SESSION ON CAVITATION

Chairman: Prof. J. P. Breslin

Cavitation Committee Memberships: J. H. J. van der Meulen (Chairman) - B. R. Parkin (Secretary) - K. V. Alexandrov - T. T. Huang - H. Kato - Y. Lecoffre - K. J. Minsaas - K. R. Suhrbier - E. A. Weitendorf.

Discussion of the Report and the Draft Recommendations of the Cavitation Committee (cf Proceedings Volume 1, p. 195-270) and Additional Contributions.

I. DISCUSSIONS

G. KUIPER - NSMB Wageningen,
The Netherlands

DISCUSSION OF THE REPORT OF THE CAVITATION COMMITTEE OF THE 17TH ITTC, 1984.

The Committee states that "in order to reduce cavitation scale effects it is necessary to stimulate the boundary layer to turbulent flow before the C_{pmin} location" (page 36), although "the minimum distance between the tripping band and the C_{pmin} location is not known" (page 12).

In practice it is extremely difficult or impossible to restrict the roughness to the region upstream of the minimum pressure point in case of model propellers because of the small leading edge radii. The roughness elements therefore have to be applied in those cases over a distance extending <u>downstream</u> of the C_{pmin} position. When this was done a better correlation with fullscale was found /49/,/Kupier 1978/. Huang et al /44/ also found that σ_i was close to $-C_{pmin}$ on headforms which were artificially roughened from the stagnation point to a location <u>downstream</u> of the minimum pressure point.

Is it not therefore somewhat premature when the committee concludes or suggests that the stimulator should be applied upstream of the minimum pressure location?

The Committee mentions "the scale effects on cavitation due to the differences of the minimum pressures of the propeller, i.e. bubble dynamics" (page 56) /3, 205, 206/. With this argument the larger cavity volumes at full-scale are explained. However, when the advance ratio and the cavitation index are the same at any scale, the dynamic behaviour of any bubble is properly scaled as long as the surface tension and the gas pressure in the vapor bubble are insignificant. This latter is the case for a bubble which has become unstable because due to its size the influence of the surface tension disappears rapidly and the gas pressure decreases. In that case the bubble growth can be approximated by the well known asymptotic solution of the Rayleigh-Plesset equation.

$$\dot{R} = \left(\frac{2}{3}\,\frac{p_V - p}{\rho}\right)^{1/2}$$

The minimum pressures at full-scale and the length of the low pressure region at full-scale are larger than at model scale /206/ but so is the propeller diameter and the relative size of the bubble remains similar. It is therefore not clear how this can explain differences in cavitation volume or extent between model and full-scale and what "the influence of bubble dynamics on unsteady sheet cavitation" (p. 49) means.

Based on (still unpublished) results /204/ the Committee concludes that a lack of nuclei occurs particularly "at very low test section pressures" (page 50) or, at a given cavitation index, at very low speeds. Our experience in the large tunnel of NSMB is opposite: at low speed the number and size of the nuclei increase significantly /38/. This can be expected since the effect of the pressure on the nuclei size and number is generally larger than the effect of the tunnel velocity. Is it possible that the mentioned decrease in nuclei content is a particularity of the tunnel?

Reference

Kuiper, G. "Cavitation Scale Effects - A Case Study", Int. Shipbuilding Progress, Vol. 25, 1978.

T. HOSHINO and E. BABA -
Nagasaki Experimental Tank,
Mitsubishi Heavy Industries, Ltd.
Nagasaki, Japan

ON MEASUREMENT OF CAVITY VOLUME AND THICKNESS

In the Committee Report it is pointed out that the disadvantage of a laser scattering technique for the measurement of cavity shape is rather time consuming. The present discussers would like to report an effort in saving measurement time by use of the laser scattering technique.

In the original method developed by Dr. Ukon of the Ship Research Institute /71/, measurements both under cavitating condition for cavity surface and non-cavitating condition corresponding to the blade surface were necessary to obtain thickness of the cavity at one point on the blade at one phase angle. Thus, frequent change of the static pressure in the cavitation tunnel was necessary in the course of measurements and it was time consuming.

We developed a new method [1], [2], which combines a mini-computer with the laser scattering system. Instead of the measurement of blade surface position, coordinates of measuring point on the blade surface are calculated geometrically by mini-computer. Thus the cavity thickness distribution is obtained from the reading of cavity surface coordinates only, and the unsteady cavity profile on a propeller blade is simultaneously displayed on a screen. The merits of the present method are the shortening of measuring time and the capability of measurement of cavity shape in super-cavitating condition.

References

[1] HOSHINO, T., and TANAKA, Y.: "Measurement of Unsteady Cavity on the Blades of a Propeller Operating in Non-Uniform Flow", Flow Visualization, Vol. 3, No. 10, 1983, pp. 167-172.

[2] HOSHINO, T.: "A System for Measurement of Unsteady Cavity on Propeller Blades Using a Laser Beam", Mitsubishi Juko Giho, Vol. 21, No. 3, 1984, pp. 472-478.

Y. UKON and Y. KUROBE -
Ship Research Institute, Tokyo, Japan
(Presented by H. Takahashi)

CONCERNING PROPELLER INDUCED HULL PRESSURE FLUCTUATIONS

In the Ship Research Institute, several efforts have been made to investigate scale effects on pressure fluctuation by cavitating propellers and to measure the hull fluctuating pressures in the cavitation tunnel with a high accuracy.

In 1982, the systematic full scale measurement on the "Seiun-Maru" propellers was performed [1]. Accordingly the model experiment on these propellers behind a complete model with flow liners was carried out in the No.2 working section of the SRI large cavitation tunnel [2]. The flow liners were used to simulate the wake distribution estimated by the Sasajima's method without employing a dummy model.

The comparison of hull pressure amplitudes $Kp_5 = \Delta p_5/\rho n^2 D^2$ between two kinds of full scale propellers and models is shown in Fig. 1 in order to compare with the "Sydney Express" propeller discussed in the Committee Report. The model results are slightly higher than the full scale results for both the conventional propeller CP and the highly skewed propeller HSP. The agreement of the observed cavitation extent between model and full scale was excellent.

In the model experiment, artificial nuclei seeding by electrolysis or

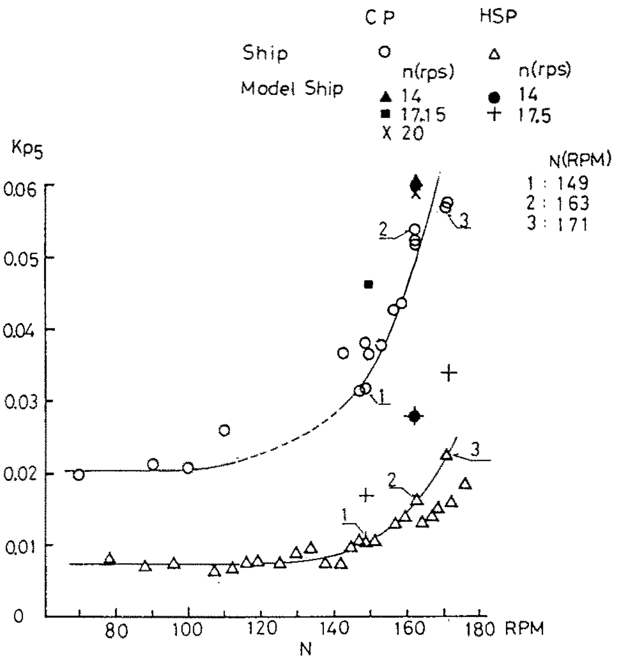


Fig 1 Comparison of Hull Pressure Amplitudes Kp5 between Model and Full Scale

leading edge roughness by carborundum particles was utilized to get the stable sheet cavitation on a propeller blade in particular at the portside angular positions [3].

Concerning the effect of revolution number of the tested model propeller, the present results indicate big difference from the measured results of the "Sydney Express" propeller in HSVA. The nondimensionalized first blade rate pressure amplitudes measured at twelve points on the stern hull of the model ship in the SRI cavitation tunnel are little affected by the revolution number of the model propeller in the range from 14Hz to 20Hz. The measured data scatters widely unless one of the abovementioned artificial techniques which give the same results is applied [3]. The length of the SRI cavitation tunnel shown in Fig. 2 is almost same as the HSVA large cavitation tunnel because the type of both tunnels are K-16 originally designed by Kempf & Remmers.

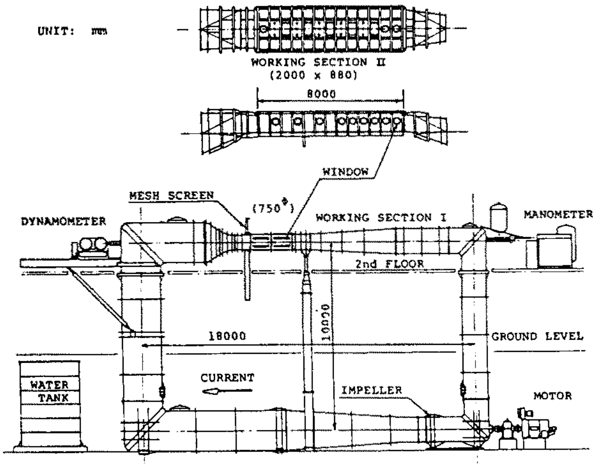


Fig 2 General Arrangement of the SRI Cavitation Tunnel

For these reason, I suppose that the scatter in the measured pressure amplitude should be attributed not to standing pressure wave phenomena but to other effects, e.g. insufficient nuclei in the flow field around model propellers and so on.

References

[1] Takahashi, H.: "Full Scale Messurements on Training Ship 'Seiun-Maru'", Presentation to the Group Discussion of the 17th ITTC, Göteborg, 1984

[2] Kurobe, Y., et al: "Measurement of Cavity Volume and Pressure Fluctuations on a Model of the Training Ship 'Seiun-Maru' with Reference to Full Scale Measurement", Report of the SRI, vol. 20, No. 6, 1983

[3] Ukon, Y., et al: "Pressure Fluctuations Induced by Cavity Volume on Highly Skewed Propellers for a Ro/Ro Ship", Report of the SRI, vol. 19, No. 3, 1982

K. TAKEKUMA and H. TANIBAYASHI -
Nagasaki Experimental Tank, Mitsubishi Heavy Industries, Ltd., Nagasaki, Japan

ON THE REPORT OF THE CAVITATION COMMITTEE

Topic of Discussion: 4.4 Hull Pressure Fluctuations

The discussers thank the Committee for presenting the present status of hull fluctuation measurements. The result of comparative tests made in four organizations have provided valuable information on this topics.

According to this comparative test program, reference is made only to the first blade frequency component of the pressure fluctuations and noise. Conclusions and recommendation also seem to refer to the first blade frequency component.

The discusser should like to point out, however, that the higher order blade frequency components have been acquiring growing concern in connection with inboard noise and habitability problems. Little has been investigated into these problems, and there is an indication that the model-ship correlation is much poorer than for the first blade frequency as illustrated in Fig. A. This shows the results from fullscale measurement on a medium sized tanker, model results in the medium sized cavitation tunnel in the Nagasaki Experimental Tank (NET) and those in the large cavitation tunnel in SSPA where wake distribution was simulated by accommodating a ship model.

With such situation in mind, the discussers propose the Committe to extend and stimulate the study on higher order frequency components of propeller-induced pressure fluctuations.

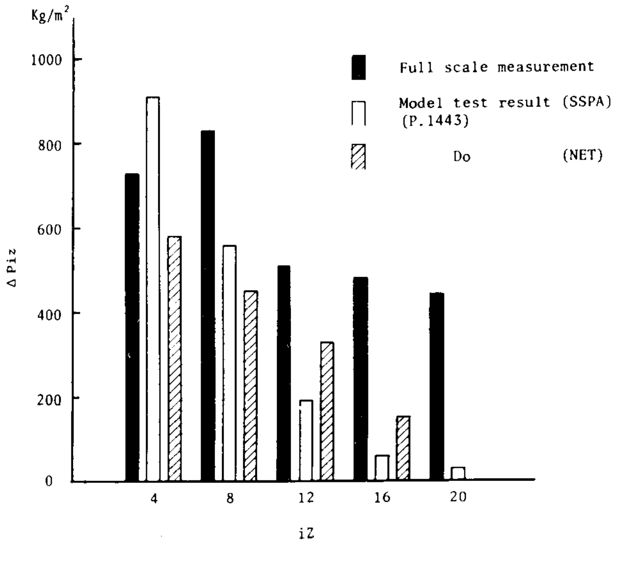


Fig A Pressure fluctuations

T. SASAJIMA and H. TANIBAYASHI -
Nagasaki Experimental Tank, Mitsubishi Heavy Industries, Ltd, Nagasaki, Japan

ON THE REPORT OF THE CAVITATION COMMITTE

Topic of Discussion: 6. Cavitation Noise

In Appendix 4 of the Committe Report comparisons of noise level of cavitating propeller are made among various laboratories by use of a "Sydney Express" propeller model of diameter 375 mm. The discussers would like to present supplementary data measured by use of a "Sydney Express" propeller model of smaller diameter (D = 250 mm) in the cavitation tunnel with measuring section 0.5 m x 0.5 m in the Nagasaki Experimental Tank (NET). Measurements of cavitation noise were made in the following conditions:

i) Propeller revs 20 rps and 30 rps

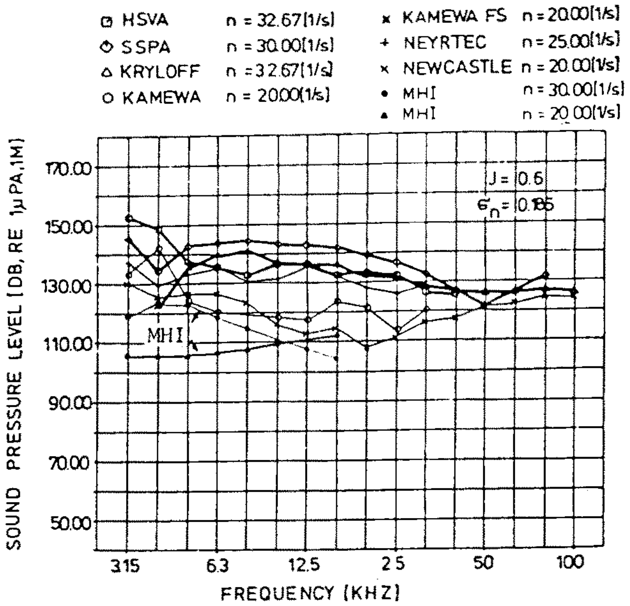
ii) Advance constant J = 0.6, 0.7, 0.9

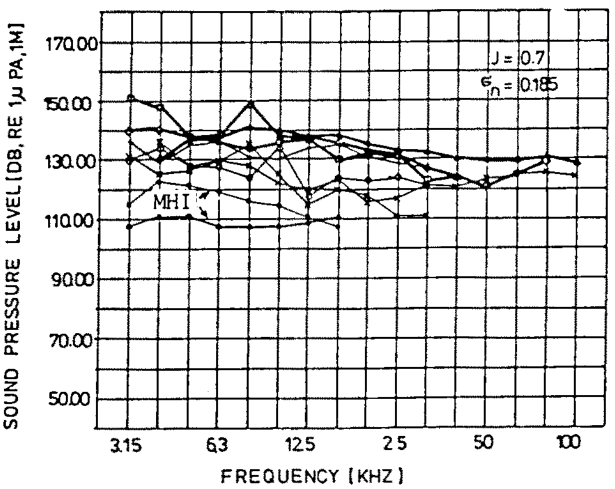
iii) Cavitation number

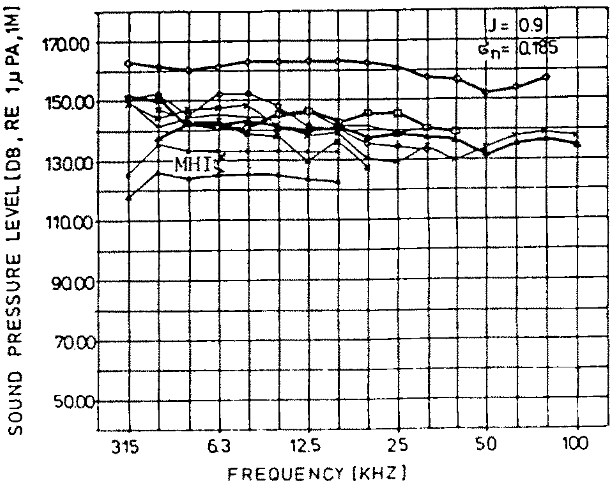
$$\sigma_n = \frac{p_o - p_v}{\rho/2(\pi n D)^2} = 0.185$$

iv) Air content ratio α/α_s = 0.3 and 0.4

Measured data are plotted for the case of air content ratio 0.3 in the figures presented in the Committe Report (Figs 4.1, 4.2 and 4.3). In our case also higher noise level was obtained for higher propeller revolutions. This trend







and order of magnitude are consistent with the data presented in the Committee Report. Further, it is noted that lower noise level is measured in the NET cavitation tunnel. This may be due to the usage of a propeller of smaller diameter than that of the cooperative work. Estimation of the change of noise level due to the difference of propeller diameter was made on the scale method according to Levkovskii:

$$L_1-L_2=20\ \log\{\lambda^{3/2}\left(\frac{n_1D_1}{n_2D_2}\right)\left(\frac{\sigma_{n1}}{\sigma_{n2}}\right)^{1/2}\frac{r_2}{r_1}\}$$

where L: Sound pressure level in dB ref 1μPa
n: Rate of revolutions of propeller
D: Propeller diameter
r: Distance from source point to field point
λ: D_1/D_2 = Geometric scale factor

In the present case $L_1 - L_2 = 8.8$ dB. Order of magnitude approximately agrees with the difference observed in the measured data. This is an encouraging result in views of testing techniques and scale effect of propeller cavitation noise.

L. ACCARDO and A. COLOMBO - CEIMM, Rome, CETENA, Genova, Italy.

ON CAVITATION NOISE MEASUREMENTS WITH THE "SYDNEY EXPRESS" SHIP PROPELLER MODEL

This experimental work was carried out to participate in the program of comparative noise measurements suggested by the Cavitation Committee of the 16th ITTC. All information regarding test conditions for noise measurements were kindly sent to CETENA from Hamburgische Schiffbau Versuchsanstalt.

The measurements were carried out in uniform flow at the CEIMM Cavitation Tunnel of the Italian Navy in Rome.

Propeller Model

Due to the medium size of the testing section of CEIMM Cavitation Tunnel (square section with B = 600 mm), it was impossible to test the large diameter propeller model (D = 375 mm) as proposed by ITTC. Therefore, measurements were conducted on the 250 mm propeller model manufactured by HSVA, which kindly lent it us.

Test Conditions

All measurements were conducted at a constant frequency of propeller model rotation, n = 45 Hz, which was the maximum allowed for these specific tests where, to fulfill the prescribed cavitation numbers, unbearable pressure values should have been set up.

It must be pointed out that to obtain the correspondance with full scale circumferential velocity at J = 0.7, the measurements should have been conducted with propeller model rotating at n = 49Hz.

The above mentioned limits of our facility do not allow to reach such rotational speed.

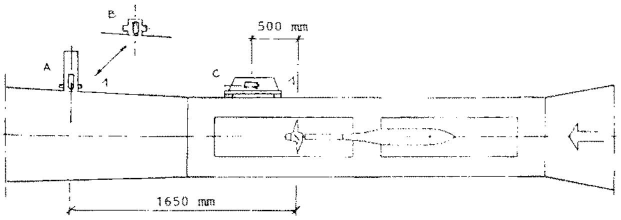


Fig 1 Hydrofones Location and Mounting

The three required values of the advance ratio

$$J = V_A/nD = 0.6,\ 0.7 \text{ and } 0.9$$

were obtained by changing the flow velocity V_A.

The four required cavitation numbers, according to the blade tip rotational speed,

$$\sigma_n = \frac{p - pv}{1/2\rho(\pi n D)^2} = 0.185,\ 0.193,\ 0.202,\ 0.211,$$

were obtained by suitable chosing the pressure p in the oncoming flow. As regards the flow air content in the cavitation tunnel it was maintained at

$$\alpha/\alpha_s = 0.5$$

Hydrophone Location and Mounting

For noise measurements two hydrophones were used according to the scheme of Fig. 1. They were located inside water-filled boxes. Results herein reported were obtained from the nearest hydrophone propeller plane. Its box was mounted on a window, so that water into the box was separated from the inner flow by a plexiglass plate.

The hydrophone and propeller model centre are about 0.5 m separated. Recordings by the other hydrophone are at present under analysis.

Results of measurements and data analysis

All propeller model noise measurements were analysed by means of a B&K 1/3 Octave Band Analyser 2131, equipped with a Frequency Expansion Unit (Upper frequency: 200 K. Hertz. In Table 1 stan-

Table 1 Results of Noise Measurements (in dB)

J →	0.6					0.7					0.9				
σ / Frequency Hertz	0.185	0.193	0.202	0.211	X	0.185	0.193	0.202	0.211	X	0.185	0.193	0.202	0.211	X
630	124	119	117	114	107	119	110	105	102	105	106	107	106	107	110
800	113	111	111	109	106	108	110	103	103	102	99	99	98	98	101
1.000	106	104	104	103	106	100	102	102	104	111	102	102	101	102	111
1.250	111	108	106	105	103	104	106	105	103	102	108	110	108	108	95
1.600	112	111	109	107	93	100	102	103	103	95	109	109	108	108	95
2.000	109	113	110	113	105	113	112	112	112	106	115	110	115	113	10
2.500	104	103	102	102	102	100	101	101	101	103	106	107	106	105	10
3.150	109	109	109	108	100	102	102	102	102	102	114	114	114	111	10
4.000	113	114	113	114	95	114	114	113	114	95	110	111	110	109	95
5.000	101	101	101	101	93	99	98	99	99	92	105	106	105	105	92
6.300	101	100	100	101	92	97	98	98	98	90	107	107	107	107	92
8.000	98	97	97	98	82	93	93	93	94	80	105	105	105	104	82
10.000	94	94	95	97	87	94	94	94	93	82	106	106	106	105	86
12.500	95	94	93	93	86	95	93	93	93	79	112	112	111	111	86
16.000	96	96	95	95	80	96	96	96	94	74	112	112	112	111	80
20.000	93	93	93	93	81	95	94	94	92	72	111	111	110	110	80
25.000	92	92	92	93	82	91	91	91	90	70	107	107	107	105	79
31.500	91	91	92	94	77	90	89	89	89	68	105	104	105	103	77
40.000	88	88	88	89	65	88	87	87	86	60	103	103	103	100	76
50.000	84	84	83	83	60	85	84	83	83	59	98	97	98	95	69

X Background Noise

dard 1/3 Octave noise spectrum levels are listed, after correction to the distance of one meter, as dB (1 μ Pa; 1 m; 1 Hz).

Also the background noise levels of the tunnel (without propeller model) are shown, respectively for the three water speeds related to the different advance ratios. The various cavitation numbers showed a very light influence on background noise levels (the scattering being limited within 1 dB).

In Fig. 2 for the cavitation number σ_n = 0.185 and for the three different advance ratios both spectrum levels due to propeller and to background noise are shown. Unfortunately, as it can be seen from this figure, at frequencies lower than 3.15 KHz the propeller model noise and background noise levels are of the same order of magnitude.

The causes of such an high background noise level under this frequency are at present under investigation at Cavitation Tunnel in Rome in order to improve its acustical characteristics.

Cavitation Conditions

The propeller model cavitation pattern, at the various propeller working conditions, are shown in Fig. 3 and can be summarized as follows:

- at J = 0.6 there is some back sheet cavitation and a strong tip vortex cavity;
- at J = 0.7 only a moderate tip vortex cavity was observed;
- at J = 0.9 a well developed sheet pressure side cavitation was observed.

A comparison with noise measurement results from other conventional tunnels is reported in Figs. 4, 5, 6 respectively for the three different propeller operating conditions (J = 0.6, 0.7, 0.9 and σ_n = 0.185).

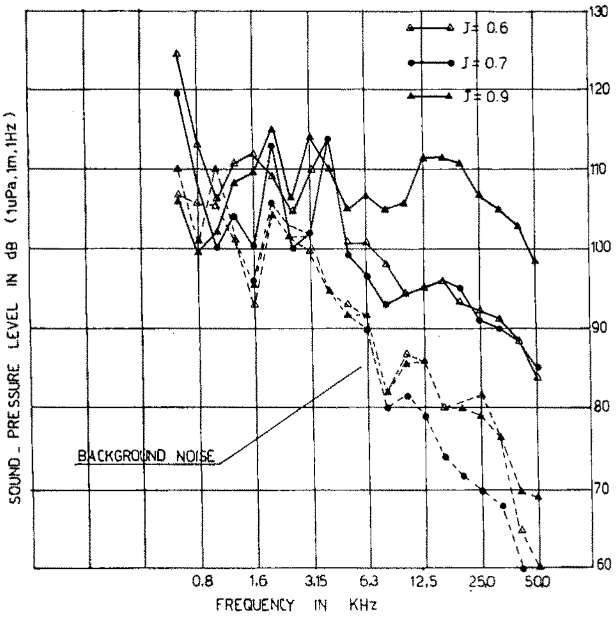


Fig 2 Noise Measurements Results at CEIMM Cavitation Tunnel

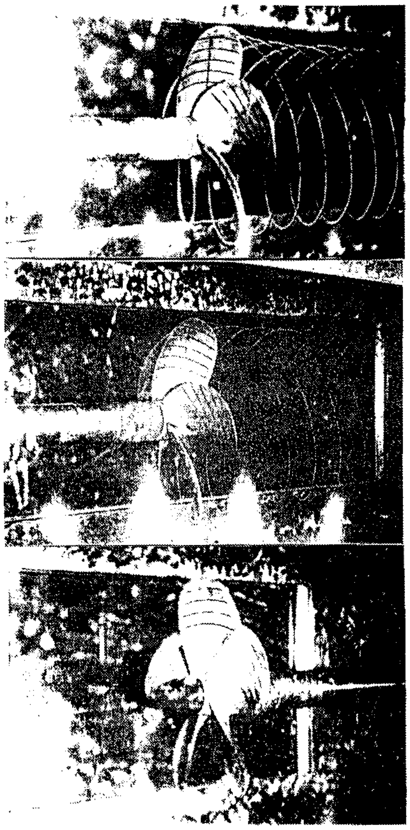


Figure 3

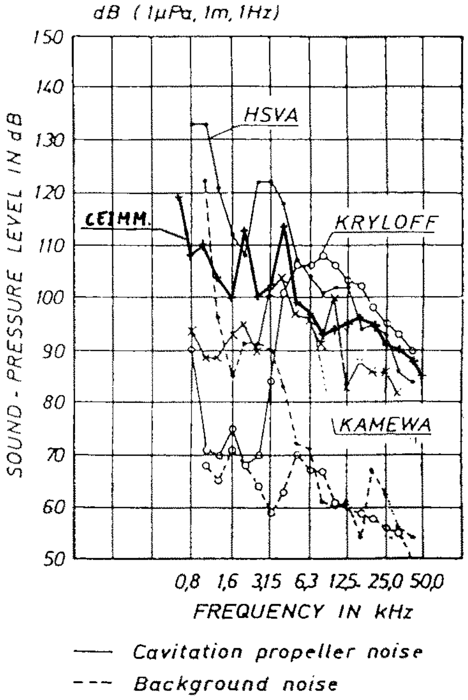


Fig 5 Noise Measurements of Conventional Tunnels

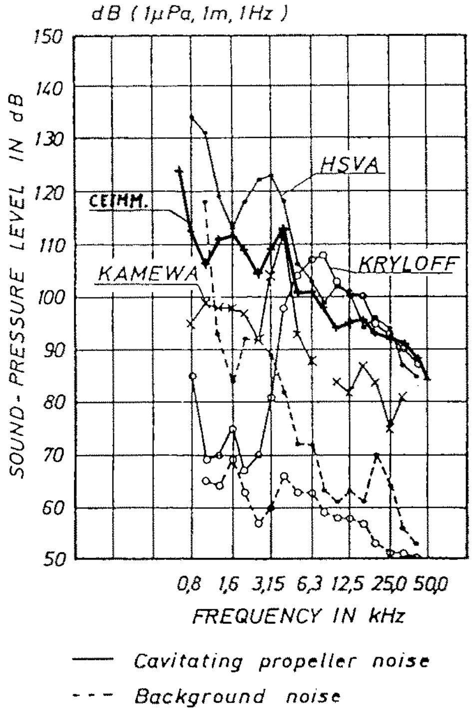


Fig 4 Noise Measurements of Conventional Tunnels (Suction Side Cavitation)

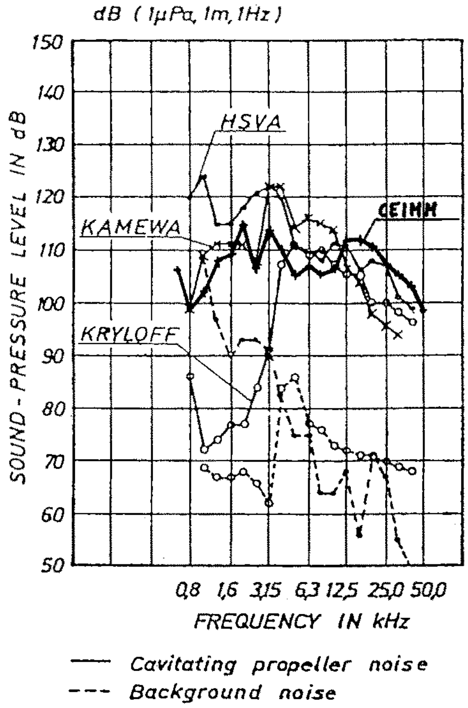


Fig 6 Noise Measurements of Conventional Tunnels (Pressure Side Cavitation)

W. ZHU, H. WANG and B. ZHU -
Shanghai Jiao Tong University,
Shanghai, People's Republic of China.
Presented by Sheng Chen Pang

ON PRELIMINARY PREDICTION OF SHIP PROPELLER CAVITATION NOISE

Ship propeller cavitation noise is one of the principle underwater noise sources of the ships. In this report, we make a preliminary prediction of propeller cavitation noise.

The derivation of the fundamental prediction formula of the propeller cavitation noise spectra in the sea is based on the fact that during the collapse of a single low air-content bubble, the acoustic radiation coefficient β remains approximately constant. In accordance with the method of dimensional analysis in the theory of analogy, in the case of a single low air-content bubble collapsing in water, acoustical radiation law of a single bubble can be derived. Meanwhile, through analysing the statistical property of a bubble aggregate, the cavitation noise of air bubble can be considered as a random impulse process, so the mathematical model of cavitated bubbles of a propeller may be established [1]. Therefore we prove that the form of propeller cavitating noise spectrum is the same as that of single acoustical pulse. Thereby we can derive the following basic prediction formulae of the prototype propeller cavitation noise simply by substituting diameter D of the propeller for the maximum radius of the air bubble R_1 in the single bubble case [2], [3],

$$\left.\begin{aligned} f_p &= f_m \cdot \frac{1}{\lambda} \cdot \left(\frac{\Delta P_{op}}{\Delta P_{om}}\right)^{1/2} \\ (L_p)_p &= (L_p)_m + 10 \lg \left[\lambda^3 \cdot \left(\frac{\Delta P_{op}}{\Delta P_{om}}\right) \cdot \left(\frac{r_m}{r_p}\right)^2\right] \end{aligned}\right\} \quad (1)$$

where f, L_p represent the frequency and the sound pressure level with 0dB=1 μPa, respectively

$\lambda = \frac{D_p}{D_m}$, geometrical factor for scaling;

D represents the diameter of the propeller; the subscript p represents the prototype and m the model;
$\Delta P_o = P_\infty - P_v$, and P_∞ is the static pressure at infinite distance, P_v is the saturated vapour pressure in the air bubbles.

r = distance from propeller surface to the observation point.

Whereas formulae (1) are derived under the ideal conditions, in practice, the air content of bubbles can neither be considered to be very low, nor very high, so we have to consider both the water compressibility and the variable β. Therefore, prediction formulae with aircontent correction term can be expressed by

$$\left.\begin{aligned} f_p &= f_m \cdot \frac{1}{\lambda} \cdot \frac{\Delta P_{op}}{\Delta P_{om}}^{1/2} \\ (L_p)_p &= (L_p)_m + 10 \lg \left[\lambda^3 \cdot \left(\frac{P_{op}}{P_{om}}\right)^n \cdot \left(\frac{r_m}{r_p}\right)^2\right] \end{aligned}\right\} \quad (2)$$

where n represents the correction index for air content of bubbles, with $1<n<3/2$; its exact value depends on the experimental conditions of both model and prototype.

The experiments for the prediction of prototype propeller cavitation noise spectrum are performed in the cavitation tunnel of Shanghai Jiao Tong University. To make the measured data accurate and reproducible, the following four analogy conditions must be satisfied during the experimental processes [4]:

(a) Model propeller must be geometrically similar to the prototype;
(b) Flow fields must be similar;
(c) Bubbles must be operated under similar conditions, and
(d) Acoustical analogy must be established.

In all cavitation tests, the first three conditions must be satisfied. In order to satisfy the condition of accustical analogy, it is necessary to make corrections for both back-ground noise and tunnel wall effects [5] to reduce the measured value to those corresponding to free field conditions. After these sound field corrections, the cavitation noise spectrum of model propeller can be used for prediction.

The predicted noise spectra of the ship were calculated by formulae (1) and (2), for seven performance conditions. The average errors and variances were tabulated as in Table 1. As can be seen from this table, the predicted values calculated from formula (1) are lower than those measured with prototype propeller. With air-content correction formula (2), average errors become smaller, ranging ±1dB, the average value of the errors in the seven performance conditions is only 0.14dB, and this proves that the correction of air content is a reasonable step.

TABLE 1

Order No of experiments	average error (dB)		variance (dB)	
	using form. (1)	using form. (2)	using form. (1)	using form. (2)
1	-0.65	0.65	1.98	1.98
2	-2.1	-0.8	2.8	2.02
3	-3.38	-1.08	3.77	1.98
4	-2.75	-0.45	2.98	1.24
5	-2.19	0.11	2.73	1.63
6	-1.65	0.75	2.88	2.47
7	0.4	1.8	1.93	2.61
The average value of the errors	-1.76	0.14	2.72	1.99

References

[1] MOROZOV, V. P.: "Cavitation Noise as a Train of Sound Pulses Generated at Random Times", Sov. Phys. ac., Vol. 14, No. 3, 1969

[2] LEVKOVSKII, V. L.: "Modeling of Cavitation Noise", Sov. Phys. ac., Vol. 13, No. 3, 1968, pp. 337-339

[3] BRUIJN, A. D. & WILDE, T. T.: "Measurement and Prediction of Sound Inboard and Outboard of Ship as Generated by Cavitating Propellers" Symposium on High Powered Propulsion of Large Ships, Wageningen 10th-13th Dec. 1974

[4] STRASBERG, M.: "Propeller Cavitation Noise after 35 Years of Study", Noise and Fluids Engineering, 1977

[5] ZHU, W., WANG, H. and YE, W.: "Measurement of Tunnel Wall Effect in the Cavitation Noise Tests"

Proceedings of the 16th ITTC, 1982, pp. 237-240.

KOZHUKHAROV, P. G., and YOSIFOV, K. Y. - Bulgarian Ship Hydrodynamics Centre, Varna, Bulgaria

ON AN EXPERIENCE WITH SOFT SURFACE TECHNIQUE IN PROPELLER EROSION TESTS

It is known that soft surface technique is commonly used in many laboratories as a standard practice for qualitative evaluation of propeller erosion characteristics [1]. Usually tests are performed as prescribed values of propeller thrust coefficient (K_T) and cavitation number (σ_n), based on propeller rate of rotation (n). The choice of the actual value of n seems to be in a certain extent arbitrary, depending on the experimental practice of each laboratory. On the other hand, propeller rate of rotation serves as an integral measure of propeller dynamic phenomena, including development of cavitation on propeller blades. At the same time in model test conditions (at σ_n = idem and K_T = idem) rate of rotation could be considered as a representative for resultant inflow velocity at given propeller blade section. It is well established that flow velocity has a strong effect on cavitation erosion intensity. Recent investigations of foils, reviewed in [2], show considerable influence of cavity dynamics on erosion rate. Therefore a development of quantitative erosion prediction method, as proposed by the ITTC Cavitation Committee [1],[2], should account for the mentioned factors, connected with more precise analysis of the flow kinematics. For these reasons the perfect choice of propeller rate of rotation appears to be an important moment in model erosion tests.

A special research programme dedicated to propeller erosion testing has been carried out recently at the Bulgarian Ship Hydrodynamics Centre [3]. A new paint used as a soft surface has been developed. Series of erosion tests with a number of propeller models are performed in non-uniform flow created by wire-mesh screen. It is established that the new paint can be successfully applied to obtain qualitative picture of blade eroded areas. Special attention is paid to the effect of propeller rate of rotation. It is observed that cavitation patterns on propeller blades at given main operating conditions (i.e. K_T and σ_n) are not seriously affected by the choice of rotative speed. However, the indications on the paint are different regarding their intensity, being much more clear and pronounced at higher values of model rate of rotation. In order to illustrate this effect, the time of the first indication appearance (t) is chosen as a representative parameter. Each 5-8 minutes the conditions of the painted blades are checked until peeled off areas appear. Some typical results are presented in Figs. 1 and 2, from which it can be seen that the propeller rate of rotation, having a strong effect on erosion intensity in full scale, has certain influence on the occurrence of indications on the paint in model scale. This means that the paint is sensitive to the dynamics of cavitation collapse, which can not be registerd visually. Some scatter of the data is probably due to technological reasons, connected with the preparation of the model.

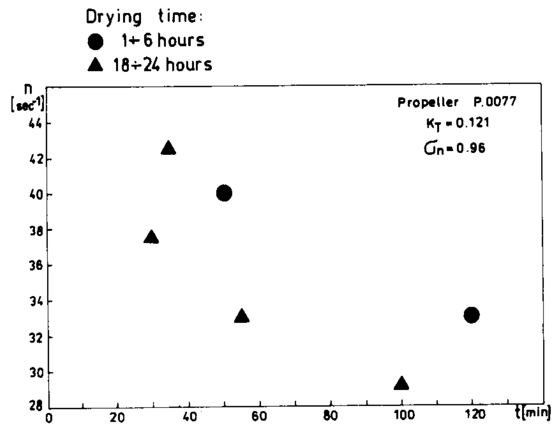


Fig. 1

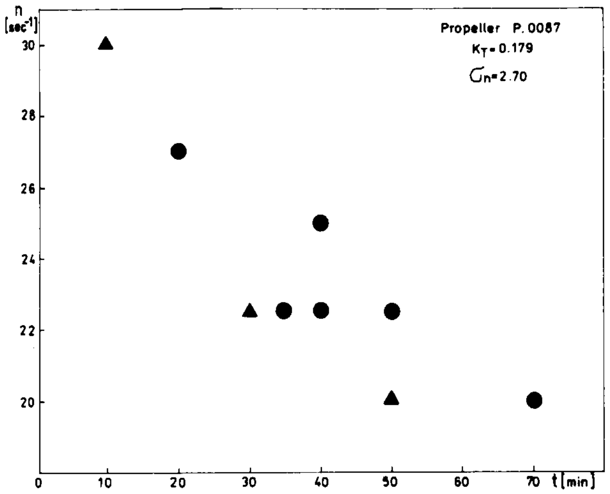


Fig. 2

Particularly it is found that the drying time has certain influence.

It is concluded that the choice of propeller rate of rotation plays an important role in model erosion testing. The new paint developed could be suitable for quantitative predictions of the propeller erosion, using a method similar to that described in [4].

References

[1] Report of the Cavitation Committee, 16 ITTC, 1981

[2] Report of the Cavitation Committee, 17 ITTC, 1984

[3] KOSHUKHAROV, P. G.: "Development of Soft Surfaces for Propeller Model Erosion Tests", BSHC Internal Report June 1984 (in Bulgarian)

[4] GEORGIEVSKAYA, E. P.: "Propeller Erosion and Methods of Its Prevention" Sudostroenie Publ. House, Leningrad, 1978 (in Russian)

KOZHUKHAROV, P. G., and YOSIFOV, K. Y. - Bulgarian Ship Hydrodynamics Centre, Varna, Bulgaria

INVESTIGATION OF TIP CLEARANCE EFFECT ON SUPERCAVITATING PROPELLER PERFORMANCE CHARACTERISTICS

As mentioned in the Cavitation Committee Report [1], certain discrepancies exist in some experimental results concerning the influence of wall proximity on the cavitating propeller characteristics. This problem is of vital importance for the high-speed propeller testing and fast craft performance prediction.

At the Bulgarian Ship Hydrodynamics Centre, a special investigation dedicated to the effect of propeller tip-wall clearance has been completed recently. The experimental programme includes propeller tests in cavitation tunnel in uniform axial and oblique flows. The tests are performed using a special dynamometer with inclinable shaft providing a stepless variation of vertical propeller position in the tunnel working section. It has to be emphasized that the propeller model is positioned upstream and operates in uniform inflow

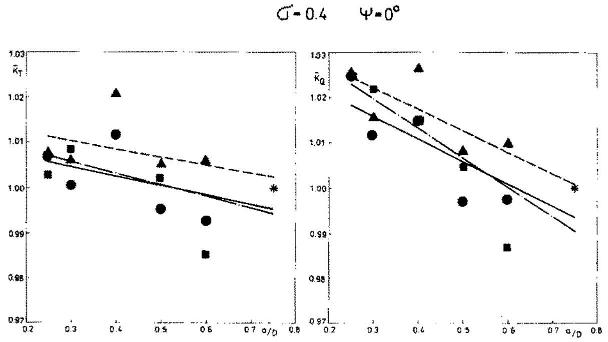


Fig. 1

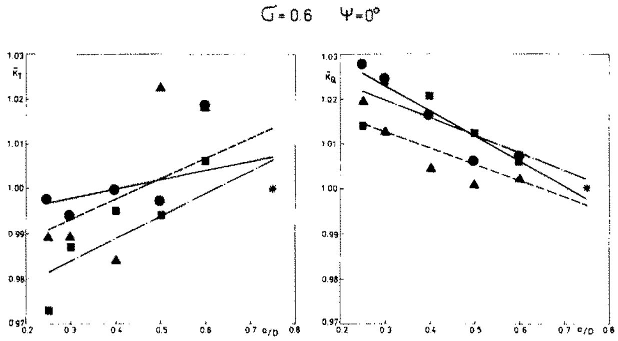


Fig. 2

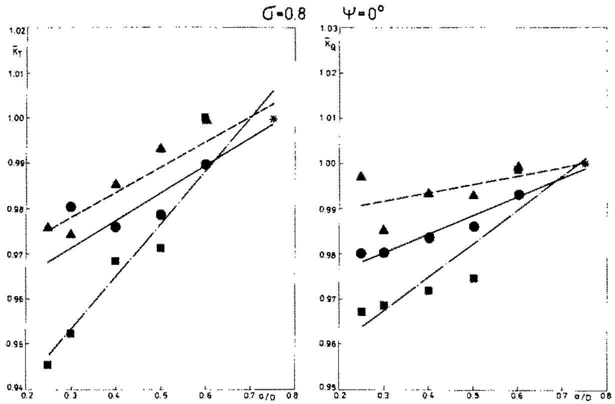


Fig. 3

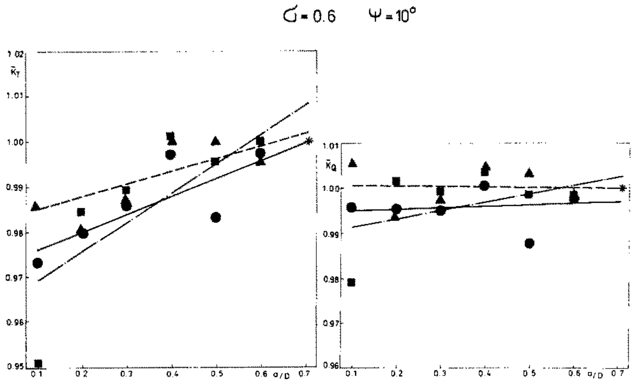


Fig. 4

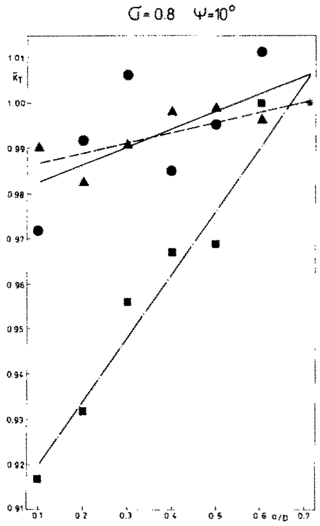


Fig. 5

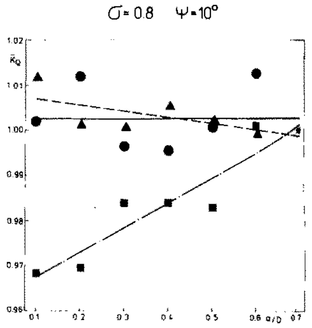


Fig. 6

velocity field. More details on BSHC cavitation tunnel and propeller dynamometer are given in [2].

A three-bladed supercavitating propeller model is tested in axial ($\psi = 0^{\circ}$) and oblique ($\psi = 10^{\circ}$) flows at different values of advance coefficient J and cavitation number σ, based on static pressure at the centre of propeller disc and mean flow velocity at the entrance of the tunnel working section. Some typical experimental results are presented in Figs. 1 through 6. Actual experimental points are presented as well as least-square fit lines, following the symbols given in the Table below:

Advance ratio	Experimental points	Least-square fit lines
0.75 P/D	△	- - - - - -
0.80 P/D	○	————
0.85 P/D	□	—·—·—

P/D - propeller mean pitch ratio

Following [3], the results are presented in a form of propeller thrust (K_T) and torque (K_Q) coefficients versus vertical tip clearance (a) to the wall. For convenience relative values are used:

$$\bar{K}_T = \frac{K_T}{K_T(a_{max})}; \quad \bar{K}_Q = \frac{K_Q}{K_Q(a_{max})}$$

where a_{max} is the maximum attainable clearance, i.e. when centre of propeller disc lies on the working section's horizontal axis. In the case treated, $a_{max} = 0.75$ D for $\psi = 0^{\circ}$ and $a_{max} = 0.71$ D for $\psi = 10^{\circ}$ (D - propeller diameter).

It can be seen that the influence of tip clearance on propeller performance characteristics depends mainly on the extent of cavitation. At low cavitation numbers (Fig. 1) a tendency for thrust and torque increase exists when reducing the tip clearance. An opposite tendency is observed at high cavitation numbers, which is more pronounced for the thrust. In certain stages of cavitation development (i.e. combination of σ and J) thrust or torque coefficient remain practically unchanged. This is valid both for axial and oblique flow conditions. With respect to a quantitative evaluation of the results it could be seen that the changes of propeller characteristics at low cavitation numbers are rather small.

It is concluded that the influence of the tip clearance on supercavitating propeller performance characteristics depends on Cavitation number and propeller loading. Therefore in high-speed propeller testing the propeller-hull clearance has to be taken into account, because in some cases it could seriously affect ship performance predictions.

References

[1] Report of the Cavitation Committee, 17 ITTC, 1984

[2] SADOVNIKOV, Y. M., FROLOV, V. A., KALCHEV, R. Z., KOZHUKHAROV, P. G.: "Tests of Series of Cavitating Screw Propellers in Oblique Flow", Proc. BSHC Jubilee Scientific Session, Vol. 1, 1984.

[3] RUTGERSSON, O.: "Supercavitating Propeller Performance. Influence of Propeller Geometry and Interaction between Propeller, Rudder and Hull", SSPA Publ. No. 82, 1979.

KRUPPA, C. - Technische Universität Berlin,
Institut für Schiffs- und Meerestechnik,
Berlin, F.R.G.

ON 17TH ITTC CAVITATION COMMITTEE REPORT

The Report of the Cavitation Committee discusses at some length the fundamental differences between effects of cavitation observed on oscillating foil sections on one hand, and on propellers operating in wakes in the other hand. Without wishing to elaborate further on this particular aspect I would like to draw the attention of the Committee to some recent investigations by *Lu* [1] dealing with unsteady flow effects in oscillating foils.

Based on Giesing's time-step calculating procedure cavitation-free angle of attack ranges are determined for simple sinusoidal pitching motions of arbitrary foil sections, in terms of the minimum pressure coefficient. The results reveal certain unexpected effects as a function of reduced frequency. Whereas an increase in reduced frequency usually widens the cavitation-free angle of attack range the opposite may be true for certain combinations of foil section geometry and reduced frequency. In particular, it was found that for high reduced frequencies, large thickness-chord ratios and small pitching amplitudes the value of $-C_{pmin}$ could increase considerably over and above that for steady-state conditions.

In further paper by *Kruppa* and *Lu* [2] various types of periodic pitching motions are investigated with regard to the value of $-C_{pmin}$. For 3 different reduced frequencies pure sinusoidal motion is compared, for example, with periodic oscillation containing higher order harmonics (Fig. 1). As can be seen from Figs. 2, 3 and 4 the content of higher order harmonics may significantly increase the value of $-C_{pmin}$, in particular at high reduced frequencies. It should be pointed out that this increase in $-C_{pmin}$, over and above the value for steady-state conditions, is always associated with a suction peak close to the mid-chord position of the foil section and with an instantaneous phase angle of nearly zero degrees.

References

[1] LU, R. J.: "Beitrag zur instationäre Tragflügeltheorie", Dissertation (Doctor Thesis), Technische Universität Berlin (D83), December 1983.

[2] KRUPPA, C. and LU, R.J.: "Theoretica Prediction of Cavitation-Free Ranges for Arbitrary Foil Section", to be presented at Symposium on Cavitation Inception, ASME Annual Winter Meetin New Orleans, La., December 1984.

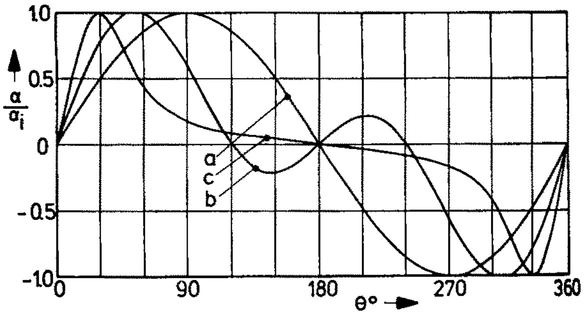


Fig.1 Periodic pitching motion with different order of harmonic content for

$\alpha = \alpha_i \sum_{\nu=1}^{n} m_\nu \sin \nu \theta$

(a: n=1, b: n=2, c: n=12)

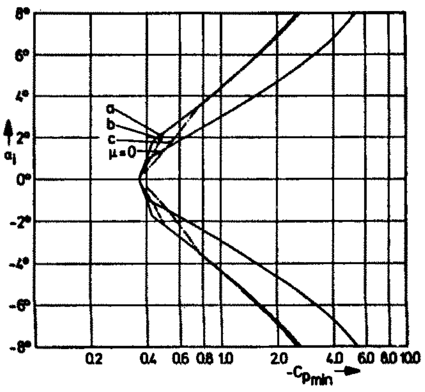


Fig.2 Bucket curves for NACA 16-015 at $\mu = 0.5$ for the periodic motion defined in Fig.1

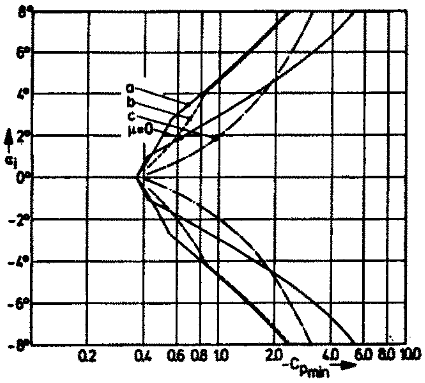


Fig.3 Bucket curves for NACA 16-015 at $\mu = 1.0$ for the periodic motion defined in Fig.1

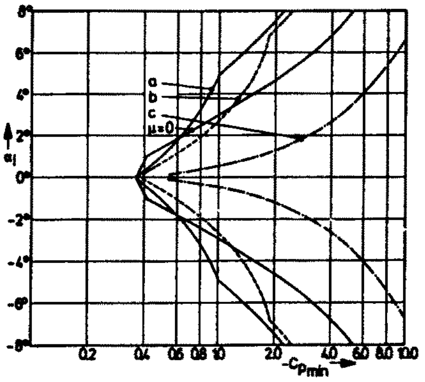


Fig.4 Bucket curves for NACA 16-015 at $\mu = 2.0$ for the periodic motion defined in Fig.1

RUTGERSSON, O. - SSPA Maritime Consulting AB, Göteborg, Sweden

I would like to congratulate the Committee to their most interesting Report. Especially the part of interest to me, the part about High-Speed Propulsion I do find very well written.

Mr Suhrbier, whom I believe is responsible for this part of the Report, and I have had some disagreements about the importance of propeller hull influence on the prediction procedures. However, after reading the Report I find that our disagreements become smaller and smaller. One remaining argument could however be that I believe that the importance of the shaft inclination on the propulsive coefficients is too much emphasized in the Report. For instance, for the determination of the mean wake I think it is more convenient to use the open water characteristics for horizontal shaft, as is done for single screw ships. I believe that also on most single screw ships the propeller is working in a considerably oblique flow relative to the propeller shaft and yet we are using the horizontal shaft characteristics with good results.

Finally I like the idea proposed in the Report of accepting different prediction methods of increasing refinement. This is an idea proposed by the High-Speed Marine Vehicle Committee and I look forward to a future co-operation between the Committees on developing some kind of procedures for performance predictions for High-Speed Ships.

JOHNSSON, C-A. - SSPA Maritime Consulting AB, Göteborg, Sweden

ON THE CORRELATION OF PRESSURE FLUCTUATION MEASUREMENTS

In a written contribution to discussion *Dr Tanibayashi* proposed that the Committee should extend their activities to the correlation problems occurring in connection with the determination of the higher order components of the pressure fluctuations. To illustrate the need for this he showed a diagram, which indicated large discrepancies between model and full scale tests for amplitudes of 3-5 times blade frequency.

As a comment to this proposal I think it is fair to say that, if the Committee undertake this task, they should take a close look at the full scale side of the problem and not automatically assume that all the differences occuring emanate from imperfections in the model testing technique and scaling procedures.

At SSPA we have been aware of these problems for some time and, among other things, undertaken very careful model - full scale comparisons, including the determination of the influence of vibration on the pressure signals. Thus, for instance, transfer functions have been established in full scale, based on measurements of the acceleration close to the pressure pick-ups, in connection with exciter tests.

The results of these activities indicate that, if one tries to extend ones comparisons to high orders and/or large distances from the propeller, the influence of the plate vibrations soon gives corrections of the same order as the measured amplitudes. Depending on the phase differences between the vibration and pressure amplitudes, the corrections to be applied have to be either subtracted or added to the measured values.

However important this area of research may be, I doubt that a sufficient number of complete data is available to motivate a state of the art approach to the problem. If any progress is to be made, I believe that the Committee will have to initiate special investigations or formulate rules for measurements and/or calculations to be performed. I wish the Committee good luck in such a task.

II. REPLY BY THE CAVITATION COMMITTEE

We thank *Dr. Kuiper* for his valuable contribution. The Committee considered two types of turbulence stimulators to reduce scale effects on cavitation inception: a tripping band and distributed roughness. It is true that the minimum distance between the tripping band and the C_{pmin} location is not known. The functional relationship of this minimum distance d_m may be assumed in the form of

$$\frac{U_k\, d_m}{\nu} = K + f\,[d_m\,(\frac{U}{U_o})\,\frac{d(\frac{U}{U_o})}{dx}],$$

where U_k is the velocity at the tip of the tripping band, whereas the constant K and the functional form of the pressure gradient effect f are to be determined experimentally. The Committee did not recommend the use of an isolated tripping band in the case of model propellers. If the isolated tripping band would be used, it was suggested that this type of stimulator should be applied upstream of the minimum pressure location. Instead, the use of distributed roughness was preferred. This type of stimulator must be applied from the leading edge of the propeller blade to a distance downstream of the minimum pressure location. However, the exact size of the distributed roughness capable of stimulating the boundary layer around the C_{pmin} location had not been determined yet. According to the discusser's work, 60 µm particles were found to be adequate for most propeller testing conditions. With regard to Dr. Kuiper's argument about the dynamic behaviour of bubbles, the following is stated. As shown in Table 2.2 the minimum pressure at 0.9 radius for each model propeller used is different. This means that for the more negative minimum pressure cavitation inception occurs earlier. Therefore, at Froude number conditions, i.e. lower water speeds and lower test section pressures, cavitation will be delayed. This seems to be confirmed by the results presented in Figure 2.7. That the Froude number condition leads to a smaller cavity volume has been theoretically derived by Isay /207/, who applied for the cavity calculation both the Rayleigh-Plesset equation and available nuclei data, together with a bubble coalescence factor for the local gas volume. Also a reduction of the tensile stress was taken into account. For the pressure he used pressure calculations for the propeller blade sections. He showed that the cavity volume did depend on the propeller number of revolutions. Isay's results are presented in Figure A1. Dr. Kuiper also questioned the statement made in the Section on High-Speed Propulsion regarding the lack of nuclei at very low test section pressures. We agree, of course, with him that bubble sizes increase at low test section pressures and speeds. We were however mainly referring to relatively normal test speeds (say 6 m/s) and very low test section pressures (corresponding to low σ, down to 0.25 or so). Under these conditions relatively large bubbles can develop and the smaller bubbles - which mainly act as cavitation nuclei and participate in the cavitation inception process - do often not exist in sufficient quantities. This phenomenon has also been found in the other tunnels, as referred to in the references given, and we believe it could occur in other facilities, too. This should be especially true for tunnels without provision for nuclei generation.

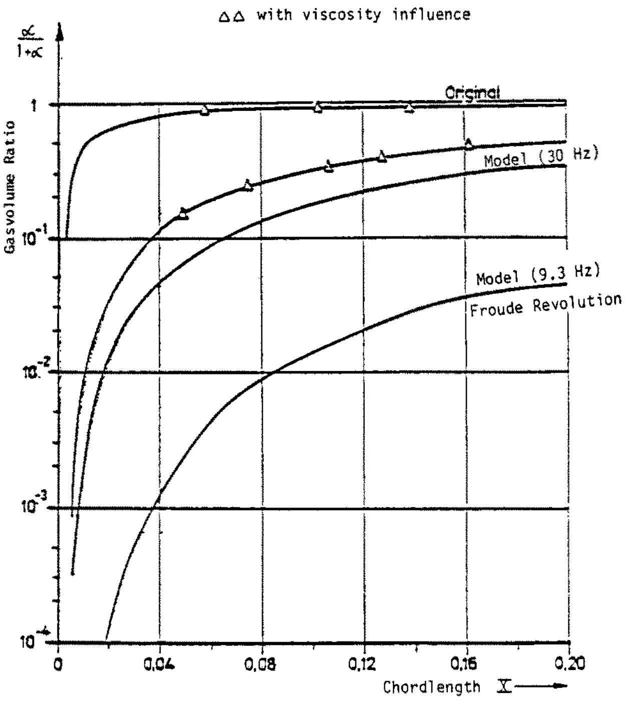


Fig. A1 - Influence of Number of Revolutions on Cavitation According to Isay /207/

The Committee appreciates the contribution by *Dr. Hoshino* and *Dr. Baba* on reporting a new method for the measurement of the cavity thickness. The different structure of the cavity surface - glassy on model scale and foamy on full scale - might influence the results found with the laser scattering (or reflection) technique. Therefore, the Committee would encourage comparisons between model and full scale cavity thicknesses in which the differences in cavity structure are taken into account.

The contribution by *Dr. Ukon* and *Dr. Kurobe* is a worthwhile addition to the complex subject of scale effects on propeller induced hull pressure fluctuations. The differences between the model and full scale measurements for the high skew propeller seem to underline the cavitation scale effects for skewed propellers mentioned in the Committee's report. Regarding the effect of standing pressure waves in cavitation tunnels, the Committee feels that this effect could be of great importance. At the HSVA the effect was investigated in detail. The local distribution was measured along the whole length of the tunnel; next, a damping device was constructed based on the results of the standing pressure wave measurements and fitted to the tunnel. Results of pressure fluctuation measurements with and without this damping device are presented in Figures 4 to 6 of Ref. /244/. Further, as shown in /220/, the maxima and minima of standing pressure waves are strongly dependent on the tunnel length. Having this in mind, the two tunnels mentioned here are not equal. The SRI tunnel is at least 2 m longer and has a square test section, whereas the HSVA tunnel has a circular test section.

The Committee would like to thank *Dr. Takekuma* and *Dr. Tanibayashi* for pointing out the importance of higher order blade frequency components of pressure fluctuations, and fully agrees with this statement. In this regard the 16th ITTC report /3/ already mentioned the following phenomena as possible causes for higher order pressure fluctuations:

- the bursting or breakdown of the tip vortex cavity /245/
- the cavitating tip vortex with nodes /152/
- the dynamic development of the cavity volume of the sheet cavity in the hull wake field /69/.

The Committee agrees with the opinion of the discussers that further investigations on these topics are needed.

The Committee appreciates the contribution by *Dr. Sasajima* and *Dr. Tanibayashi* on presenting supplementary noise data. As mentioned in the report, the comparative noise data have not been scaled. Scaling procedures, such as the one used by the discussers, are needed to obtain consistent comparisons. This is in accordance with Recommendation 3 to the 18th ITTC Cavitation Committee.

The contribution by *Mr. Colombo* and *Mr. Accardo* is a valuable addition to the work of the Committee regarding comparative noise measurements. The good quality of the test results presented, and obviously achieved by applying an almost full scale propeller tip speed in the model tests, stresses the validity of this test prescription. The noise results for the medium and large "Sydney Express" model propellers now available enable further ITTC work on comparative noise measurements, in particular on noise scaling (Recommendation 3 to the 18th ITTC Cavitation Committee).

The Committee is most grateful to *Prof. Zhu Wuhua*, *Mr. Wang Hongzhen* and *Mr. Zhu Beili* for presenting an interesting comparison between model and full scale noise measurements. In their scaling formulae they introduce a correction index n for the air content. In order to comment on their results the Committee would need more information on the working conditions for model and prototype, like type and extent of cavitation, free and dissolved air contents, number of revolutions etc. In the report, reference is made to Løvik /148, 170/ who performed an experimental study on the influence of the gas content on cavitation noise and erosion of propellers. In a theoretical study he considered the influence of the gas content both on the shape and the absolute values of the noise spectrum. One of the conclusions derived was that the influence of the gas content was different from one frequency range to another, being strongest for the higher frequencies. Accordingly, it is expected that the correction index n in equation 2-2 of the discussion should be a function of both frequency and differences in air content.

The Committee appreciates the valuable contribution on soft surface techniques in propeller erosion testing by *Mr. Kozhukharov* and *Dr. Yosifov*. The Committee agrees with their conclusion that the choice of the propeller rate of rotation is important in model erosion testing. The rate of rotation is usually chosen in such a way that a proper erosion pattern is obtained within a certain length of testing time. The Committee also agrees that the drying time of the paint has a certain influence on the results. The present results show, however, that a longer drying time makes the paint less resistant to erosion. This is contrary to our own experiences. Therefore, the Committee would appreciate obtaining more detailed information on the test procedures applied. Finally, the Committee would like to point out that paint test results might be influenced by many other factors, such as air content, material of the model, roughness of the blade surface and so on. Details were given in the 16th ITTC report /3/.

The contribution of *Mr. Kozhukharov* and *Dr. Yosifov* on the propeller/wall clearance effects in the case of cavitating propellers is of considerable interest to the Committee. According to their description the experiments seem to be carried out in exactly the same way as those of /198, 199/ and yet the answers are rather different, in fact more like those of SSPA (Ref. /86/, of which all the test details have not been published). The subject is certainly most intriguing and it will probably be necessary for the next Committee to investigate and compare in more detail the measuring techniques used in these various experiments. We have now two kinds of results from five different sources. The Committee is grateful to BSHC for making this additional material available.

The Committee owes its thanks to *Prof. Kruppa* for presenting these detailed results on dynamic cavitation buckets and their comparison with corresponding buckets for steady flow. Aside from isolated observations by Shen and Peterson /175/, the detailed analysis summarized by Prof. Kruppa is the first of its kind. Had the existence of this work been known to the Committee at the time we prepared our report, these fundamental results would have figured prominently in our discussions. The Committee concurs with Prof. Kruppa's assessment of the importance of dynamic cavitation buckets, as opposed to the use of static ones, for the appraisal of cavitation inception on marine propeller blades. We also believe that it is useful to have this specific example of the effect of different nonsteady profile motions placed before the 17th ITTC, because it gives a clear demonstration of matters discussed in the Cavitation Committee

Report (Vol. 1, pp. 224 - 228).

The Committee appreciates very much the stimulating contributions we have had from *Dr. Rutgersson* and also the contacts with him during this period as a member of the HSMV Committee. With regard to the emphasis in the report on shaft inclination, referred to in his discussion, we like to say we agree, of course, that it may for routine work be difficult to always look at all its effects. However, we attempted to primarily deal with the effects of cavitation (rather than procedures, as agreed with the HSMV Committee) and shaft inclination does, as described, affect all the propulsion parameters. It was therefore felt that only by taking account of this, a reasonable understanding of the problems can be expected, the most important effects be isolated and, hopefully, data obtained for first assessments and future predictions. The wake fraction can, as suggested by Dr. Rutgersson, of course more conveniently be determined from 0° or open water tests. It is also an important parameter for the designer. But it can often, without too much difficulty, also be corrected for oblique flow effects, if required for a different approach or special studies. We certainly hope that future committees can, in cooperation, make progress on suitable test and prediction procedures and thank Dr. Rutgersson for his comments.

In conclusion, the Cavitation Committee would like to express its gratitude to all discussers for their valuable contributions.

ADDITIONAL REFERENCES

244. Weitendorf, E.A., "Improvement of Ship Vibration Excitation caused by Unsteady Cavitation Phenomena and Hull Pressure Fluctuations", WEMT Conference, Paris, July 1984.

245. English, J.W., "Cavitation Induced Hull Surface Pressures-Measurements in a Water Tunnel", RINA Symposium on Propeller Induced Ship Vibration, London, Dec. 1979, pp. 55 - 72.

III. ADDITIONAL CONTRIBUTIONS TO THE REPORT OF THE CAVITATION COMMITTEE

E.-A. WEITENDORF - Hamburg Ship Model
Basin (HSVA), Hamburg, FRG, and
P. BUCHHAVE - DANTEC-Elektronik A/S,
Skovlunde, Denmark

The application of a Laser-scattered-light instrument at the cavitation tunnels of HSVA showed that this technique was connected to physical difficulties, e.g. the inversion of light distribution within the laser beam. This led to an inhomogenous instead of an homogenous light intensity distribution in the measuring control volume. Thus it was found that either a correction method for the Laser-scattered-light instrument or further instrument developments would be necessary.

In a cooperation between HSVA and DISA (DANTEC) Elektronik A/S Copenhagen starting in 1980 the development for

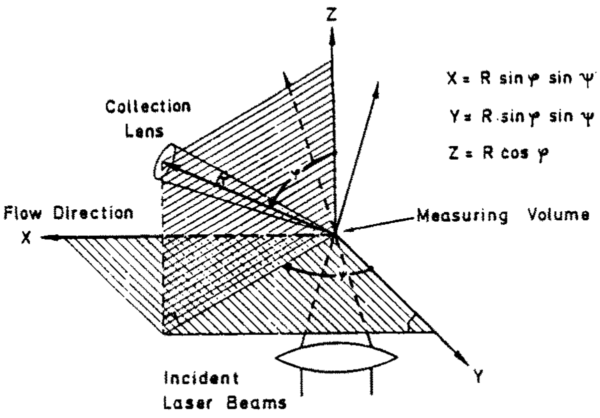


Fig. 1 SCATTERING GEOMETRY

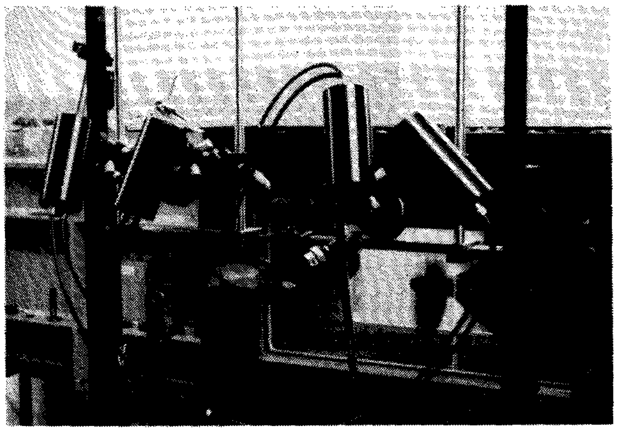


Fig. 2 Fotomultiplies Arrangement in Front of Test Section

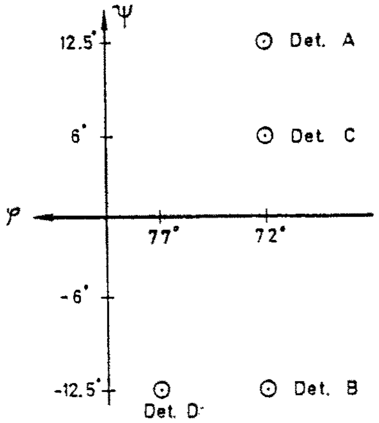


Fig. 3 DETECTOR POSITIONS

a new instrument was pursued. During the work on different physical principles a novel method was applied, based on the measurement of the phase differences between the Doppler signals (Fig. 1) from two or more receivers (Fig. 2) located at different points in space (Fig. 3). By means of this Doppler phase difference (DPD) method it is theoretically possible to measure bubbles sizes from 0 to some hundreds of micron. Measurements with this prototype were performed at the DISA (DANTEC) laboratory and the small HSVA tunnel (Fig. 3).

For the laboratory tests a special calibration device was developed producing bubbles in an electrolytical way. Further, it was shown that according to the DPD-method a discrimination between bubbles and solid particles was possible.

The measurements at HSVA were made under operating conditions of the small cavitation tunnel which is connected to a vacuum tank for degassing the water and further with a gassing system of six nozzles for nuclei seeding.

Data were taken for

- the tunnel water background, i.e. for a slow tunnel water speed with atmospheric condition in the tunnel,
- a normal cavitation test with the propeller in a hull wake field simulated by wire meshes
- and a normal propeller cavitation test as just mentioned, but with the nuclei seeding working.

Those results mentioned above can be found in Ref. [1].

The results of all measurements show that the determination of the size of individual bubbles by means of the novel DPD-method is feasible and that the test situations of the small HSVA cavitation tunnel have distincly different bubble distributions.

The momentary situation of this instrument development project is that an improved calibration method is under development. The difficult point here is that in connection with the Gaussian distribution of the Laser beams the control volume for each bubble size depends on the bubble diameter itself.

Further, experience with the instrument has to be gained and the results have to be validated. This novel instrument is very promising, since the diameter determination does not depend on an amplitude but on an frequency method. This means a cruxial step forward in this field. Further advantages are mentioned in Ref. [1].

Concluding it has to be acknowledged that the development of the whole project was accompanied by an advisory group of experts from areas of applied physics, Laser-Doppler-technique, and cavitation.

Reference

1. SAFFMAN, M., BUCHHAVE, P., and TANGER, H.: "Simultaneous Measurements of Size, Concentration and Velocity of Spherical Particles by a Laser-Doppler-Method". Second International Symposium on Applications of Laser Anemometry to Fluid Mechanics, 2-4 July 1984, Lisbon.

K. TAMURA, H. KATO and H. YAMAGUCHI - Department of Naval Architecture, University of Tokyo, Tokyo, Japan.

MEASUREMENT OF CAVITATION NUCLEI BY LIGHT SCATTERING METHOD

As mentioned in the Report of Cavitation Committee, the light scattering technique is the most promising method for the routine measurement of microbubbles in water. However, it has a disadvantage that calibration is difficult, i.e. it is difficult to obtain the relation between bubble diameter and scattered light intensity. Recently the discussers have developed a reliable calibration technique using hydrogen bubbles generated by electrolysis in a cavitation tunnel and statistical analysis.

Experiments were performed at the Marine Propeller Cavitation Tunnel, University of Tokyo. A 15mW He-Ne gas laser was used as a light scource. Statistical analysis of data obtained by using unprocessed laser light was adopted in this measurement, since it was found difficult to obtain uniform distribution of light intensity as recently pointed out by some researchers [1]. By traversing a platinum wire with a diameter of 10 μm, the size of control volume and light intensity distribution in it were measured. The results showed that the light intensity distribution in the direction perpendicular to the laser beam was Gaussian with standard deviation of 0.33 mm and in the direction parallel to the laser beam was uniform with length of 0.86 mm. Fig. 1 shows a hydrogen bubble generator used in the calibration procedure where a thin needle type cathode was used to generate tiny hydrogen bubbles. Bubbles of diameter in the range

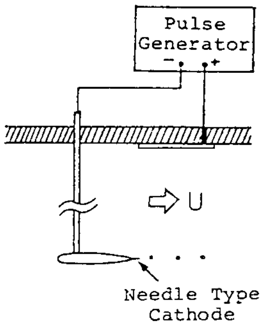


Fig.1 Bubble generator

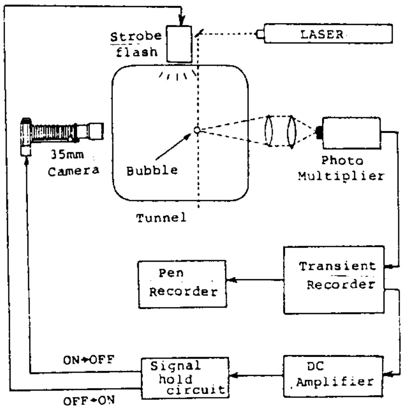


Fig.2 Diagram of calibration procedure

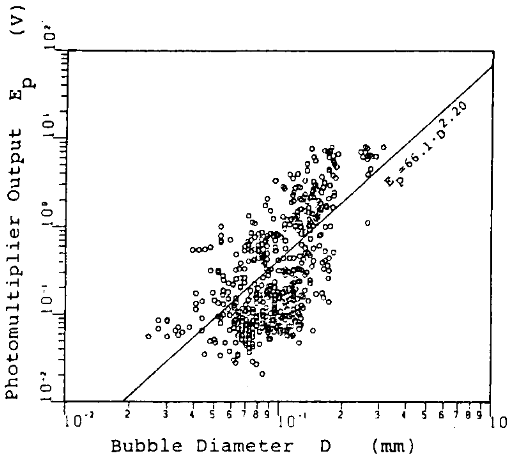


Fig.3 Relation between bubble diameter and photomultiplier output

of 20 to 300 µm can be obtained, controlling height and width of voltage pulse, flow velocity and cathode diameter. Fig. 2 shows the calibration system. When a bubble crosses the control volume, the light scattered by it is transduced by the photomultiplier into a voltage pulse proportional to the light intensity. This in turn is sent to the pen recorder through the transient recorder. This voltage pulse is also used as a trigger in order to take a photograph of the bubble. The bubble diameter is measured from this photograph. In actual measurement after the calibration, a pulse height analyzer was connected to the photomultiplier instead of the transient recorder in order to classify the voltage pulse based on peak values.

Fig. 3 shows the relation between measured bubble diameter D and peak voltage of respective pulses, E_p, being result of about 650 of the above-mentioned measurements. Scattered distribution of data in the vertical direction is due to the Gaussian light intensity distribution in the control volume. The regression fit to these data is

$$E_p = 66.1 \times D^{2.20} \qquad (1)$$

The intensity of light scattered by a small (but not too small) particle of spherical shape in a beam with uniformly distributed intensity is proportional to its diameter squared [2]. From power of D in equation (1), it can be considered that the above mentioned relation is realized closely in this experiment. Therefore, the E_p value of a bubble which passes at a distance of Y from the center of the laser beam can be expressed by

$$E_p = \alpha D^2 \exp\left(-\frac{Y^2}{2\sigma_Y^2}\right) \qquad (2)$$

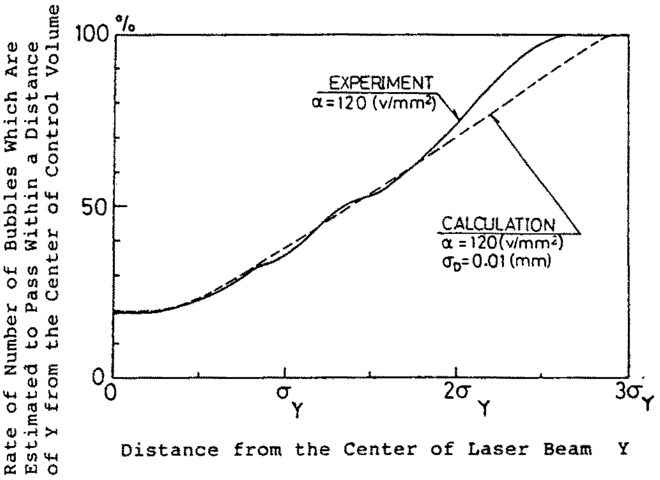


Fig.4 Comparison between theoretically and experimentally obtained cumulative probability distributions of bubble passage position

where α is an unknown constant and σ_Y is standard deviation of the light intensity distribution (=0.33 mm in this experiment as previously mentioned). The α value is decided by counting bubbles which pass within a distance of Y from the center of the control volume, assuming that the bubbles pass the control volume at random. With respect to Fig. 3, this procedure is to count the data above the line expressed by equation (2) with certain values of α and Y. The solid line in Fig. 4 denotes the result of this procedure for α = 120. The dotted line in this figure is obtained theoretically, assuming that the distribution of measurement error of bubble diameter is a Gaussian one with standard deviation σ_D of 0.01 mm which can be considered adequate. The good agreement of two lines denotes that this α value is adequate. The reason for the discrepancy between the two lines at the region of large Y value might be that more bubbles passed near the edge of the control volume because of wake of the bubble generator. In this way, the output voltage of photomultiplie has been obtained as a function of the bubble diameter and the position of its passage in the control volume. The correction of the results obtained by the pulse height analyzer in the actual measurement can be performed by solving simultaneous equations which represent the distortion of histogram of bubbles due to the nonuniformity of light intensity distribution in the control volume.

Cavitation nuclei measurements were performed both 10 mm upstream of the leading edge and downstream of the trailing edge of a cavitating foil section shown in Fig. 5. The model foil is 150 mm long and of symmetrical form whose ratio of maximum thickness to chord length is 8 %. Length of generated stable sheet cavity is about 10 % of the chord length and the test condition is shown in Table 1. The nuclei number distribution functions obtained by this experiment is shown in Fig. 6 together with those obtained by the other researchers [3]. The present result derived upstream of the leading edge agrees with the other results. It can

Table 1 Test condition

Angle of Attack	:	6.2
Cavitation Number	:	2.01
Uniform Flow Velocity	:	6.0m/s
Air Content Ratio	:	30.5%
Water Temperature	:	15.4 C

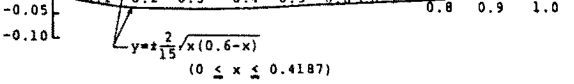


Fig.5 Foil section and cavity shape

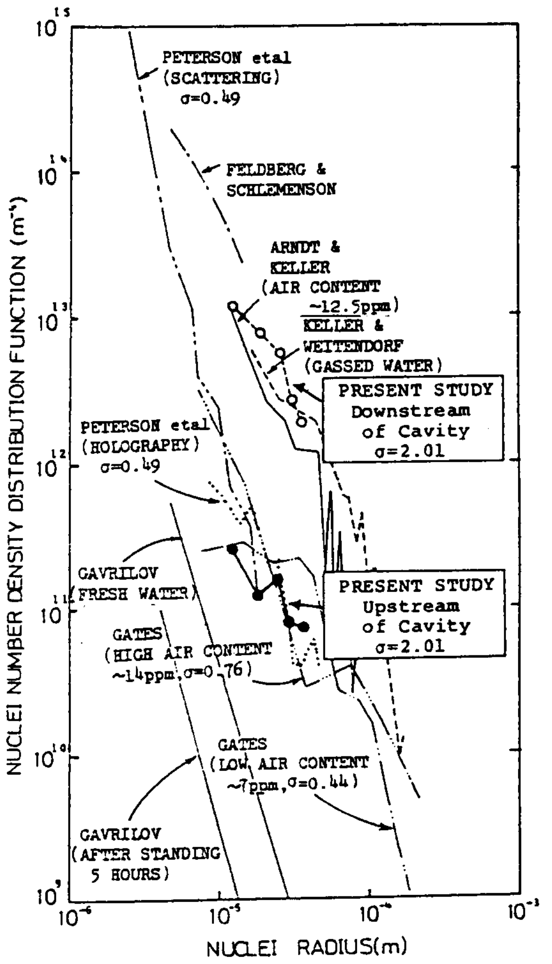


Fig.6 Comparison of nuclei number distribution functions derived from experimental results of several investigation

also be recognized that a cavity generates a large number of nuclei since the number of bubbles downstream of the trailing edge is found to be nearly hundred times larger in comparison to that upstream of the leading edge, in spite of the relatively short and stable cavity.

Last but not least the discussers wish to thank Dr. A. Keller for the many valuable suggestions.

References

[1] SHEN, Y. T. and PETERSON, F. B.: "Cavitation inception - A Review of Progress Since 19th ATTC", 20th ATTC, 1983.

[2] VAN DE HULST, H. C.: "Light scattering by small particles", John Wiley 1957.

[3] GATES, E. M., and BACON, J.: "A note on the determination of cavitation nuclei distributions by holography",J. Ship Res., Vol. 22, No 1, 1978

H. KATO and H. YAMAGUCHI -
Department of Naval Architecture,
University of Tokyo, Tokyo, Japan.

APPLICATION OF STEREOSCOPIC TECHNIQUE TO MEASUREMENT OF PROPELLER CAVITY THICKNESS

The measurement of cavity thickness is very important for the prediction of surface force induced by a cavitating propeller. Though several elegant methods have been developed and used for the measurement, [1], [2], sometimes the measurement takes a long time to obtain sufficient number of data. In this respect stereoscopic techique is very convenient because only a pair of photographs is necessary to obtain data for the subsequent stereoscopic analysis. In addition, this method also has some other advantages, namely, momentary data can be obtained, re-analysis using stored photographs can be made at any time. In spite of these advantages, however, this method have

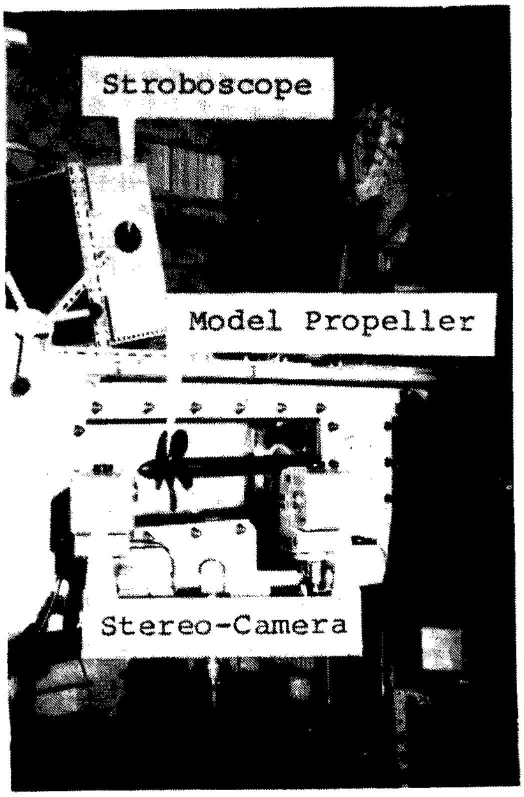


Fig 1 A setup of stereo-camera

not been applied except for a few example because of the intricacy of the analysis and the poor accuracy of the results due to refraction effects. Recently the discussers have developed a new application method of the stereoscopic technique where these shortcomings were overcome by the computer processing.

In order to obtain sufficient number of cavity surface coordinates, it is desirable to take photographs at a small angle to the propeller axis as shown in Fig. 1. However, the coordinates of cavity surface can not be obtained in practice by theoretical analysis based on refraction law since it is significantly affected by the shape of the boundary surface of three different media, namely water, observation window and air. Therefore, distortion of stereoscopic image (stereomodel) is approximated by quadratic forms in coordinate transformation as expressed by

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} a_1 \\ a_2 \\ a_3 \end{pmatrix} + \begin{pmatrix} b_1 & c_1 & d_1 \\ b_2 & c_2 & d_2 \\ b_3 & c_3 & d_3 \end{pmatrix} \begin{pmatrix} x_m \\ y_m \\ z_m \end{pmatrix}$$

$$+ \begin{pmatrix} e_1 & f_1 & g_1 \\ e_2 & f_2 & g_2 \\ e_3 & f_3 & g_3 \end{pmatrix} \begin{pmatrix} x_m^2 \\ y_m^2 \\ z_m^2 \end{pmatrix} + \begin{pmatrix} h_1 & i_1 & j_1 \\ h_2 & i_2 & j_2 \\ h_3 & i_3 & j_3 \end{pmatrix} \begin{pmatrix} x_m y_m \\ y_m z_m \\ z_m y_m \end{pmatrix}$$

where (x, y, z) denotes Cartesian coordinates in real scale and (x_m, y_m, z_m) in stereomodel with the refraction effects included. Unknown matrixes in this equation are obtained using the known coordinates of several points (at least 10 points) inside the test section of cavitation tunnel.

Photographs of a cavitating propeller in a wire-mesh generated wake were taken at the Marine Propeller Cavitation Tunnel, University of Tokyo. The tested model propeller with a diameter of 220,95 mm is a conventional MAU type design and its prototype was fitted to the training ship "SEIUN-MARU" till 1982 [2]. An example of a pair of photographs are shown in Fig. 2. Measurement errors in propeller axis direction, which mainly affect the accuracy of measured cavity thickness, were less than 0.15 mm (0.07 % of the propeller diameter). Although the errors in the other directions exceeded 1.0 mm at some points, it was mainly due to the lack

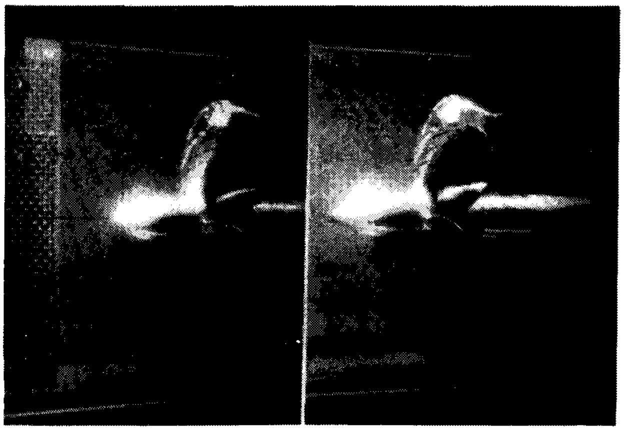
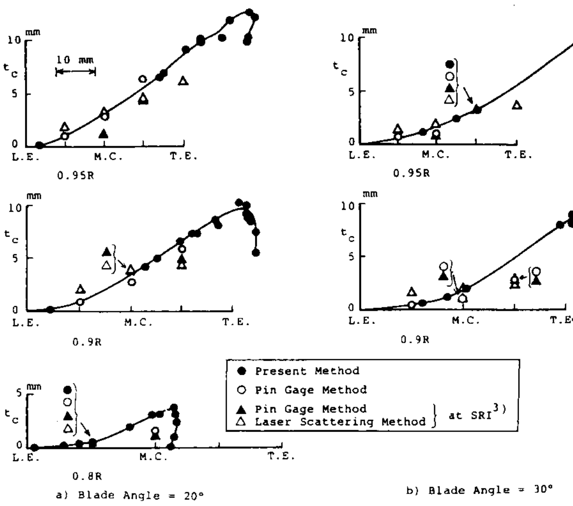


Fig 2 An example of stereo-photographs of cavitating propeller; $K_T=0.219$, $\sigma_n=2.71$ (171 rpm), blade angle = 30°

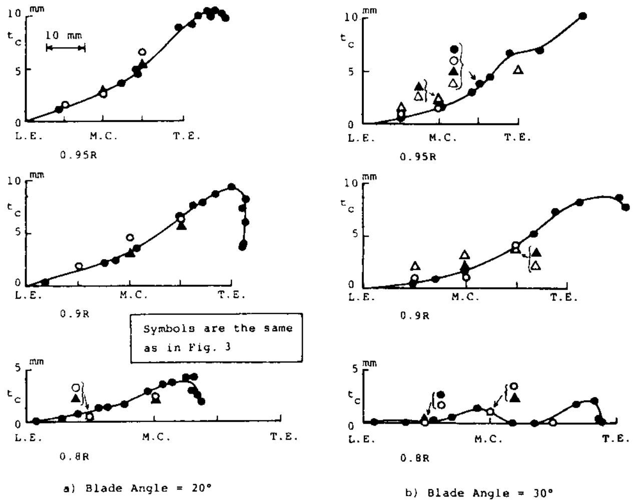
of experience and an accuracy of ± 0.4 mm has been achieved in later efforts. Figs, 3 and 4 show the distribution of cavity thickness, t_c, at each radius position obtained by the present method (symbol ●) together with those of the pin gage method (symbol ○) and the pin gage and laser scattering method performed at Ship Research Institute (symbols ▲ & △) [3]. The results in b) of Fig. 4 were obtained from Fig. 2. The cavity thickness distributions obtained by the present method agrees well with those of the other methods. Total measurement time, which includes taking photographs and the analysis of eleven pairs of them, is about one day. From these results, it can be concluded that this measurement method is relatively convenient and has good accuracy in comparison with that of the other methods.



a) Blade Angle = 20°

b) Blade Angle = 30°

Fig 3 Cavity thickness distribution; $K_T=0.207$, $\sigma_n=3.06$ (163 rpm)



a) Blade Angle = 20°

b) Blade Angle = 30°

Fig 4 Cavity thickness distribution; $K_T=0.219$, $\sigma_n=2.71$ (171 rpm)

References

[1] CHIBA, N., SASAJIMA, T., and HOSHINO, T.: "Prediction of propellerinduced fluctuating pressures and correlation with full-scale data", 13th Symp. Naval Hydrodynamics, Tokyo, 1980.

[2] KODAMA, Y., TAKEI, Y., and KAKUGAWA, A.: "Measurement of cavity thickness on a full scale ship using lasers and TV camera",Papers of Ship Research Institute, No. 73, 1983.

[3] KUROBE, Y., UKON, Y., KOYAMA, K., and MAKINO, M.: "Measurement of cavity volume and pressure fluctuations on a model of the training ship 'SEIUN-MARU' with reference to full scale measurement", Rep. Ship Research Institute, Vol. 20, No. 6, 1983 (in Japanese).