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NUMERICAL ANALYSIS OF THE FLOW IN THE GAP BETWEEN THE SHIP HULL AND THE FAIRWAY BOTTOM IN EXTREMELY SHALLOW WATER

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SUMMARY

The paper presents the results of the computational study on the flow around a Post-Panamax container ship cruising in a restricted shallow channel in model scale. The study aimed next to numerical prediction of dynamic sinkage and trim at the analysis of the flow regime in the gap between ship's hull and waterway's bottom.

NOMENCLATURE

L_{wl}	Waterline length (m)
ρ	Density of water (kg/m^3)
B	Ship beam (m)
T	Ship draft (m)
h	Fairway depth (m)
λ	Model scale (-)
U	Ship speed (m/s)
S_B	Squat at the bow (m)
S_H	Squat at the stern (m)
y^+	Dimensionless wall distance (m)

1 INTRODUCTION

Through years of experimental tests in model scale to predict ship induced wave loads on bank protection in channels and waterways at BAW, a comprehensive collection of squat measurements had grown, allowing to draw some principal and systematic conclusions on the squat effect in shallow and restricted waters. One was the observation of a significant increase of the trim angle when water depth to draft ratio is decreased to less than h/T = 1.3. Change in the flow regime was suspected to be responsible for this effect. In order to avoid the complicated experimental investigations it was decided to utilize computational methods to gain an insight into the flow regime and underlying mechanisms of the described effect. In the presented research a series of computations covering a representative range of h/T and different ship speeds were performed using both RANS and a scale-resolving approach - the hybrid RANS/LES model of Kornev et al. [1]

2 CONSIDERED PROBLEM AND COMPUTATIONAL SETUP

2.1 MODEL PARAMETERS

The model PPM55 used for the simulations corresponds to a Post-Panamax container ship to the scale 1:40. The parameters of the model are presented in the Table 1. In this research the bare hull without propeller and rudder was investigated, even though in the experiment the model was self-propelled. Influence of propeller suction force on squat as well as the flow in the bottom is out of the scope of the current study and will be investigated in the further research.

2.2 FAIRWAY PARAMETERS

A symmetric channel with the flat bottom and the bank slope 1:3 was considered, which corresponds to the geometry, used in the BAW model basin for the experimental investigations of squat (see Fig.1). For the RANS calculations the channel depth was varied from h/T=1.15 to h/T=1.75, for hybrid calculations only the lowest value was studied. In order to keep the slope constant for different depths, the breadth of the channel was changed accordingly. The ship was assumed to move in the centre of the channel.

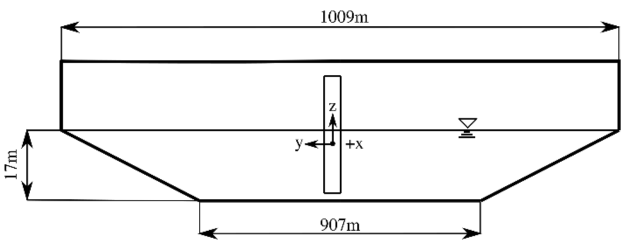

Figure 1. Channel geometry at the full scale, h/T = 1.06

Table 1. PPM55 Parameters

L_{wl}	8.89
B	1.375
T	0.4
C_B	0.689
λ	1:40

2.3 RANS SQUAT COMPUTATION SERIES

The RANS computations were performed for twenty five cases with the parameters listed in the Table 2. The corresponding range of Reynolds numbers is

$$4.3 \cdot 10^6 \text{ - } 1 \cdot 10^7$$

Numerical solution was obtained using the quasi-steady state VOF-solver LTSInterDyMFoam, which is a development of the chair of modelling and simulation at the University of Rostock, based on a CFD toolkit

OpenFOAM. In the framework of the local time stepping (LTS) method the time step is not constant over the computational domain, rather than it is a scalar field, depending on the local Courant number. This way the solution process can be considerably speeded up, compared to unsteady formulation. The simulation started with the fixed ship attitude and after the convergence of the wave system the model was allowed to sink and trim. For turbulence modelling $k-\omega$ SST model of Menter was used with the automatic wall functions [4]. Unstructured hexa-dominant computational grids were generated by StarCCM® trimmer mesher with the average $y^+=40$. The middle line plane was considered a symmetry plane and thus only a half of the ship flow was calculated. For a half a ship meshes about 2M cells were produced. Computational cells near the ship hull had an isotropic cubic form with the edge length of 0.01m at the bow and at the stern and 0.02m in the cylindrical part of the hull. Cells, located at the free surface were refined down to 0.005m in vertical direction. At the inlet and the outlet of the domain the control volumes were stretched in longitudinal direction. Domain length was equal to $5L_{wl}$: $2L_{wl}$ in front of the model and $2L_{wl}$ after (it was chosen according to experience [2])

Table 2. Summary of the considered cases (U in m/s)

h/T U	1.15	1.2	1.3	1.5	1.75
0.48	RANS, RANS/LES	RANS	RANS	RANS	RANS
0.64	RANS, RANS/LES	RANS	RANS	RANS	RANS
0.81	RANS, RANS/LES	RANS	RANS	RANS	RANS
0.97	RANS, RANS/LES	RANS	RANS	RANS	RANS
1.13	RANS RANS/LES	RANS	RANS	RANS	RANS

Discretization of convective terms was done using linear upwind interpolation. Diffusive terms were approximated using Green-Gauss scheme with linear interpolation and explicit correction of mesh non-orthogonality. For time-stepping the Euler implicit scheme was employed.

The computational methodology described above had already been successfully applied for the prediction of squat in a restricted fairway [2]. For the description of the OpenFOAM VOF algorithm the reader is referred to [3].

2.4 HYBRID RANS/LES COMPUTATIONS

For the hybrid computations only five cases were selected (see Table 2). There were two reasons for this. First of all hybrid simulations should be conducted on finer meshes compared to RANS ones and therefore they are much more computationally expensive. The second reason is that the aim was to investigate the unsteady effects in the wake and these were assumed to be the most intense at the lowest h/T.

Simulations were carried out using the unsteady VOF solver interDyMFoam. Initial trim and sinkage as well as the initial conditions for velocity, pressure and volume fraction fields were obtained from the local time stepping solver (see section 2.3). As previously, the model was free to sink and trim, but this time rigid body dynamics was also taken into account. For the integration of the equations of rigid body dynamics second order leapfrog method was adopted. Coupling with fluid dynamics was performed in an iterative manner [5].

Since the symmetry condition cannot be applied for scale-resolving simulations, the mesh was constructed for the whole ship and contained about l3M cells. The average y^+ value was approximately 1. The gap between the ship hull and the fairway bottom was resolved using 35 cells, including viscous layers. No wall functions were applied. The viscous layers were also added to the channel bottom.

The RANS/LES turbulence model of Kornev et al. blends the Lilly's version of Germano subgrid stress model with the $k-\omega$ SST model of Menter depending on the ratio between the integral length scale and the local cell size. Details of the model implementation and validation can be found in [6] and will be omitted here. As it was described by some authors [7], application of upwind-biased schemes (even high-order) for the discretization of the convective term can influence the quality of hybrid simulations because of the increase of dissipation and therefore it is recommended to use centred schemes. Unfortunately the latter may become unstable in some regions of the flow and thus the blending between upwind and centred schemes is proposed, in which the blending factor depends on the local flow characteristics (strain rate, vorticity, turbulent viscosity, etc.) [7], so that the scheme turns to upwind in the RANS zone and to a centred one in the LES region. For all the hybrid simulations in the present study the convective term was discretized using the mixture of a second order linear upwind scheme with a centred one. The time stepping was performed by means of the Crank-Nicolson scheme. Diffusive terms were approximated in the same way as in RANS calculations (see Sec. 2.3).

3 RESULTS AND DISCUSSION

3.1 RANS RESULTS

Computational results for the squat effect at the bow and at the stern are presented in the Fig. 2 and 3. From the computed data one can identify the following tendency.

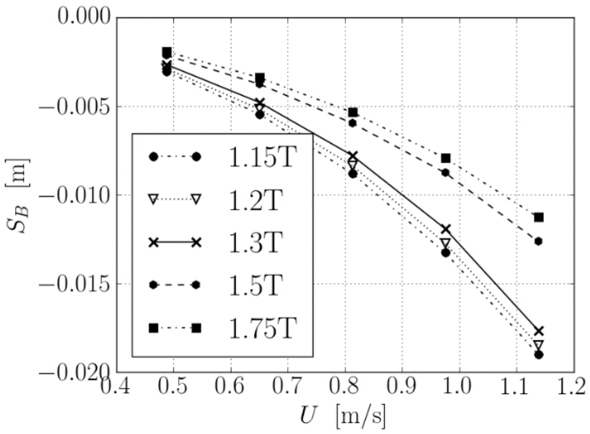

Figure 2. S_B **of PPM55 at different speeds and depths**

At the small speeds the ship is normally trimmed to the bow ($S_B > S_H$). With the increase of the speed the direction of the trim is changed to the stern. Already at 0.81m/s in all cases the trimming moment was negative. Further speedup of the ship caused the reduction of the under keel clearance (UKC) and the increase of the trim angle. As it is known, squat is in general intensified when the channel depth decreases and the speed increases, which means that the proper tendency was reproduced by the numerical method.

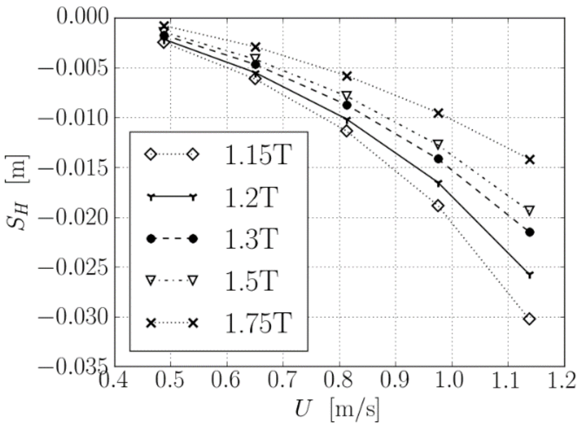

Figure 3. S_H **of PPM55 at different speeds and depths**

The most interesting results were obtained for the velocity distribution in the gap between the ship and the channel bottom.

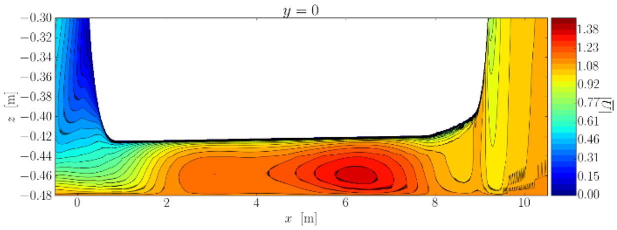

Figure 4. Velocity magnitude distribution at the middle line plane of PPM55 at h/T**=1.15, U=1.13m/s. AP at x=0.**

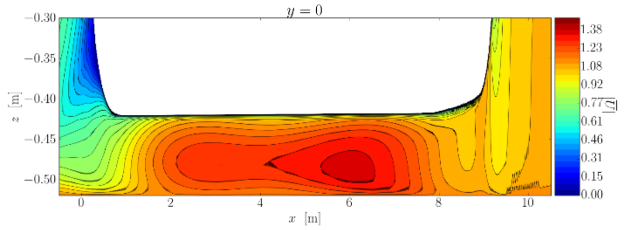

Figure 5. Velocity magnitude distribution at the middle line plane of PPM55 at h/T**=1.3, U=1.13m/s. AP at x=0.**

In Figures 4, 5 and 6, one can see the distribution of the velocity magnitude at the middle line plane at different depths at the speed of 1.13 m/s. In the presented figures the following phenomenon can be observed. At $h/T = 1.75$ one can distinguish two separate boundary layers growing in the gap: one on the bottom and one on the ship hull. As h/T decreases, these two get united so that there is no region, for which it could be stated that the viscous effects are negligible there (see Fig. 4). This phenomenon leads to the decrease of the flow velocity starting from the midship. Since the Bernoulli equation in its inviscid form

$$p + \frac{\rho u^2}{2} = const \qquad (1)$$

is no more applicable in this region, the deceleration of the flow does not lead to the increase of pressure and reduction of the trimming moment. Because of the pressure drop Δp due to viscous effects, pressure in the stern p_H decreases even stronger:

$$p_H = p + \frac{\rho(u^2 - u_H^2)}{2} - \Delta p \qquad (2)$$

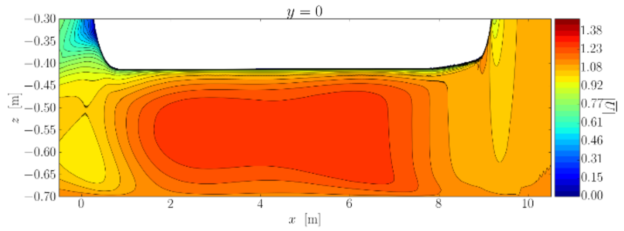

Figure 6. Velocity magnitude at the middle line plane of PPM55 at h/T**=1.75. AP at x=0.**

Thus, compared to the cases with higher h/T the trimming moment (which is mostly due to the low pressure at the stern) increased, even though the local velocity in the stern area became lower. If one takes the above discussion into account, it becomes clear, why the decrease of h/T results in a substantial trim change. One of the reasons for this is obviously the asymmetric distribution of the pressure loss relative to the midship.

One additional effect which deserves attention is the formation of the flow separation below the stern bulb at lower depths. The separation zone is pronounced in the Fig. 4 and 5 for h/T=1.15, h/T=1.3 respectively, whereas at h/T=1.75 only the moderate separation is observed. The longitudinal evolution of the flow in this separation region can be seen in the Fig. 7. The boundary layer detaches at approximately x=1.5 and a separation bubble is built up downstream.

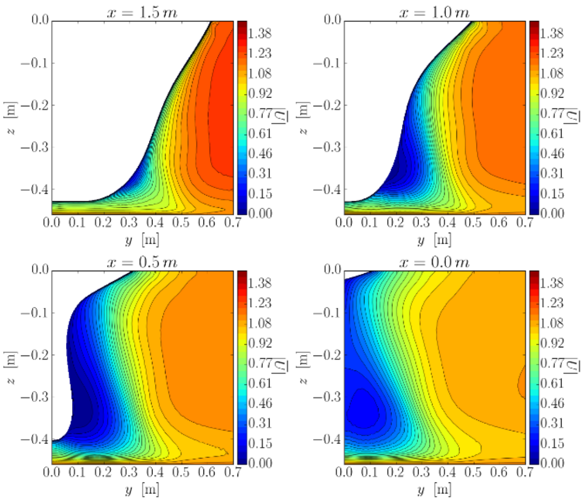

Figure 7. Velocity magnitude distribution at different x-slices in the ship stern. The development of the separation region can be observed. AP at x=0

It is known, that RANS models generally don't perform well in separation regions [8], and therefore in such cases application of hybrid methods or LES is recommended.

3.2 HYBRID RANS/LES RESULTS

In all the RANS/LES simulations periodic oscillations of the trim angle and the squat at the midship were observed.

The period of the oscillations was approximately equal to the eigenfrequency of the model hull and therefore one can say that the observed oscillations are physically adequate.

Since the hybrid simulations started from a RANS solution, it took some time till the instabilities are developed. In the Fig. 8 one can see an example of the time history of squat oscillations at the stern. It can be noticed that the oscillations are periodic ($T_o \approx 1s$) with the amplitude slightly changing in time.

For U=0.48, 0.65, 0.81 m/s the amplitude of S_H and S_B oscillations was approximately equal to 10% of the mean value. The maximum amplitude of fluctuations was observed for U = 0.97 m/s, where the amplitude reached about 50% of the mean value. Further increase of the ship speed led to the reduction of the fluctuation intensity to 3.5%. This stabilization of the ship dynamics can be of a numerical as well as of a physical nature. On the one hand when the gap between the ship and the bottom is getting narrower, the unsteadiness in the stern can become less intense because the amount of water passing under the ship will decrease and this can weaken the vortical structures.

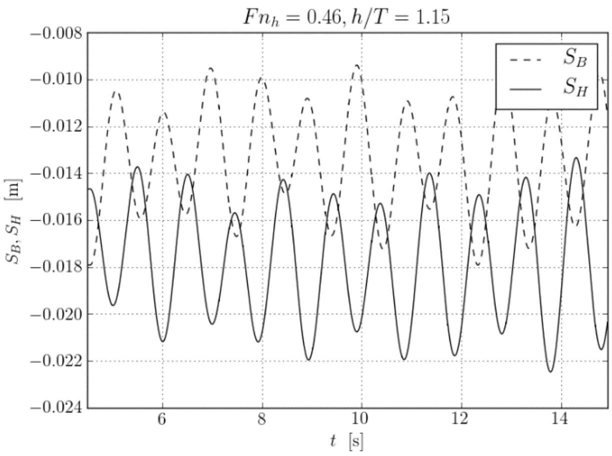

Figure 8. Time history of the stern squat oscillations for h/T=1.15 and U=0.97m/s (figures for other regimes are omitted in the present work)

On the other hand, the decrease of the gap size can force the hybrid model to switch to RANS in a broader region of the flow, causing in this way a stabilization. In order to clarify, which of these scenarios led to the observed effect, additional computations should be conducted. In most cases the application of the hybrid methods did not lead to considerable change of the mean trim and sinkage, even though the oscillations were observed. . The only exception is the case with U = 1.13 m/s, where S_B, S_H increased (signed value) by approximately 5%.

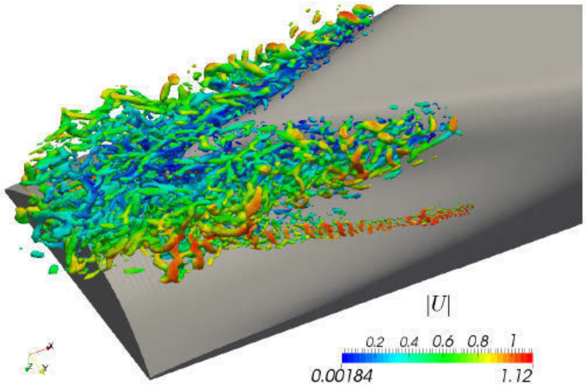

Figure 9. Instantaneous snapshot of the coherent structures at the stern of PPM55 at h/T=1.15, U=0.97m/s

Analysis of the vortical structures in the wake (see Fig 9) has revealed, that the unsteady behaviour of the ship was caused by the hydrodynamic effects. In RANS computations a separation region at the stern bulb was observed, but the dynamics of the bubble could not be resolved in time. On the contrary to RANS the hybrid method switched to LES in the stern region and this way the periodically detaching vortices were captured. These unsteady vortices caused the periodic fluctuations of forces and moments on the hull, which influence can be observed in the Fig. 8. The breadth of the region filled with eddies and the intensity of the latter point out that the hull oscillation amplitude is likely to be realistic.

Once the main part of the hybrid simulations was accomplished it was decided to carry out some additional numerical study in order to determine, whether the observed hull oscillations were caused by the unsteady separations or the flaws of the coupling between the fluid dynamics and rigid body dynamics. For this purpose a few additional RANS/LES simulations with the fixed ship attitude were carried out, during which the velocity fluctuations in the separation bubble were recorded at 3 points along the stern bulb.

The Fourier analysis of the recorded data for the separation bubble (see Fig. 10) with the fixed hull showed, that there is indeed a velocity fluctuation mode close to the eigenfrequency of the hull oscillations (around 1/s). This finding made the authors more confident that the observed unsteady behaviour of the ship had a physical background and was not a result of numerical instabilities.

Unfortunately, since no experimental data for the velocity in the ship wake is available it is hard to conclude, to which extent (quantitatively) the observed effect is close to reality. However, the experience shows, that sometimes during the towing tank as well as self-propelled trials under extreme shallow water conditions ship models can indeed noticeably oscillate.

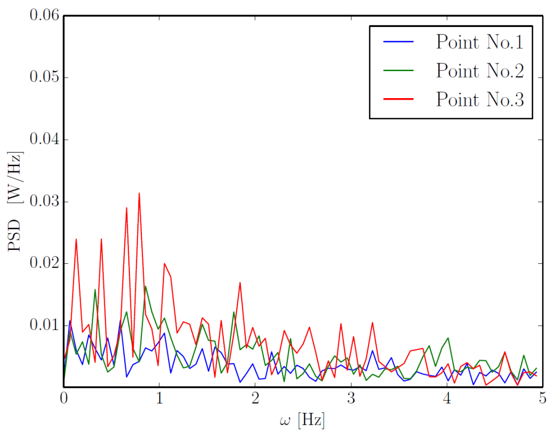

Figure 10. Power spectral density of the velocity fluctuations in the wake of PPM55

4 CONCLUSIONS

The presented paper describes the results of a series of RANS and RANS/LES computations of squat effect under extreme shallow water conditions. The main aim of the numerical study was to determine, which effects lead to the dramatic intensification of squat at $h/T < 1.3$, which is often observed in experiments. After the extensive analysis of the velocity distribution in the flow under the ship and pressure distribution along the hull at different motion regimes it was found out, that at low values of h/T the boundary layers, which grow on the ship hull and at the channel bottom unite, which causes the increase of pressure drop along the hull due to the intensified friction.

Additionally it was shown, that at low depths considerable separations occur in the stern region. Due to the high diffusivity of RANS closure models it is problematic to capture the influence of these separations on the dynamics of the hull. However, if a hybrid model is applied, the unsteady effects in the wake can clearly be seen and they lead to considerable oscillations of the model. Application of the hybrid approach, however, did not lead to any noticeable change in the average values of dynamic trim and sinkage.

5 ACKNOWLEDGEMENTS

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7 AUTHORS' BIOGRAPHIES

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