THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING IN SHIPPING AND MARINE TECHNOLOGY

Improved Power Predictions of Ships Using Combined CFD/EFD Methods for the Form Factor

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ABSTRACT

Performance prediction of a ship is one of the most important tasks during the design phase. Once the design is finalized, the speed attained at a certain power consumption has to be verified with the most accurate prediction as it is specified at the contract of a new ship order and also required by the legal authorities. Considering the current commercial tendencies and the requirements enforced by legal authorities, towing tank testing and the extrapolation methods recommended by the International Towing Tank Conference (ITTC) are used and regarded as a highly accurate power prediction methodology for common cargo vessels. However, some aspects of this methodology have been questioned such as the scale effects on the form factor and its determination method.

It is argued in this thesis that if a part of the Experimental Fluid Dynamics (EFD) based measure or the extrapolation procedure causes higher uncertainty than the numerical uncertainty and modelling errors of a Computational Fluid Dynamics (CFD) application, the corresponding part of the performance prediction method can be replaced or supplemented by CFD. In this study, the possibility to improve the power predictions by the introduction of a combined CFD/EFD Method was investigated by replacing the experimental determination of the form factor with double body computations based on the Reynolds-Averaged Navier-Stokes (RANS) equations, i.e. CFD based form factors.

As a result of a joint, study where the double body simulations performed with seven different CFD codes, the CFD based form factors compared well with the experimentally determined form factors. Additionally, the standard deviations of the CFD based form factors were similar to the experimental uncertainty of the form factors even though the abundance of unsystematically varied methods and grids.

Following the Quality Assurance Procedure proposed by the ITTC, a best practice guideline has been derived for the CFD based form factor determination method by applying systematic variations to the CFD set-ups. After the verification and validation of the CFD based form factor method in model scale, the full scale speed-power-rpm relations between large number of speed trials and full scale predictions were investigated using the CFD based form factors in combination to the ITTC-57 line and the numerical friction lines. It is observed that the usage of CFD based form factors improves the predictions in general and no deterioration in the prediction accuracy is noted within the limits of this study. Therefore, the combination of EFD and CFD is expected to provide immediate improvements to the 1978 ITTC Performance Prediction Method.

Keywords: CFD, Combined CFD/EFD Methods, form factor, numerical friction line, measurement uncertainty, verification and validation, power prediction

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LIST OF PUBLICATIONS

This thesis consists of an extended summary and the following appended papers:

Paper I	K. B. Korkmaz, S. Werner, and R. Bensow. “Numerical Friction Lines for CFD Based Form Factor Determination Method”. *VIII International Conference on Computational Methods in Marine Engineering MARINE 2019*. Göteborg, Sweden, 2019
Paper II	K. B. Korkmaz, S. Werner, and R. Bensow. “Investigations for CFD Based Form Factor Methods”. *Numerical Towing Tank Symposium (NuTTS 2019)*. Tomar, Portugal, 2019
Paper III	K.B. Korkmaz, S. Werner, N. Sakamoto, P. Queutey, G. Deng, G. Yuling, D. Guoxiang, K. Maki, H. Ye, A. Akinturk, S. Sayeed, T. Hino, F. Zhao, T. Tezdogan, Y.K. Demirel and R. Bensow. ”CFD Based Form Factor Determination Method”. *Accepted for publishing in Ocean Engineering*
Paper IV	K.B. Korkmaz, S. Werner and R. Bensow. ”Verification and Validation of CFD Based Form Factors as a Combined CFD/EFD Method”. *submitted to Journal of Marine Science and Engineering*

Contents

1 Introduction

Performance prediction of a ship is one of the most important tasks during the design phase. The required confidence level for the prediction of speed-power-rpm relations increases as the ship design progresses towards the end. The final design must be verified with the most accurate prediction method since the contract speed, which is the speed attained at a certain power consumption in a speed trial run, is specified at the contract of a new ship order. In the case that the speed power prediction is too optimistic and the speed attained at the trial run does not meet the specifications, a penalty is enforced to the yard depending in the terms in the contract. On the other hand, too conservative predictions will be a lost order. Therefore designers are under a pressure of being just within the limits [27]. In addition to rising competitiveness of the market, the legal authorities led by the International Maritime Organisation (IMO) have also been taking steps towards reinforcing the energy efficiency of ships due to environmental concerns. Therefore, the significance and the demand on a higher accuracy of the power predictions are increasing ever more.

Methods for prediction the speed-power relation emerged over a century ago. The last breaking point for the highly accurate power prediction methods occurred approximately four decades ago as a result of the remarkable joint efforts of many institutions led by the International Towing Tank Conference (ITTC). The introduction of the 1978 ITTC Power Prediction Method [15] led to standardized towing tank testing practices and extrapolation procedures. Since its introduction, several modifications have been applied to the ITTC-78 method, however, the bulk of the assumptions and the formulations remained the same.

Considering the majority of commercial tendencies presented by shipyards and ship owners, towing tank testing is still considered as the last step of the performance prediction. Legal authorities also consider towing tank testing as a mandatory step in their evaluations such as EEDI calculations as enforced by the IMO [10] where the applicable ships must go through the pre-verification by model testing during the design phase of a new ship. However, there are inherent and well known shortcomings due to scale effects since the model tests are carried out at Froude similarity while Reynolds similarity cannot be fulfilled simultaneously. In order to limit the effects of the shortcomings, towing tank facilities must rely on experience and large databases of both model tests and sea trials.

The endeavour towards improved prediction methods have been continuing with mainly focusing on Computational Fluid Dynamics (CFD) as it can handle the scale effects experienced by the Experimental Fluid Dynamics (EFD). Since 1980s when the "numerical methods started to become really useful in ship design" [26, p. 2], the development of the Reynolds Averaged Navier-Stokes (RANS) based methods have been continuing. However, the verification and validation (V&V) of CFD methods have been performed overwhelmingly in model scale instead of full scale mainly due to lack of full scale experimental data. Therefore, it is hard to advocate the maturity of CFD computations for the full scale computations with the limited CFD studies in the literature unlike the computations in model scale which has been thoroughly verified and validated for decades.

An alternative method is to combine the CFD and EFD on their strong points instead of choosing one or the other. As identified by the ITTC Specialist Committee on the

Combined CFD/EFD Methods, if a part of the extrapolation procedure or the towing tank tests causes higher uncertainty than the numerical uncertainty and the modelling errors of the CFD applications, the accuracy of the power predictions can be expected to increase. In the 1978 ITTC Performance Prediction method, the form factor has been identified by the Specialist Committee as a major cause of uncertainty, due to the EFD based Prohaska method [31] for the form factor determination and the scale effects on form factors for the determination of full scale resistance of ships. The double body RANS computations are suggested as an alternative or supplementary method to the Prohaska method as the double-body computations are able to replicate the appropriate conditions described in the original form factor hypothesis [9] while being relatively simple in numerical implementation. As the ITTC Specialist Committee on the Combined CFD/EFD Methods suggests, combination of the well accustomed, verified and validated methods can introduce immediate improvements to the 1978 ITTC Performance Prediction Method.

1.1 Purpose

The main purpose of the work behind this thesis has been to formulate a sound basis for the applicability of the CFD based form factors and to demonstrate how combined EFD/CFD methods can introduce improvements to today's procedures. Based on the holistic analysis performed on the formulation of an effective CFD method, determination of the experimental uncertainties in form factor determination and finally sea trial analyses, the ultimate goal of this thesis is to replace the current power prediction procedures with the proposed combined EFD/CFD methods: CFD based form factors.

2 Extrapolation Methods

Experimental Fluid Dynamics (EFD) has been utilized by the towing tanks to generate a specific data set unique for a hull form and its propulsive arrangement. Such data set is then used for predicting the performance of a ship in deep and calm water. The prediction for the full scale ship has to be made in the form of extrapolation since the data set belongs to the model tested in towing tank where Froude and Reynolds similarities cannot be fulfilled simultaneously. The extrapolation procedures of William Froude pioneered the way towards reliable and highly accurate methods for power predictions for ships in the 1870s by implementing a set of assumptions and testing techniques. In the following decades, the International Towing Tank Committee (ITTC) was founded in 1933 to standardize and improve the model testing practices and extrapolation procedures.

In the early prediction methods, the power and propeller turning rate were predicted by scaling the self propulsion tests and using simple overall correction factors [28]. A survey conducted by ITTC [14] in 1969 showed that the prediction methods used by most of the institutions were diverse in the way of implementing newly emerging concepts and formulas such as form factor, friction line, wake scaling and roughness allowance. As a result, the Performance Committee recommended to "compile and compare the various procedures and attempt to formulate a common method with a sound physical basis for future ship-model correlation studies" [14]. An important step towards this recommendation was taken in 1973 when computer programs with different assumptions and extrapolation methods were created by SSPA as requested by the ITTC [28]. Ten institutions within ITTC evaluated each method by comparing the power and propeller turning rate predictions with the speed trials [15]. The 1978 ITTC Performance Prediction Method emerged as a result of the joint effort of comparing approximately one thousand sea trials with model test predictions. After several revisions applied to the originally recommended method such as updating the roughness allowance by replacing the previous formulation with Townsin and Dey [37], introducing a new correlation allowance formulation [16] and modification of the calculation of air resistance [17], the ITTC-78 method [18] is still in effect after 42 year.

In this study, the ITTC-78 method [18] is used to extrapolate the towing tank test results to full scale. The full scale resistance of a ship is described as,

$$C_{\mathrm{T}} = (1+k)C_{\mathrm{FS}} + \Delta C_{\mathrm{F}} + C_{\mathrm{A}} + C_{\mathrm{R}} + C_{\mathrm{AAS}} \ , \tag{2.1}$$

where k is the form factor, C_{FS} is the frictional resistance coefficient in full scale (the subscript 'S' signifies the full scale ship), C_{R} is the residual resistance coefficient, ΔC_{F} represents the roughness allowance, C_{A} is the correlation allowance and C_{AAS} is the air resistance coefficient. The key components in the determination of the full scale resistance: the form factor concept and the friction line will be reviewed with their historical backgrounds in Section 2.1 and Section 2.2.

2.1 Friction Line

The frictional resistance coefficients have been one of the most debated aspects of the early prediction methods since they were based on the Froude method which obtained the residual resistance as,

$$C_{\mathrm{TM}} = C_{\mathrm{R}} + C_{\mathrm{FM}} \ . \tag{2.2}$$

Eq. 2.2 assumes that the frictional resistance of a ship is equal to that of the equivalent flat plate and the rest of the total resistance apart from C_{FM} is the residual resistance which is equal in model and full scale. As a result of this assumption, the frictional resistance had a decisive importance on the final predictions. As reported in the Skin Friction Report of ITTC [12], before 1948 the European towing tanks used the method and coefficients of Froude, while the Schoenherr formulation [34] was adopted by the American Towing Tank Conference (ATTC). As a result of the 5th ITTC, the opinion was unanimously in favor of leaving the Froude's coefficients but no unanimous agreement was made to accept any other particular line as final. Instead, it was agreed that either Froude or Schoenherr line can be used to "make easy the transition of the results from one system to the other" when a final agreement is obtained on a final friction line. No proposals were made for an alternative friction line in the following two conferences, however, a definitive statement for the need for a new friction line given at the Scandinavian Conferences in 1954 [30]. It should be noted that the form factor concept of Hughes [9], which is adopted later in the ITTC-78 method and is still in use today, was proposed with a new friction line in the same year of the Scandinavian conference. As a result of growing disposition to abandon the Froude coefficients and the reluctance to entail the universal use of the Schoenherr line, the Madrid Conference [13] were appointed to formulate a new "conference" line that

1. "must produce, on the average, better correlation among geosim models of a variety of forms at different scales than does the Schoenherr line; and
2. must produce lower smooth-ship resistance in order to avoid the small or negative roughness allowances found for model all-welded hulls when the Schoenherr line is used for prediction of ship resistance" [13, p.73].

The specification mentioned in item 2 describes the main motivation behind the urgent need for a new line: a major shift from riveted hulls to all-welded hulls. The change of ship building technique (welding) and improved surface finish of the hulls reduced the full scale resistance significantly so that the existing extrapolation methods had to apply small or negative roughness allowances to be able to correlate with the sea trials. The item 1 describes the incentive towards a three-dimensional flow analysis instead of using the two-dimensional method, i.e. form factor approach instead of Froude's method. The investigation of the Committee on the existing flat plate and geosim test data did indicate a line that is somewhat steeper than the Schoenherr line [13]. However, satisfying the item 2 predominated in the determination of the steepness of the curve at model scale. The Skin Friction Committee decided that the line given the formula

$$C_{\mathrm{F}} = \frac{0.075}{(\log_{10}(Re) - 2)^2} \tag{2.3}$$

was adopted as the ITTC 1957 model-ship correlation line, "it being clearly understood that this is to be regarded only as an interim solution to this problem for practical engineering purposes" [13, p.324].

In order to demonstrate what was achieved by adopting a line when the Froude's method is used and the C_{F} values of the ITTC-57 and the Schoenherr lines can be compared. At a typical model scale Reynolds number of $\log_{10}Rn = 6.0$, C_{F} from the ITTC-57 line is 2.78×10^{-4} higher than the Schoenherr line. Using the Eq. 2.2, C_{R} will be effectively 2.78×10^{-4} lower when ITTC-57 line is used. Since C_{R} is only dependent on the Froude number and the C_{F} of ITTC-57 and Schoenherr lines are nearly identical at $\log_{10}Rn = 8.0 <$Rn, the full scale total resistance will be 2.78×10^{-4} lower at the corresponding speed when the ITTC-57 line is used compared to Schoenherr line. Note that the commonly used roughness allowance coefficient at that time was constant and equal to 4.00×10^{-4}. Therefore, the full scale smooth-ship resistance predictions were lowered by more than half of the magnitude of the roughness allowance by the adoption of the ITTC-57 line and the specification of a new engineering line was satisfied in general [13].

In the following decades of adoption of the ITTC-57 line, alternative C_{F} formulations have been proposed by Grigson [7] and Katsui et al. [22] who criticized the empirically derived lines as measurements includes inevitable defects such as edge effects and measurement uncertainties. Therefore, Grigson and Katsui lines are analytically derived and the flat plate friction resistance is calculated from the integral form of the two-dimensional boundary layer equations in zero pressure gradient similar to Coles [1]. Even though the theoretical framework is similar between the Grigson [7] and Katsui [22] lines, the assumed behaviour of Coles' wake parameter [1] varies between the two lines through the Reynolds number range, and therefore leading to significantly different friction lines.

Eça and Hoekstra [4] and Wang et al. [39] derived friction lines by numerical calculation of the frictional resistance coefficients of an infinitely thin plate. A similar study is presented in Paper I where the computations were performed at Reynolds numbers from typical model to full scale using Reynolds Averaged Navier Stokes (RANS) equations and two turbulence models. The curve fits applied to the computed data points at different Re. Hence, Numerical Friction Lines (NFL) are obtained for $k - \omega$ SST and EASM turbulence models. NFLs derived in Paper I are compared with ITTC-57 line [13], Schoenherr [34], Hughes [9], Toki [36], Katsui [22], Grigson [7] and the two numerical friction lines proposed by Eça and Hoekstra [4] and Wang et al. [39]. In Figure 2.1 the friction lines are presented relative to the NFL of $k - \omega$ SST in order to enhance the visual visibility. As can be seen from Figure 4, the $k - \omega$ SST lines of by Eça and Hoekstra [4] and Wang et al. [39] are within ±2% of the C_{F} values obtained in Paper I of the same turbulence model at all Reynolds numbers. All numerical friction lines lead to lower C_{F} values than the other lines at the model scale Rn but the discrepancy between all lines is reduced considerably in full scale Rn except the Hughes line which shows lower C_{F} values throughout the whole Rn range.

Even though the ITTC-57 line was intended as an interim solution, it remained in the extrapolation procedures including the up to date recommended ITTC-78 Power Prediction Method [21]. The investigations conducted by Toki [36] showed that the expected gain by the revision of the ITTC-57 line in the ITTC-78 method is limited.

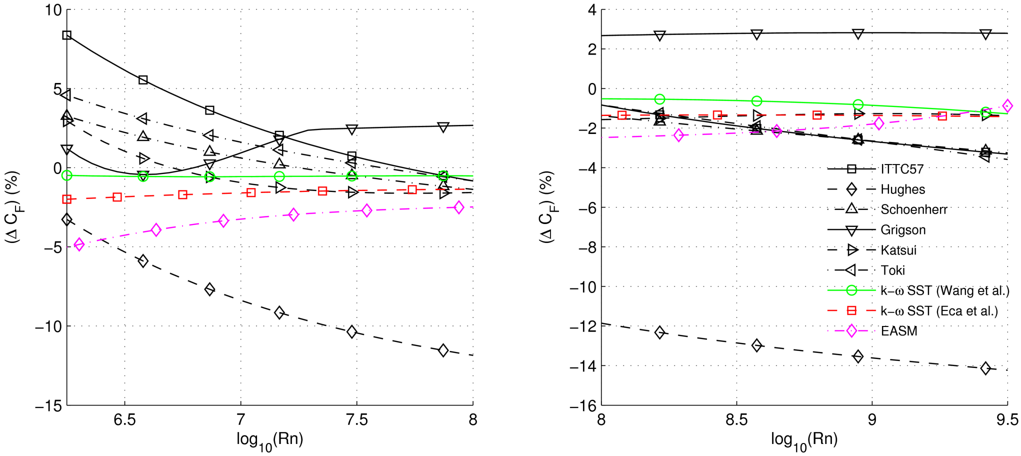


Figure 2.1: *Friction lines in comparison to numerical friction line of SHIPFLOW with* $k-\omega$ *SST turbulence model, from study conducted in Paper I*

Additionally, changing the friction line is likely to require changing the well accustomed correlation factors of each institution as well.

2.2 Form Factor Concept

The idea of having a separate extrapolator (such as the form factor concept) for each hull instead of relying on a two-dimensional flow analysis (such as the Froude's method) has been long discussed since the early 20th century. In 1954, the Skin Friction Committee [30] stated that the extrapolation of resistance from model to ship scale should take account of the effects of three-dimensional flow, and a suitable smooth turbulent friction line must be generated. The argument for three-dimensional flow can be easily justified because the frictional resistance of an actual curved hull surface cannot, in general, be equal to that of the two-dimensional frictional resistance of a flat plate. However, the contribution of the three-dimensional shape of the hull cannot be distinguished explicitly in the Froude's assumption shown in Eq. 2.2 but it exists implicitly in the residual resistance as C_{R}=C_{PV}+C_{W} where C_{PV} is the viscous pressure coefficient caused by the shape of the hull and C_{W} represents the wave resistance. Considering that C_{R} is a function of Fn in the Froude's method, C_{R} remains unaltered when the coefficient is scaled from model to ship at the same value of Froude number. ITTC [13] stated that "in the view of the fact that some of the resistance represented by C_{PV} is undoubtedly of a skin friction nature scaling with Reynolds number".

Hughes [9] suggested the separation of the C_{R} into C_{PV} and C_{W} and to scale the viscous pressure resistance with Re on the assumption that C_{PV} is a constant percentage of C_F for any given hull form, leaving on C_W to scale with Froude number. The total resistance formulation suggested by Hughes [9] is

$$\begin{aligned} C_{\mathrm{T}} &= C_{\mathrm{F}} + C_{form} + C_{\mathrm{W}} \ , \\ C_{form} &= k \ C_{\mathrm{F}} \ , \end{aligned} \tag{2.4}$$

where C_{F} is the resistance equivalent to a flat plate, the new term introduced by Hughes [9], C_{form}, is form resistance due to the shape of the hull, C_{W} is wave resistance resistance and k is the form factor. C_{form} is proportional to C_{F} when the flow is turbulent, the given hull is smooth, the flow is free from separation and the hull has a symmetrical form when towed at zero incidence angle. C_{form} is made up of components due to the additional skin friction caused by the curvature effects, the eddy-making and the flow in transverse directions [9].

The form factor concept of Hughes [9] was adopted by the ITTC 1978 Power Prediction Method as the predictions using the three-dimensional analysis showed better correlation to the sea trials [15]. However, the discussions regarding the scale effects on the form factor rarely ever ceased including the 15th ITTC Conference when the ITTC-78 method was accepted [15]. The re-analysis of geosim test data performed by García Gómez [6] and Toki [36] confirmed the scale effects. The model tests performed on geosim families of KVLCC2 and KCS hulls indicated that scale effects were observed on the form factor for both hulls [38]. Additionally, the CFD studies performed by Pereira, Eça, and Vaz [29] showed speed dependency of the form factor larger than the numerical uncertainties. Terziev, Tezdogan, and Incecik [35] indicated that form factors are not only Reynolds number dependent but also varies with the Froude number. The CFD investigations presented by Raven et al. [32]; Wang et al. [39] and Dogrul, Song, and Demirel [2] supported the existence of speed dependency on form factor and indicated that the main cause of the scale effects are due to the "ITTC 57 model-ship correlation line" rather than the hypothesis of Hughes [9]. The speed dependency of the form factors have been also investigated in Papers II, III and IV by computing the form factors at different speeds and using different friction lines including the numerical friction lines derived in the Paper I. The form factors calculated for 8 different tests cases all exhibited speed dependency when the ITTC-57 line was used, however, this dependency nearly disappeared when numerical friction lines were applied except for one test case with mild flow separation. Similar observations were made in Paper III where three different CFD codes were used for the calculation of the form factors of the KVLCC2 and KCS test cases.

2.2.1 Experimental Determination of the form factor

The form factor determination method described by Hughes [9] was challenging and impractical since the speed range for the resistance tests must be lowered to very low Fn and Rn where fully turbulent flow may not be ensured during the tests even though turbulence stimulators are used. Additionally, the worsening accuracy of the measurements at low speeds can hinder the form factor determination of Hughes [28].

Alternatively, Prohaska [31] suggested a simple method to derive the form factor description of Hughes. The wave resistance coefficient, C_{W}, can be expressed as Eq. 2.5

which is the asymptotic expansion formula of wave-making resistance coefficient presented by Inui as cited in [36],

$$C_W = a \times Fr^4 + b \times Fr^8 + c \times Fr^{12} + d \times Fr^{16}\ . \tag{2.5}$$

C_T at model scale at Eq. 2.4 is then expressed together with the Inui's asymptotic expansion formula, Eq 2.5, as

$$C_\mathrm{Tm} = (1+k) \times C_\mathrm{F} + C_\mathrm{W} = (1+k) \times C_\mathrm{F} + a \times Fr^4 + b \times Fr^8 + c \times Fr^{12} + d \times Fr^{16}\ . \tag{2.6}$$

Neglecting the higher order terms of Eq. 2.6 as they are close to zero at low Froude numbers and dividing each side by C_F, the following linear relationship is obtained,

$$C_\mathrm{Tm}/C_\mathrm{F} \approx (1+k) + a \times Fr^4/C_\mathrm{F}\ . \tag{2.7}$$

Prohaska [31] noted that when the results of approximately 200 model tests have been plotted with Eq. 2.7, the $C_\mathrm{T}/C_\mathrm{F}$ values for a great majority of the models plot on straight lines when Fn was between 0.1 and 0.2. However, exceptions such as hull forms with $C_B > 0.75$, twin-screw models with appendages and models with full aft body lines have been identified where the $C_\mathrm{T}/C_\mathrm{F}$ values deviated from a straight line. The exceptions were explained by substantial changes in sinkage and trim during the tests and flow separation [31]. However, the main weakness of the Prohaska method discussed in the literature is the bulbous bow near the water surface and partly submerged bulbous bow in partial loaded conditions which is not mentioned by Prohaska [31] since the model test data used by Prohaska dates back to 1966 and earlier when bulbous bows were not a popular design concept. The detection of flow separation in the model tests and treatment of deeply submerged transoms remain as additional challenges of the Prohaska method.

In Paper III, the two major sources of the uncertainties of the form factor determination caused by the Prohaska method were addressed. The first source of uncertainty is due to the applicability of the Prohaska method to the ships with medium or large bulbous bow. As illustrated in Paper III, $C_\mathrm{T}/C_\mathrm{F}$ values of hulls with large protruding bulbous bows did not follow a straight line within the recommended Fn range due to existence of steep waves that are generated by the bulb. The applicability of the Prohaska method is even less for the the partially submerged bulbs as even steeper waves are generated in the ballast loading condition which is the condition most of the sea trials are performed. Considering that the bulbous bows are now a common feature of the modern ship design, it is hard to advocate the validity and practicality of the Prohaska method for all hull designs and loading conditions.

The second source of the uncertainty caused by the Prohaska method originates from the experimental uncertainty of the resistance tests. As shown in Paper III and IV, the experimental uncertainty of the form factor is larger than the uncertainty of the individual measurement points because of the additional uncertainty caused by the data reduction process of the Prohaska method, i.e. linear regression. Therefore, the measurement uncertainty of the form factor can be substantially large even when the hull lines do not feature a large bulb.

2.2.2 CFD Based form factor determination

The CFD based form factor method considered for the Papers II, II, and IV follows the assumptions of Hughes [9] and is derived using the relation,

$$(1+k) = \frac{C_{\mathrm{F}}^{'} + C_{\mathrm{PV}}^{'}}{C_{\mathrm{F}}} = \frac{C_{\mathrm{V}}^{'}}{C_{\mathrm{F}}} \ , \tag{2.8}$$

where the frictional resistance coefficient ($C_{\mathrm{F}}^{'}$) and viscous pressure coefficient ($C_{\mathrm{PV}}^{'}$) are obtained from a double body CFD simulation as explained in Section 3. C_{F} in the denominator of Eq. 2.8 is the equivalent flat plate resistance in two dimensional flow obtained from the same Reynolds number as the computations. In Papers II, III and IV, the ITTC-57 model-ship correlation line [13] and numerical friction lines presented in Paper I were used, while additionally the Katsui line [22] was included in the analysis of the Paper III.

Some of the drawbacks mentioned in Section 2.2.1 for the Prohaska method also applies to the CFD based form factor method in similar ways such as hulls with large protruding bulbs and submerged transoms. In the case when a large bulb is too close to the still water surface (the mirror plane for the double body simulations), the flow may be overly accelerated and in some cases even be separated around the bulb. Raven et al. [32] suggested that if the bulb is submerged more by trimming the hull bow down, this issue can be prevented. A similar strategy can also be used for a large submerged transom which will cause the flow to be separated behind the ship wake. In Paper II, the loading condition of KVLCC2 and KCS hulls were varied to quantify the sensitivity of the form factor to the changing the sinkage and trim in small steps. The variation of the form factor due to changing the sinkage and trim was limited for both hulls as noted in Paper II. Additionally, the variation between the form factors calculated from the sinkage and trim at rest and the dynamic sinkage and trim was smaller than the numerical uncertainties. Therefore, the suggestion of altering the loading condition in order to prevent the issues due to a large bulb near the water surface and a deeply submerged transom is feasible as indicated in Paper II.

A crucial criteria for the CFD based for factor method to be accepted and widely used would be its applicability by the majority of the CFD codes and the consistency of the predictions between different codes as investigated in Paper III with the contributions from nine organisations with seven different codes. As a result of this ITTC Specialist Committee of Combined CFD/EFD Methods initiated study, it was observed that most of the codes with a certain CFD setup showed consistent patterns of form factor predictions among different test cases. However, different codes indicated varying dependencies on the CFD setups and general recommendations for all CFD setups cannot be made specifically for the sake of form factor determination. On the condition that trends observed in the Paper III are confirmed with more hulls, application of correlation factors (C_{P}-C_{N} or C_{A}) unique for each code and method will be able to reduce the differences in full scale predictions even more.

3 Simulating the double body flow for the CFD Based form factors

This section aims to highlight some important factors of the double body simulations used for obtaining the CFD based form factors through the investigations performed in Papers II, III and IV. The double body RANS simulation for the viscous resistance of a smooth hull is one of the first CFD applications that became available for industrial use [26] because of it being far less complicated than free surface, self propulsion, sea keeping and maneuvering applications. Despite the long term use of the double body simulations and decades of verification and validation (V&V) studies, the plethora of numerical methods available in current CFD codes encumber forming a common Best Practice Guideline (BPG).

In Paper III, the CFD based form factors are calculated and compared with the model test data for the KVLCC2 and KCS test cases. The model scale double body computations were performed by SSPA, Chalmers University of Technology, National Maritime Research Institute (NMRI), LHEEA CNRS Ecole Centrale de Nantes, Shanghai Ship and Shipping Research Institute (SSSRI), CSHL University of Michigan, Ocean, Coastal and River Engineering (OCRE), Yokohama National University, China Ship Scientific Research Centre (CSSRC) and University of Strathclyde with seven different codes, six different turbulence models, varying grid topologies and types with wall functions and wall resolved approaches.

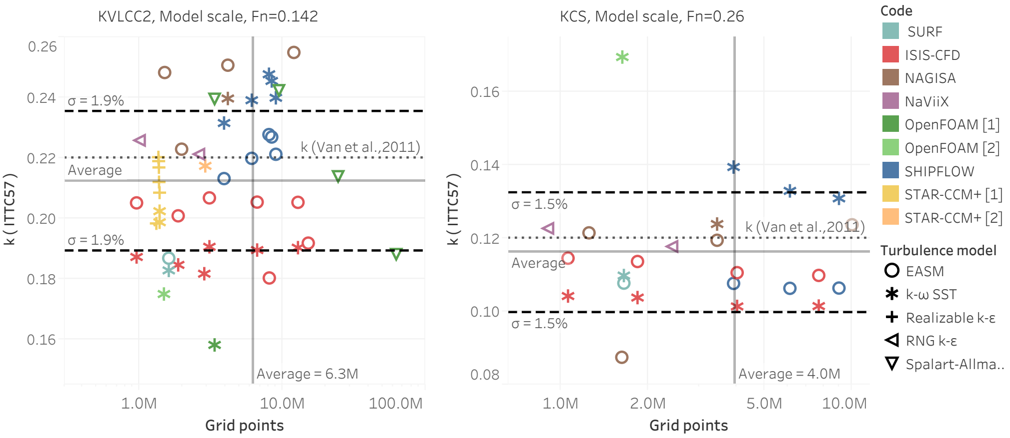


Figure 3.1: *Form factor, k, based on ITTC-57 line versus grid size for KVLCC2 in design loading condition at Fn=0.142 (left) and KCS in design loading condition at Fn=0.26 (right), from the study conducted in Paper III*

The form factor predictions with the ITTC-57 line from the computations with the recommended or standard CFD setups compared well with the experimentally determined form factors for KVLCC2 and KCS in design loading condition at design speeds as presented in Figure 3.1. The form factors from all test cases reported in Paper III indicated 1.5 to 2.5% standard deviation in percentage of $(1+\overline{k})$ even though the abundance of unsystematically varied methods and grids. It should be noted that these standard deviations are similar to the experimental uncertainty of the form factors presented in Papers III and IV. Additionally, the standard deviations on the form factors are in line with the standard deviations of the resistance computations in the Tokyo 2015 Workshop [8]. However, different codes indicated varying dependencies on CFD setups, and therefore general recommendations for all CFD setups could not be made specifically for the sake of form factor determination.

Following the conclusions obtained from Paper III, the investigations presented in Paper IV have been carried out to demonstrate the Quality Assurance (QA) of CFD based form factor method at an organisational level. The new procedure for the Quality Assurance jointly proposed by the two ITTC committees were followed instead of adopting a common BPG and applying a conventional V&V study. Following the first two steps of the proposed QA procedure, a BPG is derived for the CFD based form factor determination method using SHIPFLOW version 6.5 and the QA of the best practice guideline is performed by a V&V analysis.

In the determination of a best practice guideline for the CFD based form factors, systematic variations have been applied to the CFD set-ups such as the grid density, the non-dimensional cell height normal to the wall, additional grid refinement at the stern, domain size and model scale speed were analysed. These variations are applied to six test cases using the turbulence models $k-\omega$ SST and EASM. The observations and recommendations regarding to the derivation of the BPG are summarized in Section 3.1 to Section 3.3. Note that some recommendations may be specific to the SHIPFLOW code and may become outdated due to the modifications on the numerical methods. Therefore, the BPG should be updated when there is a major change in the numerical methods.

3.1 Grid Generation

The grid generator of the SHIPFLOW code, XGRID, is used for the derivation of the best practice guideline. The body fitted structured grids are generated by the parametric definition of XGRID which ensures almost identical grid distribution in the longitudinal and circumferential directions for the most conventional hulls. The grid distribution in the normal direction to the hull varies with respect to Re , therefore, different first cell sizes in the normal direction to the wall and cell growth ratios are obtained to achieve the y^+ target values. The appendages such as rudders and grid refinements are implemented through the overlapping grid technique [33].

Prior to the derivation of the BPG, sensitivity of form factors to the varying grid distributions in the longitudinal direction were investigated in Paper II. The stern and the bow region of the KVLCC2 have been coarsened at a time while the rest of the grid kept identical to the baseline grid. The sensitivity of form factor to the grid density at the aft body is larger than the forebody and it can be argued that unless the grid resolution at the aftbody is extremely coarse in the longitudinal direction, sensitivity of form factors to the grid resolution at the other parts of the hull is rather low as reported in Paper II.

The first cell size normal to the wall and the grid resolution near the wall are essential parameters for the calculation of the wall shear stresses accurately. As reported in Paper III, the first cell size normal to the wall and grid resolution near the wall did not show general trends applicable for all CFD codes, however, they were identified as one of the significant parameters for the form factor predictions.

In Paper IV, the first cell size normal to the wall have been systematically varied for six test cases. Due to the curvature and the boundary layer growth of conventional hulls, y^+ is likely to vary significantly when fixed first cell height is applied. As concluded in Paper IV, the target for the average y^+ should be maximum 0.5 for the SHIPFLOW code in order to make sure that nearly all no-slip cells are $y^+ < 1$.

Additionally, the numerical uncertainties are highly effected by the choice of the first cell size normal to the wall as shown in Eça and Hoekstra [4] and Eça, Pereira, and Vaz [5]. In order to achieve numerical uncertainty of frictional resistance coefficients below 1%, SHIPFLOW required approximately average $y^+ \leq 0.4$ for both the EASM and the $k-\omega$ SST models for the flat plate simulations, as reported in Paper I.

3.2 Turbulence Modelling

It is evident that the turbulence modelling plays a key role not only for the calculation of the forces but also the correct representation of the flow around the hull. The thorough investigations on ship hydrodynamics at the 2015 Tokyo Workshop [8] indicated that the two-equation turbulence models predict the resistance better than the more advanced models, while the anisotropic non-linear statistical turbulence models are better at prediction of the local flow than the simpler models. For the CFD based form factors, it is crucial to predict the viscous resistance correctly. However, the local flow should always be checked especially at the stern of hull for flow separation as the form factor concept is valid only when there is no flow separation [9] (see Section 2.2).

For all papers presented in this thesis, turbulence modelling stood out as the largest modelling error. The form factor predictions from the SHIPFLOW code with the $k-\omega$ SST model are approximately 10% higher than the computations with EASM using the same grid as reported in Papers II, III and IV. However, the opposite trend was observed for the form factors obtained from NAGISA and FINE$^{\text{TM}}$/MARINE codes as reported in Paper III.

Another modelling error, which can be related to the turbulence modelling, is the transition of the flow from laminar to turbulent. Contrary to common belief, the flow is not completely turbulent around all parts of the hulls in model scale with wall resolved approach as was the case for the flat plate simulations presented in Paper I. The investigations on the local skin friction coefficients of six test cases in Paper IV showed that the transition of flow in the double body computations occurred no later than the location where the turbulence stimulators are fitted in the model tests, making sure that the modelling errors due to different flow characteristics between CFD and EFD are negligible. However, this condition may not be the case when the CFD based form factors for the models with large scale factors are predicted as the Reynolds numbers will be smaller.

3.3 Verification and Validation

The development and evaluation of the Reynolds Averaged Navier-Stokes (RANS) methods in model scale have been carried out since 1980 [25]. The verification and validation (V&V) of CFD methods in model scale is now a well established practice especially for the resistance simulations. Verification and validation of CFD codes and methods are essential measures not only for the improvement of the CFD methods but also the quality assurance of the CFD applications such the double body computations for the CFD based form factors.

As reported in Paper IV, grid dependence studies were performed to quantify the numerical uncertainty (U_{SN}). Four geometrically similar grids were generated for each of the six test cases and the procedure proposed by Eça and Hoekstra [3] was used to predict the numerical uncertainties. The predicted uncertainties on C_{F} varied between 0.6 to 1.5 percent of the computed result of the finest grid, while large fluctuations were observed on the grid uncertainty of the C_{PV}. As result, the grid uncertainty on the viscous resistance coefficient varied between 1.1% and 10.2%. The reason for the large variation in the grid uncertainties were explained by the scatter in the computed values which strongly penalizes the estimated uncertainties [3]. The computed resistance components showed an oscillatory behaviour which is significantly more for the C_{PV}. The fluctuations stems mostly from the grid generation strategy (see Section 3.1) which is structured grid with stair-step profile in the stem and stern profiles. As the curvature around the bulb changes rapidly, the structured grid that captures the profile of the bulb changes abruptly with changing grid refinement. Considering the tip of the bulb where the stagnation point is often situated and followed by a steep pressure gradient, it is expected that C_{PV} will be influenced more than C_{F}. On the other hand, it was reassuring to observe that the difference between the two finest grids for C_{V} is less than 0.2% for the most test cases.

In order to complete the verification and validation study, the experimental uncertainties, U_{D}, were determined using the procedure as presented in [20]. The validation uncertainty, U_{V}, was bigger than the absolute comparison error for all test cases with the $k - \omega$ SST turbulence model and the EASM model except for one test case. The validation was achieved at U_{V} level, i.e. the comparison error is below the noise level. However, it should be noted that the U_{V} of the two test cases were are exceptionally high due to very large U_{D}.

4 Comparison of the full scale predictions

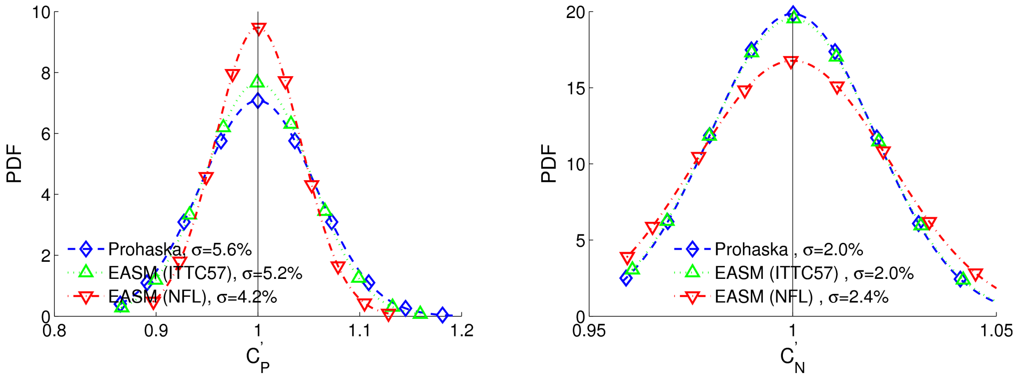
The first two steps of the proposed quality assurance procedure was presented in Section 3. In the last step of the proposed quality assurance procedure, the comparison between the speed trials and the full scale predictions based on model tests carried out at SSPA are compared. As indicated by Werner and Gustafsson [40] and Insel [11], the combination of the precision and bias limits of single speed trial result in approximately 10% of the power. Therefore, a large number of sea trials are required for such comparisons to be meaningful as the uncertainty of each trial is large.

Correlation of model test power predictions to the speed trials are quantified with the *correlation factors* using the correlation scheme of C_P - C_N as described in [19]. In order to obtain these coefficients, the correlation factors of each individual speed trial, $C_\mathrm{P}^{'}$ and $C_\mathrm{N}^{'}$, are calculated as

$$C_\mathrm{P}^{'} = \frac{P_{\mathrm{D}\ trial}}{P_{\mathrm{D}\ tank}} \quad \text{and} \quad C_\mathrm{N}^{'} = \frac{n_{trial}}{n_{tank}} \tag{4.1}$$

where the $P_{\mathrm{D}\ trial}$ and n_{trial} are the power and propeller turning rate from a speed trial, while $P_{\mathrm{D}\ tank}$ and n_{tank} represent the corresponding predictions based on the model test. The power, P_D, is derived from the faired speed-power curve at the design speed.

As reported in Paper IV, $C_\mathrm{P}^{'}$ and $C_\mathrm{N}^{'}$ are quantified by using three different sources of form factors: the Prohaska method, CFD based form factors with EASM model using the ITTC-57 line and the numerical friction line. All predictions used the same model test data but only the source of the form factor is changed. The probability density functions (PDFs) of the normalized correlation factors, $C_\mathrm{P}^{'}$ and $C_\mathrm{N}^{'}$, are calculated for 18 test cases and 78 speed trials.



(a) *asd* (b) *Cp*

Figure 4.1: *The probability density functions (PDFs) of the normalized correlation factors for the standard ITTC-78 method, CFD-based form factors with EASM model using the ITTC-57 line and the numerical friction line, from the study conducted in Paper IV*

In addition to the PDF curves, the standard deviations (σ) of $C_{\mathrm{P}}^{'}$ and $C_{\mathrm{N}}^{'}$ are also presented in Figure 4.1 as the standard deviation were used as the main measure to rank different extrapolation methods when ITTC-78 method was decided. The comparison of the standard deviations for the power predictions (C_{P}) indicates that the scatter is reduced significantly when the CFD based form factors from the EASM turbulence model are used compared to the Prohaska method. The propeller rate of revolution predictions remained the same with CFD based form factors using the ITTC-57 line but slightly worsened by the predictions with CFD based form factors using NFL when the standard deviation is considered. It can be noted that the reduction of scatter in the power predictions is a more significant measure than the propeller turning rate since the scatter in power prediction is considerably larger than the prediction of propeller turning rate. Therefore, it was concluded that the usage of the CFD based form factors with ITTC-57 line improves the predictions in general or at least do not deteriorate them. The improvement of the predictions were significantly larger with the CFD based form factors with numerical friction line.

5 Summary of Papers

5.1 Paper I

K. B. Korkmaz, S. Werner, and R. Bensow. “Numerical Friction Lines for CFD Based Form Factor Determination Method”. *VIII International Conference on Computational Methods in Marine Engineering MARINE 2019.* Göteborg, Sweden, 2019

Motivation, Results and Conclusions

The main motivation for this study is to derive a Numerical Friction Line (NFL) which can be used for the CFD based form factor determination and the extrapolation methods. The frictional resistance coefficients of an infinitely thin 2D plate have been computed at 14 Reynolds numbers covering the typical model scale to full scale range. At each Reynolds number, five geometrically similar structured grids were simulated in order to perform reliable grid dependency studies. All computations were performed with the direct application of the no-slip condition at the wall and two turbulence models were used, the $k-\omega$ SST and the EASM. The grid independent frictional resistance coefficients calculated using the SHIPFLOW code at 14 Rn have been transformed into separate numerical friction lines for the $k-\omega$ SST and the EASM turbulence models by applying curve fits.

Additionally, comprehensive grid dependency studies were performed at $\log_{10}(Re) = 6.25$ using the SHIPFLOW and the FINE$^{\text{TM}}$/MARINE codes. Noticeable differences were observed in the calculated C_{F} and the predicted numerical uncertainties between the CFD codes even though the same grids were used for the both solvers.

Two main modelling errors were identified: turbulence modelling and transition of flow from laminar to turbulent. The investigations on the latter error source showed that the flow around the flat plate is not fully turbulent. With respect to the turbulent intensity levels in the computations, the transition occurs at too low Reynolds numbers corresponding to around 5% of the plate featuring the laminar flow at the lowest Re. Considering that the turbulence stimulators in model testing are usually placed at 5% of L_{PP} from the fore perpendicular, the amount of wetted surface covered by laminar flow in a model test is comparable to the numerical conditions. Hence, the requirement for the fully turbulent two dimensional flat plate friction line for the form factor method is largely fulfilled.

The derived numerical friction lines were compared to the friction lines available in literature. The slope of the line derived from the $k-\omega$ SST model is similar to numerical friction lines computed by others with the same turbulence model. The friction line when the EASM model was used exhibits significantly less slope at both ends of the Re range and differing from all other friction lines in the high Re range except the Hughes line to some extent.

When using a numerical friction line for the ship resistance extrapolation, it should be considered that the results could be highly dependent on several factors: non-dimensional wall distance (y^{+}), choice of turbulence model, boundary conditions such as turbulence intensity and the other numerical methods. Therefore, it is not recommended to use a general numerical friction line for CFD based form factor determination but instead the NFL of the same code and the same turbulence model should be used.

All authors participated in the conceptualisation, the development of the methodology, and the review and editing of this paper. The literature study, CFD computations, post-processing, validation, data analysis, investigation, visualisation and writing of the original draft were performed by the first author.

5.2 Paper II

K. B. Korkmaz, S. Werner, and R. Bensow. "Investigations for CFD Based Form Factor Methods". *Numerical Towing Tank Symposium (NuTTS 2019).* Tomar, Portugal, 2019

Motivation, Results and Conclusions

This study was intended to be a foundation for the further studies on the CFD based form factors. The form factor hypothesis of Hughes [9], same form factors for the model and full scale, was tested by analyzing the results obtained from simulations performed on the KVLCC2 and KCS hulls.

Following grid dependency studies, different grid density distributions were simulated for KVLCC2 in order to determine which grid density is acceptable and which grids should be avoided. It has been concluded that unless the grid density in the longitudinal direction is too coarse, the sensitivity of the form factor to the grid resolution at the other parts of the hull is rather low.

The sensitivity of the form factors to the varying loading conditions was investigated for KVLCC2 and KCS. The double model simulations were performed at dynamic sinkage & trim, and at draught and trim at rest. It was observed that the change in the calculated viscous resistance between the loading conditions were nearly one order smaller than the numerical uncertainties of both KVLCC2 and KCS.

The speed dependency of the form factors was investigated by performing double body computations at model and full scale. It was shown that when the ITTC-57 line is used, the scale effects are unavoidable. However, when the numerical friction lines which was derived in Paper III are applied, speed dependency of the form factors was eliminated almost completely for both hulls.

All authors participated in the conceptualisation, the development of the methodology, and the review and editing of this paper. The CFD simulations, post-processing, validation, data analysis, investigation, visualisation and writing of the original draft were performed by the first author.

5.3 Paper III

K.B. Korkmaz, S. Werner, N. Sakamoto, P. Queutey, G. Deng, G. Yuling, D. Guoxiang, K. Maki, H. Ye, A. Akinturk, S. Sayeed, T. Hino, F. Zhao, T. Tezdogan, Y.K. Demirel and R. Bensow. CFD Based Form Factor Determination Method. *Accepted for publishing in Ocean Engineering*

Motivation, Results and Conclusions

This paper emerged as a result of the joint study initiated by the ITTC Specialist Committee of Combined CFD/EFD Methods with contributions from SSPA, Chalmers University of Technology, National Maritime Research Institute (NMRI), LHEEA CNRS Ecole Centrale de Nantes, Shanghai Ship and Shipping Research Institute (SSSRI), CSHL University of Michigan, Ocean, Coastal and River Engineering (OCRE), Yokohama National University, China Ship Scientific Research Centre (CSSRC) and University of Strathclyde.

This paper investigated the possibility to improve the power predictions by introducing the combined CFD/EFD Method where the experimental determination of form factor is replaced by double body RANS computations applied for open cases KVLCC2 and KCS, including first-time published towing tank tests of KVLCC2 at ballast condition including an experimental uncertainty analysis specifically derived for the form factor. CFD based form factor predictions from nine organisations and seven CFD codes were compared to the experimental results. The form factor predictions for KVLCC2 and KCS in design loading condition compared well with the experimental results in general. The CFD based form factors were mostly under-predicted for KVLCC2 in ballast loading condition compared to experiments. However, the majority of the CFD based form factors were within the experimental uncertainty.

The computations performed in model scale included not only the CFD setups according to the best practice guidelines or standard settings but also CFD setups that deviated from the recommended guidelines. The analysis of the computations with the non-standard CFD setups indicated that it is essential to describe the boundary layer with a good grid quality in terms of the grid resolution and the first cell size normal to the wall. The computed form factor is considerably more sensitive to the grid density at the aft of the model than the other regions and the type of the wall function may play a significant role when used in combination with certain turbulence models.

The form factor predictions were further investigated in order to highlight the dependencies of the CFD codes and methods. The identified dependencies of turbulence modelling, first cell size normal to the wall and grid resolution near the wall did not show general trends but different codes indicated varying tendencies on CFD setups. Therefore general recommendations for all CFD codes could not be made specifically for the sake of form factor determination. Instead, it was observed that most of the codes with a certain CFD setup showed consistent patterns of form factor predictions among different test cases. If these trends are confirmed with more hulls and test cases, application of correlation factors (C_P-C_N or C_A) unique for each code and method will be able to reduce the differences in full scale predictions further.

The model scale computations were performed at two speeds in order to investigate the speed dependency of the form factors. Speed dependency is observed with the application of the ITTC-57 line, it is reduced with the Katsui line and nearly eliminated by numerical friction lines. Comparison of the full-scale viscous resistance predictions obtained by the extrapolations from model scale and direct full-scale computations show that the Combined CFD/EFD Method show significantly less scatter and may thus be a preferred approach.

All authors participated in the CFD computations and the review and editing of this paper. The conceptualisation and the development of the methodology were conducted by the K. Burak Korkmaz, Sofia Werner and Rickard Bensow. The model test experiments, uncertainty assessment method for the Prohaska method, CFD-simulations, setting up and arranging the joint work of nine participants, data analysis, validation, formal analysis, data curation, visualisation and writing of the original draft were performed by the first author.

5.4 Paper IV

K.B. Korkmaz, S. Werner and R. Bensow. Verification and Validation of CFD Based Form Factors as a Combined CFD/EFD Method. *submitted to Journal of Marine Science and Engineering*

Motivation, Results and Conclusions

This paper aims to demonstrate the use of the new procedure of Quality Assurance proposed by the ITTC Specialist Committee of Combined CFD/EFD Methods. The new QA procedure is proposed to respond to the need for a practical procedure for the organisations that regularly perform CFD predictions on similar cases. This study serves as an example of how the procedure can be applied in practice to a problem: CFD based form factors. The quality assurance of this practical problem is demonstrated in three parts: the content and derivation of the Best Practice Guideline of the SHIPFLOW code used in this study, the quality Assessment of the BPG methodology through verification and validation studies and finally the demonstration of quality by the comparisons of 78 speed trials to the predictions made by combined CFD/EFD methods explained.

In order to investigate and derive a best practice guideline for CFD based form factors, systematic variations were applied to the CFD set-ups. The non-dimensional cell height normal to the wall, additional grid refinement at the stern, domain size and model scale speed were analysed.

The variation of the domain size had an extensive effect on the form factors as it caused the turbulence quantities to change. Further investigations on the local skin friction coefficient, C_f, indicated that the flow is not all fully turbulent as observed in Paper I for the flat plates. The transition of flow in the double body computations occurred not later than the location where the turbulence stimulators are fitted in the model tests, making sure that the modelling errors due to different flow characteristics between CFD and EFD are negligible.

The speed dependency of the form factors with the ITTC-57 line were observed for all test cases. Similar trends are expected by all CFD codes as the main reason of the dependency is the ITTC-57 line rather than the numerical methods. The application of numerical friction lines of the same code and turbulence model to the CFD based form factor determination, the speed dependency of the form factors was nearly eliminated when there was no flow separation.

The full scale speed-power-rpm relations between the speed trials and the full scale predictions were investigated for 18 test cases and 78 sea trials. The full scale predictions were based on different extrapolation methods but using the same model test data. The usage of CFD based form factors with the EASM turbulence model improved the prediction regardless of the friction line used. However, the most promising method out of the five investigated extrapolation methods is the CFD based form factors using the EASM turbulence model and the numerical friction line.

All authors participated in the conceptualisation, the development of the methodology, and the review and editing of this paper. The CFD computations, post-processing, validation, data analysis, investigation, visualisation and writing of the original draft were performed by the first author.

6 Concluding Remarks

As suggested by the ITTC Specialist Committee of the Combined CFD/EFD Methods, the combination of EFD and CFD can be a feasible solution to increase the accuracy of power predictions in conditions when a part of the model testing or extrapolation procedure causes higher uncertainty than the numerical uncertainty and physical modelling errors of the CFD applications. In this thesis, CFD based form factors have been investigated as a combined CFD/EFD method.

The theoretical background of the experimental determination of the form factor in the ITTC-78 method, the Prohaska method, is explained together with its main drawbacks and lack of applicability for the modern hull forms with bulbous bows in Section 2.2 and Paper III. As presented in Section 3 and Paper IV, the double body RANS computations are able to replicate the required conditions described in the original form factor hypothesis of Hughes [9]. The form factors obtained from the computations performed according to the best practice guidelines compared well with the experimentally determined form factors and were within the experimental uncertainty for variety of ship types.

As a final step, the full scale speed-power-rpm relations between the speed trials and the full scale predictions were investigated using large number test cases with variety of ship types and their corresponding sea trials in Section 4. The scatter between the speed trials and predictions were considerably reduced for the power predictions while the propeller turning rate predictions were slightly worsened. The CFD based form factors and extrapolations based on the numerical friction lines yielded significantly better correlation to the speed trials compared to ITTC-57 line. Further investigations on the full scale speed-power-rpm relations indicated that it is hardly possible to achieve a better accuracy than the presented results as the main source of the scatter originates from the spread of the speed trials among sister ships and the standard deviation of the comparison error of the predictions with the CFD based form factors using the EASM turbulence model and the NFL are close to to the minimum value that could be obtained from the speed trial data set.

In the light of the results presented in this thesis, the CFD based form factors as a combined CFD/EFD method is expected to provide immediate improvements to the 1978 ITTC Performance Prediction Method. However, this recommendation should be interpreted with care as the number of test cases and speed trials evaluated within the scope of this study is limited and nowhere near the joint effort present in the making of the ITTC-78 method. Therefore, it is recommended that further studies should be performed with many more test cases of different ship types, sizes and hull design characteristics for the comparison of speed trials and power predictions. The importance of evaluating large number of speed trials could not be stressed more when different full scale predictions methods (EFD, CFD or combined CFD/EFD methods) are compared as the uncertainty of sea trials are often very large.

This study is also intended to serve as an example of how the new procedure of quality assurance proposed by the ITTC Specialist Committee of Combined CFD and EFD Methods can be applied to a practical CFD application such as the computation of the CFD based form factors.

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