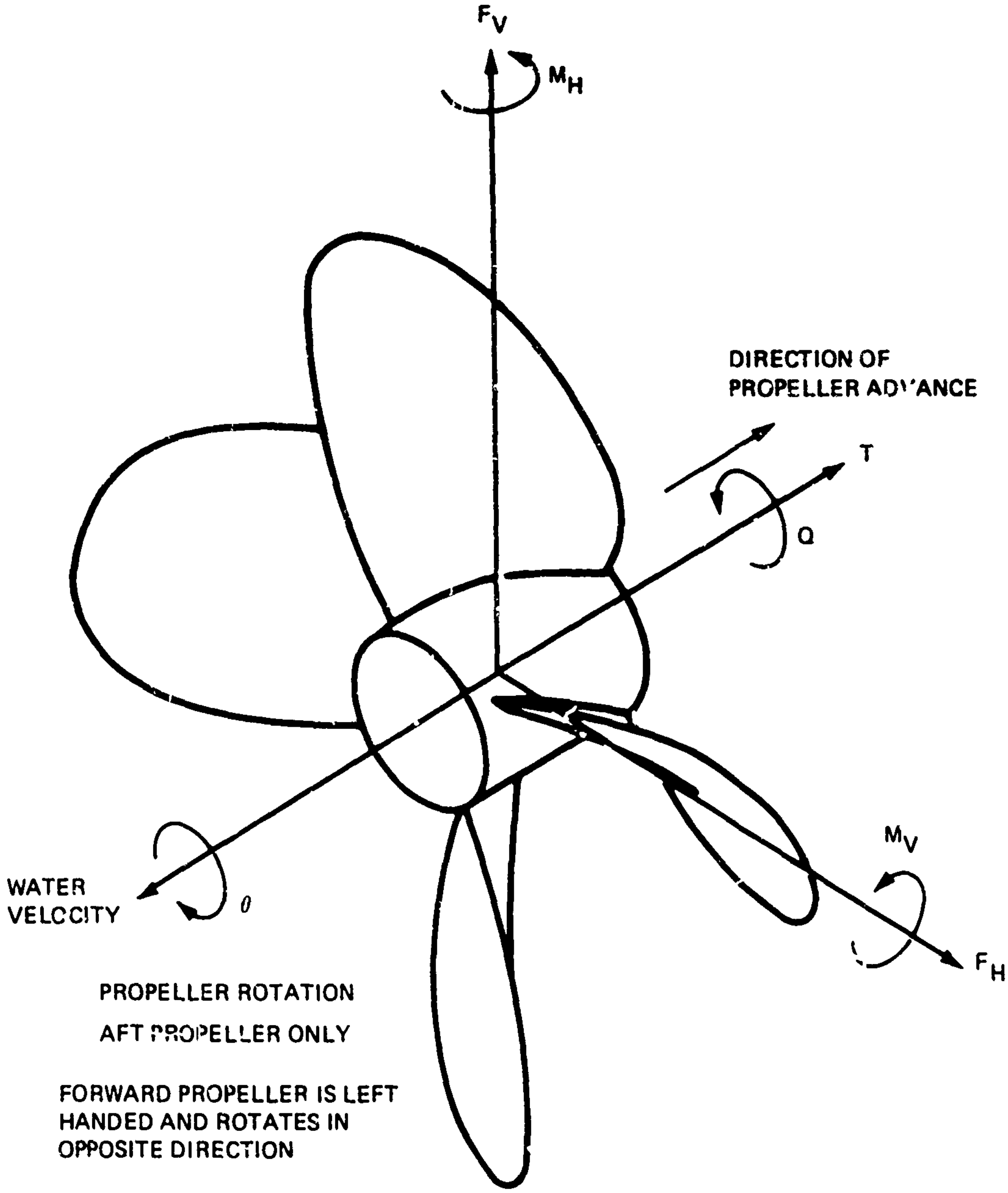


Figure 4 Direction of Forces and Moments

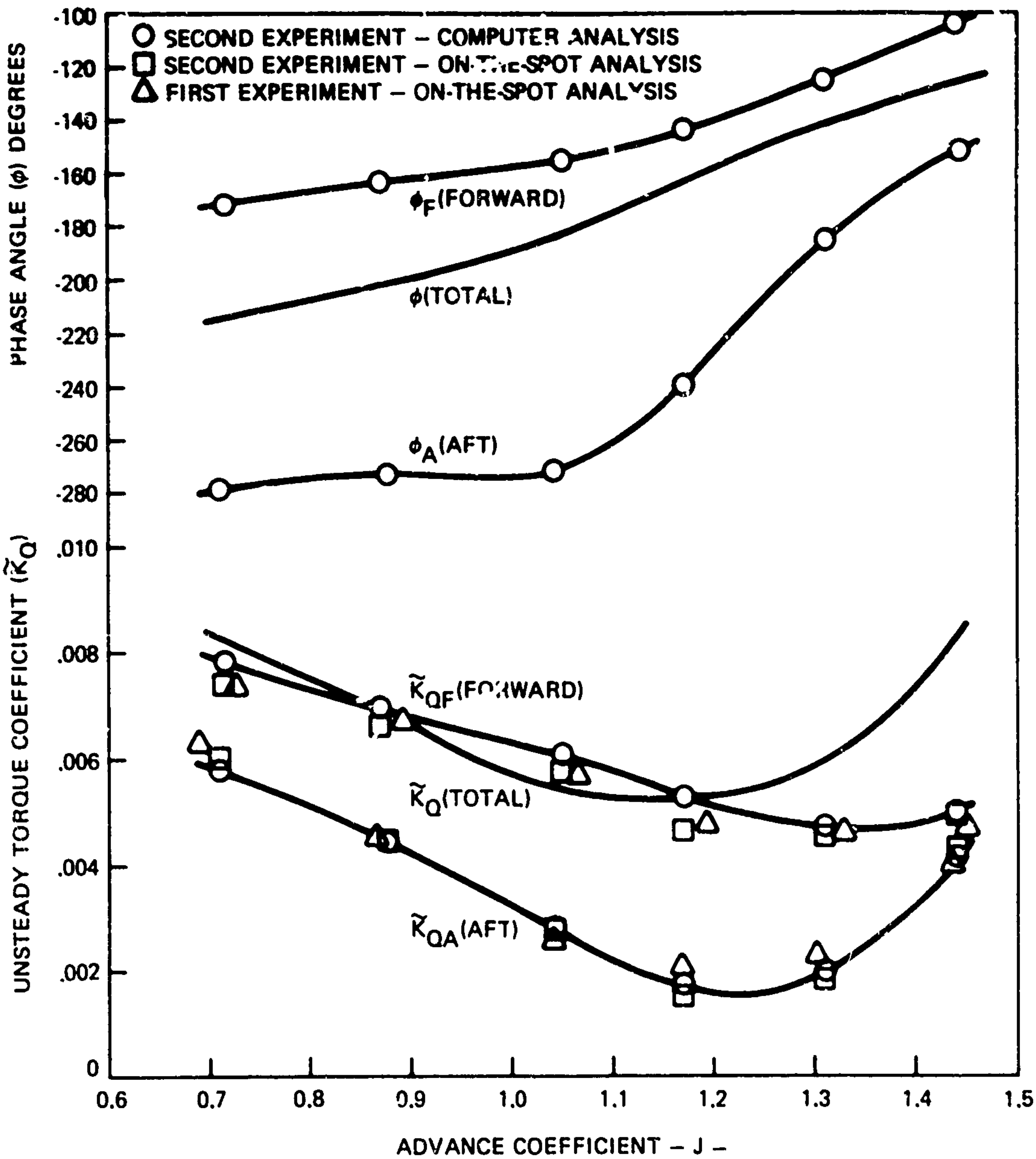


Figure 5 Unsteady Torque on 4 X 4 Set at Eight Times Shaft Frequency

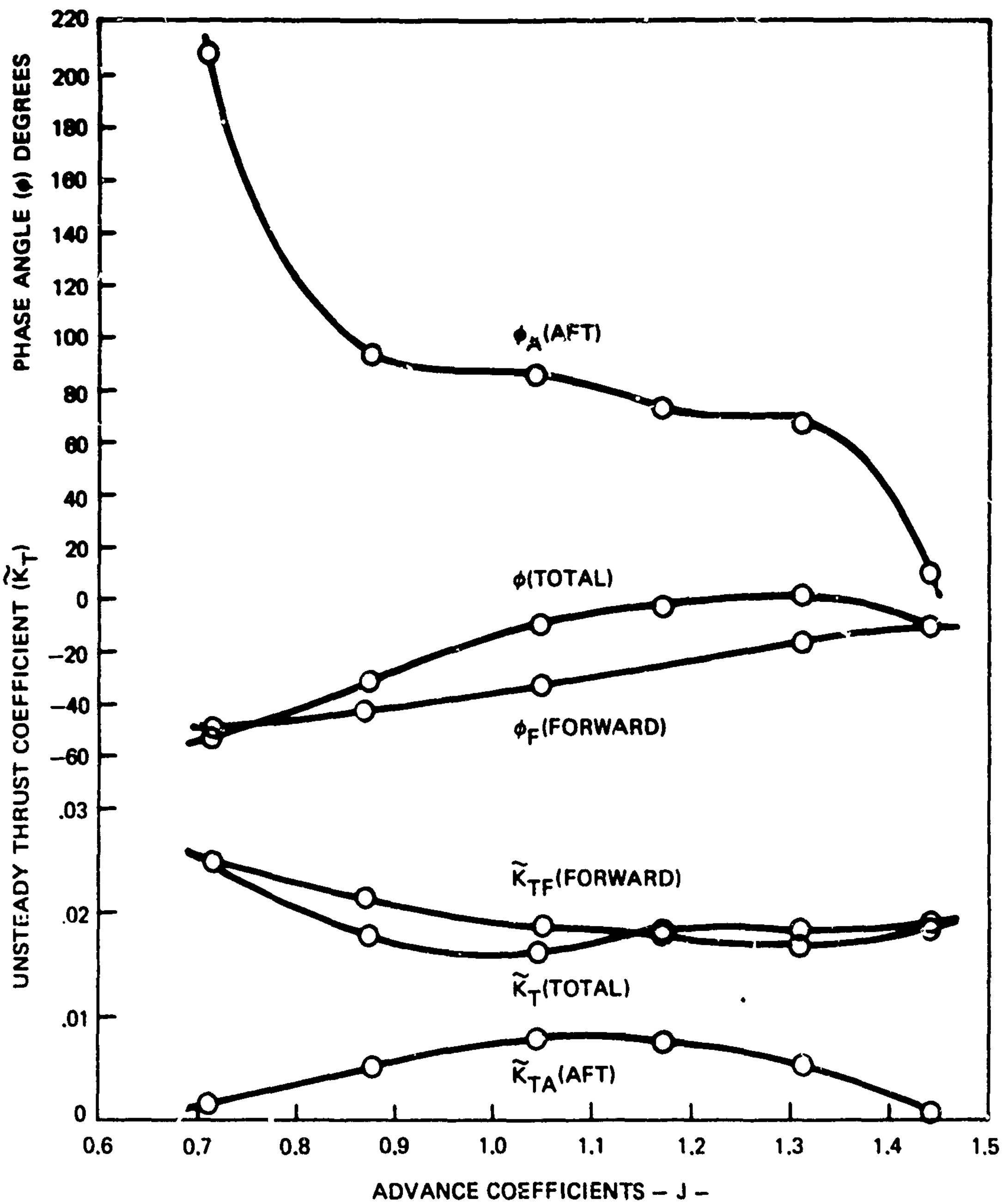


Figure 6 Unsteady Thrust on 4 X 4 Set at Sixteen Times Shaft Frequency

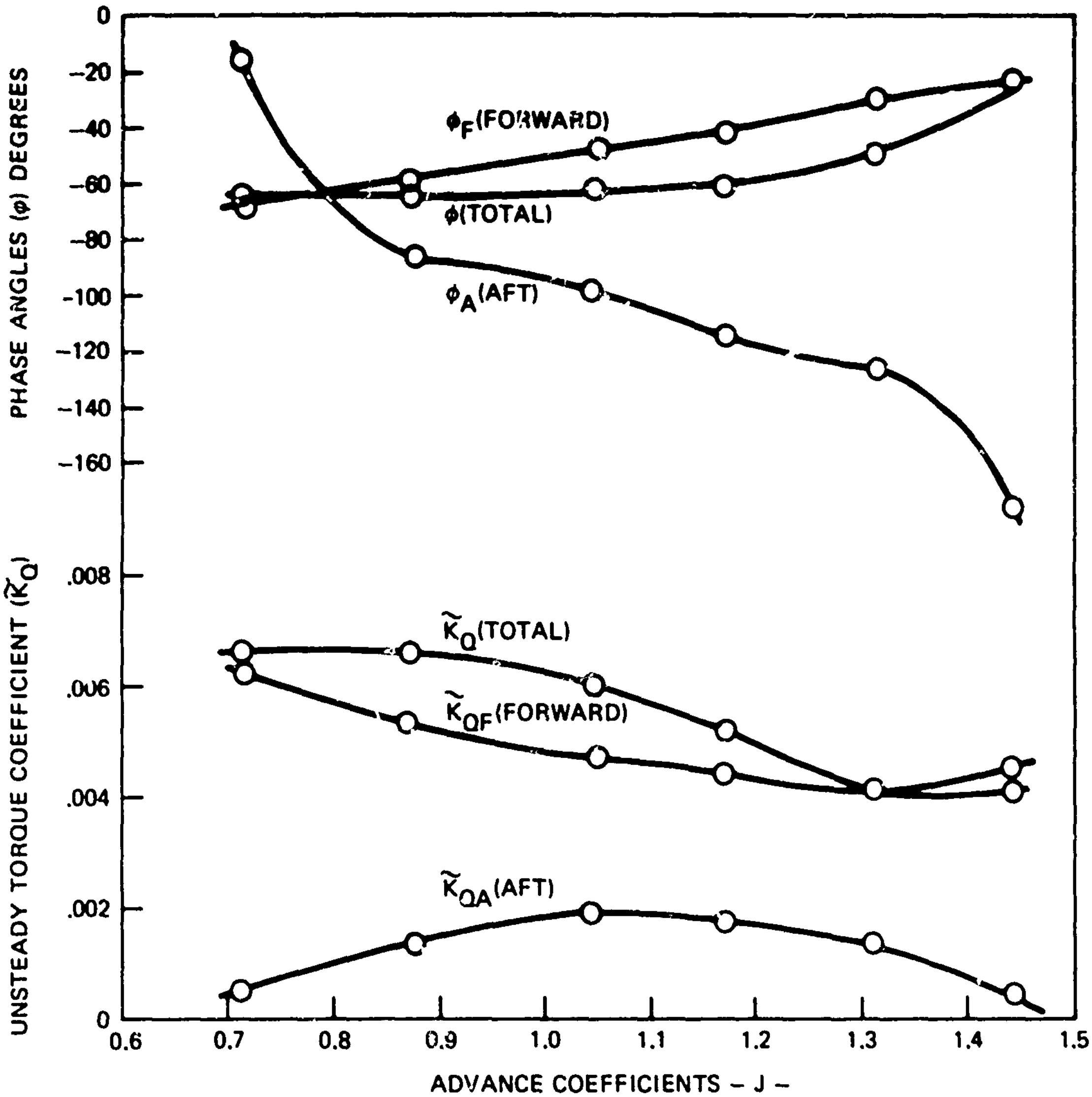


Figure 7 Unsteady Torque on 4 X 4 Set at Sixteen Times Shaft Frequency

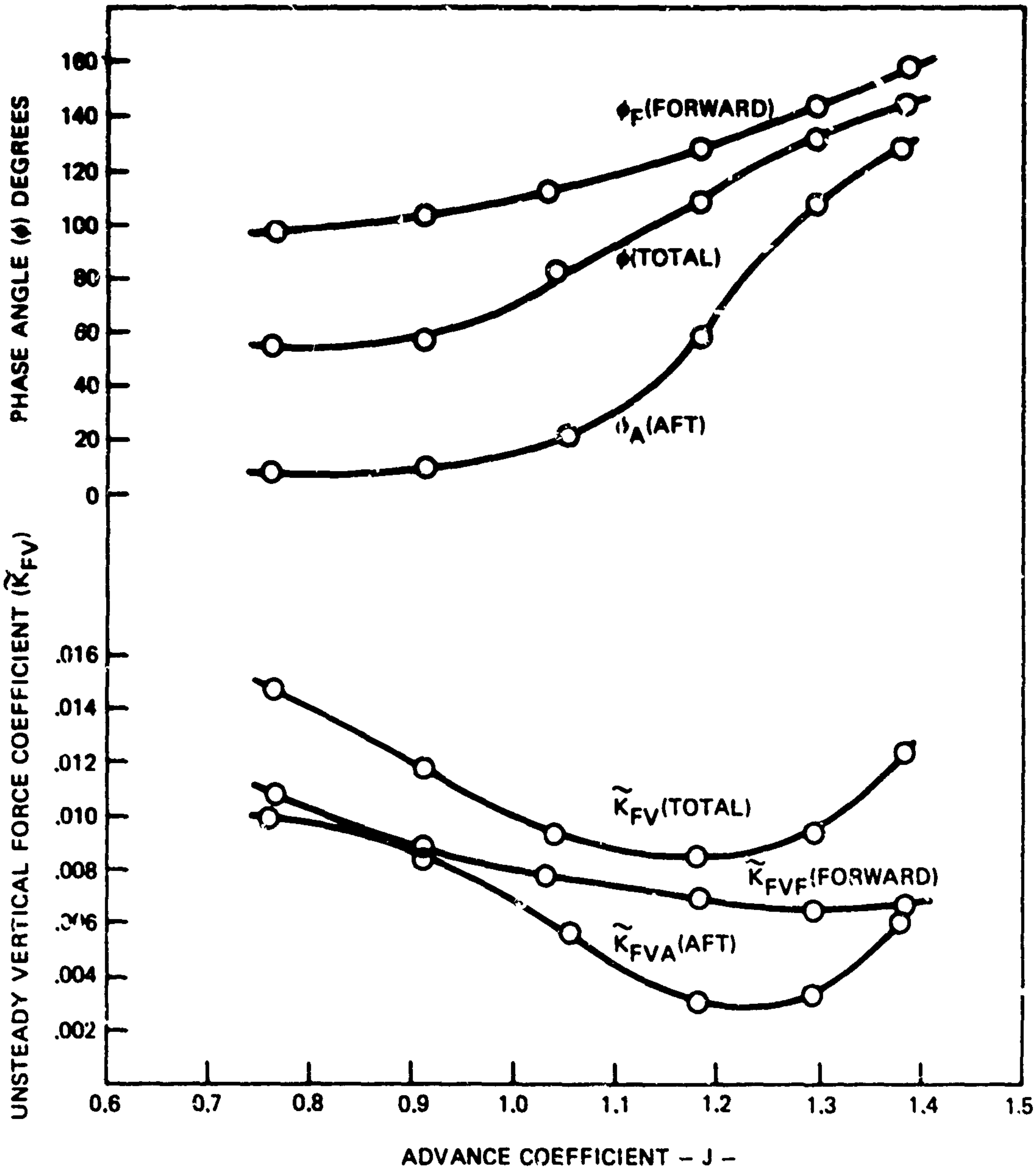


Figure 8 Unsteady Vertical Side Forces on 4 X 5 Set at Nine Times Shaft Frequency

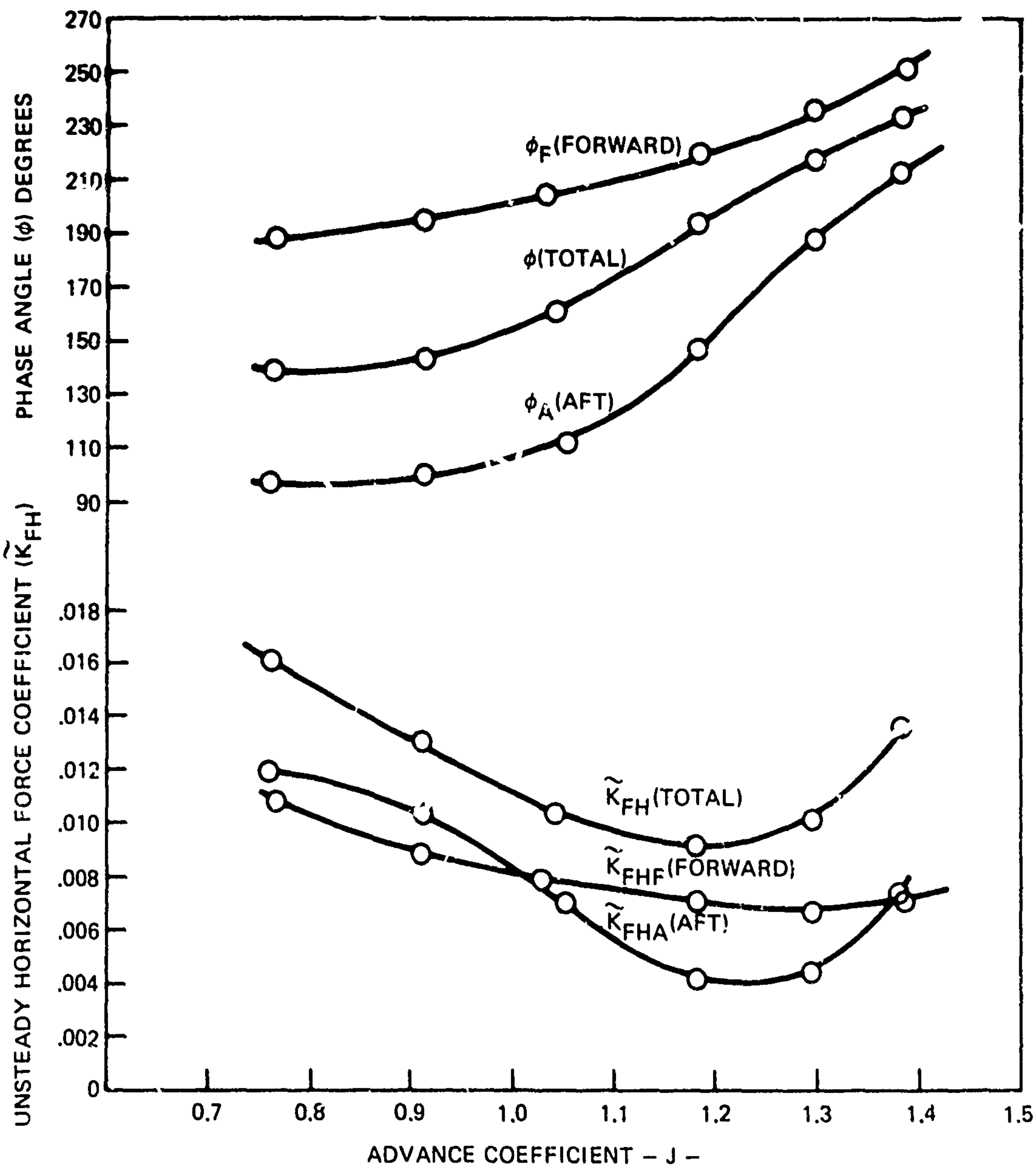


Figure 9 Unsteady Horizontal Side Forces on 4 X 5 Set at Nine Times Shaft Frequency

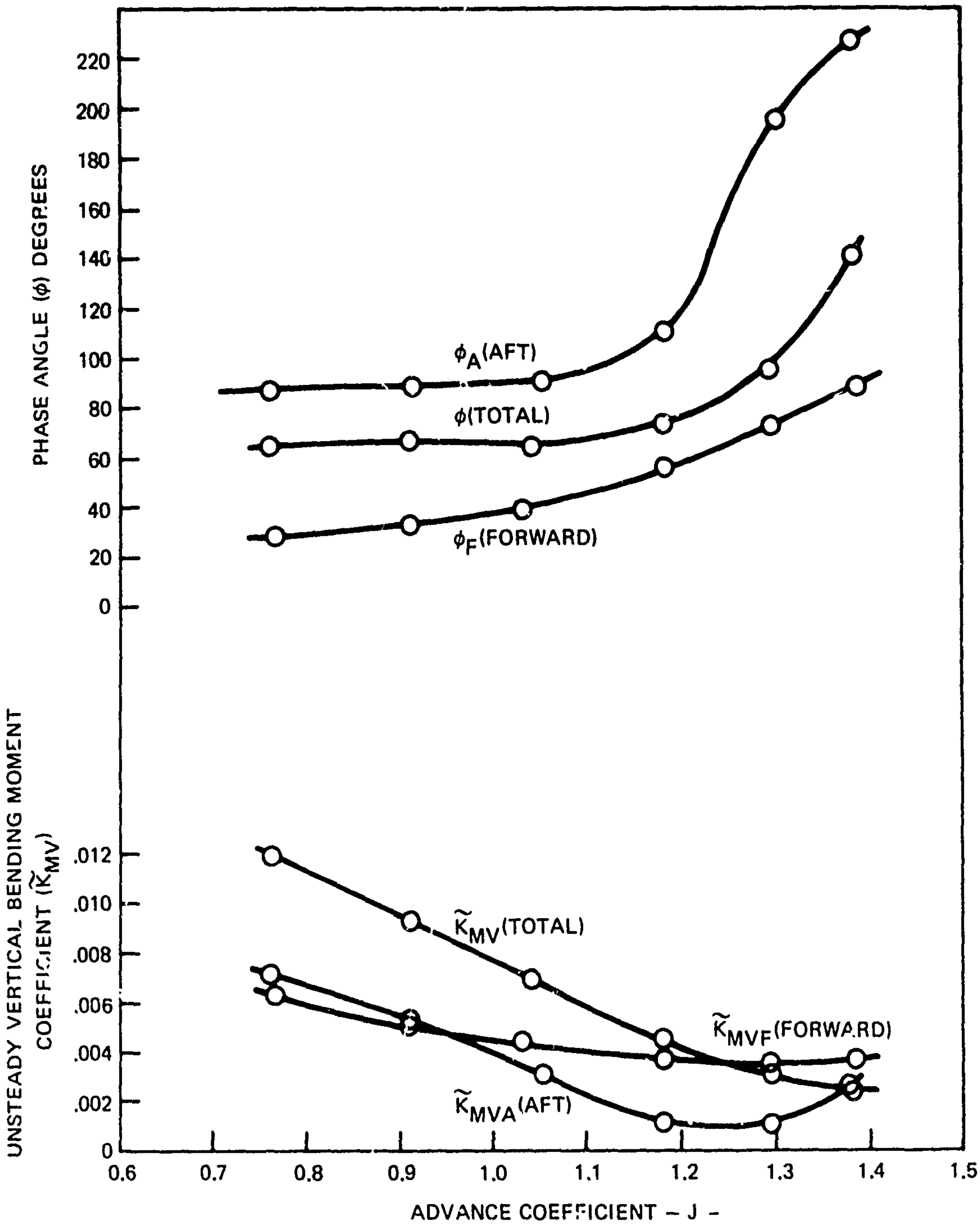


Figure 10 Unsteady Vertical Bending Moment on 4 X 5 Set at Nine Times Shaft Frequency

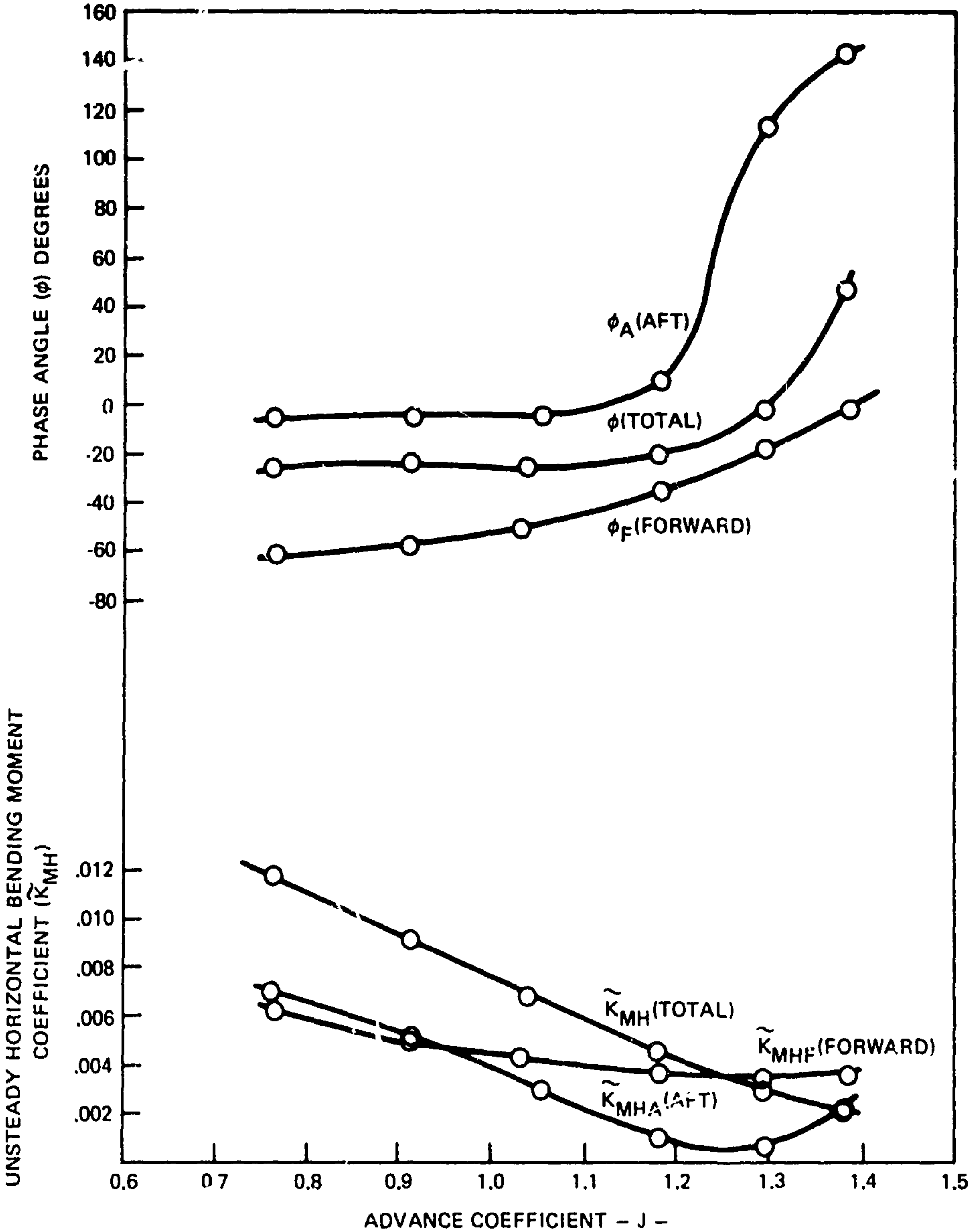
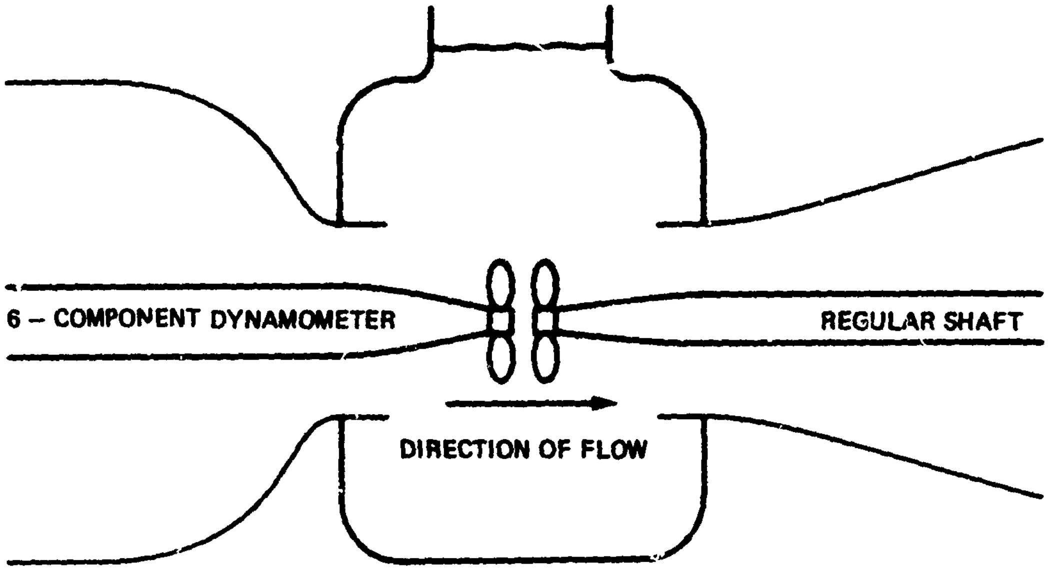
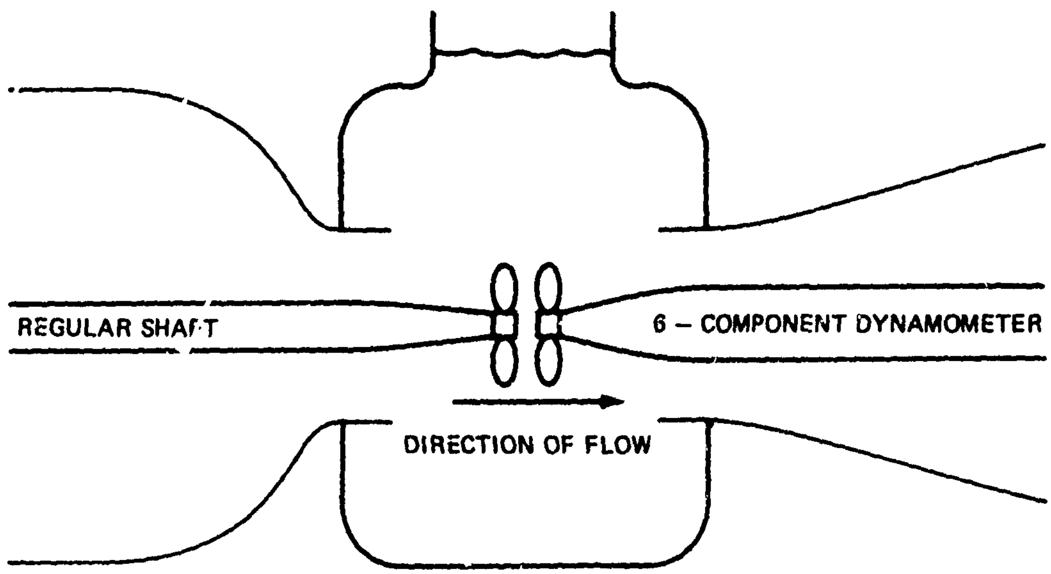


Figure 11 Unsteady Horizontal Bending Moment on 4 X 5 Set at Nine Times Shaft Frequency



MEASURING FORWARD PROPELLER FORCES



MEASURING AFTER PROPELLER FORCES

Figure 12 – Diagram of Experimental Set-up

Table 1 – Design Details of Model Propeller 3686

Position	Forward
Number of Blades	4
Diameter	12.017 inches (0.3052 m)
Pitch at 0.7 R	15.510 inches (0.3940 m)
Expanded Area Ratio	0.303
Section Meanline	NACA a = 0.8
Section Thickness Distribution	NACA 66 modified
Rotation	Left Hand

r/R	P/D	C/D	t/C	f_M/C
0.2	1.426	0.1075	0.2214	0.0018
0.3	1.396	0.1250	0.1688	0.0364
0.4	1.366	0.1400	0.1321	0.0430
0.5	1.336	0.1548	0.1027	0.0396
0.6	1.310	0.1695	0.0785	0.0353
0.7	1.291	0.1787	0.0604	0.0280
0.8	1.278	0.1750	0.0463	0.0249
0.9	1.269	0.1500	0.0367	0.0206
0.95	1.267	0.1220	0.0344	0.0175
1.00	1.267	---	---	---

Table 2 – Design Details of Model Propeller 3687 A

Position	After
Number of Blades	4
Diameter	11.776 inches (0.2991 m)
Pitch at 0.7 R	15.662 inches (0.3968 m)
Expanded Area Ratio	0.324
Section Meanline	NACA a = 0.8
Section Thickness Distribution	NACA 66 modified
Rotation	Right Hand

r/R	P/D	C/D	t/C	f_M/C
0.2	1.289	0.1100	0.2161	0.0020
0.3	1.291	0.1335	0.1581	0.0303
0.4	1.295	0.1530	0.1203	0.0351
0.5	1.302	0.1700	0.0935	0.0339
0.6	1.311	0.1823	0.0727	0.0319
0.7	1.326	0.1898	0.0569	0.0280
0.8	1.344	0.1833	0.0442	0.0242
0.9	1.361	0.1520	0.0362	0.0216
0.95	1.369	0.1220	0.0345	0.0199
1.00	1.376	---	---	---

Table 3 – Design Details of Model Propeller 3849

Position	After
Number of Blades	5
Diameter	11.785 inches (0.2993 m)
Pitch at 0.7 R	15.168 inches (0.3853 m)
Expanded Area Ratio	0.379
Section Meanline	NACA a = 0.8
Section Thickness Distribution	NACA 66 modified
Rotation	Right Hand

r/R	P/D	C/D	t/C	f_M/C
0.2	1.169	0.1075	0.2214	---
0.3	1.207	0.1250	0.1688	0.0269
0.4	1.243	0.1400	0.1321	0.0299
0.5	1.277	0.1543	0.1027	0.0290
0.6	1.288	0.1695	0.0784	0.0273
0.7	1.287	0.1785	0.0604	0.0238
0.8	1.293	0.1750	0.0463	0.0208
0.9	1.321	0.1500	0.0367	0.0182
0.95	1.349	0.1220	0.0344	0.0176
1.00	1.390	---	---	---

Table 4 – Comparison of Calculated and Measured Values for 4 X 4 Propeller Set

Forward Propeller 3686
After Propeller 3687-A
Axial Spacing = 0.28 forward propeller radius
J = 1.1

	THEORY		EXPERIMENT
	Without Thickness	With Thickness	
Q = 0, Steady State			
Forward $(\bar{K}_T)_F$	0.126*	0.1639*	0.125
Forward $(\bar{K}_Q)_F$	0.0295*	0.0373*	0.0315
After $(\bar{K}_T)_A$	0.145*	0.1335*	0.150
After $(\bar{K}_Q)_A$	0.0330*	0.0308*	0.0315
Q = 2N = 8			
Forward $(\tilde{K}_T)_F$	0.0485	0.0747	0.0285
Forward $(\tilde{K}_Q)_F$	0.0101	0.0154	0.0058
After $(\tilde{K}_T)_A$	0.1156	0.1524	0.0095
After $(\tilde{K}_Q)_A$	0.0242	0.0312	0.0022

*Including friction.

Table 5 – Comparison of Calculated and Measured Values for 4 X 5 Propeller Set

Forward Propeller 3686
After Propeller 3849
Axial Spacing = 0.28 forward propeller radius
$J = 1.1$

	THEORY		EXPERIMENT
	Without Thickness	With Thickness	
$Q = 0$, Steady State			
Forward $(\bar{K}_T)_F$	0.087*	0.1076*	0.130
Forward $(\bar{K}_Q)_F$	0.0207*	0.0254*	0.030
After $(\bar{K}_T)_A$	0.161*	0.1073*	0.130
After $(\bar{K}_Q)_A$	0.0361*	0.0255*	0.028
$Q_F = 2N_A - 1 = 9$			
Forward $(\tilde{K}_{FH})_F$	0.0079	0.0239	0.0075
Forward $(\tilde{K}_{FV})_F$	0.0079	0.0239	0.0074
Forward $(\tilde{K}_{QH})_F$	0.0062	0.0053	0.0040
Forward $(\tilde{K}_{QV})_F$	0.0062	0.0053	0.0041
$Q_A = 2N_F + 1 = 9$			
After $(\tilde{K}_{FH})_A$	0.0231	0.0275	0.0057
After $(\tilde{K}_{FV})_A$	0.0231	0.0275	0.0046
After $(\tilde{K}_{QH})_A$	0.0159	0.0181	0.0023
After $(\tilde{K}_{QV})_A$	0.0159	0.0181	0.0023

*Including friction.

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