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Investigation of Scale Effects on Ships with a Wake Equalizing Duct or with Vortex Generator Fins

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ABSTRACT

A typical container ship with a wake equalizing duct of Schneekluth design (WED) and with vortex generator fins (VGF) was investigated. The special focus of this paper investigates the knowledge of the Reynolds number effect on the flow around the appendages and on the inflow to the propeller.

The measured thrust deduction and wake fractions of the ship with and without the appendages WED or VGF have been used for the propulsion prognosis with the ITTC 1978 method. In addition, the propulsion coefficients of these ships have been calculated for the propulsion point in model and full-scale with ANSYS CFX. The agreement between the predicted scale effects (ITTC 1978) and the CFD calculations is good.

The investigations has shown that knowledge of the wake field in full-scale is necessary for the accurate design of the propeller and the prognosis of the cavitation behaviour and propeller induced pressure fluctuations. This is also important for ships with WED or VGF. Thus CFD calculations should be used to predict the propeller inflow for ships with a wake equalizing duct or with vortex generator fins.

Keywords

Propulsion, propeller, wake equalizing duct, vortex generator fins, wake field.

1 INTRODUCTION

Important aspects of the ship and propeller design are the propulsion efficiency and the vibration level in the aft ship. There are increasing demands to reduce the propeller induced pressure fluctuations as well as the underwater noise and to improve the propulsive efficiency.

The dominant feature for ships with vibration problems is cavitation at the propeller. The cavitation behaviour of the propeller can be influenced by the propeller design, the inflow to the propeller and the working conditions. One possibility to improve the propeller inflow is the fitting of appendages such as wake equalizing ducts, vortex generator fins or spoilers on the ship. The technologies for the use of these appendages exist for many years but there is still little knowledge about scale effects on influencing the propeller inflow with these appendages. The knowledge of the scale effects on ships with wake equalizing ducts or with vortex generator fins is, among other factors important for the design of the appendages and the propellers, for the propulsion prognosis on the base of model tests and for the prediction of propeller induced pressure fluctuations.

CFD calculations have been carried out for a typical container ship with and without appendages in model and full-scale to analyse the resistance, the propulsion, the propeller inflow and the cavitation behaviour of the propeller. In addition tests were carried out with the ship model or with dummy models with and without WED or VGF in the towing tank and the cavitation tunnel to check the test and prognosis procedures.

2 SUBJECT OF STUDY

A container ship had been selected for the viscous flow calculations and the model tests. The model of this vessel was built in a scale of $\lambda = 25.6$. The propeller and the vortex generator fins were designed by the SVA. The wake equalizing duct was designed by Schneekluth Hydrodynamik Entwicklungs- und Vertriebsgesellschaft.

The main data of the container ship and the propeller are summarised in Table 1.

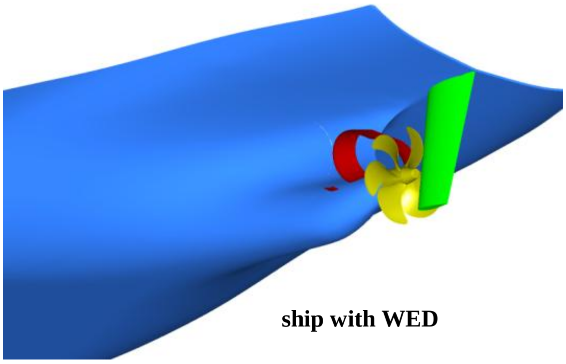
Table 1: Main dimensions of the container ship and propeller

			Ship	Model
Length	L_{PP}	[m]	173.54	6.7789
Breadth	B	[m]	25.20	0.9844
Draught	T	[m]	9.50	0.3711
Diameter	D	[m]	6.40	0.250
Area ratio	A_E/A_0	[-]	0.75	0.750
Number of blades	Z	[-]	6	6

The Figure 1 shows the arrangement of the appendages at the container ship.

The wake equalizing duct (WED) effects a change of the velocity field in the range of the wake peak. The propeller inflow is more uniform (Ok 2004), (Schneekluth 1986), (von der Stein 1996).

Vortex generators are fins, arranged in the aft ship (Han et al. 2006), (Johannsen 2000), (Ødegaard 2006). The VGF generates a vortex. The size of the VGF depends on the thickness of the local boundary layer. The design parameters are the position in longitudinal and vertical direction, the angle and the size. The design, the size and the positioning of the VGF are based mostly on empirical model tests on the ship model in connection with cavitation tests and pressure fluctuation measurements.



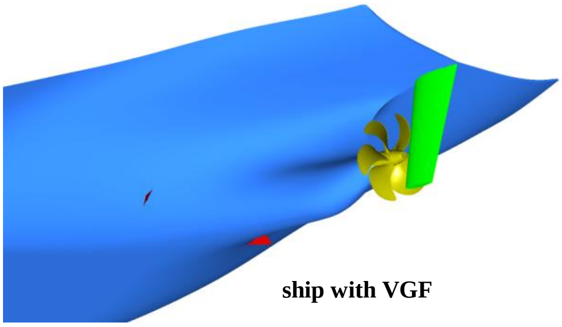


Figure 1. Container ship with appendages

3 CALCULATION OF THE WAKE FIELDS

3.1 Numerical Grids for the Calculations

The analysis of the nominal wake field in model and full-scale was carried out with the viscous flow solver ANSYS CFX. For turbulence modelling the SST-turbulence model with C(urvature) C(orrection) was used.

The calculations were accomplished under considering the dynamic trim and sinkage of the ship for the investigated operation point. During the calculation the position of the ship was fixed. A prescribed free surface elevation was considered as the upper boundary of the computational domain. It was calculated prior to the viscous flow calculation with the in-house potential flow code KELVIN. Symmetry condition was employed amidships, therefore only the port side of the ship was simulated.

A block structured numerical mesh was generated for the geometries “only ship” and “ship with VGF”. Collecting of the physical phenomena of the effect of the VGF was a great challenge. First, a coarse mesh with 1.42 mio. nodes for “ship with VGF” (variant A) was generated. The second grid was the fine mesh with 3.37 mio. nodes (variant B). The nodes were concentrated at the aft ship and at the VGF (Figure 2).

After calculation some flow details were described accurately in the fine mesh variant. The results of nominal wake fraction and resistance of both variants show minor differences. The computing time with the fine mesh was, however, longer around factor 2.3.

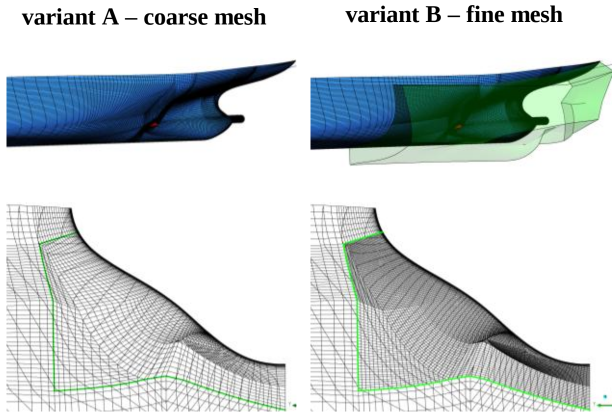


Figure 2. Numerical grids for the ship with VGF

Due to the complex geometry for the “ship with WED”, a hybrid mesh was generated (Figure 3). The modelling of the WED was carried out with a TETRA-mesh. The other regions were modelled with a HEXA-mesh. In the fore- and midship region the mesh has the same topology and mesh discretisation as the mesh for the other variants. The connection of both meshes was made with general Grid Interfaces. For the mesh generation ANSYS ICEM CFD was used.

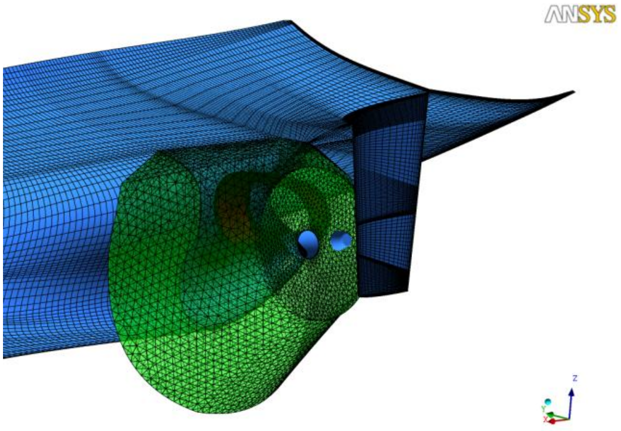
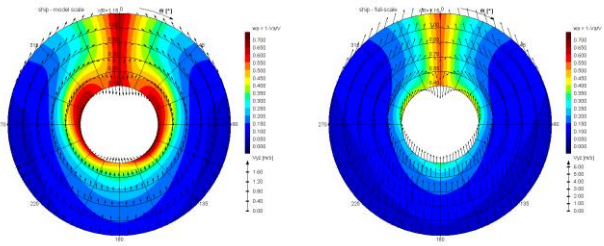


Figure 3. Numerical grid for the ship with WED

3.2 Nominal Wake Fields

The analysis of the scale effect on the flow around single screw ships shows, in general, the following tendencies. The higher Reynolds number at the ship affects a relatively smaller boundary layer than at the model: the wake peak at the ship is distinctly smaller, and the wake gradient is larger. The calculated maximum wake fractions at the ship are smaller in comparison with the model wake.

Figure 4 shows the calculated nominal wake fields for the container ship without appendages for the model und full-scale Reynolds numbers. The scale effect on the propeller inflow is evident.

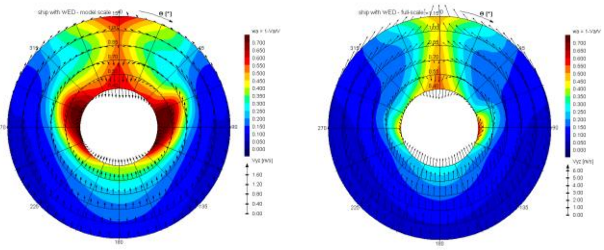


model scale, Re_M = 1.3 10^7 **full-scale, Re_S = 1.7 10^9**

Figure 4. Calculated wake fields - ship without appendages

The measurement or calculation of the nominal wake field of a ship with a wake equalizing duct isn't standard. The main reason for this is that the wake equalizing duct and the spoilers are seen as a part of the propulsion system.

Figure 5 presents the results of viscous flow calculations for the container ship with WED for the model and the full-scale Reynolds numbers. The calculations show that the wake equalizing duct accelerates the water in the range of the wake peak (the maximum wake fractions are lower). The effect of the WED on the propeller inflow is more developed in full-scale.

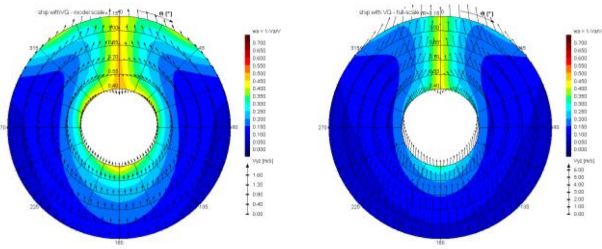


model scale, Re_M = 1.3 10^7 **full-scale, Re_S = 1.7 10^9**

Figure 5. Calculated wake fields - ship with WED

CFD calculations were used for the design of the vortex generator fins. The extent of the fin with 0.896 m was appointed with the calculated thickness of the boundary layer on the ship in the range of frame 3. The length of the fin at the ship hull should be two times of the height. The angle of attack of the vortex generator fins was 12 degrees against the ascending flow at frame 3 or 29 degrees against the basis line of the ship.

The vortex generator fins produce a distinct reduction of the wake peak. In model scale the vortices of the vortex generator fins touch the propeller disc. In full-scale the vortices lie above the propeller disc (Figure 6).



model scale, Re_M = 1.3 10^7 **full-scale, Re_S = 1.7 10^9**

Figure 6. Calculated wake fields - ship with VGF

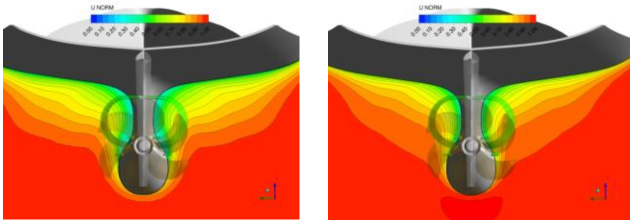
4 PROPULSION

Propulsion tests had been carried out with the model with and without appendages. The ITTC 1978 method had been used for the propulsion prognoses.

CFD calculations had been carried out for the ship and the model with and without appendages with working propeller at the design speed. Three to four steady calculations with different numbers of revolutions of the propeller were necessary to get the propulsion point of the ship or of the model.

4.1 Scale Effects on Propulsion Coefficients of the Ship with WED

The Figure 7 shows the iso-lines of the axial inflow speed in front of the wake equalizing duct in model and full-scale. The resulting inflow speed of the duct and the spoilers at the full-scale Reynolds number is higher than in model scale.



model scale, Re_M = 1.3 10^7 **full-scale, Re_S = 1.7 10^9**

Figure 7. Calculated inflow of the WED

The WED will be considered normally as a part of the propulsion system. The calculations showed that the duct and the spoilers generate an additional resistance at this ship. The resistance coefficient of the WED is in the propulsion condition (with working propeller) higher than in the resistance condition (without propeller). The resistance coefficients of the WED calculated with the ship speed are similar in model and full-scale (C_{TMWED} = 0.01711; C_{TSWED} = 0.01888).

The Table 2 contains propulsion coefficients (thrust deduction fraction $t = (T-R_T)/T$, thrust wake fraction $w_T = 1-V_A/V$ (V_A determined from thrust identity) and hull efficiency $\eta_H = (1-t)/(1-w)$) of the ship with and without WED, predicted on the base of model tests and on CFD calculations.

Table 2: Propulsion coefficients, ship with and without WED

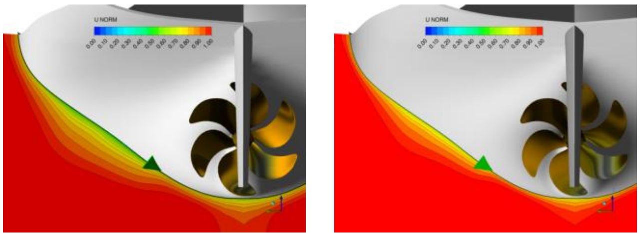
Model test (ITTC 1978)	V_M [m/s]	t_S/t_M [-]	w_{TS}/w_{TM} [-]	η_{HS}/η_{HM} [-]
without WED	2.054	1.0000	0.8486	0.9433
with WED	2.054	1.0000	0.8311	0.9319

CFD	V_M [m/s]	t_S/t_M [-]	w_{TS}/w_{TM} [-]	η_{HS}/η_{HM} [-]
without WED	2.054	0.9928	0.8266	0.9421
with WED	2.054	0.9680	0.7963	0.9355

The CFD calculations show a larger scale effect on the effective wake fraction than the prediction using the ITTC 1978 method. The CFD calculations deliver a small reduction of the thrust deduction fraction while the ITTC 1978 method use the assumption that the thrust deduction fraction will be similar in model and full-scale. The predicted and calculated hull efficiencies are so close together that the ITTC 1978 method can be used for the propulsion prognosis for ships with WED.

4.2 Scale Effects on Propulsion Coefficients of the Ship with VGF

The calculated inflow of the vortex generator fins in model and full-scale is illustrated in Figure 8. The resulting inflow speed of the vortex generator fins is due to the relative smaller boundary layer thickness at the ship higher than at the model.



model scale, Re_M = 1.3 10^7 **full-scale, Re_S = 1.7 10^9**

Figure 8. Calculated inflow of the VGF

The vortex generator fins are parts of the ship (appendages). The work of the propeller has no influence on the resistance of the vortex generator fins. The resistance coefficient of the VGF calculated with the ship speed is in model scale smaller than in full-scale (C_{TMVGF} = 0.165; C_{TSVGF} = 0.220).

Table 3 presents propulsion coefficients of the ship with and without VGF, predicted on the base of model tests and CFD calculations.

Table 3: Propulsion coefficients, ship with and without VGF

Model test (ITTC 1978)	V_M [m/s]	t_S/t_M [-]	w_{TS}/w_{TM} [-]	η_{HS}/η_{HM} [-]
without VGF	2.054	1.0000	0.8486	0.9433
with VGF	2.054	1.0000	0.9081	0.9677

CFD	V_M [m/s]	t_S/t_M [-]	w_{TS}/w_{TM} [-]	η_{HS}/η_{HM} [-]
without VGF	2.054	0.9928	0.8266	0.9421
with VGF	2.054	0.9945	0.8875	0.9688

The comparison of the results of the propulsion prognosis on the base of model tests with the CFD calculations shows a higher reduction of the effective wake fraction due to the scale effects in the CFD calculations. The hull efficiency is very similar in the propulsion prognosis and in the CFD calculations due to the reduction of the thrust deduction in the CFD calculations.

5 CAVITATION BEHAVIOUR AND PRESSURE FLUCTUATIONS

The cavitation behaviour of the propeller in the wake field has a large influence on the pressure pulses at the aft ship. Important is thereby not only the thickness of the cavitation but also the time in which the cavitation is developing and disappearing. The prognosis of the cavitation in connection with the propeller inflow is the determining factor for the calculation of the propeller induced pressure fluctuations.

The measurement of the three dimensional wake field components at model scale has become routine during the design phase of ships. The Reynolds numbers for model tests are in the range 10^6 to 10^7. The ships are working mainly at Reynolds numbers of 10^9. As shown in Chapters 3 and 4, and in different papers (Lübke 2002), (Heinke 2003), the flow around the ship is strongly influenced by the Reynolds number.

To study the influence of the wake scale effect on the cavitation behaviour of the propeller on the ship with WED or VGF wake fields had been simulated with help of the dummy models DM69M and DM69S (λ = 35.56, L_{OA} = 2.266 m). Nine pressure pick-ups were arranged in the aft ship of the dummy model (Figure 9).

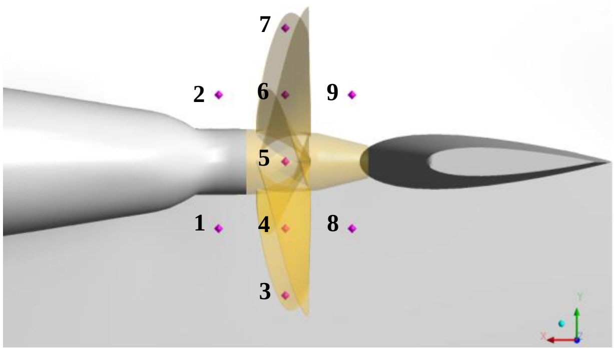
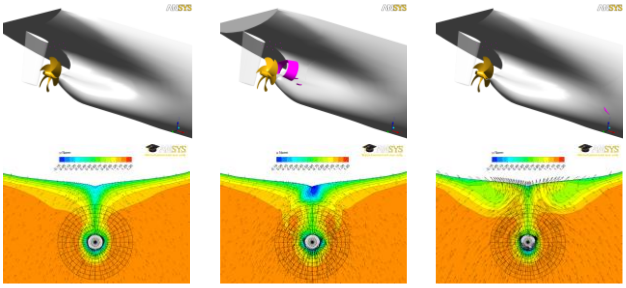


Figure 9. Positions of the pressure pick-ups

The nominal wake fields of the dummy model DM69S with and without the appendages WED and VGF in the test section of the cavitation tunnel have been calculated with ANSYS CFX (Figure 10). The calculations show that the influence of the WED and VGF on the propeller inflow can be simulated with shorted models (dummy models).



DM69S **with WED** **with VGF**

Figure 10. Wake fields of the DM69S variants

The diagrams in Figure 11 show the simulated axial wake fractions in the radii r/R = 0.85 and 1.0. The wake of the dummy model DM69M represents the propeller inflow in model scale. The characteristic change of the propeller inflow due to the Reynolds number influence has been simulated with the dummy model DM69S. The maximum wake fractions and the wake peak are distinctly smaller behind the DM69S. The differences in the simulated model and full-scale wake fields are larger than in the CFD calculations (chapter 3.2).

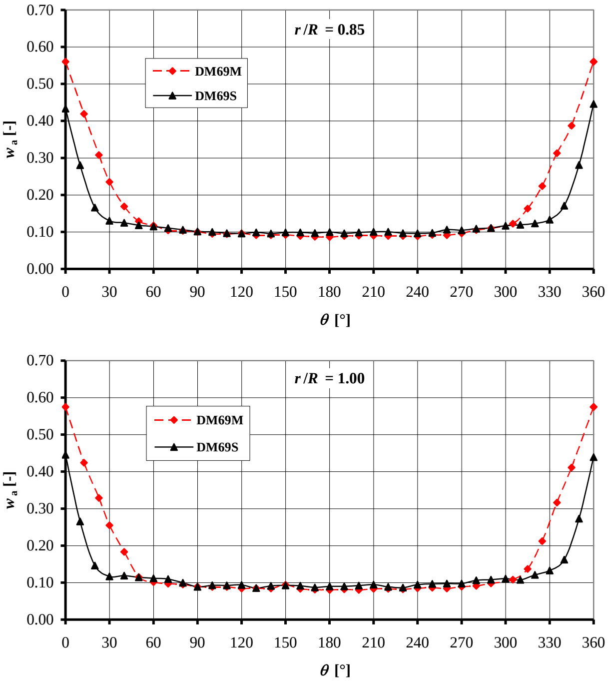


Figure 11. Axial wake fractions in two radii of wake fields, simulated with the dummy models DM69M and DM69S

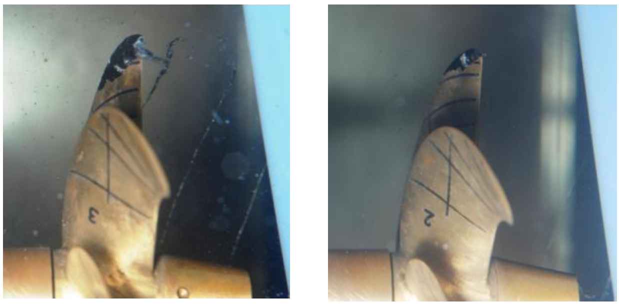
The photographs in Figure 12 present the cavitation extent at the model propeller for the rotation angle 30 degrees, working at the dummy models DM69M and DM69S with and without appendages.

The cavitation behaviour of the propeller at the ship without appendages is changing with the wake field. The cavitation extent and the cavitation thickness are in the simulated full-scale wake field smaller. In addition, the angle range in which cavitation appears is smaller.

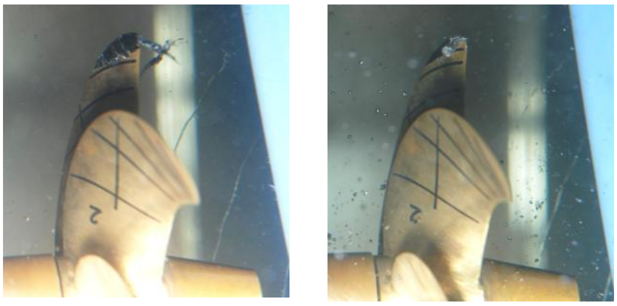
The analysis of the cavitation observation showed that the tip vortex cavitation is only weakly developed if the propeller works in the wake field simulated by the DM69S. This effect could be an indication of necessary investigations about the interaction of scale effects on the wake field and on the cavitation, especially the tip vortex cavitation.

The nominal full-scale wake field can be computed with reasonable accuracy in a short time for some years. Calculated full-scale wake fields will be used more and more in the propeller design process and this increases the necessity to study the possibilities of using simulated full-scale wake fields or other wake scaling methods in cavitation tests (Heinke 2003), (Ligtelijn et al. 2004).

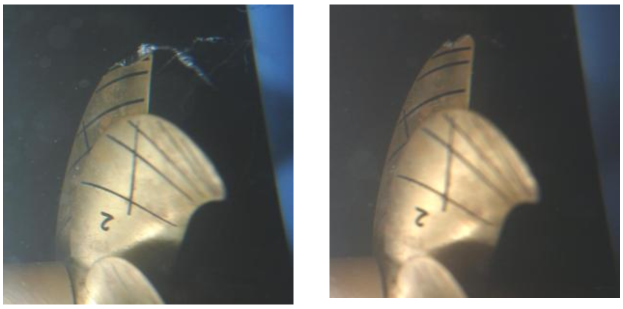
DM69M **DM69S**



ship without appendages



ship with WED



ship with VGF

Figure 12. Comparison of cavitation extents, influence of the wake field

The pressure fluctuation amplitudes in the blade frequency (first harmonic order) of the cavitating propeller are smaller in the simulated full-scale wake field (Figures 13 and 14). This is a result of the lower thrust loading in the full-scale wake field due to the higher inflow speed in the wake peak (Heinke 2003), (Ligtelijn et al. 2004).

The pressure fluctuation amplitudes in the second and third harmonic orders are often higher in the full-scale wake field. The pulsation of the cavity is stronger due to the smaller wake peak.

The use of the wake equalizing duct or of the vortex generator fins leads to a reduction of the cavitation in the simulated model and full-scale wake field.

The WED causes in the model and full-scale wake field a reduction of the propeller induced pressure fluctuations in the first and second harmonic orders (Figures 13 and 14).

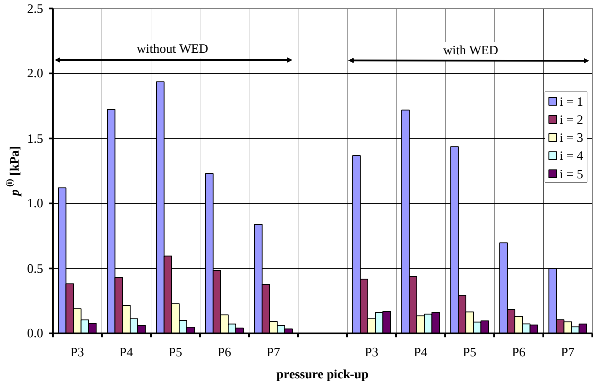


Figure 13. Influence of the WED on the pressure fluctuations in the simulated model wake field

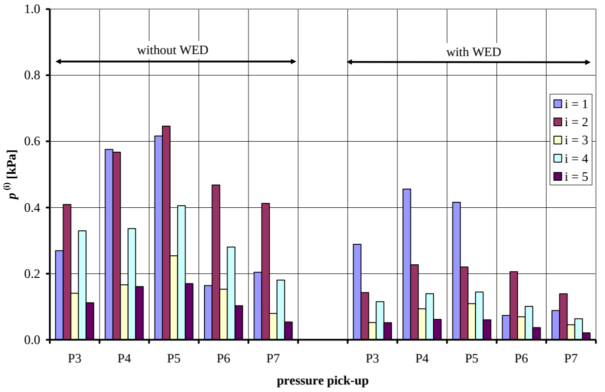


Figure 14. Influence of the WED on the pressure fluctuations in the simulated full-scale wake field

The pressure fluctuation measurements with the dummy model with different angles of attack of the vortex generator fins showed an increasing of the pressure fluctuation amplitudes in the angle range 5.5 to 25.5 degrees in the model wake field. Only with angles larger than about 30 degrees will a reduction of the pressure fluctuation amplitudes be achieved (Figure 15).

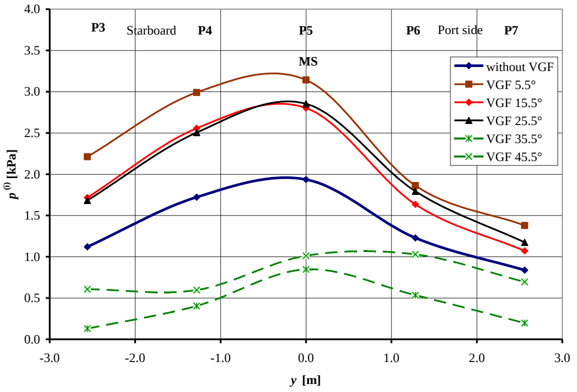


Figure 15. Influence of the VGF angle on the pressure fluctuations in the simulated model wake field

The pressure fluctuation amplitudes of the propeller in the simulated full-scale wake field are very low. Nevertheless, each angle of attack of the vortex generator fins leads to a further reduction of the pressure fluctuations (Figure 16).

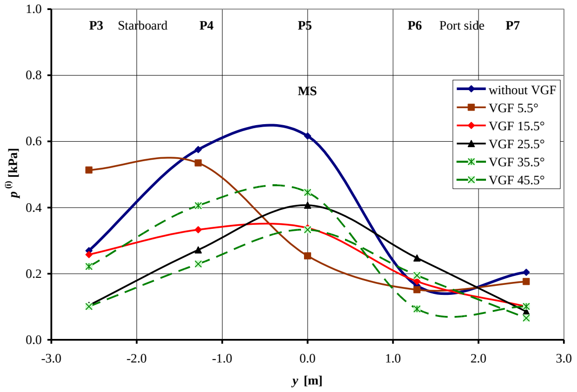


Figure 16. Influence of the VGF angle on the pressure fluctuations in the simulated full-scale wake field

6 CONCLUSIONS

The inflow of the propeller is influenced by the Reynolds number effect on the flow around the ship. The wake peak and the maximum wake fractions are on the ship smaller in comparison with the model.

The wake equalizing duct (WED) and the vortex generator fins (VGF) are working in the model and full-scale due to the different boundary layer thickness at various inflow speeds. The resistance coefficients of the WED or VGF, calculated with the ship speed, are in a similar dimension.

CFD calculations in model and full-scale show that the change of the propulsion coefficients thrust deduction fraction, wake fraction and hull efficiency of ships with WED or VGF can be predicted with a good accuracy with the ITTC 1978 propulsion prognosis method.

The suction side sheet cavitation and the tip vortex cavitation are lesser developed and pulsate more at tests in a simulated full-scale wake field than in a model scale wake field. The result is a decreasing of the propeller induced pressure fluctuation in the first harmonic order and an increasing of the pressure fluctuation amplitudes in the higher harmonic orders. Further investigations are necessary to study the influence of the wake scaling on the cavitation. Especially the Reynolds number effect on the tip vortex cavitation must be considered in this connection.

The use of a WED leads to a reduction of the propeller induced pressure fluctuations in the first and second harmonic orders.

Vortex generator fins can reduce the propeller induced pressure fluctuations distinctly. The optimisation of the angle of attack of the vortex generator fins is influenced by the Reynolds number.

The calculated wake fields for ships with WED or VGF can be used for the prediction of the cavitation and the propeller induced pressure fluctuations with potential flow programs. The Figure 17 shows results of pressure fluctuation calculations with the potential flow propeller analysis program UNCA. The effect of the WED and

VGF as well as of the wake scaling can be reproduced with these calculations.

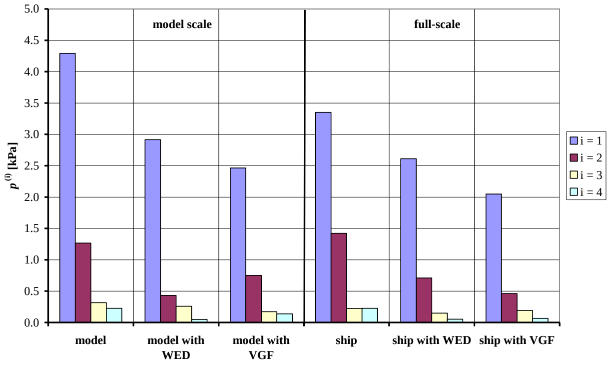


Figure 17. Pressure fluctuations amplitudes, using the CFD calculated wake fields

The calculation of the nominal wake field of ships with WED or VGF will be recommended to support the propeller design and the prediction of propeller cavitation and pressure fluctuations.

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