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The use of Modern Computational Tools in the Design Process of Unconventional Propellers for Performance Prediction and Full-scale Extrapolation

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Abstract. Most of the traditional procedures for the design of conventional propellers do not yield reliable outcomes in the case of unconventional propellers, for which high-fidelity predictions of performance characteristics are necessary. It is generally understood and recognized, for instance, that the standard ITTC'78 procedure for model to full-scale extrapolation of performance is not reliable in case of unconventional propellers. CFD calculations, on the other hand, are becoming a standard analysis tool to be used for unconventional propeller design and performance predictions. In the present paper, it will be shown, for both a CLT® and a new generation CLT® propellers, that the extrapolation from model tests to full-scale cannot be reliably carried out by standard procedures. A CFD calculations campaign is, consequently, carried out to simulate the performance of both designs in open water condition, both at model and full-scale, incorporating transition models to determine with more detail laminar, transitional and turbulent flow areas. Results are also compared with the performance predictions obtained with empirical and strip method scaling procedures developed by SISTEMAR S.A. The comparison shows that both methods are sufficiency reliable in the early design stage and for the extrapolation and comparison of model tests.

Keywords. CLT®, new generation CLT®, propeller performance, scale effect, StarCCM+, OpenFOAM

1. Introduction

Most of the traditional procedures used for the design of conventional propellers do not yield reliable outcomes in the case of unconventional propellers, for which high fidelity predictions of performance characteristics and full scale extrapolations of model test results, at least when model tests are used to check and compare alternative designs,

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are necessary. It is generally understood and recognized, for instance, that the standard ITTC'78 procedure for model to full-scale extrapolation of propeller performance is not reliable in case of unconventional propellers [1]. CFD calculations, on the other hand, are becoming a standard analysis tool and they can thus be used for unconventional propeller design and performance predictions. Among unconventional propellers, CLT® and the new generation of CLT® [2,3] represent one of the most widely adopted solution for the increase of the full-scale propulsive efficiency. The first generation of end plate propellers was called TVF (Tip Vortex Free) and was developed between 1976 and 1986 in AESA (Astilleros Españoles, S.A.) and later on in SATENA (Sociedad Anónima de Tecnología Naval). A more advanced second generation of end plate propellers called CLT® (Contracted Loaded Tip) was developed in 1986. Since then, its development has been carried out by the Spanish company SISTEMAR S.A., created in 1987 with the objective to develop and commercialize these propellers worldwide.

CLT® propellers are included in the category of Unconventional propellers and ITTC has repeatedly insisted that standard procedures for extrapolation of model tests results like the ITTC'78 Performance Prediction Method [4] cannot be applied to this kind of propellers [1]. This is a major obstacle to the implementation and the commercialization of unconventional propellers because sometimes the improvements that they can generate at full scale are not properly shown at model scale. A new extrapolation procedure must be developed for this kind of propellers. Recently, a workshop devoted to this specific problem, has been promoted by the ITTC Commitee on Propulsion itself, and preliminary results, collected from many research groups all around the world, on the PPTC Test case [5] and on a tip loaded propeller, still show a certain uncertainty in robust model scale numerical prediction when a significant laminar boundary layer development is expected due to insufficiently high Reynolds number during measurements.

Among the procedures proposed in literature for full scale scaling, in the case of CLT® and new generation CLT®, three main approaches have been mainly developed over the years:

- *Semi-empirical methods*: a good example of this method is the procedure published and applied by SISTEMAR S.A. and CEHIPAR to CLT® designs [6]. This method was based on the addition of new correlation coefficients for propeller blade and for end plate to the formulation used in the Performance Prediction Method of ITTC'78. These coefficients have been adjusted to obtain a good correlation with sea trials results.
- *Strip methods*: the scaling is achieved by dividing the propeller in a series of chord-wise strips, by calculating the local scale effects on each strip, and finally by integrating the local scale effects in order to obtain the global propeller scale effect. Some different methods with this approach have been published [7,8] to be applied in case of non-conventional propellers.
- *CFD based methods and/or Panel Methods*: there are several variants of these methods and several commercial or in-house developed available codes. General approach to use these methods to compute open water tests corrections is to compute independently for model scale and full scale cases and correlate the results [9].

In the present paper, the case of a first generation CLT® propeller designed in 2007 for a Spanish corvette is presented and compared with a new generation CLT® propeller designed in 2016 in the framework of a Research and Development project partially granted by the Spanish Ministry of Defence. Both propellers have been tested at model scale and sea trials results for the vessel equipped with the first generation CLT® are also available. These data, which clearly show the inappropriateness of standard procedures for the extrapolation of model scale performance to full scale, represent the validation basis for extensive numerical calculations using CFD tools, aimed at demonstrating the high level of confidence which can be reached in the numerical prediction of unconventional geometries. In the specific, model and full scale performance in open water conditions are addressed, using transitional models (the $\gamma - Re_\theta$ [10] from StarCCM+, the $k - k_L - \omega$ [11] implemented in OpenFOAM) so as to determine with more detail laminar, transitional and turbulent flow areas over the blades at different functioning conditions. In the end, RANS calculations are also compared with the performance predictions obtained with both empirical and strip method scaling procedures developed by SISTEMAR S.A. The comparison shows that both methods are sufficiency reliable in the early design stage and for the extrapolation and comparison of model tests.

2. The Test Cases: CLT-Ref and CLT-Final

In the framework of a Research and Development project co-sponsored between SISTEMAR S.A. and the Spanish Ministry of Defence, inside the Program called *COINCIDENTE*, the Spanish Corvette BAM class, shown in Figure 1, has been selected to develop an optimization process of propeller blades. The class is currently formed by 4 sister vessels in operation and another 2 already ordered and under construction. The ship has an overall length of 93.9m and a maximum beam of 14.2m. It is equipped with a twin shaft CODOE propulsion plant, with two operation modes: diesel for maximum and electric for patrol speed. Propellers are of controllable pitch type, with CLT blades. CLTs are very well suited for this case due to the proven capacities of CLT blades to maintain performance efficiency when reduced pitch is required by off-design modes of operation. Thanks to the high efficiency achieved by using CLT blades, range is maximized when ship is in patrol duties.

Figure 1. A spanish patrol vessel of the BAM (Buques de Acción Marítima) class.

The reference propeller geometry currently mounted on board underwent a significant optimization process, analysing several alternatives in order to obtain a better cavitation behaviour in behind conditions without losing propulsive efficiency. The design

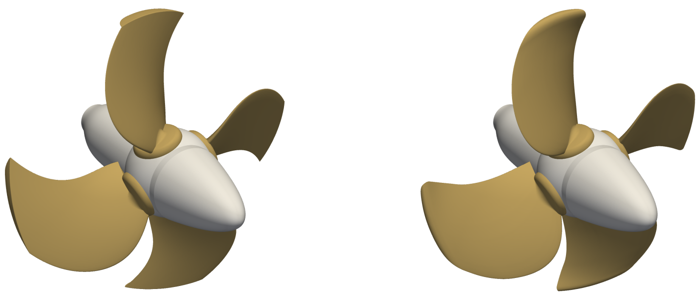


Figure 2. CAD models of the original CLT design (CLT-Ref, on the left) and new geometry CLT design (CLT-Final, on the right).

Table 1. Design point for the reference and the final CLT propellers.

Model Diameter	D	[m]	3.45
Area ratio	A_E/A_O	[-]	0.55
Number of blades	Z	[-]	4
Advance Coefficient	J	[-]	0.7905
Thrust Coefficient	C_{Th}	[-]	0.6193

point is summarized in Table 1. The outcomes of this design activity suggested that blades based on the new generation of CLT can achieve an even higher efficiency and can be particularly useful to further improve the performance of these unconventional type of propellers.

The three-dimensional representation of the propellers is show in Figure 2. The CLT-Ref is the reference CLT propeller, which currently equips the ship, while the CLT-Final is the geometry from the optimization implementing the new geometry of CLT blades with a smooth transition from the blade to the endplate.

2.1. Model Test Results

The model scale experimental campaign was carried out at the INTA-CEHIPAR Model Basin. Test conditions are summarized in Table 2 while he resulting open water diagrams are those of Figure 3. The comparison of model scale measurements clearly demonstrated the outcomes of the optimization process carried out for the Reference geometry and the effectiveness of the smooth transition from the blade to the endplate adopted for the new generation CLT. At almost unvaried thrust coefficient (in the range J = 0.4 - 0.8), the absorbed torque is significantly reduced and an increase of efficiency up to 8% at the design point is achieved.

The average, chord-based, Reynolds number of both tests, on the other hand, is particularly low, suggesting a significant influence of laminar to turbulent transition phenomena on model scale propeller performance which have to be taken into account for reliable numerical predictions.

Table 2. Towing tank conditions for propeller open water tests.

		CLT-Ref	CLT-Final
Temperature of fresh water	°	19.5	12.1
Density of fresh water	kg/m^3	998.14	999.27
Viscosity of fresh water	m^2/s	$1.016 \cdot 10^{-6}$	$1.232 \cdot 10^{-6}$
Rate of revolution	RPS	12.5	15
Reynolds number	[-]	$5.9 \cdot 10^5$	$4.2 \cdot 10^5$

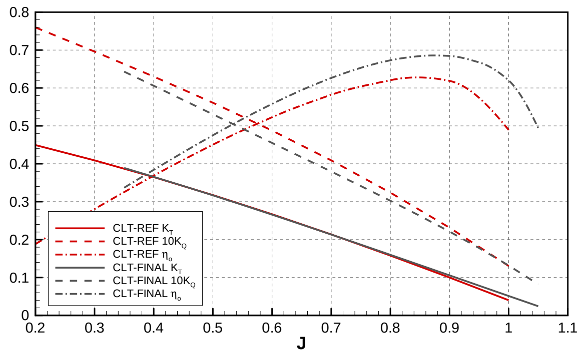


Figure 3. Open water test results for the reference and the final CLT propellers. Towing tank measurements.

3. CFD tools for Propeller Performance Prediction

To assess the reliability of Strip Method for the extrapolation of model tests results to full scale in case of unconventional propeller geometries, extensive calculations in model and full scale have been performed with two finite volume CFD codes, StarCCM+ and OpenFOAM. Both codes where used to solve the flowfield under the RANS assumption. With the hypotheses of incompressible and steady flow, the time-averaged continuity and momentum equations can be written in the differential form proposed in Eq. 1, assuming $x_{i=1,2,3}$ as the Cartesian coordinates and $V_{i=1,2,3}$ the Cartesian components of the velocity vector in the body-fixed reference frame:

$$\begin{cases} \dfrac{\partial V_i}{\partial x_i} = 0 \\ \rho V_j \dfrac{\partial V_i}{\partial x_j} = -\dfrac{\partial p}{\partial x_i} + \dfrac{\partial}{\partial x_j}\left[\mu\left(\dfrac{\partial V_i}{\partial x_j} + \dfrac{\partial V_j}{\partial x_i}\right)\right] + \dfrac{\partial \tau_{ij}}{\partial x_j} \end{cases} \tag{1}$$

The fluid static pressure and density are, respectively, p and ρ, μ is the fluid viscosity and τ_{ij} are the Reynolds stresses resulting from the averaging process of the momentum equations, which are treated on the basis of the Boussinesq hypothesis, then proportional to the trace-less mean strain rate tensor times the eddy viscosity μ_T. Modelling the eddy viscosity using simplified relationship is the key point of any turbulence model. Fully turbulent calculations in model and full scale have been carried out using for both Star-CCM+ and OpenFOAM the $SST k-\omega$ model. Model scale analyses, in addition, have been carried out using transition enabled turbulence models in order to account for the portion of laminar flow over the blade (and its transition to the turbulent regime) when a sufficiently high Reynolds number ($10^5 - 10^6$), as during model scale tests, cannot be achieved to ensure fully developed turbulent flow.

In present calculations, two different transition enabled turbulence models have been employed. For calculations with StarCCM+, the $\gamma - Re_\theta$ model has been used [10]. It belongs to the family of intermittency based models for laminar to turbulent transition: coupled with the $SST k-\omega$ models, the intermittency function γ is used to activate the production term of the turbulent kinetic energy downstream of the transition point in the boundary layer. The Reynolds number based on the boundary layer momentum thickness (Re_θ) is used, locally, to determine where, in the flow, the transition criteria are satisfied.

The $k - k_L - \omega$ model [11], instead, has been used in case of the model scale calculations carried out with OpenFOAM. The model is based on the concept of laminar fluctuations and laminar kinetic energy (k_L): the rise in the fluctuation-energy level in the laminar regime is used to start and let grow the turbulent kinetic energy of a conventional $k-\omega$ model and turn the flow from laminar to turbulent.

Calculations have been carried out by exploiting the periodicity of the problem when homogeneous inflow is addressed. Then, only a blade passage with periodic boundary conditions and a moving reference frame has been modelled [12]. To avoid any interference from boundaries and resemble the towing tank conditions, velocity inlet and pressure outlet were placed respectively 3.5 diameters in front and 7.5 diameters aft the propeller plane. The outer boundary, treated as symmetry, lays on a cylindrical surface 10 diameters far from the propeller shaft. Computational meshes (an example of StarCCM+ is shown in Figure 4) have been arranged in order to comply with the requirements of transition enabled models: the number and spacing of prism layers (20 for StarCCM+ calculations, 23 for OpenFOAM) have been selected to achieve an average non-dimensional distance over the blades below 1. Resulting meshes consist in 10 and 6.5 million cells for StarCCM+ and OpenFOAM respectively.

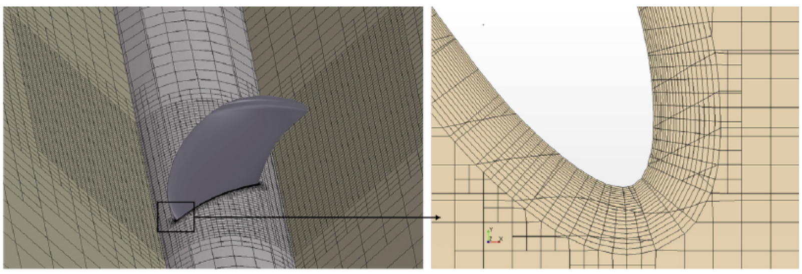


Figure 4. Example of hexa-dominat mesh used in StarCCM+.

4. Results

4.1. Model scale calculations

With the aforementioned numerical setup, open water propeller performance have been computed for both the geometries. Results have been compared with the Towing Tank measurements of Figure 3. Calculations have been carried out using, for both the codes, fully turbulent and transition enabled turbulence models. Results are collected and compared in Figure 5. The comparison is, overall, good even if some remarks are worth of note. The general trend of calculations (and the capabilities of turbulent or transitional enabled turbulence models) are similar. For the reference CLT, in fully turbulent mode (using the $SST k-\omega$ turbulence model for both StarCCM+ and OpenFOAM), the delivered propeller thrust is slightly underestimated. A certain underestimation, amplified in the case of StarCCM+ calculations, can be highlighted as well for the torque, leading to an open water efficiency always underestimated. Switching to the transition enabled models, it is possible to appreciate the slight increase of thrust predicted by both approaches, which makes, in particular for the OpenFOAM calculations, numerical predictions particularly close to measurements. The reduction of skin friction due to a large portion of blade area subjected to laminar flow further reduces the predicted torque, overstating the differences already evidenced in fully turbulent mode. The resulting efficiency, in turn, results overestimated by both StarCCM+ and OpenFOAM, with StarCCM+ results slightly better due to the simultaneous slight underprediction of thrust associated with a significant underestimation of torque.

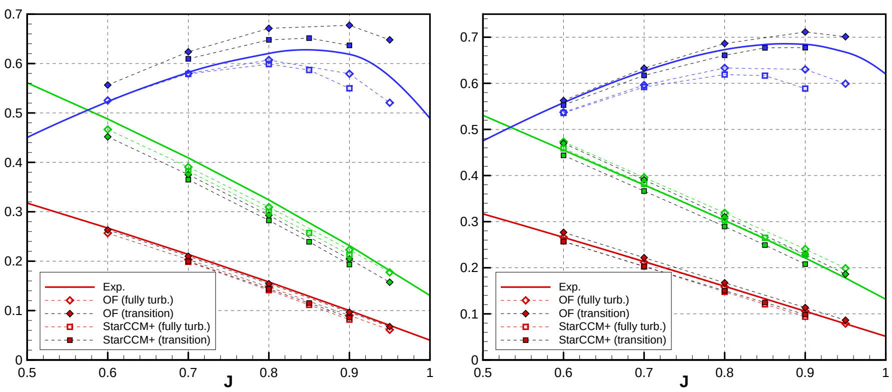
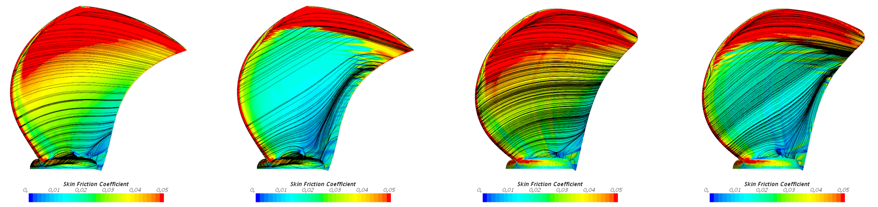
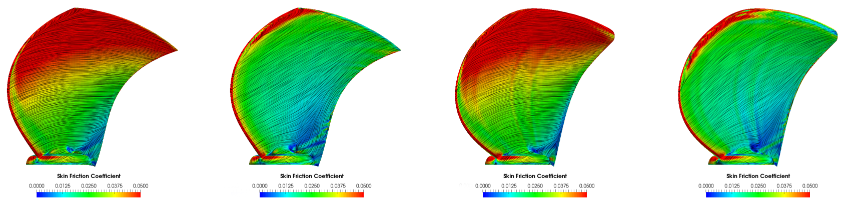


Figure 5. Open water propeller performace at model scale. Comparison among Towing tank measurements, fully turbulent and transition enabled turbulence models with StarCCM+ and OpenFOAM. CLT-Ref on the left, CLT-Final on the right.

In the case of the CLT-Final geometry, the overall behaviour of numerical calculations is very similar to what observed for the CLT-Ref. In this case, however, slightly better predictions of thrust and torque when the OpenFOAM solver is employed can be evidenced. Also in this case, the development of laminar flow is seen, by both the models, as a slight increase of thrust and a more significant reduction of the absorbed torque. Since the reference values of torque in fully turbulent mode are very close (StarCCM+) or slightly overestimated (OpenFOAM) with respect to measurements, the inclusion of the transition effect turns into a closer to experiments torque curve with respect to the calculations for the CLT-Ref geometry. Efficiency, which is subjected to the combinations of errors seen for thrust and torque, is slightly better predicted by StarCCM+ but in both the cases an overall better agreement with experiments is possible only by applying the transition enabled turbulence models. By looking at the skin friction coefficient (non-dimensional with respect to the advance speed) and the corresponding streamlines of Figure 6 it is possible to appreciate some differences in the prediction of the transition phenomena by the two turbulence models employed in the calculations. Since the fully turbulent $SST k-\omega$ model is considered, both predictions show very similar skin friction distributions. Streamlines highlight the presence of leading edge vortex as well as an hint of flow separation at the root close to trailing edge. When, instead, transition is considered, there are substantial differences between the two models. Both, indeed, predict substantially lower values of friction for a large portion of the blade, with laminar separation at root and the typical azimuthal behaviour of streamlines. At higher radii, instead, with the $\gamma - Re_\theta$ models streamlines resemble the behaviour observed in fully turbulent calculations and are mainly oriented along the tangential direction while those from the $k - k_L - \omega$ have a radial dominant orientation. The local skin friction coefficient computed using StarCCM+ in the outer portion of the blade, in addition, is significantly higher that that from OpenFOAM calculations.



(a) CLT-Ref, Fully turbulent, StarCCM+ (b) CLT-Ref, Transition, StarCCM+ (c) CLT-Final, Fully turbulent, StarCCM+ (d) CLT-Final, Transition, StarCCM+



(e) CLT-Ref, Fully turbulent, OpenFOAM (f) CLT-Ref, Transition, SOpenFOAM (g) CLT-Final, Fully turbulent, OpenFOAM (h) CLT-Final, Transition, OpenFOAM

Figure 6. Comparison of predicted skin friction coefficients and streamlines on the blade suction side. CLT-Ref (on the top) and CLT-Final (on the bottom) at J = 0.8.

4.2. Full scale predictions

Full scale extrapolations represent the key point for reliable powering predictions and the dimensioning of the entire propulsion system, but generally only an indirect validation through the delivered engine power is possible. In the case of unconventional propellers the extrapolation procedure is further stressed due to the recognized inconsistencies of conventional scaling approaches. For the aims of the present work, the comparison is proposed by considering the Propeller Prediction Method proposed by ITTC'78 [4], the Strip Method developed and calibrated by SISTEMAR S.A. [6,8] on the basis of its experience with unconventional propellers and full scale fully turbulent calculations using OpenFOAM.

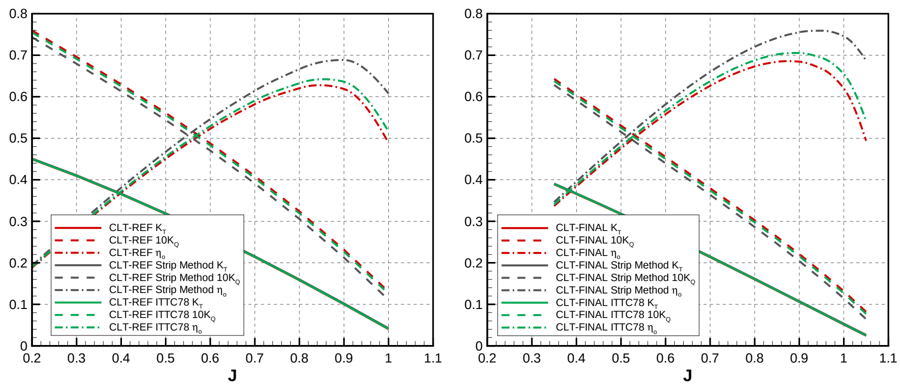


Figure 7. Open water propeller performance at full scale. Comparison between ITTC'78 Performance Prediction Method and SISTEMAR Strip Method. Reference CLT on the left, CLT-Final on the right.

The Strip method and the ITTC'78 procedure are compared in Figure 7. As already shown in [9] the performance increase foreseen by the Strip Method (Figure 7) for both the Reference CLT and the Final CLT based on the new generation blade shape is significantly higher than that obtained by simply applying the ITTC'78 procedure that was developed during the years mainly for conventional, tip unloaded, propellers. Close to the design point, the efficiency increase due to full scale Reynolds number is of about only 2% for both propellers, versus an increase higher than 7% when the Strip Method is applied. The reliability of the Strip Method (in turn, the unreliability of conventional scaling approaches) is demonstrated in Figure 8 for the Reference CLT configuration currently in use for the BAM class Spanish Corvette. The predicted shaft power, when the full scale propeller performance are obtained by using the Strip Method, agrees significantly better with the sea trials measurements than the calculations based on the ITTC'78 approach. Full scale propeller performance calculated with OpenFOAM, shown in Figure 9, agrees well with the full scale extrapolations using the Strip Method, in particular in the case of the Reference CLT configuration. A good agreement with sea trials measurements can consequently be expected as a proof of the reliability of direct full scale numerical calculations in the case of unconventional geometries.

5. Conclusions

In this paper fully turbulent and transition enabled turbulence models have been used to predict, using two RANS solvers, the performance of two unconventional CLT pro-

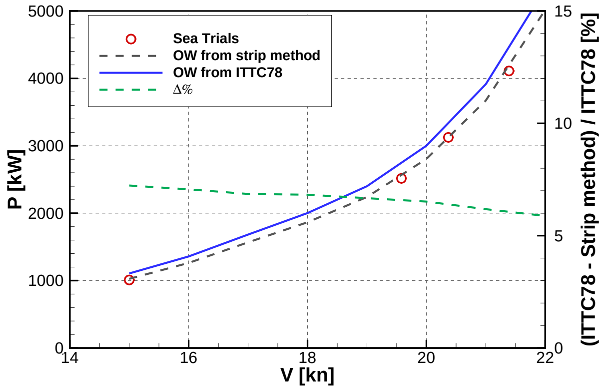


Figure 8. Power vs. Speed at full scale. Comparison between sea trials, ITTC'78 and SISTEMAR Strip Method.

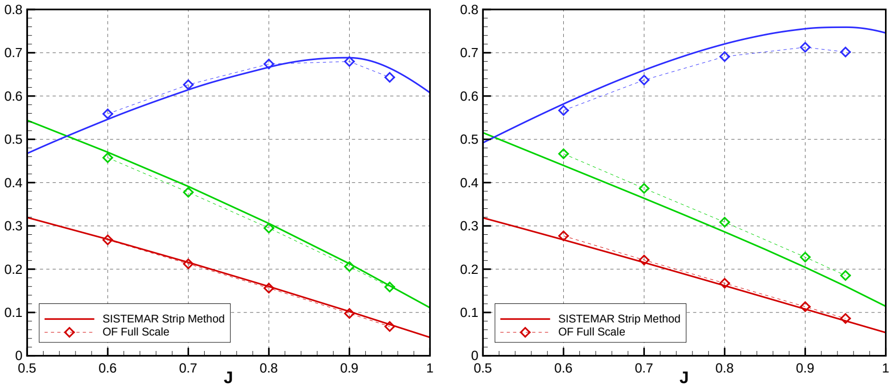


Figure 9. Open water propeller performace at full scale. Comparison between SISTEMAR Strip Method and OpenFOAM full scale calculations. CLT-Ref on the left, CLT-Final on the right.

pellers. Model scale calculations have been compared with towing tank measurements while full scale calculations have been verified against sea trials results. Results from a dedicated Strip Method for full scale extrapolation have been included as well.

Comparison at model scale demonstrated that the use of transition enabled models improves the accuracy of numerical predictions even if, at least in the case of the Reference CLT propeller, the underprediction of the torque coefficient is significant.

Full scale analyses and the comparison with sea trials measurements, on the other hand, demonstrated once more that standard power prediction methods, as that proposed by ITTC, are not reliable in case of unconventional propellers. Strip methods, taken into consideration the detailed geometry of unconventional propellers, are more adequate to produce better full scale predictions. Direct CFD calculations at full scale have a level of accuracy comparable to that of calibrated and experience-based methods. Their computational costs, however, is rewarded by the complementary information extracted from simulations which could be of extreme importance for detailed design procedures.

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