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PANELIZATION STUDY FOR FREE SURFACE POTENTIAL FLOW COMPUTATION

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ABSTRACT

The present work concerns the space discretion of the free-surface potential flow computation based the boundary element method. A series of systematically sensitivity studies on the number of panels and distribution on the body and on the free surface have been performed in order to find the optimum panelization in terms of accuracy and computational time. Finally, based on the sensitivity studies some recommendations will be outlined.

Keywords: panelization, free-surface, potential flow.

1. INTRODUCTION

The numerical solution of the differential equations with partial derivations described by the mathematical model involves the approximation of the continuous domain of the problem by means of discrete representation. In general, discretization methods, such as finite difference method, finite element method, finite volume method, border element method have been successfully applied to resolve differential equations, but in order to apply the above mentioned methods a spatial discretization is needed. Discretization is the action to select of the physical domain points in which the approximate numerical solution is computed.

The discretization of the analysed field is usually represented by means of a grid/mesh/panelization. The practice of numerical hydrodynamics has shown that an unsuccessful grid can have negative consequences on the accuracy of the solution. Techniques for generating meshing are described in extenso in monographs such as [1],[2],[3].

Generally, the CFD simulation methods are based on a series of hypotheses and approximations that lead to numerical errors. For the proper use of these methods, it is important to define a range of simulation validity and, as far as possible, to estimate the magnitude of errors in this area.

The selection of the specific methods of numerical analysis in a given problem depends on the experience of the scientific researcher. Usually the validation of the numerical results confirms the correctness of the choice made.

The development of viscous flow modelling has evolved fast in the last decade, potential methods continue to be used extensively in naval hydrodynamics due to the clear benefits it gives. Due to the hypotheses involved, the accuracy of this method has long been considered inferior to those based on the integration of the differential equations written for the viscous fluid. However, the method is widely used in the practice of ship hydrodynamic research.

The most important advantages are in terms of numerical efficiency and enough robustness.

In the present paper, the consistency of the results obtained using the boundary element method is verified by means of sensitivity studies for the number of panels on the body and the panel refinement of the free surface. Sensitivity analysis is generally defined as a procedure to determine the response of output quantities to changing input parameters [4]. Sensitivity analysis is used to find out how a model will behave if one or more input parameters are systematically varied and it determines the degree of influence that each parameter has on the numerical calculation results.

Accuracy, one of the components of numerical computational efficiency, is influenced by a number of factors presented by Lisekin [3]: the mesh size, the mesh topology, cell shape and size, and the consistency of the mesh with respect to geometry. The option of increasing mesh points and reducing cell size allows to study the solution convergence rate and to improve the calculation accuracy. Another factor that can influence the accuracy of the solution is how the mesh approximates the geometric shape of the studied field.

Considering that the paper propose is to solve the potential flow with a free surface using the boundary element method, which involves only the discretization of the surface of the body and the free surface. In this respect, for the generation of panelization used in the calculation of the potential numerical solutions performed in this paper, the pre-processing module XMESH, the module of SHIPFLOW software was used. It basically relies on the interpolation between the border points inside the domain, the distribution of the nodes along the lines of the meshing network being controlled by redistribution in one or two directions, which only involves the use of various transformation functions such as: hyperbolic sinus, hyperbolic tangent, exponential and geometric progression.

A large number of panels cause a convergent solution to reach a reasonable margin of error. On the other hand, too fine meshing can lead to too long calculation time to achieve the purpose. In the following, numerical studies are performed to clarify the influence of the grid refinement on the hull and free-surface on the consistency of the calculated solution.

2. DEFINITION OF SHIP BODIES FOR THE NUMERICAL STUDY

For this purpose, numerical studies were carried out for four ship bodies with different complex geometries. Three of the four hulls (Wigley, Series 60 and DTMB 5415) are benchmark tests and were chosen due to a wide range of experimental results published in the literature. The fourth body, the 7500 tdw tank, was the subject of study under the CEEX M1C2 grant no. X2C16 / 2006, "Models and Advanced Methods in Liquefied Gas Transport Engineering", in which experimental resistance and propulsion tests were carried out at the ICEPRONAV towing tank. the Wigley hull is a slender, double symmetrical body, characterized by a simple surface without complex curvature. The Series 60 hull is also a slender body with a block coefficient of 0.6 and a spoon stern. The fore hull shape of the DTMB 5415 is dominated by the presence of a prominent sonar in the lower part of the bow, which increases the complexity of the surface to be panelized. In the aft, the ship has pram stern with slightly submerged transom.

The geometry of the 7500 tdw chemical tank is characterized by full shapes (0.77 block coefficient) and a large parallel area. The bow has a gooseneck bulb, and the transition from the bow to the cylindrical area is fast, leading to areas with large curvature. The bow is pram type, as in the case of the combatant, but the mirror is not submerged. In addition, the aft has a gondola attached to create space for the engine. The geometrical characteristics of the four ship bodies are shown in Figures 2.1-2.4.

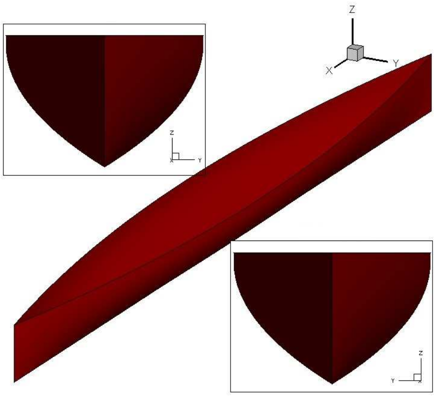

Fig.2.1 Wigley hull form characteristics

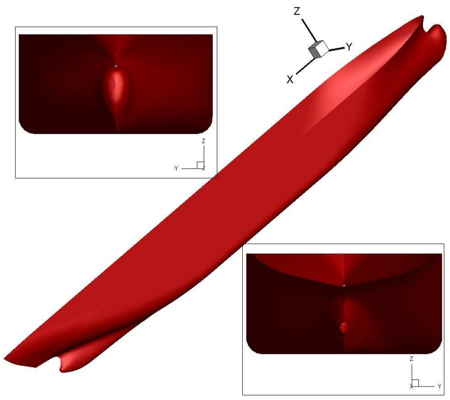

Fig.2.4 7500 tdw tank hull form characteristics

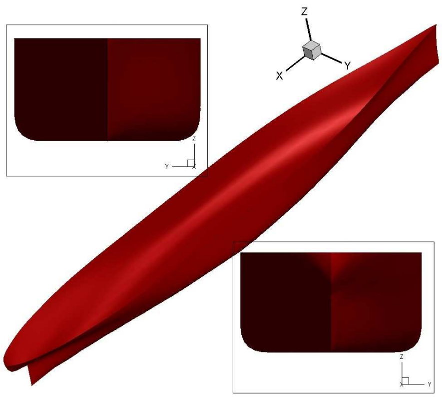

Fig.2.2 60 Series hull form characteristics

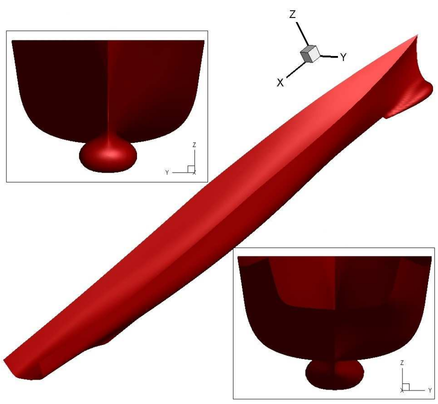

Fig.2.3 60 Series hull form characteristics

3. DEFINITION OF PANELIZATION DENSITY FACTORS

Having defined a correct geometry of the body followed by an appropriate dimensioning of the computing domain, the next step in the numerical solutioning the flow around the ship is to generate the panelization. As mentioned above, in the case of potential flow only the boundaries of the domain are discretized. In this sense, the panelizations are generated starting from lower topologies (flat or curved segments) to top topologies (straight or curved planes). In most practical case studies of the flow around the hull, both the flow and the hull of the ship are symmetrical with respect to the centreline plane of the ship so that only half the ship is considered in order to reduce the computational effort. Considering the particularities of the boundary element method, the numerical investigations on the computational domain panelization were carried out in two directions: the body panelization and the free surface panelization. For practical reasons, two factors of grid density were defined for the simultaneous modification of the number of panels in both directions (longitudinal and transversal), both on the body and on the free surface: a density factor of the body panelizaton (*fdc*) and a density factor of free surface panelization (*fdsl*). Based on the two factors the number of panels on the body, respectively the free surface, is changed.

Table 1 and Table 2 show the number of stations, the number of points on a station and the number of panels, depending on the panel-specific density factors. Figures 3.1 and 3.2 show body and free body panelizations, generated for 1, 2 and 3 density factors.

Table 1. Variation of the number of panels function of hull density factors

fdc	Points	Stations	Panels
0.50	5	25	156
0.75	8	37	406
1.00	11	50	790
1.25	14	62	1274
1.50	17	75	1904
1.75	20	87	2622
2.00	22	100	3339
2.25	25	112	4272
2.50	28	125	5373
2.75	31	137	6540
3.00	34	150	7887

Table 2. Variation of the number of panels function of free-surface density factors

fdsl	Points	Stations	Panels
0.50	43	5	3817
0.75	63	10	4197
1.00	83	16	4857
1.25	103	20	5557
1.50	123	24	6417
1.75	143	28	7437
2.00	163	32	8617
2.25	183	36	9957
2.50	203	40	11457
2.75	223	44	13117
3.00	243	48	15408

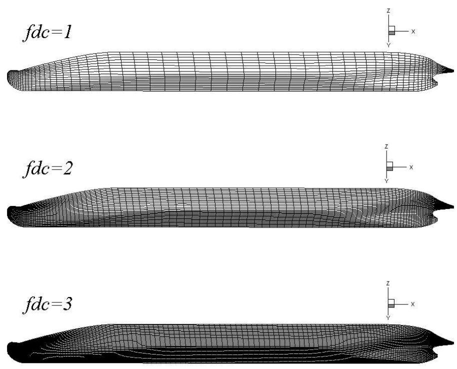

Fig.3.1 Panelization on the body for different density factors. 7500 tdw tanker hull

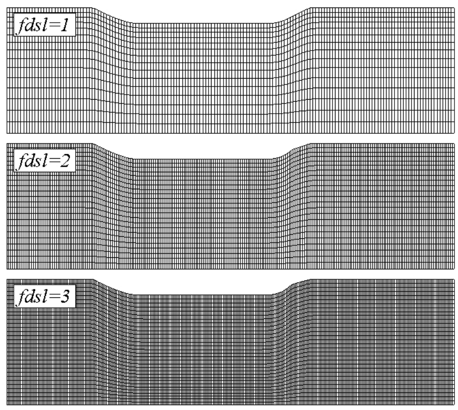

Fig.3.2 Panelization on free-surface for different density factors. 7500 tdw tanker hull

4. STUDY ON HULL PANELIZATION

In order to investigate the level of approximation of the geometric shape of the ship hull by the panelization refinement, Figures 4.1-4.4 show the variations of the wetted body surface coefficient (*Sref*), depending on the panelization density factor (refining), for both type of panels, the first order and the higher order panels. It can be seen that with the increase in the number of panels on the body, the wetted surfaces, calculated with first order and higher order panels, tend to the same value, but higher order panels lead to that value of the wetted surface faster than the first order; for higher order panels, *Sref* does not change significantly for values of *fdc* greater than 2, where panelization seems to be the best approximation of the hull geometry. In the case of the Wigley hull, the *Sref* values calculated with both types of panels are similar, which is explained by the very simple geometry.

The accuracy of the solution is influenced by the panelization of the wetted surface, if we take into account the fact that by integrating the pressure on the immersed ship hull, the wave resistance coefficient (*cw*) is numerically calculated. The first set of tests are aiming to study the effect of hull surface panelization refinement on the accuracy of the numerical solution. For this reason, the potential flow calculation around the double free surface model was sufficient to assess the influence of the change in the number of panels on the surface of the ship hull. A verification test can be performed by comparison the numerical solution with an analytical one. From the theoretical point of view, according to D'Alambert's paradox, in the case of potential flow around fully immersed double model, the integral of the local pressure on the ship body is zero because there is no rotation or energy loss in the vicinity of the body. Due to meshing errors, the value of the total pressure coefficient (*cpxi*), which is calculated by integrating in the x direction the pressure on the deep submerged submerged body, is different from zero. By analogy with the experimental test methodology, *cpxi* can be considered as the "zeros" of the wavelength coefficient and therefore its value should be subtracted from the final value of *cw*.

Consequently, *cpxi* size directly affects the size of *cw*, but remains unchanged at the Froude number change, which means that the error determined by the body panelization in *cw* decreases with the increase of the Froude number. To maintain the body panelization error below 1% of *cw*, Lee [5] recommends that *cpxi* should be less than $5x10^{-6}$ in the case of Froude numbers between 0.2 and 0.25 and *cpxi* less than $2x10^{-5}$ in the case of numbers Froude between 0.25 and 0.32. From this point of view, *cpxi* can be considered the criterion that can determine an optimal structure of panelization on the body.

In order to clarify the influence of panelization refinement on *cpxi*, over 40 sets of calculations were performed in order to compute the flow around the double free surface model, for *fdc* between 0.5 and 3.

Figures 4.5-4.8 show variations of the total pressure coefficient *cpxi* according to *fdc* variation, both for first order panels (FO - first order) and for higher order panels (HO - higher order). Analyzing the four figures, it is noted that in the case of higher order panels, the *cpx* values decrease as the *fdc* increases. In the case of the Wigley body with simple shapes the calculated values of *cpxi* are almost identical for the case with the first and the highest order panels, fact explained by the simple hull geometry. In addition, it can be seen that in the case of higher order panels the *cpxi* values are 10^{-6} for *fdc* greater than or equal to 2.5.

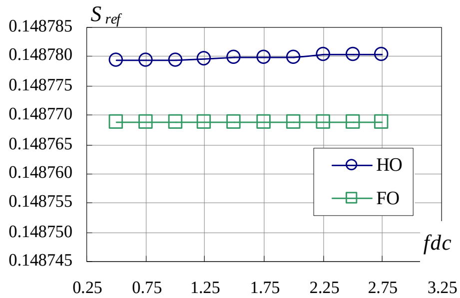

Fig.4.1 Density area variation according to density factor for first order (FO) and upper order (HO) panels. Hull Wigley

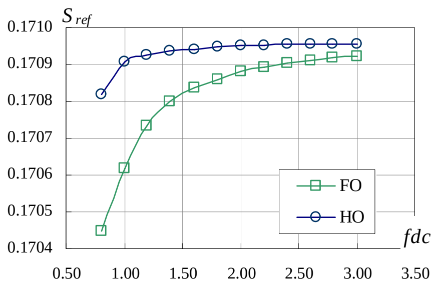

Fig.4.2 Density area variation according to density factor for first order (FO) and upper order (HO) panels. Hull Seria 60

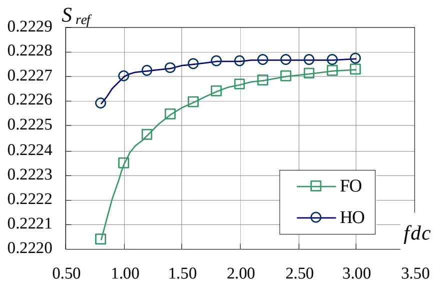

Fig.4.3 Density area variation according to density factor for first order (FO) and upper order (HO) panels. Tank 7500 tdw

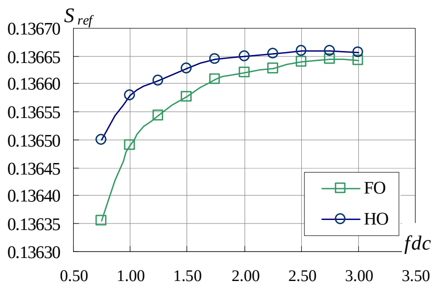

Fig.4.4 Density area variation according to density factor for first order (FO) and upper order (HO) panels. Hull DTMB 5415

Based on the results of the above mentioned study, we can conclude that optimal panelization on the body is that of *fdc*=2.5 for the density of the panelization (approximately 125 stations in the longitudinal direction and 25 points in the transverse direction) that allows a good approximation of the surface of the body with upper-order panels, as well as a body panelization error of not more than 1% of *cw*.

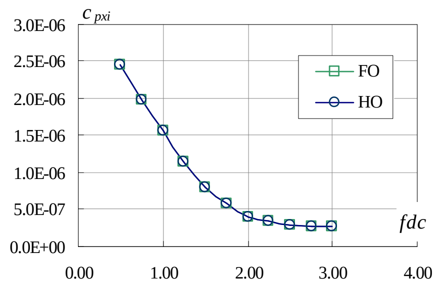

Fig.4.5 *Cpxi* variation for the double-order fdc pattern for first order and higher order panels. Hull Wigley

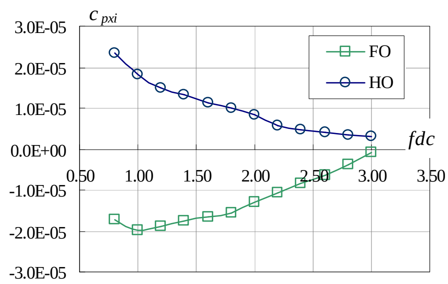

Fig.4.6 *Cpxi* variation for the double-order fdc pattern for first order and higher order panels. Hull 60 Series

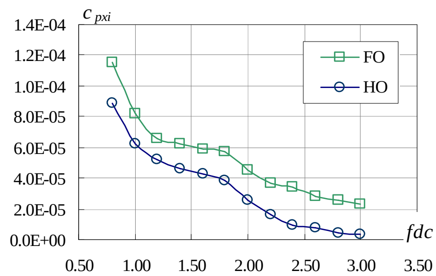

Fig.4.7 *Cpxi* variation for the double-order fdc pattern for first order and higher order panels. Tank 7500 tdw

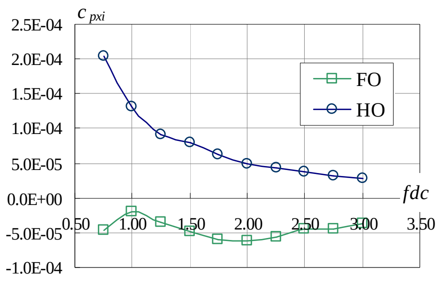

Fig.4.8 *Cpxi* variation for the double-order fdc pattern for first order and higher order panels. Hull DTMB 5415

5. STUDY ON FREE SURFACE PANELIZATION

The propose of the following study is to analyze the influence of the number of panels of free surface on the numerical solution. The first series of tests involves the investigation of the influence of the number of panels in the longitudinal direction, keeping the number of panels constantly in the transverse direction. The wavelength is calculated by the expression $\lambda = 2\pi LFr^2$. The change in the number of panels in the longitudinal direction was made according to the number of panels arranged on a wave length. The number of panels per wave length recommended by Janson [6] is 30 panels/λ. The value of the wave resistance coefficient calculated for 30 panels/λ is considered to be the reference value for comparisons of relative values of *cw*. The results presented in Table 3 show an increase of *cw* when the number of panels of free-surface in longitudinal direction increases. It should be noted that the difference between *cw* calculated for 20 panels/λ and that corresponding to 30 panels/λ is between 7.21% and 17.78%, while for increasing the number of panels from 30 panels/λ to 40 panels/λ, the difference is reduced to between 8.39 and 12.20%. Concluding, the study showed a pronounced sensitivity of the wave resistance coefficient when only the number of panels in the longitudinal direction was changed.

Table 3. The *cw* variation according to the number of panels per wavelength

pan	$c_w \times 10^3$	dc_w [%]	$c_w \times 10^3$	dc_w [%]	$c_w \times 10^3$	dc_w [%]
15	-	-	0.4636	-21.9	0.2117	-15.2
20	0.4824	-17.8	0.5191	-12.6	0.2320	-7.2
25	0.5463	-6.9	0.5632	-5.2	0.2372	-5.0
30	0.5867	0	0.5938	0	0.2497	0
35	0.6163	5.1	0.6130	3.2	0.2663	6.6
40	0.6359	8.4	0.6384	7.5	0.2802	12.2
45	0.6474	10.3	0.6494	9.4	0.2912	16.6
50	0.6597	12.4	0.6579	10.8	0.3028	21.3

The second series of tests aimed by the panelization refinement involves investigation of the influence of the number of panels in the transverse direction of the free surface on the computed *cw*. Note that the number of panels in the longitudinal direction has been kept constant. The number of panels in the transverse direction was chosen such that the length / width ratio of the panel had values between 0.5 and 2. There were considered five different panelization having from 20 to 40 panels on the transverse direction. Comparing the wave elevation contours for 20 and 30 panels (Figures 5.1-5.3), one can see that the wave system generated by the ship is sensitively different downstream of the body. Given that a coarse panelization can introduce a pronounced numerical "damping" effect on the calculated solution, the difference between the two topologies can be explained by a possible numerical "damping" produced by large panels. Comparing the contours of the wave heights for the panels of 30 and 40 panels it can be noticed that there are no significant differences between the two topologies of the free surface, which confirms the previous statement.

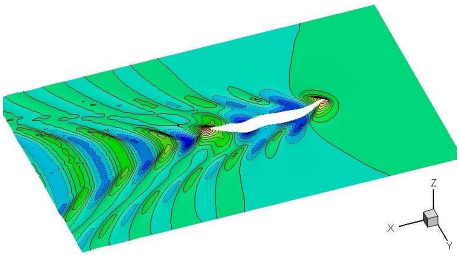

Fig. 5.1 Comparison between free surface topologies calculated for 20 and 30 panels per domain width. Hull Series 60

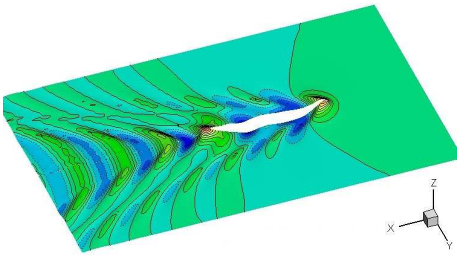

Fig. 5.2 Comparison between free surface topologies calculated for 20 and 30 panels per domain width. Hull Tank 7500 tdw

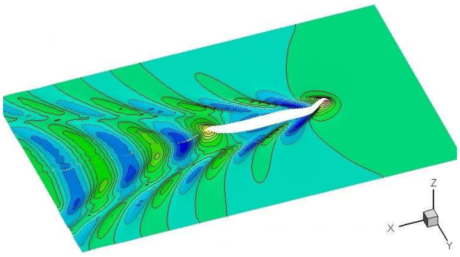

Fig 5.3 Comparison between free surface topologies calculated for 20 and 30 panels per domain width. Hull DTMB 5415

Analyzing the results from Table 4 a decrease in *cw* was noticed when the number of panels increased on the free surface in the transverse direction. It also should be noted that when the number of panels increases from 20 to 30, the wave resistance coefficient increase from 3.93 to 9.85%, while for an increase in the number of panels from 30 to 40 the increase in the *cw* ranges between 0.11 and 1.52%, with a single value exceeding 1%.

Table 4. Variation *cw* according to the number of panels in the transverse direction

Hull	60 Series		7500 tdw tanker		DTMB 5145	
pan	$c_w \times 10^3$	dc_w [%]	$c_w \times 10^3$	dc_w [%]	$c_w \times 10^3$	dc_w [%]
20	0.6581	8.2	0.5729	9.9	0.2686	3.9
25	0.6163	1.3	0.5309	1.8	0.2632	1.9
30	0.6082	0.0	0.5216	0.0	0.2585	0.0
35	0.6083	0.0	0.5174	-0.8	0.2578	-0.3
40	0.6089	0.1	0.5136	-1.5	0.2578	-0.2

In order to clarify the influence of panelization refinement on the free surface on the numerical solution, the number of panels in both directions (longitudinal and transversal) was changed simultaneously.

The systematic change in the number of panels in both directions was achieved by the density factor of panelization of the free surface *fdsl*. Numerical tests were performed for a series of *fdsl* with values between 0.75 and 2.75. Figures 5.4-5.7 show a comparison of the free surface topologies calculated for *fdsl* 1.5 and 2.0 for each of the four hulls considered. Figures 5.8-5.11 present the variation of wave resistance coefficient function of *fdsl* values. One can see the increasing *cw* tendency when the number of panels on the free surface increases, which was to be expected. In addition, at the increase of *fdsl* over 2.5 it can be considered that the variation *cw* is insignificant. Thus, with the *fdsl* change from 2.5 to 2.75, for Wigley the increase is 0.006%, 0.35% for the 7500 tank, 0.26% for the 5415 combatant and 0.91% for the 60 Series hull. The percent variations of *cw* are calculated taking as a reference the value of *cw* calculated for *fdsl* equal to 2.50. Considering the results obtained from this study, it can be considered that in general a *fdsl* of 2.5, that is, about 200 panels per length and 40 per width of the computing domain, are sufficient to obtain an efficient calculation.

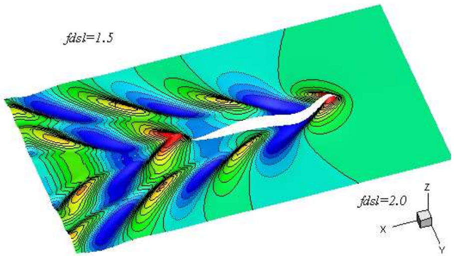

Fig. 5.4 Comparison of free surface topologies calculated for *fdsl* = 1.5 and 2.0. Wigley hull

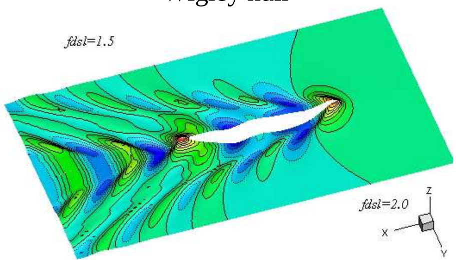

Fig. 5.5 Comparison of free surface topologies calculated for *fdsl* = 1.5 and 2.0. Seria 60 hull

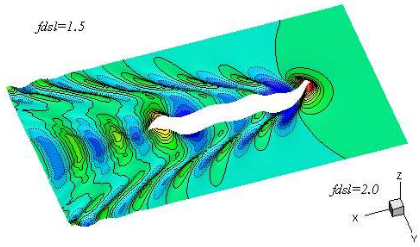

Fig. 5.6 Comparison of free surface topologies calculated for *fdsl* = 1.5 and 2.0. Tanker 7500 tdw hull

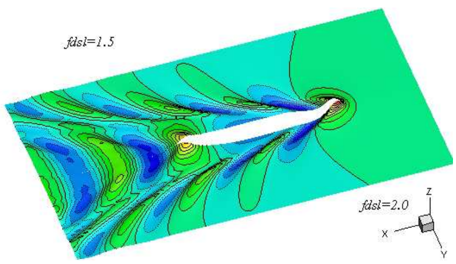

Fig. 5.7 Comparison of free surface topologies calculated for fdsl = 1.5 and 2.0. DTMB 5415

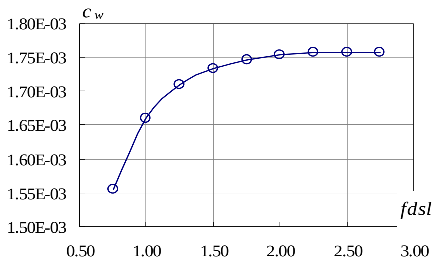

Fig. 5.8 The variation *cw* according to the density factor for HO panels. Wigley hull

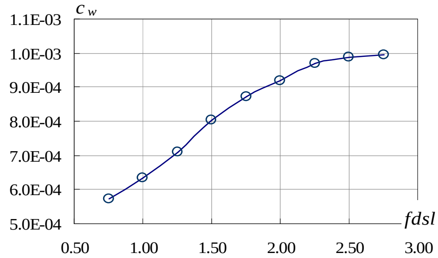

Fig. 5.9 The variation cw according to the density factor for HO panels. Wigley hull. Seria 60 hull

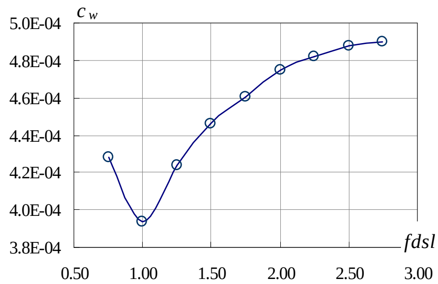

Fig. 5.10 The variation cw according to the density factor for HO panels. Wigley hull. Tanker 7500 tdw hull

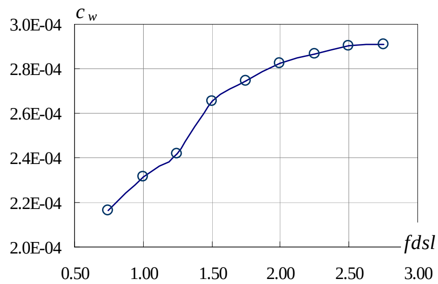

Fig. 5.11 The variation cw according to the density factor for HO panels. DTMB 5415 hull

6. CONCLUZIONS

In the first part of this subchapter, calculations with and without a free surface were developed, in which the panel refinement were systematically modified, in order to verify the consistency of the solution and to establish the parameters of the panelization that would lead to the optimal use of SHIPFLOW potential flow code. Calculations without free surface have shown that for *fdc* greater than or equal with to 2 the optimal approximation of the body surface of the ship is obtained. Also a *fdc* of 2.5 (approximately 125 longitudinal and 25 transverse) provides a panelization of the body resulting in a meshing error of less than 1% of *cw*. As a result of the calculations with free surface, it can concluded that the distribution of the panels on the free surface has a significant influence on the results, and the increase of the number of panels on the free surface leads to a significant improvement of the accuracy of the solution. An increase in the number of panels on the free surface will result in a better representation of the wave system generated by the ship, but excessive refining of the panelization leads to convergence problems. In addition, there was a pronounced sensitivity of *cw* to modification of the number of panels only in the longitudinal direction. Moreover, these calculations lead to optimal panelization (a number of panels on the free surface of about 200 on the length and 40 on width of the domain) on the free surface that ensure the efficiency of the numerical calculation.

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