Fifty years of the Kings College Propeller Series at the Emerson Cavitation Tunnel

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Since the founding of the Emerson Cavitation Tunnel in 1949, collaborative research into advancing propeller design has been undertaken at the facility. The British Admiralty initiated a systematic propeller series known as the Kings College Admiralty (KCA) series that was developed and tested in the King's College Tunnel (now the Emerson Cavitation Tunnel), between 1950 and 1955. The KCA series was unique as it not only encompassed 30 propeller designs, but considered the effect of cavitation in the resulting diagrams. The original design diagrams for the KCA series were constructed using 'drawing office' practice. No spline fits or regression methods were available to fit the data and therefore the data was faired by hand using French curves. This required significant level of checking and re-testing to verify the accuracy of the method. The intention of this paper is to re-visit the original experimental data taken when the KCA propellers were tested in 1950 and re-assess the data using modern numerical methods.

1 INTRODUCTION

The use of standard propeller series has wained in recent years with the need for more detailed wake optimised designs. The ubiquitous B_P-δ diagrams have given way to computerised methods of polynomial fits and artificial neural network solutions. Whilst the format of the design data may be changing to take advantage of computing power the underlying data of the series remains robust. One of the more important and still widely used series is the Kings College Admiralty (KCA) series for high speed craft. The series is unique as it provides design data not only for propeller performance but for thrust breakdown due to cavitation.

In an attempt to build a numerical method to assist designers in using this data, the original experimental results were re-analysed prior to implementing complex numerical solution methods. This was deemed prudent as the curve fits used on the data were all hand drawn. Therefore the objective of this paper is to provide a platform from which to build future numerical models. The robustness of the early data will be undertaken to assess the curve fit methods and to select a data set to be used in further analysis for the development of multiple regression or ANN models. Following this introduction the history of the Emerson Cavitation Tunnel is described. This is followed by a review of the instrumentation used on the KCA propellers and the development of the series is given. An analysis of the original model test data provides the main findings of the paper and the study concludes with recommendations for future work.

2 TUNNEL HISTORY

The roots of the Emerson Cavitation Tunnel are related to an original tunnel at Pelzerhaken in Germany, which was dismantled and brought to Newcastle after the Second World War. The original tunnel was not a cavitation tunnel for testing propellers, but was a horizontally disposed tubular circuit. It is believed tht the tunnel was used for underwater acoustic research such as the inception of cavitation on sound domes and the pioneering development of anechroic tiles still used today on submarine hulls. A detailed history of the Emerson Cavitation Tunnel is given in Atlar (2000).

The original tunnel was part of the Department of Naval Architecture at King's College, Newcastle. The tunnel had a measuring section of 32 inches by 40 inches with radiused corners and was dedicated to propeller testing. The shell of the tunnel was erected as a vertical closed channel cavitation tunnel by Vickers-Armstrong with the support of the principal propeller manufacturers of the UK. The tunnel had a temporary housing in the steam laboratory, a position it still maintains to this day. Figure 1 shows the tunnel schematic in 1949 and Figure 2 the test section in 1949.

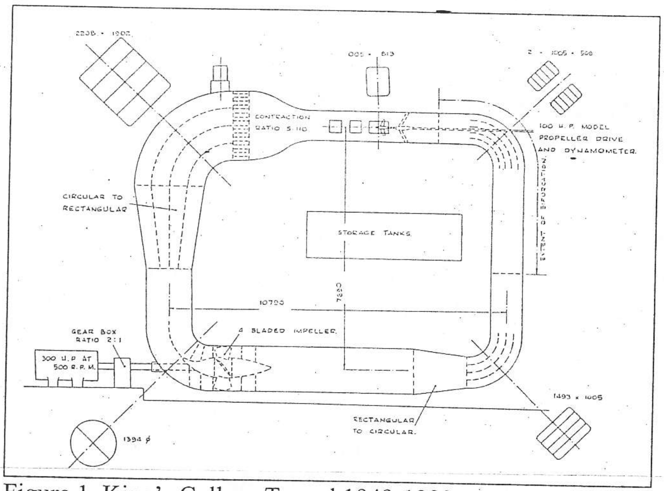

Figure 1. King's College Tunnel 1949-1980

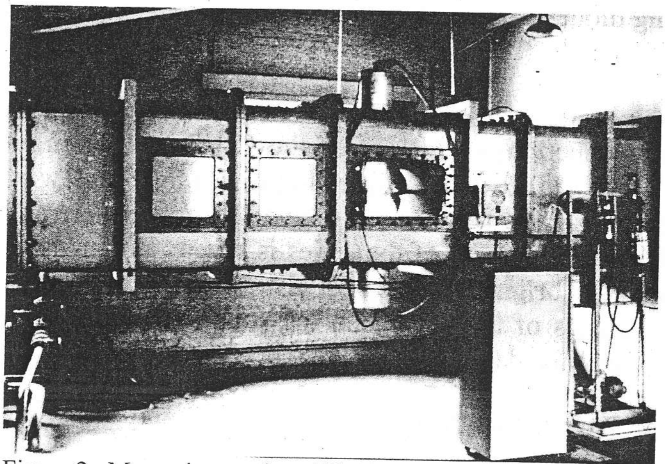

Figure 2. Measuring section - King's College Tunnel

With the rapid increase in merchant ship size and in the power transmitted on a single shaft, the needs of the cavitation tunnel changed. A larger measuring section was required to allow the placement of hull shaped bodies referred to as *"Dummy Hulls"* in front of the propellers to help simulate the extremely non-uniform wake caused by fuller single screw hullforms. After 25 years of continuous use the tunnel was upgraded to modernise the ageing machinery and equipment and replace the upper portion of the tunnel (contraction, diffuser and measuring section). At the official opening ceremony in 1980 the tunnel was named *"The Emerson Cavitation Tunnel"* after Dr. Arnold Emerson, the superintendent of the tunnel. The section had square corners, bigger windows and better access to provide a new cross section of 1.22m width x 0.81m height in comparison to the 0.81m width x 1.02 m height of the old King's College Tunnel cross section. The long propeller shaft and dynamometer of the old tunnel was replaced by a new electroninc dynamometer unit with a 90^0 drive from the top.

In 2007, again driven by the demands of industry the ECT was modified to make the tunnel more laser friendly. The measuring section was replaced for one with large windows and a new honeycomb and guide vanes, automated control system and quick degas unit were fitted. Finally the impeller, shaft and impeller bearing were overhauled. Figure 3 shows the tunnel schematic in 2007 and Figure 4 the test section in 2007.

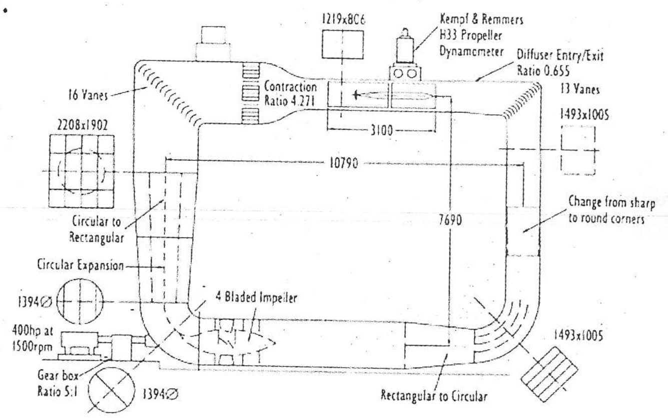

Figure 3: Emerson Cavitation Tunnel (2007)

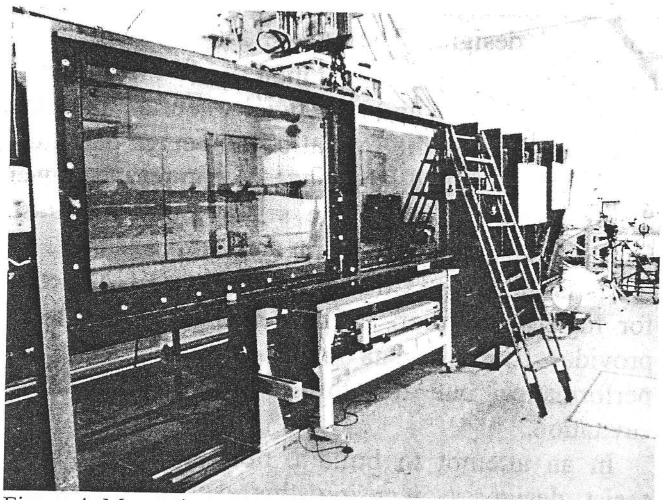

Figure 4: Measuring section - Emerson Cavitation Tunnel

3 INSTRUMENTATION & EQUIPMENT

In the original cavitation tunnel, to drive the propellers and measure the propeller loads an AC drive controlled by means of a phase change gear and a rather novel Variable Speed Gear (VSG) drive was adopted. This measuring gear would allow a maximum thrust of 4903 N and a maximum torque of 510 Nm at a maximum rate of rotation of 2000 rpm and was able to test model propellers up to 20" (508 mm) in diameter. Unlike todays electronic systems this unit was operated using a completely mechanical system. The propeller shaft was free to move in the longitudinal direction and was held in position using weights and a spring balance connected through a lever system to a thrust bearing sleve on the shaft. The thrust was also corrected for pressure differences inside and outide the tunnel. The propeller torque was measured by weighing the reactions on the pinnions of the epicyclic drive to the propeller shaft this measurement was also corrected for idle torque from the friction of the shaft bearing. In both the thrust and torque measurements no data logging system was used, the operator recorded the displayed analogue value which effectively represented the mean load. As the dial gauges were often moving this took a level of skill and experience to obtain consistent results. This system was upgraded in 1980 to a Kempf and Remmers H33 dynamometer which has a lower load rating for thrust and torque and is therefore unable to test the large KCA propellers. The data logging has also advanced with full digital systems now commonly sampling all of the test data between 2-10kHz. The flow velocity in the test section was originally measured using a water manometer. This system is still in use in the ECT however most tests are now supported by the Laser Doppler Anemometry (LDA) measurements. Finally a Van Slyke gas measurement was used to measure and control gas levels. As mercury is now considered a hazzardous substance; the Van Slyke has been superseeded by digital DO_2 system.

4 DEVELOPMENT OF THE KCA SERIES

One of the first tasks for the newly erected King's College Tunnel was collaboration with the British Admiralty on developing the KCA propeller series. The Director of Naval Construction, Department of the Admiralty placed contracts with the King's College Tunnel to investigate the propulsive characteristics of a methodical series of propellers. this series consisting of some 30 propellers to be tested at 6 cavitation numbers and would generate the well-known *"KCA "or "Gawn-Burrill"* systematic series and associated data. The design and range of models including test requirements were to Admiralty requirements and the experiments and results rested with the University. The extensive test period lasted from 1950 – 1955 and consisted of over 3000 propeller tests and some 1600 photographs of cavitation patterns. Collectively the information gathered was equal to that of 6 extensive propeller series in a towing tank, one for each cavitation number of the test. The KCA propeller series was important and it was published for 3 main reasons:

1. To help design propellers that do not erode in service.
2. To allow the best possible propeller design under thrust breakdown conditions.
3. To allow high speed propeller data to be compared against full scale and theoretical conditions.

Using this above approach propellers can be easily designed to absorb a design power at a design rpm, which do not erode in service and have high efficiencies.

The parent propeller of the series was KCA 110 shown in Figure 5. The propeller was a 3 blade propeller with constant face pitch ratio of 1.0 blade area ratio of 0.8 and blade thickness ratio of 0.045. The blade sections were segmental over the outer half of the blade at the inner radii the flat face was washed back at the leading and trailing edges, with the blade outline being elliptical.

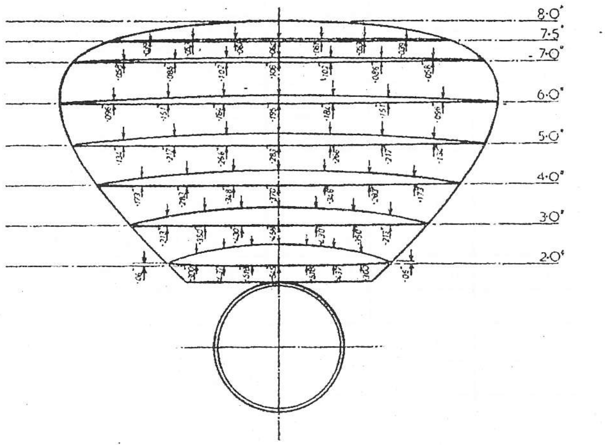

Figure 5: KCA 110 Expanded blade sections

From this basic propeller, 4 other propellers of the same pitch ratio were derived but with BAR of 0.5, 0.65, 0.95 and 1.1 respectively. For each of these designs the new propeller was obtained by multiplying the expanded blade width with at each radius of the basic screw by a constant factor to give the required area. For each blade area ratio, the expanded outline was used with different face pitch ratios. The full range of pitch ratio variations tested was 0.6, 0.8, 1.0, 1.2, 1.4, 1.6, and 2.0. The nomenclature adopted for the propeller names was as follows. The first digit in the numbers designates the BAR, digits 3, 4, 1, 5, 2 refer to BAR of 0.5, 0.65, 0.80, 0.95 and 1.1 with the last 2 digits relating to the pitch ratio. Thus KCA 420 has a BAR of 0.65 and pitch ratio of 2.0. Table 1 shows the section geometry for KCA 110 and Table 2 shows a list of propellers in the series.

Table 1. Section geometry for KCA 110

BAR	r/R 0.25	r/R 0.375	r/R 0.5	r/R 0.625	r/R 0.75	r/R 0.875	r/R 0.9375	EXP A.R.
0.5	3.35	4.55	5.555	6.33	6.74	6.32	5.25	0.51
0.65	4.38	5.93	7.25	8.26	8.79	8.25	6.86	0.665
0.8	5.38	7.30	8.92	10.18	10.80	10.16	8.42	0.82
0.95	6.56	8.90	10.87	12.38	13.16	12.37	10.28	1.00
1.10	7.73	10.49	12.80	14.60	15.53	14.58	12.11	1.18
w/w = 0.5	0.604	0.819	1.000	1.14	1.212	1.139	0.946	

Table 2. Complete propeller list of KCA Series

Propeller	BAR	P/D	Sigma
306	0.5	0.6	8.3, 2.0, 1.5, 1.0, 0.75, 0.5
308	0.5	0.8	6.3, 2.0, 1.5, 1.0, 0.75, 0.5
310	0.5	1.0	6.3, 2.0, 1.5, 1.0, 0.75, 0.5
312	0.5	1.2	6.3, 2.0, 1.5, 1.0, 0.75, 0.5
320	0.5	2.0	6.3, 2.0, 1.5, 1.0, 0.75, 0.5
406	0.65	0.6	8.3, 2.0, 1.5, 1.0, 0.75, 0.5
408	0.65	0.8	6.3, 2.0, 1.5, 1.0, 0.75, 0.5
410	0.65	1.0	6.3, 2.0, 1.5, 1.0, 0.75, 0.5
412	0.65	1.2	6.3, 2.0, 1.5, 1.0, 0.75, 0.5
414	0.65	1.4	6.3, 2.0, 1.5, 1.0, 0.75, 0.5
416	0.65	1.6	6.3, 2.0, 1.5, 1.0, 0.75, 0.5
420	0.65	2.0	6.3, 2.0, 1.5, 1.0, 0.75, 0.5
106	0.8	0.6	8.3, 2.0, 1.5, 1.0, 0.75, 0.5
108	0.8	0.8	6.3, 2.0, 1.5, 1.0, 0.75, 0.5
110	0.8	1.0	6.3, 2.0, 1.5, 1.0, 0.75, 0.5
112	0.8	1.2	6.3, 2.0, 1.5, 1.0, 0.75, 0.5
114	0.8	1.4	6.3, 2.0, 1.5, 1.0, 0.75, 0.5
116	0.8	1.6	6.3, 2.0, 1.5, 1.0, 0.75, 0.5
120	0.8	2.0	6.3, 2.0, 1.5, 1.0, 0.75, 0.5
508	0.95	0.8	6.3, 2.0, 1.5, 1.0, 0.75, 0.5
510	0.95	1.0	6.3, 2.0, 1.5, 1.0, 0.75, 0.5
512	0.95	1.2	6.3, 2.0, 1.5, 1.0, 0.75, 0.5
514	0.95	1.4	6.3, 2.0, 1.5, 1.0, 0.75, 0.5
516	0.95	1.6	6.3, 2.0, 1.5, 1.0, 0.75, 0.5
520	0.95	2.0	6.3, 2.0, 1.5, 1.0, 0.75, 0.5
208	1.1	0.8	6.3, 2.0, 1.5, 1.0, 0.75, 0.5
210	1.1	1.0	6.3, 2.0, 1.5, 1.0, 0.75, 0.5
212	1.1	1.2	6.3, 2.0, 1.5, 1.0, 0.75, 0.5
214	1.1	1.4	6.3, 2.0, 1.5, 1.0, 0.75, 0.5
216	1.1	1.6	6.3, 2.0, 1.5, 1.0, 0.75, 0.5

5 THE KCA SERIES MODEL TEST

The uniqueness of the KCA propeller series lies in the fact that each propeller was tested at 6 cavitation numbers. For the experiments the free stream cavitation number was used (σ_v = 6.3, 2.0, 1.5, 1.0, 0.75 and 0.5). The tunnel velocity and cavitation number were held constant whilst thrust, torque and shaft revolution measurements were made over a range of advance coefficients. In Gawn & Burrill (1955) the results of the KCA propellers are presented in non-dimensional format, for thrust (K_T), torque ($10K_Q$), and efficiency (η_o) to a base of advance coefficient for each cavitation number as shown in Equations 1 to 4. The value of V_T was corrected for tunnel wall interference using the well known Wood & Harris (1920) method.

Cavitation number $$\sigma_v = \frac{p-e}{\frac{1}{2}\rho (V_T)^2} \qquad (1)$$

Thrust coefficient $$K_T = \frac{T}{\rho n^2 D^4} \qquad (2)$$

Torque coefficient $$K_Q = \frac{Q}{\rho n^2 D^5} \qquad (3)$$

Efficiency $$\eta_o = \frac{K_T}{K_Q} \times \frac{J}{2\pi} \qquad (4)$$

As mentioned previously data aquisition was almost non existant at the time of these experiments. Where the present day open water test can be fully automated and executed with a neat report as soon as the test is finished, in 1950 the reality was quite different. From the original test data it is possible to observe that each group of test spots typically took 2 hours, as rpm was increased, manometer stabilised and the weight pans adjusted to calculate the measurement. The output therefore relied on the care and patience of the experimenter and was a naturally attenuated analogue result giving a single mean value. To this end, no time domain records were at all possible and simple repeat testing was the only cross check. However, also lacking at this time was the ability to manipulate the tabulated data that was gathered. The raw experimental data at non-uniform advance coefficients was plotted in large format by hand and the results graphically interpolated to obtain standard J values needed for generation of diagrams. Without the assistance of computers the curve fitting which is taken for granted today had to be performed by hand using french curves. No numerical curve fitting method was employed and the fairness of the curves relied on the skill of the drawing office. The faired data was subsequently generated into B_P δ diagrams and the results cross plotted and checked until suitable convergence was achieved, often by generating curve drawings of enormous size.

The core motivation of this paper is a preliminary study of the original unprocessed test data in conjunction with the hand faired results; the latter being published widely. As the use of B_P δ diagrams now primarily rests as a useful teaching tool for the Naval Architecture student or for guidange of the keen boat owner, a more preferential format is numerical representations suitable for incorporation into performance prediction software. The data is commonly given as polynomial coefficients from multiple linear regression such as Van Lammeran et al. (1969) and Yosifof et al. (1986) or more recently as tables of weights for the use in Artificial Neural Networks (ANN) such as Koushan (2007). Either of these formats can then be incorporated into Naval Architecture software allowing rapid development of basis propeller designs.

Prior to selecting a suitable method for the analysis the basis data needed to be assessed. Mitchell (2006) noted that the method and compilation of the original KCA data may provide different results when modern analysis procedures were applied to the data. In the original KCA propeller reports by Emerson and Burrill (1955), 2 tables of experimental data are given for each test that is raw and fitted. This paper presents the first stage in the project and compares the fitted curve data from 1955 with the raw experimental data fitted and faired with a 6th order polyniomial regression curve. In this manor the goodness of fit can be assessed. The polynomial method does have limitations and it is not ideally suited to the curve fitting for the entire KCA series due to the thrust breakdown effect. Figure 6 shows that when cavitation develops on the blade sections the performance is modified and rapidly deviates from the standard K_T curve.

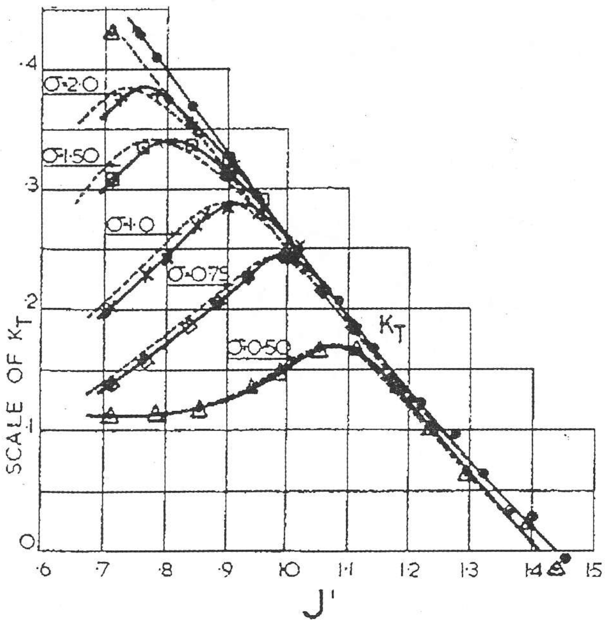

Figure 6. Sample of KCA 514

The discontinuity increases the order of the curves signinfcantly until quite often the Runge (1901) phenomenon occurs at the extremities of the data, that is erratic curve fitting when using polynomial interpolation with polynomials of high order. A preferable solution is to use a cubic spline interpolation however the fitting of each curve of every propeller test was beyond the scope of this paper. Therefore this introductory study was limited to the atmospheric conditions (σ_v = 6.3), which represented performance curves, which could easily have been obtained from towing tank or cavitation tunnel. On these curves no thrust breakdown occurred. Lines joining the test spots represented constant static head in the tunnel but not constant cavitation number due to tunnel wall interference and increase in static pressure with thrust. The constant cavitation number lines needed for the B_P-δ diagrams were obtained by plotting the values at the same advance coefficient (J) on a basis of corrected cavitation number and lifting off the values at each particular constant cavitation number.

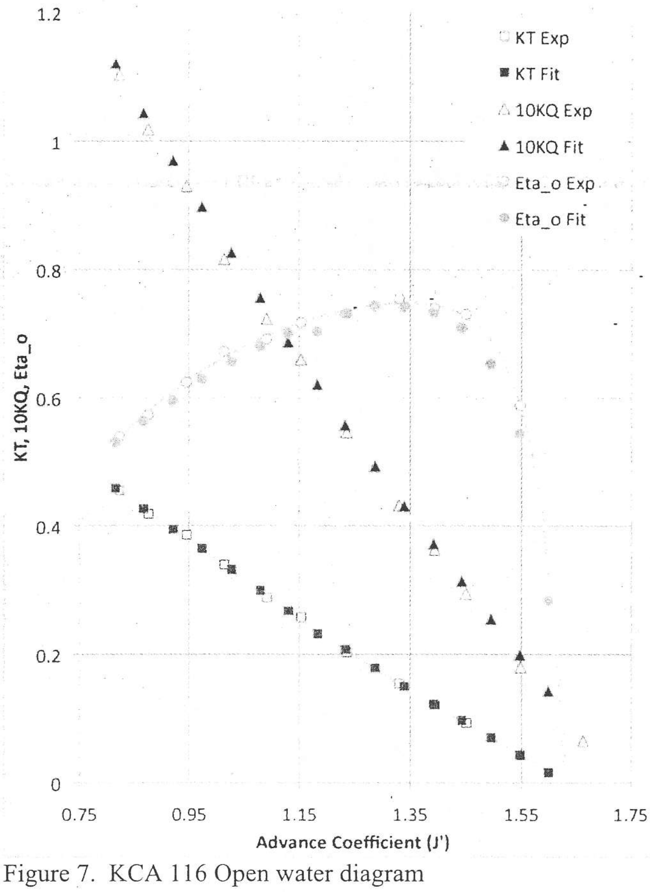

Figure 7. KCA 116 Open water diagram

Figure 7 shows the open water plot for KCA 116 at atmospheric conditions. In the plot the experimental test spots at non-uniform J values are shown with the open shapes. The fitted test spots i.e. those faired and taken at uniform J spacing are shown with filled shapes. From Figure 7, it is possible to see that there are slight differences in the performance curves, particularly the torque curve. These differences are relatively small, however they have a far greater effect on the efficiency curve, which in itself was still relatively small. The lines shown in the figure were created as 6^{th} order polynomials through the original experimental data. All of the curves show good agreement and the trend suggests a slight biasing of the data from the hand fit method however given that this was made on the performance curve and not the efficiency curve this gives a good level of confidence in the results. This also suggests that the original KCA propeller data is robust and the analysis methods adopted at the time were appropriate. However Figure 7 represents a single case therefore this study was extended to the entire series. Figures 8 to 12 show the open water efficiency curves for the entire KCA propeller series taken at the atmospheric condition ($\sigma_v = 6.3$). In the figures the original experimental data with a polynomial fit is given with the solid line and the hand faired standard J experimental results, which have been used in publication are given with the broken lines.

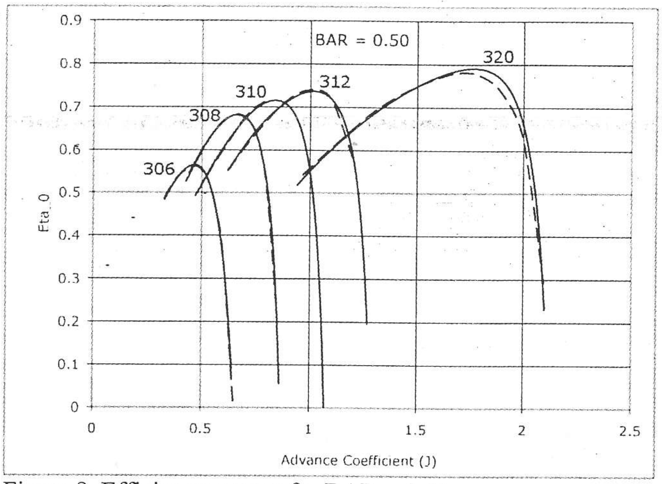

Figure 8. Efficiency curves for BAR = 0.50

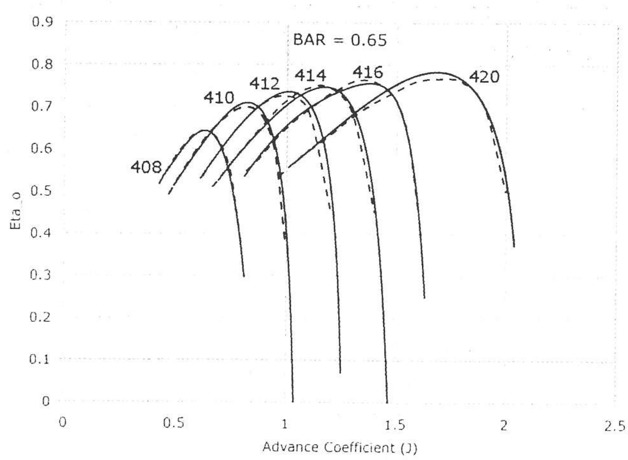

Figure 9. Efficiency curves for BAR = 0.65

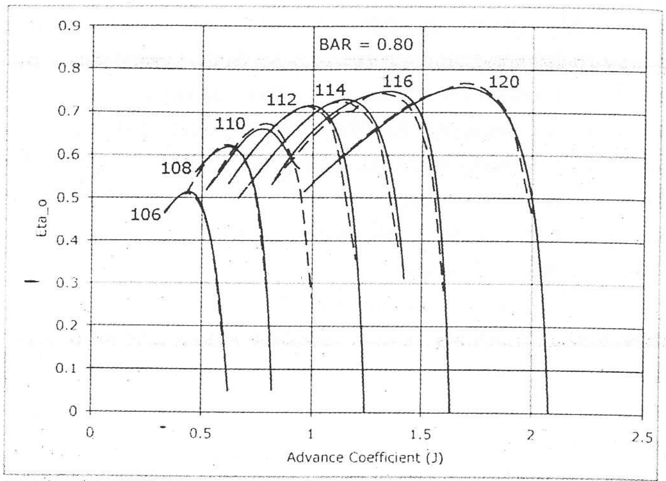

Figure 10. Efficiency curves for BAR = 0.80

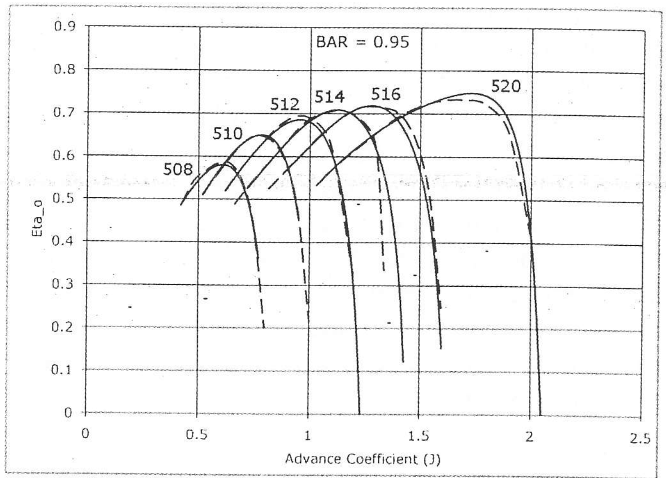

Figure 11. Efficiency curves for BAR = 0.95

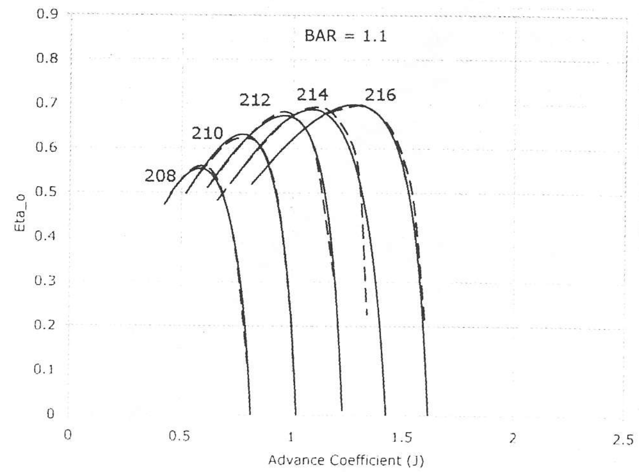

Figure 12. Efficiency curves for BAR = 1.10

As the performance curves were difficult to assess only the efficiency curves are given in the figures. In general the two methods of curve fit show good agreement with the most variation occurring in the high J areas of the test commonly associated with lower Reynolds numbers. As the hand fairing method relied to a great extent on the skill of the operator and some bias may be present. From the plots there is no real trend or bias difference between the 2 methods. However the published curves (hand faired) are more often underneath the actual experimental values making the published results for this condition conservative and giving a beneficial margin to the work.

Finally one of the advantages of propeller testing in a cavitation tunnel is highlighted in Figures 13 – 16 which shows a sample of the photographs taken during the propeller testing, something not possible in the towing tank. The photography method was developed by Townsin (1955) and was able to capture a blade at a repeatable angular location. When the cavitation extent recorded in the photographs is correlated with the numerical results the power of this standard series becomes clear. In the figures shown the atmospheric condition shown for KCA 420, despite a developed tip vortex and foaming sheet cavitation no thrust breakdown was recorded for the conditions shown.

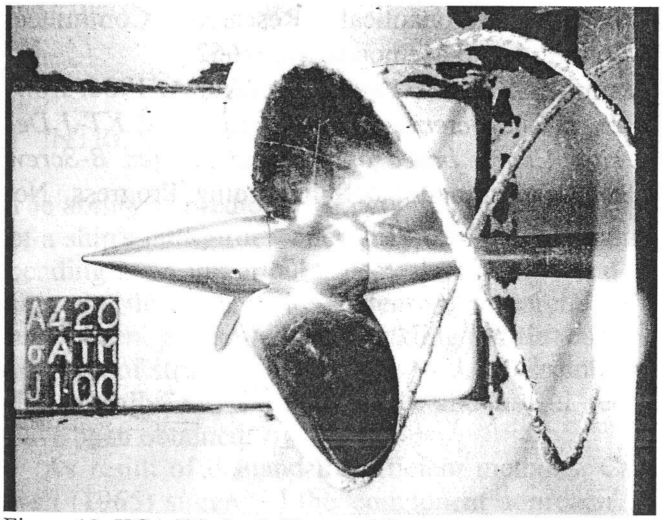

Figure 12. KCA420, J = 1.00, $\sigma_v = 6.3$

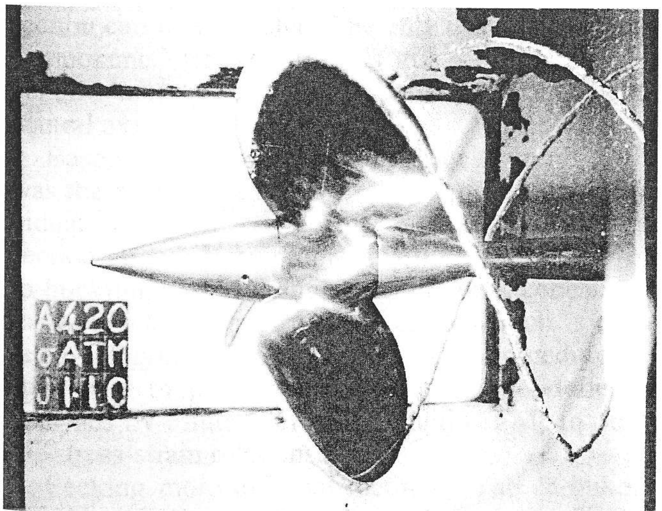

Figure 13. KCA420, J = 1.10, $\sigma_v = 6.3$

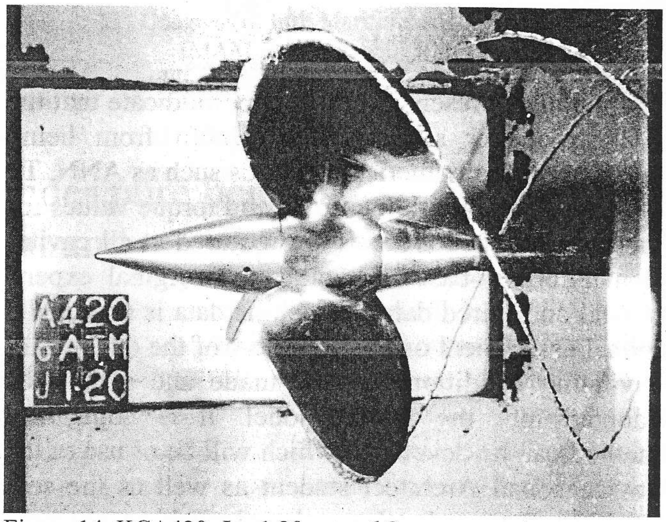

Figure 14. KCA420, J = 1.20, $\sigma_v = 6.3$

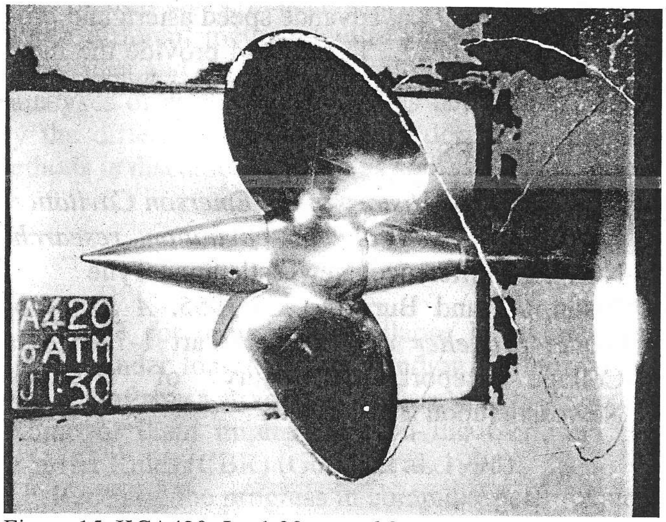

Figure 15. KCA420, J = 1.30, $\sigma_v = 6.3$

6. CONCLUSIONS

The original and unpublished experimental data from the KCA propeller series measured at the atmospheric condition has been re-analysed and compared with the faired data. From the study the following was concluded:

- The hand fairing methods used on the original data gave a good fit based on comparison with the original un-faired data.
- The original un-faired data responded well to 6[th] order polynomial regression techniques.
- For lower cavitation numbers the polynomial regression technique was not suitable.
- The faired data gave a more conservative estimate of the efficiency when compared to the experimental data.

7. FUTURE WORK

The findings presented in this paper indicate that the KCA propeller series would benefit from being transposed into numerical methods such as ANN. To complete such a task the thrust and torque values for the entire propeller series are required at all cavitation numbers, based on either the original experimental and faired data. Once this data is obtained a global assessment on the goodness of the data for all cavitating conditions can be made and a data set adopted into the future model. It is hoped the method can be developed which will be of use to the novice Naval Architect student as well as the seasoned Professional. It is also desirable to extend the scope of the series by introducing measurements in the 4th quadrant i.e. advance speed astern and propeller rotation ahead. This would provide the most complete data reference for the design possible.

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