Comparative Joint Investigations in the Cavitation Tunnels of SVA and BSHC on the Prediction of Propeller-Induced Pressure Pulses

Dipl.-Ing. Dietrich Schmidt und Dipl.-Ing. Wolfgang Selke, Schiffbau-Versuchsanstalt Potsdam GmbH
Dipl.-Ing. G. Gerchev, Bulgarian Ship Hydrodynamics Centre Varna, Bulgaria

Abstract

The paper presents results of propeller-induced pressure pulse measurements and routine investigations of the hydrodynamic and cavitation characteristics of SYDNEY EXPRESS propeller models performed in SVA and BSHC cavitation tunnels of the type K-15. The model tests have been carried out in the small as well as in the large sections of the cavitation tunnels.
A brief description is given about the measurement procedures of the propeller-induced pressure pulses applied at both laboratories. Comparisons have been made between the results of the cavitation characteristics and propeller-induced pressure pulse data obtained at different experimental conditions, such as type of wake simulation, rate of propeller revolutions, air content ratio. The comparisons include full scale results published in the specialized literature, as well as numerical results obtained by the methods applied at SVA and BSHC. Conclusions have been drawn about the model experiment prediction possibilities of propeller-induced pressure pulses and the open problems that have to be solved for the improvement of the correlation, have been specified.

Introduction

In spite of the fact that on the problem of the prediction of propeller-induced hull pressure pulses work has been done for more than 30 years, this prediction still seems to be inadequate at present. The comparative measurements made with the "SYDNEY EXPRESS" propeller by the 17th and 18th ITTC Cavitation and Propulsor Committees show a poor correlation between model and full-scale measured (calculated) propeller-induced pressure pulses [4], [5]. In the committees reports since the 15th ITTC up to now considerations are taken and analysis are made on the problem of determination of the propeller-induced pressures.
During the last 5 years joint comparative investigations have been carried out in the cavitation tunnels of Schiffbau-Versuchsanstalt (SVA) Potsdam and Bulgarian Ship Hydrodynamics Centre (BSHC) Varna to clarify the reasons for the above mentioned poor correlation. The program of the investigations included comparison of the results obtained by the application of the following standard hydrodynamics experimental procedures for:

- wake simulation with wire-mesh screen;
- propeller open water tests;
- propeller cavitation tests;

and procedures for determination of propeller-induced pressure pulses:

- measurement procedure with a flat plate;
- measurement procedure with a ship model or a dummy model;
- calculation procedure for numerical prediction.

This paper presents a part of the results obtained by the joint investigations. Special attention has been paid to the parameters, influencing the propeller-induced pressure pulse measurements, such as wake distribution, propeller model rate of revolutions, air content ratio, etc.

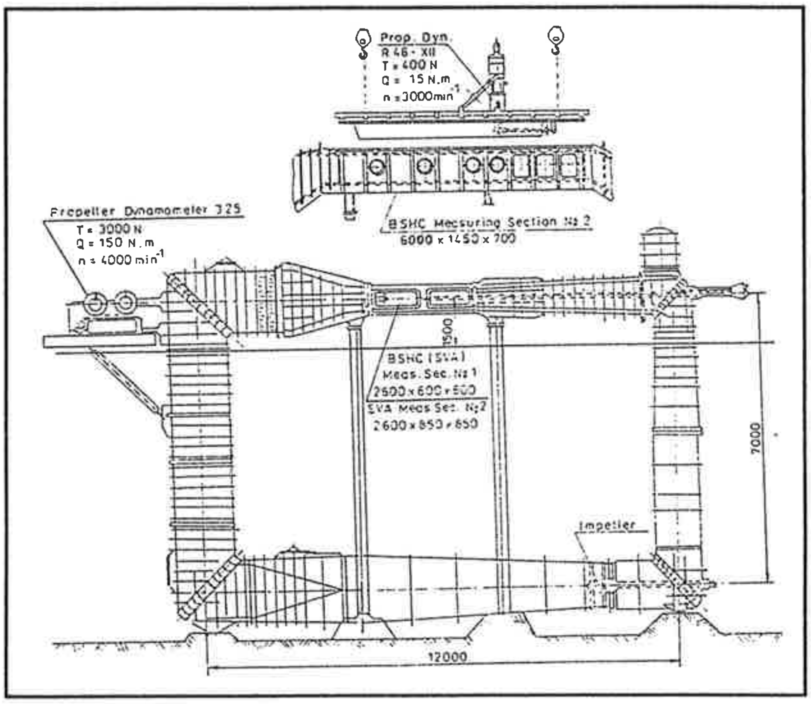


Fig. 1. General Lay-Out of SVA and BSHC Cavitation Tunnels

1. Experimental Facilities

The cavitation laboratories of SVA and BSHC are equipped with cavitation tunnels of type K 15 A and K 15 B, Kempf & Remmers, respectively the characteristics of which are very similar. Both tunnels are of closed recirculation type with a closed working section (Fig. 1).
The model tests were carried out in both measuring sections (No. 1 and No. 2) of SVA and BSHC cavitation tunnels.
The SVA and BSHC cavitation tunnel measuring section No. 1 has following basic dimensions:

- cross section: 0,60 m x 0,60 m
- length: 2.60

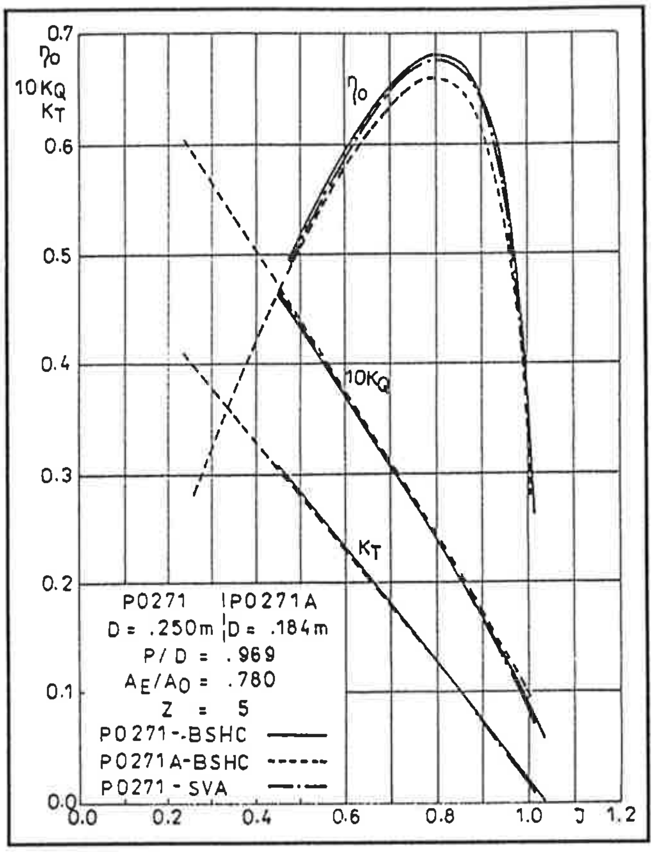


Fig. 2. Open Water Characteristics of "Sydney Express" Propeller

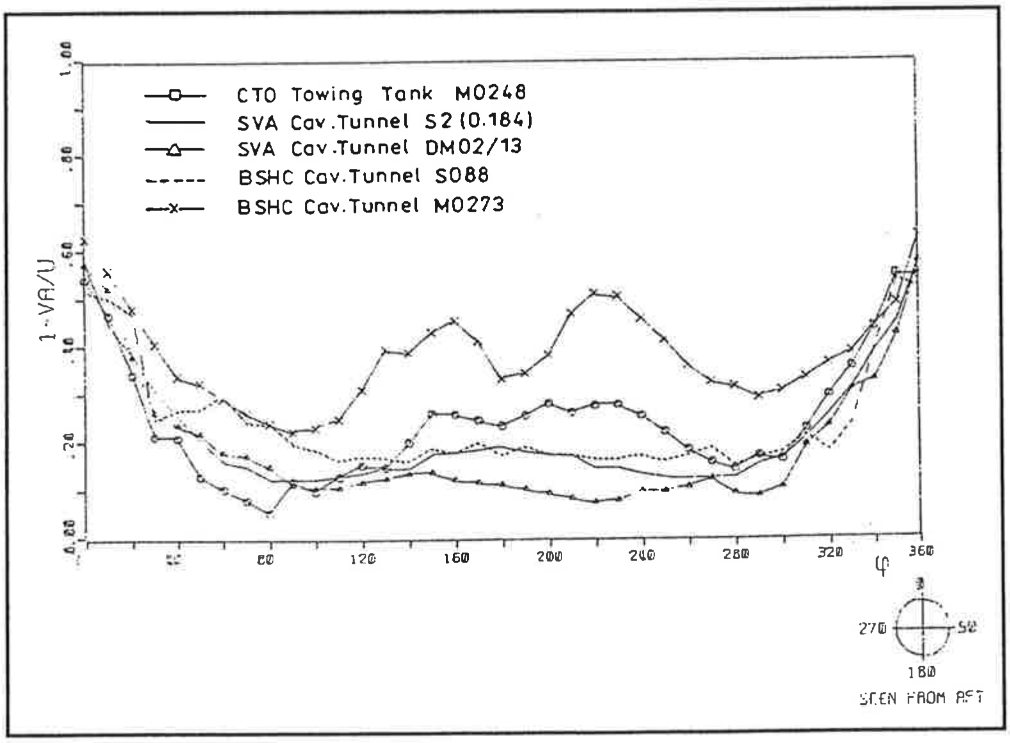


Fig. 3. Distribution of Representative Simulated Wakes at Radius r/R = 0,8

Propeller dynamometers of type J25, Kempf & Remmers, were used.
The SVA cavitation tunnel measuring section No. 2 has following basic dimensions:

- cross section: 0,85 m x 0,85 m
- length: 2,60 m

The size of this section allows the mounting of a dummy body with a length of about 2 m and a breadth of about

0,6 m. The height of the dummy model is determined from the shaft position of the propeller dynamometer of H36, Kempf & Remmers type.
The BSHC Cavitation tunnel measuring section No. 2 has the following basic characteristics:

- cross section: 1,45 m x 0,70 m
- length: 6,00 m

The dimensions of this measuring section allow the mounting of a whole or a slightly shortened ship model with a length up to 5,00 m, a breadth of 0,70 - 0,80 m and a height (draught) up to 0,35 m. The propeller model is driven by the dynamometric device R46-XII, Kempf & Remmers.

2. Model Main Data

The comparative model tests in the measuring sections No. 1 of the SVA and BSHC cavitation tunnels were performed with the two model scales $\lambda = 28$ and 38. The propeller models P 0271 and P 0271 A of BSHC and P 1231 of SVA were used. The propeller model main data are shown in table 1. The measurements of propeller-induced pressure pulses in measuring sections No. 1 of both cavitation tunnels were performed on a flat plate.

	P 0271	P0271 A	P1231
Facility	BSHC		SVA
Scale	28	38	
D [m]	0,250	0,1842	
$P/D_{0,69\,R}$		0,969	
A_E/A_O	0,780		
Z	5		
r_H/R	0,172		

Table 1. Propeller Model Main Data

The investigations in the measuring sections No. 2 of SVA and BSHC cavitation tunnels were carried out at scale 38, at SVA with the dummy model DM 02 and at BSHC with the ship model M 0273. The principal particulars of the models are shown in table 2.

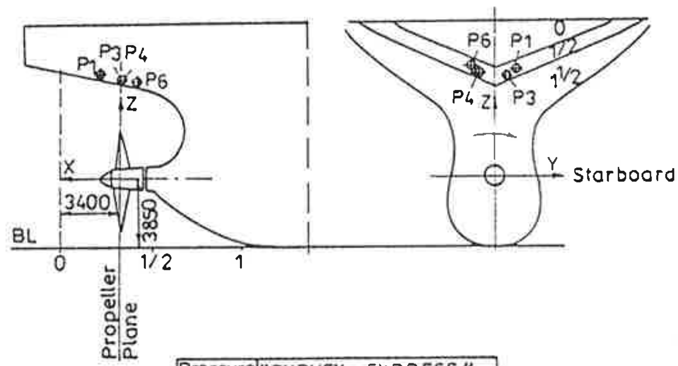
	M 0273	DM 02 (dummy)
Facility	BSHC	SVA
Scale	38	
L_{PP} [m]	4.976	1.934
B [m]	0.803	0.550
T_A	0.256	0.4065
T_F	0.253	0.4065

Table 2. Ship Model Principal Particulars

The design of the SVA dummy model is based on the concept of "equivalent relative thickness of the boundary layer" and also on the geometric dimensions of the measuring section No. 2 of the tunnel. The dummy model afterbody is scaled up to the second station of the lines drawing.
The BSHC model M 0273 is 0,550 m shorter in its cylindrical part to match the dimensions for measuring section No. 2 of the cavitation tunnel.

3. Standard Hydrodynamics Model

The open water characteristics of the two propeller models P 0271 and P 0271A obtained in the BSHC and SVA cavitation tunnels are shown in fig. 2.
The wake distributions in the measuring sections No. 1 of SVA and BSHC cavitation tunnels were simulated by wire-mesh screens. The wake distribution was measured by the LDA technique at SVA and by a wake rake at BSHC.
The wake measured in the CTO (Gdansk) towing tank at the scale 28 [6] was accepted as the initial nominal wake distribution of the "SYDNEY EXPRESS".
Three wire-mesh simulators were manufactured for the measuring section No. 1 of the SVA cavitation tunnel. The simulators S1 (0,184), S2 (0,184) and S1 (0,250) had been designed for the experiments with the propellers with the diameter D = 0,1842 m and 0,250 m. With variant 2 of the smaller simulator S2 (0,184) the distribution of the velocity field beyond the propeller diameter up to radius r/R = 1,3 was simulated (see table 3).
To investigate the effect of the ship wake simulation on propeller-induced pressure pulses, seven wire-mesh simulators for the measuring section No.1 of the BSHC cavitation tunnel were manufactured - four for the propeller model with the diameter D = 0,250 m and three for D = 0,1842 m. Besides the CTO wake as initial wake distribution, the wake distribution measured in the BSHC deep water towing tank at scale 38, the full scale wake, estimated by Tanaka's method (based on the BSHC towing tank measurement data) and the wake distribution, measured by the Hamburgische Schiffbau-Versuchsanstalt (HSVA) in the towing tank at scale 26.67 were used. The numbers of these simulators are given in table 3. The initial wake and



Pressure pick-ups	"SYDNEY EXPRESS" X,mm	Y,mm	Z,mm
P1	1150	1255	5880
P3	0	815	5600
P4	0	-815	5600
P6	-525	-1255	5600

Fig. 4. Arrangement of Pressure Pick-Ups at Full-Scale

the wire-mesh wake distributions, as well as details of the investigation itself about the influence of the wake simulation on propeller cavitation and propeller-induced pressure pulses are presented in [1].

No.	Institution	Wire-Mesh Simulator	Initial Wake	Propeller Diameter [m]
1	SVA	S1 (184)	CTO tank	0.1842
2	SVA	S2 (184)	CTO tank	0.1842
3	SVA	S1 (250)	CTO tank	0.250
1	BSHC	S074	CTO tank	0.250
2	BSHC	S091	BSHC tank	0.250
3	BSHC	S090	Estimated for ship	0.250
4	BSHC	S096	HSVA tank	0.250
5	BSHC	S088	CTO tank	0.1842
6	BSHC	S085	BSHC tank	0.1842
7	BSHC	S084	Estimated for ship	0.1842

Table 3. Wire-mesh Simulators for Measuring Section 1 of the Cavitation Tunnels

The wake simulation in the measuring section No. 1 of SVA and BSHC cavitation tunnels has shown that the modelling of the wake flow for inside radii r/R = 0,3 and 0,4 is difficult due to the propeller drive shaft, which diameter is relatively large with regard of the propeller diameter. However, this is not so essential for the propeller hydrodynamic characterisitics and the pressure pulses, because the stationary and instationary propeller loading is determined by the occurences in the reach r/R = 0,65...0,85 and the cavitation behaviour is determined first of all by the occurences in the reach r/R = 0,75...1,00. For this reach an adequate modelling of the wake flow is given.

In measuring section No. 2 of the SVA cavitation tunnel a dummy model was used for the wake simulation. The wake was measured by a 3-hole tube rake. Since the peak and the gradients of the wake could not be properly simulated, additional wire-meshes were mounted at the stern at station 1.5. Many mesh variants were tested, so that hardly with the 13th variant a very good simulation of the axial flow component was achieved and a dummy model DM 02/13 was finally used.

In the measuring section No. 2 of the BSHC cavitation tunnel the complete ship model M 0273 was used for the wake simulation. The wake was measured by a 5-hole wake tube. The distribution of the nominal velocity field in the propeller disk showed adequate coincidence with the experimental data obtained from the same model in the BSHC deepwater towing tank.

Fig. 3 shows some examples of the angular distributions of simulated axial wake at the radius r/R = 0,8. The tangential component of the wake was only registered in the measuring sections No. 2 of the SVA and BSHC cavitation tunnel without any effort to model it.

4. Test Procedure for Propeller-Induced Pressure Measurements

The propeller-induced pressure pulses were measured in 4 points P1, P3, P4 and P6 corresponding to full-scale trials 7 (fig. 4). The pressure pick-ups were flush mounted in the flat plate or the ship model. The size of SVA flat plate was 660 x 330 x 5 mm and that of BSHC plate was 850 x 350 x 11 mm. The vertical clearance between the propeller model and the plate was fixed at 0,3 D, so the pressure pick-up P1 was positioned slightly lower in comparison to the full-scale position. The arrangement of the pressure pick-ups on the plate is shown in fig. 5.

In the BSHC cavitation tunnel strain gage pressure pick-ups were used with a capacity of 0,2 MPa, a natural frequency above 20 kHz and a diaphragm Ø = 6 mm. The SVA pick-ups of piezoelectric type have a capacity of 0,6 MPa, a natural frequency of 45 kHz and a diaphragm O = 6 mm.

The data acquisition, processing and analysis were based on the ensemble averaging technique and were computer-operated. The pressure signal discretization was triggered by external pulse series (100 pulses per revolution in BSHC cavitation tunnel and 50 pulses in SVA tunnel). The averaging pressure signal per 1 revolution was the result of ensemble averaging of 144 propeller revolutions for BSHC respectively 20 propeller revolutions for SVA. The averaging signal was subjected to Fourier analysis and pressure harmonic content was obtained in the following

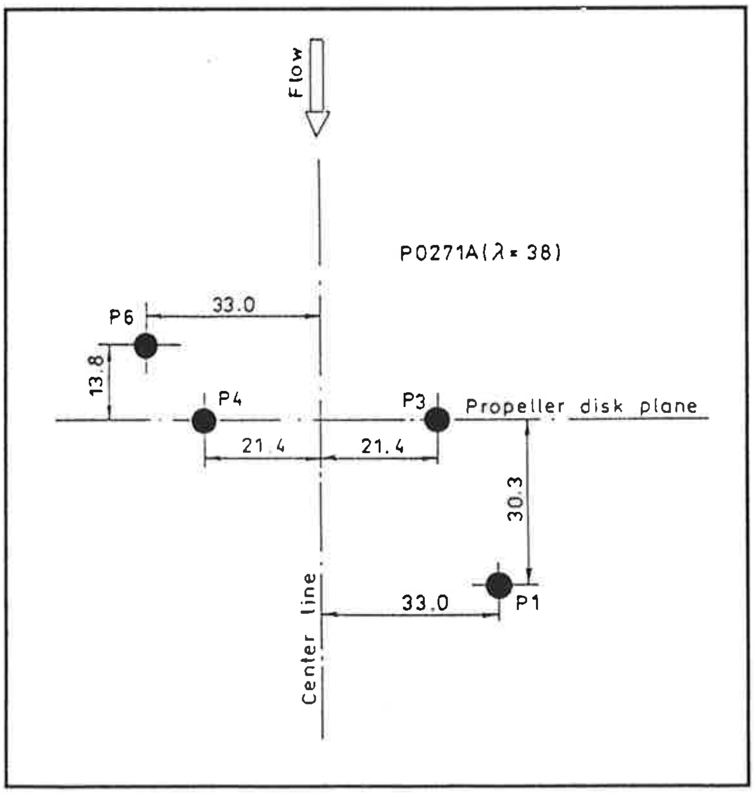


Fig. 5. Arrangement of Pressure Pick-Ups on the Flat Place

No.	Conditions					
	Full - Scale Measurements					
1	HSVA					
2	VWS					
	Calculation by computer programs					
3	NV 570 W					
4	HOTAJA					
5	EARLY					
5a	EARLY 1					
	Model Tests in Cavitation Tunnels					
	Measu- rement on	Wake Simulation	D [m]	P . No.	α/α_s	n [s^{-1}]
	SVA					
6	Plate	S1 (0.184)	0.1842	1231	0.40	20, 22, 25, 30
7		S2 (0.184)			0.42	
8		S2 (0.184)			0.70	
9		S1 (0.250)	0.250	0271	0.40	15, 18, 22, 25
10	Dummy model	DM 02/13	0.1842	1231	0.20	20..30
11					0.35/ 0.43	
12					0.68	
13				0271A	0.35/ 0.40	
14		DM 02/0			0.41	
	BSHC					
15	Plate	S074	0.250	0271	0.33.. 0.39	15, 18, 22, 25
16		S091				22
17		S090				22
18		S096				15, 18, 22, 25
19		S088	01842	0271A		18, 22, 25, 30
20		S085				25
21		S084				25
22	Model	M0273				19, 21, 22, 23

Table 4. Comparative Conditions of Propeller-Induced Pressure Pulses Estimation

form:

$$p = \sum_{q=0}^{\infty} p_q \sin (q\phi + \Phi q).$$

Block-diagrams of SVA and BSHC systems for propeller induced pressure measurements are shown in the figures 6 and 7.

The pressure pulses were measured at various numbers of propeller revolutions in both facilities and also at various total gas content in the SVA cavitation tunnel. During the experiments the total gas content was monitoring by an oxygen content meter in the SVA and by a Van Slyke equipment in the BSHC.

5. Experimental Conditions

The experimental conditions were determined in corresponding to the full-scale trial No. 16 [7], i.e. thrust coefficient K_T = 0,173 and cavitation number $\sigma_{n\,0,8\,R}$ = 0,185, where

$$\sigma_{n\,0,8R} = \frac{p_o - p_v}{0.5\,\rho(\pi \times n \times D)^2}$$

$p_o = p_a + \rho \times g(h_s - 0{,}8R) + \rho gh$ is the hydrostatic pressure at the propeller radius r = 0,8R, when the propeller blade is in the vertical position.

In the measuring section No. 1 of the SVA cavitation tunnel the model tests with a flat plate were performed with the propellers P 1231 and P 0271.

Experiments with P 1231 were carried out in nonuniform flow simulated by the wire-mesh simulator S1 (0,184) at medium air content ratio α/α_s = 0,40 and in nonuniform flow of the simulator S2 (0,184) at medium and high air content ratio, namely α/α_s = 0,42 and 0,70. The experiments were performed at different rate of propeller model revolutions n = 20; 22; 25; 30 s^{-1}. The measurements with P 0271 were performed in the wake simulated by the wire-mesh simulator S1 (0,250) at α/α_s = 0,40 with the revolutions n = 15; 18; 22; 25 s^{-1}.

In the measuring section No. 2 of the SVA cavitation tunnel three cycles of measurements of the propeller-induced pressure pulses on the dummy model DM 02/13 were performed with the propeller model P 1231 at low, medium and high air content ratio, namely: α/α_s = 0,20; 0,35...0,43 and 0,68. The rate of revolutions were in the range n = 20...30 s^{-1}. The measurements with the BSHC smaller propeller model P 0271A were also performed at α/α_s = 0,35...0,40, and finally measurements with P 1231 model operating behind a "naked" (without additional wire-meshes) dummy model DM 02/0 at α/α_s = 0,41 were conducted at the same rates of revolution.

The experiments with the bigger propeller model P 0271 in measuring section No. 1 of the BSHC cavitation tunnel were carried out in nonuniform flow simulated by the four wire-mesh simulators S 074; S 091; S 090; S 096 at medium air content ratio α/α_s = 0,33...0,39. The measurements with S 074 and S 096 were performed at different rate of propeller revolutions - n = 15; 18; 22; 25 s^{-1} and with the rest two simulators at n = 22 s^{-1}. The experiments with the smaller propeller model P 0271A were performed in wakes simulated by the wire-mesh simulators S 088; S 085; S 084; at the above air content ratio. For S 088 the rate of propeller revolutions was varied - n = 18; 22; 25; 30 s^{-1} and for the other two simulators it

was constant - n = 25 s^{-1}.
The model tests in the measuring section No. 2 of the BSHC cavitation tunnel with the ship model M 0273 with P 0271A were carried out at high air content ratio and various propeller rotations - n = 19; 21; 22; 23 s^{-1}.
The conditions of wake simulation, rate of propeller revolutions and air content ratio are systematized in table 4.

6. Experimental Results

The comparisons of the cavitation extent on the propeller

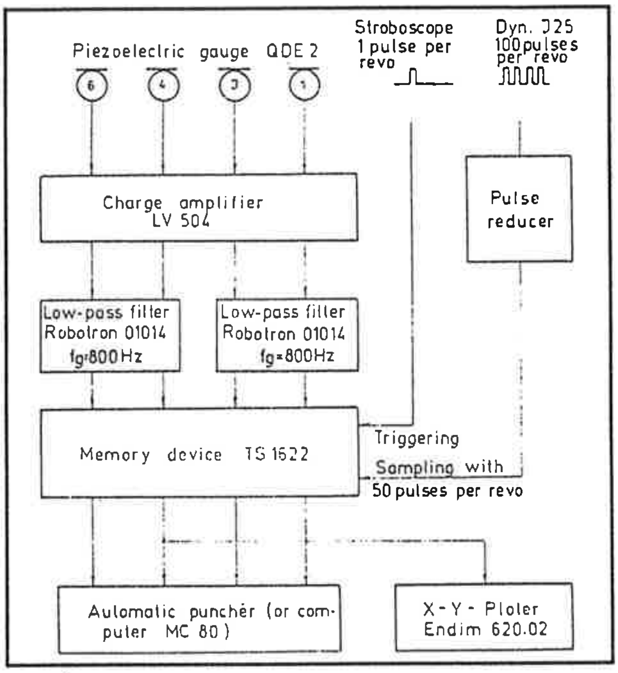


Fig. 6. Block-Diagram of SVA System for Propeller Induced Pressure Measurements

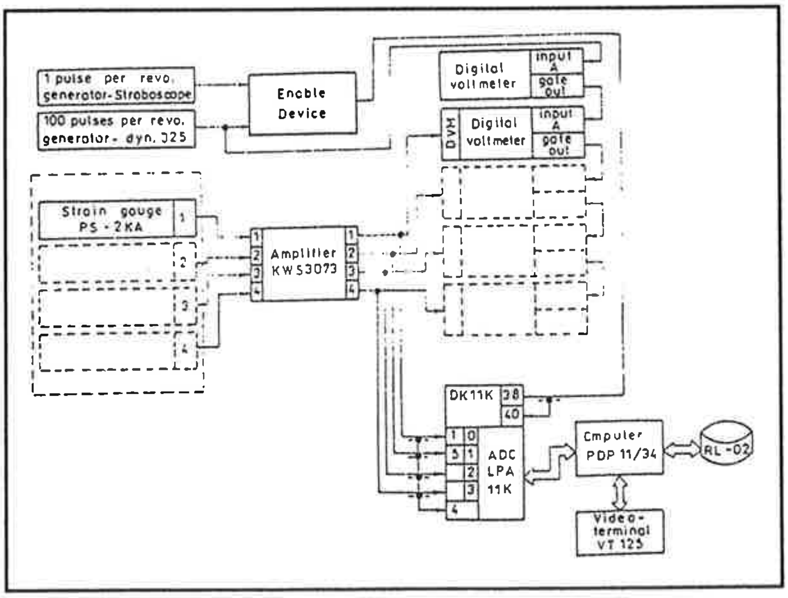


Fig. 7. Block-Diagram of BSHC System for Propeller Induced Pressure Measurements

blades obtained at the variety of experimental conditions in SVA and BSHC cavitation tunnels are shown on the figures 8 and 9. The model test numbers of the cavitation patterns shown on these figures correspond to the notations of table 4. It can be seen from the figures 8 and 9 that the cavitation patterns at different wake simulations, air content ratios and propeller revolutions, on the one hand they differ in-between, and on the other hand they differ also from the cavitation patterns at full-scale conditions presented by HSVA [7]. The cavitation patterns with the SVA dummy model DM 02/13 (model test No. 13), the BSHC ship model M 0273 (model test No. 22) and the BSHC wire mesh simulator S 074/P 0271 (model test No. 15) show the best correspondence to the full-scale cavitation patterns. It is typical for all model tests that the cavitation inception occurs later and the sheet cavitation is not so developed as at full-scale conditions.
The results of propeller-induced pressure measurements at the blade frequency obtained in the SVA and BSHC cavitation tunnels are given in the figures 10 and 11. The individual beams are designated with the rate of revolution. This figures show also the full-scale measurements according to data of HSVA [7] and VWS [8]. (The latter results must be interpolated for corresponding cavitation number.) All these results show a significant scatter, obviously owing to the influence of the different factors that have been investigated. The conclusions of the analysis made concerning the effect of these factors are given further on in the item "Conclusions".

7. Numerical Calculations

The computer programs used at the SVA and the BSHC were applied for numerical prediction of the propeller-induced pressure pulses. The calculations were made for full-scale trial No. 16. The wake distribution of CTO tank[6] was taken as reference one. The results of the calculations have been compared with the full-scale results in fig. 12.

The BSHC computer program EARLY is based on *Holden's* method [2]. It is based on the regression analysis of the numerical prediction results of the propeller-induced pressure pulses and their full-scale measurements on 72 vessels. BSHC program EARLY1 contains an improvement by *Reastad* and *Skaar* [9]. The SVA calculations were performed with the computer program NV 570W created by Det norske Veritas on the basis of the modified lifting surface technique [3]. Calculations were performed also using SVA computer program HOTAJA. It is a modified Holden's method in which the wake gradient is taken into consideration and the phase angle difference between the pressure from cavitation and the pressure from noncavitating propeller has a smaller influence.

Conclusions

In the present joint work comparative investigations on cavitation and induced pressure pulses of "SYDNEY EXPRESS" propeller were performed in the measuring sections No. 1 and 2 of the SVA and the BSHC cavitation tunnels. Propeller- induced pressures were measured on a flat plate, a complete ship

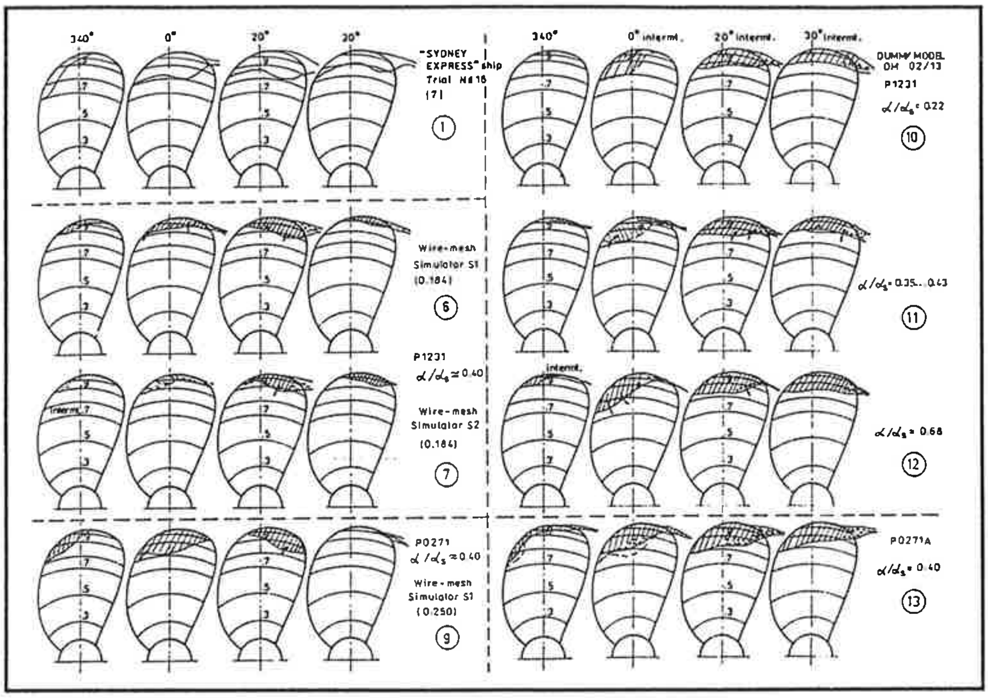


Fig. 8. Cavitation Pattern in the Measuring Sections No. 1 and No. 2 of SVA Cavitation Tunnel and at Full-Scale Trial According 7 ($K_T = 0.173$; $\sigma_n = 0.185$)

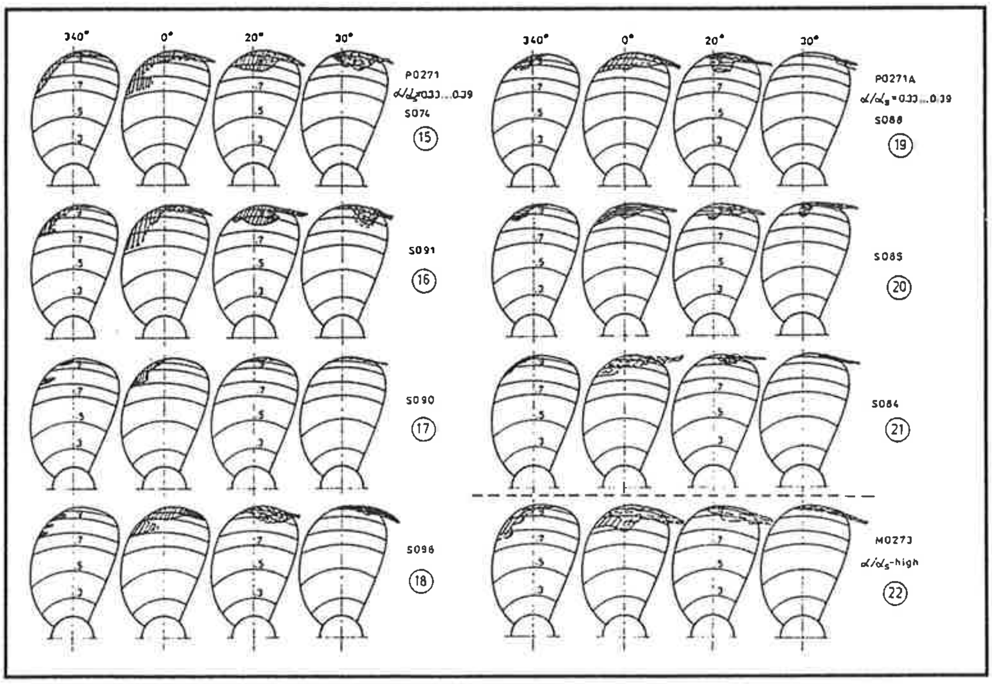


Fig. 9. Cavitation Pattern in the Measuring Sections No. 1 and No. 2 of BSHC Cavitation Tunnel ($K_T = 0.173$; $\sigma_n = 0.185$)

model and a dummy model. The effects of wake simulation, rate of propeller model revolutions and air content ratio were investigated. In spite of the certain differences of the experimental conditions in the SVA and BSHC tunnels, the measurement results of the propeller-induced pressure pulses (total 16 model tests) are comparable, and therefore common conclusions could be drawn:

1. The comparison of propeller blade cavitation patterns shows some differences between the cavitation extent observed in the SVA and BSHC cavitation tunnels (fig. 8 and 9). The reason could be in the differences of the simulated wake distributions (Fig. 3) and the different gas and nuclei content.

2. The wake simulation with the wire-mesh screens (SVA and BSHC), a dummy model (SVA) and a complete ship model (BSHC) shows that concerning the correlation of the measured propeller-induced pressure pulses to full-scale values, the 3-dimensional simulation with a complete ship model or with a dummy model gives the best results.

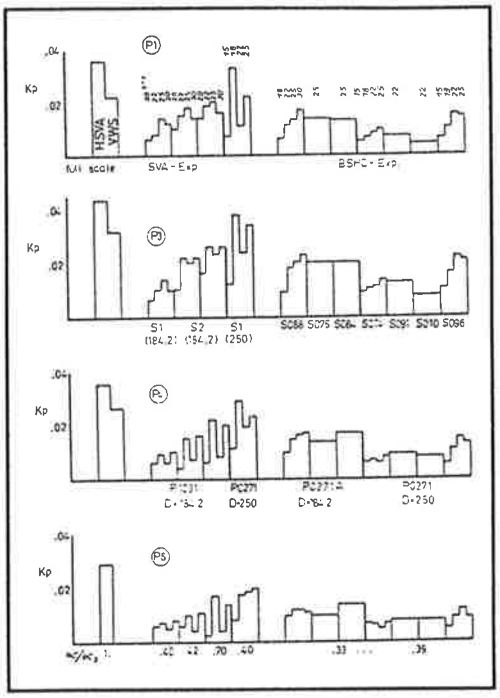


Fig. 10. Pressure Pulses for SYDNEY EXPRESS
Measurements in Wire-mesh Simulated Model

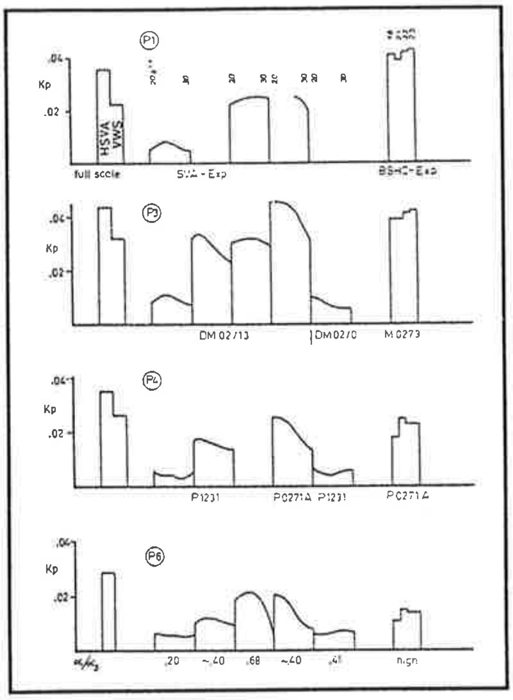


Fig. 11. Pressure Pulses for SYDNEY EXPRESS
Measurements with Model or Dummy Model

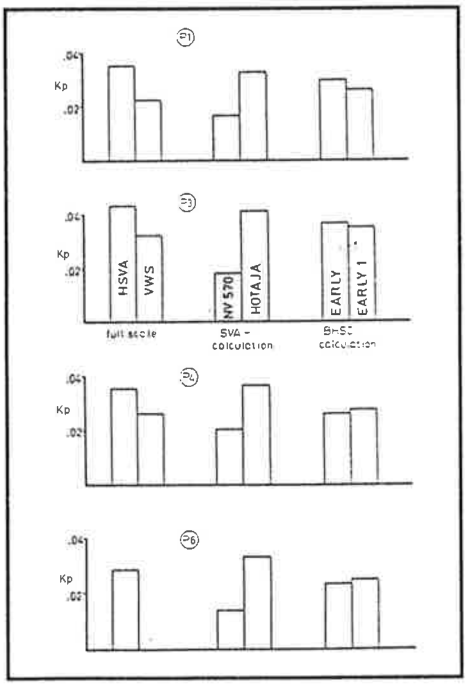


Fig. 12. Pressure Pulses for SYDNEY EXPRESS
Measurements at Full-Scale and Calculations

3. The BSHC investigations of the wake simulation effect, conducted with seven wire-mesh simulators, show that the results of the pressure pulses on a plate do not differ greatly from one another and the measured values are 25 ... 50% of those on the ship at full-scale conditions. The SVA investigations of the wake simulation effect show that the wire-mesh screen simulating over r/R = 1.0 up to r/R = 1.3 is a reason for significant changes of the higher blade harmonics of the pressure pulses.

4. The air content in the cavitation tunnel is an important factor influencing the propeller cavitation extent and the propeller-induced pressure pulses. The SVA cavitation observations show that at high air content ratio the cavitation is stable whereas at low air content ratio the cavitation behaviour is sporadic and intermittent. The pressure pulse measurements on the dummy model show that at α/α_s = 0.68 the results are close to the full-scale ones and at α/α_s = 0.20 the model results are only 25% of the full-scale data.

5. The investigations on the influence of the rate of propeller model revolutions show that this influence is negligible for the cavitation extent, but the influence on pressure pulses is great. It seems to be a consequence of vibrations of the flat plat or of the model or dummy model.

6. The comparison of the numerical results obtained by four numerical methods for prediction of the propeller-induced pressure pulses shows that the relatively simple methods could give results, which are adequate to the full-scale trial ones.

The joint investigations just performed suggest that further steps for the improvement of the reliability of the propeller-induced pressure model test results are necessary. This should be done by further studies of the factors, such as nuclei content control by artificial nuclei seeding, vibration of the measuring devices, tunnel wall effects.

Nomenclature

A_E/A_O	-	Propeller expanded blade area ratio
B	-	Ship breadth, m
D	-	Propeller diameter, m
g	-	Acceleration due to gravity, m s^{-2}
h	-	Stern wave heigth, m
hs	-	Immersion of the propeller axis, m
J	-	Propeller advance coefficient, = v/nD
K_P	-	Pressure coefficient, = $P/\rho\ n^2D^2$
K_Q	-	Propeller torque coefficient, = $Q/\rho\ .\ n^2\ .\ D^5$
K_T	-	Propeller thrust coefficient, = $T/\rho\ .\ n^2\ .\ D^4$
Lpp	-	Ship length between perpendiculars, m
n	-	Propeller revolutions, s^{-1}
P/D	-	Propeller pitch ratio
p	-	Propeller-induced pressure, Pa
p_a	-	Atmospheric pressure, Pa
p_o	-	Hydrostatic pressure, Pa
p_q	-	Propeller-induced pressure amplitude, of order q, Pa
p_v	-	Vapour pressure of water, Pa
Q	-	Propeller torque, Nm
q	-	Order of harmonic
r	-	Propeller section radius, m
R	-	Propeller radius, m
r_H	-	Hub radius, M
T	-	Propeller thrust, N
T_A	-	Ship draft at aft perpendicular, m
T_F	-	Ship draft at forward perpendicular, m
V	-	Propeller speed of advance, m x s^{-1}
Z	-	Number of propeller blades
α/α_s	-	Air content ratio
η	-	Propeller efficiency in open water
λ	-	Scale ratio
ρ	-	Water density, kg/m^3
ϕ	-	Angular coordinate used to define propeller angular position, + from the vertical axis in clockwise direction, looking forward, rad or deg
σ_n	-	Cavitation number, = $(p_o - p_v)/(0{,}5\ \rho\ (\pi \times n \times D)^2)$
Φ	-	Pressure phase angle, rad

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