Ships Maneuvering Simulations in a Seaway – How close are we to reality?

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Abstract **— This paper provides overview of the currently available theoretical methods and their capabilities in relation to simulations of the maneuvering behavior of displacement type of ships in a seaway. It has been considered that the ships are engaged in typical type of maneuvers such are for example Zig-Zag and Turning maneuvers according to IMO maneuvering standard and requirements (Faltinsen, 2005) while operating in the same time in deep and open, i.e. unconfined waters and encountering irregular wave field described by long- or short crested wave spectral formulation. Nowadays, most of the maneuvering simulation models, with an exception of limited number of the computational fluid dynamics (CFD) models, are traditionally developed on the potential fluid flow theory with partial inclusion of the viscosity effects. Although their applicability and reliability is already well proven fact through the series of carried out validation and verification procedures related to maneuvering ships in calm water situations, their capabilities in recent years start to be questioned when it comes to maneuvering simulations of ships in a seaway. In this context, a unified maneuvering and seakeeping analysis appears to have a significant role. From the perspective of a maneuvering ship which advances through the wave field and may occasionally experience the wind loading effects it can be recognized that the maneuvering and seakeeping analysis are mutually interconnected. Furthermore, due to fact that their combination represents a complex problem the approach to its solution from the side of related research communities developed gradually. Commonly accepted formulation of a seaway through the linear superposition of regular waves on a certain way dictated approach to combined maneuvering and seakeeping problem having consequence that the problem should be studied mainly in two phases. Usually, in the first phase one will address the regular wave field scenarios while the second phase will account for the irregular wave field scenarios. Theoretical methods capable of combined maneuvering and seakeeping analysis in regular waves are mainly classified in two groups; one based on the (linear) convolution integral approach (Bailey et al., 1997; Fossen, 2005) and the second one based on two-time scale approach where the wave effects upon the maneuvering ship are estimated by the mean 2nd order wave loads (Skejic and Faltinsen, 2008). Present work describes both mentioned methods with focus on their capabilities from the context of a ship executing maneuvers in regular waves. The problem of a maneuvering ship in irregular wave environment started to be analyzed recently in works by Seo and Kim (2011), Prpić-Oršić and Faltinsen (2012). The mentioned authors focused on a special case of a maneuvering ship in a seaway where it was assumed that the maneuvering ship is advancing on the straight line course, i.e. the ship has the constant heading and zero rudder angle. Mentioned special case is further generalized to arbitrary ship headings and rudder angles by Skejic and Faltinsen (2013). In conclusion, and based on the above described theoretical methods, the present paper discusses the analysis of the propulsive coefficients in the single hull-propeller-rudder arrangement from the wave environment point of view.**

Keywords — Combined maneuvering and seakeeping analysis; Convolution integral approach; Unified two-time scale model; UnsteadyCFD analysis; Propulsive coefficients in a seaway

1. INTRODUCTION

In recent time within the research community orientated towards ship hydrodynamics an increasing attention has been paid to simultaneous solution of the combined maneuvering and seakeeping problem. This is not a surprise due to fact that nowadays ship operators require safe and economically justified ship's exploitation plans while the ships are operating in different environmental conditions (waves, wind, current) and in complex and very often resource(s) demanding marine operations with variable time duration. As a consequence, the traditional analysis of ship maneuvering behavior in calm water conditions according to IMO standards and requirements (Faltinsen, 2005) is currently expanding towards inclusion of the ship seakeeping performances in a seaway which in turn gives realistic and reliable description of ship maneuvering capabilities in waves, as for example shown on Fig. 1, at the initial ship design stage or in real time.

Fig. 1. A typical Zig-Zag ship maneuver in a seaway. Source: Cooperative Research Ships, Wageningen, The Netherlands.

The maneuvering of ships in a seaway started to be investigated by Hirano et al. (1980) who carried out the experimental work and simplified estimation of the mean 2nd order wave loads upon the maneuvering ship in regular waves. Shortly after, first theoretical models dealing with the ship maneuvrability in regular wave field conditions started to appear. Most probably, the first proposed unified mathematical model, including maneuvering and seakeeping capable to describe the maneuvering of a ship in waves was given by Bailey et al. (1997). Their model was based on Cummins (1962) work who established a time domain formulation of the equations of motions with linear convolution integrals and works by Ogilvie (1964) and Bishop and Price (1981) who gave the relationships between the seakeeping inertial and maneuvering body-fixed coordinate systems. More recently, Fossen (2005), Sutulo and Soares (2008, 2009) and, Schoop-Zipfel and Abdel-Maksoud (2011) adopted the same linear convolution integral approach where the last authors in addition considered the non-linear hydrodynamic loads that is due to instantaneous wetted surface of the maneuvering ship in regular waves then in work by Bailey et al. (1997). The methods do not properly account for all second-order order wave-body interaction effects that matter for a maneuvering ship in waves. Models which does not account for the memory effects due to ship motions started to appear with work of McCreight (1986) which was followed by Ottosson and Bystrom (1991). Recently, similar approach is followed by Fang et al. (2005), and Sutulo and Soares (2008, 2009) who implemented direct evaluation of the hydrodynamic loads at encounter frequency in time domain. In the work by Skejic and Faltinsen (2008) an alternative way of defining the regular wave effects upon the maneuvering ship is introduced. The authors established a two-time scale combined seakeeping and maneuvering slender body theory model based on modular approach, i.e. MMG model by Kose et al. (1981), where the wave field loads are estimated by the mean 2nd order wave loads obtained on rational way in direct time domain computation. Two-time scale approach was also used by Yasukawa and Nakayama (2009) and followed by Yen et al. (2010), and Seo and Kim (2011) who used a fully 3D approach in estimation of the mean 2nd order regular wave loads in the horizontal plane. Concerning the simulation in irregular wave environment, Prpić-Oršić and Faltinsen (2012) applied two-time scale approach to investigate the problem of ship forward speed drop in long-crested irregular waves while the ship advances on the straight line course with zero rudder and heading angle. More recently, Skejic and Faltinsen (2013) carried out generalization of the two-time scale approach to arbitrary ship maneuvers performed in irregular wave field. Coupling between the maneuvering and seakeeping analysis for regular wave conditions is also addressed by Subramanian (2012) who deployed so called 'blended method' (Beck and Sun, 2011) based on 2D body exact slender body theory in time domain. According to the author, a time dependent instantaneous wetted body surface is used for a prediction of the wave loads consequently allowing simultaneous capture of high frequency seakeeping and low frequency maneuvering performances of a ship. At this point it should be noted that

Shao and Faltinsen (2010) developed 3D body-fixed panel method in time domain capable to address 2nd order diffraction/radiation problems with a current or small forward speed of the object (ship) in regular waves. In addition, the authors discussed capabilities of the method in the context of combined maneuvering and seakeeping of an advancing displacement type of ship with small forward speed. Continuously increasing modern computational software and hardware capabilities over the past decades gradually led to development of the Computational Fluid Dynamics (CFD) methods which are nowadays able to address the unsteady (regular) wave problems. However, from a particular perspective of a maneuvering ship in a seaway the unsteady CFD techniques based on the Unsteady Reynolds-Averaged Navier-Stokes Equations (URANSE) and continuity equation sufficient to describe all physical features of the fluid flow around the ship hull are still considered as a subject of research than the state of the art in industry, i.e. engineering practice (Peric and Bertram, 2011; ITTC, 2011; Bertram 2012). There are several reasons for that. The most important are associated with the complexity of the fluid flow which is now viscous and rotational in comparison to above discussed potential fluid flow models, time dependent free surface geometry and effects, adequacy of the selected turbulence models, adequacy of the propeller(s) and rudder model under large angle of attack, appearance of the crossflow shed vortices. In addition to stated factors it should be recognized that URANSE methods require large computational resources and long CPU time.

2. COMBINED MANEUVERING AND SEAKEEPING ANALYSIS

The objective of the present section is to provide insight into the specific features of the above introduced theoretical methods. In particular, focus is given to methods based on the convolution integral, two-time scales approach and URANS CFD analysis since they nowadays constitute majority of the methods capable to address complex analysis of a ship maneuvering in a seaway. For each of the outlined group the advantages and disadvantages will be discussed and correspondingly exemplified where appropriate. By doing this the requirement for the real time simulation and accuracy within the engineering practice is kept in mind.

A. Convolution Integral model

The convolution integral approach in solving the maneuvering and seakeeping problem simultaneously was most probably first introduced in work by Bailey et al. (1997). Soon followed by other authors, among whom Schoop-Zipfel and Abdel-Maksoud (2011) are one of the recent, the original linear convolution integral model by Bailey et al. (1997) experienced several changes which consequently over the past decade contributed to better verification and validation of the model. Those together with the main features of the method can be summarized as follows.
First and probably one of the most important modifications is related to more accurate estimation of the nonlinear hydrodynamic loads when the maneuvering ship advances with moderate forward speed (Froude numbers Fn <= 0.25) through the regular wave field. The nonlinear effects are accounted for in the restoring matrix and Froude-Krylov loads by taking into consideration exact ship wetted surface geometry, as determined by the intersection of the undisturbed incident regular wave and the instantaneous position of the ship (draft, trim and heel). This in turn significantly improves consistency and accuracy of the Bailey et al. (1997) model since their model in its original formulation accounted only for the nonlinear effects in the restoring loads. However, at this point it should be noted that although the introduced modifications are nowadays contributing positively toaccuracy of the convolution integral models their consistency concerning the nonlinear effects is not completely satisfied. This is because the described models do not account for all nonlinear effects which are normally present in the direct pressure integration method by Faltinsen et al. (1980) used in the unified two time scale maneuvering and seakeeping model developed by Skejic and Faltinsen (2008) described the text which follows. In spite of this, the authors such as de Kat (1994), Beck and Reed (2001) and recently Belknap (2008) and Beck and Sun (2011) argued that the models are sufficiently adequate for the engineering applications since they capture the most significant nonlinear excitation load effects in regular waves from the time-varying ship wetted surface point of view. The stated approach according to author knowledge is currently adopted practice during formulation of the linear convolution integral based models for combined seakeeping and maneuvering analysis.

Next important feature of the linear convolution integral models is that the models need accurate estimation of the (impulse response) retardation functions. Their accuracy depends strongly on the asymptotic behavior and limiting (zero and infinite) values of either the encounter frequency dependent maneuvering body fixed added mass or damping coefficients. The presence of the forward speed (loss) introduces additional difficulties in the evaluation of the retardation functions (Skejic, 2008). The first order excitation forces/moments need to be transferred also into time domain by means of Fourier transform (Newman, 1992;Skejic, 2008). Because they change with changing encounter frequency (change of ship speed and heading angle), the evaluation of the response impulse functions associated with the first order wave forcing will be frequently executed. Consequently this fact together with direct evaluation of the convolution integrals will increase the CPU time and the maneuvering simulation is difficult to execute in the real time.

This is especially true in situations when the models are going to be applied in realistic irregular wave field scenarios. However, the difficulties associated with the CPU time and real time simulation can be reduced to some extent if one decides to employ the low order state-space evaluation of the convolution integral terms (see for instance Kristansen and Egeland, 2003; and Perez and Fossen, 2008) instead of a direct approach. Obviously, this in turn will require understanding of the type, magnitude and behavior of error(s) due to introduced approximation so that the accuracy of the theoretical model within the engineering practice will not be compromised.

In conclusion of this section let us point out that linear properties of the convolution integral model may cause inadequate prediction of the forward speed drop of a maneuvering ship when she experiences significant changes in the heading angle. In this situation, as shown by Skejic and Faltinsen (2008, 2013), the ship maneuver starts to be affected by gradually growing temporal nonlinearities which will strongly influence the prediction of the involuntary speed reduction and consequently the ship maneuvering path. This is especially true for the tight circle maneuvers or maneuvers with large rudder angles, Abkowitz (1964). Therefore in these kinds of maneuvers the nonlinear convolution integral formulation will be required (see for instance Hasselmann, 1966; Neal, 1974) which, as can be expected, will be quite hard task to accomplish if for instance one of the tasks is to satisfy the real time simulation scenario.

B. Unified Two-Time Scale model

The maneuvering behavior of an advancing displacement ship in regular deep water waves can be also described by considering combined seakeeping and maneuvering as a two–time scale problem (Skejic and Faltinsen, 2008). The linear wave induced motions of a ship are assumed to occur on a more rapidly varying time scale than the maneuvering. When the ship has a mean forward speed and does a maneuvering in a seaway, the wave–frequency problem is affected by the slowly–varying maneuvering. On the other hand, the effect of the seakeeping on the maneuvering analysis is in terms of slowly varying mean 2nd wave loads that account for the changing ship speed and wave heading as shown in Fig. 2 part a).

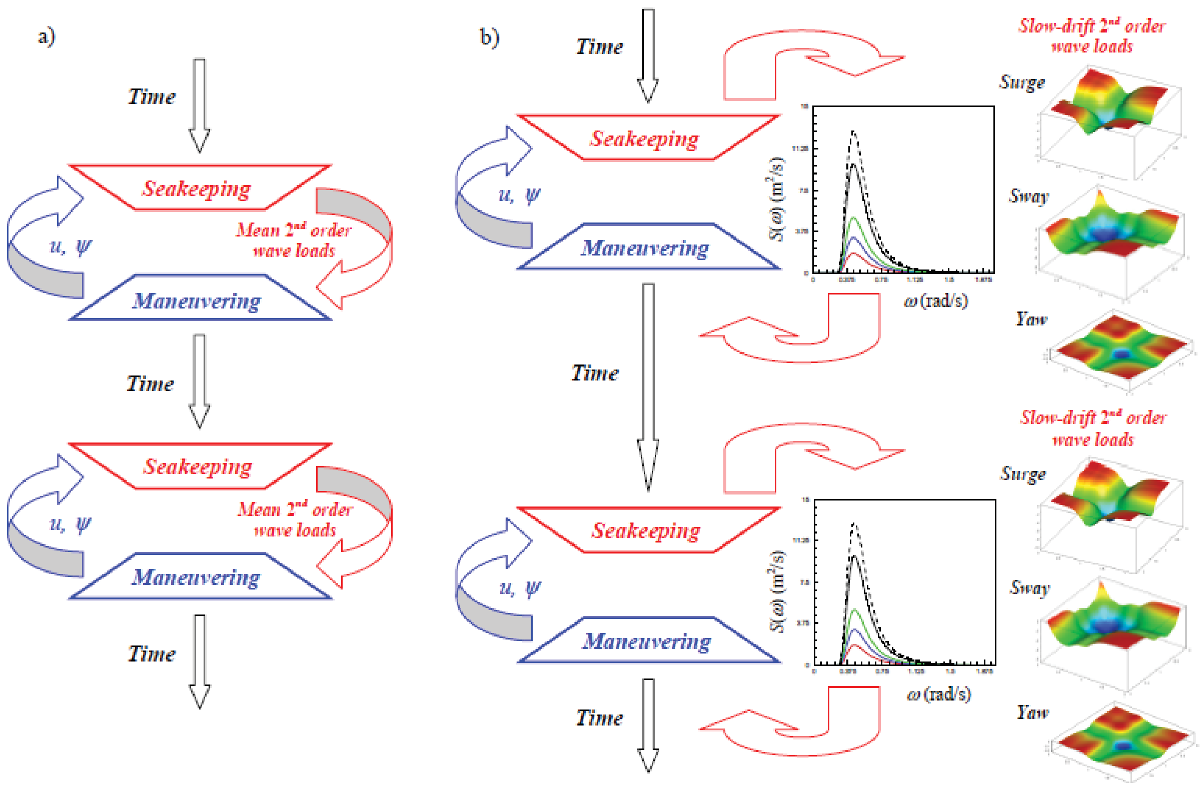

Fig. 2. Unified two-time scale seakeeping and maneuvering model - communication between the time scales: a) regular waves, b) irregular waves.

In the past couple of years up to the present time the two-time scale model experienced its validation in regular wave field scenarios defined with the preselected wavelength values covering the complete wavelength range of interest for a maneuvering ship in a seaway (Yasukawa, 2006; 2009). Furthermore, the model has been improved from the perspective of evaluation of the mean 2nd order regular wave loads in the horizontal plane with application of 3D boundary element method (Yen et al., 2010; Seo and Kim, 2011). More recently, Prpić-Oršić and Faltinsen (2012) extended the model for irregular waves while addressing the problem of ship involuntary speed drop in a seaway when the advancing ship with zero rudder and heading angles is operating in head (bow) waves. The applicability of two-time scale model for irregular waves was further expanded by Skejic and Faltinsen (2013) who account for the arbitrary ship maneuvers in irregular wave field scenarios according to long-crested 2D spectral

Irregular wave field scenarios: $H_{1/3}$ = 7.0 m, T_2 = 10.0 s with **Seeds:** S_1 = 123457,

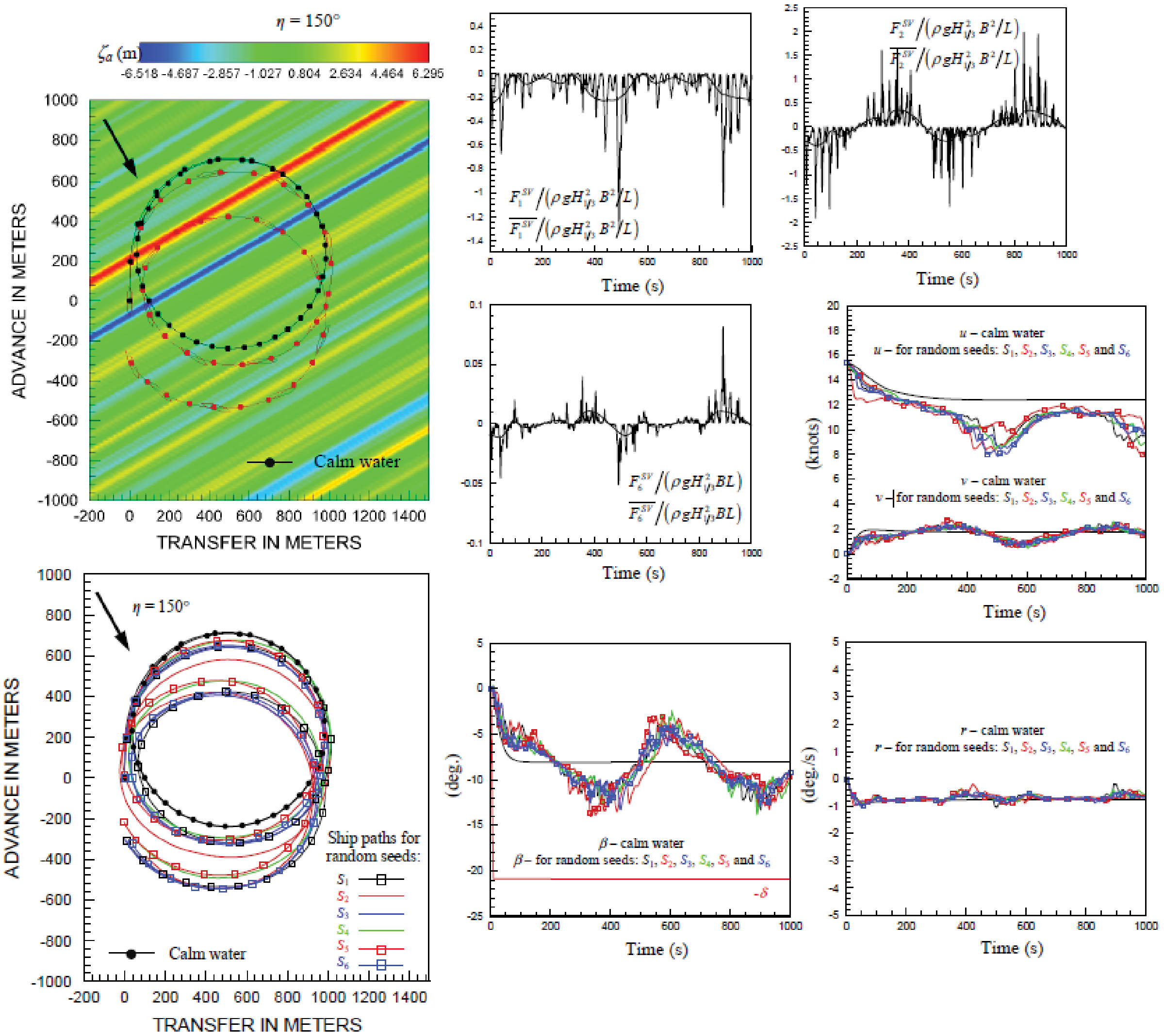

Fig. 3. 'MARINER' hull with 20.9° starboard-turn maneuver in deep-water irregular long-crested wave field condition with significant wave height $H_{1/3}$ = 7.0 m and mean wave period T_2 = 10.0 s according to ISSC spectrum formulation ITTC (1978) with different random seeds (S_i; i = 1, ..., 6) of random wave phase angles $\varepsilon \in [0, 2\pi]$. Irregular waves direction angle is η = 150° and the ship approach forward speed is 15.4 knots. Seakeeping computations at intervals $\Delta\psi_c$ = 3°. Initial position of the 'MARINER' hull in Earth-fixed coordinate system $OX_EY_EZ_E$ is (0 m, 0 m) and the ship heading angle is ψ = 0°.

formulation of a seaway with predefined incident wave direction. The wave loading upon the maneuvering ship has been estimated by slow-drift 2nd order wave loads in the horizontal plane according to Newman (1974) approximation as shown in Fig. 2 part b).

For the illustrative example of the maneuvering displacement type of a ship in irregular waves the author of the present work decided to present here one part of the numerical studies carried out in Skejic and Faltinsen (2013). Fig. 3 shows how the irregular wave effects are manifesting itself in respect to maneuvering trajectory of a 'MARINER' type of a ship and associated ship's main maneuvering parameters. As can be seen from the figure the drift of the ship is in direction of imposed wave direction η as it can be normally expected and the ship path behavior is quite similar to that one in regular wave conditions. However, on the other hand behavior of the slow-drift 2nd order wave loads in time is quite different from distribution of mean 2nd order wave loads in regular wave field (see Skejic and Faltinsen, 2008). Later ones have a significantly smoother behavior in comparison to former ones. In spite of this, as figure shows, it seems that the effect of rapidly (oscillating) time varying slow-drift 2nd order wave loads has negligible effect upon the ship maneuvering path. This, however, is not a case for the rest of maneuvering parameters such are the ship speeds u, v and r, and drift angle ® which clearly indicates that it will be completely wrong to generally conclude that the ship is totally insensitive to mentioned oscillatory behavior of the irregular wave loading effects. In addition, the presented results illustrate presence of the statistical uncertainness caused by the presence of random wave phase angles (see lower left part of Fig.3) and consequently indicate a need to propose statistical averaging procedure which will according to author believe lead to reliable prediction of ship maneuvering simulation in irregular wave field scenarios.

C. CFD approach

As an alternative to the previously described models, the CFD based methods may be employed for a prediction of ship maneuvering performances in a seaway. They solve the basic field (fluid domain) equations subject to boundary conditions by approaches involving a large number of (mathematically 'relatively simple') 3D (control volume) elements. As can be expected the direct consequence of this is that the CFD based methods are in the same time computationally demanding and time consuming.

The most adequate CFD technique for hydrodynamically ship orientated problems is based on the Finite Volume Method (FVM) (Peric and Bertram, 2011; Bertram, 2012). In comparison to Boundary Element Method (BEM) techniques (discussed above) which discretizes the boundaries of the hydrodynamic problem of interest, the FVM is commonly called ‘field method’ since it employs discretization of the whole fluid domain. In particular, the FVM based on URANSE and usage of the unstructured (Chimera) grids seems to be most adequate and promising to solve unsteady ship maneuvering problem in imposed wave field conditions. Furthermore, the method, as shown already for instance by Carrica et al. (2010), is capable to account for rudder(s)-propeller(s)-(single) hull interaction while, the water (and air in 2 phase flow) viscosity effects are accounted for through utilization of the adequate (most frequent k-ε, k-ω) turbulence models and pressure-velocity couplings (SIMPLE or PISO schemes) (see for instance Ferziger and Peric, 2010; Bertram, 2012).

In the present stage of development and from the perspective of wave environment, the research activities related to application of the CFD URANS methods are carried out mainly for the scenario when the ship (with zero rudder angle) is advancing forward along the straight line in the 'pure' regular wave field environment. The ship usually has preselected number of degrees of freedom (DOF) in the (most frequently) vertical plane or she is completely restrained in order to reduce the complexity of the unsteady problem. As an illustrative example of the mentioned case one part of the results from Chen and Yu (2008) and Peric and Bertram (2011) is presented here in Fig. 4.
As can be seen from the figure, the fluid flow around the ships is very complex with appearance of the green water on deck and breaking waves. This in turn, from a general point of view, indicates that the higher attention should be given to the understanding of physics behind the problem. In addition, sufficient care should be given to CFD preprocessing process (adequate discretization of the fluid volume and set up of the initial and (periodic) boundary conditions) before the CFD URANSE solver is employed in order to achieve the convergence and reduce uncertainty in the results.

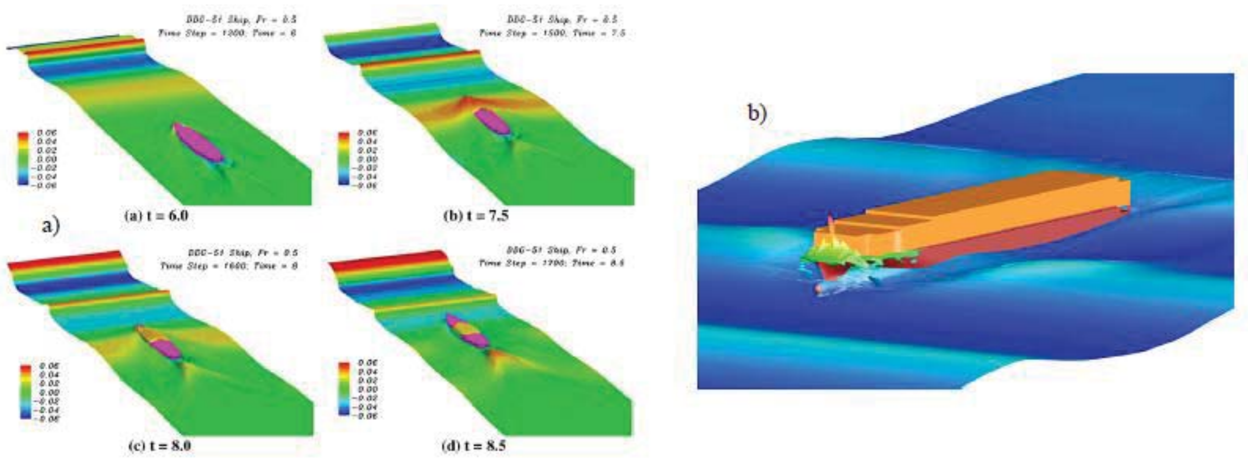

Fig. 4. CFD URANS application in (bow) head sea conditions (regular waves). a) Free surface elevation contours around advancing DDG-51 ship at Froude number Fn = 0.5, Chen and Yu (2008); b) Simulation of the fluid flow around the ship (both motion and deformation of ship are accounted for), Peric and Bertram (2011).

In case of an advancing ship on an arbitrary course and regular wave field the problems with the spatial (insufficient mesh resolution, mesh skewness and non-orthogonally) and temporal (numerical diffusion) discretization (see for instance Jasak, 1996, and Jacquin et al., 2006), the uncertainty in the results and their disagreement with the experimental data are likely to be increased.

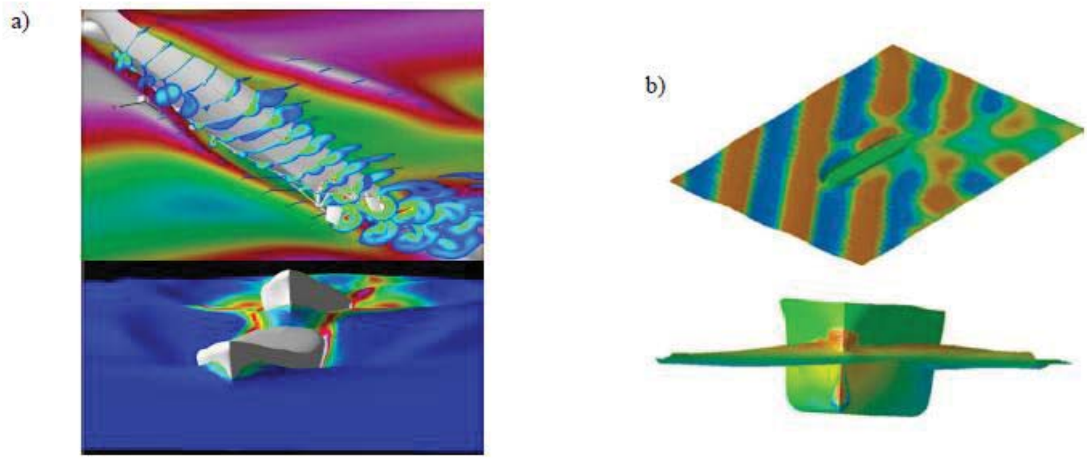

Fig. 5. CFD URANS application in turn maneuver in regular waves - asymmetry of the free surface elevation and fluid flow (shed vortices) around a) US Navy Combatant, DTMB 5415 during execution of turn maneuver, Stern (2008), b) SR108 ship, Akimoto (2010).

However, this is normally to be expected since the fluid flow around the ship hull in comparison to previous described scenario is much more complex and not any more longitudinally symmetric like mentioned previously. In spite of this, first successful research works related to maneuvering of ships in regular waves started to appear in last five years period. For example Fig. 5 illustrates the results for US Navy Combatant, DTMB 5415 and SR108 ship obtained by Stern (2008) and Akimoto (2010), respectively where the asymmetry of the fluid flow and presence of the shed vortices is clearly shown.

From above presented discussion it can be concluded that the tendency of unsteady CFD analysis is clearly to move towards the goal where it will be able to carry out the fully unsteady 6 DOF numerical simulations of a maneuvering ship (with forward speed) in (preselected) regular waves and to take naturally into account the viscous effects of the fluid flow around the hull (and appendages), the wake in the propeller plane, and the nonlinear interaction effects in the single hull-propeller-rudder configurations. In fact, one of the first attempts in this direction is carried out by Carrica et al. (2008). However, although it can be expected that the stated goal will be realistically achievable in the upcoming time period, one should be aware of the fact that the related investigations will be still mostly confined to the research communities worldwide and not to the industry (engineering) related sector. The main reason for this obviously lays in the complexity of combined seakeeping and maneuvering problem which requires in the same time high expertise (physical understanding of the problem) and large computational resources frequently beyond single or limited group of developers and/or users. Consequently, this in turn suggests that fulfillment of the real time simulation requirement is hardly to be satisfied from a realistic point of view.

In closure of this subsection, it should be stressed out that for the analysis of a maneuvering ship advancing forward on an arbitrary course through the irregular wave field one can expect that the application of current CFD URANS based methods is hard task to achieve when the solution of the fluid flow and rigid body (ship) is going to be simultaneously analyzed. In fact, there is currently only one research study, according to author knowledge, carried out by Carrica et al. (2008) who addressed the particular broaching event in the context of a maneuvering ship in a seaway. This in turn indicates that nowadays CFD URANS methods, in spite of their constant and strong development in the past decade, are still in their research phase concerning the maneuvering analysis of ships in waves.

3. Propulsive coefficients in a seaway

Present section will shortly emphasize the importance of propulsive coefficients, i.e. the thrust deduction t and the (effective) wake fraction w coefficient from a perspective of maneuvering performances of a displacement type of (single hull) ship in accordance to IMO maneuvering standard and requirements (Faltinsen, 2005).

It is a well know from the theoretical and experimental investigations of ship maneuvering performances in calm (and deep/shallow) water environment that the variation of the mentioned coefficients affects the propeller design and, as well as, the maneuvering trajectory of a ship, respectively (see for instance Kijima et al., 1993; Faltinsen, 2011). Knowing for this fact it is normally to ask ourselves what is happening, both quantitatively and qualitatively, with the stated propulsive factors due to presence of the waves when the ship executes maneuvers in a seaway. As shown experimentally by Nakamura and Naito (1977) and theoretically by Faltinsen et al. (1980) and Faltinsen and Minsaas (1984) and more recently by Hinatsu and Hino (2002) the wake fraction w, the thrust deduction t coefficient and the propeller propulsive coefficients are all affected by the presence of waves, occurrence of ventilation and immersion of the propeller. Furthermore, although the work of mentioned authors was carried out for a (bare single hull) ship advancing on the straight line course and experiencing deep water head (ship bow) incident regular waves (the flow field around the ship was longitudinally symmetric) it revealed that the propulsive coefficients are depended on the wave height and pitch natural period.

The longitudinal symmetry of the fluid flow cannot be normally a case for a maneuvering ship in waves since the ship heading (incident wave direction) is changing temporally and the consequence is, as expected, asymmetric flow field from the perspective of the ship vertical plane of symmetry. Obviously, due to this, the propulsive coefficients mentioned above will be affected and consequently the ship maneuvering parameters including the ship trajectory will be influenced. In addition, it should be noted that the complexity related to estimation of the propulsive coefficients will be additionally increased if the complete (single hull) ship, single propeller and single rudder configuration is accounted for due to presence of time dependent spatial changes associated with the mesh generation (discretization) of geometries (free surface plus rigid bodies) considered in the problem as illustrated in Fig. 6 related to application of CFD URANS methods.

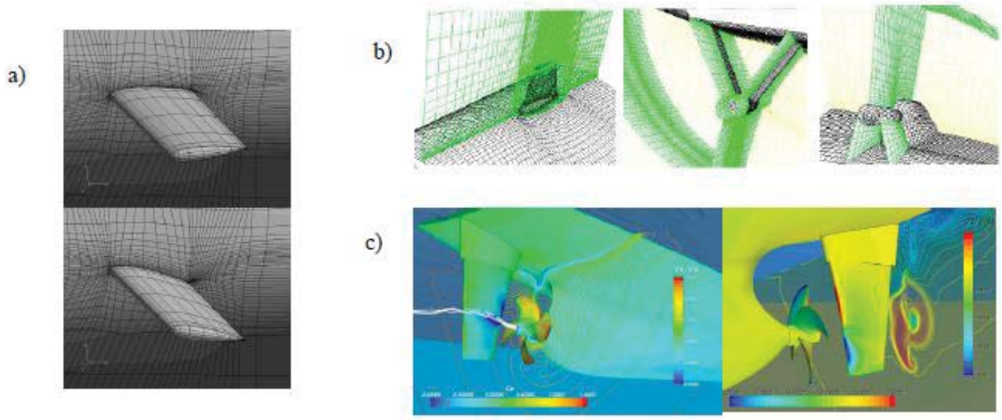

Fig. 6. CFD URANS model: The examples of time dependent grid topology around the ship appendages and theoretical predictions. a) Jacquin et al. (2006), b) Zhang et al. (2006), c) Peric and Bertram (2009).

In conclusion, judging from the importance of the mentioned coefficients in the context of calm water maneuvering and/or combined maneuvering and seakeeping analysis discussed above, it should be noted that further investigations in mentioned direction are needed in order to obtain more reliable and accurate predictions of maneuvering simulations in the future.

4. Concluding Remarks

The present work describes status of nowadays mostly adopted theoretical methods capable to address the complex problem of a maneuvering displacement type of a ship in a seaway. The methods are generally classified into the potential fluid flow theory based methods and CFD unsteady methods which accounts for the viscosity effects. Their advantages and disadvantaged are discussed from the perspective of single hull-propeller-rudder configuration, real time simulation requirement and predefined regular or irregular wave field environment which is surrounding the maneuvering ship. In close relation to this, it was stressed out that present unsteady CFD methods in the context of combined seakeeping and maneuvering analysis of ships in waves need further improvements in order to reach the level of their industrial (engineering) applicability. Finally, the importance of the propulsive coefficients which are influencing the ship maneuvering behavior in a seaway was outlined and necessity for their further theoretical and experimental investigation has been pointed out.

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