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COMPARISON OF DIFFERENT SCALING METHODS FOR MODEL TESTS WITH CLT PROPELLERS

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CLT and other tip loading propellers designs can be checked by model tests as in the case of conventional propellers. In this paper the problem of the scaling of the model tests results of these propellers is reviewed. A way of solving this problem consists in the introduction of new procedures for scaling of the Open Water model tests results while maintaining the rest of the scaling procedures for resistance and propulsion tests. ITTC'78 standard method is widely used but some Institutes and Model Basins have their own more or less similar procedures. A series of technical approaches used for the scaling of Open Water tests results are presented here and applied to a reference case that has been very deeply studied in several Research Projects. The conclusion is that it is definitely necessary to use specific Open Water model tests results scaling procedure for CLT propellers in order to obtain full scale predictions with the same level of accuracy than in the case of conventional propellers.

1. Introduction

Propulsive efficiency, hence energy saving, is a primary objective, if not the first and probably still the most important one, especially considering the present worldwide economic crisis, in the design of marine propellers. In parallel to this, the stricter regulations in terms of air pollution, and the lower limits for emissions require ever more efficient designs. CLT propellers represent an opportunity to increase ship propulsion efficiency (Gomez and Adalid, [1]); however, being unconventional, their design is unknown to a large part of the shipping community and it presents larger difficulties, among which the necessity for suitable scaling procedures from model to full scale.

As it is well known, the propulsive performances of a propeller are usually checked by means of Open Water Tests in uniform flow and Self Propulsion Tests with hull; both SPT and OWT are carried out at much lower Reynolds number than full scale, so that model test results are affected by viscous scale effects, and suitable extrapolation procedures are needed.

CLT propellers are affected by larger scale effects than conventional propellers because of the higher tip loading and of the complex phenomena related to the presence of the end plate, with possible separation phenomena at model scale. In order to overcome this issue, SISTEMAR and CEHIPAR have introduced ad hoc corrections to the ITTC 1978 OWT results scaling procedure (ITTC, [10]), taking into account scale effects on lift and viscous forces over the blades and on viscous forces over the end plates (Gomez and Adalid, [2]). This CLT scaling procedure has been validated and refined by means of the continuous comparison between model and full scale tests, increasing the database for the correlation coefficients and thus the reliability of the procedure.

The Propulsion Committee have recommended to the 26th ITTC (ITTC, [11]) that some alternative scaling procedure must be developed for unconventional propellers, like end plate propellers, PBCF, pod's, and the effort summarize in the paper is trying to give a technical response to ITTC statement.

In present work, possible alternatives to the usually adopted procedure are considered, in order to have a better insight into this phenomenon. In particular, a scaling method, based on the strip method developed by SINM (Gennaro, [3]) is presented, together with direct calculations in model and full scale made with panel methods developed by UNIGE (Bertetta et al. [4]), and with direct computations by a RANS solver made by VTT (Sánchez-Caja et al. [5, 12]).

The corrections in K_T and K_Q derived by means of different approaches are compared, considering a reference case, the high speed ferry "Fortuny" of the Spanish company ACCIONA TRASMEDITERRANEA, for which reliable model test and sea trials results with CLT propellers are available thanks to a previous R&D project sponsored by the Spanish authorities in 2003 (Gomez et al. [6]) and have been already used in several European Projects. This comparison allows assessing the merits and shortcomings of different methods; moreover, the analysis of the numerical calculations adopted allows to obtain a more direct view of the various phenomena typical of the CLT propellers, gaining further information for the development of suitable scaling procedures.

2. Theoretical background

In present section, a brief overview of the various methods adopted for the CLT propeller performances scaling is reported.

2.1. *SISTEMAR / CEHIPAR – Semi-empirical corrections*

SISTEMAR's scaling procedure takes advantage of the experience gained with the ITTC'78 procedure (ITTC, [10]) and incorporates some special corrections in the propeller open water curves as shown in Figure 1, to take into account scale effects on viscous forces over the blades, lift forces over the blades and viscous forces over the end plates. This procedure has been developed inside R&D programs and validated with the data base of sea trials of CLT propellers. The extrapolation procedure was presented by Sobrino et al. [2].

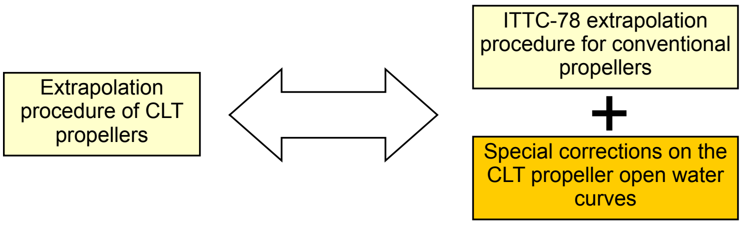

Figure 1: Base for the SISTEMAR extrapolation procedure.

In particular, the values of K_{TS} and K_{QS} coefficients corresponding to full scale are obtained by adding three different corrections, obtained as briefly summarized in the following.

$$\begin{aligned} K_{TS} &= K_{TM} + \Delta K_{T1} + \Delta K_{T2} + \Delta K_{T3} \\ K_{QS} &= K_{QM} + \Delta K_{Q1} + \Delta K_{Q2} + \Delta K_{Q3} \end{aligned} \qquad (1)$$

- *Viscous forces over the blades*

  Due to the laminar boundary layer separation existing in the pressure side of the CLT blades, some extra corrections must be introduced in addition to those included in ITTC'78. It has been checked that this scale effect can be taken into account by introducing in C_{DM} an additional term equal to $-\boldsymbol{\Delta C_M}$.

$$\begin{aligned} \Delta K_{T1} &= -0.3\,\Delta C_D\, H/D\, C_r/D\, Z \\ \Delta K_{Q1} &= 0.25\,\Delta C_D\, C_r/D \\ C_{DM} &= 2(1+2t/C_r)\,(0.044/\,\Re_M^{1/6} - 5/\Re_M^{2/3} - \boldsymbol{\Delta C_M}) \qquad (2) \\ C_{DS} &= 2(1+2t/C_r)\,(1.89 + 1.62\log(Cr/(30*10^{-6})))^{-2.5} \\ \Delta C_{DS} &= C_{DS} - C_{DM} \end{aligned}$$

- *Lift forces over the blades*

The scale effect corresponding to the lifting forces acting on the propeller blades annular section of a CLT propeller can be evaluated by means of these expressions. It is remarkable that this correction has no significant effect in the open water efficiency but in the matching of propeller rpm.

$$\Delta K_{T2} = \chi K_T$$
$$\Delta K_{Q2} = 0.7/2\, \chi K_T \tan(\beta_i) \qquad (3)$$

- *Viscous forces over the end plates*
  By projecting the viscous force acting on the tip plate at model field and at full scale on the direction of the shaft line and its perpendicular, taking moments and making non-dimensional the mathematical expression obtained, the following expressions are deduced:

$$\Delta K_{T3} = -0.5\, V^{*2}/(n^2D^4)\, S_t \sin(\gamma)\, \Delta C_D$$
$$\Delta K_{Q3} = 0.25\, V^{*2}/(n^2D^5)\, S_t(D+t_t) \cos(\gamma)\, \Delta C_D Z \qquad (4)$$
$$\Delta C_D = 2(1+K_T)\,(C_{FS} - C_{FM})$$
$$C_F = 0.075/(\log\Re-2)^2$$

The correlation coefficients $\mathbf{\Delta C_M}$ and χ, used in the scaling procedure, have an important influence in the predictions of the open water efficiency and have been empirically obtained by correlation among model tests results and reliable sea trials of the SISTEMAR data base and are continuously updated.

2.2. *SINM - Strip method*

The basic idea behind a strip method is to consider the global scale effect of the propulsor as the result of the individual scale effects relevant to each annular station of each propeller blade. This is achieved by dividing the propulsor into a series of annular "strips" for which lift and drag scale effects are computed.

The first advantage of this type of extrapolation in respect to the ITTC'78 method is that it is not needed to relay on a single "equivalent" profile, on the contrary the actual geometry of the propulsor can be accounted for. Therefore the real radial distribution of chord, thickness, pitch and camber, as well as the presence of "non-conventional" features (such as end plates) are duly taken into account.

A subsequent advantage is that the scale effects are calculated according to the flow conditions in way of each strip, therefore, instead of applying a "mean" scale effect to all profiles, the flow regimen at each profile can be evaluated both at model and full scale and compared (e.g. laminar flow, turbulent smooth, turbulent rough, and relevant transition regimens, presence of laminar separation).

The calculation routine, for each degree of advance, is as follows:

- Lift and drag coefficients and related forces are calculated, at each strip, both at model and full scale;
- Thrust and torque are calculated, at each strip, both at model and full scale;
- Thrust and torque are calculated by integration over the entire propulsor, both at model and full scale;
- Measured and Calculated model scale K_T and K_Q are compared;
- Calculated model scale K_T and K_Q are corrected to ensure identity with the measured ones;
- Calculated Full scale K_T and K_Q are corrected on the basis of the identity of model scale K_T and K_Q.

It should be noted that to operate at K_T and K_Q identity at model scale is needed for consistency, since the strip method is just a simplified hydrodynamic calculation of the propulsor, and therefore the calculated scale effects have to be weighed against the actual magnitude of the measured K_T and K_Q. It should be noted that constrain on K_Q identity is rather loose, being K_Q largely dependent on K_T,

The current implementation of the method allows to use different friction lines at model and full scale and it also allows to model scale effects on both lift and drag forces in case of laminar separation, a phenomenon that was found to play a large role in CLT propellers operating at model scale. The proposed approach takes advantage from the long experience on laminar-turbulent flow modelling on 2D wing shapes, able to capture very complex phenomena, which are nowadays still very difficult to be addressed with direct calculations, even applying advanced viscous codes. Moreover, its suitable calibration during years against a large database of experimental results in both model and full scale for CLT propellers, allows to successfully deal with scaling problems.

2.3. *UNIGE - Panel method*

Among the potential approaches, still extensively adopted for the design (lifting line, lifting surface) and for the analysis of the flow around marine propellers, Boundary Element/Panel Methods represent the most accurate way to exactly model the actual geometry of the propeller. Panel methods, moreover, may be applied as a design tool, coupled with optimization algorithms, thanks to their computational efficiency and good capabilities to rank different propeller geometries in terms of efficiency and cavitation avoidance/extension, as shown in Bertetta et al. [13] for a conventional CPP at different pitch settings.

In the case of CLT geometries, for which the presence of the endplate at the propeller tip may pose relevant issues for the application of traditional lifting line and lifting surface methods, BEM can be useful to reasonably account for the inviscid efficiency (Bertetta et al. [4], Gaggero and Brizzolara [7]) of the propeller and, if conveniently corrected, to partially evaluate the influence of the viscosity corrections, usually adopted in model scale, on the scaling of open water performances from model to full scale.

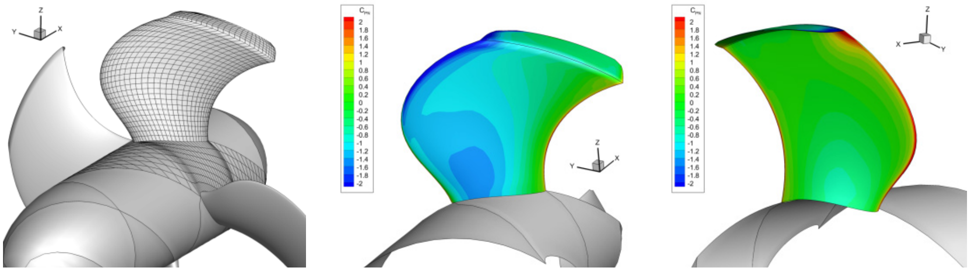

Figure 2: Surface mesh, based on hyperboloidal panels, for BEM computations and predicted inviscid pressure distributions on the suction and on the pressure side of the blade.

The prediction of the viscous forces, in principle neglected by the potential assumption, represents the core of the propeller performances scaling from model to full scale. A thin boundary layer solver, coupled through transpiration velocities to the inviscid solution, allows to obtain a local estimation of the frictional coefficient (naturally more accurate than the usual application of a drag correction coefficient to the inviscid forces) and, above all, even if partially, to account for the interaction and the mutual influence that the development of the boundary layer has on the inviscid pressure distribution. This approach, though being applied successfully for the analysis of conventional propellers (Hufford [8], Gaggero [9]) , poses some issues of convergence in very off design conditions and suffers from the tip influence on streamlines on which the "strip" boundary layer calculation is performed. Assuming, instead, that the inviscid pressure forces, naturally obtained by the panel method (Figure 2), are not influenced by the geometrical scale of the computation (i.e. neglecting the interaction with the boundary layer) a simpler, but reasonable, estimation of the viscous forces (both in model and in full scale, depending on the Reynolds number) can be carried out applying usual frictional line approaches. The frictional coefficient, radial section per radial section, can be computed employing the Van Oossanen formulation, based on local chord, thickness/chord and sectional chord Reynolds number. More accurately, as adopted in present computations, the influence of viscosity can be accounted for locally, on the basis of local inviscid flow features. In correspondence of each control point, on which inviscid velocities and pressure are computed by the BEM, also the local Reynolds number, assuming, as the reference length, the distance, on that radial section, of the control point from the section leading edge and, as velocity, that computed locally by the inviscid approach, can be evaluated. The resulting frictional coefficient (laminar or turbulent, depending on the Reynolds number itself and the frictional line assumption) can thus be applied to calculate the frictional forces. Scale effects are, consequently, taken into account directly through the estimation of the Reynolds number, not only in terms of changes in the frictional coefficient value but also in terms of empirical estimations of laminar/turbulent extensions. An example of calculations of model scale CLT propeller performances, compared with the experimental measurements, is shown in Figure 4 (right), showing a reasonably good accordance.

2.4. *VTT – RANS solver*

The RANS equations are solved by a finite volume method using the FINFLO code with the pressure correction method. In FINFLO, the solution is extended to the wall. A feature in the code is to separate flux calculation from the solution. Solutions in coarse grid levels are used as a starting point for the calculation in order to accelerate convergence. Three turbulence models were used in the computations: the SST k-ω, the Chien's low Reynolds number k-ε and the Spalart-Allmaras turbulence models. For the k-ε turbulence model the computations were carried out forcing low background turbulence in order to have a partial laminar flow and thus to obtain a pattern similar to that in paint tests with smooth surfaces. In Figure 3 some results in model scale in terms of pressure distribution and streamline are reported. As it can be seen, the k-ε computations present laminar flow detachment at the lower radii.

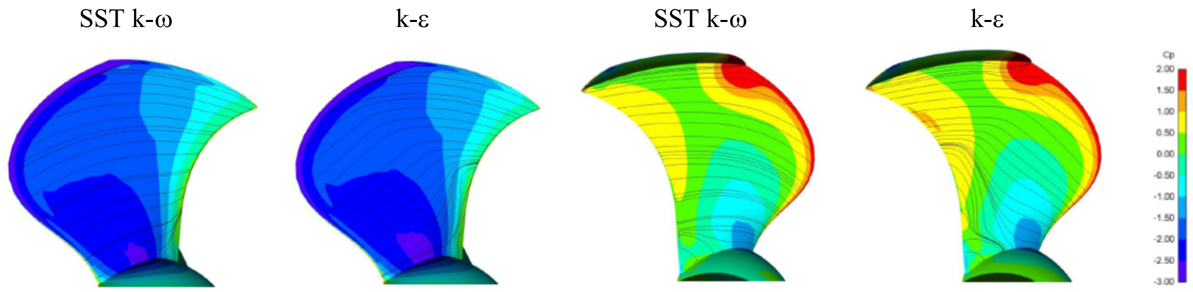

Figure 3: Streamlines from RANS on the suction (left) and pressure (right) sides of the blade at design condition.

Figure 4 (left) compares RANS numerical performance coefficients to model tests results. The thrust and torque coefficients are well predicted in the computations as well as the efficiency for Chien's k-ε model. The efficiency prediction for the SST k-ω model is somewhat underpredicted. The efficiency is larger with the k-ε model due to the lower skin friction connected to laminar flow. The calculations for propeller coefficients scaling will be made with the SST k-ω model, assuming at model scale also fully turbulent flow.

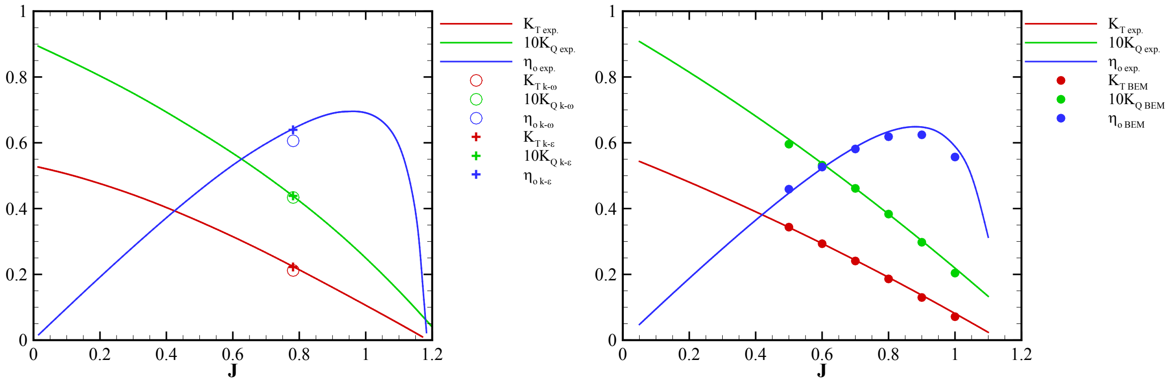

Figure 4: An example of calculations of CLT propellers open water tests – Comparison of numerically predicted and experimental results. RANS (left) and BEM (right) in model scale.

3. Test case

The high speed ferry "FORTUNY", shown in Figure 5 (right) of the Spanish company ACCIONA TRASMEDITERRANEA has been adopted as test case for the evaluation of different scaling procedures. The ship main particulars are summarized in Table 1. The ship is equipped with two shaft lines driven each one by a main engine of 14480kW, the propellers are of CP type, optimized for the absorption of 85% MCR at 183.8rpm. The 4.368m diameter CLT blades are shown in Figure 5 (right) and some relevant geometrical characteristics are, again, given in Table 1. The Open Water tests were carried out at CEHIPAR model basin at constant rate of revolutions (20 RPS) on the propeller model (scale 17.96) C-2465Br. Measurements from the experimental campaign are reported in Table 2.

Figure 5: M/V Fortuny (left) and CLT blades (right).

Table 1: Hull and Propeller main characteristics.

"Fortuny" high speed ferry		CLT 2465Br propeller			
L_{PP} [m]	157.00	D [m]	4.368	Pitch at tip [m]	5.1174
Beam [m]	26.20	Z	4	Chord at tip [m]	1.4056
Draft [m]	6.20	B.A.R.	0.52	f/c at tip	0.0079
		$P_{0.7R}/D$	1.108	End plate width [m]	0.2600
		Chord at 0.7r/R [m]	1.4796	End plate thickness [m]	0.0300
		t/c at 0.7r/R	0.0672		

Table 2: Model scale propeller performances.

J	K_{TM}	$10K_{QM}$	η_o	R_{NP} (10^6)	C_{TH}	J	K_{TM}	$10K_{QM}$	η_o	R_{NP} (10^6)	C_{TH}
0.1	0.5228	0.8774	0.0948	0.85645	133.13	0.6	0.2938	0.5372	0.5223	0.88684	2.0782
0.2	0.4803	0.8146	0.1877	0.85910	30.577	0.7	0.2430	0.4614	0.5867	0.89787	1.2628
0.3	0.4361	0.7492	0.2779	0.86349	12.339	0.8	0.1907	0.3831	0.6338	0.91042	0.7588
0.4	0.3903	0.6811	0.3648	0.86961	6.2118	0.9	0.1367	0.3023	0.6477	0.92445	0.4298
0.5	0.3429	0.6105	0.4470	0.87740	3.4928	1.0	0.0810	0.2189	0.5889	0.93987	0.2063

4. Comparison of results

Taken as a basis the model tests results of the test case, predictions for full scale has been computed using the different scaling methods (SISTEMAR Semi empirical corrections, SINM strip method, BEM, RANS) explained in section 2 of this paper, including the original ITTC'78 procedure. Figures 6 and 7 present the results of these methods for the scaling of K_T and $10K_Q$ and the resulting values of the Open Water Efficiency at ship scale.

Using the same values of resistance and propulsive coefficients (t, W_{ts} and η_r) derived from model tests (Gomez et al. [6]) and applying the different predicted Open Water values, curves of predicted shaft power values can be computed; these results, compared with the sea trials measurements, are shown in Figure 7 (right).

The results obtained can be commented as follows:

- Predictions made by applying ITTC'78 standard method to CLT propeller are far away from the sea trials results. This fact has been several times recognized by specialized Committees of ITTC (ITTC, [11]),
- All the methods, which are based on very different technical approaches, predict higher values of the Propulsive Efficiency of the CLT propellers at full scale, based on the same model tests results.
- The best approaches in this case to the sea trials results correspond to SISTEMAR scaling method and to the strip method used by SINM, thanks to the large database of experimental results gathered during years of activity,

- Panel method, despite providing a certain insight into the propeller flow and sufficiently good results in model scale, are not able by their nature to correctly capture all the scale related phenomena, such as the laminar flow detachment shown in Figure 3,
- RANS calculations are more suitable for this aim, nevertheless some discrepancies are still present, with the necessity of further improvements,
- At 23 knots, power predictions differences with respect to sea trials are 1% (SIST and SINM), 4% (RANS), 9% (BEM) and 13% (ITTC).

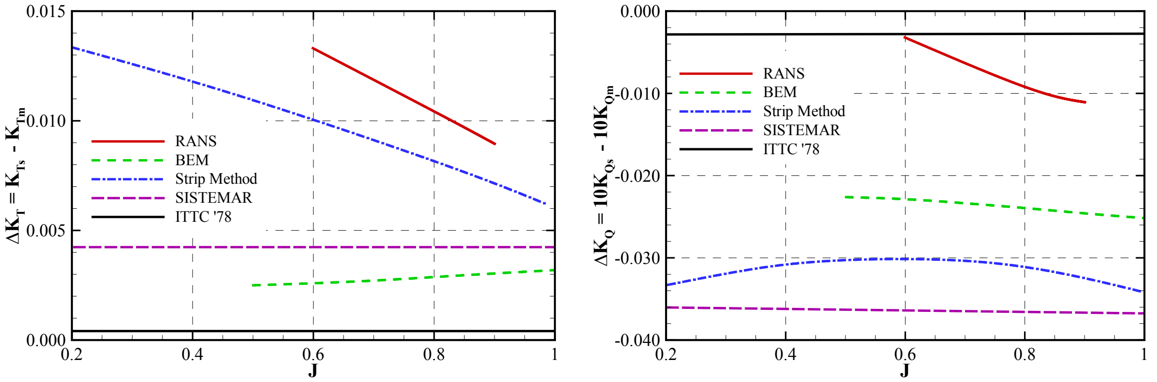

Figure 6: Scaling of K_T and $10K_Q$values obtained by different methods.

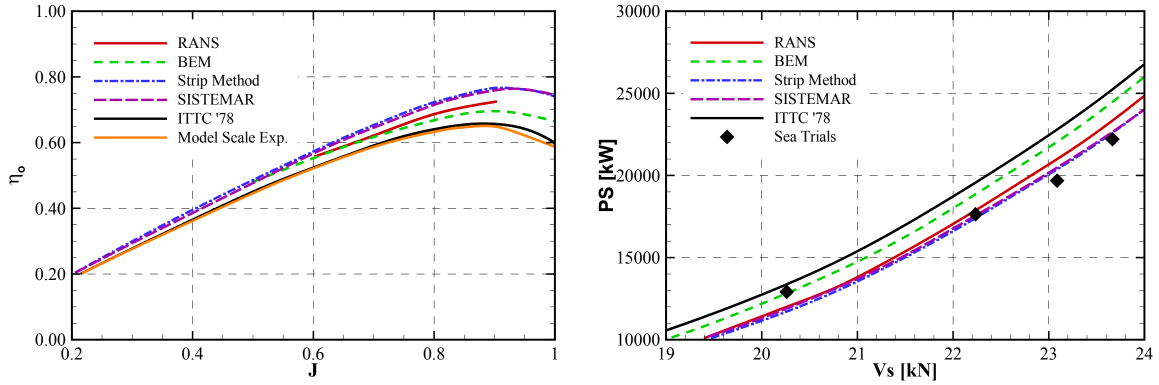

Figure 7: Scaled values of η_o (Open Water Efficiency) and of PS at ship scale obtained by the different methods.

5. Conclusions

CLT propellers are considered one of the most efficient and advanced propellers in order to obtain reductions of fuel consumption in maritime transportation with reliable applications to tankers, bulkers, containers and ferries.

Design studies of CLT propellers can be performed based on model tests results as in the case of conventional propellers, but scaling of CLT propellers from model tests results to full scale predictions must be performed by specific procedures different from the ITTC'78 standards. The main difference can be reduced to the scaling of the Open Water model tests results. Several technical approaches have been applied in this report to a test case showing in all cases a better prediction than simply adopting ITTC'78 standard procedures.

In particular Boundary Element/Panel methods (BEM) and other CFD method like the RANS solver FINFLO, presented in this report, show that the flow pattern developed on the blades of the CLT propellers are quite different than in the case of conventional propellers, being this fact probably the reason to need specific scaling procedures for this kind of propellers. The viscous effects in the end plate must be also taken into consideration. The complex phenomena present are correctly captured by semi-empirical approaches, thanks to the very large (and successful) database of data gathered during years, which allow for their suitable calibration.

To this aim, the direct approaches still fail in providing a comparable level of accuracy. Panel method, by its nature, does not allow to consider (if not with very large approximations) viscous related phenomena like flow separation; a correction of the code considering an approach similar to the strip one could improve the results, even if it could be too much related to particular cases, not having the general applicability which RANS codes could reach. Panel methods, however, on the light of a "design by optimization", may represent a reliable and computationally fast tool for the prediction of model scale propeller performances and for the design of optimal geometries, starting from which the calibrated scaling methodologies, like the strip methods, could give a reasonable estimation of full scale propeller characteristics. RANS represent a better approach than panel methods for a direct calculation of model and full scale propeller performances, showing already very good capabilities, even if currently further improvements would be needed in order to enhance their performances. To this aim, the continuous application to other different cases and the extension of the database of propeller analyzed could be very beneficial, as already demonstrated for the SINM and SISTEMAR approaches.

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