On the evaluation of propeller induced pressures during initial design stages

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Abstract. The purpose of the paper is to investigate and to evaluate the tools and information that are available and can be used during the preliminary design stages in order to determine the propeller induced pressures which have an important impact on ship vibrations and, in the end, on the comfort onboard. The designer is often sandwiched within the process of creating a reliable and performant design and the milestones of the building process. Starting from a practical situation, the necessity of further clarifications leads to more detailed evaluations, which could be useful for the preliminary design perspective. The application has been carried out for a double ended passenger car-ferry. The importance of the influence exerted by the wake field on the level of propeller induced pressures and, as a consequence, on the level of vibrations is evaluated and discussed.

Keywords. Propeller induced pressures, ship vibrations, ship hydrodynamics, CFD tools, initial hydrodynamic design

1. Introduction

The capability to predict the characteristics and the performances of the ship before it is built [1] became a very important task when taking into account the tight time schedule which has to be observed during the whole process. The time allocated to the preliminary design stages is shorter and shorter and reliable design tools have to be fully integrated into the design process. The Basic/Class design flow is presented in Figure 1.

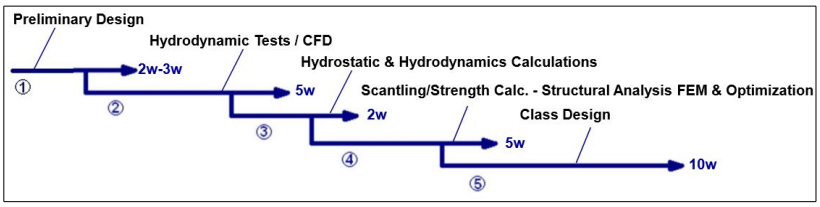

Figure 1. Basic/Class design flow.

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It has to be underlined that the Basic/Class design flow is a repetitive process, during which changes, adjustments, improvements and optimization take place. Once a stage is achieved, it is often the case that the conclusion will result in having some rework, which can set back the project 2-3 steps until the technical solution is viable and accepted [2]. In this respect, the design organizations should comply with the presented reality and find answers in order to fulfill owner's requirements, to increase the quality and the accuracy of the documentation and to be competitive. To this purpose, the existence of a fully integrated design platform that can allow an easy data migration in order to reduce the lead time would be a reliable perspective. Realistically, starting from statistic data and formulas, simple punctual applications, diagrams etc., and continuing with sophisticated CFD applications and towing tank tests necessary to validate the calculations, there isn't an integrated strong tool to "automatically" feed the next design stages.

Sometimes, due to certain reasons, the level of changes could have a major impact which has to be absorbed during next design stages, mainly during the detail design one and has to be minimized and carefully controlled as far as the economic aspects and ship performances are of paramount importance. If the effect of modifications wasn't correctly understood and handled then, during full scale trials, the results will clearly show the impact on ship performances a limited number of solutions being available to be used in order to minimize the negative effects [3].

Consequently, the initial hydrodynamic design is, practically, the most important issue and reliable tools are needed in order to ensure the fulfillment of the requested performances. These aspects become a real challenge when modern hull forms such as cruise liners, ferries, mega-yachts, and ro-pax vessels with different and complex aft configurations and appendages arrangements have to be considered [4], [5]. It has to be also taken into account the increasingly higher requirements to reduce the marine environment pollution by minimizing the greenhouse gases emissions from ships.

The present paper evaluates and discusses the importance of the influence exerted by the wake field on the level of propeller induced pressures for a double ended passenger car ferry. The ship's main characteristics are described in Table 1 while the body lines are depicted in Figure 2.

Table 1. Principal characteristics of the ship

Characteristic	Value	Unit
Length over all, L_{OA}	92.00	[m]
Length between perpendiculars, L_{PP}	86.90	[m]
Waterline length, L_{WL}	86.90	[m]
Moulded breadth, B	20.10	[m]
Moulded depth, D	7.00	[m]
Design moulded draught, T	4.50	[m]
Block coefficient, C_B	0.437	[-]
Maximum speed, V	14.00	[kn]

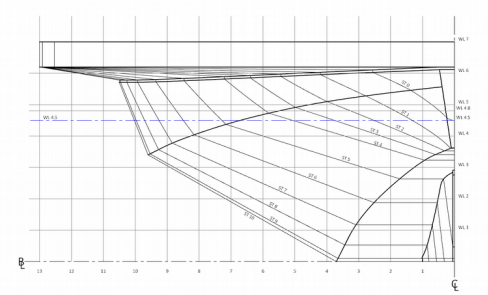

Figure 2. The Body plan of the ship.

2. Evaluation of the nominal and effective wake

In order to properly evaluate the propeller induced pressures, it must be solved the main hydrodynamic problem consisting in the determination of the wake values. To this purpose, during the preliminary design stages, there are several options which can imply the use of simple empirical or statistical formulas or of more elaborated methods based on statistical evaluations (Holtrop–Mennen), on Computational Fluid Dynamics (CFD) simulations or on towing tank tests results, if available. All these tools, as previously mentioned, have to be logically integrated in the ship design flow in order to reduce the led time and to avoid as much as possible the volume of rework. It is well-known that the most accurate values are provided by wake measurements in the towing tanks. Unfortunately, these results are conditioned by increased costs and deadlines.

2.1. The evaluation of nominal wake using simple formulas

The first step that can be performed in the early design stages is the utilization of simple, empirical formulas. These types of formulas take into account only few parameters and ship's forms, with particular attention on the aft part of the body that could significantly affect the wake values to be further considered in design. The mean wake field evaluation, together with other parameters, is of fundamental importance for the propeller design [6]. For the present study, all the evaluations are made for a single-screw case, the wake value, *w*, referring to Taylor formulation, as follows:

$$w = 1 - \frac{V_A}{V} \tag{1}$$

where:

- V_A is the speed of advance [m/s];
- V is the speed of the ship [m/s].

As Eq. (2), Eq. (3) and Eq. (4) show, there are very simple formulas that can be accounted for the general purpose and preliminary predictions [7]. Thus, for the single-screw case, the wake can be estimated by applying:

- Simple formulation

$$w = -0.05 + 0.55C_B \tag{2}$$

- Barnaby suggestion

$$w = 0.80C_B - 0.26 \tag{3}$$

- Taylor formula

$$w = 0.5C_B - 0.05 \tag{4}$$

More elaborated formulas are based on more or less systematic towing tank results, as Eq. (5), Eq. (6) , Eq. (7) and Eq. (8) reveal:

- formula which fits Harvald data [7]

$$w = \left[1.095 - 3.4C_B + 3.3C_B^2\right] + \left[\frac{0.5C_B^2 \cdot \left(6.5 - L/B\right)}{L/B}\right] \tag{5}$$

- formula suggested by British Ship Research Association (BSRA) based on data regression [7]

$$w = -0.0458 + 0.3745C_B^2 + 0.159D_w - 0.8635Fr + 1.4773Fr^2 \tag{6}$$

- formula suggested by [6]

$$\overline{w} = 0.10 + 4.5\frac{C_{pv}C_{ph}\left(B/L\right)}{\left(7 - C_{pv}\right)\left(2.8 - 1.8C_{ph}\right)} + \frac{1}{2}\left(\frac{E}{T} - \frac{D_p}{B} - k\eta\right) \tag{7}$$

- formulation given by Papmel [8]

$$w = 0.165C_B\left(\frac{\nabla^{1/3}}{D_p}\right) - 0.1\left(F_n - 0.2\right) \tag{8}$$

2.2. The evaluation of nominal wake using Holtrop-Mennen method

The method elaborated by Holtrop and Mennen [9] is based on a large volume of experimental results. The current study considers the Holtrop-Mennen approach, a common practice during ship preliminary design stages when is widely used at least for a first evaluation.

At first, the calculations have been performed for the 1/12.049 model scale in order to have a direct comparison between the theoretical and the experimental results. The analysis has been made focusing on five model speeds corresponding to full scale values ranging from 12 up to 16 knots. The two charts are presented in Figure 3.

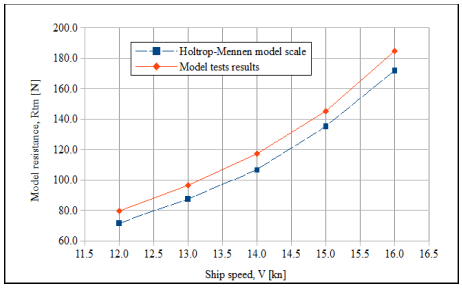

Figure 3. Model resistance – calculations and model tests results.

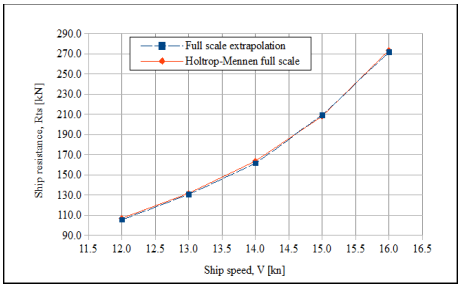

Figure 4. Ship resistance – calculations and extrapolated model tests results.

It has to be mentioned that the characteristics of the ship lead to ratio values slightly over the recommended limits of the method but the second criterion is fulfilled. The comparison shows differences between the Holtrop-Mennen and the model tests results. The calculations overestimate the experimental output by about 11% on the entire range of speeds. The value of the wake, calculated for the model case, corresponding to the ship speed of 14 knots (2.075 m/s model scale speed) is w = 0.069, while the experimentally evaluated value is w = 0.105. Based on propeller open water tests and self-propulsion tests, using the thrust identity principle, the mean effective wake ratio for the model was evaluated to w_e = 0.103. No corrections have been applied for the extrapolated values of the effective wake.

The second step was to calculate the full scale ship resistance by using Holtrop-Mennen method. The obtained results have been compared with the experimental ones that were extrapolated to full scale by using the ITTC ’57 friction line methodology. The comparative analysis is shown in Figure 4.

Practically, the full scale extrapolated model results are similar to the Holtrop-Mennen method calculated ones. However, being based on a statistical method, the result is merely a coincidence and can’t be looked as a reliable procedure to be used for practical applications. It was also found that both the full scale and the model scale estimated wake fraction have close values, in this case w = 0.069.

2.3. The evaluation of nominal wake using CFD tools

Given as a viable alternative of the experimental tests, the numerical integration of the incompressible Reynolds-Averaged Naiver-Stokes (RANS) equations is standing for the hydrodynamic investigation of the wake field developed in the aft part of the ship.

Having this objective, two different academic licensed commercial CFD applications were considered with the mention that, at the preliminary stage, the comparative results are not used as a tool in order to evaluate the merits of the numerical applications. The goal is to highlight the advantages presented by the early implementation of the CFD type techniques.

For a direct comparison basis, all the bare hull numerical calculations have been carried out for the 1/12.049 model scale, at a model speed varying with 0.15 m/s step from 1.778 m/s up to 2.371 m/s, corresponding to full scale values ranging from 12 up to 16 knots.

Due to the starboard-portside symmetry only the starboard part of the ship was modelled. All the computations, with both CFD1 and CFD2 applications, were done for a full hexahedral unstructured mesh of 1.6 million cells for CFD1 and 0.8 million cells for CFD2. As Figure 5 reveals, the three-dimensional grid is clustered near the hull in all considered directions, enabling the necessary resolution for obtaining adequate numerical solutions.

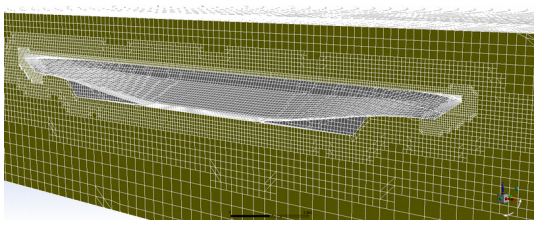

Figure 5. Computational grid CFD1 – 1.6 million cells

The additional number of equations needed because of the so-called "closure problem" entered as a consequence of the Reynolds averaging of the Navies-Stokes equations, is given by the *k-ω SST* turbulence model [10], in all considered situations.

Consequently, the results of the hydrodynamic bare hull model scale resistance for the CFD1, CFD2 and experimental model tests are comparatively presented in Figure 6. The analysis shows a very good agreement between the measured and calculated data for the CFD1 case and a satisfactory accordance for the CFD2. The explanation is the lower density of the mesh used in the second application.

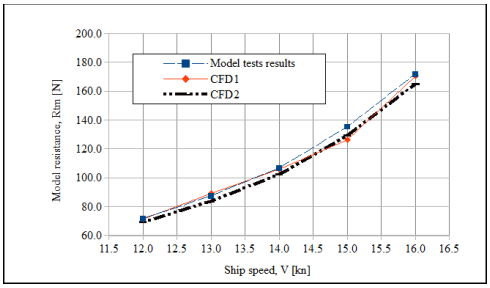

Figure 6. Hydrodynamic resistance. Comparison of numerical and experimental results.

Although the CFD2 outputs underestimates the experimental results, the magnitude of the error, under 5%, and the required computational time and resources recommend this approach to be used since early design stages.

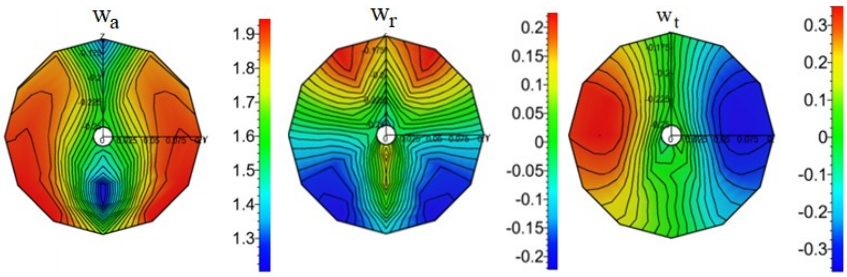

Figure 7. Axial (w_a), radial (w_r) and tangential (w_t) velocity distribution în propeller plane (CFD2)

Regarding the nominal wake, it was calculated based on the axial velocity distribution in the propeller plane. A global value of 0.190 was determined for CFD1, while for CFD2 the obtained value is 0.150. Compared with 0.105 - the nominal wake value measured during experimental tests, the CFD2 result gives the best approximation. The second application gives better results in terms of nominal wake because, during the grid generation process, a special attention was given to the aft part of the ship. The goal of the special aft refinement was to show that, even in the case of a coarse grid, the desired results can be obtained with focus on the areas of interest. The axial, radial and tangential velocity distribution, for CFD2, are depicted in Figure 7.

3. Evaluation of propeller induced pressures

During early design stages, simple evaluations methods are used. According to [11], the propeller induced pressure, p_z, is a combination between two main components given by the cavitation pressure, p_C, and the non-cavitation pressure, p_0, respectively:

$$p_z = \left(p_0^2 + p_C^2\right)^{1/2} \tag{9}$$

The evaluation of the two components can be performed using the empirical formula given by [11]:

$$p_z = \frac{(ND)^2}{70}\frac{1}{Z^{1.5}}\left(\frac{K_0}{d/R}\right) \tag{10}$$

$$p_C = \frac{(ND)^2}{160}\frac{V_S\left(w_{T_{\max}} - w_e\right)}{\sqrt{(h_a + 10.4)}}\left(\frac{K_C}{d/R}\right) \tag{11}$$

where,

- N is the propeller revolution [rpm];
- D is the propeller diameter [m];
- V_S is the ship speed [m/s];
- Z is the blade number [-];
- R is the propeller radius [m];
- d is the distance from *0.9R* to a position on the submerged hull when the blade is at the top dead center position [m];
- $w_{T_{\max}}$ is the maximum value of Taylor wake fraction in the propeller disc [-];
- w_e is the mean effective full scale Taylor wake fraction [-];
- h_a is the depth of shaft centerline [m].

The wake values, as input data, play a very important role, the cavitation pressure being directly dependent on the accuracy of wake evaluation and that is not a simple task. This can be easily observed if the induced pressures, calculated on the basis of Eq. (9), Eq. (10) and Eq. (11), are evaluated according to the formulas and methods mentioned in paragraph 2.1. The results are synthetically presented in Table 2 and graphically shown in Figure 8.

Table 2. Propeller induced forces according to different sources and CFD results

Method	Nominal wake, $w_{r_{max}}$ [-]	Induced pressure, p_z [Pa]
Equation (2)	0.190	3402.28
Equation (3)	0.090	2915.13
Equation (4)	0.169	3199.89
Equation (5)	0.287	4744.22
Equation (6)	0.433	7329.17
Equation (7)	0.213	3668.76
Equation (8)	0.447	7592.17
Holtrop-Mennen (model scale)	0.069	2984.70
Holtrop-Mennen (full scale)	0.069	2984.70
Model tests	0.105	2903.34
CFD1	0.190	3402.28
CFD2	0.150	3057.18

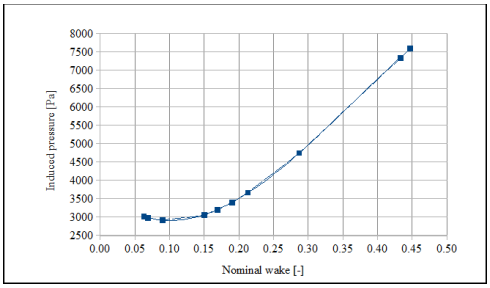

Figure 8. Influence of nominal wake on induced pressures

Figure 8 shows that the influences of the nominal wake on the propeller induced pressures can be described by a simple relation. Unfortunately, the large range of results is clearly creating a serious problem to the designer in his attempt to evaluate, with reasonable accuracy, the propeller induced pressures. Consequently, accurate tools are required at this design stage. As Table 2 reveals through a simple comparison between the induced pressures predicted by model test results and the induced pressures calculated by means of CFD2 nominal wake solution, the CFD approach can be the needed one. The estimated error between the two given values is 5%.

As a next step of the CFD computation, the ship was fitted with an operating pulling type azimuth thruster, a simplified model being considered in order to avoid the significant wake alterations due to appendages. The aft arrangement is presented in Figure 9 whereas a picture of the tetrahedral mesh used for the calculation is shown in Figure 10. For the ship equipped with propeller case, the simulation was made for 2.075 m/s model scale speed corresponding to the ship speed of 14 knots. The main dimensions of the propeller operating at the model self-propulsion point (14.518 rps) are given in Table 3.

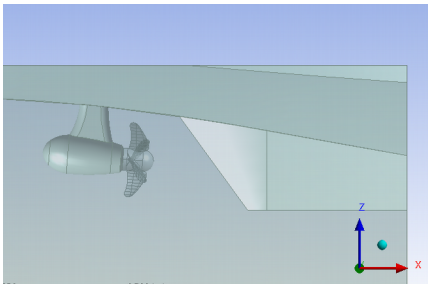

Figure 9. Aft part configuration.

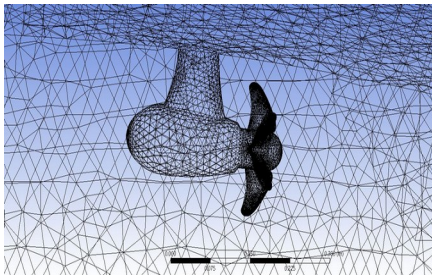

Figure 10. Aft part discretization.

Table 3. Propeller main dimensions

Characteristic	Value	Unit
Propeller diameter, D	2.40	[m]
Number of blades, Z	4	[-]
Depth of shaft centerline, h_a	2.985	[m]
Propeller revolution, N	257	[rpm]

Figure 11 shows the mechanism of appearance of propeller induced pressures while Figure 12 shows the surface effects, i.e. the induced pressures. For the hull equipped with propeller CFD simulation the induced pressure is 3044 Pa. Comparing this value with 3057.18 Pa CFD2 induced pressure, it may be concluded that, for the preliminary design stages, a simplified CFD analysis, on a coarser grid, optimized in the area of interest, can be enough. This type of approach can provide the desired results with minimum time and computational effort.

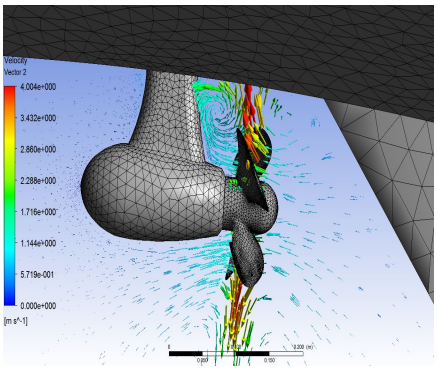

Figure 11. Side view of velocity vectors

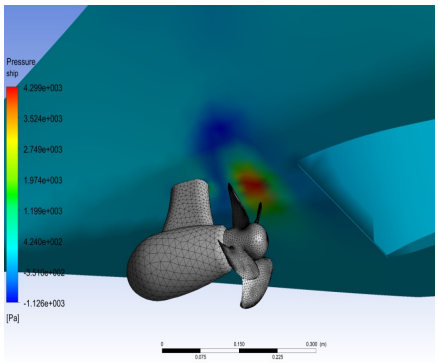

Figure 12. Induced pressures on the aft part area

4. Conclusions

Based on a request to investigate the possible structural problems created by propeller induced pressures, using a high value of the wake, w = 0.55, as an input, it was found that an important volume of structural modifications are required. Consequently, the

necessity to carry out a more detailed investigation appears to be mandatory. It can be considered as a typical example of fluid – structure interaction.
The first step was the evaluation of the wake fraction. It was found that the literature is offering a large amount of formulations to evaluate the wake fraction. However, it has to be noticed that most of them are based on old databases and statistics and their utilization, mostly for modern ships, is disputable. Practically, the most relevant conclusion is that, during the preliminary design stages, the utilization of simple formulas or even more elaborated ones do not offer to much support in order to make reliable decisions.

The very limited time allocated to find simple and efficient solutions could create serious troubles which will be reflected in vibrations, lack of comfort on-board, structural damages etc. Unfortunately, it could happen that such kinds of malfunctions are found during later design stages or full scale trials when the possibility to find efficient and cheap solutions are almost impossible.

One of the possibilities to avoid the above mentioned problems are the CFD tools in combination with structural analysis codes. The results are practically confirming the efficiency of these approaches as being adequate during the early design stages. The present study needs to be developed latter as far as many other advantages of the CFD tools have not been used and, if possible, to be validated by experimental tests.

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