POLISH MARITIME RESEARCH 1(59) 2009 Vol 16; pp. 29-34
10.2478/v10012-008-0007-7

A complete design of ship propellers using the new computer system

Tadeusz Koronowicz, Prof.
Zbigniew Krzemianowski, Ph. D.
Teresa Tuszkowska, Ph. D.
The Szewalski Institute of Fluid Flow Machinery
of the Polish Academy of Sciences in Gdansk
Jan A. Szantyr, Prof.
Gdansk University of Technology

ABSTRACT

The computer system presented in this article is composed of several program blocks for the complete design of ship propellers. The design calculations are based on a combination of the modified lifting line theory and on the vortex lifting surface theory. The system enables solution of the following design problems:

- *calculation of the scale effect on the ship wake velocity field, including the influence of the propeller and rudder on this field at the propeller location*
- *maximization of the propulsive efficiency*
- *optimization of the propeller blade geometry on the basis of the compromise between the cavitation and blade strength requirements*
- *optimization of the number of propeller blades and blade geometry on the basis of the acceptable level of induced pressure pulses and unsteady shaft bearing forces*
- *calculation of the blade spindle torque for the controllable pitch propellers.*

The computer system is equipped with many numerical options for graphical visualization of the input data, including an easy possibility of their correction and control of the intermediate and final results of calculations.

Key words: ship propellers, design methods, computational fluid dynamics

INTRODUCTION

In the recent years a computer system has been developed, which enables the complete design calculation of the different ship propulsor types, including their analysis in the wake velocity field behind the full scale ship hull. For this purpose the design and analysis blocks of the system are supplemented with the block for calculation of the wake scale effect and the influence of the propeller operation and presence of the rudder on the ship model wake.

The main design process is based on the modified lifting line model and on the model of vortex lifting surface theory. The analysis of the designed propeller operation in the non-uniform velocity field is based on the extensively modified program UNCA [2, 3, 4].

The propeller design system enables solution of the following design problems:

⇨ calculation of the effective ship wake velocity field, including the scale effect at the propeller location
⇨ correction of this field for the presence of the rudder (measurements of the wake in model scale are usually performed without the rudder)
⇨ maximization of the propeller efficiency
⇨ optimization of the propeller blade geometry, resulting from the compromise between the cavitation and strength requirements
⇨ optimization of the number and geometry of the propeller blades on the basis of the acceptable level of the pressure pulses generated on the hull and of the unsteady bearing forces
⇨ calculation of the blade spindle torque for the controllable pitch propellers.

The system is based on the conversational principle and it is equipped with an extensive set of graphical programs. It enables an easy control and correction of the input data and of the results of calculations of every block of the system. All data modifications are recorded and they may be used, if necessary, in any further design calculation.

The results of calculations may be presented in the form of printouts, graphical diagrams or films, showing the variation of the pressure distribution or cavitation phenomena on a rotating propeller.

The system includes three main program blocks:

➲ the program for determination of the design velocity field
➲ the program for propeller design,

➲ the program for analysis of propeller operation in the non-uniform inflow field.

The block diagram of the system is shown in Fig. 1. The expected final effect of the propeller design process may be achieved only through proper interaction between these programs. The calculations may be controlled from the computer screen, without preparation of the special data sets for the respective blocks of the system. The special graphical procedures enable an easy control of the input data and of the intermediate results, including also correction of the propeller blade geometry directly from the computer screen at all stages of the design process.

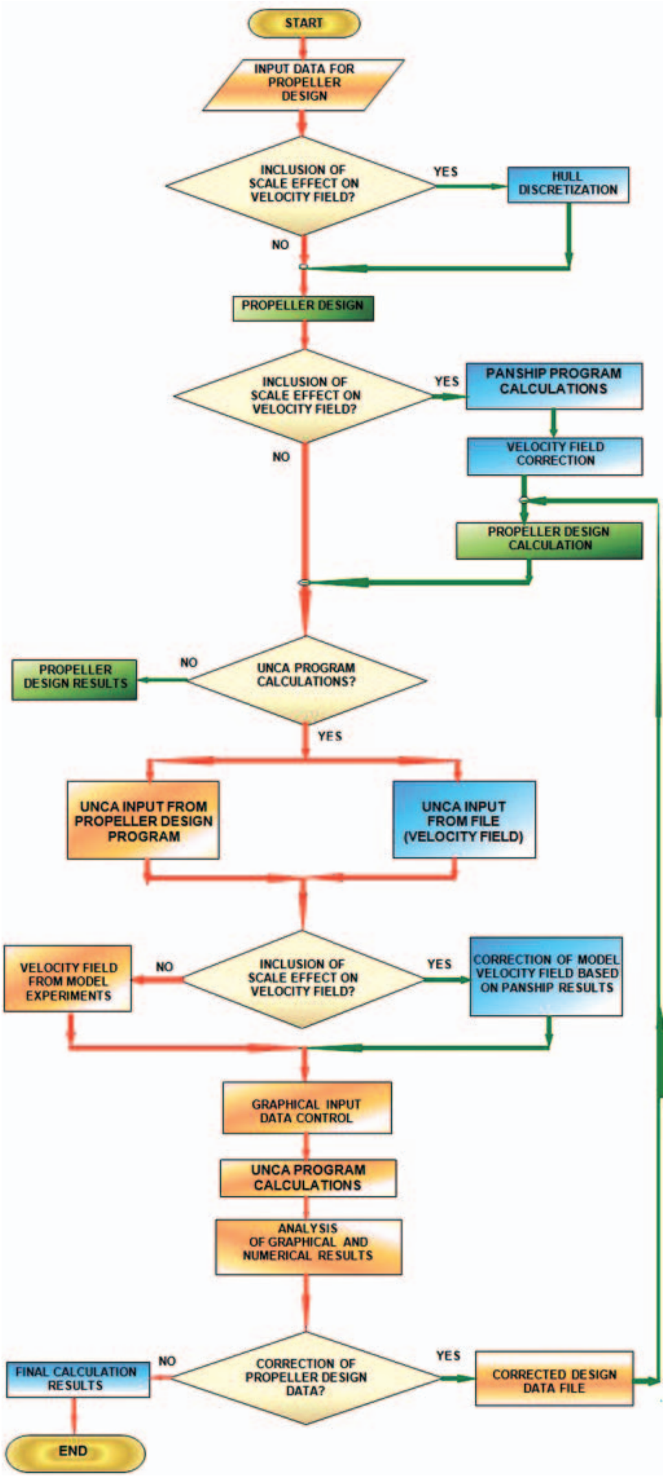

***Fig. 1.** The block diagram of the computer system for the complete design of ship propellers*

DESCRIPTION OF THE MAIN BLOCKS OF THE SYSTEM

The input data

The input data include all quantities necessary for the initiation of the four alternative versions of the calculations:

★ propeller design calculation without correction of the velocity field and without the analysis of the propeller operation in the non-uniform velocity field,
★ propeller design calculation without correction of the velocity field, but including the analysis of the propeller operation in the non-uniform velocity field,
★ propeller design calculation including the correction of the velocity field for the scale effect and the analysis of the propeller operation in the non-uniform velocity field, but without the correction for the presence of the rudder,
★ propeller design calculation including corrections of the velocity field both for scale effect and rudder presence and including the analysis of the propeller operation in the non-uniform velocity field.

The input data may be introduced in the form of the pre-prepared input data file or they may be introduced directly from the computer screen in the conversational mode. The program is equipped with graphical procedures for control of the correctness and for modification of the input data.

The program block for calculation of the scale effect and of the rudder and propeller influence on the wake velocity field

In order to perform the calculation including the scale effect on the wake velocity field the appropriate data describing the hull geometry (typically the set of theoretical hull frames and outlines of the bow and stern) must be available. Alternatively, the earlier prepared data file containing the hull geometry defined as the set of panels may be used as input. The selection between these two options is made from the screen. In the first option the program for transformation of the hull geometry into the set of panels is used.

Calculation of the scale effect on the wake velocity field does not require a large number of panels describing the hull geometry. The practical experience shows that the sufficiently accurate results may be obtained using:

- 60 panels along the hull length
- 20 panels along the hull frame (at one side of the hull).

Such a number of panels may be accurately defined if the set of 16 theoretical frames is available, with more dense distribution in the bow and stern regions. Fig. 2 shows an example of the hull represented by the set of panels, viewed at a certain rotation angle. Such a presentation enables efficient control of the distribution of the panels, which should have the form of quadrangles possibly close to squares.

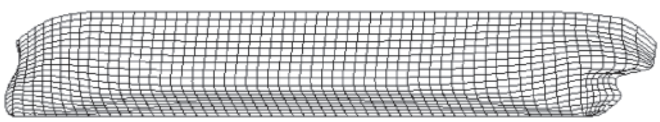

***Fig. 2.** The ship hull viewed at a rotation angle around the x axis*

The correct representation of the hull as the set of panels allows further calculation using the PANSHIP program [9, 10, 11, 12], in order to determine the scale effect on the hull wake velocity field at propeller location and to calculate the propeller design velocity field.

The hull represented by the set of panels may be supplemented with the rudder described by a separate set of panels. The rudder is usually not taken into account in calculations for model scale (if the model experiments have been performed without the rudder), but it is always included in the full scale calculations.

The determination of the design velocity field

Taking into account the scale effect on the velocity field at propeller location is a very important aspect of the propeller design process. The design procedure itself, which determines the propeller performance and blade geometry, requires only the radial distribution of the circumferential average of the axial component of the velocity field. However, the complete design process requires information about the entire velocity field (three components distribution over the propeller disc) in full scale, including the effect of propeller operation (the effective field) and the effect of the rudder presence. This may be achieved only using the computation procedure based on the "computer model basin". Such a procedure has been developed on the basis of the computer model basin PANSHIP [10, 12].

Example of application of such a procedure is presented in Figs. 3 and 4. Fig. 3 shows the results of measurements of the axial component of the velocity on the tanker model, while Fig. 4 shows the corresponding design velocity field calculated for the full scale ship. The influence of rudders of different thickness on the velocity field at propeller location is shown in Figs. 5 and 6 [6, 12].

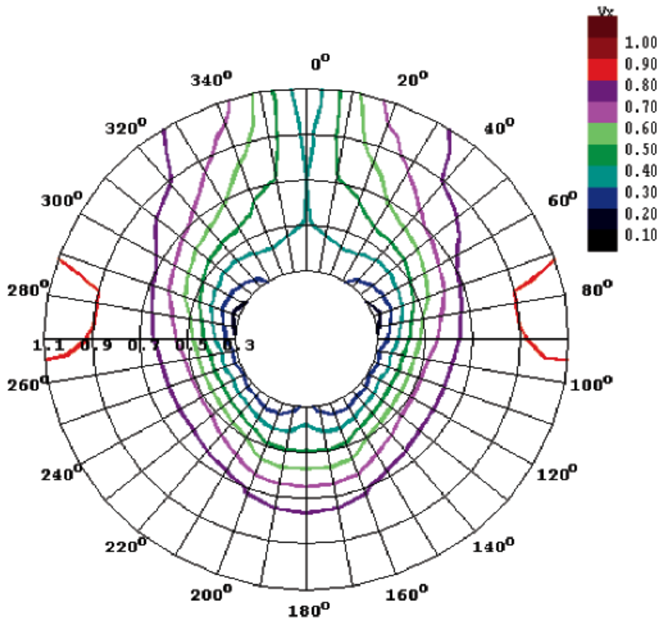

Fig. 3. Results of measurements of axial velocity component behind the tanker model Lpp = 6.53 [m]

The results presented in these figures show the meaningful scale effect and visible influence of the rudder presence on the velocity field at propeller location. The analysis of theses results leads to the conclusion that either model experiments should be conducted with the rudder or the appropriate corrections may be calculated using the computer model basin (e.g. PANSHIP). As the velocity field should be corrected both for the scale effect and for the rudder effect, these corrections may be integrated in one procedure, leading to the effective full scale velocity field. Only such a velocity field enables correct analysis of the propeller operation behind the ship hull.

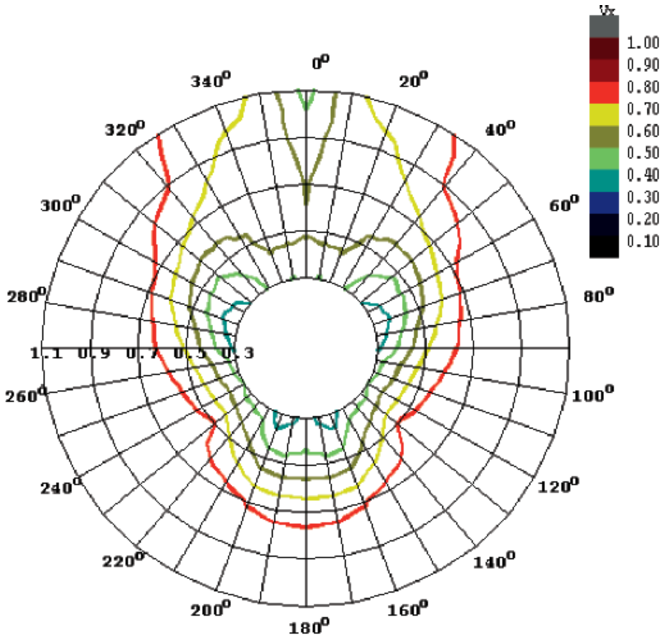

Fig. 4. Results of calculation of the design velocity field for the full scale tanker Lpp = 200 [m]

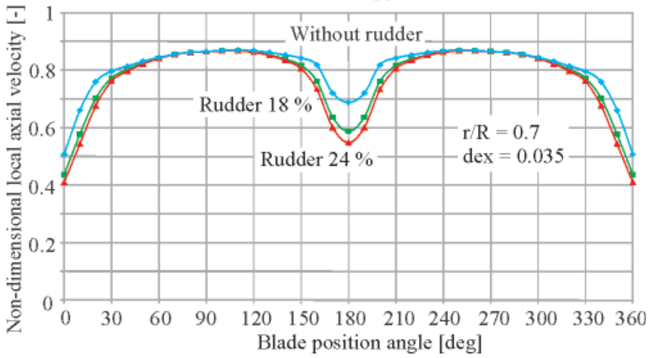

Fig. 5. Influence of the rudders of different thickness on the axial velocity component at the propeller location

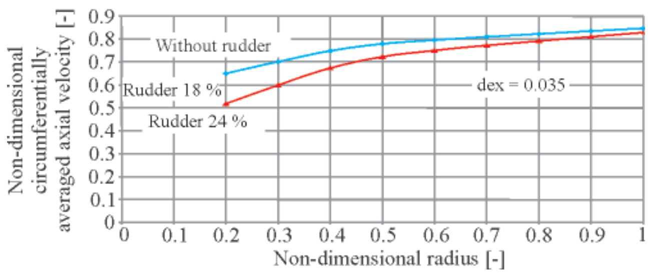

Fig. 6. Influence of the rudders of different thickness on the radial distribution of the circumferential average of the axial component of velocity at propeller location

The design program block

The algorithm of the design program has been described in great detail in [1, 8]. The program based on this algorithm has been functioning over many years and it has been extensively verified.

The design calculations are performed in all cases, irrespective of the version selected in the Section 2.1 above. In case of version **a)** these are the only and final calculations, ending with the results which are presented in the form of tables (cf. Figs. 7 and 8) and pictures shown on the computer screen (cf. Figs. 9, 10 and 11). The pictures may be easily printed. The full results are included in the file Design.OUT.

In the case of version **b)** the design calculations are conducted alternating with the analysis program UNCA, until the appropriate criteria regarding e.g. cavitation phenomena or pressure pulses and unsteady bearing forces are fulfilled.

Summary – Propeller

Design ship velocity [knots]	22.000
Advance coefficient [-]	0.7285
Thrust coefficient [-]	0.4855
Torque coefficient [-]	0.1027
Efficiency [-]	0.5484
Cavitation number [-]	2.4936
Cavitating tip vortex kernel diameter [mm]	138.2382
Circulation distribution coefficient [-]	0.5409
Blade area ratio [-]	0.975
Thrust [N]	2748402
Power [kW]	38741.8945
Mass of the blades [kg]	36753.66
Moment of inertia of the blades in air [kg*m^2]	494764.06
Moment of inertia of the blades in water [kg*m^2]	759142.5
Cavitation	Yes
Laminar cavitation - suction side	Yes
Laminar cavitation - pressure side	No
Bubble cavitation – suction side	Yes
Bubble cavitation – pressure side	No
Intermittent cavitation – suction side	Yes
Intermittent cavitation – pressure side	No
Tip vortex – suctionside	Yes
Tip vortex – pressure side	No

Fig. 7. The main results of the design task

*******************DESIGN CALCULATION OF THE FIXED PITCH PROPELLER****************
THE TASK WAS TO CALCULATE DELIVERED POWER FOR FIXED PROPELLER THRUST
BLADE SECTION PROFILE NACA 35 NACA65
STRENGTH CALCULATION ACCORDING TO ICE CLASS

NO. OF BLADES	5	WAKE FRACTION	0.3160
DIAMETER (M)	7.0000	RAKE (DEG)	0.0000
HUB DIAMETER (M)	1.4000	SKEWBACK (DEG)	4.8991
DESIGN SPEED (W)	22.0000	BLADE AREA RATIO	0.9750
REVS. PERMIN	91.0000	THRUST (N)	2748402.00
SHAFT IMMERSION (M)	4.5000	POWER (KW)	38741.8945
WAT. DENSC (KGM-3)	1025.00	ADVANCE COEFF.	0.7285
CAVIT. NUMBER	2.4936	THRUST COEFF.	0.4855
TIP VORTEX KERNEL (MM)	138.2382	TORQUE COEFF.	0.1027
COEFF. OF DISTR. CIRCU	0.5409	EFFICIENCY	0.5484

X	R(M)	C(M)	LE(M)	P(M)	M(M)	T(M)	LS(M)	CL	CD
0.2000	0.7000	2.1399	1.0700	8.2679	0.1252	0.4263	0.0000	0.0000	0.0080
0.3000	1.0500	2.3594	1.2651	8.3451	0.1557	0.3290	-0.0854	0.6419	0.0080
0.4000	1.4000	2.5705	1.4014	8.4995	0.1756	0.2618	-0.1162	0.6291	0.0080
0.5000	1.7500	2.7687	1.4984	8.5046	0.1845	0.2114	-0.1141	0.5625	0.0080
0.6000	2.1000	2.9463	1.5326	8.5454	0.1830	0.1680	-0.0595	0.4804	0.0080
0.7000	2.4500	3.0872	1.5086	8.8629	0.1725	0.1288	0.0350	0.3985	0.0080
0.8000	2.8000	3.1525	1.3711	9.2855	0.1547	0.0917	0.2051	0.3121	0.0080
0.9000	3.1500	3.0096	1.0155	9.8592	0.1290	0.0560	0.4893	0.2272	0.0080
1.0000	3.5000	0.3010	-0.8995	10.4328	0.0115	0.0280	1.0500	0.0001	0.0080
X	WR	C/D	LE/D	P/D	M/C	T/D	LS/D	G	CR/CL
0.2000	0.5478	0.3057	0.1529	1.1811	0.0585	0.0609	0.0000	0.0000	********
0.3000	0.4691	0.3371	0.1807	1.1922	0.0660	0.0470	-0.0122	0.0463	0.0125
0.4000	0.4390	0.3672	0.2002	1.2142	0.0683	0.0374	-0.0166	0.0647	0.0127
0.5000	0.4190	0.3955	0.2141	1.2149	0.0666	0.0302	-0.0163	0.0765	0.0142
0.6000	0.4090	0.4209	0.2189	1.2208	0.0621	0.0240	-0.0085	0.0833	0.0167
0.7000	0.3689	0.4410	0.2155	1.2661	0.0559	0.0184	0.0050	0.0856	0.0201
0.8000	0.2687	0.4504	0.1959	1.3265	0.0491	0.0131	0.0293	0.0802	0.0256
0.9000	0.1685	0.4299	0.1451	1.4085	0.0428	0.0080	0.0699	0.0623	0.0352
1.0000	0.1285	0.0430	-0.1285	1.4904	0.0384	0.0040	0.1500	0.0000	80.0000

Fig. 8. The table of the results of design calculations (the first page only) copied from the file Design.OUT

The program block for analysis of the propeller operation in the non-uniform velocity field

The program UNCA for the analysis of propeller operation in the non-uniform velocity field is the very important element of the propeller design process. The main part of the algorithm of this program deals with the determination of the extent and intensity of different forms of cavitation present on the blades of the propeller operating in the non-uniform velocity field. The original theoretical model integrates the unsteady vortex lifting surface theory with the dynamically varying cavitation bubbles. The detailed description of this program is included in [2, 3, 4].

Fig. 9. The rendered picture of the designed propeller blades

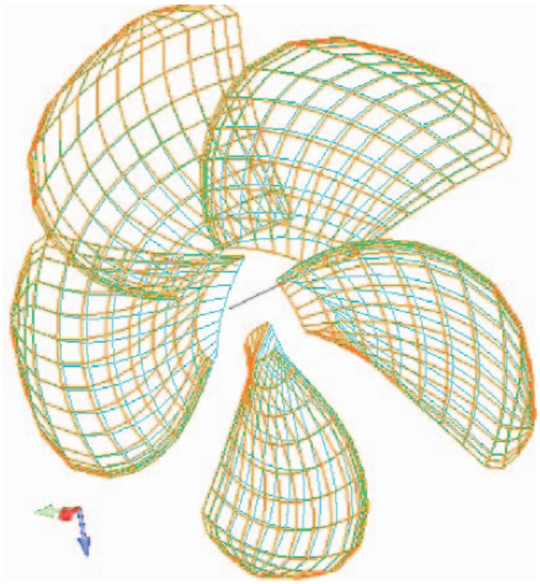

Fig. 10. The designed propeller blades shown in the grid form

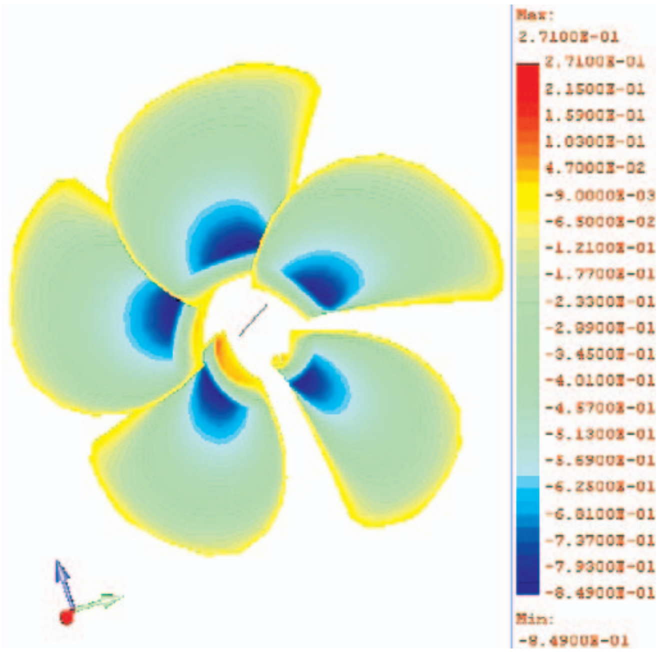

Fig. 11. The distribution of pressure coefficient on the suction side of the blades in the propeller design condition

The input data to the analysis program are introduced from the appropriate file (the velocity field – either given or computed in the system according to Section 2.3) and from the results of the design task performed in Section 2.4 (geometry of the propeller and some additional data). These input data may be controlled from the screen as the **Summary of the Analysis Task Settings.** An example of such a table is shown in Fig. 12.

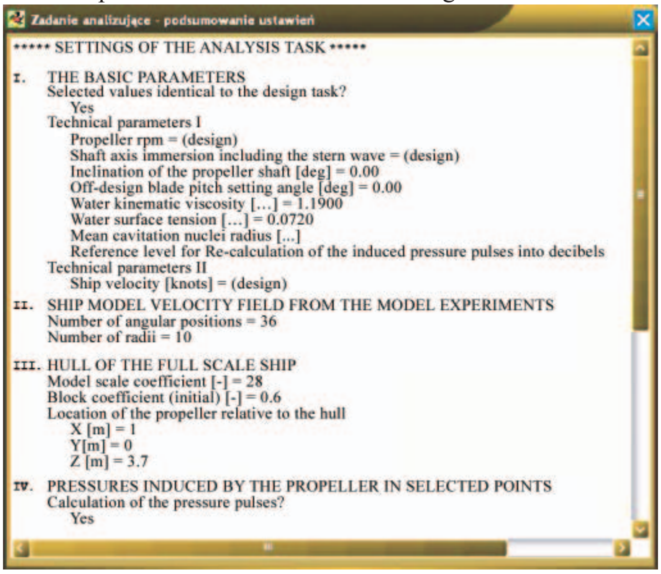

Fig. 12. *Summary of the Analysis Task Settings*

The newly designed propeller is analysed using the program UNCA from the following points of view:

- presence of the different forms of cavitation in the selected angular propeller blade positions in the non-uniform velocity field
- values of the induced pressure pulses either on the ship hull or in the surrounding space,
- values of the unsteady bearing forces.

After the analysis of the results of these calculations the appropriate modifications to the designed propeller geometry may be introduced and the design calculations may be repeated. For example the following propeller geometry parameters may be changed:

- the values and the radial distribution of the blade skewback
- the values and the radial distribution of the blade profile chord lengths
- the values and the radial distribution of the blade profile maximum thickness
- the type of chord-wise profile thickness distribution
- the type of chord-wise profile mean line camber distribution
- the radial hydrodynamic loading (circulation) distribution
- the number of blades.

The analysis of propeller operation in the non-uniform field of flow may be performed for the design ship speed and propeller rate of rotation or for the off-design values of these parameters (without changing the blade geometry and the velocity field). This is very convenient when the propeller is designed for the compromise design condition, e.g. for a fishing vessel, a tug boat or a navy ship. For such ships more than one ship speed is important (e.g. towing speed, free running speed or maximum speed) and the designed propeller should ensure the optimum performance over the entire range of operating conditions.

An example of the selected results of the calculations of the unsteady bearing forces and cavitation extent is presented in the following figures.

```
UNCA93 LIFTING SURFACE PROGRAM FOR UNSTEADY PROPELLER CAVITATION ANALYSIS
************************************************************************
PROJECT NO=        1
CALCULATED FOR=Desmax
PAGE NO=  1

CONTROL PRINTOUT OF THE INPUT DATA
**********************************
 K1= 1      M1= 9       NZ =        5 (-)      CVC =  1.1900*10-6(M2S-1)
 K2= 3      M2=15       VS = 11.3178 (MS-1)   WCP = 2500.00  (NM-2)
 K3= 1      M3= 9       PD =  7.0000 (M)      SDW = 1025.00  (KGM-3)
 K5= 3      M4=36       HD =  1.4000 (M)      WTS =  0.0720  (NM-1)
 K7= 1      M5= 8       RPS=  1.5167 (S-1)    RAVE=  0.0500*10-3(M)
 K8= 2      M6=70       WSD=  4.5000 (M)      RLP =0.100000  (PA)
                        SFI=      0.0 (DEG)   DLF =      0.0 (DEG)

  RR       PI       CI       SI       RKI      TMI      CMI      RLI
 0.20000 1.18110 2.13990 0.00000 0.00000 0.42630 0.12520 0.05000
 0.30000 1.19220 2.35970-0.08540 0.00000 0.32900 0.15570 0.04000
 0.40000 1.21420 2.57040-0.11620 0.00000 0.26180 0.17560 0.03500
 0.50000 1.21490 2.76850-0.11410 0.00000 0.21140 0.18440 0.03000
 0.60000 1.22080 2.94630-0.05950 0.00000 0.16800 0.18300 0.02500
 0.70000 1.26610 3.08700 0.03500 0.00000 0.12880 0.17260 0.02000
 0.80000 1.32650 3.15280 0.20510 0.00000 0.09170 0.15480 0.01500
 0.90000 1.40850 3.00930 0.48930 0.00000 0.05600 0.12880 0.01000
 1.00000 1.49040 0.30100 1.05000 0.00000 0.02800 0.01160 0.00500
UNCA93 LIFTING SURFACE PROGRAM FOR UNSTEADY PROPELLER CAVITATION ANALYSIS
************************************************************************
```

Fig. 13. *The table of results of the analysis of the propeller in the non-uniform velocity field (the first page only) copied from the file Unca.OUT*

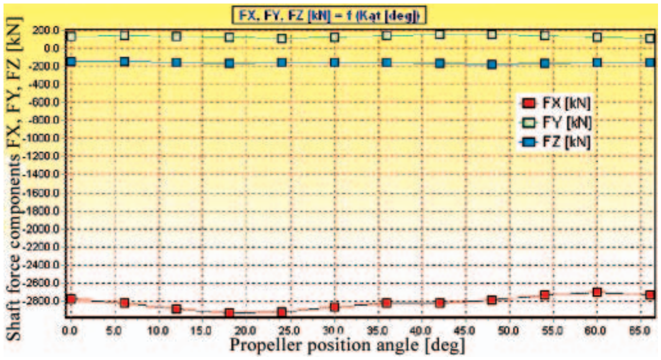

Fig. 14. *The components of the unsteady bearing force as the function of propeller angular position*

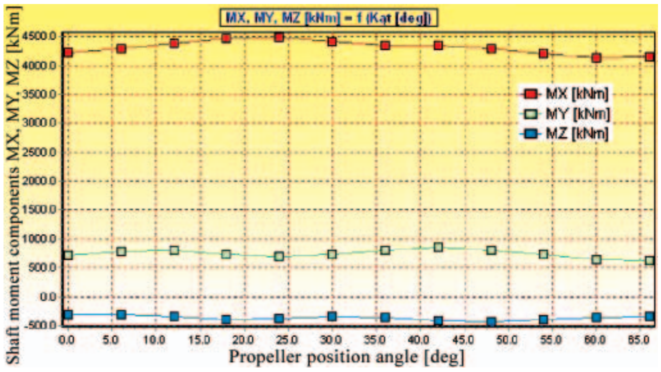

Fig. 15. *The components of the unsteady bearing moment as the function of the propeller angular position*

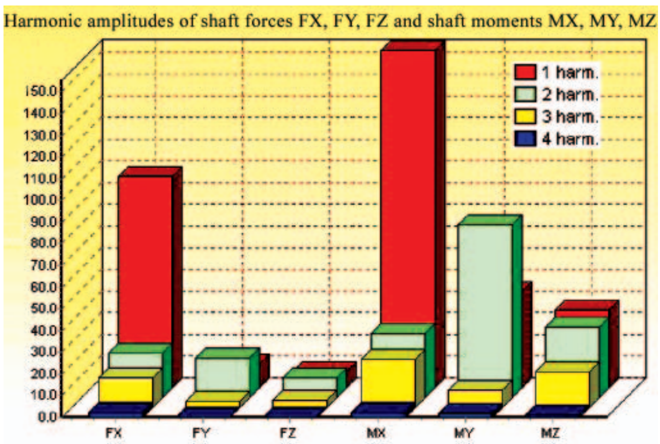

Fig. 16. *The harmonic amplitudes of the three components of the bearing force and three components of the bearing moment*

Apart from the static pictures of the calculated cavitation phenomena on the propeller (Figs. 17 and 18), the program can generate a moving picture of the cavitating propeller. In this film the propeller performs full revolution, showing the dependence of the cavitation phenomena on the local details of the inflow velocity field. All numerical results of the program UNCA are included in the file Unca.OUT.

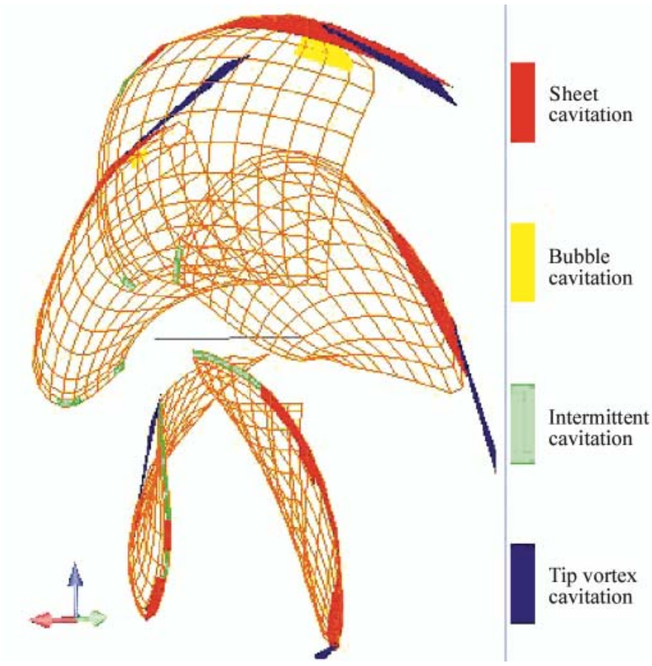

Fig. 17. *The example of visualization of the calculated cavitation phenomena on the propeller*

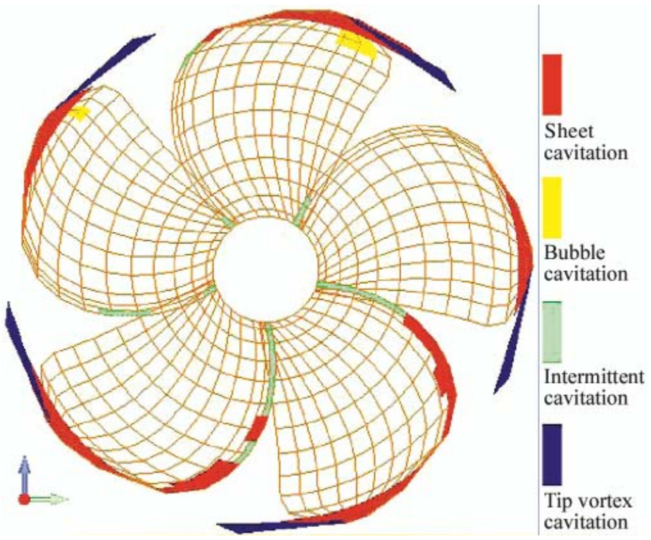

Fig. 18. *The frontal view of the calculated cavitation phenomena on the propeller*

FINAL REMARKS

- The above presented system for the complete design of ship propellers enables an integral treatment of the hull-propeller-rudder system in the process of propeller design. The extensive graphical procedures for input data control and modification and for presentation of the results in the form of pictures and films are an important practical advantage of the system, facilitating its practical use by the designers.

- The system has been developed with the support of the Research Grant No. 4T07C06630 of the Polish Ministry of Science and Higher Education, together with other design systems for three special ship propulsor types, namely:
  - ducted propellers
  - tandem co-rotating propellers
  - tandem contra-rotating propellers.

- Description of these systems will be the subject of separate publications in the future.

BIBLIOGRAPHY

1. Koronowicz T.: *Algorithm of the Design Program Based on the Single Layer Lifting Surface Model Applied to the Arbitrarily Skewed Propellers* (in Polish), IFFM Report No. 295/86
2. Szantyr J. A.: *A Computer Program for Calculation of Cavitation Extent and Excitation Forces for a Propeller Operating in the Non-uniform Velocity Field*, Int. Shipbuilding Progress, Vol. 26, No.296, 1979
3. Szantyr J. A.: *A Deformable Lifting Surface Method for Determination of Unsteady Cavitation on the Propeller Blade and Its Hydrodynamic Consequences* (in Polish), Bulletin of IFFM No. 183/1110/84, 1984
4. Szantyr J. A.: *A Method for Analysis of Cavitating Marine Propellers in Non-uniform Flow*, Intern. Shipbuilding Progress, Vol. 41, No. 427, 1994
5. Koronowicz T., Tuszkowska T., Waberska G., Krzemianowski Z., Chaja P., Góralczyk A.: *Design Algorithm of Screw Propellers* (in Polish), IFFM Report No. 6103/06
6. Koronowicz T., Waberska G., Krzemianowski Z.: *The Influence of the Rudder on the Velocity Field Behind the Hull* (in Polish), IFFM Report No. 4493/03
7. Koronowicz T., Waberska G., Krzemianowski Z., Góralczyk A.: *The Scale Effect of the Velocity Field Behind the Hull* (in Polish), IFFM Report No. 7103/07
8. Koronowicz T., Szantyr J. A., Krzemianowski Z., Tuszkowska T. Waberska G.: *The System of Programs for Screw Propeller Design* (in Polish), IFFM Report No. 148/08
9. Bugalski T., Koronowicz T., Szantyr J. A., Waberska G.: *A Method for Calculation of Flow Around the Hull of a Ship Moving in Calm Water with Constant Velocity*, Mar. Tech. Transactions, Vol. 5, 1994
10. Koronowicz T.: *The Computer Method for Prediction of the Velocity Field Behind a Full-scale Ship Hull,* Polish Maritime Research Vol. 10, No. 1, 2003
11. Koronowicz T., Szantyr J. A., Chaja P.: *A Computer System for the Complete Design of Ship Propellers,* paper presented at the XVII International Conference on Hydrodynamics in Ship Design, Polanica Zdrój, Poland 19-21 September 2007
12. Koronowicz T., Krzemianowski Z., Szantyr J.: *Numerical Determination of the Propeller Design Velocity Field Including Scale Effect and Rudder Influence*, paper presented at the 11th Numerical Towing Tank Symposium, Brest, France, September 7-9, 2008.

CONTACT WITH THE AUTHORS

Tadeusz Koronowicz, Prof.
Zbigniew Krzemianowski, Ph. D.
Teresa Tuszkowska, Ph. D.
Institute of Fluid-Flow Machinery,
Polish Academy of Sciences
Fiszera 14
80-952 Gdańsk, POLAND
e-mail : ttk@interecho.com

Jan A. Szantyr, Prof.
Department of Turbomachinery
and Fluid Mechanics,
Gdańsk University of Technology
Narutowicza 11/12
80-958 Gdańsk, POLAND
e-mail : jas@pg.gda.pl