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Numerical and Experimental Investigation of the Possibility of Forming the Wake Flow of Large Ships by Using the Vortex Generators

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ABSTRACT

Introducing the vortices to the boundary layer in the aft part of the vessel can improve the propeller inflow quality, as the vortices equalize the axial velocity distribution and prevent the flow separation in some cases. This can be achieved by using the vortex generators – small fins fitted to the aft part of the vessel. The research described in the paper is focused on optimization of the configuration of vortex generators (VG) for a particular vessel, characterized by large block coefficient and relatively low speed.

The works realized in order to maximize the profit from using the vortex generators include:

- Preliminary CFD investigation of the efficiency of vortex generators for two types of vessels (at model scale); one of them was chosen for further analyses;
- CFD optimization of the configuration of vortex generators for the chosen vessel (number, size and angle of attack);
- Experimental validation of the CFD results and extended optimization of their configuration;
- Resistance and propulsion model tests for the hull with vortex generators – for selected configurations;
- CFD analysis of the scale effect for bare hull.

The results obtained so far show large possibility of forming the wake flow by vortex generators, but no direct profit in propulsion efficiency was achieved yet.

Keywords

Wake, CFD, Vortex generators

1 INTRODUCTION

The basic idea of using the vortex generators for improving the wake flow of large ships consists of introducing the vortices to the boundary layer in the flow around the aft part of the hull, realized by small fins fitted to the hull shell plating at some angle of attack relative to the streamlines. The vortices show the tendency to stick to the hull, which allows preventing the flow separation; moreover, the presence of vortices in the boundary layer causes an equalizing of the axial velocity distribution by mixing the low velocity region and high velocity region of the boundary layer. The described mechanism is presented schematically in Figure 1 (the sketch was taken from the paper by Schmöde (2008)).

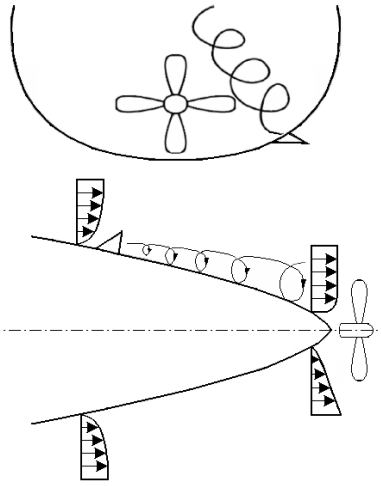

Figure 1: Principle of the operation of vortex generators

Equalizing the axial velocity distribution results in reduced propeller vibration and cavitation, it can also possibly improve the overall propulsion efficiency by reducing the suction coefficient, and allowing for using the propeller of higher efficiency. The possible profits would be achieved at the cost of additional resistance induced on the vortex generators, which makes it especially difficult to achieve a positive balance of profits and losses.

Potential efficiency of the vortex generators depends on the type of vessel; it is expected that the profit of using them will be possible to achieve for vessels characterized by blunt, complex stern shapes and highly non-uniform wake flows.

The work presented here includes: the preliminary CFD analysis, carried out in order to validate the computational model and to choose a vessel for which using vortex generators is more profitable; further optimization of the configuration of vortex generators, carried out using both CFD and towing tank experiments; and resistance/propulsion model tests and preliminary CFD computations realized to estimate the scale effect.

2 GEOMETRY OF THE ANALYZED OBJECTS

In this chapter, main characteristics of the vessels used as test cases are presented, as well as the typical configuration of the vortex generators and details of the generator geometry

2.1 Vessels used as test cases

As mentioned above, two vessels were considered in the analysis: car carrier and bulk carrier. The car carrier shape is presented in Figure 2, the bulk carrier shape in Figure 3. Main parameters of both vessels are listed in Table 1.

Figure 2: Car carrier hull shape

Figure 3: Bulk carrier hull shape

Table 1: Main parameters of the analyzed vessels

Vessel	Car carrier	Bulk carrier
Length b.p. [m]	188.00	250.80
Breadth [m]	32.23	44.40
Draught [m]	9.00	13.00
Block coefficient [-]	0.582	0.836
Speed [kn]	20.0	15.0
Froude number [-]	0.240	0.156
Model scale factor [-]	26.6	38

2.1 Typical configuration of the vortex generators

For both analyzed vessels, a typical configuration of vortex generators consisted of an array of two to four fins fitted to the vessel's skeg. In most cases, their angle of attack relative to the streamlines (derived for bare hull flow) was such that they were deflecting the streamlines upwards. An example of typical configuration with three vortex generators is presented in Figure 4

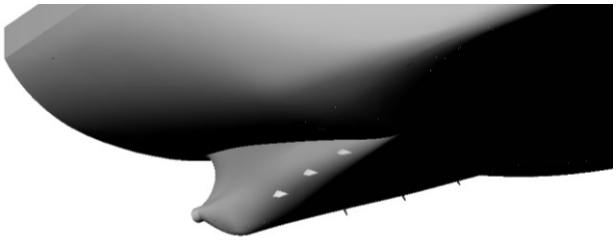

Figure 4: Typical configuration of vortex generators

2.2 Geometry of vortex generators

In each of analyzed cases, vortex generators are trapezoidal fins, presented in Figure 5. The fin profile is NACA 0010-35. Proportions of the fin dimensions are constant and equal to: $a/h = 2$, $b/h = 1$. The fin base length a is used as a characteristic dimension; in the presented study, three sizes of the fins were used: $a = 20$ mm, $a = 30$ mm, and $a = 40$ mm at model scale (note that the scale of the two towing tank models was different, so the size of the fins in full scale will be different for each vessel).

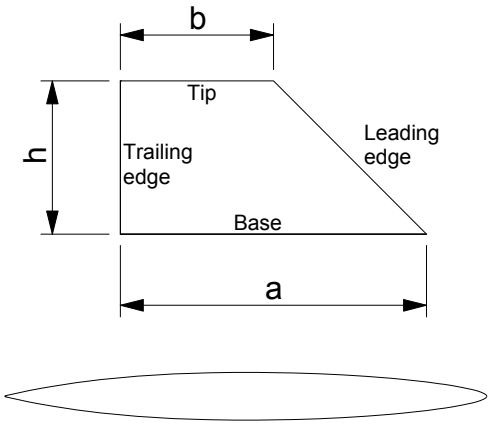

Figure 5: Geometry of the vortex generator

3 COMPUTATIONAL MODEL

This chapter presents important features of the computational model, details of the computational meshes and comparison of the results achieved for bare hulls with experimental results.

3.1 Basic assumptions

The following assumptions, based on existing experience, were made during preparing the computational model of the flow around the hull with vortex generators:

- RANSE flow model was applied to simulate the flow in entire domain; the STAR CCM+ solver was used;
- Standard two-equation turbulence models do not work correctly for complex wake flow structures. Accurate prediction of the wake flow requires the turbulence model which is sensitive to the curvature of streamlines; for the purposes of the presented analysis, the Reynolds Stress Model (RSM) was applied;
- The free surface deformation was not taken into account, assuming that the influence of free surface on the wake flow is negligible; for the same reason, the dynamic trim and sinkage of the hull were neglected. Such assumption is justified by moderate values of Froude number. Neglecting the free surface greatly reduces the computational effort and improves the stability, especially when using the sophisticated RSM turbulence model;
- Although the flow was expected to converge to steady-state solution for each case, the computations were carried out using unsteady model in order to improve stability.

3.2 Details of numerical meshes

The computational mesh of hexahedral, unstructured, locally refined type was used for the computations. Local refinement of the mesh is crucial for the presented analysis, due to very large difference between the dimensions of the vortex generators and dimensions of the hull. The number of mesh cells varied between 2 and 4 million, depending on the case (both bare hulls and hulls with several vortex generators were analyzed).

Details of the mesh are presented in Figures 6-8.

Figure 6: Mesh on the hull surface – bare hull, aft part

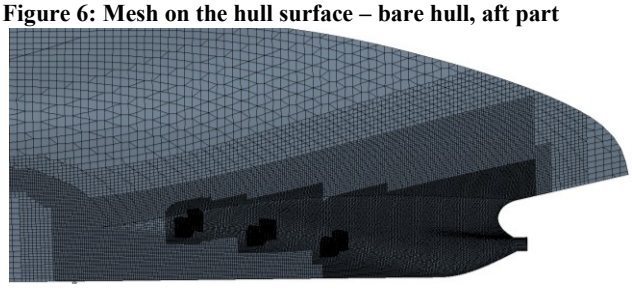

Figure 7: Mesh on the hull with vortex generators

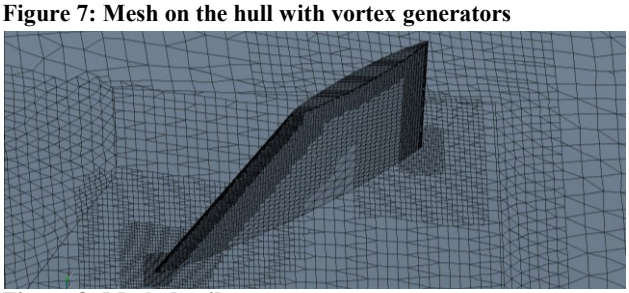

Figure 8: Mesh details on a vortex generator

3.3 Validation

The reliability of the presented numerical model was verified basing on the existing experimental results – measured wake fields for bare hulls of the considered vessels. Comparison of the computed and measured velocity fields in the propeller disc are presented in Figures 9 and 10.

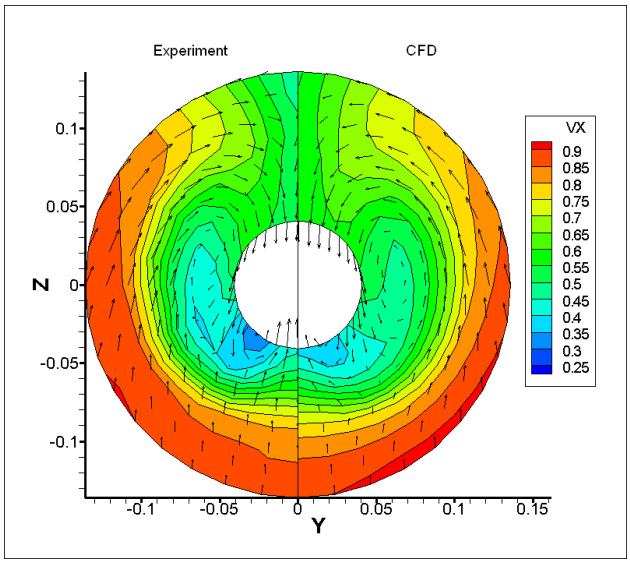

Figure 9: Validation of the computations for bare hull of car carrier

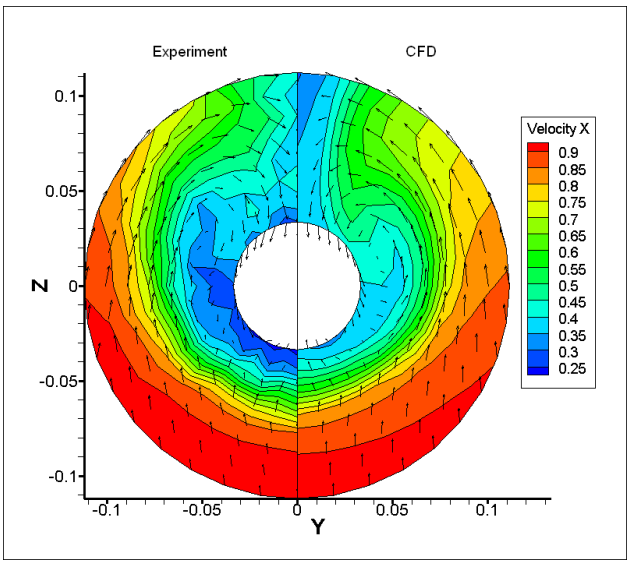

Figure 10: Validation of the computations for bare hull of bulk carrier

For the car carrier, comparison of the CFD results for bare hull with the experiment reveals satisfactory agreement, both qualitative and quantitative. However, a general tendency is observed in the CFD results to underestimate the axial velocity range: computed highest values of the velocity (far from the propeller axis) are lower than the measured values, while in the low velocity region, close to the propeller axis, the computed velocity is higher than the measured velocity.

For the bulk carrier, this tendency is even stronger, leading to notable quantitative difference between computations and experiment. However, subsequent refinements of the mesh did not result in better agreement with the experiment.

It was decided that, despite the observed discrepancies, the computational model is accurate enough to investigate the influence of vortex generators on the wake flow.

4 PRELIMINARY INVESTIGATION OF THE EFFICIENCY OF VORTEX GENERATORS FOR BOTH VESSELS

As mentioned above, the preliminary study of the efficiency of vortex generators was carried out for two vessels in order to select the shape, for which the results are more promising, i.e., the influence on wake field is stronger and the resistance increase is lower. It should be noted, however, that more promising results at this stage do not necessarily mean that the propulsion efficiency will be improved; the goal of this preliminary study is to select the shape, for which an attempt on increasing its propulsion efficiency by using vortex generators is potentially more efficient.

For both vessels, few configurations of the vortex generators were proposed. Their location was chosen based on the run of streamlines released upstream from the propeller disc, while their size and angle of attack were based mainly on intuition and results of subsequent computations. The following simplified criteria of the efficiency of vortex generators were assumed:

- Visual assessment of the uniformity of velocity distribution;
- Average value of axial velocity component in the propeller disc; it was assumed, that larger average value means better uniformity and improved efficiency due to reduced suction;
- Increase of resistance compared to bare hull.

The most successful configurations of vortex generators, characterized by largest acceleration of the wake flow and lowest increase of resistance, are presented in Figures 11 (car carrier) and 13 (bulk carrier). The computed wake fields are presented in Figures 12 (car carrier) and 14 (bulk carrier). Quantitative results are listed in Tables 2 and 3, respectively.

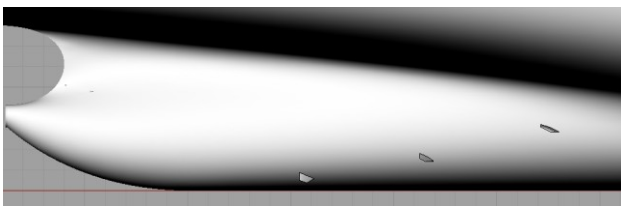

Figure 11: Vortex generators – car carrier

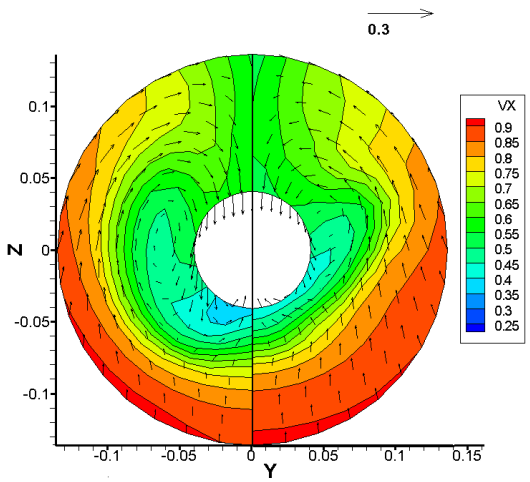

Figure 12: Wake flow without (left) and with VG – car carrier

Table 2: Quantitative results – car carrier

	Bare hull	With VG
Average axial velocity [-]	0.640	0.703
Resistance	62.7	64.3

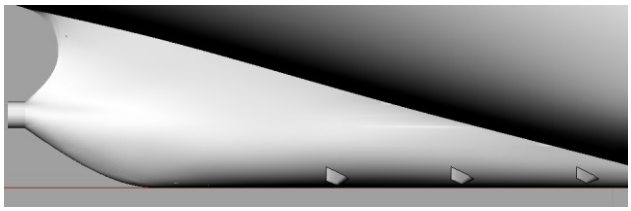

Figure 13: Vortex generators – bulk carrier

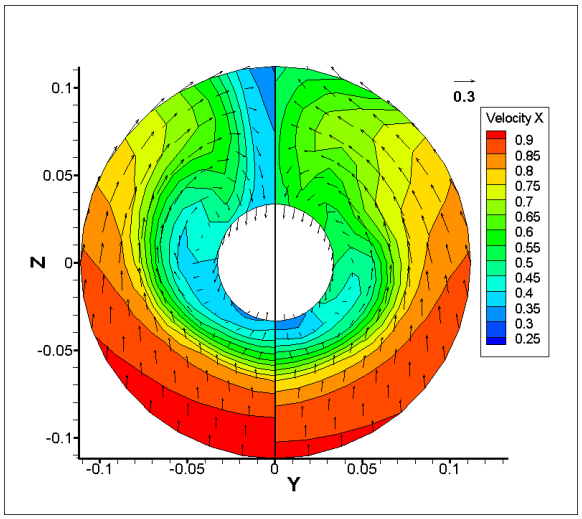

Figure 14: Wake flow without (left) and with VG – bulk carrier

Table 3: Quantitative results – bulk carrier

	Bare hull	With VG
Average axial velocity [-]	0.620	0.678
Resistance	34.3	30.4

The result obtained for the bulk carrier (Figure 14) is much closer to the expected one, presented in idealized form in Figure 1. The computed resistance values for bare

hull and hull with vortex generators (VG) are surprising, as the computed resistance with VG is considerably lower. This result was considered not reliable, at it was not confirmed by model tests; a possible reason for obtaining such result is that the flow character in the aft part was found to be very different for bare hull and for hull with VG (Figure 15).

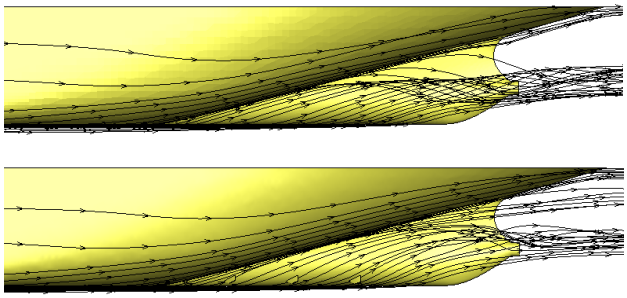

Figure 15: Streamlines without (top) and with VG – bulk carrier

For bare hull, large region of separated flow was observed; in such conditions, the RANSE model can produce unphysical results.

The bulk carrier was finally chosen for further analysis and optimization of the VG configuration, mainly due to the fact that resulting wake field with vortex generators was in accordance with the expectations.

5 CFD AND EXPERIMENTAL OPTIMIZATION OF THE VG CONFIGURATION

After obtaining the first promising result for one of the vessels, the configuration of vortex generators underwent further optimization, assuming the same goal functions: wake flow uniformity, average axial velocity in the propeller disc and total resistance of the hull with vortex generators.

The variable parameters in the optimization process were: size and angle of attack of the fins. Their location on the hull was the same for each case. The configuration of vortex generators is also the same on both sides of the vessel; asymmetrical configurations were not considered at this stage.

An array of three vortex generators was used on each side of the vessel. Their longitudinal location was as follows (the order of numbering is from bow to stern):

Table 4: Location of vortex generators

Generator No.	x/L_{PP}
1	0.147
2	0.118
3	0.091

The experiment was carried out in the towing tank using standard Pitot probe technique for velocity measurements; thus, it is not described here in detail.

Only selected results are presented here:

- An example showing the agreement between CFD and experiment for the hull with vortex generators;
- Experimental results, for which the largest acceleration of the wake flow was achieved;
- Experimental results for the configuration, which seems to be optimal in respect of relation between wake flow improvement and resistance increase.

Definition of the VG configuration used here consists of six figures: size a [mm] of first, second and third vortex generator, and angle of attack φ [deg] of first, second and third generator relative to the streamlines. The following notation will be used:

$$a_1 - a_2 - a_3 / \varphi_1 - \varphi_2 - \varphi_3$$

Figure 16 shows the comparison of experimental and CFD results for bare hull in the entire region of measurement, while Figure 17 shows similar comparison for the hull with vortex generators in configuration $40-40-40/15-15-15$.

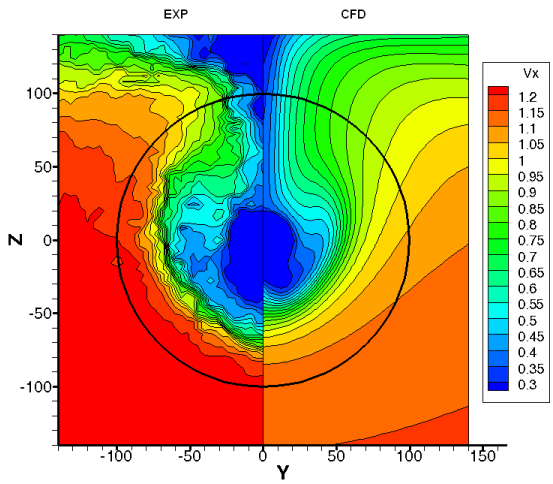

Figure 16: Comparison of experimental and CFD results for bare hull

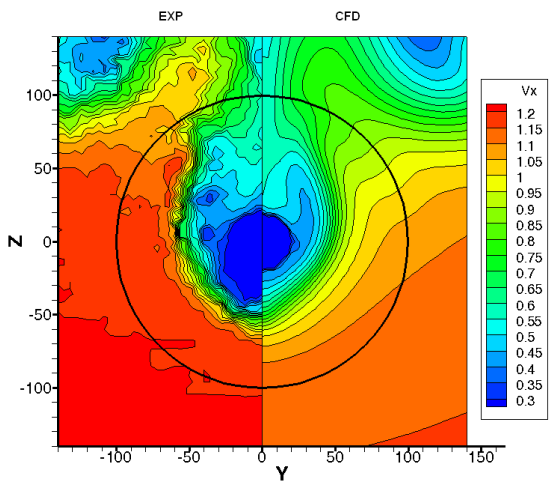

Figure 17: Comparison of experimental and CFD results for hull with VG

The comparison presented above indicates considerable overall underestimation of the axial velocity in the region of interest. However, quite accurate prediction of the flow character with and without VG was achieved with CFD. The characteristic flow structures occurring in Figure 17 were predicted correctly. Especially the disappearance of the narrow region of low velocity in the propeller disc, visible in Figure 16 and very important for the propeller inflow quality in respect of vibration, was captured. Expected effect of the vortex generators was then proved both numerically and experimentally.

Largest acceleration of the flow in the propeller disc (by 25%) was achieved for the configuration:

$40-30-30/30-30-30$.

However, such large acceleration of the flow was achieved at the cost of considerable increase of resistance – by 2.9% (the quantitative results are listed in Table 5).

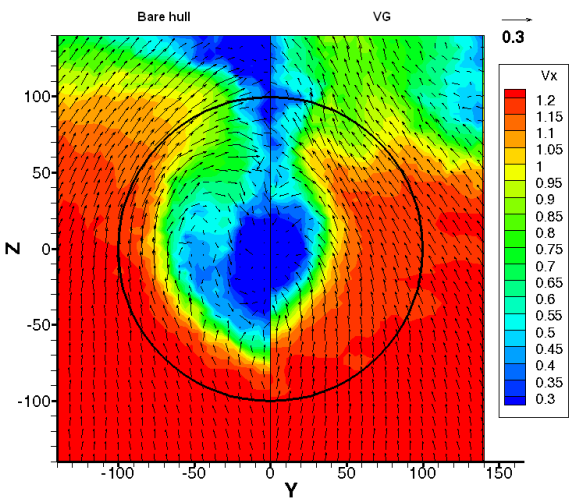

Figure 18: Comparison of experimental results for bare hull and with VG (configuration 40-30-30/30-30-30)

Table 5: Quantitative results – config. 40-30-30/30-30-30

Average axial velocity	+24.9%
Resistance	+3.2%

In order to make the comparison reliable, only the left (port side) parts of measured velocity field are compared, which eliminates the difference resulting from asymmetry of the measured velocity fields.

For configuration $30-20-20/30-30-30$, the most promising compromise between improvement of wake field and increase of resistance was achieved. The comparison of velocity field for this configuration with bare hull is presented in Figure 19, and the quantitative results in Table 6.

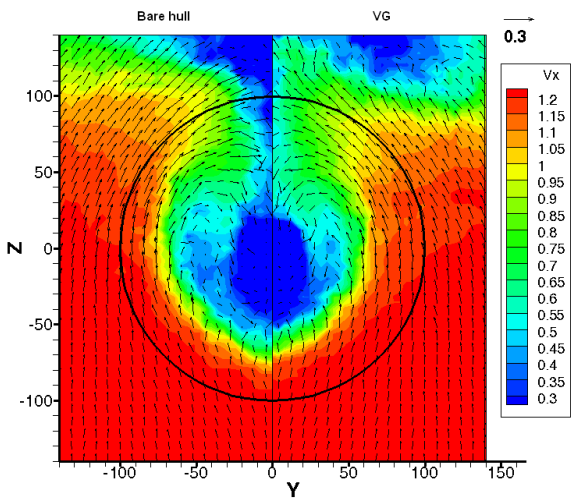

Figure 19: Comparison of experimental results for bare hull and with VG (configuration 30-20-20/30-30-30)

Table 6: Quantitative results – config. 30-20-20/30-30-30

Average axial velocity	+13.1%
Resistance	+0.4%

For the two configurations presented above, the propulsion tests were realized, and the results were compared with the results for bare hull. This comparison of propulsion efficiency with and without vortex generators is presented in the form of required power prediction for full scale vessel, with and without vortex generators (Figure 20).

Configuration $40-30-30/30-30-30$ is marked with "VG – 1" and configuration $30-20-20/30-30-30$ with "VG – 2".

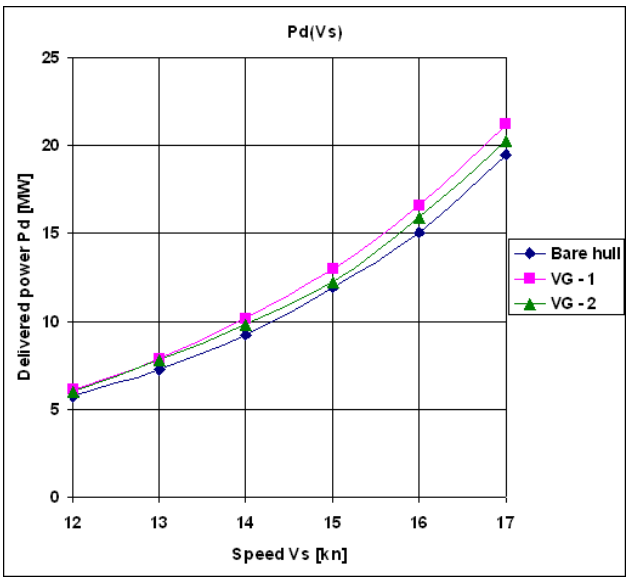

Figure 20: Power prediction for the hull with and without VG

Figure 20 shows that, unfortunately, for both configurations of vortex generators, the required power is

larger than for bare hull. In such situation, the only possibility that the vortex generators can improve the efficiency anyway is the fact that the propeller was designed for bare hull. Thus, another step will be done: propulsion tests with the propeller designed for the wake field modified by vortex generators.

6 CFD ANALYSIS OF THE SCALE EFFECT

The CFD analysis of the scale effect includes:

- Comparison of wake flow for bare hull in model and full scale - Figure 21;
- Comparison of the wake flow for bare hull and hull with vortex generators (configuration $40-30-30/15-15-15$ - Figure 22.

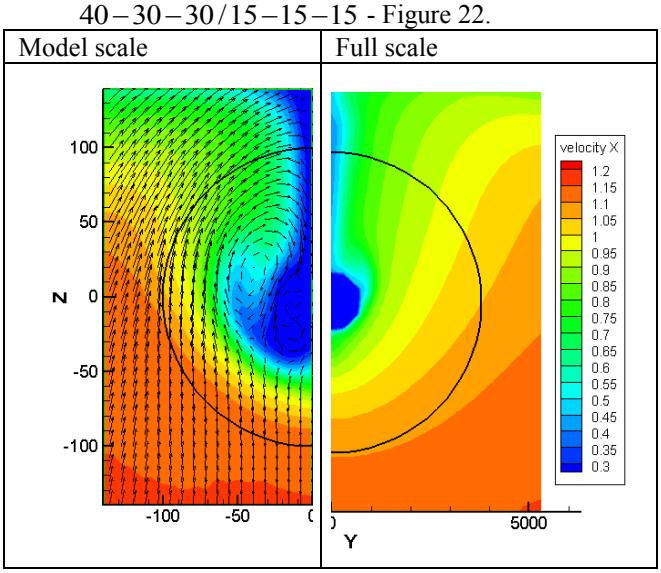

Figure 21: Comparison of the flow for bare hull at model and full scale

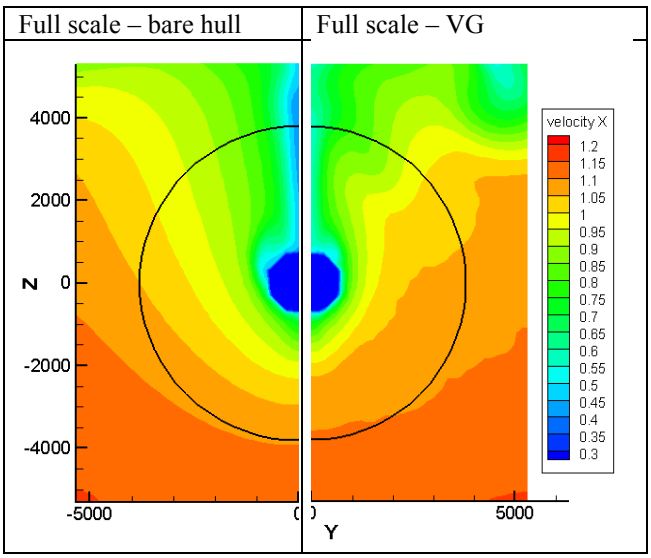

Figure 22: Comparison of the flow at full scale without and with vortex generators

Comparison of the results reveals completely different flow character for model and full scale (no "hook" observed at full scale); however, qualitative effect of the presence of vortex generators at full scale is similar to that observed at model scale (Figures 14, 18, 19). Such results allow assuming that if the vortex generators are efficient at model scale (which was not achieved yet), they should give similar effect at full scale.

7 CONCLUSIONS AND FURTHER WORK

The following conclusions can be made basing on achieved results of CFD and experimental analyses:

- Large possibility of forming the wake flow of large vessel by using vortex generators was proved; however, no improvement of propulsion efficiency was achieved till now (the propulsion efficiency with VG is even slightly worse for the analyzed vessel);
- Additional analysis of the propulsion efficiency with new propeller, designed for modified wake field, is required;
- Further numerical studies of propeller vibration and cavitation with and without vortex generators will be carried out; it is expected that these devices can reduce these phenomena, even if they do not improve the propulsion efficiency for a particular vessel;
- The analysis of the scale effect reveals completely different flow character for bare hull at model and full scale; however, the qualitative effect of introducing the vortex generators at full scale is similar to that observed at model scale.

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