The Propulsor Committee

Final Report and Recommendations to the 20th ITTC

I GENERAL

Membership and Meetings

The members of the Propulsor Committee of the 20th ITTC are as follows:

G. Caprino
S.-T. Dong
A. Gorschkov
K. Koyama
A.M. Kracht
R. Quereda Lavina
F. B. Peterson
J. Pylkkanen
C. Wills

F. Peterson was elected chairman by the conference and C. Wills was elected Secretary by the committee.

The meetings of the committee after the 19th ITTC were held as follows:

Lee-on-the Solent, UK, January 1991 (8)
Virginia Beach, USA, September 1991 (6)
Berlin, Germany, May 1992 (6)
Genova, Italy, December 1992 (8)

where the numbers in parentheses indicate members present.

Recommendations of the 19th ITTC

The recommendations for the work of the Propulsor Committee as given by the 19th ITTC are as follows:

1. In a variety of test facilities, carry out comparative experiments on steady state Reynolds number effects by circulating a single propeller. Use flow visualization, laser doppler velocimetry, and pressure measurements to validate boundary layer and Navier-Stokes solver calculations.

2. Evaluate the use of surface panel methods in the design and analysis of marine propulsors, possibly in a workshop format.

3. Review improvements in mathematical models for propulsors including surface panel method, lifting surface method, boundary layer, shear-propeller interaction, and Navier-Stokes solver.

4. Survey and review the use of computer-aided design and manufacturing (CAD/CAM) for propulsors.

5. The incorporation of cavitation reduction/control in the design approach of propellers should be evaluated.

6. The effect of leading edge boundary layer tripping on lift reduction and drag increase and on new blade sections ("Eppler-Shen") should be evaluated.

Recent Propulsor Publications

The present committee has continued the tradition of collecting a database of the recent propulsor literature. Each entry in the database has one or more keywords drawn from the list in Table 1.1.

The references, reviewed by the committee, are divided into three parts; the first part covers the period up to and including 1988 and the second covers the period of 1989-1992. The third part of the references also covers the period of 1989-1992 but was not accessible to the Committee or was not reviewed in detail. The second and third parts contain 464 references. It should be pointed out that the literature reviewed by 19th Propulsor Committee is not referred here unless specific entries were mentioned in the text part of this report.

Each reference was given one or more keywords as may be seen at the end of its entry in the listing. A database analysis was performed to examine the occurrence of each keyword and the results are presented in matrix form in Table 1.2. On the diagonal, the total number of occurrences of each keyword is shown, while the off-diagonal elements give the concurrence of two keywords. Along the bottom row of the matrix are added the results of database analysis of the 19th Propulsor Committee.

The top two keywords MATHMOD and SPEC have a very large number of occurrences. For the keyword MATHMOD, the following observations are pertinent.

1. The Surface panel method as a new analytical tool is being actively developed .

2. Most of the papers concerned with the lifting surface methods extend the methods to the for design and performance prediction of special propulsor devices. It may be related to the efforts to develop energy saving propulsors.

3. Solving propeller flow problems with viscous methods rather than potential methods has emerged and is of interest to an increasing number of researchers.

The high occurrence of the keyword SPEC indicates that the development and application of energy saving propulsor devices remain an area of active publication interest. Among those devices, various ducted propellers, contra-rotating propellers, propeller with pre or post swirl vanes and the propeller boss cap fin propeller have been applied on ships, and further research and development continues.

In frequency of occurrence, the next two keywords are DES and PERF. Developing design methods for un-conventional propulsors is a main topic under keyword DES and, in addition, some papers are related to improving design techniques. Efforts are continuing to improve the techniques for performance prediction.

Comparing with the 19th ITTC Propulsor Committee database, it is seen that the number of papers dealing with keywords FLOW and DRAG have increased significantly. It may indicate more attention to the viscous flow around the Propulsor.

New blade sections and their applications remain an important topic. However, the number of papers had only a minimal increase, compared with the 19th ITTC report.

Relatively few papers were published related to fluctuating pressure. This number does not reflect the state-of-the-art since the accuracy of prediction for this topic is still not satisfactory and needs further improvement.

Symposia and conferences at which the propulsor has been a central theme are:

- SNAME PROPELLER/SHAFTING '91, Virginia Beach, VA, USA, 1991
- MARIN JUBILEE MEETING, WORKSHOP C, PROPULSOR-HULL INTERACTION, Wageningen, The Netherlands, 1992
- STG INTERNATIONAL. SYMPOSIUM ON PROPULSOR AND CAVITATION, Hamburg, Germany, 1992
- THE SECOND INTERNATIONAL. SYMPOSIUM ON PROPELLER AND CAVITATION (ISPC '92), Hangzhou, China, 1992

Textbooks related to the propulsor and published in the period from 1980-1990 but not mentioned by the previous Propulsor Committees are:

- Sheng, Z. B. & Wang, G.Q., 1985: Ship Propulsion, in Chinese, Shanghai Jiao-Tong University
- He, Y. S. & Wang, G. Q., 1987: Exciting Forces of Propeller, in Chinese, Shanghai Jiao-Tong University.

KEYWORD	COVERED TOPICS
Design (DES)	Description of procedures/ experimental verification of design
Performance (PERF)	Information on efficiency, power consumption/open water and installed condition/off design behavior
Mathematical Model (MATHMOD)	Theory/numerical models/ experimental verification/ interference (shear flow)
Drag (DRAG)	Reynolds number/roughness/ boundary layer/model-full-scale correlation
Special Devices (SPEC)	Novel devices/compound/ systems/nozzles/controllable pitch
Testing (TEST)	Procedures/facilities/ simulation of conditions
Manufacture (MANUF)	Accuracy/strength/stress levels/shafting
Automation (AUTOM)	Computer aids/data analysis
Cavitation (CAV)	Cavitation types/erosion/ calculations
Noise (NOISE)	Noise/acoustics
Blade (BLADE)	Hydrofoils/blade sections/ blade tips/skew/circulation distribution
Operation Conditions (OPERAT)	Ship wake field/ship motions/waves
Propeller Pressure Field (PRESS)	Hull pressures/vibration excitation
Propeller Flow Field (FLOW)	Slipstream/Induction/LD Velocimetry/Effective Wake
Aircraft (AIRCRAFT)	Literature on aircraft screw propellers

(abbreviations in brackets are used in reference list and in Table 2)

Table 1.1: Keywords and Covered Topics

	Mat	Des	Spec	Perf	Nois	Cav	Pres	Flow	Blad	Test	Manu	Drag	Open	Auto	Air
Mat	134	18	26	17	2	13	4	30	6	5	1	10	5	1	2
Des		94	35	23	4	9	9	2	10	6	3	2	1	1	0
Spec			133	29	4	4	4	2	1	8	1	3	1	0	3
Perf				80	3	5	3	2	3	4	4	7	3	0	0
Nois					30	10	5	0	0	2	2	2	0	0	2
Cav						68	7	5	11	7	1	6	0	0	0
Pres							36	1	3	7	3	0	1	0	1
Flow								52	3	8	0	6	5	0	0
Blad									34	8	0	1	0	0	2
Test										49	4	7	2	0	1
Manu											22	0	0	0	0
Drag												36	1	0	0
Open													12	0	0
Auto														3	0
Air															11
19th ITTC	138	115	115	63	40	36	35	32	30	29	22	20	11	9	2

Table 1.2: Occurrences of each keyword and concurrent entries of two keywords

Quality Control

The Propulsor Committee endorses the efforts of the 20th ITTC Quality Control Group. All of us have experienced the concern that quality control was not adequately discussed in conjunction with published experimental or numerical data. Today the credibility of the author or the organization is all that is typically available to determine the extent to which quality control was exercised. Over time, some data achieves an enhanced level of credibility because of independent collaborating evidence.

With the increased reliance on ISO-9000 by organizations and countries worldwide for quality assurance, it is imperative that the ITTC focus on the subject of quality control.

Prior to receiving correspondence from the Quality Control Group, the Propulsor Committee sent a questionnaire to the ITTC membership to solicit participation in a comparative experiment where a Laser Doppler Velocimeter (LDV) is used to map the near field flow around a propeller. The intent is to develop a database and to document the accuracy of the LDV in propeller measurements of benchmark data to validate viscous flow codes. The response was less than enthusiastic. It is our opinion that discretionary money to do non-standard experiments is in short supply, especially when it does not address a high priority issue of the organization. In essence, to carry out the steps of a validation task requires non-standard procedures and tests to assess the experimental accuracy. After the committee receipt of the results from the first organization that performed a related experiment, it was apparent that non-standard tests must be quantified in detail. Three issues must be addressed: hardware must be selected that clearly emphasizes the phenomenon of interest, the actual hardware geometry must be documented in considerable detail, and the experimental test plan must be specifically developed to document accuracy. The 21st Propulsor Committee must give these three issues serious consideration since they are not typical procedures.

CSSRC, in WUXI, PRC, has volunteered to do an experiment of benchmark quality if an international group of skilled experimentalists can be assembled to assist in the test plan development and to monitor the experimental methods. The Propulsor Committee will determine whether such a group can be assembled and the tests performed in the summer of 1993. The committee success in this endeavor will determine what the committee can expect in its future efforts to obtain benchmark quality data. Without this type of data the use of new experimental methods will be of uncertain quality, guidance to the ITTC on physical phenomena will be of questionable merit, and new software will not have a reliable basis for validation.

A more traditional approach has been and is to compare numerous calculations of a common geometry, with or without experimental data, to look for outliers. This approach also allows the assessment of numerical methods and numerical approximations of the various physical phenomena. There remains value in the comparative tests and comparative calculations for organizations to see how close they are to the efforts of others. Often these comparisons are simply done relative to the published literature.

The propulsor Committee has been unable to identify experimental data that could qualify as a benchmark. The lack of a detailed description of the uncertainty analysis is the primary impediment. Member ITTC organizations should support the efforts of the technical committees to obtain data sufficiently well documented to allow uncertainty analysis to be carried out thus determine its acceptability as a benchmark.

II COMPARATIVE PROPELLER EXPERIMENTS ON STEADY REYNOLDS NUMBER EFFECTS

Introduction

The 19th ITTC recognized the importance of viscous effects in propulsor performance tests and therefore the 20th ITTC Propulsor Committee was charged with the following task:

"In a variety of test facilities, carry out comparative experiments on steady state Reynolds number effects by circulating a single propeller. Use flow visualization, laser doppler velocimetry, and pressure measurements to validate boundary layer and Navier-Stokes solver calculations".

The objectives of this task are to promote a better understanding of the importance of viscous effects and to provide a data base for the validation of viscous flow calculations.

In order to maximize the number of organizations that could take part in the comparative experiments the diameter of the candidate propellers were chosen to be 250 mm. This implied that direct pressure measurements were impractical because pressures can be obtained indirectly from the Laser Doppler Velocimetry (LDV) measurements over a whole blade. For LDV measurements the candidate propeller must be of simple low skew design which may not exhibit strong Reynolds Number effects unless tested at off design conditions. On the other hand modern high skew marine propellers can be very sensitive to Reynolds Number effects but the blade shape obstructs LDV measurements. Therefore, the Propulsor Committee decided on two candidate propellers. Since a large amount of data is already available from tests with the DTRC designs Prop. No. 4119 and No. 4842, these two propellers were selected for the studies. This information, given in a dissertation by Stuart Jessup (1989), has been made available to participants in the study.

The tests will be conducted with smooth blades and the minimum Reynolds number will be that typical of the minimum achieved in model propulsion tests. The range of Reynolds numbers will be determined from details of the test facilities proposed for the tests, as provided by the participants.

The data produced should fall into two categories: first, information on the general effects of Reynolds number variation, and second, "benchmark" data for comparison with theoretical predictions. The former will be provided by flow visualization and extensive LDV measurements, the latter can be obtained from LDV measurements at a limited number of locations.

Participants will be asked to provide information on experimental accuracy including repeat tests. These data are needed for the register of completed uncertainty analysis and benchmark data as recommended by the ITTC Executive Committee. Experimental data collection and evaluation will be based on the recommendations described in "Measurement Uncertainty, Part 1" as forwarded by the ITTC Quality Control Group; copies will be available to the participants. This material is considered a standard reference on measurement uncertainty analysis.

VWS, the Berlin Model Basin, will be responsible for administering the project, for maintaining and mailing the propellers, and finally for collating the data.

Questionnaire

The Propulsor Committee decided to consult the ITTC member organizations, via a questionnaire relative to the comparative experiments. The questionnaire was forwarded to 38 organizations It was divided into the following parts:

- Ability to take part in the tests
- Type of test
- open water tests at different Reynolds numbers in towing tank
- flow visualization
- LDV measurements
- Facility availability
- Technical questions on details of propeller support and measurement of basic inflow velocity in cavitation tunnel

It was originally hoped that numerous organizations would be able to make LDV measurements both outside and in the blade boundary layer, since these measurements were considered to be the most important tests of Task 1.

From the analysis of the questionnaire replies it became clear that only two organizations could make complete 3-component LDV measurements. In order to increase the community of participants in Task 1 the Propulsor Committee decided to include towing tank open water tests.

Organization		Open Water Tests	Flow Visual Tests	LDV Components	LDV Measurements			Remarks
					Up/Down Stream	Inner Radii	Bound Layer	
EUROPE								
SVA	Vienna	Yes	Yes	No Instrumentation Available				In 1992#
SVA	Potsdam	Yes	Yes	2-D_	Yes	No	No	Tests Performed
VWS	Berlin	Yes	Yes	1-D	Yes	No	No	Open Water Perf.
DGA	Paris	No	Yes	2-D	Yes	Yes	Yes	In 1993
MARIN-TEK	Tronheim	Yes	Yes	—	No Answer			?
CTO	Gdansk	Yes	Yes	No Instrumentation Available				In 1992#
El Prado	Madrid	Yes	No	2-D	Yes	?	?	After July '93
KAMEWA	Sweden	Yes	No	No Instrumentation Available				In 1992#
DRA	Haslar	Yes	Yes	2-D	Yes	Yes	Yes	In 1992#
KRYLOV	St. Petersburg	Yes	Yes	No Instrumentation Available				?
JAPAN								
Univers.	Tokyo 113	No	Yes	LDV*	Yes	No	No	In 1992#
SRC	Tokyo 171	Yes	Yes	No Instrumentation Available				?
SRI	Tokyo	Yes	No	1-D	Yes	No	No	In 1993
AKISHIMA	Tokyo 196	No	Indif	No	—	—	—	?
Nagasaki	Exp. Tank	Yes	Yes	LDV	Yes	No experience		After March '93
IHI	Yokohama	Yes	Yes	1-D	Yes	No experience		After April '93
NKK	Tsu, Mie	Yes	Yes	No Instrumentation Available				In 1992#
KOREA								
HMRI	Ulsan	Yes	Yes	2-D	Yes	Yes	?	Tests Performed
KRISO	Daejeon	Yes	Yes	No Instrumentation Available				Tests In Progress
CHINA								
CSSRC	Wuxi	No	No	3-D	Yes	Yes	Yes	In 1993
USA								
DTRC	Bethesda	Yes	Yes	3-D	Yes	Yes	Yes	?

*) LDV-system with forward scatter
?) the question is left open
#) as announced in the questionnaire

Table 2.1 Questionnaire Reply Summary for Participants In Task 1

From the total of 38 questionnaires mailed out, 26 replies were received with 21 organizations willing to take part in the comparative experiments. Two responders want to participate at a later date, and three will not participate.

The participants replies to the questionnaire are summarized in Table 2.1.

Comparative Experiments

The comparative experiments with the candidate propellers will include three types of open water tests: flow visualization, towing tank open water and water tunnel. Measurements over as large a Reynolds number range as possible are encouraged to investigate the effect of laminar and turbulent flow over the blades at various operating conditions.

Water tunnel velocity measurements are intended to map the flow near the leading edge (upstream flow), at and near the trailing edge (downstream flow) and nearfield velocities (velocities between the blades). Where instrumentation is available, velocity scans normal to the blade surface to measure the blade boundary layer velocities will be performed.

The committee decided against pressure measurements on the propeller blades. Since the propellers are relatively small, installation and maintenance of the transducers and the shaft plugs are very difficult. The flow associated with the blade tip and the root will not be included due to the difficulty in making measurements and the extensive test time required.

To assure that all participants execute the experiments and present the test results in the same way, the committee has prepared a "COMMENTS AND RECOMMENDATIONS FOR THE TESTS AND PRESENTATION OF THE RESULTS" document. This document is for use by each participant.

Propeller Models

Both propellers and LDV measured data are presented in the report by Jessup (1989), a copy of which is provided to all participants. The first candidate propeller is the DTRC Prop. No. 4119, a three-bladed and right-handed propeller of relatively simple geometry. The propeller was designed for uniform inflow by DTRC in 1968 using lifting line calculations for torque and thrust while pitch and camber distributions are calculated with lifting surface procedures. Design conditions are J=0.833 and K_T=0.154. This propeller has relatively straight blades with a symmetrical outline and a cylindrical hub. Thus it is very conducive to LDV measurements of the surface flow over the entire blade. For this simple geometry, Reynolds Number effects are more prominent when the propeller is tested at off-design conditions.

Since the diameter of the original DTRC aluminum propeller was too large a new propeller model of 250mm in diameter was manufactured of brass by the Berlin Model Basin (VWS) using a master blade (scale 2.4:1) and a copy milling machine. Blade tip radii and leading edges were finished by hand. This propeller is now referred to as VWS 1464.

The second candidate propeller is the DTRC Propeller No. 4842, with five high skewed blades representing a modern marine propeller geometry with non linear skew distribution. It is a wake adapted design at design conditions J = 0.905 and K_T = 0.305. This propeller was completely machined by numerically control at DTRC and, therefore, represents a high accuracy model. This propeller is less conducive to LDV measurements because the twisted blade shape restricts the measurements to outside the swept area of the blade. However it is more sensitive to Reynolds Number effects and, therefore, more suitable to investigate the effects of various laminar and turbulent flow extents over the blade at the design condition.

The main data of both ITTC propellers are:

Prop. No.:	VWS 1464	DTRC 4842
Dm:	0.250 m	0.250 m
P/D at 0.7R:	1.084	1.488
Ae/Ao:	0.608	—
d/Dm:	0.200	0.323
# of blades:	3	5
Rotation:	Right Hand	Right Hand
Material:	Brass	Brass

Test Program

General Remarks. The flow velocity measurements should be made using collection programs synchronized with a shaft encoder. This procedure allows the accurate mapping of the flow in the vicinity of the blade surface and allows automated data collection. Details of this procedure are also found in Jessup (1989). The results should be given in numerical and graphical form.

Open Water Tests. Open water tests may be performed as routine tests in a towing tank and or a circulating tunnel. The lowest Reynolds Number should correspond to that used in normal self propulsion tests. The range of Reynolds Numbers should include that used in flow visualization tests and be as large as possible.

Flow Visualization Tests. It is left to each participant to execute the flow visualization tests in accordance with their own experiences. The resulting records of suction and pressure side flow should be recorded and provided as sketches or photographs.

LDV Measurements Of Upstream And Downstream Flow. To realize a more or less parallel inflow to the blade roots the hub of Prop. No. 1464 has been designed with a cylindrical hub. A cosine spacing of the radial measurement locations is recommended for the space between 0.20R and 0.95R (inner radii). From 0.975R to 1.1R four additional radii are recommended.

LDV Measurements Of Near Blade Velocities. The chordwise distribution of the velocity should be measured at four selected radii on pressure and suction sides of the blade and outside the boundary layer.

LDV Measurements Of The Velocity Profile Normal To Blade Surface. For the estimation of the boundary layer thickness LDV measurements of the velocity profile normal to blade surface should be performed at five different points at each selected radius.

Duration of Test Program

The Propulsor Committee realizes that not only are the tests time consuming but also the logistics associated with mailing the propellers needs considerable time. Furthermore, the questionnaire replies indicated that some of the organizations can test in 1992 but many prefer a later date. Thus the world wide comparative experiments cannot be finished in this committee term and must be extended into the 21st ITTC term if Task 1 is to be completed successfully.

First Results

Immediately after manufacturing Prop. No. 1464, the first open water tests were performed in VWS for control purposes. Then the propeller was sent to SVA Potsdam, Germany for tests. SVA was the first organization to perform the tests as announced. SVA was followed by HMRI Ulsan (Korea). The experiments executed and reported are summarized in Table 2.2 and Table 2.3, respectively.

Open Water Tests. Figure 2.1 shows the open water test results provided by SVA Potsdam and VWS Berlin. These initial results appeared to reflect more the experimental variability than Reynolds number effects. These tests have been performed as routine tests where arithmetic average values of the test quantities were taken several times during the different steps of data acquisition and evaluation. The results are represented as functions using polynomial approximations or spline functions. These initial results are graphic indications that a more direct involvement of the committee is required as a matter of data quality control.

The wall effect of the "open water test" results provided by SVA cavitation tunnel tests have been corrected using Glauert's method.

The results provided by SVA Potsdam cover a Reynolds-number range of $0.27*10^6$ to $0.78*10^6$ with the general tendency

Laminar		Turbulent
$KT(0.27*10^6)$	$<$	$KT(0.78*10^6)$
$KQ(0.27*10^6)$	$>$	$KQ(0.78*10^6)$

which is a result of the boundary-layer flow over the blades. As demonstrated by the flow visualization tests (Figure 2.2 to 2.7) at low Rn the boundary layer is mainly laminar over the major part of the blades while at higher Rn the turbulent boundary layer predominates.

Tests	Facility	Rn 0.7R	Remarks
Open Water Tests	Towing Tank	$0.26*10^6$ $0.51*10^6$ $0.81*10^6$	
Flow Visualization			
"Open Water Tests"	Cavitation Tunnel	$0.96*10^6$ $1.59*10^6$	
LDV Measurements Forward Scatter Vx (axial) Vr (radial)	Cavitation Tunnel Section: $0.85*0.85m^2$	$1.19*10^6$	x = -0.3 (upstream) x = +0.3281 (downstream) x = +0.9510

Table 2.2 Details of comparative experiments executed at SVA Potsdam (Germany).

Tests	Facility	Rn 0.7R	Remarks
Flow Visualization	Cavitation Tunnel	$0.57*10^6$ $1.15*10^6$ $1.43*10^6$	
"Open Water Tests"	Cavitation Tunnel	$0.60*10^6$ $0.90*10^6$ $1.22*10^6$ $1.43*10^6$	
LDV Measurements Back Scatter Vx (axial) Vr (radial) Vt (tangential)	Cavitation Tunnel Section: $0.6*0.6\ m^2$	$1.45*10^6$	x =-0.3 (upstream) x = +0.3281 (downstream) x = +0.9510
		$1.47*10^6$	inner radii: r/R = 0.70 r/R = 0.90 r/R = 0.95

Table 2.3 Details of comparative experiments executed at HMRI Ulsan (Korea) in cavitation tunnel only.

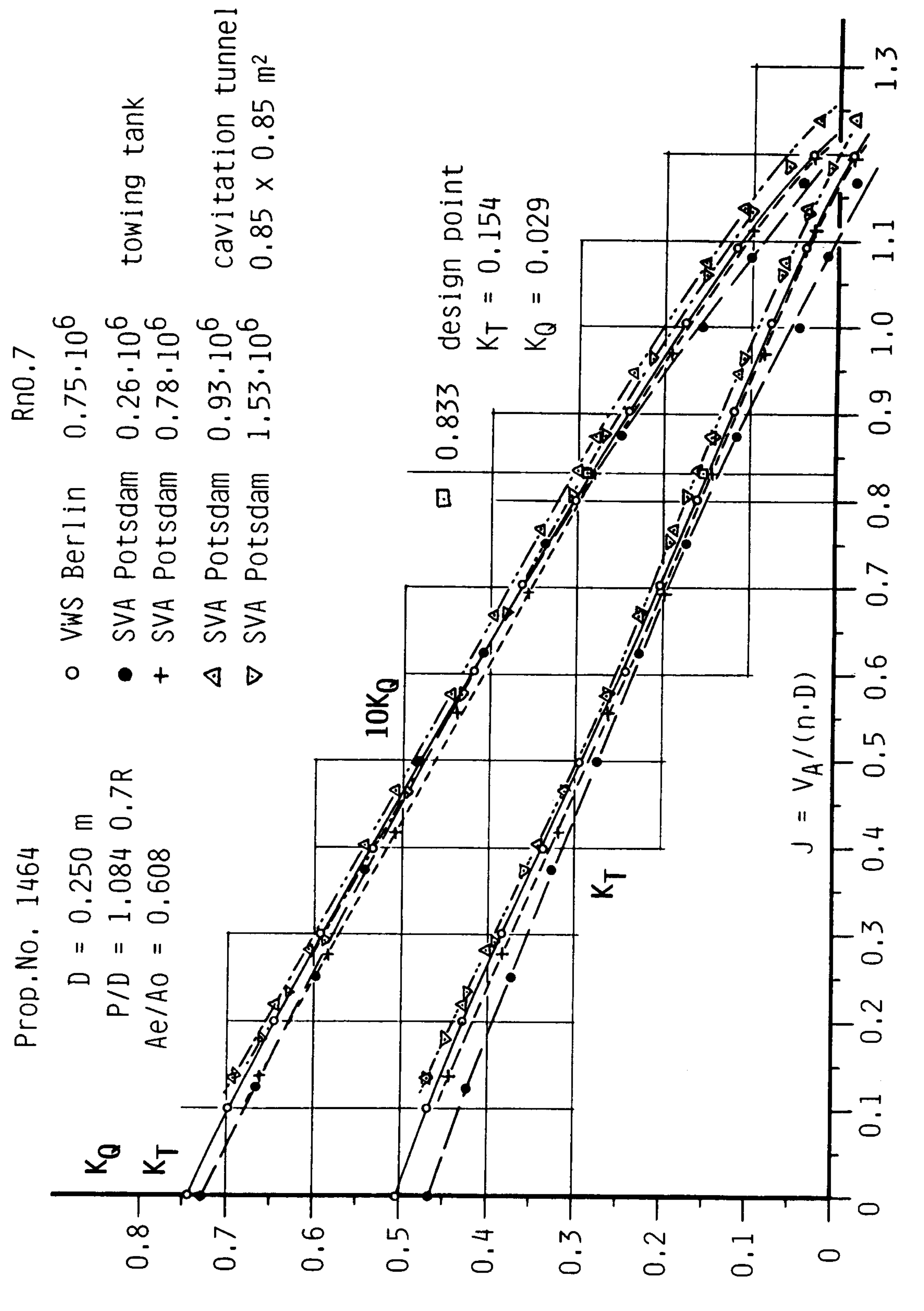
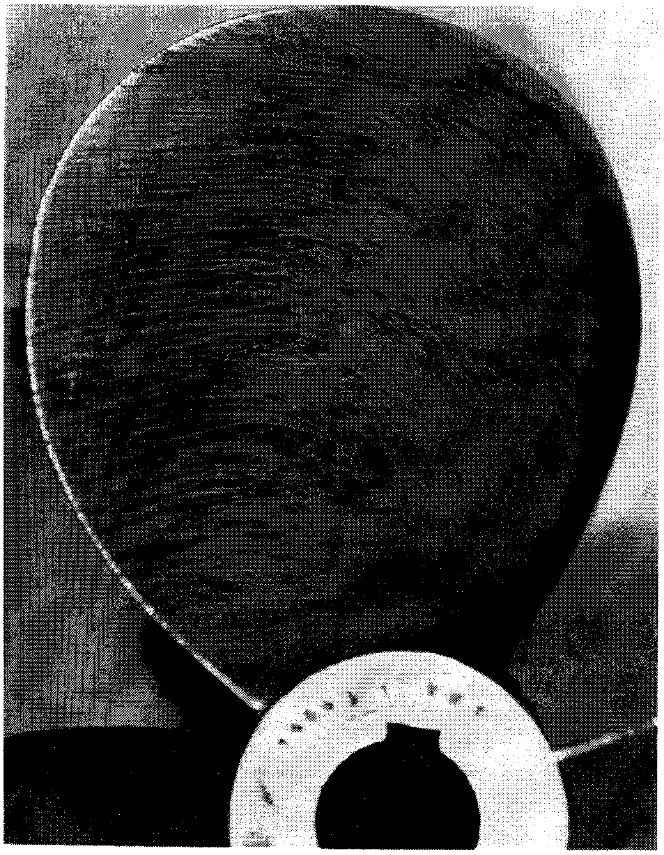


Figure 2.1 ITTC Prop. No. 1464, Open Water Test Results



← Leading Edge

Figure 2.2 Flow Visualization Test: Paint Test
Press Side, RPS = 9.6, V= 2.0 m/sec, Rn*E-6 = 0.573

Leading Edge →

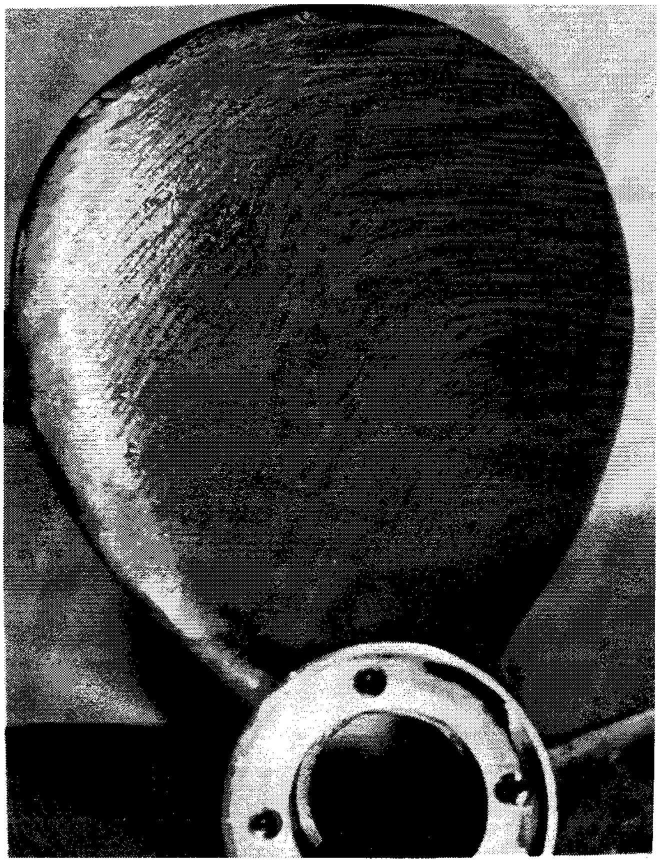
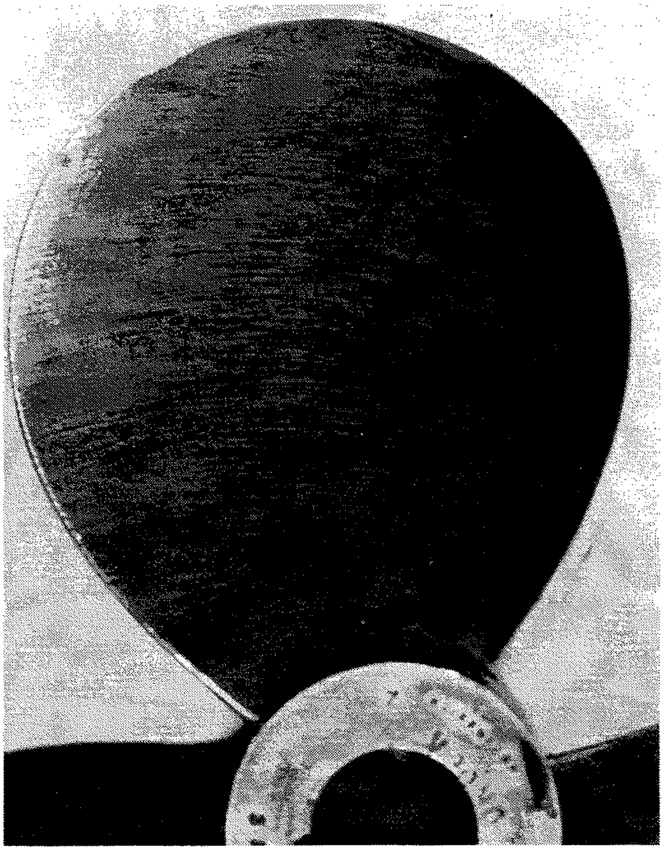


Figure 2.3 Flow Visualization Test: Paint Test
Suction Side

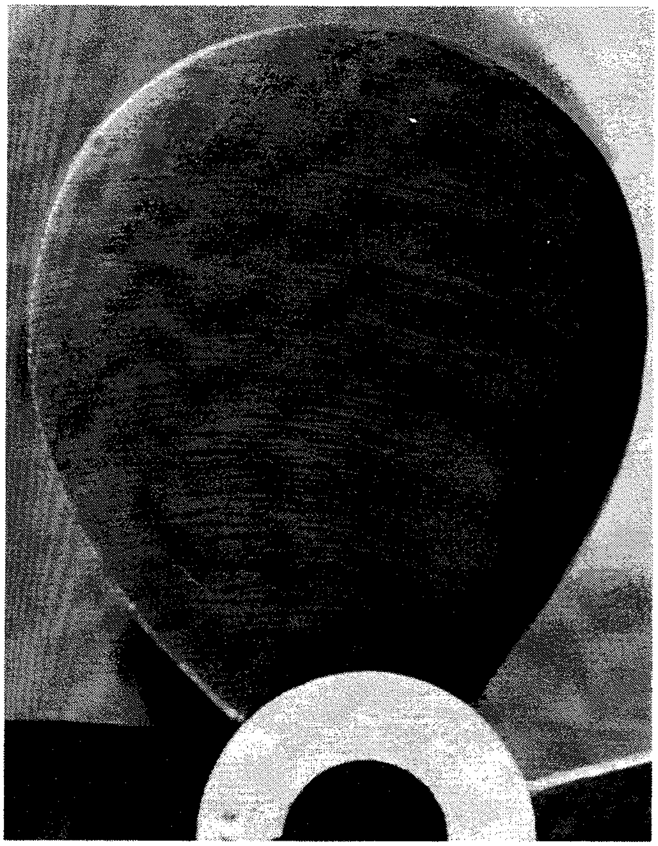


← Leading Edge

Figure 2.4 Flow Visualization Test: Paint Test
Press Side, RPS = 19.2, V= 4.0 m/sec, Rn*E-6 = 1.146

Leading Edge →

Figure 2.5 Flow Visualization Test: Paint Test
Suction Side



← Leading Edge

Figure 2.6 Flow Visualization Test: Paint Test
Press Side, RPS = 24, V= 5.0 m/sec, Rn*E-6 = 1.432

Leading Edge →

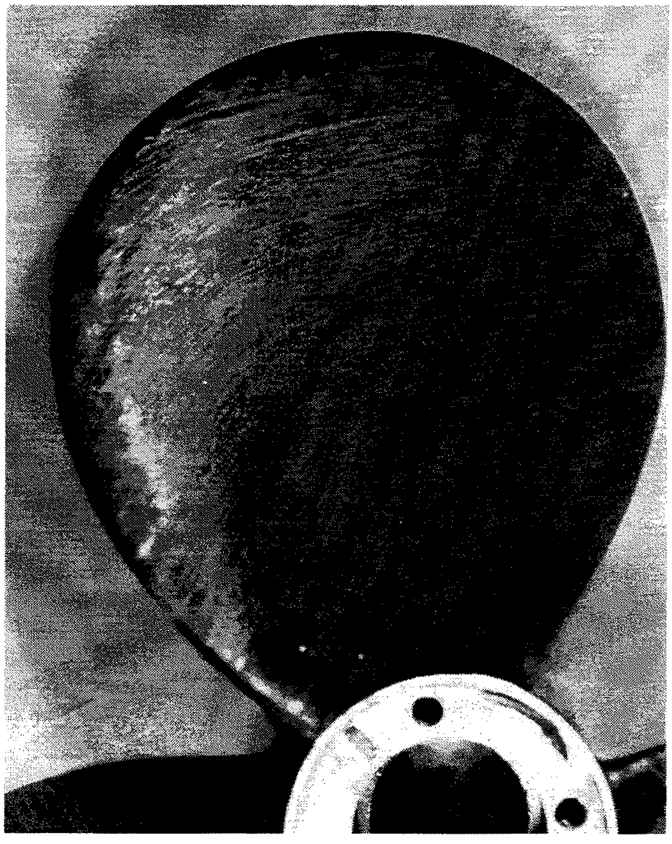


Figure 2.7 Flow Visualization Test: Paint Test
Suction Side

The effects of both types of boundary layers on thrust and torque follow from their different properties. Although the laminar skin friction drag is low, the laminar boundary-layer separated due to the pressure increase. This separation increased the pressure drag of the profile which resulted in a reduction of thrust and an increase in torque of the propeller. On the other hand the skin friction drag is higher with turbulent boundary-layer flow, but this boundary layer has less tendency to separate. Above a critical Reynolds Number the pressure drag is low which results in a thrust increase and a torque decrease.

Flow Visualization Tests. The first results of flow visualization tests provided by HMRI Ulsan are given in the Figs. 2.2 to 2.7 showing flow patterns on pressure and suction sides of the propeller blades at three different Reynolds numbers, $0.57*10^6$, $1.14*10^6$, and $1.43*10^6$. The excellent photographs demonstrate clearly that the near-blade-surface flow in the chordwise direction is characterized by a laminar boundary-layer flow which turns turbulent in a transition zone.

In Table 2.4 the zones of different boundary-layer flows are summarized and given as percentages of the blade area for the pressure and suction sides. These results show that the turbulent boundary-layer region increases significantly when the Rn is increased from $0.57*10^6$ to $1.146*10^6$ with the largest change on the suction side. A further increase of Rn to $1.43*10^6$ gives a smaller increase in the turbulent flow region.

Pressure Side of the Blade			
$Rn*10^6$	Laminar	Transition	Turbulent
0.573	36%	12%	42%
1.146	22%	10%	68%
1.432	16%	8%	76%
Suction Side of the Blade			
$Rn*10^6$	Laminar	Transition	Turbulent
0.573	65%	13%	22%
1.146	36%	14%	50%
1.432	36%	4%	60%

Table 2.4 Different types of boundary-layer flow expressed as percentages of the blade area.

In the laminar boundary-layer region the streamlines slope outwards to the blades' tip due to centrifugal and Coriolis-forces acting on the fluid in the boundary-layer. The flow pattern in the turbulent boundary-layer region reflects a flow more in the chordwise direction. The change of flow direction takes place in a transition zone within which turbulence develops. These results coincide qualitatively with Meyne's (1972) results and many more recent tests.

LDV Measurements. It is premature to report results of the LDV measurements. At SVA Potsdam a 3-beam 2-component LDV system with forward scatter is in use to measure the flow upstream and downstream of the propeller.

At HMRI Ulsan a 2-component LDV system with back scatter is in use which allows measurements of the flow fields upstream and downstream of the propeller plus the flow between the blades.

Evaluation of the results is in progress and the best method of presenting the data is currently under consideration.

III WORKSHOP ON SURFACE PANEL METHOD FOR MARINE PROPELLERS

Introduction

A workshop on the use of the surface panel method for marine propellers was carried out by the 20th ITTC Propulsor Committee, according to the recommendation by 19th ITTC Propulsor Committee. The task for the Propulsor Committee is as follows:

"Evaluate the use of surface panel methods in the design and analysis of marine propulsors possibly in a workshop format."

The intent of the task is to evaluate and promote the use of surface panel methods.

Comparative calculations of marine propeller performance by the surface panel method and a workshop for the discussion of the comparison were carried out. These efforts draw attention to the accuracy of the panel method for the analysis of marine propellers and reviewed the applicability of the method. This was accomplished through the comparison of extensive numerical results by many panel methods. The purpose of the comparison is not as a competition but rather as a method to assess the various numerical issues that may be important.

The committee distributed a questionnaire outlining the plan to 98 organizations on June 24, 1991. 16 organizations signified their intention to perform the comparative calculation. The committee furnished them with the calculation documents on Feb. 4, 1992. 15 organizations sent the committee the results of their calculations. The workshop was held in Seoul, Korea on August 23, 1992.

In the workshop 19 participants attended, 10 participants presented the results of their calculations and the use of the surface panel method for marine propellers was discussed.

Sample Propellers and Calculation Conditions

It goes without saying that the experimental data are very important for the evaluation of the surface panel method. S. D. Jessup (1989) presented detailed experimental data for flow around propellers in his dissertation. One of his propellers DTRC4119 is used in the comparative experiments on viscous effects for Task 1 of this 20th ITTC Propulsor Committee. (Note: in Chapter II this propeller is referred to as VWS 1464).

Two propellers DTRC4119 and DTRC4842 were selected as the propellers for the comparative calculation. DTRC4119 is a three bladed propeller with neither rake nor skew. DTRC4842 is a five bladed propeller with high skew. Their geometry is presented in Table 3.1(a), (b) and (c).

Diameter, D: 1.00 ft. (0.305 m)
Rotation: Right Hand
Number of Blades: 3
Hub-Diameter Ratio: 0.20
Skew, qr, Rake, iT: none
Design Advance Coefficient, J: 0.833
Section Thickness Form:
NACA66(DTRC Modified)
Section Meanline: NACA, a=0.8
Design Thrust Coefficient, KT: 0.150

r/R	C/D	P/D	qr	IT/D	tm/C	fm/C
0.2	0.320	1.105	0	0	0.2055	0.01429
0.3	0.3635	1.102	0	0	0.1553	0.02318
0.4	0.4048	1.098	0	0	0.1180	0.02303
0.5	0.4392	1.093	0	0	0.09016	0.02182
0.6	0.4610	1.088	0	0	0.06960	0.02072
0.7	0.4622	1.084	0	0	0.05418	0.02003
0.8	0.4347	1.081	0	0	0.04206	0.01967
0.9	0.3613	1.079	0	0	0.03321	0.01817
0.95	0.2775	1.077	0	0	0.03228	0.01631
1.0	0.0	1.075	0	0	0.03160	0.01175

Table 3.1(a) Geometry of DTRC 4119

Diameter, D: 1.219 ft. (0.3717 m)
Rotation: Right Hand
Number of Blades: 5
Hub-Diameter Ratio: 0.323
Design Advance Coefficient, J: 0.905
Section Thickness Form: NACA66
(DTRC Modified)
Section Meanline: Specified
Design Thrust Coefficient, KT: 0.306

r/R	C/D	P/D	qr	IT/D	tm/C	fm/C
0.323	0.2015	0.9321	0.38	0.0010	0.2179	0.0100
0.35	0.2181	1.0790	3.07	-0.0090	0.1871	0.0158
0.4	0.2494	1.2361	-6.82	-0.0229	0.1415	0.0253
0.5	0.3113	1.4194	-9.02	-0.0369	0.0854	0.0365
0.6	0.3664	1.4892	-7.57	-0.0325	0.0581	0.0390
0.7	0.4031	1.488	-3.24	-0.0136	0.0444	0.0371
0.8	0.4090	1.329	4.34	0.0165	0.0379	0.0319
0.9	0.3651	1.0759	13.75	0.0423	0.0356	0.0264
0.95	0.3106	0.9012	19.25	0.0509	0.0363	0.0247
1.0	0.0700	0.6981	25.42	0.0561	0.0880	0.0243

Table 3.1 (b) Geometry of DTRC 4842

x_C	t/C	f/C,4119	f/C,4842
0.0000	0.0000	0.0000	0.0000
0.0125	0.2088	0.0907	0.0875
0.0250	0.2932	0.1586	0.1530
0.0500	0.4132	0.2712	0.2625
0.0750	0.5050	0.3657	0.3585
0.1000	0.5814	0.4482	0.4415
0.1500	0.7042	0.5869	0.5803
0.2000	0.8000	0.6993	0.6955
0.3000	0.9274	0.8635	0.8630
0.4000	0.9904	0.9615	0.9630
0.4500	1.0000	0.9881	0.9907
0.5000	0.9924	1.0000	1.0000
0.6000	0.9306	0.9786	0.9750
0.7000	0.8070	0.8892	0.8777
0.8000	0.6220	0.7027	0.6760
0.9000	0.3754	0.3586	0.3613
0.9500	0.2286	0.1713	0.1785
1.0000	0.0666	0.0000	0.0000

Table 3.1 (c) Thickness and Camber Distributions for DTRC 4119 and 4842

At the workshop the comparative calculations were discussed for the fictitious propeller DTRC4842 instead of DTRC4842 because of confusion over the rake distribution of DTRC4842 as described in Jessup (1989). After the workshop many participants re performed the calculation for the actual DTRC4842. The results for the actual DTRC4842 are presented in this report.

The advance coefficients J=0.833 and J=1.100 are for DTRC4119, and J=0.905 for DTRC4842. Details of the calculation conditions are shown in Table 3.2.

A) DTRC4119
- J=0.833 — recommended paneling
- without hub — linear wake

B) DTRC4119
- J=0.833 — reference paneling
- without hub — linear wake

C) DTRC4119
- J=0.833 — recommended paneling
- with hub — linear wake

D) DTRC4119
- J=0.833 — recommended paneling
- without hub — devised wake

E) DTRC4119
- J=0.833 — recommended paneling
- with hub — devised wake

F) DTRC4119
- J=1.100 — recommended paneling
- without hub — linear wake

G) DTRC4119
- J=1.100 — recommended paneling
- without hub — devised wake

H) DTRC4842
- J=0.905 — recommended paneling
- with hub — devised wake

Recommended Paneling :
Paneling participants recommend or use

Reference Paneling :
Fine or course or lower order or higher order paneling which shows the validation of the paneling participants recommend

Linear Wake :
Blade vortex wake maintains its location at the point it has emanated in spite of induced velocity

Devised wake :
Modeled wake or calculated wake

Table 3.2 Standard Calculation Cases

Comparative Calculation

The list of contributors from the 15 organizations who sent the calculation results is shown in Table 3.3.

1) Dr. Cheng-I Yang, David Taylor Model Basin (DTMB), USA
2) Prof. J. E .Kerwin, Dr. C. Y. Hsin, Dr. S. Kinnas, Massachusetts Institute of Technology (MIT), USA
3) Dr. B. Maskew, Analytical Methods, Inc. (AMI), USA
4) Dr. J. T. Lee, Mr. Y. G. Kim, Dr. J. C. Suh, Prof C. S. Lee, Korean Research Institute of Ships and Ocean Engineering (KRISO), and Chungnam National University (CNU), KOREA
5) Dr. T. Hoshino, Mitsubishi Heavy Industries, Ltd. Nagasaki R&D Center (MHI), JAPAN
6) Dr. S. Ryo, Research Institute, Nippon Kaiji Kyokai (NK), JAPAN
7) Mr. H. Yamasaki, Yokohama National University (YNU), JAPAN
8) Dr. K. Koyama, Ship Research Institute (SRI), JAPAN
9) Dr. G. Caprino, Centro per gli Studi di Tecnica Navale (CETENA), ITALY
10) Dr. Dieter Lohmann, Deutsche Forschungsanstalt fur Luft und Raumfahrt (DLR), GERMANY
11) Prof. P. Bogdanov, Bulgarian Ship Hydrodynamics Centre (BSHC), BULGARIA
12) Dr. R. Baubeau, Bassin d'Essais des Carenes (DGA), FRANCE
13) Dr. P. Sander, Institut fur Schiffbau Universitat Hamburg (Hamburg), GERMANY
14) Dr. H. Streckwall, Hamburgische Schiffbau - Versuchsanstalt GmbH (HSVA), GERMANY
15) Mr. Dang Jie, and Mr. Tang Denghai, China Ship Scientific Research Center (CSSRC), China

Table 3.3 List of Participants to Comparative Calculation

The calculation method and the characteristics of the program are shown in Table 3.4. Many researchers use a potential based panel method and employ plane panels or hyperboloidal panel. Many researchers also use the pressure Kutta condition. The coarsest paneling in the table is NR*NC=7*8. The finest paneling is NR*NC=30*20 and 15*30.

		Calculation Method	Panel Type	NR × NC	Kutta Condition
1)	DTMB	Potential based P.M. (DTMB ver. of VSAERO)	Quadrilateral plane panel	10 × 29	
2)	MIT	Potential based P.M. (MIT-PSF-10)	Hyperboloidal	30 × 20	Iterative Pressure Kutta Condition
3)	AMI	Potential based P.M. (VSAERO, USAERO)		15 × 30	
4)	KRISO/ CNU	Potential based P.M. (KPA11)	Hyperboloidal panel	10 × 20	Pressure Kutta Condition
5)	MHI	Potential based P.M.	Hyperboloidal quadrilateral panel	12 × 12	Pressure Kutta Condition
6)	NK	Direct Formulation of BEM (Potential based P.M.)	Triangular element	8 × 13	Pressure Kutta Condition
7)	YNU	Surface Vortex Lattice M.	Horse-shoe	10 × 12	Nothing
8)	SRI	Potential based P.M. Time-Stepping code	Quadrilateral plane panel	7 × 8	Modified Morino Kutta Condition
9)	CETENA	Potential based P.M.	Quadrilateral plane panel	17 × 12	Trial And Error technique based on linear interpolation
10)	DLR	Lifting Surface Theory based on FW-H equation	plane panel	10 × 15	Geometric Kutta Condition (bisector, 2% of chord)
11)	BSHC	Lifting Surface Theory		15 × 9	
12)	DGA	Lifting Surface Theory Quasi-Continuous Method		12 × 12	
13)	Hamburg	Lifting Surface Theory Continue Method(Mode Function Method)			
14)	HSVA	Lifting Surface Theory Vortex-Lattice Method		10 × 10	
15)	CSSRC	Potential Based P.M. (MBPM-V1.0)	Hyperboloidal quadrilateral panel	10 × 16	Pressure Kutta Condition

NR : number of panels in radial direction
NC : number of panels in chordwise direction

Table 3.4 (a) Calculation Method

		Cal. of Velocity	Viscous Correction
1)	DTMB		Sectional drag coefficient (empirical correction)
2)	MIT	2nd Oder Finite Difference Scheme	Sectional drag coefficient
3)	AMI		Boundary layer calculation
4)	KRISO/ CNU	Numerical Differentiation Piecewise Quadratic Inter.	Viscous friction coefficient C_f=0.004
5)	MHI		Empirically determined formula for frictional drag
6)	NK	Numerical Differentiation 1st order shape function	drag coefficient
7)	YNU	Numerical cal.by Biot-Savart Low	Prandtl-Schlichting formula for drag
8)	SRI	Numerical Differentiation Quadric curved surface	Exp. data for section drag and circulation reduction Abbot and Von Doenhoff
9)	CETENA	Numerical Differentiation Pot. expressed by parabola	Van Oossanen $C_r = C_f\,(1+1.2t/c+70(t/c)^4)$
10)	DLR		Transpiration method - boundary layer calculation from previous pressure distribution
11)	BSHC		drag coefficient and circulation reduction
12)	DGA		integrating local flat plate friction coefficient
13)	Hamburg		
14)	HSVA	Biot-Savart	Sectional drag coefficient
15)	CSSRC	Numerical Differentiation	Viscous friction coefficient $C_f=0.026Re_s^{-1/7}$

Table 3.4 (b) Calculation Method

Some calculations based on lifting surface theory were contributed to the workshop and were included for reference.

Calculation Results

Standard calculation conditions are case A, case B, and case H as shown in Table 3.2. Some participants carried out calculations for all cases. Others carried out some parts of the cases. Results of all the calculations were discussed in the workshop. However three cases, case A, case E, and case H are mainly shown here owing to the limited pages. Details of all the calculation results will be presented in

K. Koyama,
"Comparative Calculation of Propellers by Surface Panel Method,
---Workshop organized by 20th ITTC Propulsor Committee ---"
Papers of Ship Research Institute, Vol. 30, 1993.

Examples of paneling for the propellers are shown in Figure 3.1 (a), (b). The figures are quoted from the materials presented by AMI.

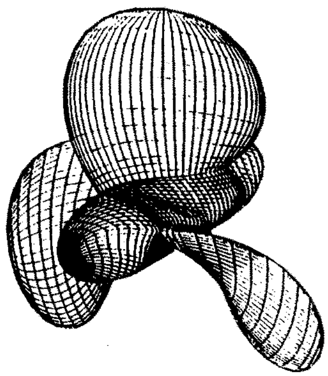


Figure 3.1 (a) Paneling for DTRC4119

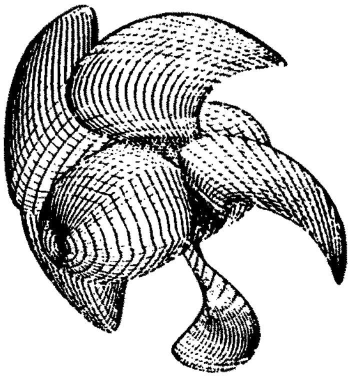


Figure 3.1 (b) Paneling for DTRC4842

Calculation results for thrust coefficient KT and torque coefficient KQ are shown in Figure 3.2 - Figure 3.4. Calculation results for pressure coefficient CP are shown in Figure 3.5 - Figure 3.7.

The case A (DTRC4119, J=0.833, without hub, linear wake) without viscous correction is the most basic case. The case is suitable for the validation of numerical results. KT, KQ values for the case are shown in Figure 3.2 (a), (b). Correlation between calculation and experiment is reasonable. However the scatter of the calculation results is somewhat unexpected. A possible reason for the scatter may be that some calculations modify the pitch of the vortex wake in spite of linear wake specification.

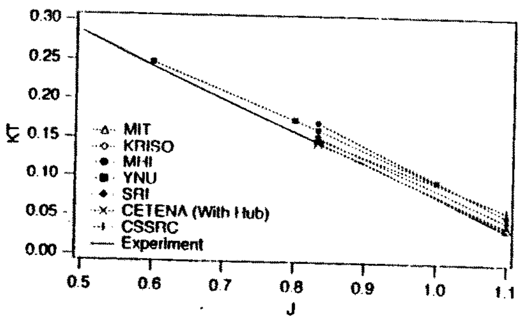


Figure 3.2 (a) KT for Case A (DTRC4119, Without Hub, Linear Wake) without Viscous Correction

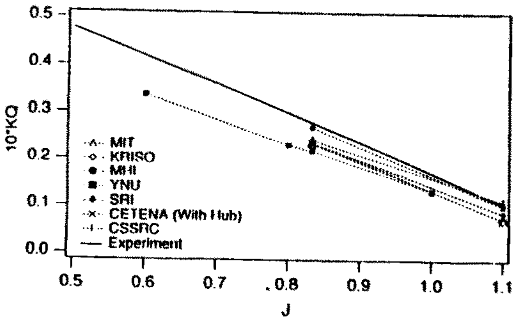


Figure 3.2 (b) KQ for Case A (DTRC4119, Without Hub, Linear Wake) without Viscous Correction

The case E (DTRC4119, J=0.833, with hub, devised wake) with viscous correction is the most realistic case. The case is suitable for comparison with experiment. K_T, K_Q values for the case are shown in Figure 3.3(a),(b). Correlation between calculation and experiment is good which demonstrates the value of the surface panel method. The correlation for K_Q is not as good as that for K_T. Although viscous effect, devised wake effect and hub effect are included in case E, the viscous effect is dominant for K_Q.

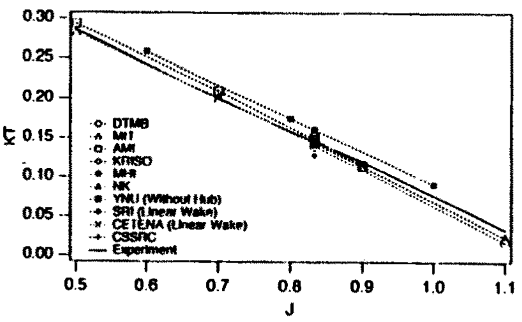


Figure 3.3 (a) KT for Case E (DTRC4119, With Hub, Devised Wake) with Viscous Correction

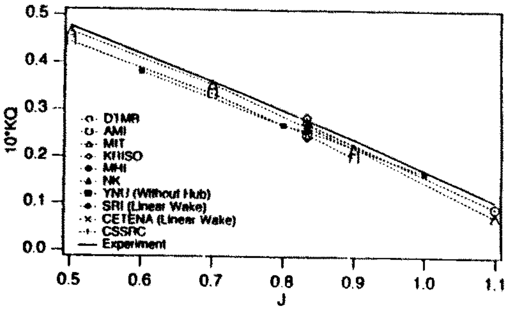


Figure 3.3 (b) KQ for Case E (DTRC4119, With Hub, Devised Wake) with Viscous Correction

Calculation results of the case H for DTRC4842 are shown in Figure 3.4(a), (b). The correlation between calculation and experiment has the same tendency as the case for DTRC4119.

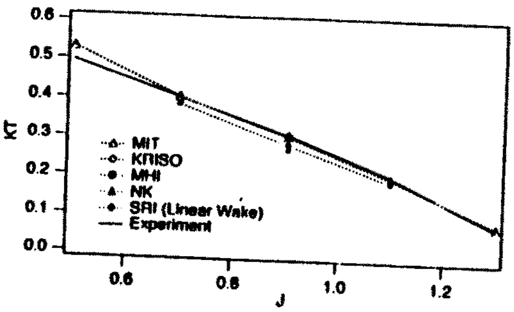


Figure 3.4 (a) KT for Case H (DTRC4842, With Hub, Devised Wake) with Viscous Correction

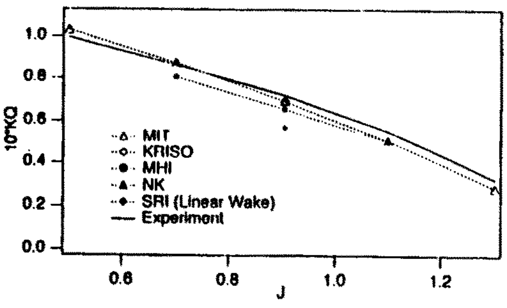


Figure 3.4 (b) KQ for Case H (DTRC4842, With Hub, Devised Wake) with Viscous Correction

Pressure coefficients CP for the case A are shown in Figure 3.5 (a), (b), (c), (d), (e), (f). The small scatter shows the merit of surface panel methods. On the whole the results for CP on the blade are considered to be satisfactory although there is considerable scatter near the root, tip, leading edge, and trailing edge.

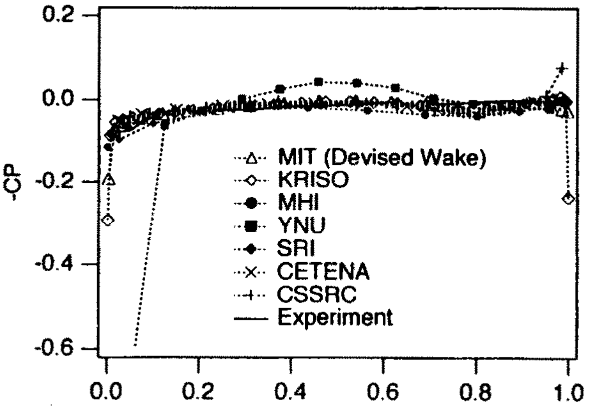


Figure 3.5 (a) CP for Case A (DTRC4119, J=0.833, Without Hub, Linear Wake) on 0.9R Face

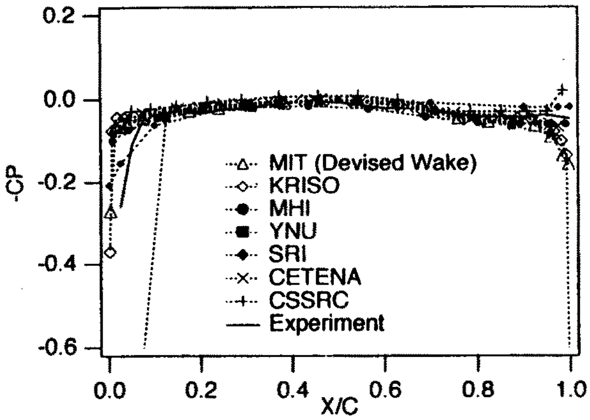


Figure 3.5 (b) CP for Case A (DTRC4119, J=0.833, Without Hub, Linear Wake) on 0.7R Face

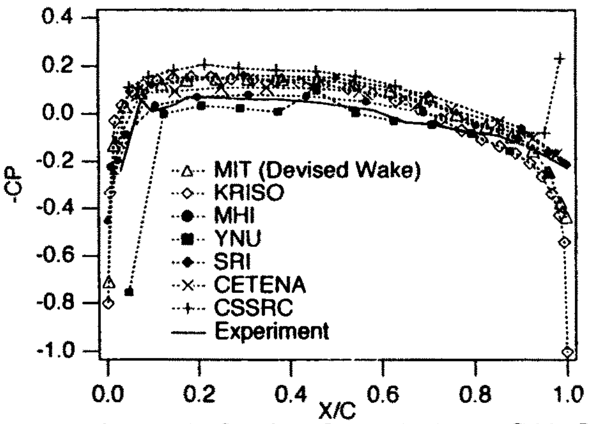


Figure 3.5 (c) CP for Case A (DTRC4119, J=0.833, Without Hub, Linear Wake) on 0.3R Face

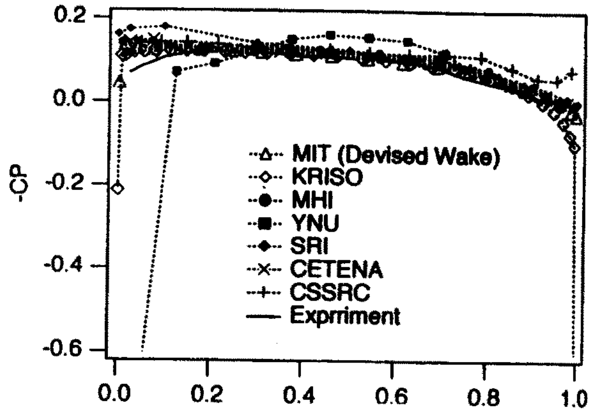


Figure 3.5 (d) CP for Case A (DTRC4119, J=0.833, Without Hub, Linear Wake) on 0.9R Back

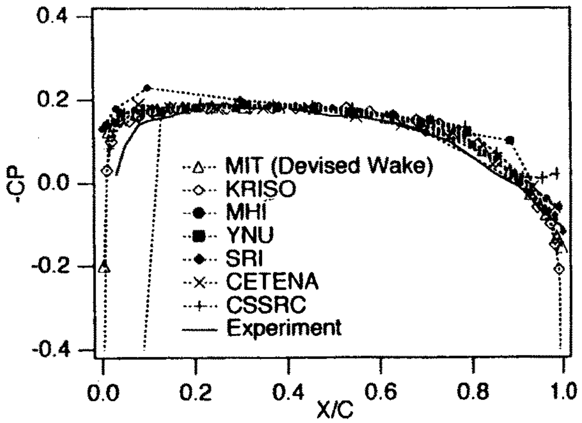


Figure 3.5 (e) CP for Case A (DTRC4119, J=0.833, Without Hub, Linear Wake) on 0.7R Back

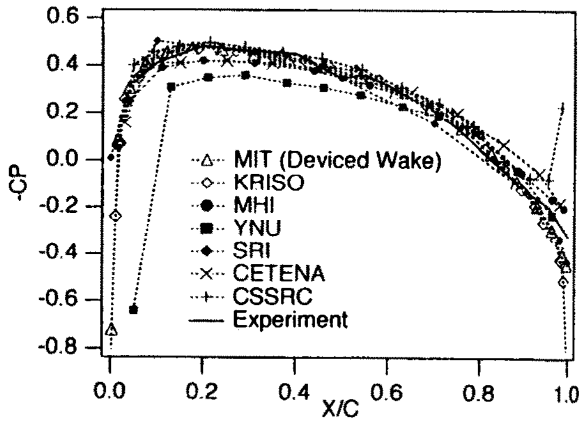


Figure 3.5 (f) CP for Case A (DTRC4119, J=0.833, Without Hub, Linear Wake) on 0.3R Back

Pressure coefficients CP for the case E are shown in Figure 3.6 (a), (b), (c), (d), (e), (f). Correlation between calculations and experiment in general, is good although many calculations for Cp near the root r/R=0.3 is higher than the experiment.

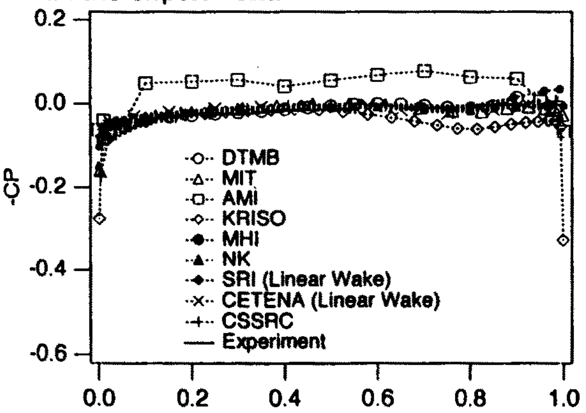


Figure 3.6 (a) CP for Case E (DTRC4119, J=0.833, With Hub, Devised Wake) on 0.9R Face

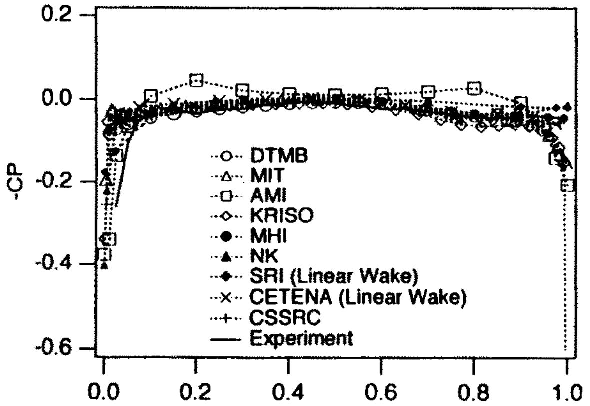


Figure 3.6 (b) CP for Case E (DTRC4119, J=0.833, With Hub, Devised Wake) on 0.7R Face

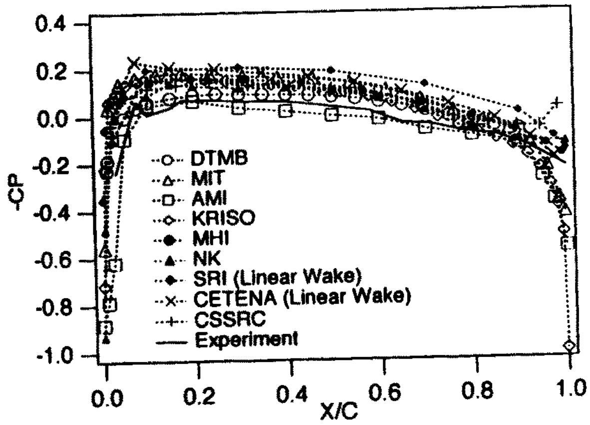


Figure 3.6 (c) CP for Case E (DTRC4119, J=0.833, With Hub, Devised Wake) on 0.3R Face

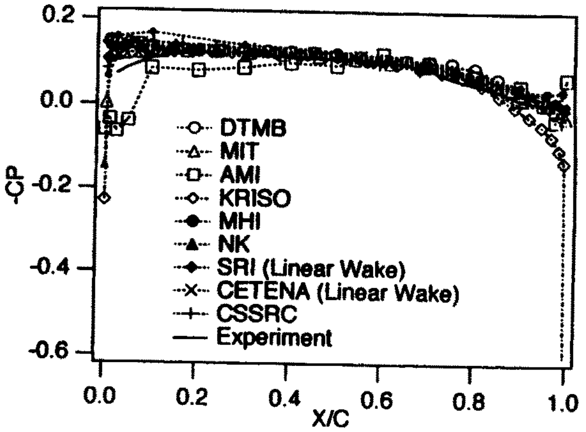


Figure 3.6 (d) CP for Case E (DTRC4119, J=0.833, With Hub, Devised Wake) on 0.9R Back

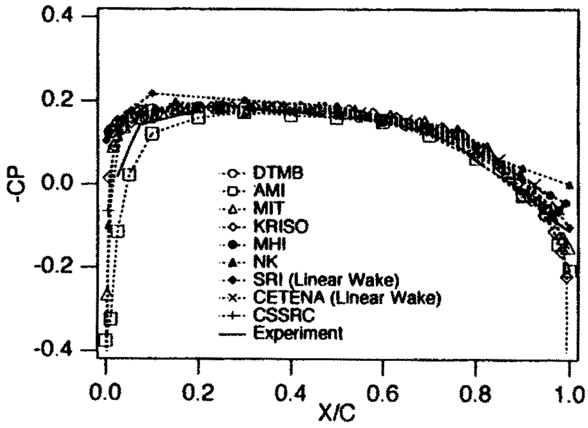


Figure 3.6 (e) CP for Case E (DTRC4119, J=0.833, With Hub, Devised Wake) on 0.7R Back

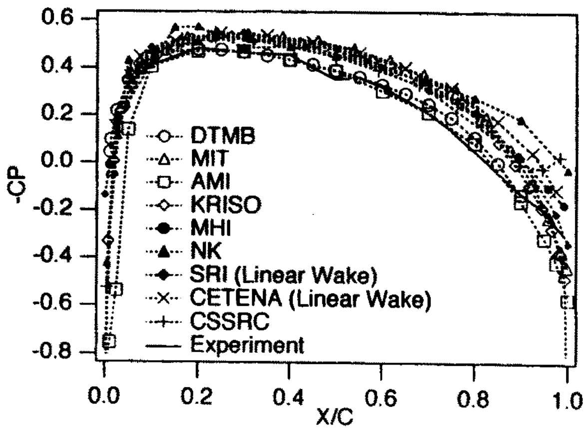


Figure 3.6 (f) CP for Case E (DTRC4119, J=0.833, With Hub, Devised Wake) on 0.3R Back

Pressure coefficients CP for the case H are shown in Figure 3.7 (a), (b), (c), (d), (e), (f). There seems to be more scatter in the results here than the case of DTRC4119.

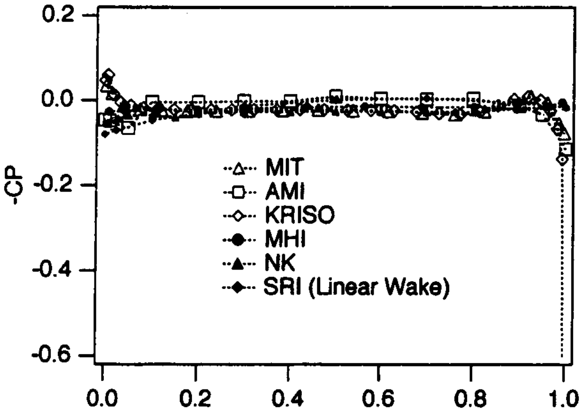


Figure 3.7 (a) CP for Case H (DTRC4842, J=0.905, With Hub, Devised Wake) on 0.9R Face

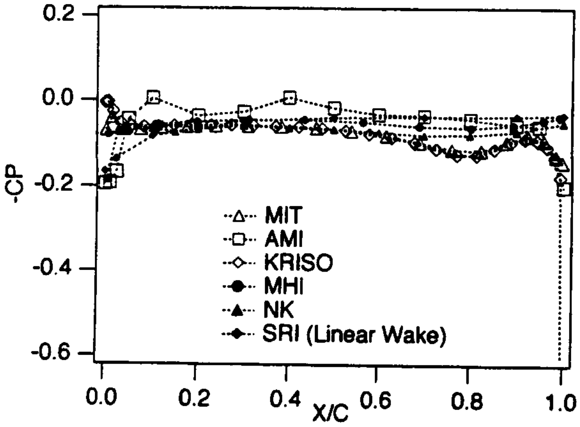


Figure 3.7 (b) CP for Case H (DTRC4842, J=0.905, With Hub, Devised Wake) on 0.7R Face

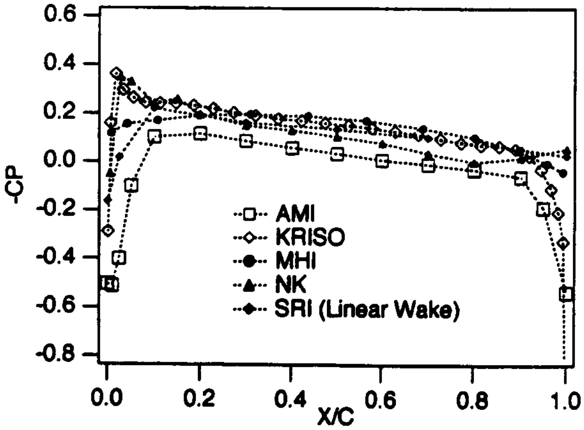


Figure 3.7 (c) CP for Case H (DTRC4842, J=0.905, With Hub, Devised Wake) on 0.4R Face

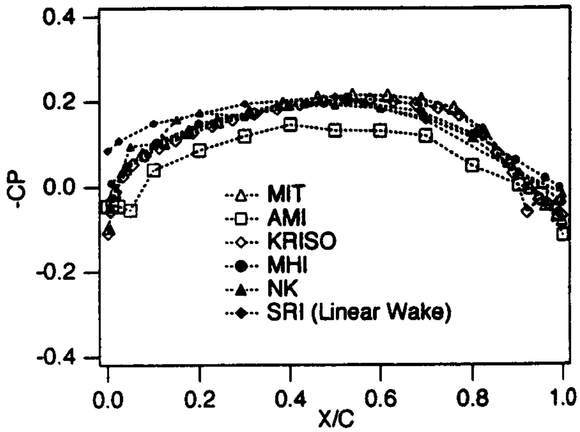


Figure 3.7 (d) CP for Case H (DTRC4842, J=0.905, With Hub, Devised Wake) on 0.9R Back

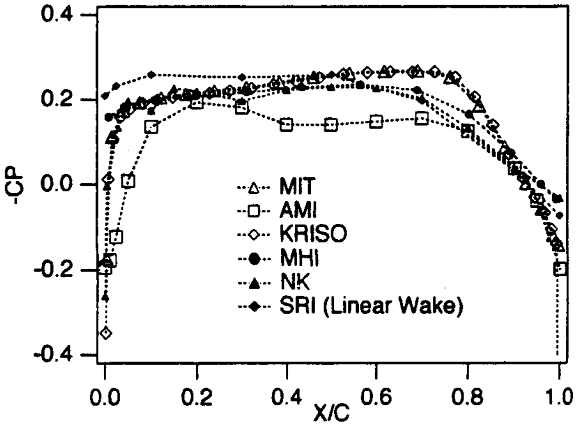


Figure 3.7 (e) CP for Case H (DTRC4842, J=0.905, With Hub, Devised Wake) on 0.7R Back

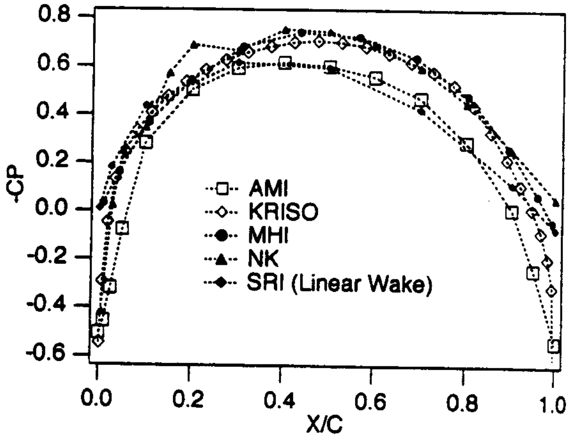


Figure 3.7 (f) CP for Case H (DTRC4842, J=0.905, With Hub, Devised Wake) on 0.4R Back

Viscosity affect on KT and KQ values is shown in Figure 3.8 (a), (b) (The Figures are quoted from the materials presented by DTMB). Viscous drag correction is essential to the correct prediction of the torque. Its affect on the prediction of the thrust is marginal.

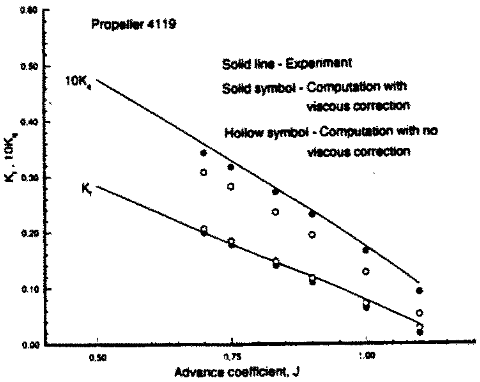


Figure 3.8 (a) Open Water Performance Curve, DTRC4119 ---Viscous Effect

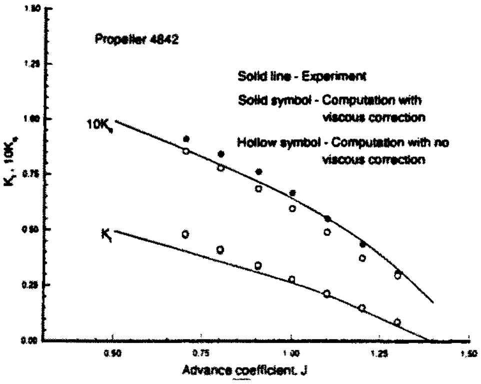


Figure 3.8 (b) Open Water Performance Curve, DTRC4842 ---Viscous Effect

The affect of hub appears as a high pressure on the blade near hub. The affect of the hub on thrust and torque is small in this calculation case. The details of the affect is discussed in materials presented by MIT. To understand the affect of the hub geometries, they have calculated the forces on propeller DTRC4119 by using three different hub geometries, along with the no hub results. Besides the hub model suggested by ITTC, they also used hub geometries with constant radii downstream and upstream. This is to simulate the real experiments in which the propellers may be driven either from upstream, or from downstream. Figure 3.9 shows these three different hub models. Results of their calculation are shown in Figure 3.10.

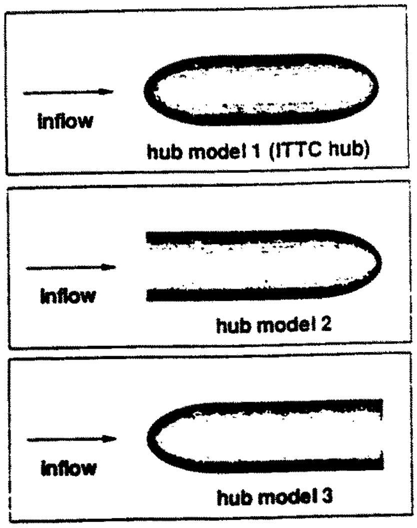


Figure 3.9 Different Hub Models

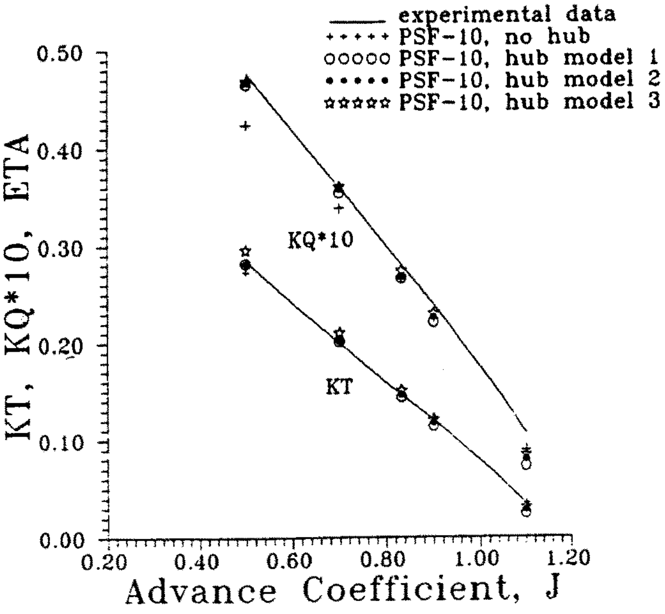


Figure 3.10 Open Water Performance, DTRC4119 With Different Hub Models

Although the affect of the devised wake does not seem to be completely clear, the devised vortex wake is very different from that of classical propeller theory. Examples of the devised wake are shown in Figure 3.11 (materials presented by MHI). Further study on the deformation of the vortex wake is expected.

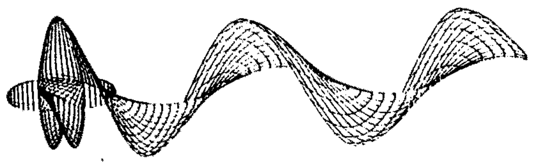


Figure 3.11 (a) Panel Arrangement of Devised Wake for DTRC4119

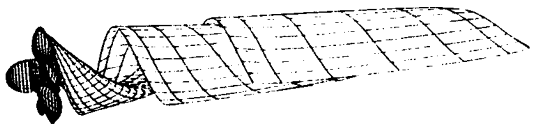


Figure 3.11(b) Panel Arrangement of Devised Wake for DTRC4842

Conclusion

1. The contributions to the workshop demonstrated the value of panel methods for propeller analysis. Most of the methods were potential based, rather than velocity based.

2. The predictions of performance for propellers were generally in good agreement with the experimental data.

3. Panel methods predicted the pressure distribution well except near the root, tip, leading edge and trailing edge. Further investigation on the arrangements of panels close to the root, tip, leading edge and trailing edge is required in order to improve the accuracy of predictions.

4. A rich numerical database was obtained from the workshop. These workshop results can be validated if the experimental data of Task 1 produces data of Benchmark quality.

5. For further development, the treatment of viscous corrections and the slipstream wake model must be studied.

Acknowledgments

These comparative calculations and the workshop were accomplished through the considerable effort of all participants. Participants in the comparative calculations are listed in Table 3.3 and the participants in the workshop are as follows:

- Massachusetts Institute of Technology, USA
- Analytical Methods, Inc., USA
- Chungnam National University, KOREA
- Korean Research Institute of Ships and Ocean Engineering, KOREA
- Hyundai Heavy Industries, KOREA
- Samsung Heavy Industries, KOREA
- Mitsubishi Heavy Industries, Ltd. Nagasaki R&D Center, JAPAN
- Nippon Kaiji Kyokai, Research Institute, JAPAN
- Yokohama National University, JAPAN
- Ship Research Institute, JAPAN
- Cento per gli Studi di Tecnica Navale, ITALY
- Bassin d'Essais des Carenes, FRANCE
- Maritime Research Institute Netherlands, The Netherlands
- Delft University of Technology, The Netherlands
- Versuchsanstalt fur Wasserbau & Schiffbau, GERMANY
- Canal Experiencias Hidrodinamicas, SPAIN

Our Korean colleagues contributed in the preparation for the workshop and KTTC supported the workshop with the conference room and many conveniences. The 20th ITTC Propulsor Committee would like to express their sincere gratitude to all participants, Korean colleagues and KTTC.

IV REVIEW IMPROVEMENTS IN MATHEMATICAL MODELS FOR PROPULSORS

Introduction

Developments in theoretical methods for ship hydrodynamics are progressing quickly due to both the recent advances in high-speed computers and the refinement of numerical algorithms. Awareness of this is reflected in the task to: "Review improvements in mathematical models for propulsors including surface panel method, lifting surface method, boundary layer, shear-propeller interaction, and Navier-Stokes solver. The objective of the present effort is therefore to continue the work undertaken within the last ITTC, reviewing of the achievements in mathematical modeling for propulsors, covering the period from 1990 to 1993.

Propeller-type flow-fields are common to a number of engineering applications, such as airplane propellers, ship propellers, helicopter rotors, and turbomachinery rotors. Ship propellers, however, take a special position within this wide range of applications as they work in a thick stern boundary layer. In addition, the flow-field is interactive, in that the propeller-induced flow depends on the inflow and inflow in turn is affected by the propeller action. Due to the complexity of this propeller-hull interaction problem, the development of methods for theoretical analysis of the ship viscous wake and propeller performance has progressed separately. Only recently have methods been developed that allow simultaneous consideration of both.

Very recently Reynolds Averaged Navier Stokes (RANS) equation solvers have been used to calculate the propeller/hull or inflow/propeller interaction and appear to be a promising method for a comprehensive treatment of the problem. On the other hand propeller flow is generally computed by means of potential flow based methodologies which range from simplified design techniques based on lifting-surface theory to fully 3-dimensional advanced panel methods. These methods account for the influence of the hull only via prescription of the effective inflow due to the wake past the stern and dealing with viscous effects at the propeller blades via semi-empirical corrections.

Despite their simplifying assumptions lifting-surface methods remain the most widely utilized tools in propeller design. Recently, surface panel methods have proven successful in analyzing the detailed flow structure around propellers and appear to improve the predictive ability, especially for highly skewed blades or ducted propellers. In the following sections the latest developments in lifting-surface methods, surface panel methods and RANS solvers for propeller flow predictions are reviewed .

Lifting Surface Methods

Lifting surface theory still has a dominant role in both propulsor design and performance prediction. For performance prediction it is simpler to use than the surface panel method and requires less computer time. This can be seen in the works of Chen (1990,1992), Chen and Tang (1990), van Gent and Holtrop (1992), Petrov et al (1992), Caprino et al (1992), Xu and Wang (1992), and Ikehata and Yamasaki (1992). During the three years since 1990, there are a few papers concerned with research on the analytical model and numerical methods. However, most of the propulsor papers presented in this period are concerned with extending the lifting surface method to solve problems in special applications or to design special propulsor devices and to predict their performance.

Conventional Propellers. Wang et al (1992) and Ishii (1992) determined the geometry of the slipstream wake by a solution of the flow. Wang et al treat the wake as part of the solution by a time-dependent vortex shedding procedure that begins with the start of the propeller rotation. They developed an unsteady vortex lattice method with this kind of model. However, Ishii used a simplified lifting surface method to determine the geometry and vortex strength of the slipstream wake. Then the usual lifting surface method is used after the geometry and vortex strength are determined through an iteration procedure. Ishii has found that sometimes the prediction of K_T and K_Q at off-design and low advance speed conditions are underestimated and considers that the influence of the tip vortex separation is worthy of being examined.

Wang et al (1992) have compared the calculations for two cases, with and without tip vortex separation. They show that K_T and K_Q are increased slightly when tip vortex separation is taken into consideration. However, the influence is even smaller on a highly skewed propeller than on a conventional propeller. Ishii (1992) presented his treatment of the model of tip vortex separation. The trailing vortices and tip vortices are rearranged through an iteration procedure started with a primary arrangement of tip vortex separation. The displacement of separation in the axial direction at the trailing edge of the blade, H_X tip, was measured by LDV and Ishii compared this with the calculated result shown in Figure 4.1.

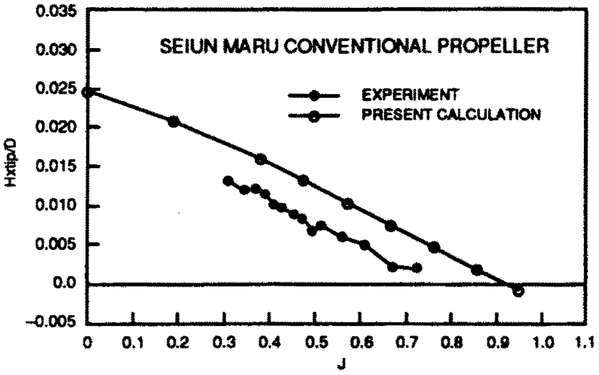


Figure 4.1 Displacement of tip vortex from blade surface versus advance coefficient

Ishii also calculated the K_T and K_Q for DTNSRDC 4118 with and without the tip vortex separation model and compared them with open water test results, shown Figure 4.2. With the separation model some improvement is observed but there still exists an under estimation at the low advance speed.

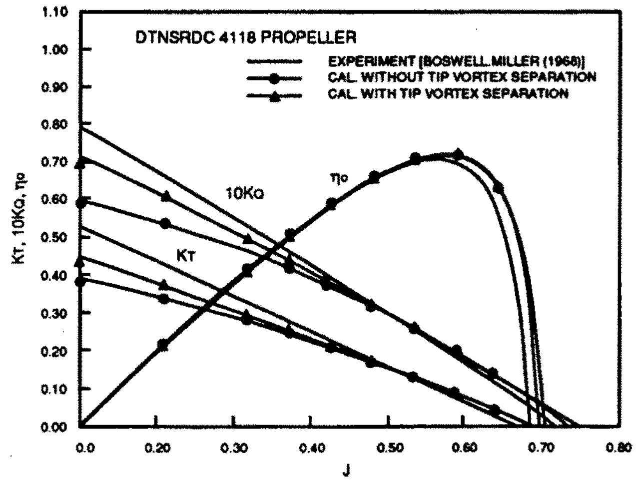


Figure 4.2 Comparison between calculated and measured open water characteristics.

Chen & Dong (1989) presented a vortex lattice method that takes into account the tip vortex and leading edge vortex separation. A new model representing the leading edge vortex separation is proposed. The separated leading edge vortex of the model rolls up and forms a concentrated vortex passing over the suction side of the blade to simulate the phenomenon observed. It shows that the K_T and K_Q are further increased if the leading edge vortex separation is modeled, however the calculated results are overestimated.

Liu and Cheng (1992) proposed a new treatment for the wake model which they call a partial roll-up wake model. They treat the contractions and pitch angles of the tip and hub vortices in the transition region in an empirical manner. The trailing vortex filaments between the tip and hub vortices are determined by a flow field calculation based on a force free principle. An iteration procedure is used. The authors further assume a thickness of the vortex sheet and a uniform distribution of vortices within the thickness. If any field point is located within the thickness of the vortex sheet, the induced velocity is treated as if it is inside a viscous wake. The induced velocity is calculated as a potential flow and the vortex sheet with zero thickness when the field point is outside the vortex sheet. Calculations for a sample case show that the position of the tip vortex core gradually separates from the trailing vortex sheet as it goes downstream. This phenomenon agrees with experimental measurements.

Wang et al (1992) theoretically investigated the influence of the water free surface on propeller performance when the propeller has shallow submergence. The authors use a vortex and source lattice lifting surface model and the existing solutions of the potential of a point source and a dipole under a linearized free surface. Equations are then set up to solve for the unknown dipole (vortex) distribution based on the no-penetration (boundary) condition on the camber surface. A simplified model of a propeller with infinite number of blades, zero thickness, without skew and rake is employed for that part of the calculation dealing with free surface effect since it is rather time consuming. The comparisons given by the authors show a good agreement between the calculated and experimental results. The authors extended their method by combining with the ventilation conditions on the blade surface to model a partially submerged ventilated propeller. The method had been presented earlier by Wang (1990).

Politis & Segos (1991) presented a computational method for lifting surface theory using general tensor analysis. The wake models are essentially the same as existing models. The authors use two wake models, i.e. the helicoidal model determined by empirical formulas and a rolled up model with some preassigned parameters. The effects of the difference between the models and changing model parameters on calculated K_T and K_Q are shown. The authors introduce a pitch correction to mainly account for the effect of boundary layer displacement thickness and a viscous correction to take account of the viscous drag. The calculated results are compared with the model experiments of NSRDC propeller 4381, 4382, 4383 and 4384. It is claimed that the deviation is rather large when $J < 0.5$ and the correlation is relatively good when $J > 0.5$.

Yang and Tamashima (1990) presented a method to predict propeller performance including the effect of the boss. The authors account for the boss effect with a surface source distribution and incorporate this with a lifting surface vortex lattice method. A prescribed wake model suggested by authors is used. The wake is also subdivided into the near wake where the pitch and radius of trailing vortices vary and the far wake which contains vortices of non-varying pitch and radius. The wake parameters i.e. pitch angles at trailing edge and at the end of near wake, contracted tip and hub vortex radii, and the position of the end of near wake, are all determined in an empirical and simple way. Both pitch and radius of trailing vortices in the near wake are linearly interpolated. The authors said that a small clearance is kept between the innermost blade section and the boss to avoid numerical difficulties. It is found that the shape of the upstream part of the boss has negligible influence on thrust, torque, and pressure providing that the upstream length is longer than twice the boss diameter. The numerical examples indicate that the influence of the boss is quite small as far as thrust and torque are concerned, but the boss has to be considered if the blade pressure distribution near the root is to be predicted accurately.

Glover (1991), using Choi's (1987) method, analyzed the propeller slipstream deformation. The alignment of both the lifting surface and the free vortex sheets with resultant flow is considered. To avoid expensive computer time, the author does not carry out the alignment at each iterative step. The initial alignment of the lifting surface, with a coarse lattice grid on the key blade, is carried out assuming that the slipstream is of regular helical form. The deformation of the slipstream is then calculated and is assumed to remain unchanged during the consequent final alignment of the lifting surface using a finer lattice grid. The calculated design camber ratio and nose-tail pitch distributions are compared with each other in cases using deformed and regular helical slipstream, respectively. The results are also compared with those from the M.I.T. lifting surface design program PBD10. It is seen that the discrepancy between pitch distributions are rather significant while the agreement between maximum camber distributions is relatively good.

Lee et al (1991) have developed new blade sections. Using lifting surface theory, they have designed propellers with their new blade sections and investigated the influence of chordwise loading shapes on the propeller performance. A comparison between the model test and the full scale trial indicates that the design was successful. Dang (1989,1990,1992) and Dang et al (1992) use a steady vortex lattice method for design and an unsteady vortex lattice method for performance assessment of the propeller at non-uniform inflow conditions. Dang incorporates a modification for new blade section design with the examination of unsteady performance in an iterative process for optimization. The Eppler method of profile design is used by Dang.

Stanier (1992) used the lifting surface codes GBPL 85 (by Szantryr 1985) and PSF - 2 (by Greely and Kerwin 1982), a panel method code PSF - 10 (Hsin et al 1991) and a viscous analysis code MACHO to predict K_T and K_Q, for three propellers designed with new blade sections. The calculated results were compared with those from experiments. The comparison shows that GBPL 85 and PSF - 2 did not accurately predict the performance of those three propellers and PSF - 10 gave an improved prediction but still had significant error. The viscous analysis code MACHO gave results in good agreement with the experiments. Therefore, the author proposes that the blockage effect on the flow through the blade passage due to blade thickness and the boundary layer of the blades plays an important role. The lifting surface methods can not produce the blockage effect. The surface panel methods have only the blockage effect from thickness while the viscous analysis methods have the blockage effect from both the thickness and the boundary layer.

Kim et al (1991) presented a transient analysis of propellers using a vortex lattice method. The authors think that the vortex lattice method is not limited by aspect ratio, camber or angle of attack as long as vortex breakdown does not occur above the surface of the model and separation occurs only along sharp edges. The authors keep the slipstream wake force free to obtain the position of the wake at each step of the calculation. The propeller was analyzed at the steady condition and in the transient maneuvering process. For the steady condition, the discrepancy between the calculated results and experiment for K_T increased with increasing load. The discrepancy for K_Q is significant within the whole range of J analyzed. So far, no experimental data of the transient process is available for validation.

Genoux et al (1990) solved the flow problem of the propeller with a body of revolution in front of it. However, it is considered as a potential flow and a linearized lifting surface theory, where the angle of advance is assumed to be the pitch angle of slipstream vortex line, is applied to the propeller. The authors claimed that the results are in satisfactory agreement with the experiments. Maruo (1990) gave his comments on their paper based on his experience. His opinion is that the simple linearized lifting surface theory is not able to provide results in satisfactory agreement with experiment. Maruo stated that the nonlinear deformation of the trailing vortex sheet in the slip stream must be taken into account.

Zhou and Yang (1992) use the streamline - iteration method for calculating the turbulent flow in the wake of a body of revolution. This method is combined with the lifting surface method to predict propeller performance with hull-propeller interaction taken into account. An iteration procedure is followed.

Wang and Cao (1992) presented a method to determine the optimum blade skew distribution. In the method, the bearing forces are calculated by a quasi-steady lifting surface theory.

Ishii (1992) extended his lifting surface method to predict partial and super cavitation occurring on propeller blades in uniform and non-uniform inflow fields. In the latter case, a quasi-steady method is employed. Comparisons between calculated and experimental results are provided in the paper.

The following two papers refer to the application of the Quasi-Continuous Method (QCM) lifting-surface approach to propeller design.

Murakami et al. (1991) and Nakatake et al. (1992) presented a QCM approach to calculate propeller characteristics in uniform inflow. The QCM uses the basic straight vortex and concentrated line source systems which sometimes gives undesirable vortex distributions near the blade tip in the case of coarse paneling. They propose a practical QCM that uses only a basic vortex system and the concept of the equivalent two-dimensional wing, by which the propeller characteristics and the pressure distributions on the blade surfaces are calculated. This method is applied to a conventional propeller and a highly skewed propeller operating in uniform inflow. Calculated results are compared with other calculations and experiments. Fairly good agreements are obtained.

Murakami et al. (1992) used the QCM to estimate the unsteady characteristics of propellers in a wake based on the method proposed in their previous paper. Taking into consideration the effect of the shed vortex system in addition to the bound and trailing vortex system, they obtain the strength of bound vortex distribution and then calculate the unsteady thrust and torque of propellers. For the pressure distribution on the propeller blade, they introduce the concept of an unsteady equivalent 2-D wing and then they calculate the pressure distribution using Moriya's method. They applied their method to the Wagner problem, to a conventional propeller, and to a highly skewed propeller which was fitted to the training ship "Seiun Maru". Compared with other numerical and experimental results, the method appears to give reasonable results.

Unconventional Propellers: End Plates. A systematical series of investigations for a propeller with end plates have been reported recently and will be reviewed here. Sparenberg (1987), de Jong & Sparenberg (1990), and de Jong (1991a, 1991b) document the optimization method for propellers with end plates. The method is concerned with determining the optimum efficiency and optimum circulation distribution along the spans of the propeller blade and end plate. The optimization approach is based on variational principles. The kinetic energy loss E_{kin}, viscous energy loss E_{visc}, potential ideal thrust T_{pot}, and viscous thrust deduction T_{visc}, are considered as a function of the circulation distribution (T_i) along the blade and end plate spans. The constraint condition is the required thrust T. The constrained variational problem is to minimize the energy loss,

$$J(T_i)=E_{kin}(T_i) + E_{visc}(T_i)-\lambda\{T_{pot}(T_i)-T_{visc}(T_i)-T\},$$

where λ is the Lagrange multiplier. The T_{pot}, T_{visc}, E_{kin} and E_{vsic} are estimated as functions of the circulation distribution.

Some parameters are selected based on lifting line design, including cavitation considerations. The optimization process and lifting surface theory are an integral part of the whole design process for a propeller with end plates as presented by de Jong (1992). It should be pointed out that all the investigations mentioned above are for the open water condition.

De Jong (1992) also discussed the effect of Reynolds number on the design. Two theoretical designs, one at model scale and another at full scale were compared and it was found that the differences were not large. De Jong suggests that the variational problem can be made considerably easier if only the kinetic energy loss is included. In the design example the gain in efficiency for the propeller with end plates relative to a conventional propeller (both at optimum condition) was nominally 1.7%.

Van Gent, et al (1992), and de Jong et al (1992) have carried out model tests for propellers with endplates and compared the results with a B series propeller. Conclusions drawn by the authors are as follows:

1. Up to 4 percent efficiency gain is possible for a propeller with endplates when both propellers are designed for the same power coefficient, diameter, rpm and advance velocity. If the rpm of a B-series propeller is allowed to be different from the propeller with endplates then the use of end plates only yields 1.8% higher efficiency at the condition of equal thrust.

2. De Jong's design method can not completely satisfy the K_T value preassigned. The authors attributed this shortcoming to the optimization and design methods used.

3. Van Gent, et al (1992) claimed that if the optimization and design fundamentals were not followed, the shape of the blades and endplates would cause an increase in both the kinetic and viscous energy loss and the propeller with endplates would have worse performance than a conventional propeller.

Unconventional Propellers: Ducted. Pylkkanen (1990) presented the optimization of duct shape and propeller location inside the duct to maximize the thrust of the duct. The optimization is defined as a combined variational and single variable extremum problem. The constraint conditions are the allowable minimum pressure for cavitation consideration and the length of roof-top region of pressure distribution on the inner surface of the duct. To simplify the problem, some assumptions were made, i.e. the propeller induced radial velocity on the duct is approximated by an empirical formula, the propeller induce velocities on the duct surface are unaffected by changes in duct geometry, the clearance between the duct and propeller tip is constant, and the propeller location has limiting constraints. The author claimed that the duct thrust can be increased by about 10-20%.

Pylkkanen (1991b) further investigated the influence of duct shape and propeller location on the performance for reference ducted propulsors and drew conclusions as follows. The duct should have a diffuser angle of about 6 degrees. The minimum diameter of the duct should be located at the distance of 0.4 chord length of duct from the leading edge of the duct and the propeller located at distance of 0.5 duct chord length from leading edge. He pointed out that the best location may be at about 0.6 chord length of the duct, however the high suction peak on the inner surface of duct will be a disadvantage. Pylkkanen (1992b) carried out open water tests of two ducted propellers which show that the conclusions mentioned above are broadly in agreement with the experimental results. Pylkkanen (1992a), also reported the result of self propulsion tests for two ships with ducted propellers located aft of the ship stern, for energy savings. The influence of advance coefficient on the performance of three different duct configurations was reported by Pylkkanen (1991a).

Kinnas and Coney (1992) developed a generalized approach to determine the optimum circulation distribution of a propeller operating inside a given duct via the use of the generalized image model. The propeller is represented by lifting lines, which are approximated by a finite number of horseshoe vortices. The optimum propeller circulation is then determined by employing a non -linear optimization technique developed by Kerwin et al (1987). A horseshoe vortex is equivalent to a constant strength dipole distribution on a surface confined by the horseshoe. The results for zero propeller tip gap cases have been shown in their paper. The circulation of the ducted propeller blade reaches its maximum value at the tip.

De Campos (1990) presented a three dimensional theory for the design of propeller ducts in a radically and circumferentially sheared axial onset inflow. The duct is modeled by a distribution of pressure dipoles and sources on a reference cylinder to represent the effects of loading and thickness of the duct. An actuator disk is used to represent the effect of propeller loading. Numerical results were given however they were not validated by comparison with other calculation methods or experimental data. From the author's results, some qualitative indication of the effect of a sheared wake field can be seen.

Other Unconventional Propellers. Yang et al (1991) extended their (1990) method to calculate the performance and flow field of a propeller with boss cap fins (PBCF). Some modifications to the wake model were made where the pitch angle of the blade trailing vortex in the near wake is aligned with the resultant flow, and includes the effect of the propeller, PBCF and boss. The calculated thrust and torque on the PBCF do not agree well with experiment data, possibly due to viscous flow effects on the PBCF and the boss. PBCF was also considered by Tamashita et al (1992) who used the VLM based on lifting surface theory as a tool in design and analysis.

Yang et al (1991) further extended their method to predicate the steady and unsteady performance of contra-rotating propellers. At the end of the near wake, trailing vortices are aligned to the circumferentially averaged flow including the velocities induced by both propellers. At the trailing edge of the propeller blade, the pitch angle of the trailing vortex is prescribed as the mean value of the nose-tail pitch angle of blade section and the angle of advance. The onset inflow velocity to a propeller consists of undisturbed inflow, the velocity induced by the hub and the time averaged induced velocity by the other propeller. Iteration is necessary.

Yang (1991) predicted the unsteady performance of contrarotating propellers operating in non-uniform inflows and at equal or unequal rates of revolution. The hub is disregarded in this case. The trailing vortex geometry determined by the corresponding steady calculation is used in the unsteady procedure and the shed vortices are taken into account. The frequency is in good agreement. However, the correlation of calculated amplitude of forces and moments with experimental data shows a significant amplitude discrepancy in the higher frequency components.

By using the vortex lattice method, Ikehata & Chanda (1989) developed a method for the theoretical calculation of the stator and propeller performance and a method for the design of the stator when the geometry of propeller is known. A stator has been represented by one spanwise line vortex along with rectangular vortex rings in the slipstream with Kerwin's roll-up model applied. The outside duct around the stator's tips is replaced by a circular vortex ring with a trailing vortex lattice cylinder downstream. The calculated results of the examples have been compared with the results of open water tests. It is claimed that good agreement has been achieved.

The lifting surface method has also been extended for the design and analysis of postswirl propulsor by Chen (1992) and ducted propellers with a postswirl stationary vanes or preswirl vanes by Zhang and Ma (1989,1992).

Hughes et al (1991) developed a method to analyze the flow around a ducted propeller with a pre-swirl stator. It is an extension of the method by Kerwin (1987). A boundary element method is used to solve for the flow induced by the duct and the hub, and a lifting surface vortex lattice method to solve for the flow induced by the propeller and stators. The duct and the hub are treated together as a single unit. The three-dimensional flow is computed separately around both the duct and hub, and the propeller and stator, with the interactions between them accounted for in a iterative manner. The interactions between the duct and the stators and between the duct and propeller are treated in a non-axisymmetric manner. However, only the circumferentially averaged interactions between the propeller and the stator are considered.

Gaafary & Mosaad (1991) solve the propeller and stator (or preswirl stator) by applying linearized lifting surface theory which is started from a linearized Euler equation. The concept of a body force is employed instead of the action of the blade force on the fluid. The equations can be reduced to Poisson's equation of pressure distribution. The mathematic treatment is essentially similar to that done by Tsakonas et al. Calculated results of a single propeller are compared with the experiments.

Surface Panel Methods

The surface panel method discussed here treats a lifting body such as the propeller blades, hub, duct, etc. by distributing singularities on surface panels on the surface of the lifting body. Flow field around the lifting body is assumed to be potential flow. In this method the flow field is solved using a boundary integral equation with the boundary condition on the flow boundary. This method is also called the, surface panel method or the boundary element method.

The method is used in the flow analysis of numerous aircraft problems. This method is also used in many nonlinear problems of ship hydrodynamics. Recently, the application of the method to the hydrodynamic analysis of marine propellers has received considerable attention.

Lifting surface theory is currently the primary analysis method for marine propellers and is widely used throughout the world. However, lifting surface theory is a thin wing theory (i.e., camber surface) and complicated approximations are necessary to treat the effect of thickness properly. For the surface panel method, the panels are on the thickness surface. Thus, the method is considered to be an improvement over the lifting surface method. The surface panel method is becoming a very useful method for analysis of marine propellers. As shown in this committee report, the surface panel method reviewed by the 19th ITTC has matured in these last 3 years. Many organizations have started to utilize the surface panel method. These advances were shown in the Workshop on the Surface Panel Method for Marine Propellers organized by 20th ITTC Propulsor Committee. The workshop evaluated the use of surface panel methods in the design and analysis of marine propulsors and the results from the workshop promote the use of the panel method in the analysis of propeller performance.

Basic features of Surface Panel Method. Surface panel method analyzes the potential flow around the lifting body with an accurately determined panel arrangement on the surface of the lifting body.

For a propeller (or duct, stator etc.) operating in an unbounded flow field, it is assumed that the vortex wake emanating from the trailing edge of the blades is infinitesimally thin and that the flow field is incompressible, inviscid and irrotational. There then exists a velocity potential in the flow field. This velocity potential in the flow field is expressed using Green's identity formula and boundary values as:

$$\phi=-\frac{1}{4\pi}\int\int\frac{\partial\phi}{\partial n'r}\left(\frac{1}{r}\right)dS+\frac{1}{4\pi}\int\int\phi\frac{\partial}{\partial n'r}\left(\frac{1}{r}\right)dS \qquad (1)$$

Equation (1) is the basic starting formula for panel methods. The velocity is expressed as:

$$V=\nabla\phi=\frac{1}{4\pi}\int\int\frac{\partial}{\partial n'}\nabla\left(\frac{1}{r}\right)dS+\frac{1}{4\pi}\int\int\phi\nabla\frac{\partial}{\partial n'}\left(\frac{1}{r}\right)dS \qquad (2)$$

The velocity field produced by the doublet distribution on panels is given by the second term of equation (2). This term can be integrated by parts to obtain:

$$V_D=\nabla\phi_D=-\frac{1}{4\pi}\iint\gamma\wedge\nabla(\frac{1}{r})dS-\frac{1}{4\pi}\iint\phi\nabla(\frac{1}{r})\wedge t dS \quad (3)$$

The surface panel method employs one of the above equations. Singularities such as source, doublet, or vorticity are distributed on the body surface which is a boundary of the flow field. The problem is solved using an integral equation with a boundary condition. The equation is discretised for numerical calculation. The variety of surface panel methods is due to the choice of the integral equations, singularities, and the method of discretisation.

Conventional propellers. The review of the surface panel method for marine propellers was started by the 19th ITTC Propulsor Committee. Studies before 1990 were reviewed in that report. Studies from 1990 to 1992 are reviewed here. The trend in this period is as follows. Numerical techniques developed in the previous period were refined and settled. Many other organizations started to utilize the surface panel method. The method is in the process of being used for a wide range of applications such as non-uniform flows on a propeller, cavitation flows around a propeller, etc.

The numerical techniques of the surface panel method for propellers presented before 1990 are Hess and Valarezo (1985), Maskew (1985), Yang and Jessup (1988), Kerwin et al. (1987), Ling et al. (1985, 1986A, 1986B), Hoshino (1989A, 1989B), Feng and Dong (1986), Koyama et al. (1986) etc. Almost all are reviewed in the 19th ITTC Propulsor Committee report.

Yang (1990) reviewed panel methods and their underlying theory with regard to hydrodynamic analysis of propeller performance. Results of propeller blade analysis with the VSAERO panel method of Maskew (1985) are presented, and compared with the vortex lattice method and with experimental data. The panel method, which includes consideration of propeller hub effects, gives predictions in good agreement with experimental data.

Hsin et al. (1991) studied a potential-based panel method for highly skewed propellers. They demonstrate that hyperboloidal panels substantially improve the performance of the method relative to the use of planar panels. A grid oriented along constant radii generates panels with high aspect ratio and high skewness near the propeller tip, which results in inaccurate calculations of velocities. They developed a "blade orthogonal grid" to solve this problem and obtained improvements with this preliminary scheme. The improved propeller panel method is tested for convergence, and compared to other methods.

Kinnas (1992) analyzed the incompressible, inviscid flow around a wing in arbitrary inflow as a perturbation expansion with respect to wing thickness, superimposed on the zero thickness lifting-surface problem. The method is applied for several wing and propeller blade geometries and the results are shown to be in very good agreement with those from the existing potential based panel method.

Suh (1992), and Suh et al. (1992) presented closed-forms for computing the induced potentials and velocities due to a bilinear density distribution of source and/or doublet singularities over a planar panel. The closed-forms are more computer-oriented and explicit than those derived previously so they can obtain the matrix elements of the linear system of algebraic equations in the application of the surface panel methods.

Ryo et al. (1992) presented the direct formulation of the boundary element method (BEM) for the analysis of three-dimensional flow around the marine propeller based on the thick wing theory. The accuracy of their method was compared with experiment results.

Hoshino (1990, 1991) measured flow fields around a propeller using a 3-component Laser Doppler Velocimeter (LDV). Based on the experimental finding that the pitch of the tip vortices are smaller than the pitch of the inboard trailing vortex sheets, the surface panel method with a deformed wake model of the trailing vortices is proposed. The pressure distributions on the blade and the flow field around the propeller are calculated by his surface panel method. Better agreement with experiment is observed for the pressure distributions near the hub when the hub effect is considered in the calculations. It is shown that the calculated flow fields around the propeller and the open-water characteristics of the propeller are in good agreement with experimental data.

Maitre and Rowe (1991) presented a nonlinear method for calculating the potential flow around lifting bodies. The perturbation potential is taken to be unknown at the surface of the body while its value is fixed inside the body. This method is particularly well suited to cases of thin structures. It is applied to calculate the flow around a noncavitating marine propeller and the problems of the Joukowski condition, the propeller mesh, and the wake description are examined and solutions proposed. The influence of the hub and the wake on numerical results is analyzed. Bogdan (1991) studied a direct boundary element method which was adapted to the peculiarity of the marine propeller.

Caprino et al.(1992) studied a surface panel method for the steady analysis of naval propellers. The method is based on a low-order potential field formulation and employs a constant distribution of sources and dipoles on flat quadrilateral panels.

Wang and Cao (1992) applied a perturbation potential based panel method to the hydrodynamic analysis of marine propellers. Detailed treatments of panel generation and influence functions are conducted to provide fast and robust computation. A new piecewise linear pattern is proposed for chordwise and radial panel spacing. A fictitious trailing edge panel approach is introduced to implement the equal pressure Kutta condition at all the trailing edges with finite thickness. Convergence of the method for the problems are shown. The results include pressure distributions and open-water characteristics and are in good agreement with experimental data.

Almost all methods mentioned above employ the potential based panel method. Yamasaki and Ikehata (1992) proposed a different method. They studied the application of the surface vortex lattice method to marine propellers. With the surface vortex lattice method based on general vortex lattice method, it is possible to simulate a lifting body with thickness and volume effects by distributing horse-shoe vortices on the surface of the body. The advantages of this method compared to other lifting body methods are that it is easy to simulate a trailing vortex wake geometry behind propeller and that the Kutta-condition is satisfied automatically by convecting the trailing vortices. The geometry of the wake can be calculated by an iterative procedure initiated with the linear wake model and all vortices are convected to new positions step by step with small time intervals. In this paper, the propeller open-water characteristics, blade pressure distribution, and the geometry of the wake for three propellers types have been calculated. The results of these calculations are in good agreement with experiments and other theoretical results.

The workshop on the surface panel method for marine propellers was planned as a task by 20th ITTC Propulsor Committee for the purpose of promoting the use of the method. Many organizations performed the comparative calculations and attended the workshop. In the workshop it was shown that many organizations recognized the importance of the panel method for the analysis of propellers and are actively using the method.

Unsteady Calculations. Since marine propellers operate behind the ship hull, surface panel methods must be developed for the analysis of propellers in unsteady flow. Kinnas et al. (1990) analyzed the unsteady flow around an open marine propeller subject to a spatially non-uniform inflow by utilizing a time marching potential based panel method. An efficient algorithm was implemented in order to ensure an explicit Kutta condition (i.e. pressure equality) at the blade trailing edge at each time step. The numerical method is shown to be very robust for a broad range of reduced frequencies as well as consistent with known analytic solutions and with an existing unsteady lifting surface method. They also developed a hybrid panel method for the analysis of the unsteady flow around ducted propellers. It combines an unsteady lifting surface method for the propeller with a potential based panel method for the duct. The propeller is essentially treated with an existing time marching vortex lattice scheme which has been developed for open propellers, with the effects of the duct being accounted for via the generalized images of the propeller singularities with respect to the duct. The proposed method is shown to be appropriate for treating unsteady ducted propeller flows especially when a given ducted propeller geometry must be analyzed for various inflow conditions.

Kinnas and Hsin (1992) analyzed the unsteady flow around a marine propeller subject to a spatially non-uniform inflow by utilizing a time- marching potential-based low-order boundary element method. Constant strength dipole or source distributions are used on each of the quadrilateral panels representing the propeller blades and their trailing wakes. Linear dipole distributions are used at the first wake panels adjacent to the blade trailing edge in order to render the method insensitive to the time step size. The numerical method is shown to be consistent with known analytic solutions for two-dimensional unsteady flows. The robustness of the method is tested in the case of a highly skewed propeller in a given wake inflow and the results are shown to converge quickly with the number of panels for a broad range of reduced frequencies.

Koyama (1992A) presented a panel method for analysis of unsteady flow around a propeller. The purpose of the study was to simulate the potential flow around a propeller operating in arbitrary flow. The numerical calculation is carried out for the unsteady flow by time marching with the development of the vortex wake. The Kutta condition at the trailing edge of the blade is discussed and an explanation is provided for the doublet matching numerical Kutta condition of the potential based surface panel method. Numerical accuracy of the paneling and time marching was investigated. Flow characteristics due to the effect of neighbor blades and the effect of existence of hub are discussed. A propeller operating in non-uniform flow was investigated with calculations carried out for sinusoidal inflow. The result were compared with an unsteady method based on frequency domain analysis.

The prediction of cavitation on the propeller blade requires accurate pressure distribution estimates, especially near the leading edge and the tip of the blades. The surface panel method is considered a useful tool for the calculation of cavitation. Kinnas and Fine (1992) studied the unsteady flow around a cavitating marine propeller with a nonlinear method that employed a low-order potential-based boundary element method and a time-marching scheme. The kinematic and dynamic boundary conditions, which are fully three-dimensional and time-dependent, are satisfied on the propeller surface beneath the cavity and on the portion of the blade wake surface which is overlapped by the cavity. The formation and algorithm were developed to treat arbitrary cavity planforms. The results from the numerical method are shown to converge quickly with the number of panels and with the number of time steps per propeller revolution. The calculated cavity shapes are shown to satisfy the imposed dynamic boundary condition with acceptable accuracy. Computed cavity planforms are compared to those from linear theory with leading edge corrections.

Lee et al.(1992A) presented a potential-based panel method for the analysis of both a super cavitating and a partially-cavitating two-dimensional hydrofoil. The method employs normal dipoles and sources distributed on the foil and cavity surfaces. It was shown that the source plays an important role in positioning the cavity surface through an iterative process. The cavity closure condition was found very effective in generating the cavity shape. Upon convergence, the method predicts the cavitation number together with the lift, drag, and surface pressure distribution for a given cavity length. Systematic convergence tests of their numerical method show fast and stable characteristics. Good correlations are obtained with existing theories and experimental results for both partially- and supercavitating flows.

Lee et al. (1992B) presented a potential-based boundary element method for the analysis of a super or partially-cavitating two-dimensional hydrofoil at a finite submergence beneath a free surface, including the effects of the finite Froude number and the hydrostatic pressure. Free surface sources and normal dipoles are distributed on the foil and cavity surfaces, their strength being determined by satisfying the kinematic and dynamic boundary conditions on the foil-cavity boundary. The cavity surface is determined iteratively as a part of the solution. Numerical results show that the wave profile is altered significantly due to the presence of the cavity. The buoyancy effect due to the hydrostatic pressure, which has usually been neglected in most of the cavitating flow analysis, was found to play an important role, especially for the supercavitating hydrofoil; the gravity field increases the cavity size in shallow submergence and decreases the size when deeply submerged, while the lift is reduced at all depths.

Unconventional Propellers. Valarezo (1991) presented a surface panel method capable of computing the flow on and about arbitrary multiple rotor propulsors. The complex rotor-to-rotor aerodynamic interaction is handled by computing time-averaged flows for each rotor and using a superposition technique to account for all rotor influences. The various features of the method are described and computed results for multiple rotor configurations are presented for both isolated and installed cases. Limited comparisons with experimental data show good agreement.

Kawakita (1992A, B) measured the velocity distribution downstream of a ducted propeller in a cavitation tunnel by the use of a 3-component Laser Doppler Velocimeter. A considerable change in the hydrodynamic pitch of the ducted propeller was observed in comparison with that of the propeller without the duct. Based on these velocity measurements around the ducted propeller, a new wake model is proposed for the panel method that consider the effect of propeller loading. The flow fields around the ducted propeller calculated by the use of this method are shown to be in good agreement with the measured data. The open-water characteristics of ducted propellers calculated by this method also show good agreement with the experimental data.

RANS Solvers

The 19th ITTC report provided a review of viscous flow methods used for propellers. For the propeller blades the reviewed methods relied on boundary-layer assumptions while computational techniques based on the solution of the Navier-Stokes (NSE) or Reynolds Averaged Navier-Stokes (RANS) equations were reviewed in connection with the problem of propeller/hull or inflow/propeller interaction.

In the following the recent developments are reviewed according to a main subdivision which groups propeller flow, propeller-hull interaction, grid generation studies and applications to unconventional/innovative concepts. A brief review of the main features of RANS solvers is included, from the point of view of propeller applications. It must be noted that the present review, besides RANS, covers also Euler solvers (that is the particularization of NSE to the inviscid flow case) as the field of application and the basic numerical aspects are quite similar.

Basic Features of RANS Solvers. RANS solvers are based on the numerical solution of the Navier-Stokes equations governing the flow of a viscous fluid. Usually these equations are time-averaged according to Reynolds. The closure of the resulting equations system is obtained by introducing suitable turbulence models relating the cross-correlation of the fluctuating fluid velocities with the time-averaged fluid velocities. The most popular turbulence models are the K-ε model and the Baldwin-Lomax model. The two parameters K-ε model requires the numerical solution of two additional Partial Differential Equations (PDEs) along with the three momentum equations and the continuity equations for pressure and fluid velocities. The Baldwin-Lomax model is a mono-parameter algebraic model dependent upon the distance normal to the wall.

The numerical solution of RANS equations is obtained by discretising the PDEs for a volume grid of the fluid domain exterior to the ship, assuming the free-surface to be rigid, that is, the so-called *double-model* approximation.

Two main alternative discretisation techniques are available, the Finite Difference Method (FDM) and the widely used Finite Volume Method (FVM). FDM is based on the discretisation of the partial derivatives on the grid points using suitable numerical scheme to produce the approximate differencing. FVM relies on the integration over control volumes of finite size (called "cells") which, taken together, wholly fill the domain under study.

In both approaches the resulting set of nonlinear algebraic equations is iteratively solved. Various techniques are adopted for the solution of the linked hydrodynamic equations for velocity and pressure in the case of incompressible fluids. The most popular are variants of the Semi-Implicit Method for the Pressure-Linked Equations (SIMPLE) algorithm and the Poisson-pressure technique. The central problem arises from the double-linking of the equations for the three velocity components: they share a pressure and they must jointly satisfy the continuity equations.

RANS equation solution requires boundary conditions to be imposed at the body surface. The physical boundary conditions would be a no-slip condition for the velocity at the body surface. To avoid the required clustering of grid points a wall-function approach is usually preferred, providing a suitable law for the velocity profile inside the near-wall boundary-layer.

RANS solvers appear to be the most promising tools to offer reliable practical answers to a variety of challenging engineering problems. It has also been pointed out by Marvin (1993) that the requirement for a careful experimental validation has increased in importance in order to determine the accuracy of physical modeling. This is especially true in the case of high Reynolds number flow conditions and ship propulsors.

There are essentially three ways of including the propeller effect on a flow field calculated using the RANS solver. The first approach is the so-called inner boundary condition method. A pressure jump Dp is specified, depending on space and time, at the propeller inlet plane, and the propeller induced velocity Vp at the outer boundary and exit plane. Dp and Vp are obtained from inviscid propeller calculations for a given inflow.

The second approach is the body-force distribution method. In this method, a body force Fb distribution, varying in time and position, is specified at the propeller location and inserted as an external forcing term in the viscous flow momentum equations. The actual body-force distribution is obtained by conventional inviscid propeller flow calculations, given the inflow velocity. Presently it seems to be the most effective methodology.

The third approach is the velocity-field distribution method. According to this approach the total velocity field V is decomposed into a propeller component Vp and an effective velocity component Ve. Vp is obtained from propeller flow calculations for a specified inflow while Ve is solved from the governing viscous flow equations.

It should be noted that, in all the three approaches, propeller characteristic variables Dp, Vp, Fb depend on the inflow velocity which in turn depends on propeller characteristics, thus an iterative procedure is needed.

Such approaches suffer however from the fact that they do not model the true geometry of the propeller and the complex phenomena of blade-to-blade interaction. This can only be properly done by including the actual rotating propeller into the viscous flow methodology.

Propeller flow. Oh and Kang (1992) presented the results of an investigation into the viscous flow around a marine propeller mounted on an axisymmetric stern. The RANS equations for the steady propeller flow were formulated in the rotating coordinate system fixed on the propeller, using a standard K-ε model for the turbulence and FVM for discretisation. The propeller inflow was imposed based on a separate viscous flow calculation for the extended region around the axisymmetric body. The propeller was modeled by an actuator disk having an uniform distribution of momentum source corresponding to the propeller thrust. To avoid the numerical difficulties related to the flow resolution near the hub/blade surface the wall-function technique was employed.

The method was applied to the 3-bladed propeller investigated by Hyun and Patel (1991) in a wind-tunnel. The propeller model was mounted at the stern of an axisymmetric body and was tested at J = 0.812 and Re = 1.55E+6 (on the body length) and 1.44E+6 (on the chord length). The mean velocity, static pressure, turbulent kinetic energy and Reynolds stress measurements were carried out downstream of the propeller using a five hole Pitot tube and a hot-wire anemometer.

The complete calculation was found to converge after about 1000 iterations and 5.5 hours CPU-time on a CRAY-2S supercomputer. Results were compared in terms of axial, tangential and radial velocity profiles and turbulent kinetic energy profiles at several cross planes and in terms of iso-wake contours and cross-velocity on the propeller plane. Agreement was good for velocity profiles downstream of the propeller and fair in the near wake region. The flow-structure, including tip-vortex generation, was predicted well by the simulation.

Stanier (1992) reported a study on the design and evaluation of propeller blade sections, based on the application of a classical lifting-surface method and an innovative RANS solver which accounts for viscous losses. An explicit, steady, incompressible RANS FVM-based solver for the marine propeller was developed from a computer code for the analysis of 3D viscous compressible flow in turbomachinery blade rows. The formulation includes a reference system rotating with the blades, which introduces extra terms to allow for Coriolis and centrifugal effects in the momentum equation. The code used a time marching method to achieve convergence to the steady-flow condition. On a CRAY 2 supercomputer the run with a double-precision version of the code required 1 CPU hour.

Uto (1992) presented an application of a RANS solver to the computation of incompressible viscous flow around an open-water marine propeller. The governing equations are formulated in a reference system fixed on a rotating blade and a pseudo-compressibility technique is used. The no-slip condition was imposed at the blade surface while on the hub surface a free-slip condition was adopted to avoid excessive grid clustering near the wall. The Kutta condition was not necessary at the tip and the trailing edge as it is implicitly satisfied within a fully viscous approach. Due to the hub free-slip boundary condition no hub-vortex system was simulated in the study.

The code was applied to the Seiun Maru 5-bladed controlled pitch propeller at Re = 10,000, far lower than model or full scale, so that a laminar flow condition over the blades could be simulated. Computations were made at relatively high advance coefficients (J > 0.7). The code was able to provide a qualitatively good description of the detailed flow structure near the blades, such as development of boundary-layers and separation on the blades, tip vortex generation and trailing vortices. The predicted tendency was confirmed by observations using LDV.

An Euler equation solver for flow analysis around a marine propeller was presented by Uto and Kodama (1992). An application was made to a configuration consisting of the Seiun Maru propeller with an axisymmetric boss. On the boss and blade surface a free-slip condition was imposed. On the blade surface a Kutta condition at the trailing edge was further imposed. Results were reported for very high pitch ratios (2, 5 and 10) in terms of pressure contours and velocity distributions on the blade and boss. A comparison with a standard lifting surface method (with and without viscous corrections) was further performed and good agreement was found for chordwise load distribution, thrust and torque coefficient.

An application from another engineering field, but closely related to the ship propeller problem, was presented by Abdallah (1990) where the Euler equation solver was used for the analysis of the flow inside a turbomachine.

Propeller-hull interaction

An example of the actuator-disc approach was given in the work of Masuko (1989), where a pressure jump model was used within a RANS solver. Calculations of the wake flow at the propeller plane were performed with and without the propeller, on a mathematical ship model with Lewis form hull lines at Reynolds number 5.2*10E+6, and were compared with the corresponding measured data. In the measured results the center of the bilge vortex appeared to shift downward due to propeller suction and the same tendency was found in the computation. The iso-wake profile calculations qualitatively agreed with the measurements in the sense that the iso-wake contours were attracted by propeller action from the lower side to the centerplane.

It has been recognized that pressure jump models introduce a discontinuity in the fluid pressure which can lead to numerical troubles in the solving algorithm and eventually to divergence of the solution. It is now widely accepted that the use of an equivalent body-force distribution over the propeller disk works better from the numerical point of view.

Zang et. al. (1992) presented an integrated methodology to study the ship wake with an operating propeller, iterating between a viscous flow procedure and a propeller flow procedure. The viscous flow was analyzed by means of a RANS solver while the propeller flow was investigated via a standard lifting line procedure.

The presence of the propeller is modeled as a steady distribution of body-force on the propeller volume. The body-force is given by the lifting-line procedure once the inflow velocity is evaluated with the viscous procedure. The inflow velocity produced by the viscous procedure depends on the prescribed body-force distribution. Thus, the lifting-line calculation is iterated until the viscous flow computation converges. Once the calculation has converged it is possible to evaluate the effective propeller performance by computing the actual thrust and torque coefficient.

Three test cases were presented. First the prediction for a propeller-shaft configuration (4-bladed propeller) was compared with measurements by Voigt (1993). Thereafter results were given for an axisymmetric body with and without an operating propeller (7-bladed propeller). Comparison was made with measurement data by Huang (1976). Finally the 3D flow around the stern of a Series 60 - Cb = 0.6 ship hull was predicted with and without the propeller (5-bladed propeller). Good agreement with the experimental data of Toda et al. (1990) was found in terms of both axial and cross-plane velocity.

Moshkin et al. (1989) presented a series of analytical and numerical studies on the Navier-Stokes equations for self-propelled bodies of simple geometry, such as a circular cylinder, a sphere, and a pair of rotating cylinders.

Grid Generation. A problem common to all CFD methods is the need for a computational grid to discretize the fluid domain. The grid must be regular (that is smooth and orthogonal or quasi-orthogonal) to ensure convergence of the numerical scheme and fine (that is, clustered in the vicinity of sharp changes in the body geometry) to provide the necessary accuracy in flow resolution. The requirement of efficient grid-generation methods is particularly demanding in the case of marine propellers, especially for propeller-hull configurations or highly-skewed propellers. In this case the employment of special multi-block techniques, that is, different separate grid zones, seem to be quite effective.

Stanier (1992) used a multigrid technique to increase the rate of convergence of the RANS solver. The method consisted of combining groups of cells into a single block. Each block can be considered as a larger single cell and handled by the flow solver in the same way as with the smaller cells.

Uto and Kodama (1992) proposed an innovative grid generation method for their Euler solver. The method, called Implicit Geometrical Method, consists of two parts, the surface-grid and the volume-grid. The first part of the method starts with the offset data for the blade and the hub and defines a spline surface. The surface grid is then iteratively built-up to ensure suitable clustering of the grid points at tip, leading-edge and trailing-edge. Once the surface grid is determined , the second part of the method sets the surface grid on a spiral surface and generates a streamwise grid along the spiral surface and a blade-to-blade grid. The grid is iteratively modified to ensure smooth grid lines and clustering of the grid points in the vicinity of the blades.

Application of the Implicit Geometrical Method grid-generation method to the RANS solver is given by Uto (1992). Two grids, one coarse and one fine, were used for the calculations. Minimum grid spacing in the circumferential direction corresponds to $0.1\sqrt{Re}$, to accurately resolve the surface blade boundary layer.

Oh and Kang (1992) utilized an algebraic grid generator for their RANS solver. The grid used for the computations was constituted by 132, 40 and 20 grid points in the streamwise, radial and circumferential directions respectively. Grid points were clustered near the leading and the trailing edges and the propeller tip.

Unconventional propellers

The application of CFD to the analysis of the interaction of a full ship stern and a propulsor allows one to handle complex design problems. These include, for example, the determination of the correct self-propelled condition for unconventional or innovative propeller-hull configurations, which cannot be accurately considered by conventional design procedures.

Examples of the integrated use of CFD codes to the practical design of a propeller-hull configuration is provided in the papers of Chen, Peterson et al. (1991) and Dai, Gorski et al. (1991), concerning the study of an IDP (Integrated Ducted Propulsor) concept. IDP consists of a large shroud (duct) enclosing a set of blade rows (rotors and stators).

In the first paper a design methodology was proposed which incorporated existing CFD codes. In particular the methodology used the XYZFS free-surface potential-flow code, including propeller effect through equivalent sink-disk representation, to determine the optimum propeller location in terms of wave-making resistance. The VSAERO lifting-body potential code was used to calculate the pressure distribution around the bare hull and the velocity distribution, including the effect of the hull boundary-layer, at the proposed inlet location of the shroud. The DTNS3D RANS code was proposed to design the entrance section from the inlet to the blades. The authors showed results of the application of the methodology to the IDP providing evidence of the feasibility of the concept and the effectiveness of the integrated use of CFD into a design procedure.

In the second paper Dai, Gorski et al (1991) presented results of DTNS3D RANS analysis of an axisymmetric body with a full stern to demonstrate some design features of the stern/ducted propulsor. RANS equations are solved by using a pseudo-compressibility technique and the Baldwin-Lomax turbulence model. The propeller effect was modeled by an equivalent actuator disk, with the propeller forces on the disk prescribed by the application of the Kutta-Joukowski law for the force acting on a bound vortex. This required the interactive use of a propeller-flow code, in particular a Vortex Lattice Method (VLM). A validation of the proposed methodology was performed by using Huang's [ibid] experimental results for an axisymmetric body with and without a conventional propeller. Calculations were performed at Re = 5.9E+6 with and without the propeller and good agreement was found with experimental results. Once validated the procedure was applied to the full stern concept, analyzing two alternative duct configurations.

A RANS solver was used in the analysis of innovative flying and swimming propulsion devices by Videv and Doi (1992). They studied the unsteady viscous flow pattern and unsteady hydrodynamic loads produced by a rigid, pitching, 2D hydrofoil. The hydrofoil performed harmonic oscillations with respect to a pivot point ahead of the trailing edge. The chord Reynolds number was 5000. In order to compare the computational results with the real flow phenomena, an experimental flow visualization of the pitching motion of a hydrofoil was performed.

Application of an Euler solver to the analysis of a water inlet for water-jet propulsors was presented by Forde et al. (1991). The governing equations were solved by a time-marching procedure. Grid generation was done by the multi-block transfinite algebraic method. Water-inlet geometry was defined on the basis of three control lines, the contour line on top of the duct, one the side contour and the third one the lower contour. Two surfaces are then generated between curve one and two and one and three. Lines and surfaces were generated using Bezier techniques. Three different design alternatives were validated using the CFD code, two flush-tip and one scoop-type inlets.

V Computer Aided Design and Manufacture for Propulsors

Introduction

Task four of the committee is to "survey and review the use of Computer Aided Design and [Computer Aided] Manufacture (CAD/CAM) for propulsors." To assist in this process, a questionnaire was sent to 60 organizations consisting of both ITTC members and others thought to be interested in this subject. A list of the questions is shown in Table 5.1 and a list of those who responded to applicable portions of the questionnaire is included in Table 5.2, both of which are at the end of this chapter.

CAM has had a dramatic affect on the industrial workplace. Manufacturing flexibility, worker productivity, product quality, and improved competitiveness have been demonstrated by those who have successfully adopted CAM. The basis of CAM is the numerical control of a machine. Numerical control (NC) is the automatic control of a machine tool based on the direct insertion of numerical instructions to the machine. In the early use of NC machining only minimal operator intervention of the machine was possible. With the addition of a computer to the numerical control unit of the machine, referred to as computer numerical control (CNC), programming flexibility and local data input became possible. A further progression in the development of NC was the use of interactive graphics based NC programs. That is, the software that develops the cutter path is pictorially based rather than manually written code. Interactive graphics based NC part-programming technology increases product quality and simplifies the process. The ability to machine simultaneously in more than three axes allows a reduced number of set-ups, improved accuracy and decreased machine time. The part programming complexity increases, however, as the number of simultaneous machining axes increases. This complexity can be more easily handled by the use of graphically based CAM software. In general, graphics software allows the user to easily visualize and define the part geometry, get immediate feedback and visualize the results.

Most commercial NC programming software today includes the geometry modeler - this is the joining of Computer Aided Design (CAD) with the NC part programming process. The initial NC programming software was based on a geometric entity described by a set of points. With the advent of more powerful and low cost computers, graphics based programs were developed for use by NC programmers. The parts to be machined can be described as a wire frame, a surface, or a solid. These are the same as are used to develop mass properties, finite elements for strength calculations and panels for flow calculations.

When the propulsor designer completes the design it is represented by the final hydrodynamic surface. However for NC machining, the propulsor must be more completely defined than is the normal outcome of the design process. In addition, the NC programmer must develop other surfaces such as those that represent the blade outline, the rough cut and the final cut. The final cut may also have an allowance for hand finishing. As sophistication of CNC machines and NC software increases, the need for a separate NC programmer is diminished. For simple parts, the programming is now often done on the shop floor by the operator and for more complex parts the programming is carried out by a design engineer.

The trend for the future is to graphically represent the part as a three dimensional solid. Based on this solid model, a high degree of automation in tool path generation is possible. This automation is already available with interactive tool path editing to take advantage of special knowledge known by the designer or machine operator. Solid modeling is the next step in the progression of software improvements. Solid modeling allows simulation of the stock, fixture and cutter. Software is now becoming available that presents the "as machined animation", that is, the graphical computer simulation for the tool path verification. As the cutter path is simulated, material removal is graphically displayed and when the cutting is complete the solid model of the intended propeller remains. This graphical capability is now used in industrial applications but was not explicitly mentioned in the questionnaire responses. This capability represents a major improvement in quality and a reduction in overall manufacturing time. Not only is the need for tool path verification models in foam, wax, plastic or metal eliminated, but also the optimization of the manufacturing process is simplified considerably. This includes the optimal selection of machining axes, cutter shape, tool paths, tool orientation, and part fixtures. Adaptive control of the cutter is also in current industrial use. Machining conditions are sensed and adjustments are made to the cutter feed and speed. The sensed conditions include spindle torque, temperature, deflection, vibration and cutter wear. The simplest and most commonly used adaptive control is to sense the torque and adjust the cutter feed rate.

Questionnaire Replies

Overall, the data developed from the questionnaire replies is based on a relatively small percentage of those who manufacture model and full scale propulsors. Those that responded are most likely among the most advanced in adopting CAM to propulsor manufacture since very few negative replies were received.

Twenty-eight positive responses were received for the CAD questions related to hydrodynamic design. Of these, one-half use 3-D graphics to visualize the design and one-third use color 3-D graphics. Over 90% indicated engineering analyses, such as stress calculations, are performed with one-third doing finite element calculations. Computer programs produce the manufacturing drawings for two-thirds of the respondees. Features such as the blade tip, root fillet and trailing edge are determined by design requirements for over 80% of the responses, rather than for the ease of manufacture. One-half of the organizations pass the design data output directly to a CAM system. Of the remaining half that must reformat the design data, essentially all use additional software. From this database of respondees it is clear that sophisticated software is in use to visualize the propulsor design and to pass the design to the CAM system.

The database for CAM related questions consists of 23 CAD respondees plus three propeller manufacturers not involved in design. The committee has restricted this database to only those respondees who are directly involved in the machining of the blade surfaces. Within the database, ten manufacture full scale propulsors and of these ten, four also manufacture model propulsors. Thus a total of 20 manufacture model propulsors.

Twenty-five of the twenty-six manufacturers use computer assisted part programming and 90% rely on workstations or minicomputers. There are no typical software packages for surface and cutter path development. Forty percent have developed their own software while the rest use commercial software with eight different systems mentioned. The method of deriving a cutter path also shows no consensus with almost one-half using mathematically defined surfaces and the other half using a discrete set of points. One-third optimize the cutter path based on the requirements of the NC machine while the rest consider only the hydrodynamic design and the machine constraints as the reference.

Insight into the motivation to adopt CAM for propulsor manufacture is seen from the following stated priorities:

PRIORITY

1. More accurate product

2 Saving in time

3 Saving in labor

4 Saving in cost

5 Saving in workshop space

Nine of the ten full scale manufacturers thought a more accurate product was of highest priority and overall 80% concurred on this point. The respondees agreed that the second highest priority was a saving in time closely followed by a desire for a saving in labor and cost. A saving in workshop space was clearly of lowest priority. One conclusion from this comparison is that more propulsors of higher accuracy can be built using CAM than is possible with the traditional manual methods. Once the investment is made in milling machines, then development of efficient machining methods becomes a priority. Three-fourths use direct numerical control of the machine control unit. Only three respondees relied solely on cutter path proving at the milling machine. Over 90% of the respondees use, at least to a significant extent, graphical cutter path proving on the computer. Furthermore, over one-half the milling machines use five simultaneous axes and essentially all full scale manufacturers have at least one five axis machine. As one may expect, there is no typical milling machine manufacturer and no obvious preference for either horizontal or vertical machine spindle axis. Which machine axes are selected appear to be based primarily on ease in machining.

With regard to machining procedures, it appears that somewhat over one-half of the respondees support the blade during machining. One half machine both sides of the blade without turning the blade over in the machine. The most common cutter is the ball ended cutter. 30% state that the blade leading edges are machined with some implying that only buffing of machining cusps is required while others rough machine only.

The amount of material removal required after machining varies considerably. For model propellers, 0.1 mm to 0.2 appears to be most typical while 0.5 mm to 1.0 mm is most typical for full scale propellers. The most common blade materials are aluminum and bronze while only a few organizations use brass, stainless steel, or white metal.

Answers to questions related to the inspection process indicate considerable variation in how and where the data is taken and what method of comparison to design is used. All do an inspection, typically after machining, but no standard for comparison with the design is followed and much data manipulation is apparent. Approximately one-half the respondees chose inspection points from those used to determine the cutter paths. At model scale an accuracy of 0.05 mm was typically stated and somewhat better accuracy was associated with the edges. One manufacturer who does both model and full scale propellers indicated that the accuracy of a handmade propeller is 10 to 100 times worse than is achieved with numerically controlled machines. It is expected that CAM should lead to closer agreement between the finished propeller and the design. However, based on the inspection methods mentioned it may he difficult to quantitatively document the improvement.

The final topic in the questionnaire was related to personnel training. Essentially all organizations trained their own employees with training periods ranging from one week to one year. The most typical training period was for one month using both software vendors and in-house staff. The over whelming preference is to do the parts programming and manufacturing in- house. Typically only special items or work over load is done outside the organization.

Conclusion

It is clear from the replies to the questionnaire that some manufacturers and ITTC members do no NC machining of propulsors. On the other hand numerous manufacturers and ITTC members have already combined CAD with interactive computer graphics based NC programming. In the past, the available software for geometry and NC programming description was limited in its application due to the complexities of the sculpted surface of a propulsor. This situation fostered within an organization the development of NC software and the training of NC programmers. Now, commercial software has been developed that is appropriate for propulsor machining. Training in its use is readily available and improvements are regularly provided. The selection of commercial software should start first with an assessment of the current requirements and the future needs and compatibility with the propulsor design software. Benchmark tests of the software should be run with typical propeller geometry.

It is the committee's opinion that the trend toward CAM will continue and more attention to this subject should be given by the ITTC. From the results of this questionnaire, the topic of inspection and dimensional accuracy is most in need of further consideration. Closely related to this is the correlation of performance variation with design geometry deviations. The continued discussion of this subject is appropriate within the context of the ISO 9000 quality assurance efforts of the next propulsor committee.

1.1. Do you use computer programs for the hydrodynamic design of the propulsor?
1.2. Does the design program include graphics, if so are they 2D or 3D, color or monochrome?
1.3. Is the program interactive?
1.4. Does the program produce manufacturing drawings?
1.5. Does the program include engineering analyses, such as stress calculation and if so what are they?
1.6. Are blade tip, root fillet and trailing edge shapes determined by design requirements or for ease of manufacture?
1.7. Is the design data output directly to a CAM system or output in a form that requires reformatting before it could be used in a CAM system.
1.8. If the data has to be reformatted, how is this done (i.e., automatic digitization of drawings)?
2.0 Do you manufacture propellers using numerically controlled machinery?
2.1 Do you manufacture model and/or full scale propellers using numerically controlled machinery?
2.2 Do you use manual or computer assisted part programming?
2.3 If you use computer assisted part programming what type of computer do you use (i.e., mainframe or PC)?
2.4 Is a commercial software package used for surface and cutter path development?
2.5 Is the cutter path derived from a mathematically defined surface or a set of discrete points?
2.6 If the cutter path is derived from discrete points, tick which method of interpolation is used between points: Linear Circular Helical Parabolic Cubic Other
2.7 Is the cutter path dictated only by the hydrodynamic design or is it optimized to the requirements of the NC machine?
2.8 What medium do you use to transfer the instructions to the Machine Control Unit (MCU) (i.e., paper tape, etc.)?
2.9 Is the cutter path proving carried on a material such as wood or foam or is it done graphically on a computer?

2.10 What type of numerically controlled machine do you use for propulsor manufacture?
2.11 Does the MCU incorporate a computer (i.e., Computer Numerical Control machine)?
2.12 Select which features are incorporated in the MCU:
Accepts Manual Input: Program Editing:
Dry Run Capability: In Process Diagnostics:
Axis Inversion Allowing Cutting Handed Parts:
Resident Diagnostics:
2.13 Is the machine spindle axis horizontal or vertical?
2.14 How many machine axes are controlled simultaneously?
2.15 How are these axes selected, (i.e., for ease of machining or are they based on machine availability)?
2.16 What type of cutter is used (i.e., ball ended, square ended)?
2.17 Are individual blades supported during cutting, if so how?
2.18 Is the propeller blade machined on both surfaces without removal from the machine, or is it turned over during machining?
2.19 How are the leading edges of the blades produced, (i.e., NC machined or hand finished)?
2.20 How much had finishing is required after removal from the NC machine (i.e., what depth of material is removed by final hand finishing)?
2.21 Is inspection carried out after machining or during the machining process?
2.22 Are the inspection points chosen from those used do determine the cutter paths?
2.23 How is inspection data compared with the design geometry?
2.24 What is the accuracy of the final geometry (i.e., after complete manufacture and including any hand finishing)?
2.25 Place the following reasons for adopting CAM for propellers in order of priority 1 to 5:
Saving in labor: Saving in cost: Saving in time:
Saving in workshop space: More accurate product:
2.26 Upon adopting a CAM system were you able to operate it with current staff or did you hire additional personnel?
2.27 If additional staff is hired, what is their specific skill?
2.28 If you maintained current staff, how many were trained and what was the amount of training provided?
2.29 Did all the training come from the software vendor?
2.30 Do you do all CAD/CAM, parts programming and manufacturing work in house?
2.31 If you send work to a contractor, what is the nature of this work?
2.32 What materials have you used for propulsor construction; what manufacturing method was employed and what was the resulting use (i.e., 7075-TG Aluminum, 5-axis NC milling, open water model tests)?
Material: Method: Use:

Table 5.1 Questionnaire on the use of CAD/CAM in Propulsor Manufacture

Naval Surface Warfare Center, Bethesda, MD, USA
Bird Johnson, Walpole, MA, USA
Stone Vickers, Erith, Kent, UK
China Ship Scientific Research Center, Wuxi, Jiangsu, PRC
Centrum Techniki Okretowej, GDANSK, Poland
Akishima Laboratories (Mitsui Zosen) Inc, Akishima Tokyo, Japan
DGA, Paris, France
Dominis Engineering Ltd, Ontario, Canada
MARIN, Netherlands
Ishikawajima-Harima Heavy Industries Co. Research Institute, Yokohama, Japan
KRSI, St. Petersburg, Russia
Kamome Propeller Co., Ltd, Yokohama, Japan
Brunvoll, Molde, Norway
Hyundai, Ulsan, Korea
Marintek, Trondheim, Norway
SSPA Maritime Consulting, Göteborg, Sweden
Bulgarian Ship Hydrodynamics Centre, Varna, Bulgaria
Defense Research Agency, Gosport, Hants, UK
Rolla, Balerna, Switzerland
Versuchsanstalt, Berlin, Germany
Stone Manganese Marine Limited, Merseyside, U.K.
Mitsubishi Heavy Industries, Ltd, Nagasaki, Japan
ARL/Penn State University, State College, PA USA
Korea Research Institute Of Ships And Ocean Engineering, Daejeon, Korea
VTT Technical Research Centre Of Finland, Otaniemi, Finland
Stone Marine Canada Limiteé, Iberville, Qué. Canada
The University Of Tokyo, Tokyo, Japan
Finnscrew, Turenki, Finland
Nakashima Propeller Company, Okayama, Japan
Baltic Shipyard, St. Petersburg, Russia
KAMEWA, Kristinehamn, Sweden

Table 5.2 Respondees to CAD/CAM Questionnaire

VI CAVITATION CONTROL IN PROPULSOR DESIGN

Introduction

The phenomenon of cavitation on marine propellers was recognized in the last century when it was identified as the cause of propeller racing and was also found to be the origin of propeller damage. The latter can take the form of material erosion or structural deformation such as the bent trailing edges reported by van Manen (1963). The 19th ITTC tasked the committee as follows: "The incorporation of cavitation reduction/control in the design approach of propellers should be evaluated."

The enhancement of propeller induced vibration and propeller noise are two other major adverse effects of cavitation. The former can cause habitability problems and if severe result in structural damage to the hull. Cavitation generated noise is particularly important in the case of warships where it presents a major detection risk and reduces the performance of the ships own sonar.

Clearly the best way to avoid the undesirable phenomena described above would be to ensure that cavitation does not occur. In many cases this is impossible, however the adverse consequences of cavitation can be minimized by careful design and this chapter of the report discusses how this may be achieved.

Cavitation Control During Propeller Design

One of the first considerations in propeller design is to avoid thrust breakdown and reduce the probability of cavitation erosion taking place. This is achieved by limiting the blade loading using criteria such as those developed by Burrill (1943, 1962) or Keller (1966). The application of these criteria result in the specification of a minimum blade area.

One of the most effective ways to reduce the adverse consequences of cavitation is to delay inception to as high a ship speed as possible. By this means cavitation may be eliminated over a significant part of the ship speed range and the severity of cavitation phenomena reduced at high speed. Hence this section of the report will first consider how cavitation inception is influenced by the propeller parameters and provide guidance on the selection of these parameters in order to maximize inception speed.

Bubble and vortex cavitation are related to the mean lift generated by the blade sections and hence the overall blade loading. Thus minimizing the blade loading will have a favorable effect on these types of cavitation.

Sheet and cloud cavitation are primarily associated with operation of the blade sections at varying incidence. The pressure changes generated by variation of incidence are proportional to the incidence changes and the flow velocity relative to the blade. Thus reducing these parameters will have a favorable effect on cavitation inception.

Low flow velocity over the blades of a propeller can be achieved by employing low shaft speed and small diameter. The latter however increases the blade loading which has an adverse effect on bubble and vortex cavitation. In addition the efficiency of a propeller is reduced as the loading is increased so that a small diameter implies a propulsive penalty. Low shaft speed leads to high swirl losses in the propeller race which also reduces the efficiency. Thus minimizing both the diameter and shaft speed of a propeller results in low propulsive efficiency. However by combining large propeller diameter with low shaft speed it is possible to delay the propulsive penalty and still achieve a reduction in the flow velocity relative to the blade. At very low shaft speed the swirl losses eventually become dominant and the propulsive efficiency cannot be maintained.

The incidence change generated as a result of the propeller operating in a wake field is inversely proportional to the shaft speed. Thus minimizing the shaft speed increases the contribution to the pressure changes due to this parameter. However, for practical propeller geometry this effect is smaller than that due to the reduction in the flow velocity over the blade. Thus the net effect of minimizing the shaft speed is to minimize the pressure changes due to operation in the wake field and hence to delay the inception of sheet and cloud cavitation.

As noted above there is a limitation on the minimum value of design shaft speed below which the propulsive losses become significant. This situation begins to occur at pitch ratios of approximately 2, so that this is likely to represent the lower limit on the shaft speed. In practice there are other constraints which will often limit the shaft speed to a higher value than that implied above. There will normally be limitations on the maximum propeller diameter, weight and shaft torque and these may be exceeded at shaft speeds higher than that implied by the above pitch ratio.

Designing for low shaft speed has an additional advantage in the case of cavitation damage because the rate at which such damage occurs is proportional to the number of passages of a blade through the wake in a given time. Thus low shaft speed increases the period before any damage becomes significant.

Having determined the shaft speed, propeller diameter and blade area the normal design practice is to perform lifting line design studies. At this stage further consideration can be given to maximizing the cavitation inception speed. In the case of blade surface cavitation this is normally carried out using the cavitation characteristics of blade sections having prescribed chordwise thickness and camber distributions. The cavitation data is presented as inception curves in terms of incidence against local cavitation number for one value of camber to chord ratio and a range of thickness to chord ratios. These characteristics may be derived from experimental data e.g. Kruppa (1963) or from theoretical predictions such as those by Rader (1954), Cox (1963), Brockett (1966) or van Oossanen (1971). The required camber to chord ratio is determined by the design lift coefficient of the sections, however the selection of the blade thickness involves a compromise between inception conditions for bubble and sheet and cloud cavitation. Low section thickness to chord ratios delay the inception of bubble cavitation but lead to early inception of sheet and cloud cavitation and vice versa. Thus large thickness to chord ratios result in sections which are more tolerant to the incidence changes which occur due to the operation of the propeller in the ship wake.

In order to use the section cavitation characteristics it is necessary to estimate the inflow conditions to a blade section. This requires a knowledge of the flow field and the velocities induced by the propeller. This information can then be used to predict the equivalent section mean incidence and local cavitation number, and their variation, during one revolution of the blade. A common method used to make these estimates is the method of Lerbs and Rader (1962).

The maximum blade surface inception speed would be obtained when suction and pressure side cavitation inception occur at the same speed. However, to reduce the risk of erosion on high speed propellers Gunsteren and Pronk (1973) recommend that pressure side cavitation be avoided at the expense of earlier suction side cavitation. Similarly, under conditions where cavitation cannot be avoided it may be desirable to stabilize sheet and cloud cavitation by using sections which promote early but stable leading edge sheet cavitation. An example of this approach applied in the design of a propeller for a container ship is given by Lee (1991).

The blade thickness distributions commonly used for marine propellers are elliptic-parabolic, NACA 16 and NACA 66, or modified versions of the last two distributions. The NACA 16 and 66 series thickness distributions were developed for aircraft wings with the objective of delaying compressibility effects by minimizing induced velocities. This feature also makes them attractive in the marine field in order to delay cavitation inception. The most widely used camber distribution is the NACA a=0.8 which has constant chordwise loading from the leading edge to 80 per cent chord followed by a linear decrease to zero at the trailing edge. Since these sections were developed, considerable improvements have taken place in wing design methods. In particular the method developed by Eppler (1974, 1980) has made it possible to design blade sections which have prescribed surface pressure distributions. For example, by specifying surface pressure distributions which minimize the occurrence of local suction peaks at the section leading edge when operating at incidence, it is possible to derive hydrofoils which have a superior cavitation performance to those based on the NACA series. Such hydrofoils have been developed by Eppler and Shen (1979, 1981, 1985). These sections have thicker leading edges and the maximum camber further aft than the forms normally employed. Similar work has been reported by Nakazaki (1986), Yamaguchi (1986), Kuiper (1990), Dang and Tang (1990), Lee (1991), Dang, Tang, and Peng (1991) and the topic was reviewed in detail in the Propulsor Committee Report to the 19th ITTC.

These new section design techniques can be applied to propeller design in two ways. The most obvious method is to consider each radial station of the propeller separately and optimize the section shape for the conditions at the radius concerned. The development of a propeller design procedure incorporating new blade sections in this way is described by Bailar, Jessup and Shen (1992). A series of 5 propellers were designed and their propulsive and cavitation performance compared with a parent having conventional sections. The results showed that the new blade section geometry's improved blade surface cavitation inception by 2-3 knots and that the cavitation volume was significantly reduced. This method of incorporating new blade section shapes into propeller design can cause difficulties in fairing between the design radii. An alternative approach is to develop a new family of sections which have a superior cavitation performance to the existing shapes and to maintain this at all propeller radii. Two propellers were designed in this way by Stanier (1992) and the results from model tests again showed that the new blade sections delayed cavitation inception.

One feature of propeller geometry that has been shown to improve cavitation performance is high blade skew. This has been demonstrated by Denny (1968), Boswell (1971), Cumming et al (1972) and Boswell and Cox (1974). The results presented by Boswell and Cox (1974) showed that replacing a straight propeller by one with a tip skew of 60 degrees increased the back and face cavitation inception speeds by approximately 3 knots. The reasons for the delay in the inception of sheet cavitation are not fully understood but are probably associated with the presence of strong radial flows. High skew also has a beneficial effect on cavitation induced vibration, Bjorheden (1979). This is because it spreads the growth and collapse of cavitation over a wider range of blade angular position than a straight blade. At high incidence the flow may separate at the blade leading edge and in the case of a highly skewed blade may roll up to form a vortex approximately parallel to the leading edge. This situation can be advantageous because this form of cavitation is more stable than sheet cavitation and does not collapse on the blade surface. In this way cavitation induced hull pressures may be minimized and cavitation erosion avoided.

Propeller tip and hub vortex cavitation occur in the vortices generated by the pressure difference between the two surfaces of the blade at the tip and root. Minimizing the loading at the blade tip and root will minimize the pressure difference between the two surfaces at these points and will thus delay the inception of cavitation. For maximum efficiency the radial load distribution is of an elliptic form having high tip and root loading. Thus off-loading the tip or root implies a penalty in propulsive performance. Typical loading distributions and their effects on performance can be found in papers by Lerbs (1949,1952), Boswell and Cox (1974), Glover (1979), Glover, Thorn & Hawdon (1979), and Patience (1991). The results given by Boswell and Cox (1974) showed an improvement in tip vortex cavitation inception speed of approximately 3 knots. The theoretically predicted loss in efficiency to achieve this improvement in cavitation performance was approximately 3 percent, however no loss in efficiency was detected in model propulsion tests.

The strength of the tip and hub vortices can also be reduced by the introduction of special features at the blade tip and on the propeller tailcone. These can be changes to the local geometry or the addition of auxiliary surfaces. A literature survey of work on techniques for delaying the inception of tip vortex cavitation has been carried out by Platzer and Souders (1979). As a result of this review four devices were recommended for further study, namely a bulbous blade tip, a porous blade tip, mass ejection at the blade tip and the application of roughness at the blade tip. The bulbous and roughened tip both increase the thickness of the boundary layer. This increases the mass flow into the tip vortex and leads to a more rapid dissipation of the energy in the vortex core. In addition the bulb acts as an end plate and inhibits the roll up process. The increase in tip vortex cavitation inception speed with increasing blade area ratio noted by Platzer and Souders may also result from a thickening of the tip boundary layer. This suggests that the use of blade outlines with wide tip chords may have a beneficial effect on tip vortex cavitation. The porous blade tip permits some equalization of pressure between the two surfaces of the blade and reduces the strength of the vortex. Mass ejection of fluid directly into the vortex increases the pressure and also increases the rate of decay through viscous interaction between the injected fluid and the rotating core. Other devices such as end plates, fences, winglets, etc. were considered but were rejected by the authors as impractical for marine propellers. However Itoh et al (1986, 1987), Jong et al (1992) and Andersen and Schwanecke (1992) have reported improvements in efficiency of between 1 and 4 per cent for propellers fitted with end plates and winglets. A delay in the inception of tip vortex cavitation was also reported by Andersen and Schwanecke (1992). Hence these devices have the potential to improve tip vortex cavitation in open water without a propulsive penalty, however, their performance may be degraded in a realistic wake field. The physical processes occurring at the blade tip are not fully understood and the design methods are not well developed, thus further study is required.

As a result of the above survey Souders and Platzer (1981) carried out an experimental investigation into the extent to which tip vortex cavitation inception could be delayed on a three dimensional foil by a bulbous tip, an artificially roughened tip and mass ejection. In the case of the last of these both active and passive ejection were employed. Flow visualization, cavitation inception and force measurement tests were carried out on a series of hydrofoils having a modified NACA 66 thickness distribution and a NACA a=0.8 camber line. The results showed that all the treatments delayed the inception of tip vortex cavitation and that this improvement was achieved with little change in lift characteristics. The maximum improvement was obtained with the artificially roughened tip, this increased the inception speed by 91 per cent compared with the parent hydrofoil. Similar experiments have been carried out by Johnsson and Rutgersson (1991) using a hydrofoil to represent the tip region of a highly skewed propeller. Three configurations of distributed roughness were applied to the pressure side of the hydrofoil, close to the leading edge. It was found that to obtain the maximum improvement it was necessary to ensure that the roughness covered the tip. Increases in inception speed of between 10 and 15 per cent were achieved. The increase in drag was found to be strongly dependent on the loading. It was estimated to be equivalent to a maximum reduction in propeller efficiency of approximately 2 per cent. A one-third scale model of the tip of a skewed propeller was also used by Faller, Farhat and Avellan (1992) to investigate the effect of roughness on tip vortex cavitation. This work showed that leading edge roughness increased the pressure coefficient at the center of the vortex and that tip vortex cavitation was delayed. The lift coefficient was not affected but the drag was increased. Studies by Inge and Bark (1983), Fruman and Aflalo (1990) and Chahine, Frederick and Bateman (1992) have shown that mass ejection of dilute polymer solution into the propeller tip vortex can delay cavitation inception. It was found that the position at which the polymer was ejected was extremely important and that reductions in cavitation number at inception of up to 35 per cent could be achieved. The ejection of the polymer solution had no adverse effect on propeller thrust or torque.

Concepts similar to those considered to improve tip vortex cavitation can also be applied to delay hub vortex cavitation. The devices most commonly used are bluff ended tailcones, vented tailcones and small foils attached to the tailcone. Bluff and vented cones were investigated by Emerson (1953) and it was demonstrated that improvements in inception speed could be achieved by these devices. However, to obtain a significant improvement in cavitation performance the tailcone had to be severely truncated. A similar performance was achieved with a vented arrangement. The vented tailcone is a passive mass ejection device which has a number of channels connecting the surface with a truncated aft end. The pressure difference between these two points induces a flow into the core of the vortex which increases the pressure and increases the rate of energy loss. By careful arrangement of the exit holes it is possible to induce swirl in the exit flow opposite to that in the hub vortex.

The experimental evaluation of a series of bluff ended divergent tailcones has been reported by Tozer (1979). This series was based on the three parameters, tailcone length, exit diameter and exit angle. A characteristic shown clearly in the results of cavitation inception tests was that the relative performance of the divergent and pointed tailcones depended on the cavitation number. At low cavitation numbers improvements were obtained with the divergent tailcones while at high cavitation numbers their performance was similar to that of the pointed tailcone. The maximum delay in cavitation inception was achieved with the longest tailcone, the largest exit diameter and the largest exit angle.

The use of foils attached to the propeller tailcone to improve efficiency by removing the swirl behind the propeller has been discussed by Ouchi et al (1988,1989). Flow visualization and 3-D LDV measurements showed that these foils considerably reduced the strength of the hub vortex. The results of cavitation tunnel tests conducted by Ouchi (1989) have confirmed that this reduction in vortex strength also produced a significant improvement in hub vortex cavitation performance.

The major forms of propeller cavitation are considered above, however areas of localized cavitation may also occur, one of the most common being at the junction between the blade root and the hub. Experimental studies reported by Gunsteren and Pronk (1973) showed that inception of this type of cavitation was delayed if the hub was slightly divergent in the downstream direction. There is also evidence that reducing the root fillet radius at the blade leading edge has a favorable effect on root cavitation on high speed propellers. A palliative often adopted on propellers which suffer from root cavitation due to high cross flow angles is to drill one or more cavitation relief holes through the blade, the position of these being determined by model tests.

Cavitation noise studies using model propellers have shown that different types of cavitation generate different noise levels. Experiments reported by Noordzij, Oossanen and Stuurman (1977) showed that the highest noise level was associated with bubble cavitation, next in level was sheet cavitation and slightly below this was tip vortex cavitation. Data presented by Matveyev and Gorshkoff (1978) showed sheet cavitation to be noisier than bubble cavitation while vortex cavitation was again associated with the lowest noise level. The results of this study also indicated that pressure side cavitation gave a higher noise level than suction side cavitation. Thus it may be advantageous to bias the propeller blade design towards early inception of specific forms of cavitation in order to minimize the overall noise level when cavitation is well developed. However the available data on the relative noise levels of different types of cavitation is conflicting and these relationships may in any case depend upon the wake field in which the propeller operates. Thus it is not possible to make specific recommendation on how to bias the propeller cavitation performance in order to optimize its acoustic performance.

Unconventional Propulsors

The development of the conventional propeller has reached a stage where the potential for further improvement in cavitation performance is limited. Thus attention must be directed to other propulsors. It is apparent from the above discussion that the major features of any propulsor which contribute to good cavitation performance are low blade loading, low shaft speed, small diameter, high ambient pressure, small variation in blade incidence and suppression of vortex flow. One or more of these attributes are present in the following propulsors.

The ability of contra-rotating propellers to achieve high propulsive efficiency has been known for many years, however much less attention has been paid to their cavitation performance. Studies into the propulsive performance of contra-rotating propellers have shown that the optimum performance is achieved at a smaller diameter for the same shaft speed, or at a lower shaft speed for the same diameter, than for the equivalent single propeller. Thus the contra-rotating propeller has two of the favorable features noted above, namely large blade area and hence low blade loading and either low shaft speed or small diameter relative to that of the conventional propeller.

Early work by van Manen and Oosterveld (1968) presented the results of propulsion tests on a systematic series of contra-rotating propellers and the experimental evaluation of designs for a tanker and a cargo vessel. The results of tests indicated that the cavitation performance of the forward propeller of the contra-rotating set and the equivalent single propeller were similar in both cases. Cavitation was also present on the aft propeller of the contra-rotating sets but it was much less than on the forward propeller. The strength of the tip vortex cavitation on the contra-rotating sets was slightly less than on the single propeller.

Another study into the application of contra-rotating propellers to a tanker has been carried out by Sasaki (1988). Three designs were evaluated, and the results of cavitation tests showed that for all three the suction side cavitation on the forward propeller was less extensive than on the single propeller. However, pressure side cavitation was also present on all three forward propellers of the contra-rotating sets but not on the single propeller. Cavitation on the aft propellers was limited to a very small area on the suction side near the tips. It was concluded that the overall performance of the contra-rotating sets was better than the equivalent single propeller. This was reflected in the results of unsteady pressure measurements which showed reduced levels for the contra-rotating sets compared with the single propeller.

The design and model and full scale evaluation of a contra-rotating propeller for a bulk carrier has recently been reported by Nishiyama et al (1990). Model tests showed that the extent of cavitation on the forward propeller was less than on the equivalent single propeller. Tip vortex cavitation was observed on the aft propeller together with a little sheet cavitation at the tip. Fluctuating pressure measurements were made during the cavitation tests and lower levels were obtained with the contra-rotating set than with the single propeller. The results of these model tests were confirmed by full scale propeller viewing trials and hull pressure measurements. The latter showed that blade frequency components of the forward propeller were dominant but that they were between 30 per cent and 50 per cent lower than those of the single propeller. The propeller noise was measured at full scale by hydrophones attached to the aperture shell plate. The results showed that the overall noise level of the contra-rotating propeller, between 125 Hz and 10 kHz, was between 3 dB and 5 dB lower than that of the single propeller. The one third octave analysis of the noise records indicated that the noise level of the contra-rotating propeller was lower than that of the single propeller below 80 Hz and above 1 kHz. Between these two frequencies both propellers had similar noise levels.

The vane-wheel is a freely rotating set of blades situated behind the propeller. The inner part acts as a turbine and the outer part produces thrust like a propeller. The additional thrust generated by the vane-wheel should allow the blade loading to be reduced and the recovery of rotational energy should enable the propeller shaft speed or diameter to be reduced. The model evaluation of a version of this type of propulsor known as a Grim Wheel has been presented by McCallum et al (1991). Results from these tests showed that the cavitation on the propeller was unchanged by the Grim Wheel and that the latter suffered from limited suction side and tip vortex cavitation, however, hub vortex cavitation was eliminated. The results from a full scale application given by Blaurock (1990) showed that the vane wheel produced a significant reduction in the pressure fluctuations on the hull compared with those of a sister ship not fitted with a vane wheel. The amplitudes of the 1st and 2nd harmonics of blade rate were reduced to approximately one half of their original value. The unloading of the propeller by the vane wheel, leading to a reduction of cavitation on the propeller, is given as a possible explanation for this reduction in fluctuating hull pressures.

The use of fixed vanes behind the propeller to recover energy from the rotating slipstream may also have potential to improve cavitation performance. Clearly the blade loading and the propulsor diameter or shaft speed can be reduced compared with that of a single equivalent propeller. A design method for a post-swirl propulsor has been developed by Chen (1992) and the propulsive performance of such devices was reviewed in the Propulsor Committee report to the 19th ITTC, however little information is available on their cavitation performance.

If a propeller is enclosed in a duct shaped to reduce the flow velocity through the propeller, the local pressure is increased and the cavitation performance of the propeller is improved. However the force on the duct opposes the propeller thrust and the efficiency is reduced relative to that of an equivalent unducted propeller. The results of tests on a series of ducted propellers with decelerating ducts have been reported by Oosterveld(1968, 1970). In practice the application of ducts to propellers has resulted in erosion of the duct inner surface caused by cavitation on the blades. Care must also be taken to avoid cavitation on the duct itself and on the arrangements for attachment to the ship hull. A favorable characteristic of any ducted propulsor is the ability to design the duct so that the blades operate at an approximately constant advance coefficient over a wide range of loading conditions. This is reflected in an increased cavitation free range between underthrusting and overthrusting compared with an open propeller and is particularly relevant in improved cavitation performance. The Pre-Propeller Fin described by Ukon and Kurobe (1992) is a form of tandem propeller in which small blades are fitted ahead of the propeller. These modify the inflow to the propeller and hence reduce the root cavitation erosion which occurs in oblique flow. This study showed that both the mean inflow angle to the propeller blades and the variation in inflow angle during one revolution were reduced by the fins.

Propulsor Inflow

It is apparent from the above discussion that the cavitation performance of a propulsor is influenced by the wake field in which it operates and which is in turn dependent upon the ship hull form and appendages. Comprehensive reviews of hull afterbody forms and their effect on wake and cavitation induced vibration have been conducted by Vossnack and Voogd (1973), Huse (1974) and Lindgren and Johnsson (1977). Afterbody forms were divided into two categories based on the cross section shape forward of the propeller. These were defined as U-shaped and V-shaped and were shown to result in markedly different axial wake distributions. On single screw ships the V-shaped form resulted in a high wake peak in the upper part of the propeller plane due to the convergence of the hull boundary layer. The flow around the bilges of the U-shaped hull form generated two vortices which produced an interchange between high and low velocity flow regions and hence could reduce the wake peak in the propeller plane. Results from cavitation tunnel tests showed that the largest unsteady pressures were obtained with a V-shaped after body. It was argued that the bilge vortices associated with the U-shaped after body had a favorable effect on cavitation performance although it was noted that in certain circumstances the bilge vortices could themselves produce high wake peaks and consequent propeller cavitation. Several studies into the use of fins to accelerate the flow and thus reduce the wake peak at the top of the propeller plane were reviewed. These showed that such fins were very effective and resulted in significant reductions in propeller excited vibration levels. Data from single screw vessels with commercial after body hull forms were compared with vibration levels for twin screw ships with relatively flat bottomed warship type sterns. This comparison showed that the latter configuration resulted in substantial reductions in propeller excited vibration levels compared with the single screw forms.

In the paper by Huse (1974) model test data was used to produce criteria for acceptable variations in axial wake for single screw commercial hull forms. A criterion for the avoidance of propeller excited vibration has been proposed by Fitzsimmons (1977). This defines a boundary between zones of moderate and high excitation forces in terms of cavitation number and axial wake variation. The latter is also related to the after body form so that the criterion can be used at the preliminary design stage to select after body hull form or to assess the performance of existing configurations. Data based on information from nine selected single screw ships over the decade to 1979 have been presented in the same form by Rutherford (1979).

The use of asymmetric preswirl vanes ahead of the propeller to improve the flow conditions at the propeller has been considered by Gearhart and Marboe (1991) and by Neely et al (1991, 1992). Both of these investigations were concerned with open stern configurations in which the propeller operated in a strong cross flow. The first was directed towards improving propulsive efficiency and the vanes were designed to introduce swirl into the inflow that was circumferentially uniform. The second study, by Neely and Chen (1991) and Neely, McMahon and Chen (1992), was to use the vanes to eliminate erosion at the root of a propeller. The erosion was shown to be due to cavitation caused by high blade incidence which was in turn due to high tangential velocity in the propeller plane. Thus the vanes were designed to reduce the tangential velocity in the root region. Theoretical studies showed that the cavitation inception speed at the radius where erosion occurred would be increased by between 3.5 and 5.5 knots without any significant effect on the propulsive performance. The results of model erosion tests reported by Smith and Remmers (1992) showed that the blade root erosion was almost completely eliminated by the preswirl vanes.

The wake equalizing duct and the Grothues spoiler are two devices which have been developed to improve the propulsive efficiency of single screw merchant ships, how-the case of a vessel which has to meet both towing and free running requirements.

As already noted sheet and cloud cavitation are associated with changing incidence as the propeller blades rotate in the wake behind the hull. One method of reducing these incidence variations is to control the blade pitch cyclically. This can be achieved either actively as investigated by Bindel (1968), Jessup (1976) and Simonsson (1981), or passively as reported by Johnsson (1987,1990). The active pitch control concept is similar to that of a controllable pitch propeller but with the addition of a system to continuously alter the pitch as the propeller rotates. All the above investigations demonstrated improvements in cavitation performance and unsteady force levels. A disadvantage of this approach is the need for mechanical linkages, bearings and actuators. These requirements are eliminated in the passive concept developed by Johnsson (1987,1990) and known as the Flexprop. The blades of this propeller are manufactured from composite materials and designed so that the deflections produced by unsteady loading alter the blade pitch so as to oppose the incidence causing the loading. The rate of this deformation has to be rapid enough to minimize the phase lag between the variation in loading and the change in effective pitch. Full scale trials of a Flexprop on the mine sweeper Viksten showed a reduction in torque variation and noise at blade rate frequency compared with the original rigid bladed propeller. However, cavitation inception was earlier, probably because the blade deflections reduced the pitch to such an extent that pressure side cavitation occurred. Although the cavitation performance was degraded in this case the Flexprop reduced the loading due to inflow variations and hence it should be possible to improve cavitation performance by this method.

A ring propeller is a propeller which has a duct, or ring, attached to the blade tips. Thus it has the potential to eliminate tip vortex cavitation and is less vulnerable to damage than individual end plates. The ring also provides some control over the pressure at the blades in a similar way to the duct on a ducted propeller. The viscous forces on the rotating ring increase the torque over that of a similar diameter open propeller, however, the optimum diameter and shaft speed are lower than for a conventional propeller. The net result is that at high loading the efficiency of a ring propeller may exceed that of an open propeller while at low loading its efficiency is lower than an open propeller. The results of a systematic series of model tests on ring propellers and experience of full scale applications have been reported by Gunsteren (1970, 1971). Trials on a coaster which had the conventional propeller replaced by a ring propeller showed a significant reduction in vibration level. An experimental investigation into the use of ring propellers on high speed craft has been carried out by Townsend (1985) and theoretical studies have been reported by Sparenberg (1969) and Slijper(1970).

A concept similar to the ring propeller is the Motor propeller as described by Kranert (1987). This is a ducted propeller in which the blades are attached at the tips to a ring which rotates in a recess in the duct inner surface. This then forms the rotor of an electric motor, the stator coils being placed within the duct. The shaft carrying the blades and ring runs in bearings supported by three struts at each end of the duct, hence there is no drive shaft from the hull. This device has similar features to the ducted and ring propeller and may therefore have the potential to improve cavitation performance.

The tandem propeller consists of two propellers fitted to a common shaft. They have been used when limitations on propeller diameter or number of shafts has precluded the design of a single propeller because of very high blade loading. In this situation the tandem configuration may result in a better cavitation and propulsive performance than a single propeller. However, under normal loading the tandem propeller is unlikely to have any advantage over a single propeller. Little information is available on the full scale performance of tandem propellers, however the results of model investigations have been reported by Hadler et al (1964, 1984, 1985) and Glover (1981). A concept known as the semi-tandem propeller (STP) is described in two papers by Chen et al (1990). This is comprised of two propellers on the same shaft, the inner portions of which are skewed in opposite directions while the outer portions are in the same plane. Thus at the inner radii the propeller has a tandem configuration while at the outer radii it is a single propeller. It is claimed that this results in reduced exciting forces and ever they also have the potential to improve propeller cavitation performance because they reduce non-uniformity in the inflow to the propeller. The development of these devices is included in the review of after body configurations presented by Blaurock (1990) and wake equalizing ducts were also considered by McCallum et al (1991). No information is presented on the effect of these devices on cavitation performance but recommendations are made that research should be undertaken in this area.

VII EFFECT OF LEADING EDGE BOUNDARY LAYER TRIPPING

Introduction

The objective of this task is to evaluate the use of tripping devices to reduce scale effects between model and full scale propulsor performance and to assess their effect on lift and drag. This task, as given to the committee is stated as follows: "The effect of leading edge boundary layer tripping on lift reduction and drag increase and on new blade sections ("Eppler-Shen") should be evaluated." The topic is of major concern in the development of new blade sections ("Eppler-Shen") because these are subject to large scale effects. The task is intended to consider other propulsors such as ducted and contrarotating propellers.

The first step in tackling this task is to collect and review data about scale effects that might lead to erroneous conclusions and full scale predictions. The ultimate goal is to give definite guidelines how to perform and analyze experiments.

Tripping Methods

Huang & Shen (1986) made comparative tests to establish the minimum value of roughness Reynolds number based on the roughness height, $R_K = u_K K/\nu$ to minimize the cavitation inception scale effects without causing premature cavitation on the roughness elements. In the definition u_K is the smooth boundary layer velocity at the tip of roughness height, K the roughness height, and ν the fluid kinematics viscosity. Based on this and other work the 18th ITTC Cavitation Committee (1987) recommended that a R_K value of 600 in the leading edge region is required to assure a satisfactory turbulent flow stimulation. The distributed roughness is to start at the nose and to terminate at x/c = 0.03. An upper value to reduce the risk of premature cavitation was not determined.

According to the ITTC-1978 extrapolation method (19th ITTC, Powering Performance Committee, 1990) the leading edge roughness will increase the sectional drag coefficient, while lift is not affected.

Johnsson (1980) has reported on early SSPA work on new blade sections. In one contra-rotating propeller case Johnsson (1989) suspects that the self propulsion test in the towing tank did not give a representative efficiency because of the small diameter of the propellers. The aft propeller had the diameter of 138 mm. After examining the relative rotative efficiencies in the towing tank and cavitation tunnel, it was decided to base the comparison on cavitation tunnel results.

Open water tests of ducted propellers in SSPA Maritime Consulting are normally carried out in the high speed section of the cavitation tunnel. The combination of high speed and large background turbulence should give representative values for the propeller characteristics. In behind conditions adequate turbulence is created by the ship model. This is found by examining the values of relative rotative efficiency. Bjärne (1990) considers that the increased roughness in full scale is contradictory to the influence of Reynolds number on the profile drag of the propeller, hence no scale corrections to the propeller characteristics are regarded as necessary.

At the Depressurized Towing Tank (DTT) of MARIN propulsion data are not generally measured with roughened propellers, because the statistics are based on smooth models (Kuiper, 1992). Ligtelijn et al. (1992) give the current standard in cavitation tests at the DTT as follows. Carborundum grains of 0.060 mm are applied over a distance 3 % of the chord on both sides of the blade. Systematic cavitation inception tests in the cavitation tunnel yielded a diagram depicting the size of the required roughness element as a function of the Reynolds number. These data could also be used for selecting the grain size in a more refined way.

Experimental and Calculated Data on Lift and Drag. In connection with cavitation investigations, Shen (1985) compared force data of NACA 16, NACA 66 (MOD) and YS-920 sections of chord length 152 mm. The NACA 66 (MOD) section was also used by Shen & Dimotakis (1989) and Shen & Huang (1989). The profile YS-920 representing the "Eppler-Shen" sections, has the design lift coefficient of 0.22 and maximum thickness-to-chord ratio of 0.09. These values are typical of marine screw propellers. Spherical glass beads of 0.094 mm nominal size were used in the experiments. To evaluate the potential flow influence of roughness on the pressure distribution on the upper surface of YS-920, calculations were performed with the bead size over its distributed area added to the profile coordinates for three values of lift coefficient. The influence of added roughness on pressure distribution is minimal at the lift coefficient of $C_L = 0.28$. At $C_L = 0.38$ the smooth foil has a relatively flat pressure distribution. In contrast to the lower lift coefficient case, at $C_L = 0.38$ a sharp suction pressure peak is present when the roughness is added. Flow visualization at the Reynolds number of $R_n = 2.5*10^6$ shows that the application of leading-edge roughness effectively eliminates the laminar separation bubble. The change from laminar to turbulent flow on the foil surface results in an increase of drag coefficient. The parasitic drag contributed by the roughness elements was estimated to be less than 5 % of the total section drag. Two figures in the paper of Shen (1985) give the measured lift coefficient vs. foil angle and polar plots. The measured zero-lift angle was increased from -2.40 to -2.15 degrees. for the roughened YS-920 section. Similarly, an increase from -2.23 to -2.00 degrees. was measured for the roughened NACA 66 (MOD) section. The lift curve slopes remain at the same smooth surface values of 0.10 per degree for both foils with the surface roughened. There is a significant increase in drag coefficient from 0.0040 - 0.0075 to 0.0085 - 0.0110 when roughness is used to stimulate transition from laminar to turbulent flow.

At DTT Kuiper (1981) tested three propellers of diameter 340.0 mm. These propellers had no skew nor rake. Two of the propellers were tip off-loaded, and one had a constant pitch. One of the tip off-loaded propellers was very thick. Grains of 0.030 mm carborundum were found to be inadequate. Kuiper recommended that for propellers roughened with 0.060 mm carborundum over about 3 % of the chord, the Reynolds corrections to the thrust and torque corrections, dK_T and dK_Q, as recommended by ITTC-1978 should be changed. In the continuation research Kuiper (1989, 1992) initially investigated the effects of turbulence stimulators on the performance of three propellers, and then on additional propellers. The measurements were carried out at the rates of rotation of 10 and 18 Hz. The measured differences in thrust and torque coefficients, $dK_T = K_T(\text{smooth}) - K_T(\text{roughened})$ and $dK_Q = K_Q(\text{smooth}) - K_Q(\text{roughened})$, were plotted as functions of the advance number. The general trend is that the two curves are fairly horizontal and close together. This made it possible to determine a single value of dK_T and dK_Q independent of the advance number. The measured thrust and torque differences due to the stimulators were interpreted in terms of the sectional lift and drag coefficients of an equivalent profile. The results show that the application of turbulence stimulation by roughness causes an increase in drag coefficient comparable to the difference between the laminar and turbulent flow over the equivalent profile. At the same time the lift of the equivalent profile decreases, in some cases considerably. For practical purposes a decrease of the lift coefficient of 0.006 can be expected for conventional propellers and of 0.018 for highly skewed propellers when the smooth propeller is taken as the reference. When the roughened propeller was taken as the reference, the ITTC-1978 method could be applied directly using the drag of the model section at the model Reynolds number resulting from turbulent boundary layer.

In the following paragraphs the experimental results of propellers with new blade sections are compared to the design. They all exhibit performance dependent on the Reynolds Number, i.e., viscous effects are influencing the performance and should be considered.

Yamaguchi et al. (1986) designed two new blade section propellers with a MAU type propeller as the parent propeller. The parent model was designated MP218 and the two new blade section propellers MP010 and MP012, respectively. The propellers MP010 and

MP012 differ from MP218 only in the blade section shape and pitch distribution. All the model propellers have the diameter of 220.95 mm. The open water model tests were made at the Akishima towing tank at the Reynolds number of $6.0*10^5$. The results of the open water tests were collated against the lifting surface calculations. The experimental thrust and torque of MP010 were considerably lower than the calculated ones. The visualization of the limiting streamline on MP010 showed that its direction changed towards the tip in the region of 97 % of the chord. This may indicate a virtual decrease of the angle of attack due to turbulent separation, or a sudden change in the development of the boundary layer near the trailing edge.

Nakazaki et al. (1986) designed three new blade section propellers each of three blades and of small blade area ratios, A_E/A_O = 0.35 & 0.25. The propeller models were designated SBA3-35, SBA3-25 and REF3-25. The model propeller diameters were 226.0 mm. In the open water model experiments they were compared with MAU type propellers of the same blade area ratios. The results of the tests were given as a function of the Reynolds number. The K_T diagrams of the new blade section propellers were similar to those measured by Bailar et al. (1992) discussed below.

Jessup (1989) experimentally investigated the viscous aspects of propeller blade flow. On the DTRC model propeller P4119 of the diameter of 305 mm, designed for shock free open water operation, two blades had their leading edges roughened with 0.06 mm distributed beads. At the 0.7 radius the pressure distribution and boundary layer velocity profiles were measured. Measurable differences in the pressure distribution were found between the smooth and rough blades near the trailing edge on the suction side, and in the leading edge domain on the suction and pressure sides.

Bailar et al. (1992) designed several new blade section propellers and tested them for powering and cavitation performance. The controllable pitch parent model, P4990, was of NACA 66 & a = 0.8 shape. Initially one, P5072, then four, P5131, P5132, P5133, and P5143, new blade section propellers were designed and model tested to refine the new section design. Variations were made in the root and tip regions to improve cavitation, and in the chordwise loading to improve powering. Thickness, camber, and chord length data are given for P4990 and P5132 in the report. The model propeller diameter was 402.9 mm. Powering performance was assessed with open water testing up to a Reynolds number of $2.4*10^6$ based on the 0.7 radius inflow. Bailar et al. (1992) give the diagrams of open water efficiency and thrust coefficient of two new blade section propellers as Figures 14 and 15. They are included in this report as Figures 7.1 and 7.2. Figure 7.1 shows the measured open water efficiency for two propellers tested on the low speed and the new high speed dynamometer/drives at DTRC. At low Reynolds numbers, both propellers suffer efficiency loss presumably due to the inner radii separation. The trailing edge separation on P5133 may gradually be subsiding with increasing Reynolds number.

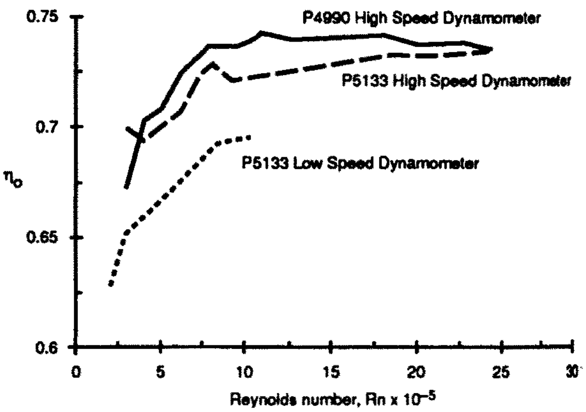


Figure 7.1 Measured Open Water Efficiency at Design Advance Number (Bailar et al 1992)

Both propellers attain the same efficiency at the highest Reynolds number tested. Figure 7.2 shows the thrust coefficient for P5132 and P5133 operating at their design advance coefficient of J = 1.27. The thrust coefficient steadily increases up to the Reynolds number of $1.0*10^6$. At higher Reynolds number the thrust of both propellers is relatively constant and approaches the thrust predicted by the panel code. The target thrust coefficient of K_T = 0.23 was not achieved for P5132, possibly indicating some inconsistencies in the design method. The panel code requires a sectional drag viscous correction, the value of C_D= 0.007 was used.

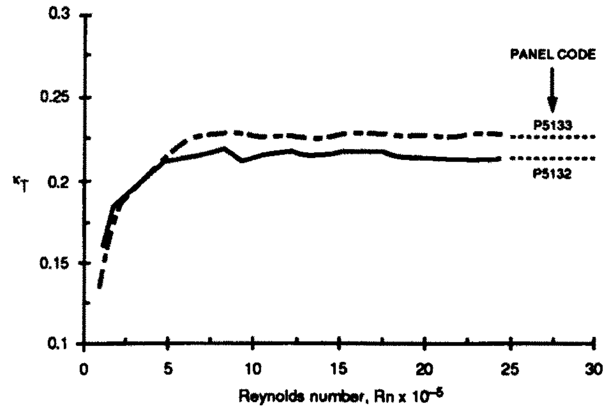


Figure 7.2 Measured Open Water Thrust at Design Advance Number (Bailar et al. 1992)

Stanier (1992) has designed three propellers, two of them with new blade sections, to operate at the advance number of J = 1.143. The parent propeller is designated C618 and the new blade section propellers C619 and C621. The paper contains the detailed geometry of the propellers. All the propellers have unusually thick sections. The model propellers were of diameter 304.8 mm, and the open water tests were made at the Reynolds number of about $1.3*10^6$ based on the 0.7 radius inflow. At the design point the propellers were analyzed with two lifting surface codes (PSF-2 & GBPL85), one panel code (PSF-10), and an incompressible Navier-Stokes solver code (MACHO). The results, together with the results of open water model tests in the No 1 Haslar Cavitation Tunnel are given in Table 7.1 of the paper of Stanier. This table is included in this chapter as Table 7.1. The lifting surface predictions broadly agree with each other, and clearly differ from the results of the model tests. The panel code predictions are somewhat closer to the model tests than the lifting surface predictions. The Navier-Stokes solver predictions are in quite good agreement with the results of the model tests. The reason for the relative failure of the lifting surface and panel codes may relate to the extreme off-loading in the root and tip regions of the propellers. This off-loading presumably changes the behavior of the boundary layer so that the simple two-dimensional drag correction is inappropriate. As a necessary additional check the open water tests for these particular propellers are to be made in a towing basin. Also the Navier-Stokes solver code should be applied to propellers of quite different geometry.

	PROPELLER C618		
Method	J	K_T	K_Q
Model	1.143	0.181	0.0499
MACHO	1.143	0.186	0.0487
PSF-10	1.143	0.213	0.0553
GBPL85	1.143	0.234	0.0617
PSF-2	1.143	0.236	0.0606
	PROPELLER C619		
Method	J	K_T	K_Q
Model	1.143	0.204	0.0562
MACHO	1.143	0.204	0.0561
PSF-10	1.143	0.237	0.0629
GBPL85	1.143	0.235	0.0618
PSF-2	1.143	0.254	0.0667
	PROPELLER C621		
Method	J	K_T	K_Q
Model	1.143	0.195	0.0538
MACHO	1.143	0.195	0.0528
PSF-10	1.143	0.226	0.0601
GBPL85	1.143	0.232	0.0609
PSF-2	1.143	0.240	0.0631

Table 7.1. Summary of a measured and predicted propeller performance (Stanier, 1992).

Shen & Dimotakis (1989) investigated the assumption that there is no scale effect on the values of negative minimum pressure coefficient. Both the calculations and the experiments were conducted on a hydrodynamically smooth two-dimensional NACA 66 (MOD) foil. Cebeci's (1986) viscid/inviscid interactive code was used to compute the viscous scale effects on the development of the boundary layer, lift, drag and pressure development on the foil. Due to the boundary layer displacement effect, the values of C_L, C_D and C_P are Reynolds number dependent. In this particular investigation, the pressure loading had a strong suction pressure peak at the angle of attack of 3 degrees. The calculated values of $-C_{Pmin}$ are as much as 12 to 15 percent lower on the model ($R_n = 3.0*10^6$) than at full scale ($R_n = 1.0*10^8$). Even at full scale the difference in suction pressure peaks between inviscid and viscid solutions is quite noticeable. In the case of a roof-top pressure loading at an angle of attack of 1 degree, the change in the pressure loading is distributed over the whole chord and the scale effect on the values of $-C_{Pmin}$ com-

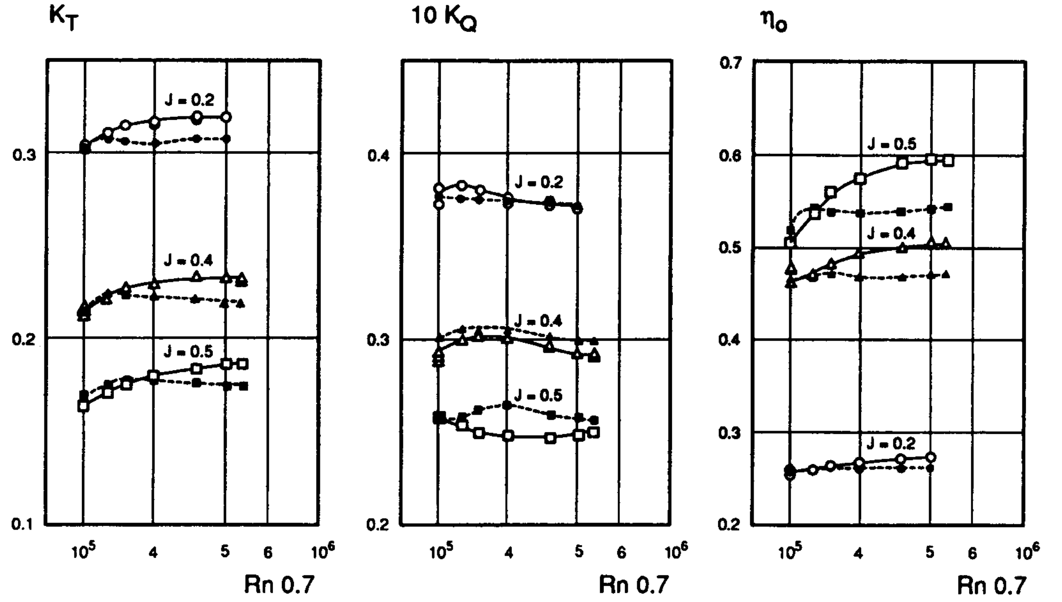


Figure 7.3 Open water characteristics of MP P072R (variable pitch) versus Reynolds number without and with roughness bead size of 0.100 mm (Ishii et al. 1983). White dots denote smooth blades and black roughened blades.

puted numerically is found to be small. Shen & Huang (1989) continued the above investigation. At the low angle of attack of (-2.5) degrees the adverse pressure gradient is so strong that the flow separates first and then reattaches to the foil immediately behind the suction peak. The conclusion was that the location of separation is insensitive to Reynolds number. Hence the scale effect on the minimum pressure coefficient is small. The zero lift angle is shifted as Reynolds number changes. Also the zero lift angle to be expected at the full scale was reasonably predicted by the inviscid solution.

Tamura & Sasajima (1977) reported on propeller open water and propulsion tests both without and with turbulence stimulators. Turbulence was stimulated by square and cylindrical studs with representative dimensions of 0.5 - 1.0 mm on propellers of 233.0 and 177.6 mm diameters. The addition of the stimulators did not affect the final results of the propulsion tests. The open water characteristics were changed to a great degree.

Ishii et al. (1983) roughened the leading edges with carborundum for cavitation tests. The beads were attached on both suction and pressure sides for a width of 1.0 - 1.5 mm on propellers of 250.0 mm diameter. The average bead sizes were 0.030, 0.100, 0.177, and 0.420 mm. The measurements and photos show that the flow characteristics rapidly change at the particle size of 0.03 to 0.04 mm. Thrust and torque coefficients are almost constant for $R_{n0.7}$ greater than $4.0*10^5$ for the smooth blades, and for $R_{n0.7}$ greater than $2.5*10^5$ for the rough blades with the bead size of 0.100 mm. The open water efficiency is weakly influenced by roughness of the size of 0.100 mm at the advance number of J = 0.2, i.e. at an off-design loading point, and strongly changed by roughness at the advance numbers of J = 0.4 & J = 0.5, the latter being the design advance number. Figure 5 of Ishii et al. (1983), depicting these relationships, is included in this report as Figure 7.3.

Fagerjord & Andresen (1982) found that the scaling procedure may have a large effect on the optimal propeller dimensions derived from systematic model tests. To clarify this aspect additional open water and propulsion tests were performed with three model propellers of diameter 250.0 - 256.7 mm. Two types of stimulators on suction and pressure sides were used. Sand strips were of 0.08 mm bead size and lengths of 3 - 8 mm. The scribed groove had a height of 0.03 - 0.04 mm.

Depending on the type of propeller the scribed groove caused a drop of open water efficiency of 0.04 - 0.018, and the sand strips a drop of 0.13 - 0.05.

Wills & Ball (1986) investigated the effect of artificial stimulation of the boundary layer on cavitation performance using two model propellers. The diameters of the model propellers, designated C578 and C586, were 305.0 mm. Three grades of silicon carbide, 0.013, 0.038, and 0.102 mm, were attached on both the back and face leading edge with a chordwise extent of 2 mm. For the type of propellers investigated, it was concluded that the maximum allowable difference between the model and the equivalent full scale profile in the region of the roughness was 0.042 mm. The report does not contain any pressure or performance data. The roughness Reynolds number of the 0.038 mm beads satisfies the criterium of $R_K > 600$ with the reference velocity based on the section inflow velocity at the 0.7 radius. The description of the technique of attaching the roughness elements of Wills & Ball (1986) is both detailed and instructive.

In early experiments at SSPA Nordström et al. (1954) tested four different sizes of sand grain on model propeller P64 of diameter 257.3 mm. The blades were completely covered with sand grain. Replotting the results of Nordström in polar form it seems that a bead size of about 0.03 mm hardly affects the lift. This bead size slightly increases the drag coefficient from about 0.0063 - 0.008 to 0.0083 - 0.010, depending on the angle of attack. A bead size of about 0.09 mm affects both lift and drag in such a way that this particular type of roughening cannot be used in model testing.

When investigating experimentally the effect of crescent planform on lift and drag van Dam et al. (1991) found it necessary to locate attachment-line trips around the leading edge at around 98 % of the span. These trips were oriented normal to the leading edge to ensure the transition of the boundary layer along the highly swept tips. This point of view could possibly be considered in marine propeller tests where the very leading edge is unroughened. In their wind tunnel experiments the Reynolds number based on the average chord was about $1.7 * 10^6$.

Schmitz (1983) has investigated six types of turbulence stimulators on wings intended for low speed aeronautical application. A trip wire ahead of the leading edge and two shallow steps in the leading edge region were among the stimulators investigated. A trip wire ahead of the leading edge was found to be the best method of ensuring turbulent flow. The final conclusion is that the size of the stimulator should be as small as possible, i.e. the disturbance caused to the flow is to be minimized. Excessive stimulation lowers lift and increases drag.

Faller et al. (1992) investigated the effect of local sand roughness applied to the leading edge region of a highly swept wing to delay the inception of tip vortex cavitation. Carborundum grains of 0.100 mm were applied at two different locations. The dimensions and shapes of the wing and sections are not given. The lift coefficients stayed almost unchanged whilst the drag coefficient was significantly increased. Sandblasting was also tried and found to be an inadequate turbulence stimulator.

Lewandowski (1989) investigated turbulence stimulation on the control surfaces of a SWATH model. Two sets of fins were tested, one having flat-plate sections and the other having NACA 0015 sections. The span was approximately 76 mm and chord 50 mm. Lift and drag were measured over a range of attack of 0 to 35 degrees. The tests covered a range of chord-based Reynolds numbers between 42000 and 150000. Turbulence stimulation was provided by Hama strips. The strips were made from double thickness of electrical tape 0.64 mm wide, cut with pinking shears to form a serrated leading edge. The thickness of the strip was about 0.036 mm and the strip was located at the distance of 0.05 % of the local chord from the leading-edge. This configuration creates three-dimensional vortex loops within the boundary layer with minimal parasitic drag. In addition, some runs were made using a trip wire as the transition device. Turbulence trips increase the measured drag and reduce the lift curve slope, most noticeable on the flat-plate fins.

Preston (1958) has investigated the minimum Reynolds number for a turbulent boundary layer and the selection of the transition device. Rather limited experimental data confirmed that the lower limit to the Reynolds number based on the momentum thickness is about 320. The choice and size of the transition device was examined in relation to this minimum Reynolds number, and an approximate theory led to a wire Reynolds number. In the case of a trip wire, this wire Reynolds number is 600. The figures in the paper of Wills & Ball (1986), depicting the radius of cavitation inception, indicate that the minimum roughness height Reynolds number is also about 600.

Ducted Units. Falcao de Campos (1983) has calculated the force coefficients and the boundary layer on the inner and outer surfaces of NSMB 19A and 37 ducts, and compared the calculations with flow visualizations and experiments. The duct model length was 100 mm. The development of the duct boundary layer was investigated by paint tests as done earlier by Kuiper (1981). The tests were made in both the deep water basin and cavitation tunnel. The correlation of experiments and calculations shows that the force coefficients measured in the cavitation tunnel agree well with turbulent separation in the calculations on the inner surface. At high advance coefficients considerable loss of thrust is caused by the leading edge separation on the outer surface. Turbulence stimulators are regularly used on the inner and outer sides of ducts at MARIN.

Dyne (1977) found that the ratio of thrust coefficients K_{TD}/K_{TP} measured in the large cavitation tank rapidly increased with increasing water speed. Laminar separation on the leading edge is the likely type of separation. Hence three different turbulence stimulators were tested, one or two rows of beads with a diameter of 1.0 mm and a separate ring located ahead of the duct. The duct length was 93 mm. The stimulating effect of the ring was dependent on the radial component of the wake field. The large size of the beads glued on the inner surface caused parasitic drag.

Contrarotating Propellers. Ukon et al. (1988) designed two sets of contrarotating propellers with an improved version of Morgan's method. The blade sections were specially designed to avoid face cavitation. This aim was not achieved for the propeller set CRP1, the pitch ratios of which were P(0.7)/D = 1.274 & 1.366, and was achieved for the CRP2 set with the pitch ratios of P(0.7)/D = 1.430 & 1.505 of the forward and aft propellers respectively. The sets were designated MP258/259 (CRP1) and MP278/279 (CRP2). Both forward model propellers had diameters of 250.0 mm. The open water tests were made with both smooth and roughened blades at different Reynolds numbers. At the design advance coefficient of J = 1.00 the thrust coefficient of the aft propeller was not changed by the addition of the roughness on the forward propeller. At Reynolds numbers less than $R_{n0.7} = 2.8*10^5$ the thrust and torque coefficients and open water efficiencies were noticeably affected by scale effects. Above this Reynolds number limit the addition of roughness decreased the open water efficiency from the smooth surface value of about $\eta_0 = 0.70$ to about $\eta_0 = 0.67$.

Conclusion

The present ITTC-1978 extrapolation method, i.e. the lift coefficient is assumed independent of Reynolds number, seems to be based on limited data obtained with propellers of small amount of skew, NACA type sections, and designed without extreme tip or root unloading. The tests and calculations made to date, do not give definite guidance how to evaluate and deal with the effect of boundary layer tripping on lift and drag, especially for new blade sections. Because of the effect of pitch and skew, two-dimensional tests and calculations patterned on the work of Shen et al. (1989) for new type blade sections are not adequate to obtain complete physical insight to the problem of tripping devices on model propulsors. Viscous flow calculations and experiments on model propellers are required to determine the type and size of the tripping device. The goal of an experimental investigation should be to find the minimum bead size, bead area, and the type of bead material that are adequate for turbulence stimulation. Rather limited experimental data indicate that to obtain a turbulent boundary layer, the minimum Reynolds number based on the momentum thickness is about 320. In the case of beads, this requirement corresponds to the bead height Reynolds number of about 600. These two limits also depend on the pressure gradient. Logically, beads of larger size would be needed in the root region than are needed in the tip region.

Based on evidence now available, open water tests of new blade section model propellers without tripping devices should be made at a Reynolds number somewhat larger than one million.

VIII REFERENCES

Reference List Acronyms

AIAA	Amer. Inst. Aero. & Astro
ATTC	Amer. Towing Tank Conf.
CMFF	ASME Cav. and Multiphase Flow Forum
CSNAME	Chinese Soc. of Nav. Arch. & Mar. Eng.
CSSRC	China Ship Scientific Research Center
DTRC	David Taylor Research Center
FVSJ	Flow Visual. Soc. of Japan
HADMAR '91	Int'l Symp. on Hydro- and Aerodynamics in Marine Engineering, 1991
HSVA	Hamburgische Schiffbau-Versuchsanstalt
ICFEMFP	Intl. Conf. on Finite Element Methods in Flow Prob.
ICNSH	Intl. Conf. on Num. Ship Hydro.
IMAEM	Intl. Cong., Varna, Bulgaria
IME	Inst. of Marine Eng.
INA	Inst. of Naval Arch.
ISP	International Shipbuilding Progress
ISPC	Intl. Symp. on Propeller and Cavitation, 1986
ISPC '92	The Second Intl. Symp. on Propeller and Cavitation, 1992
ISRP '89	The Intl. Symp. on Ship Resistance and Powering Performance, 1989
JSR	Journal of Ship Research
KSNAJ	Kansai Soc. of Naval Arch. of Japan
LIPS	Lips Propeller Symp.
MESJ	Marine Eng. Soc. of Japan
NECIES	North East Coast Inst. Engrs. & Shipbuilding
NFDC	National Fluid Dynamics Congress
ONR	Office of Naval Res. Symp. on Naval Hydro.
PRADS	Practical Design of Ships, Symp.
RINA	Royal Inst. of Naval Arch.
SNAJ	Soc. of Naval Arch. of Japan
SNAK	Soc. of Naval Arch. of Korea
SNAME	Soc. of Naval Arch. & Marine Eng.
SMSSH	Sci. & Method Seminar of Ship Hydro., Varna, Bulgaria
SHPEMA	Symp. on Hydro. Perf. Enhancement for Marine Appl.
SuH	Schiff & Hafen
STG	Schiffbautechnische Gesellschaft
WJSNA	West-Japan Soc. of Naval Arch.

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IX CONCLUSIONS

Quality Control

Quality control has been addressed by the committee from two points of view. First, it is recognized that due to a general lack of published uncertainty analyses, benchmark quality data is difficult to identify. The committee has initiated an effort to certify viscous flow measurements on a propeller. The completion of this task will be the responsibility of the 21st ITTC Propulsor Committee. Secondly, comparative experiments and numerical calculations were initiated to assist interested ITTC organizations in their refinement of experimental and numerical methods. These comparative efforts also provide the opportunity for participants to learn from the experience of others which is a valuable adjunct to the process of validation.

Comparative Propeller Experiments On Steady Reynolds Number Effects

Based on the replies to a questionnaire it appears that only a few organizations are prepared to make quantitative flow measurements of the viscous flow associated with a propeller. Preliminary data received by the committee indicated that a revised approach must be used if experiments are to produce benchmark quality data suitable for validating viscous flow codes. Comparative experiments have been initiated and plans for a single benchmark experiment have been made. This work will need to be continued by the 21st Propulsor Committee.

Workshop On Surface Panel Method For Marine Propellers

The contributions to the workshop on surface panel methods demonstrated the value of panel methods for propeller analysis. It appears, however, that few organizations have developed panel methods for propeller design. The contributed predictions of performance for the reference propellers were in good qualitative agreement with the experimental data. These comparative calculations gave valuable insight to the participants. However, due to the magnitude of the effort required, no attempt was made to assess the quantitative agreement with the experimental data. Panel methods predict well the pressure distribution on a simple propeller even at sections close to the hub. For a high skewed propeller there exists significant scatter close to the leading and trailing edge; further work is required in order to improve the accuracy of predictions for highly skewed propellers. In certain cases, panel method calculations are now of sufficient quality to assist in the assessment of the experimental data during collection. For further development, the treatment of viscous corrections and slipstream wake model must be studied. Overall, the use of surface panel methods has become sufficiently accurate such that they are in routine use in some ITTC organizations. The propulsor committee strongly encourages the ITTC members to support the future development of surface panel methods in the design and analysis of propulsors.

Review of Improvements in Mathematical Models for Propulsors

Marine propeller designs and the predictions of the propeller performance are still dominated by the use of lifting surface theory. The surface panel methods are becoming very useful for marine propellers. Most of the methods are potential based, rather than velocity based. Further investigation on the arrangement of panels close to leading and trailing edges is necessary. There are few studies on unsteady calculations. Further development is necessary in the treatment of viscous corrections and slipstream wake models for both lifting surface methods and surface panel codes.

Inclusion in the RANS equation solver of a propeller modeled by body force allows one to analyze in an exhaustive manner the propeller-hull interaction. This provides a prediction tool to solve the effective wake problem. Further investigation is necessary for a complete approach to the propeller/hull interaction problem. RANS techniques applied to open water propellers appear to provide a reasonable picture of the basic physics of propeller flow. With the increasing speed of computers, this method offers great promise for the future.

Computer Aided Design and Manufacture for Propulsors

Based on the replies from 28 organizations to a questionnaire, the committee found extensive use of CAM in both model and full scale propeller manufacture. Improvement in accuracy was stated as one of the strongest incentives for adopting CAM, closely followed by savings in time, labor and cost. The replies to the questionnaire indicated that there is no standard method for geometry inspection and subsequent comparison with design.

Cavitation Control In Propulsor Design

A large amount of data is available on methods for controlling cavitation on propellers of conventional design. However, there is only a limited amount of published information available on the cavitation performance of unconventional propulsors and cavitation control in their design. The committee concludes that there is considerable potential for controlling propeller cavitation performance by improving the propeller inflow. Progress in this area will benefit from continued support by the ITTC members.

Effect Of Leading Edge Boundary Layer Tripping

Based on the data reviewed, the committee concludes that open water tests of new blade section propellers with roughness should be made at Reynolds Numbers somewhat larger than one million. It has been found that the parasitic drag increases rapidly with increasing bead size. The size commonly used in cavitation tests is unnecessarily large. Care is required in choosing and determining the type, size, location and way of attaching the roughness elements. The committee encourages future experimental efforts to provide more detail on the use of boundary layer tripping on propulsor components.

X RECOMMENDATIONS FOR FUTURE WORK OF THE COMMITTEE

1. Evaluate experimental and theoretical prediction techniques for unconventional methods of propulsion such as, tip plate, ring, and ducted propellers.

2. Provide advice on boundary layer tripping on propulsor surfaces that exhibit significant viscous effects on model wake.

3. Update propulsor literature database.

4. Develop a guide for the use of Laser Doppler Velocimeters for the collection of propulsor data suitable for validating numerical calculations.

5. Investigations of high speed propulsors and interaction effects for high speed marine vehicles should be continued. (transferred from HSMV Committee).

6. Evaluate developments in the use of panel methods and Reynolds Averaged Navier Stokes equation codes for propulsion.

7. Evaluate the Reynolds number dependency of lift coefficient for wing sections. (transferred from Powering Performance Committee).

8. The Committee should develop standard procedures and codes of practice which conform to ISO 9000.