The effect of limited depth and width of waterway on performance of ducted propellers

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ABSTRACT

Model tests of propeller performance in bollard conditions, in deep and shallow water, were carried out at Ship Design and Research Centre in Gdańsk. Corresponding calculations of propeller performance with account for finite dimensions of canal cross-section were carried out at Wrocław University of Technology by using their own theoretical model of propeller – hull interaction. The calculations were carried out in model scale, at the same water depth as in model tests. For given hull form, propeller geometry and canal cross--section the HPSDK computer code was used to calculate wake fraction, as well as propeller thrust, torque and efficiency. The distribution of pressure on waterway bottom and ship sinkage were also determined.

Keywords : inland navigation, performance of ducted propeller

INTRODUCTION

The effect of limited depth and width of waterway on the performance of propellers, as is the case in inland navigation, have not been by now extensively reported in the literature. In the RTD project INBAT the above problem was considered important, for it is related to efficiency of propulsion. In order to investigate mutual interaction of ship and waterway both experimental and theoretical research tools were involved. Because of confinements imposed by actual diameters of stock propellers used in tests and large dimensions of model ship the model tests in shallow water were limited to bollard conditions (zero speed). Theoretical CFD methods do not impose limits on dimensions. However, many simplifications applied to the computational method, both to geometry and governing equations, make the applicability of those methods restricted. In the present investigations the experimental and theoretical methods were applied to the same ship at the same operating conditions, and provided with complementary information. Theoretical calculations were carried out in model scale in order to avoid extrapolation errors when analyzing results.

HPSDK COMPUTER CODE

When developing the HPSDK code it was assumed that hull, propeller (either screw propeller or ducted propeller) and waterway bed (banks and bottom) are considered separately, and their interaction is taken into account by using iterative solution of flow including updated disturbances. That approach was forced by low computational power of available hardware. 3-D potential flow bounded by ship hull, rigid water surface and canal bed is calculated using the technique of surface vorticity distribution. Viscous effect on velocity distribution in propeller disk is taken into account by simplified calculation of viscous flow between hull and canal bottom. The Vortex Lattice Method was applied to propeller flow at a given distribution of inflow velocity. The above mentioned methods are described in details in [1] and [2]. The flow chart of calculations is presented in Fig.1.

The computations are organized in 5 steps :

Step 1

Within this step the necessary input data are prepared for calculations. Hull form is defined and processed in SIATKA module. The data file is next read by the HPSEDKDB data editor that allows to enter a number of complementary data such as : water depth, dimensions of canal cross-section, ship speed, propeller diameter and the number of vortex panels representing water surface around the ship. The HPSEDSRC editor is dedicated to propeller geometry, and the HPSEDDSA editor to nozzle geometry in the case of ducted propeller.On the basis of the entered hull form the VORNET module computes the coordinates of grid representing the hull in subsequent calculations. The TARCIE module calculates the effect of viscosity on distribution of flow velocity under the hull.

Step 2

The HDKDK and HDKRK modules calculate potential flow around the ship and wake fraction, respectively. If the goal of calculations is to determine the nominal flow (excluding the effect of running propeller), the HDKRK module computes pressure distribution on the canal bottom, then ship sinkage is determined and the calculations are terminated. If the goal is to determine the effective flow and performance of propeller the

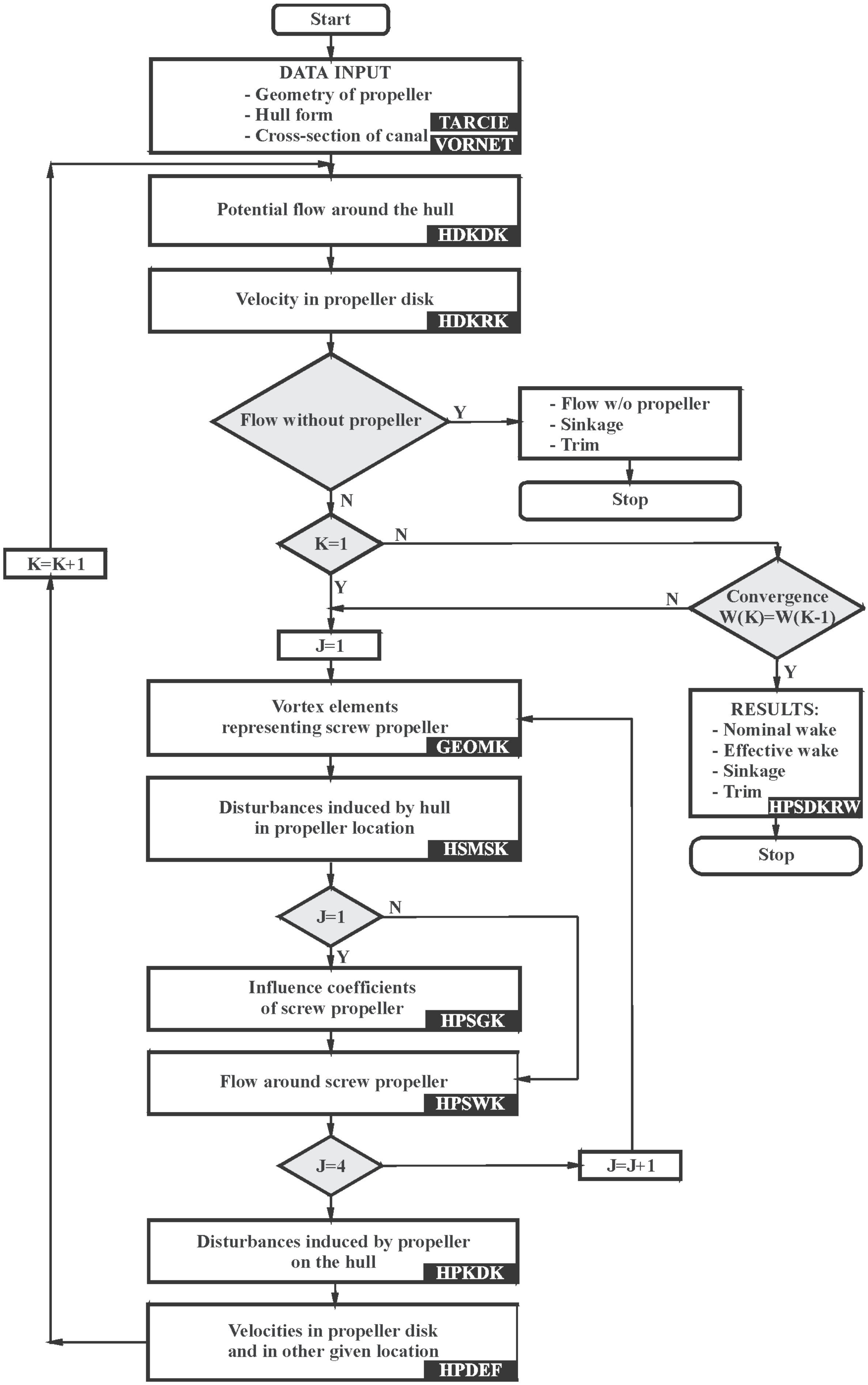

Fig. 1. *Flow chart of computations carried out by the HPSDK code*

iterative procedure must be completed and the remaining steps are pursued. The calculated flow field including viscous effects is used as input to propeller flow calculation in the next steps.

Step 3

Propeller data are prepared for solving the flow around propeller (the modules : GEOMK, HSMDK, HPDSK, HPSGK, HPDGK). A grid of vortex elements representing propeller blades and nozzle is defined and the coefficients of governing equations are computed. The effects of hull and waterway bottom are taken into account by calculating the velocity induced by vortex elements representing hull and bottom in collocation points on propeller.

Step 4

Flow around screw propeller is solved by the HPSWK module. In the case of a ducted propeller the flow is solved by the HPSWK and HPDWK modules running alternately. The HPSWK module computes the flow around impeller including disturbances (velocities) induced by nozzle. The HPDWK module solves the flow around nozzle including disturbances induced by the impeller. In the case of a hull-integrated nozzle the sector located inside the hull outline is disregarded in computations. No special adjustment is made in the area of the junction. The process of alternate solving the flows around impeller and nozzle is not illustrated in the flow chart shown in Fig.1. Thrust and torque are calculated by integrating the pressure on impeller blades and nozzle.

Step 5

Velocities induced by propeller are computed in collocation points on hull (by HPKDK module) and in propeller disk (by HPDEF module). Effective wake fraction is calculated by HDKRK module.

At this point the convergence of the iterative procedure is tested by using the values of effective wake fraction computed in the present and previous runs of HDKRK module. If the relative difference in wake fraction is less than 0.05 then computations are terminated. The above convergence value is usually reached after 2 or 3 calculation loops including steps 3 through 5. The values of thrust and torque are averaged because the results oscillate.

Propeller performance, distribution of hull pressure, distribution of bottom pressure, ship sinkage and velocity distribution in flow with and without the effect of running propeller are presented below.

PROPELLER PERFORMANCE IN BOLLARD CONDITIONS

Model tests of bollard pull were carried out at Ship Design and Research Centre by using the pushboat model in the scale of 1:4.72. The full-scale dimensions of the pushboat were as follows :

Length overall : L_{OAp} = 20.5 m
Moulded beam : B_p = 9.0 m
Moulded draught : d_p = 0.6 m

The hull form of the pushboat is shown in Fig.2. The pushboat was propelled by three propellers because of the limited draught and variable thrust demand depending on a number of barges, draught of barges and water depth. Two side propellers were the ducted ones with hull-integrated nozzle. The diameter of the model propellers used in tests corresponded to 0.690 m in full scale. The stock propellers were applied of Ka 4 -70 Wageningen propeller series, running in 19A nozzle. The central propeller was designed as a ducted propeller of Z-drive azimuthing arrangement. It is lowered to operating position at a water depth greater than 1.2 m, and retracted when water depth is smaller than that. The diameter of the central propeller was equal to 1.100 m. In the model tests the CP324 stock propeller in nozzle 19A was applied [3].

Corresponding computations were carried out for the train composed of two barges and the pushboat in model scale. Main particulars of a single barge were as follows :

L_{OAb} = 48.75 m
B_b = 9.00 m
d_b = 1.40 m

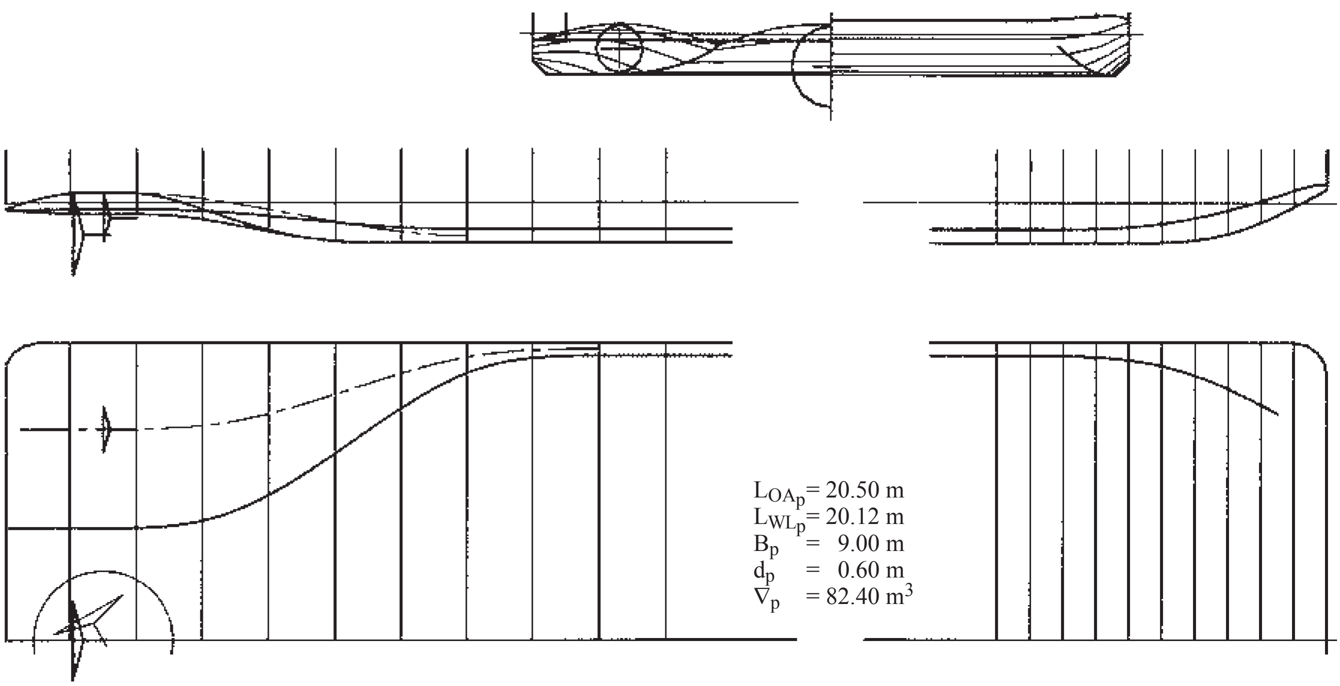

Fig. 2. *Hull form of the pushboat used for model tests and computations*

Propeller performance

Results of the model tests and computations are compared in Tab.1. The HPSDK code is not capable of computing the propeller performance exact in bollard conditions i.e. at zero ship speed. In order to overcome the problem the computations were run at low ship speed values, namely at 0.75 m/s, 0.50 m/s, 0.25 m/s, and a constant rotational speed of propellers. Propeller performance was then extrapolated to zero ship speed. The relationship between ship speed and propeller thrust appeared almost linear for both central and side propellers (Fig. 3). The results are consistent with hydrodynamic characteristics of the propellers.

Tab. 1. *Thrust of the propeller and pull of the pushboat in bollard conditions*

Propeller		Central				Side*			
Water depth		2m		5m		2m		5m	
Rotational speed [rps]		12.5	7.5	12.5	7.5	30	20	30	20
Model tests	Thrust of impeller [N]	-	-	-	-	164.9	72.6	173.5	74.6
Model tests	Thrust [N]	240.8	90.4	225.6	90.5	-	-	-	-
Model tests	Pull [N]	218.1	73.8	208.8	82.1	273.5	109.9	296.1	132.8
Computations	Thrust of impeller [N]	-	-	-	-	178	80	178	80
Computations	Thrust [N]	211	76	208	74	256	115	260	116

* Total thrust of the two impellers is given in the table

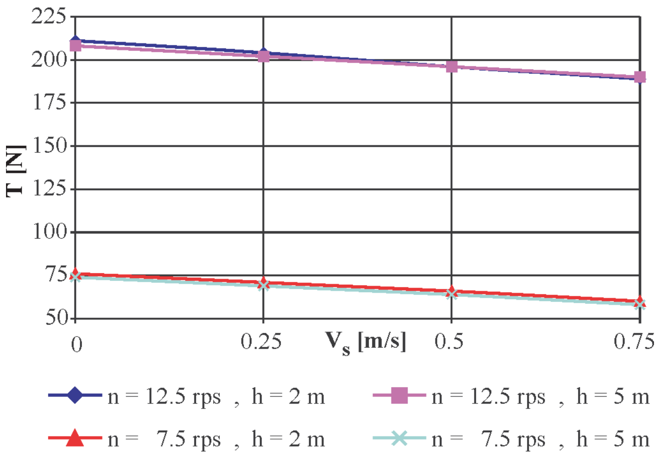

Fig. 3. *Thrust of the central propeller, extrapolated to bollard conditions*

The following magnitudes were measured during the model tests :

- the net thrust of the entire central propulsion unit (including shaft post in front of the propeller)
- the thrust of the side impellers (excluding the thrust of nozzle), and
- the pull of the pushboat [4].

In the computational model the shaft post in front of the propeller was not accounted for. The computed thrust of the central propeller, shown in Tab.1, contains only the thrust generated by impeller and nozzle.

Both the results of the model tests and computations revealed that the effect of water depth on thrust and pull at zero ship speed is insignificant.

Bottom pressure

The computations revealed that at the water depth of 2.0 m the central propeller induces, at the beginning of stern tunnels (x = -1.1m), a higher drop of pressure than side propellers (Fig.4). The results seem reasonable because the central propeller is closer to the waterway bottom than the side propellers. For smaller depths one may expect even a higher drop of bottom pressure and thus a greater destructive effect of running propeller on waterway bottom. This regularity is illustrated in Fig.5 for the side propellers. The results of computations also showed that the rotational speed of propellers within the considered range had no effect on the distribution of bottom pressure.

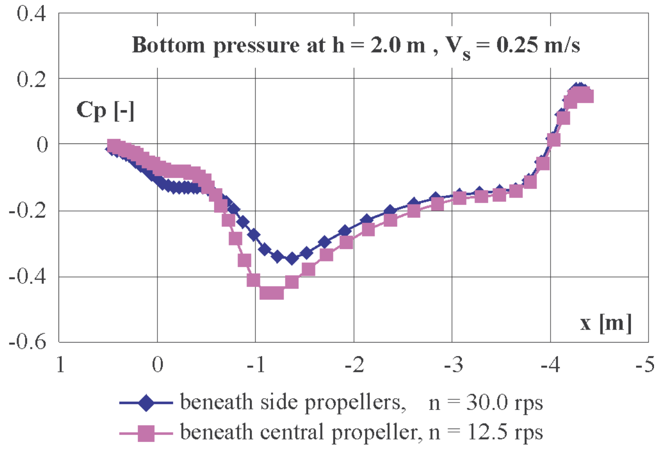

Fig. 4. *Distribution of bottom pressure at near zero ship speed (stern transom at x = 0; side propellers at x = - 0.318; central propeller at x = - 0.234)*

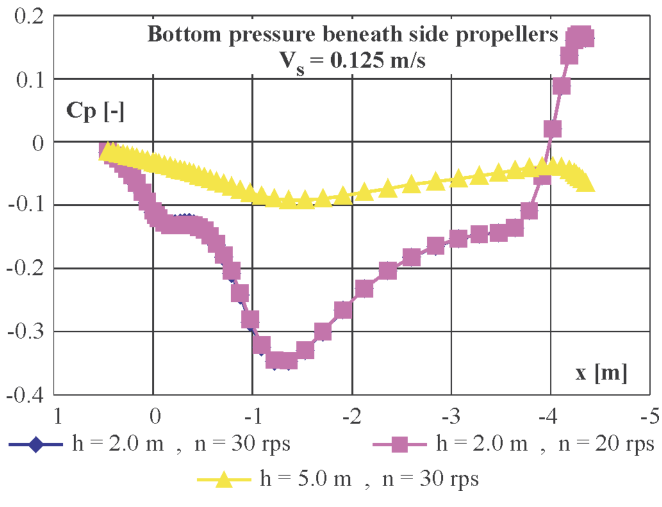

Fig. 5. *The effect of water depth and propeller's rotational speed on the distribution of bottom pressure beneath side propeller at near zero ship speed (stern transom at x = 0; side propellers at x = - 0.318)*

THE EFFECT OF CANAL CROSS-SECTION ON PROPELLER PERFORMANCE

The computations of propeller performance in the canal of trapezoidal cross-section were carried out in the scale of 1:14. The slope of banks was 1: 4. The draught of barges was assumed equal to 1.4 m. In the computations the barge train was positioned in various distances from the banks (Fig. 6). For the considered pushboat the computations were carried out separately for the central and side propellers as the interaction between propellers was experimentally proven negligible.

The results for ship scale are presented in Tab.2 and 3. The canal width b_0 is measured at the canal bottom. The advance coefficient J was calculated with account for the effective wake fraction w_e.

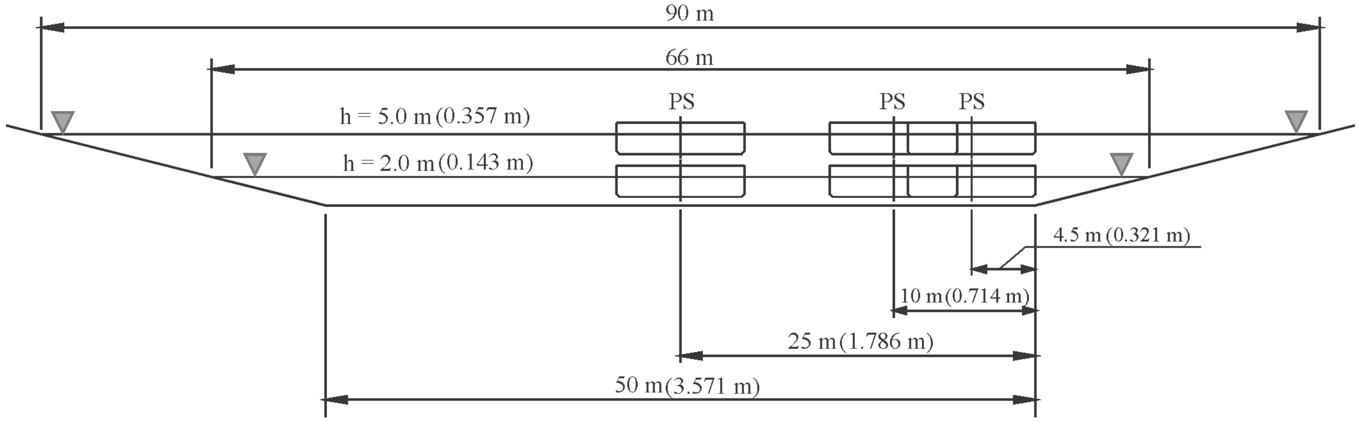

Fig.6. *Cross-section of the canal and considered positions of the barge train*

Tab. 2. *Performance of the side propeller in the canal (the propeller's diameter D = 0.690 m, and its rotational speed n = 828.5 rpm)*

Water depth h = 1.7 m						
Canal width b_0	9 m		20 m		50 m	
Ship speed V_S [m/s]	1.5	3.0	1.5	3.0	1.5	3.0
Nominal wake fraction w_n	0.289	0.523	0.243	0.475	0.109	0.331
Effective wake fraction w_e	0.834	0.753	0.788	0.707	0.640	0.558
Thrust coeff. K_T	0.331	0.319	0.330	0.315	0.325	0.303
Efficiency η	0.050	0.127	0.062	0.147	0.092	0.212
Advance coeff. J	0.030	0.080	0.038	0.094	0.057	0.142
Water depth h = 2.0 m						
Canal width b_0	9 m		20 m		50 m	
Ship speed V_S [m/s]	1.5	3.0	1.5	3.0	1.5	3.0
Nominal wake fraction w_n	0.632	0.588	0.672	0.629	0.778	0.74
Effective wake fraction w_e	0.190	0.411	0.220	0.449	0.345	0.577
Thrust coeff. K_T	0.296	0.274	0.305	0.293	0.311	0.304
Efficiency η	0.198	0.283	0.184	0.254	0.158	0.203
Advance coeff. J	0.127	0.188	0.122	0.175	0.103	0.135
Water depth h = 3.6 m						
Canal width b_0	9 m		20 m		50 m	
Ship speed V_S [m/s]	1.5	3.0	1.5	3.0	1.5	3.0
Nominal wake fraction w_n	0.222	0.216	0.250	0.244	0.302	0.296
Effective wake fraction w_e	- 0.285	- 0.004	- 0.279	0.009	- 0.23	0.060
Thrust coeff. K_T	0.265	0.217	0.282	0.255	0.284	0.259
Efficiency η	0.293	0.417	0.279	0.400	0.270	0.383
Advance coeff. J	0.202	0.316	0.201	0.312	0.193	0.295

Tab. 3. *Performance of the central propeller in the canal (propeller's diameter D = 1.100 m, and its rotational speed n = 345.2 rpm)*

Water depth h = 1.7 m						
Canal width b_0	9 m		20 m		50 m	
Ship speed V_S [m/s]	1.5	3.0	1.5	3.0	1.5	3.0
Nominal wake fraction w_n	0.185	0.341	0.156	0.307	0.073	0.212
Effective wake fraction w_e	0.717	0.535	0.662	0.490	0.529	0.371
Thrust coeff. K_T	0.459	0.407	0.456	0.402	0.448	0.384
Efficiency η	0.079	0.289	0.114	0.310	0.155	0.362
Advance coeff. J	0.068	0.289	0.081	0.247	0.112	0.302
Water depth h = 2.0 m						
Canal width b_0	9 m		20 m		50 m	
Ship speed V_S [m/s]	1.5	3.0	1.5	3.0	1.5	3.0
Nominal wake fraction w_n	0.437	0.402	0.469	0.419	0.564	0.529
Effective wake fraction w_e	0.020	0.234	0.043	0.245	0.117	0.348
Thrust coeff. K_T	0.393	0.330	0.416	0.365	0.421	0.381
Efficiency η	0.294	0.422	0.278	0.407	0.261	0.371
Advance coeff. J	0.232	0.362	0.226	0.362	0.208	0.314
Water depth h = 3.6 m						
Canal width b_0	9 m		20 m		50 m	
Ship speed V_S [m/s]	1.5	3.0	1.5	3.0	1.5	3.0
Nominal wake fraction w_n	0.165	0.161	0.185	0.181	0.223	0.219
Effective wake fraction w_e	- 0.220	0.005	- 0.204	0.221	- 0.172	0.056
Thrust coeff. K_T	0.366	0.278	0.396	0.337	0.399	0.340
Efficiency η	0.349	0.503	0.331	0.479	0.324	0.467
Advance coeff. J	0.288	0.470	0.284	0.463	0.277	0.446

Selected results are presented in Fig. 7 through 12.

The bottom pressure at the position where slope begins is presented in Fig. 7 and 8. At a lower water depth and lower canal width the destructive effect of moving ship over waterway bottom is stronger.

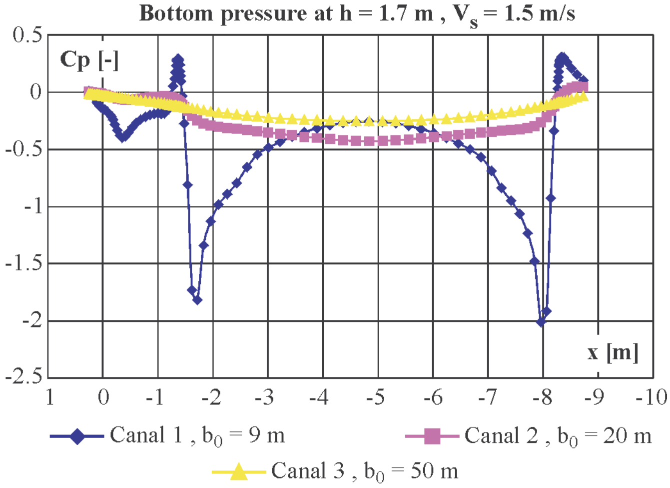

Fig.7. Longitudinal distribution of bottom pressure at the position where slope begins, for various values of canal width

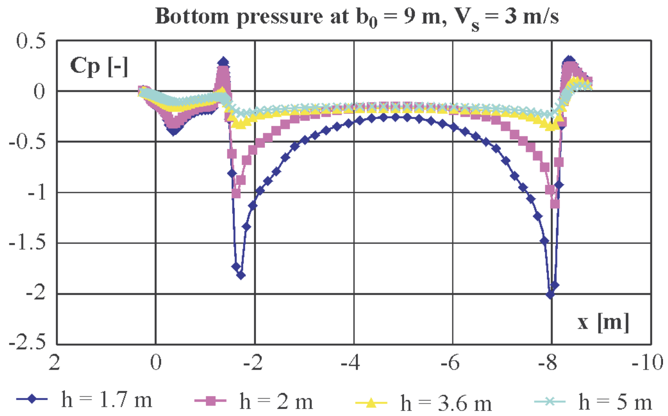

Fig.8. Longitudinal distribution of bottom pressure at the position where slope begins, for various values of water depth

The effect of canal width and water depth on performance of side propellers is presented in Fig. 9 through 12. The results show that the effect of banks is pronounced and depending on water depth. At the lowest depth h = 1.7 m the propeller thrust decreases when canal width increases. At the higher depths (h = 2.0 m and h = 3.6 m) the trend is opposite. An increase of water depth at a constant canal width causes a drop of propeller thrust. This effect can be explained by changes in water inflow to propeller that is reflected in variation of wake fraction.

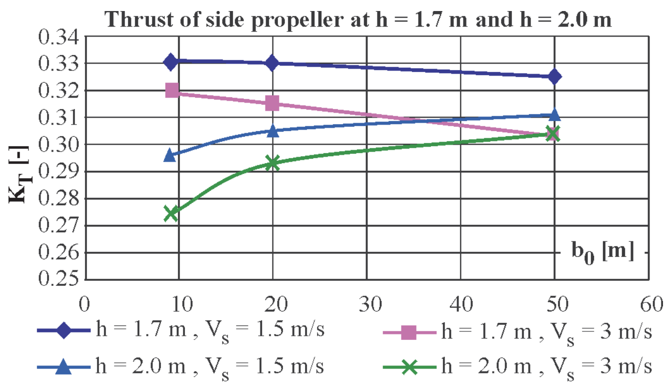

Fig.9. The effect of canal width on thrust generated by side propeller

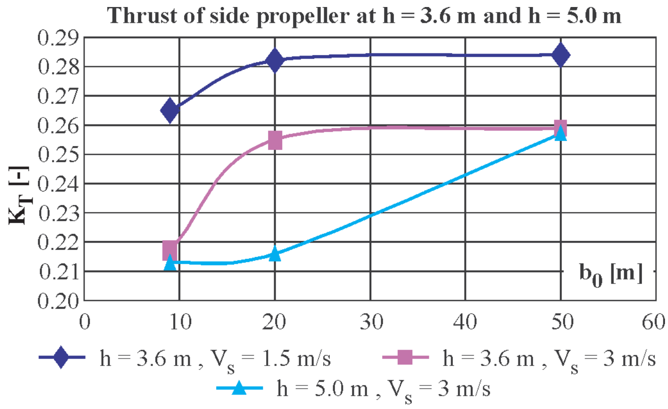

Fig.10. The effect of canal width on thrust generated by side propeller

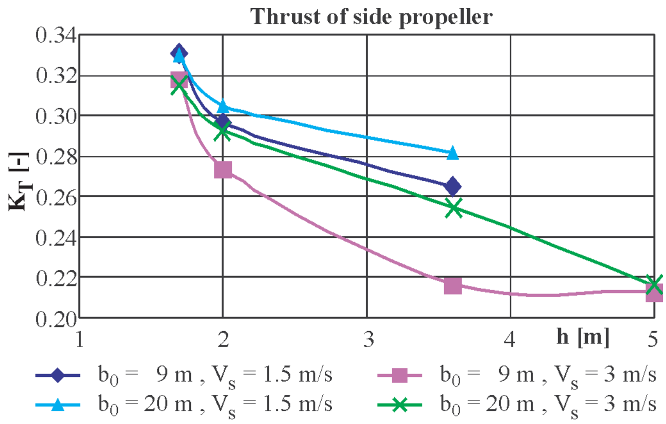

Fig.11. The effect of water depth on thrust generated by side propeller

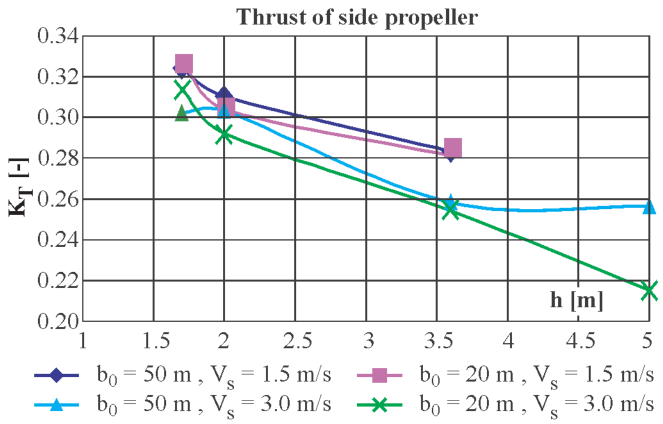

Fig.12. The effect of water depth on thrust generated by side propeller

In the case of the central propeller the effects of canal width and water depth are similar to those above presented.

If the ship is not positioned in the centreline of the canal the side propellers operate in different conditions. At the same rotational speed the starboard and portside propellers generate different thrust and the ship tends to turn if the turning moment is not compensated by rudders.

CONCLUSIONS

- It was proved that the applied computational method is a valuable tool to predict the performance of ducted propellers in shallow water, even at zero ship speed.
- Both the results of the model tests and computations reveal that the effect of water depth on thrust and pull at zero ship speed is insignificant.

- In the case of the considered barge train (d_b = 1.4 m and d_p = 0.6 m) the computed drop of bottom pressure beneath the running propeller is several times less than drop of pressure beneath bow and stern of barges. In general, it is the matter of ship and propeller arrangement as this factor leads to a greater destruction.

- The effect of canal banks and bottom on propeller performance in the case of the considered vessel is evident at the water depth below 3.6 m (h/d_b = 2.6 and h/d_p = 6.0) and the canal width below 20 m (b_0/B = 2.2). Propeller thrust at the lowest depth and width is 17% to 25% higher than that in wide and deep canal, depending on ship speed. Unfortunately the propeller efficiency drops then dramatically.

NOMENCLATURE

b_0 - canal width
B - moulded beam
c_P - pressure coefficient ($= \frac{P - P_{ref.}}{\frac{1}{2}\rho V_s^2}$)
d - moulded draught
D - propeller diameter
h - water depth
J - advance coefficient
K_T - thrust coefficient ($= \frac{T}{\rho n^2 D^4}$)
L_{OA} - overall length of ship
L_{WL} - length at waterline
n - rotational speed of propeller
P - local static pressure
$P_{ref.}$ - reference pressure (static pressure far upstream)
PS - plane of symetry
T - thrust of propeller
V_s - ship speed
w_e - effective wake fraction
w_n - nominal wake fraction
x - longitudinal co-ordinate, measured from propeller disc
η - propeller efficiency
ρ - water density
∇ - volumetric displacement

Indices

b - of barge
p - of pushboat

Acronyms

CFD - computational fluid dynamics
INBAT - innovative barge trains for effective transport on inland shallow waters
RTD - research and technological development

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Conference

A scientific seminar at Technical University of Koszalin

On 24 March 2005 the first-in- this-year scientific seminar of the Regional Group of the Section on Exploitation Foundations, Machine Building Committee, Polish Academy of Sciences, took place at the Department of Mechanical Engineering, Technical University of Koszalin.

According to the announced program of the seminar it was devoted to role of heuristics in didactic and scientific research activity. 4 papers on the topic were presented by scientific workers of the University, namely :

- *Heuristics in creative solving the educational problems* by J. Markul
- *Heuristics in innovation and development of products – – exemplified by a didactic task* – by J. Plichta
- *Heuristics as a method of solving logistic problems in manufacturing processes* – by G. Jurkowski
- *Heuristics applied to solve converse tasks in machine building* – by W. Tarnowski.

After interesting discussion the seminar's participants visited laboratories of the Department. Additionally, the hosts informed about very broad spectrum of didactic and scientific research lines of the Department's activity covering : mechanics and machine building, new technologies, solid body physics, materials engineering, optimization, automation, robotics and control, production process automation, mechatronics, data processing, modelling, simulation, artificial intelligence methods, biotechnologies, biochemistry, food processing, design, bionics.

An important form of the activity is the developing of cooperation with foreign scientific centres. In present the Department maintains contacts with three German and three French centres.