Scale effects in open water test results for performance prediction of conventional and unconventional propellers

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Abstract

ITTC'78 Performance Prediction Method is the only existing standard procedure approved by ITTC to carry out predictions of ship performance based in model tests results. It has been successfully applied from 1978 by towing tanks directly or introducing some variations. But it has been explicitly recognized by ITTC that this method must be only applied to conventional propellers and cannot be applied to Unconventional Tip Shape propellers.

This kind of propellers is one of the best options to save energy in marine propulsion. However, as at model scale these improvements are not clearly shown, the lack of a standard procedure to be applicable to this type of propellers reduces in many projects the possibilities to implement energy saving propellers.

In this study a new procedure will be explained in detail going a step deeper in the basic principles of viscous effects depending of the local section Reynolds number.

The validation work here presented confirms that ITTC'78-PPM is not useful to predict propulsion characteristics of unconventional tip shape propellers and that present proposed method predicts with reasonable accuracy propulsion characteristics of conventional and unconventional propellers, monoblock or CPP type and it is repetitive and easy to implement.

Keywords: Propellers, performance prediction, open-water tests, model to ship extrapolation, unconventional tip blade shape.

Resumen

El método ITTC'78-PPM es el único procedimiento estándar aprobado por la ITTC para llevar a cabo predicciones del comportamiento propulsivo del buque basadas en ensayos con modelos. Para hélices convencionales ha sido aplicado con éxito desde 1978 por los Canales de Experiencias directamente o con variaciones; pero ha sido reconocido por la propia ITTC que no se puede aplicar a los propulsores con formas no-convencionales del extremo de las palas.

Este tipo de hélices es una de las mejores opciones para ahorrar energía en la propulsión de buques. Sin embargo, los ensayos con modelos no detectan estas mejoras directamente y por consiguiente la falta de un método aceptado reduce las posibilidades de instalación de estas hélices con mejores rendimientos.

En este trabajo se explica en detalle un nuevo procedimiento avanzando un paso más en los principios físicos de la resistencia viscosa que depende del número de Reynolds local.

La validación realizada confirma que el método ITTC'78-PPM no se puede usar para hélices no-convencionales mientras que el método propuesto predice con una precisión razonable el comportamiento propulsivo de hélices convencionales y no-convencionales, sean de paso fijo o CPP, y que tiene un carácter repetitivo y es fácil de implantar.

Palabras clave: Propulsores, predicción del rendimiento propulsivo, ensayos de propulsor aislado, extrapolación modelo-buque, formas de extremo de pala no-convencionales.

Cita:
PÉREZ-SOBRINO, Mariano; GONZÁLEZ-ADALID, Juan; QUEREDA, Ramón; SORIANO, Cristina; MORÁN, Amadeo; GENNARO, Giulio. "Scale effects in open water test results for performance prediction of conventional and unconventional propellers". Ingeniería Naval Académica. 2016. Nº 5. Disponible en web: <http://sectormaritimo.es/numero-5-abril2016>. ISSN: 2340-4779

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1. Introduction

ITTC’78 Performance Prediction Method (1) (ITTC’78-PPM) has been successfully applied, directly or with some variations, in many Institutions, Towing Tanks and specialized companies from 1978 when it was recommended to be used by ITTC. This method includes a procedure to extrapolate propeller open water tests (OWT) results of conventional propellers from measurements at model scale to predictions at full scale. This has a large influence in the final values of power, rpm and propulsive coefficients predicted for full scale. However last ITTC Reports on propellers (2) have recognized that this method cannot be applied to others than conventional propellers, and in consequence have recommended to full Conference (that represents a very important part of the Hydrodynamics worldwide Community) to develop a standard procedure for the open water hydrodynamic characteristics scaling applicable to unconventional tip shape propellers as CLT, Kappel and tip raked type propellers.

Basic principle to apply corrections to OWT model results is the different Reynolds number of the model tests compared to full scale operation. That means that viscous effects in propeller blades are also different. In consequence propeller open water parameters K_T and K_Q measured at model scale must be corrected to obtain appropriated values to be used for predictions at full scale. Correction method for conventional propellers implemented in ITTC’78-PPM was based in an extensive work during several years before recommendation analyzing a lot of correlation data for many types of ships for which model tests and sea trials data were available (for instance see (3)). For new types of unconventional propeller blades this is not the case; there are not so many published data to allow sea trials results to be correlated with model tests results.

It is a fact that unconventional propellers have proved in many cases at full scale that ship propulsion efficiency increases with these types of propellers when comparing to conventional propellers; however at model scale this improvement is not clearly shown and therefore it is neither shown in the standard predictions of many experimental facilities. The lack of a standard procedure to be applicable to this type of propellers is many times an obstacle to the possibility to implement energy saving propellers. Perhaps for that reason a considerable amount of work has been made in recent years on this question.

In this study a new procedure based in the strip method will be derived to compute OWT corrections by applying different expressions of the friction line more in accordance with the expected type of flow in each section of the propeller blade, depending of the section Reynolds number. The simplification of equivalent profile in which ITTC’78-PPM is based will not be used anymore. So this new strip method would substitute only the calculation of OWT corrections but other components of ITTC’78-PPM will remain without changes.

The objectives of this report are to:

- Develop and describe in detail a new method to compute OWT corrections, being repetitive and easily applicable to any kind of propeller, conventional, end plate, curved rake tip, etc.
- Validate this method by applying it to a comprehensive set of propellers of conventional and unconventional types which data are available to the authors.
- Put a set of data relative to CLT propellers at the disposal of interested researchers.

2. Description of the new open water scaling procedure

2.1 OW corrections according to ITTC'78 PPM.

ITTC'78 method is used to predict rate of revolution and delivered power of a ship from model tests results. Viscous and residuary resistances of the ship are calculated from the model resistance test assuming the form factor to be independent of scale and speed. Standard predictions of rate of revolutions and delivered power are obtained from the full scale propeller characteristics. These characteristics are determined by correcting model values measured in OWT. These corrections are based in the assumption of the equivalent profile, substituting the whole blade for the station at 0.75 radius. Hence the propeller characteristics $K_T(J)$ and $K_Q(J)$ measured in Open Water model test have to be scaled to full scale using the following expressions:

$$K_{TS} = K_{TM} + \Delta K_T$$
$$K_{QS} = K_{QM} + \Delta K_Q$$

Where:

$$\Delta K_T = -\Delta C_D \cdot 0.3 \cdot \frac{P}{D} \cdot \frac{c \cdot Z}{D}$$
$$\Delta K_Q = \Delta C_D \cdot 0.25 \cdot \frac{c \cdot Z}{D}$$

The difference in drag coefficient ΔC_D is:

$$\Delta C_D = C_{DS} - C_{DM}$$

where:

$$C_{DM} = 2\left(1 + 2\frac{t}{c}\right)\left[\frac{0.044}{(R_{nco})^{\frac{1}{6}}} - \frac{5}{(R_{nco})^{\frac{2}{3}}}\right]$$

and

$$C_{DS} = 2\left(1 + 2\frac{t}{c}\right)\left(1.89 + 1.62 \cdot \log\frac{c}{k_p}\right)^{-2.5}$$

In the formulae listed above D is propeller diameter and Z is number of blades of propeller, c is the chord length, t is the maximum thickness, P/D is the pitch ratio and $Rnco$ is the local

Reynolds number at x= r/R= 0.75. The blade roughness *kp* is put to $kp=30.10^{-6}$ *m*. *Rnco* must not be lower than 2.10^5 at the open-water test.

All these formulae have been derived by using the equivalent profile theory that is a simplification of the blade element theory applied to the station x= 0.75.

Following main remarks must be taken into account about OWT corrections implemented in ITTC'78-PPM:

1.- This method is not able to distinguish different blade geometries due to the assumption of equivalent profile theory. In particular is not applicable for unconventional tip shaped propellers but even in case of blade geometries different from the "standard" type in use in the 1970's there can exist some inaccuracies. But this is a general method for conventional propellers very easy to apply and gives a good approximation to predict full scale performance from model tests within a large range of propeller diameters and model scales. Any new method that could be developed must give for conventional propellers similar corrections for scaling Open Water tests results.

2. The condition that *Rnco* must not be lower than 2.10^5 at the open-water test is the criterion generally accepted in order to avoid that laminar flow will be developed over the blade. But as this condition is usually applied to section 0.75R this not assures that there is not a significant part of the blade with laminar flow at lower radius.

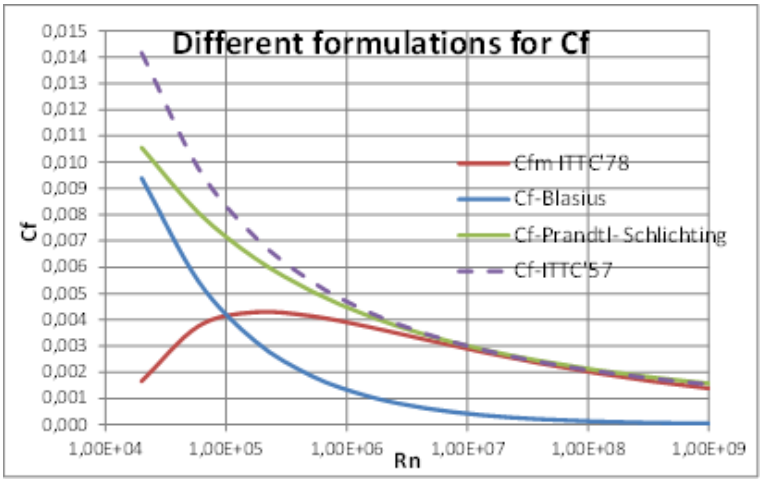

Figure 1: Comparison of different formulae for C_F.

3. It must be noticed that C_{DM} is calculated as function of *Rnco*, whilst C_{DS} is calculated based in the well-known formula derived by Prandtl and Schlichting for fully turbulent flow over roughness plates for high values of *Rn* where C_F values became independent of *Rn*. The assumption was that full scale blades had larger roughness than propeller models. Nowadays Class requirements for finishing of propeller blades have improved and it is not clear that this formula can be used for all cases.

4. However formula used for C_{DM} (or C_{Fm}) is a pragmatic approach that generates similar values that other formulae at turbulent R_n (>1.0 x 10^7), where it is not to be used, but at R_n corresponding to model tests (around 1.0 x 10^5) it matches the expression of Blasius for laminar flow, but it has a slope that avoid larger values of C_{Fm} in case that R_n of model would be lower than this value (Fig. 1). For model tests at R_n <1.0 x 10^5 it can produce results with no technical sense.

5. Calculations of OWT corrections according to ITTC'78-PPM must fulfil the conditions established in this procedure; but for different reasons sometimes the size of the model is not adequate or the value of *rps* of the test does not assure that laminar flow is not present. And in some marginal cases, when *D* of model is relatively small and *rps* of OWT are not high enough, the application of this procedure can generate corrections out of technical sense. A new version of this procedure that could take into account all this would be very useful.

2.2 Different possible approaches.

A new method must be developed trying to contribute to solve the problem that OWT corrections in ITTC'78-PPM, being based in the approach of the equivalent profile, that identifies the behavior of the whole blade with the behavior of the blade cylindrical section at 0,75R, make impossible to distinguish advanced forms of blade propellers like end plate, tip raked, etc.

Three main approaches have been published in recent years:

A) Semi-empirical methods. A good example of this method is the procedure published and applied by SISTEMAR and CEHIPAR to CLT designs (4). This method was based on the addition of new correlation coefficients for propeller blade and for end plate to the formulation used in ITTC'78-PPM. These coefficients have been adjusted to obtain a good correlation with sea trials results.

B) 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 effects. An example of these methods has been published (5) and it is applied at present in HSVA also in case of non-conventional propellers. There are several variants of this method depending mainly of the treatment of how to calculate C_D for model scale tests.

C) CFD based methods and/or Panel Methods. There are also several variants of these methods and several commercial or in-house developed available codes. General approach to use these methods to compute OWT corrections is to compute independently for model scale and full scale cases and correlate the results. This usually implies to use different mesh sizes, different turbulent models, to use of transition modelization or not, etc., being by the moment needed intensive use of large resources and time demanding. As the results depend not only of the code but of the user, it is very difficult to homologate a "standard" that can be used for many

people with same results. Quite a lot of research have been done for conventional and tip loaded propellers (7,8). Propulsion Committee of ITTC has at present open a benchmarking CFD exercise to compare results of different institutions using the same unconventional tip loaded and bent propeller P1727 designed by SVA Potsdam for an ongoing research project.

2.3 Development of new procedure.

The procedure presented in this study belongs to approach B). In this section a new method will be derived applying different expressions of the friction line more in accordance with the expected type of flow in each section of the propeller blade depending of the local Reynolds number. The simplification of equivalent profile will not be used anymore.

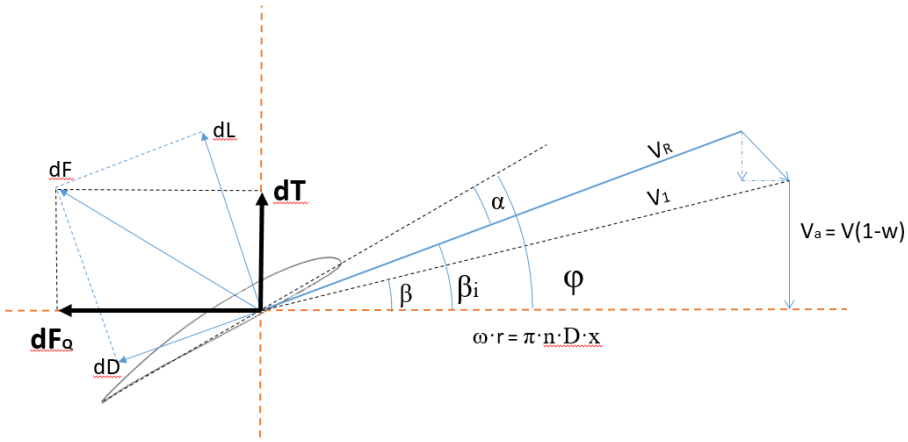

Figure 2: Diagram of velocities and forces in a blade section.

2.3.1 Basic formulation.

Starting expressions to derive the influence of viscosity in OW scaling came from blade element theory (see fig. 2):

$$dT = dL \cdot cos\beta_i - dD \cdot sen\beta_i$$
$$dF_Q = dL \cdot sen\beta_i + dD \cdot cos\beta_i$$
$$dQ = r \cdot dF_Q$$

$$C_D = \frac{dD}{\frac{1}{2}\rho \cdot V_R^2 \cdot 2 \cdot c \cdot dr} = \frac{dD}{\rho \cdot V_R^2 \cdot c \cdot dr}$$

C_D values are different in model tests and in full scale operation due to differences in Reynolds number and consequently different type of flow developed over blade surface. So assuming that there are not scaling effects in Lift, we can express the influence of a variation in C_D in OW coefficients:

$$\delta(dT) = -\delta(dD)\cdot sen\beta_i = -\delta(C_D)\cdot\rho\cdot V_R^2\cdot c\cdot dr\cdot sen\beta_i$$
$$\delta(dQ) = r\cdot\delta(dD)\cdot cos\beta_i = \delta(C_D)\cdot\rho\cdot V_R^2\cdot c\cdot r\cdot dr\cdot cos\beta_i$$

The Open Water coefficients K_T and K_Q:

$$K_T = \frac{T}{\rho\cdot n^2\cdot D^4} \qquad \text{and} \qquad K_Q = \frac{Q}{\rho\cdot n^2\cdot D^5}$$

$$K_{TS} = K_{Tm} + \delta K_T \qquad \text{and} \qquad K_{QS} = K_{Qm} + \delta K_Q$$

These corrections of the OW coefficients can be directly calculated from:

$$\delta K_T = \frac{z}{\rho\cdot n^2\cdot D^4}\int_{r_h}^{R+epw} -\delta(C_D)\cdot\rho\cdot V_R^2\cdot c\cdot sen\beta_i\cdot dr$$
$$\delta K_Q = \frac{z}{\rho\cdot n^2\cdot D^5}\int_{r_h}^{R+epw} \delta(C_D)\cdot\rho\cdot V_R^2\cdot c\cdot r\cdot cos\beta_i\cdot dr$$

According to Fig.2 we can assume:

$$V_1^2 = V_a^2 + (\pi nDx)^2 \quad \text{and} \quad V_R = V_1\cdot\cos(\beta_i - \beta)$$

$$\frac{V_R^2}{n^2\cdot D^2} = \frac{[V_a^2 + (\pi nDx)^2]\cdot\cos(\beta_i - \beta)}{n^2\cdot D^2}$$

We can also assume that *cos(βi-β)=1*, which is perfectly valid for slightly and moderately loaded propellers, being:

$$J = \frac{V_a}{n\cdot D}$$

so:

$$\frac{V_R^2}{n^2\cdot D^2} = [J^2 + (\pi\cdot x)^2]$$

And changing to the non-dimensional radius x=2r/D:

$$\delta K_T = -\frac{z}{2}\int_{x_h}^{1+epw/R} \delta(C_D)\cdot[J^2 + (\pi x)^2]\cdot\frac{c}{D}\cdot sen\beta_i\cdot dx$$

$$\delta K_Q = \frac{z}{4}\int_{x_h}^{1+epw/R} \delta(C_D)\cdot[J^2 + (\pi x)^2]\cdot\frac{c}{D}\cdot cos\beta_i\cdot x\cdot dx$$

Here *epw* means end plate width; and it express that the upper limit of the integral must be extended to the end of the tip plate if any.

In order to apply more easily this procedure it could be convenient to use βi≈φ where:

$$tg\varphi = \frac{P/D}{\pi x}$$

With these hypothesis calculations of δK_T and δK_Q can be made with only the geometrical data of the propeller blade as input:

$$\delta K_T = -\frac{z}{2}\int_{x_h}^{1+epw/R} \delta(C_D)\cdot[J^2+(\pi x)^2]\cdot\frac{c}{D}\cdot sen\varphi\cdot dx$$
$$\delta K_Q = \frac{z}{4}\int_{x_h}^{1+epw/R} \delta(C_D)\cdot[J^2+(\pi x)^2]\cdot\frac{c}{D}\cdot cos\varphi\cdot x\cdot dx$$

These formulae are valid for original CLT type propellers. Generalizing for propellers with any type of rake distribution (including CLT type) the integration must be performed using a non-dimensional curvilinear coordinate representing the length of the arc of the curve from the hub to the section considered (see fig. 3). In this way it is taken into account the differences in blade area generated by different rake distributions. It is indifferent to this procedure if the blade profiles are arranged in cylindrical sections or in conical sections arranged to be perpendicular to the rake line because it has no effect in the viscous resistance of the profile.

$$\delta K_T = -\frac{z}{2}\int_{s_{hub}}^{s_{tip}} \delta(C_D)\cdot[J^2+(\pi x)^2]\cdot\frac{c}{D}\cdot sen\varphi\cdot ds$$
$$\delta K_Q = \frac{z}{4}\int_{s_{hub}}^{s_{tip}} \delta(C_D)\cdot[J^2+(\pi x)^2]\cdot\frac{c}{D}\cdot cos\varphi\cdot x\cdot ds$$

Of course the relationship of variables *x* and *s* will depend of the type of rake distribution used.

All geometrical parameters used in these formulae, chord (c), pitch angle (ϕ) and thickness (t) correspond to each blade section, being necessary to know their distribution along the whole blade to perform these calculations. In this way this procedure will take into account different geometries of propeller blades.

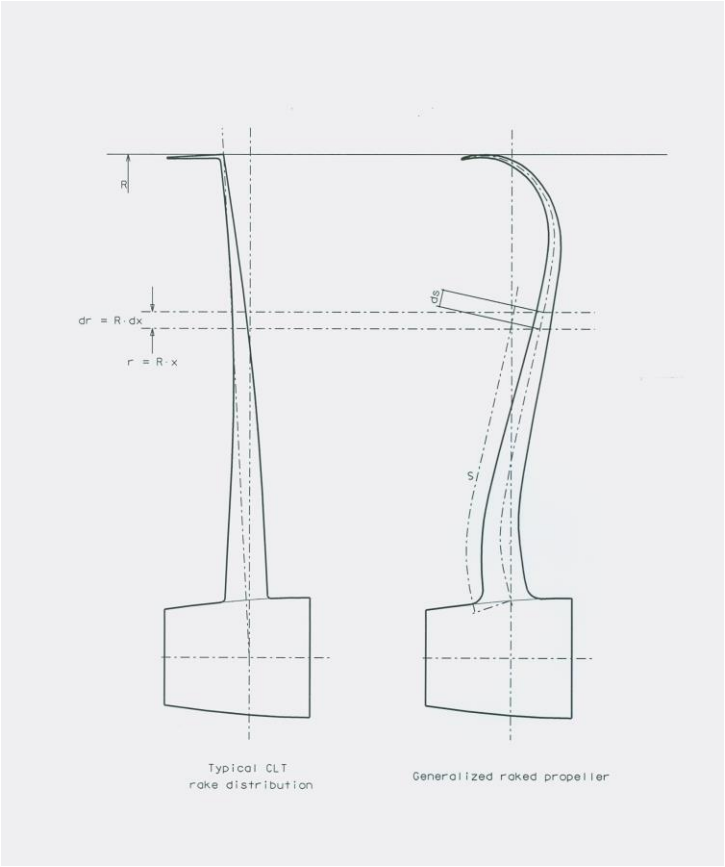

Fig. 3. Different rake distributions.

2.3.2. Viscous resistance coefficient of a section blade.

The main question is how to determine $\delta(C_D)$ that is the difference of viscous resistance of each blade section when operates at model scale and at full scale.

$$\delta(C_D) = C_{Ds} - C_{Dm}$$

It is well accepted that for the hydrodynamic profiles used in the propellers blade sections:

$$C_{Ds} = 2 \cdot \left(1 + 2\frac{t}{c}\right) \cdot C_{Fs} \quad \text{and} \quad C_{Dm} = 2 \cdot \left(1 + 2\frac{t}{c}\right) \cdot C_{Fm}$$

C_{Fm} and C_{Fs} are frictional coefficients of blade sections profiles that have been widely investigated in the past. These coefficients depend mainly on Reynolds number, surface roughness and type of flow developed.

In this procedure instead of to distinguish between model and full scale, and due to the good characteristics of blade finishing both at model and full scale nowadays, the question is to determine if the flow is laminar, or if it is in the so called transition zone or if it is fully turbulent.

For fully turbulent flow the well-known formula due to Prandtl and Schlichting for smooth plates can be used both for model and for full scale:

$$C_{FS} = \frac{0{,}455}{(\log R_n)^{2{,}58}}$$

where R_n is computed for each section blade. At ship scale the flow is generally turbulent, being:

$$R_{nx,ship} = \frac{n_{ship} \cdot D_{ship} \cdot c_{x,ship}}{\upsilon_{ship}} \left[J^2 + (x \cdot \pi)^2 \right]^{0.5}$$

These values are calculated using propeller rpm (rps) at design point.

2.3.3. Friction Coefficient at model scale.

But the problem appears at model scale; there are differences between different facilities on how to carry out OWT, although most of them try to follow ITTC procedures and recommendations (Rnco>2.10^5), this does not assure that flow in some part of the propeller blade could not be laminar or transitional. Paint tests carried out from some years ago and nowadays CFD calculations confirm also this fact.

In any case for model scale local R_n values computed for each annular section are also used:

$$R_{nx,\mathrm{mod}} = \frac{n_{\mathrm{mod}} \cdot D_{\mathrm{mod}} \cdot c_{x,\mathrm{mod}}}{\upsilon_{\mathrm{mod}}} \left[J^2 + (x \cdot \pi)^2 \right]^{0.5}$$

These values are calculated using propeller rpm (rps) of the Open Water tests that are usually carried out at constant rps varying carriage speed to measure at different J values.

When flow can be considered as laminar, the formula to be used is the well-known expression due to Blasius for laminar boundary layers on smooth surfaces [9]:

$$C_{Fm} = \frac{1{,}328}{\sqrt{R_n}}$$

For the purpose of this procedure and after the analysis of several cases of conventional and end plate propellers it has been established that there exists at each blade section a critical value of R_n to change from laminar regimen to transition zone, and that there exists another critical value of R_n above of that the flow is fully turbulent. These values depend mainly on the relative surface roughness of model blades as explained in the following:

Laminar flow. It is considered that flow will be always laminar until the critical *Rn* number:

$$R_n\ critical\ laminar\ to\ transition = 90 \cdot \frac{c}{k_p}$$

Where c is the chord of the blade section at model scale and k_p is the roughness of the propeller model. It has been considered $k_p = 20.10^{-6}\ m$ due to the better precision got in model fabrication nowadays.

That means that if a blade section is operating at R_n lower than this critical value (which depends also on the value of the chord at model scale) all the section is considered to be operating in laminar flow. If the sectional R_n is higher than this critical value probably there will be some extent of laminar flow until a point of the chord where a transition to turbulent flow will appear. For normal values of chords at model scale this expression for critical R_n gives values which correspond to the accepted limits for laminar flow in propeller section profiles.

Turbulent flow. Even at model scale the flow developed on the section blades will be turbulent if section R_n is larger than this critical number:

$$R_n\ critical\ turbulent = 415 \cdot \frac{c}{k_p}$$

The value of the constant used has been taken from (6) comparing the nominal size of the roughness grain of a section profile with the boundary-layer thickness, and it was established there that this criterion agrees very well with existing experimental data.

Transitional flow. In the middle of these two sectional critical R_n numbers, that depend on the chord of each section, there is a transition zone where there exists some uncertainty about the value of C_F. In fact flow would be partially laminar and partially turbulent along the chord of the section. The proposal is to interpolate with actual R_n of the section between the C_F values corresponding to laminar and turbulent limits. In this way the proposal does not include a specific friction line for transition zone but values of C_F in transition zone depend on each specific case and section data.

So in summary:

For	**Type of flow**	**C_F expression**
Rn<Rn critical laminar	Laminar	Blasius
Rn>Rn critical turbulent	Turbulent smooth	Prandtl-Schilchting
Rn crit lam<Rn<Rn crit turb	Transitional	Linear interpolation

Table 1: Resume table for the C_F used for different type of flow.

As an example, in fig. 4, values of C_{Fm} and C_{Fs} corresponding to the cylindrical sections of a case have been represented, at model scale and full scale, and including reference friction lines used in this procedure.

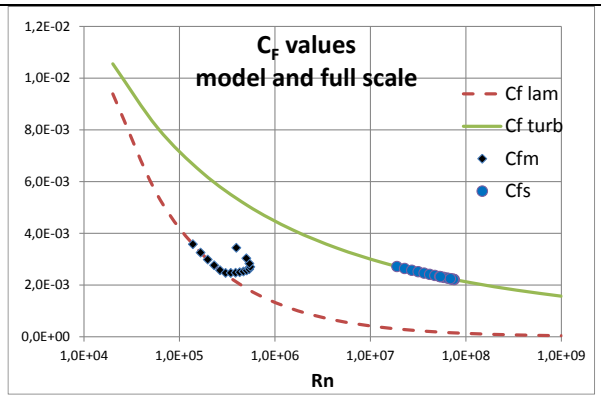

Figure 4: Values of C_F for laminar, transitional and turbulent regime of flow of each blade section.

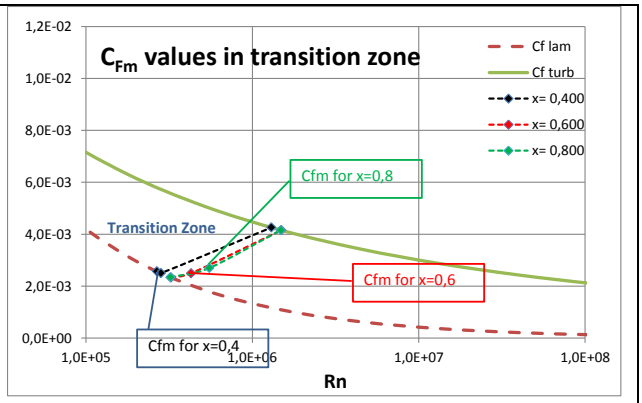

Figure 5: Values of C_{Fm} for some blade sections.

In fig. 5 a detail of three values of C_{Fm} of the same case are displayed. Value corresponding to x=0,4 is in laminar zone whilst values corresponding to x=0,6 and x=0,8 are in transition zone.

3. VALIDATION OF NEW METHOD.

This new procedure has been validated by analyzing a comprehensive set of OWT results, both for conventional and end plate tip loaded (CLT) propellers available to authors. Two criteria have been established to validate it:

Criterion for conventional propellers: corrections obtained with present method for conventional propellers have to match reasonably the values obtained with ITTC'78-PPM within a small tolerance;

Criterion for unconventional propellers: corrections obtained with present method for unconventional propellers must produce full scale predictions in accordance with sea trials results. A complete set of data with model tests results and sea trials measurements are needed for each case and unfortunately only CLT propellers cases are available to authors.

3.1. Application to conventional propellers.

A comprehensive set of calculations with conventional propellers, covering a wide range of number of blades, area and pitch ratios, have been carried out in order to show that this method generates in "normal" cases practically same values of corrections as ITTC'78-PPM. There are some marginal cases, like propellers of small D (at model or at full scale) or OWT carried out at low rps, where calculations can differ somehow; but for these marginal cases it must be noticed that ITTC'78-PPM can give also unexpected results, for instance that η_{0S} can be lower than η_{0m}.

Criteria used for selection of propeller models have been:

- 4, 5 and 6 blades
- Model diameter larger than 175mm
- Different area ratios and pitch ratios covering maximum range as possible

Next tables show main characteristics of propellers selected for this exercise taken mainly from data base of CEHIPAR.

CONV	Full scale data							Model test data		
prop ID	z=	D, m	Ae/Ao	P/D 0,75R	J design	Ktm	RPM design	Scale	RPS OW test	Dmod, mm
2021	4	5,200	0,620	0,664	0,460	0,126	184,0	25,500	16,00	203,92
2480-CPP	4	4,200	0,580	0,989	0,512	0,337	147,3	23,770	17,68	176,69
2197	4	5,900	0,620	0,723	0,480	0,139	97,4	28,800	18,00	204,86
2200	4	5,800	0,619	0,693	0,500	0,135	107,0	28,300	17,00	204,95
2204	4	6,100	0,600	0,698	0,480	0,117	97,4	26,700	16,00	228,46

Table 2: CONVENTIONAL propeller models used for validation, z=4.

CONV	Full scale data							Model test data		
prop ID	z=	D, m	Ae/Ao	P/D 0,75R	J design	Ktm	RPM design	Scale	RPS OW test	Dmod, mm
2495	5	8,250	0,780	1,013	0,700	0,1627	90,0	38,913	15,00	212,01
2473	5	2,850	0,646	1,171	0,850	0,2833	150,0	15,000	17,07	190,00
VP1304-CPP	5	3,000	0,779	1,635	1,000	0,399	260,0	12,000	15,00	250,00
2429	5	8,470	0,583	0,960	0,705	0,1764	220,0	36,385	11,00	232,79
2485	5	4,245	0,750	0,868	0,640	0,1776	91,0	20,000	14,27	212,25
2514	5	8,700	0,780	0,900	0,587	0,1875	84,4	39,430	18,00	220,64
2156	5	3,800	0,630	0,872	0,560	0,19	125,0	17,700	10,00	214,69
2166	5	5,690	0,660	0,843	0,570	0,163	107,0	26,600	15,00	213,91
2195	5	3,230	0,720	0,832	0,560	0,177	117,0	13,500	15,00	239,26
2214	5	5,862	0,630	0,782	0,530	0,149	102,0	26,600	17,00	220,38
2328	5	4,350	0,711	0,667	0,400	0,149	121,0	20,950	20,00	207,64
2458	5	3,600	0,700	0,912	0,395	0,246	193,8	14,400	10,16	250,00

Table 3: CONVENTIONAL propeller models used for validation, z=5.

Among the subset of propellers with 5 blades it has been included propeller VP1304 that is the design selected by propulsion committee of the 27th ITTC to initiate a benchmark test for CFD (Computational Fluid Dynamics) calculations to investigate the capabilities of CFD to predict scale effects on the propeller performance. This work is continued during 28th ITTC.

CONV	Full scale data							Model test data		
prop ID	z=	D, m	Ae/Ao	P/D 0,75R	J design	Ktm	RPM design	Scale	RPS OW test	Dmod, mm
2174	6	6,000	0,802	1,099	0,750	0,2207	85,0	27,000	11,50	222,22
1697	6	4,800	0,800	0,830	0,550	0,1648	122,0	21,500	14,00	223,26
1822	6	6,520	0,767	0,767	0,480	0,1621	97,0	31,000	14,00	210,32

Table 4: CONVENTIONAL propeller models used for validation, z=6.

The ranges of main characteristics of conventional propellers used for validation are represented in next figures:

- Pitch and area ratios in Fig. 6.
- Model diameter and OW test rps in Fig. 7.
- Values of Jdesign and corresponding Ktm in Fig. 8.

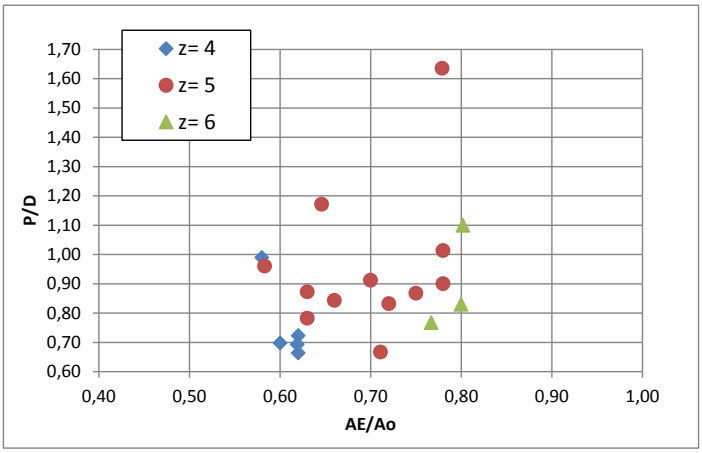

Figure 6: Set of conventional propellers used for validation. Pitch and area ratios.

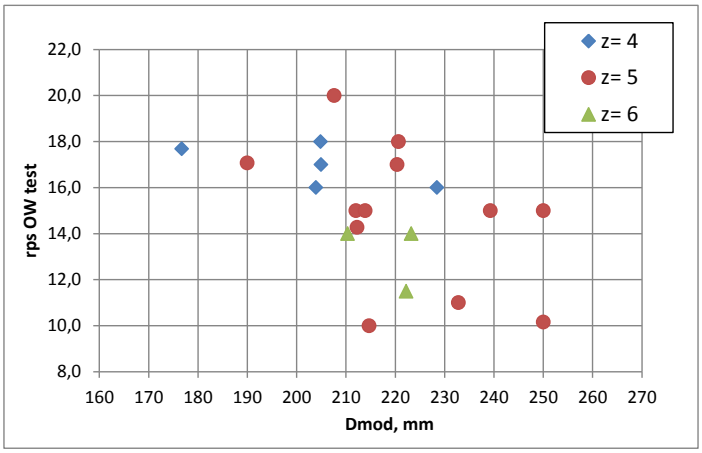

Figure 7: Set of conventional propellers used for validation. Model diameter and OW test rps.

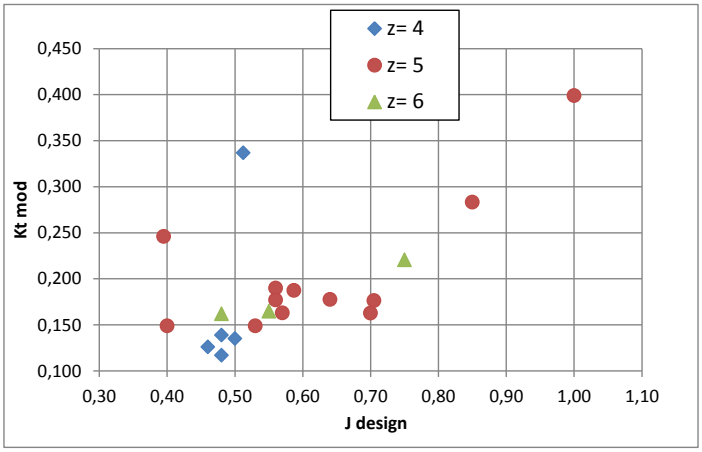

Figure 8: Set of conventional propellers used for validation. Values of Jdesign and corresponding Ktm of each conventional propeller used in validation.

It can appreciated in these figures that the propeller models used for this validation exercise are well distributed over a full range of main characteristics values so we can expect that most of conventional propellers will be within these ranges. There are 4, 5 and 6 bladed propellers and some of them are CPP type propellers, which demonstrate that the possibility of application of this strip method to any conventional type propeller is very high.

To compare calculations using this new strip method with results of ITTC'78-PPM next ratios have been calculated:

$$Ratio\ K_T = \frac{K_{TS\ (strip\ method)} - K_{TS\ (ITTC'78-PPM)}}{K_{TS\ (ITTC'78-PPM)}}\ (\%)$$

$$Ratio\ 10K_Q = \frac{10K_{QS\ (strip\ method)} - 10K_{QS\ (ITTC'78-PPM)}}{10K_{QS\ (ITTC'78-PPM)}}\ (\%)$$

$$Ratio\ \eta_0 = \frac{\eta_{0S\ (strip\ method)} - \eta_{0S\ (ITTC'78-PPM)}}{\eta_{0S\ (ITTC'78-PPM)}}\ (\%)$$

The dispersion of these ratios is presented in figure 9:

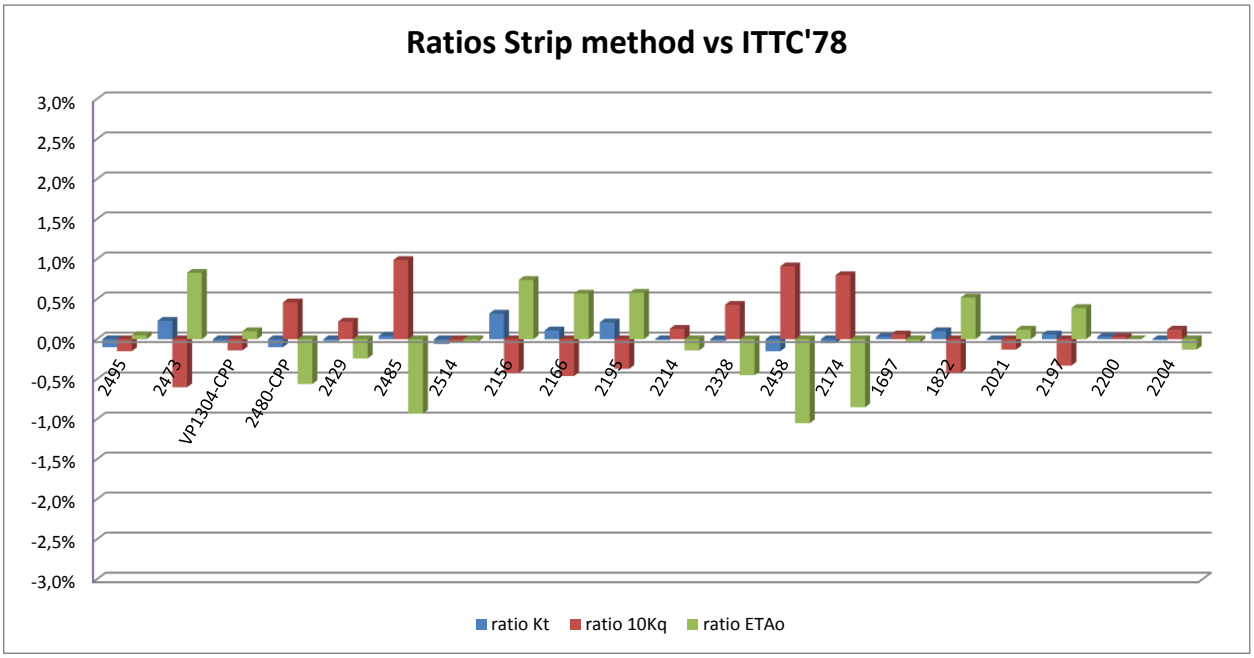

Figure 9: Distribution of comparison ratios used for validation in the case of CONVENTIONAL propellers.

It can be seen that ratios are within ±1.0% of results obtained using ITTC'78-PPM. In fact most of them are within ±0.5% meaning that both methods are almost equivalent when applied to conventional propeller. In the cases where these ratios are larger (always within ±1.0%) the differences can be explained in view of the special geometry of the corresponding propellers, so we consider these differences as an improvement of this strip method.

Data and detailed calculations for some of these conventional propellers are presented in Appendix A. These detailed calculations show some relevant results:

1.- It is common that, due to the standard conditions of Open Water tests, section blades are operating in laminar or transition flow and that the formulation established in this paper gives a good approximation to the results obtained until now with the well proven ITTC'78-PPM procedure, but allowing to distinguish the influence of different blade geometries in OW corrections. At full scale and depending of propeller characteristics and operating conditions in some cases appear that also some section blades near to hub are operating in a transitional flow.

2.- K_{TS} values are very close to that obtained by ITTC'78-PPM but $10K_{QS}$ values differs a little bit more which can be explained because the influence of $\delta(C_D)$ is larger in ΔK_Q than in ΔK_T; and because this new strip method computes viscous effects, which are main responsible for OW corrections, section by section instead of globally; so the small recorded differences are considered adequate and as an improvement over ITTC'78-PPM. These small differences will have small effects in the performance predictions of the propeller at full scale.

3.- In general it can be said that for conventional propellers present procedure can be comparable or almost equivalent to ITTC'78-PPM, being present strip method more able to establish small differences between different geometries of propellers with similar design conditions.

3.2. Application to unconventional propellers.

Main thesis of this study is that ITTC'78-PPM is not applicable to unconventional tip shape propellers; therefore validation of this new strip method must be done correlating predictions obtained by applying this method with sea trials results. To obtain predictions from model tests it is necessary that a full set of model tests data will be available and unfortunately authors only have data of their own projects with CLT propellers to perform this correlation. Authors do not know detailed published data of tests of other unconventional propellers but we expect that other interested designers will apply this method to their own projects and publish the corresponding results that hopefully will confirm the validity of this procedure.

In appendix B two cases have been studied and presented in detail. Both cases have been published in references (10) and (11) including ship-owners as authors.

First case is a series of four sister ships LEG carriers of 12000 cbm delivered in a reduced space of time (10). Detail data presented in appendix B1 include ship and propeller main particulars, resistance, Open Water and self-propulsion tests model faired raw data and sea trials results of four ships. Extrapolations have been carried out by both procedures present strip method and ITTC'78-PPM, and these correlation calculations show that present strip method gives very accurate predictions.

Second case is a twin shafts Ferry which data have been published in reference [11] and this propeller have also been used in several Research Projects funded by EU, LEADING-EDGE, SILENTV and AQUO. Only OW extrapolation data are presented but including the share of blade and end plate in the total effects ΔKt and ΔKq.

Comparison of the values of OWT corrections calculated by present strip method and ITTC'78-PPM both for conventional and for end plate propellers gives the explanation on how this strip method can give similar results to ITTC'78-PPM for conventional propellers and larger corrections in the case of unconventional tip loaded propellers. Physical interpretations of these results are coherent because viscous effects of end plate, in which are based the application of corrections to OWT, are less but of similar order of magnitude than effects of blade itself and must be added. ITTC'78-PPM cannot take these effects into account while present strip method does it.

4. Conclusions

The main conclusions of the present study are as follows:

Confirmation that ITTC'78-PPM is not useful to predict propulsion characteristics of unconventional tip shape propellers based in model tests results.

Present method, going a step deeper in the basic principles of viscous effects:
1.- Is easy to implement in any prediction method based in model tests results like ITTC'78-PPM or similar methods used by towing tanks and other institutions.
2.- Computes with reasonable accuracy corrections to be applied to OWT to predict propulsion characteristics of conventional and unconventional propellers, mono-block or CPP type.
3.- Has a repetitive character, so same result values will be obtained for different users with the same input data. This is not the case when using CFD codes because of complication of the codes and differences among users.

According to all that, authors believed that strip method presented in this paper can be a candidate to be used as a recommended procedure to calculate OWT corrections for any type of propellers being an improvement over ITTC'78-PPM.

It would be encouraging if other institutions having more data of different ships and propeller types could use this method checking and communicating their results.

In particular authors expected that ITTC next conference will take into account this new procedure and could confirm that it is a possibility that can be used for unconventional tip shaped propellers.

NOMENCLATURE

c, c_x	section chord	(m)
t	section thickness	(m)
R	propeller radius	(m)
D	propeller diameter	(m)
r	section radius	(m)
x	non-dimensional section radius= r/R	(–)
s	non-dimensional arc length of the curved rake	(-)
z	number of blades	(–)
K_T	Open Water thrust coefficient	(–)
K_Q, $10K_Q$	Open water torque coefficient	(–)
η_o	Open water propeller efficiency	(–)
J	Open water advance coefficient	(–)
P/D, H/D	Pitch-diameter ratio	(–)
A_E/A_o	Blade area ratio	(–)
C_F, Cf	Friction coefficient	(–)
C_D	Viscous coefficient	(–)
Rn, Rnco	Reynolds Number	(–)
k_p	Average roughness of a plate	(m)
v	kinematic viscosity of water	(m^2/s)
ITTC	International Towing Tank Conference	
OWT	Open Water Test	

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APPENDIX A- Detailed calculations for Conventional propellers

Some cases of the propeller listed in tables 2, 3 and 4 will be presented in detail in this appendix.

Case study A1- Propeller CEHIPAR-2480, CP Propeller type. 4 blades.

Propeller and Open Water tests data and calculations of ITTC'78 Open Water corrections:

PROPELLER DATA		
Prop nº	CONV-2480CPP	
Nº shafts=	1	
Nº blades=	4	
Diameter=	4,200	m
Ae/Ao=	0,580	
Scale=	23,770	
H/D(0.75R)=	0,9890	
c (0.75R)=	1,6595	m
t (0.75R)=	0,0721	m
t/c(0.75R)=	0,0434	
Design RPM=	147,3	rpm

OPEN WATER TEST DATA	
General Data	OWT
Test nº	E17528
Temp fresh water (ºC)=	11,1
Dens fresh water (Kg/m3)=	999,44
Visc fresh water (m2/s)=	1,2682E-06
Nº of J values	15
dens salt water (Kg/m3)=	1025,93
Visc salt water	1,1883E-06
Nº Reynolds mod.=	4,011E+05
rate of rev (rps)=	17,680

	CONV-2480		
X	H/D	Chord, m	Thickness, m
0,300	0,9686	0,7120	0,1844
0,350	0,9736	0,8660	0,1680
0,400	0,9779	1,0100	0,1551
0,450	0,9815	1,1440	0,1420
0,500	0,9845	1,2680	0,1300
0,550	0,9868	1,3800	0,1179
0,600	0,9886	1,4750	0,1060
0,650	0,9896	1,5530	0,0944
0,700	0,9900	1,6140	0,0831
0,750	0,9890	1,6595	0,0721
0,800	0,9793	1,6600	0,0613
0,850	0,9609	1,6155	0,0508
0,900	0,9338	1,5260	0,0406
0,950	0,8940	1,3050	0,0307
1,000	0,8414	0,0100	0,0210

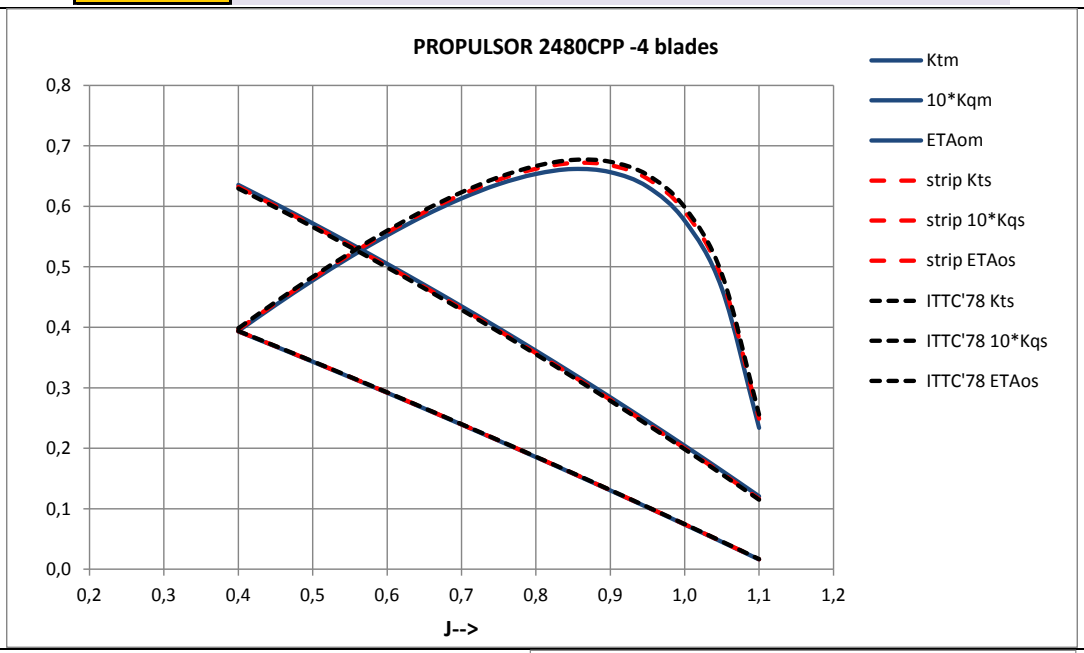
Open Water Results - MODEL SCALE			
J	Ktm	10*Kqm	ETAom
0,400	0,3932	0,6354	0,3940
0,450	0,3683	0,6040	0,4367
0,500	0,3431	0,5718	0,4775
0,550	0,3176	0,5388	0,5160
0,600	0,2918	0,5049	0,5519
0,650	0,2657	0,4702	0,5846
0,700	0,2392	0,4347	0,6130
0,750	0,2125	0,3984	0,6367
0,800	0,1854	0,3612	0,6535
0,850	0,1581	0,3232	0,6618
0,900	0,1303	0,2843	0,6565
0,950	0,1023	0,2446	0,6324
1,000	0,0739	0,2041	0,5763
1,050	0,0452	0,1628	0,4640
1,100	0,0161	0,1206	0,2337

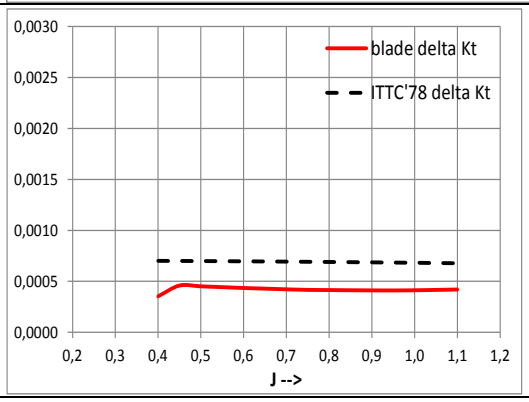
OWT corrections according to ITTC'78-PPM

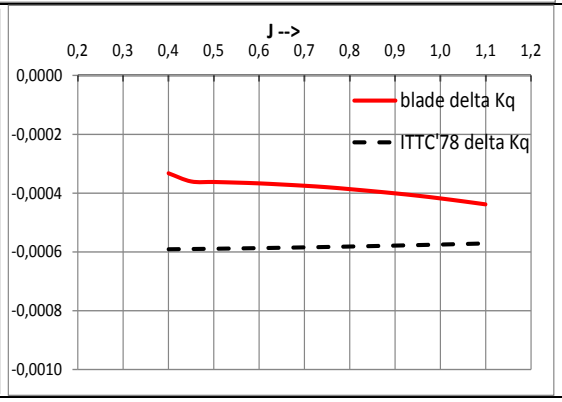
kp=	3,000E-05					ship			
CDs=	7,665E-03		ITTC'78	ITTC'78	ITTC'78	ITTC'78	ITTC'78	ITTC'78	ITTC'78
Js	Rnm	CDm	delta CD	delta Kt	delta Kq	Kts	10*Kqs	ETAos	Kt/J2s
0,4000	3,844E+05	9,161E-03	-1,495E-03	7,012E-04	-5,908E-04	0,3939	0,6295	0,3984	2,4619
0,4500	3,860E+05	9,159E-03	-1,493E-03	7,002E-04	-5,900E-04	0,3690	0,5981	0,4419	1,8222
0,5000	3,878E+05	9,156E-03	-1,491E-03	6,991E-04	-5,891E-04	0,3438	0,5659	0,4834	1,3752
0,5500	3,898E+05	9,154E-03	-1,488E-03	6,979E-04	-5,880E-04	0,3183	0,5329	0,5228	1,0522
0,6000	3,920E+05	9,151E-03	-1,485E-03	6,966E-04	-5,869E-04	0,2925	0,4990	0,5597	0,8125
0,6500	3,944E+05	9,148E-03	-1,482E-03	6,951E-04	-5,857E-04	0,2664	0,4643	0,5935	0,6305
0,7000	3,969E+05	9,144E-03	-1,479E-03	6,936E-04	-5,844E-04	0,2399	0,4289	0,6232	0,4896
0,7500	3,996E+05	9,141E-03	-1,476E-03	6,919E-04	-5,830E-04	0,2132	0,3926	0,6482	0,3790
0,8000	4,024E+05	9,137E-03	-1,472E-03	6,902E-04	-5,815E-04	0,1861	0,3554	0,6667	0,2908
0,8500	4,055E+05	9,133E-03	-1,468E-03	6,883E-04	-5,800E-04	0,1588	0,3174	0,6768	0,2198
0,9000	4,086E+05	9,129E-03	-1,464E-03	6,864E-04	-5,783E-04	0,1310	0,2785	0,6737	0,1617
0,9500	4,120E+05	9,125E-03	-1,459E-03	6,843E-04	-5,766E-04	0,1030	0,2388	0,6520	0,1141
1,0000	4,155E+05	9,120E-03	-1,455E-03	6,822E-04	-5,748E-04	0,0746	0,1984	0,5984	0,0746
1,0500	4,191E+05	9,115E-03	-1,450E-03	6,800E-04	-5,729E-04	0,0459	0,1571	0,4881	0,0416
1,1000	4,229E+05	9,110E-03	-1,445E-03	6,776E-04	-5,710E-04	0,0168	0,1149	0,2557	0,0139

Calculation of Open Water corrections by present Strip Method:

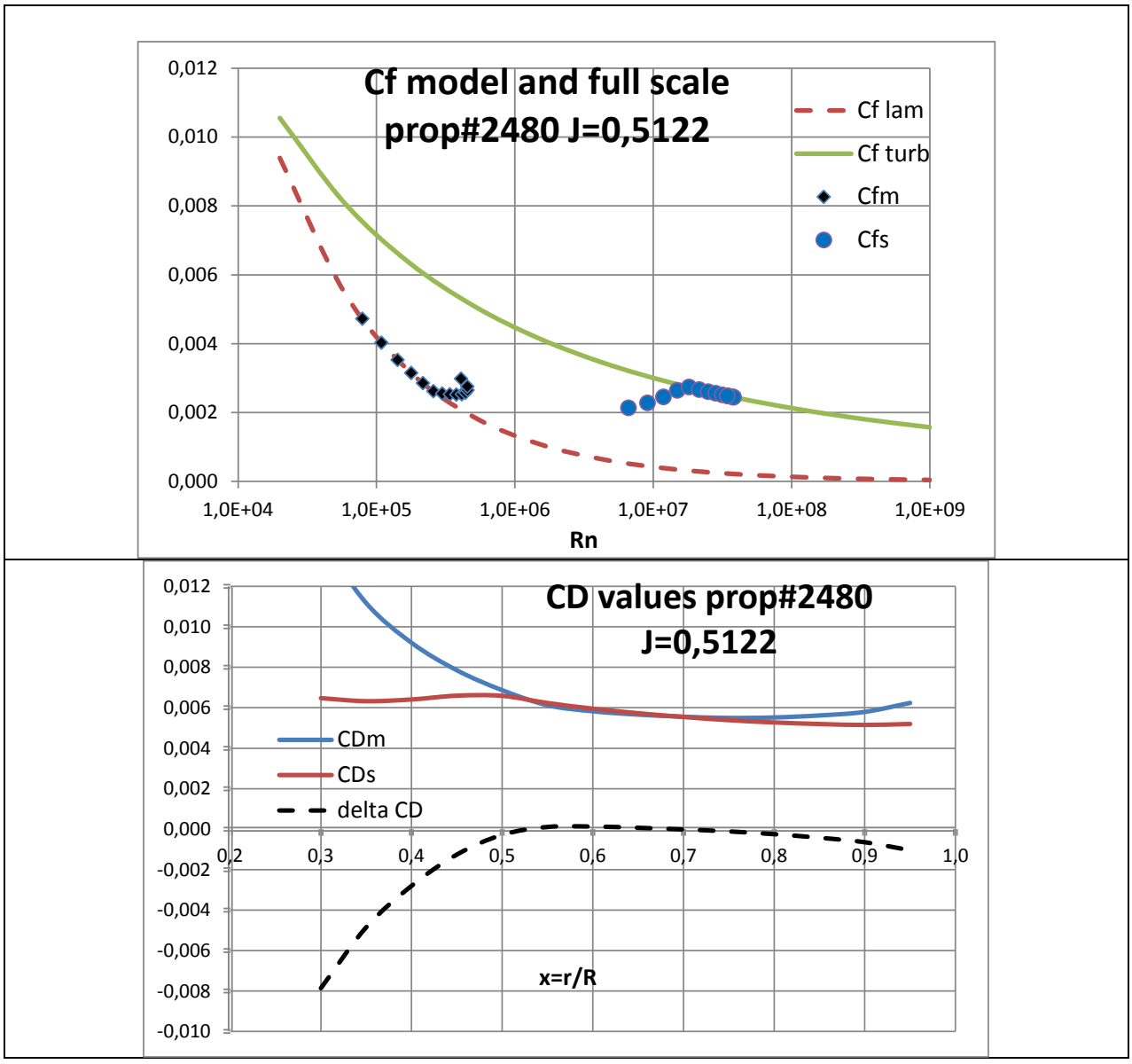
	OWT corrections according to present strip method				
	blade	blade	strip blade	strip blade	strip blade
Js	delta Kt	delta Kq	Kts	10*Kqs	ETAos
0,4000	3,531E-04	-3,324E-04	0,3936	0,6321	0,3964
0,4500	4,589E-04	-3,602E-04	0,3688	0,6004	0,4399
0,5000	4,513E-04	-3,620E-04	0,3436	0,5682	0,4812
0,5500	4,431E-04	-3,642E-04	0,3180	0,5352	0,5202
0,6000	4,349E-04	-3,667E-04	0,2922	0,5012	0,5568
0,6500	4,285E-04	-3,706E-04	0,2661	0,4665	0,5902
0,7000	4,219E-04	-3,748E-04	0,2396	0,4310	0,6195
0,7500	4,165E-04	-3,798E-04	0,2129	0,3946	0,6441
0,8000	4,146E-04	-3,863E-04	0,1858	0,3573	0,6621
0,8500	4,129E-04	-3,933E-04	0,1585	0,3193	0,6717
0,9000	4,114E-04	-4,007E-04	0,1307	0,2803	0,6680
0,9500	4,108E-04	-4,087E-04	0,1027	0,2405	0,6457
1,0000	4,125E-04	-4,178E-04	0,0743	0,1999	0,5916
1,0500	4,161E-04	-4,278E-04	0,0456	0,1585	0,4809
1,1000	4,201E-04	-4,382E-04	0,0165	0,1162	0,2489







Detailed analysis of values of C_F and C_D of section profiles at model and full scale, at design J=0.5122:



This case shows that developed strip method applied to a conventional CP propeller gives similar final results than ITTC'78-PPM. According to the strip method there appear that some sections of propeller model blades are operating in laminar flow and others in transition zone; but at full scale there are also some sections operating in transition flow conditions.

Case study A2- 28th ITTC benchmark CP propeller VP1304. 5 blades.

Propeller and Open Water tests data and Calculations of ITTC'78 Open Water corrections:

PROPELLER DATA		
Prop nº	VP1304	
Nº shafts=	1	
Nº blades=	5	
Diameter=	3,000	m
Ae/Ao=	0,779	
Scale=	12,000	
H/D(0.75R)=	1,6307	
c (0.75R)=	1,2762	m
t (0.75R)=	0,0453	m
t/c(0.75R)=	0,0355	
Design RPM=	260,0	rpm

OPEN WATER TEST DATA	
General Data	OWT
Test nº	E17035
Temp fresh water (ºC)=	15,05
Dens fresh water (Kg/m3)=	998,94
Visc fresh water (m2/s)=	1,1395E-06
Nº of J values	15
dens salt water (Kg/m3)=	1025,93
Visc salt water	1,1883E-06
Nº Reynolds mod.=	9,621E+05
rate of rev (rps)=	17,070

	VP1304		
X	H/D	Chord, m	Thickness, m
0,300	1,3985	0,5400	0,1619
0,350	1,4575	0,6750	0,1443
0,400	1,5054	0,7850	0,1279
0,450	1,5443	0,8950	0,1126
0,500	1,5759	0,9750	0,0985
0,550	1,6009	1,0600	0,0855
0,600	1,6197	1,1300	0,0737
0,650	1,6317	1,2000	0,0631
0,700	1,6360	1,2500	0,0536
0,750	1,6307	1,2762	0,0453
0,800	1,6136	1,2850	0,0381
0,850	1,5815	1,2785	0,0321
0,900	1,5309	1,2500	0,0273
0,950	1,4573	1,1300	0,0236
1,000	1,3559	0,9200	0,0211

Open Water Results - MODEL SCALE			
J	Ktm	10*Kqm	ETAom
0,200	0,8663	1,8638	0,1479
0,300	0,8107	1,7475	0,2215
0,400	0,7514	1,6292	0,2936
0,500	0,6902	1,5115	0,3634
0,600	0,6288	1,3964	0,4300
0,700	0,5685	1,2851	0,4929
0,800	0,5100	1,1780	0,5512
0,900	0,4536	1,0749	0,6044
1,000	0,3994	0,9749	0,6520
1,100	0,3468	0,8761	0,6930
1,200	0,2949	0,7761	0,7258
1,300	0,2425	0,6716	0,7470
1,400	0,1878	0,5588	0,7486
1,500	0,1285	0,4330	0,7087
1,600	0,0623	0,2888	0,5493

OWT corrections according to ITTC'78-PPM

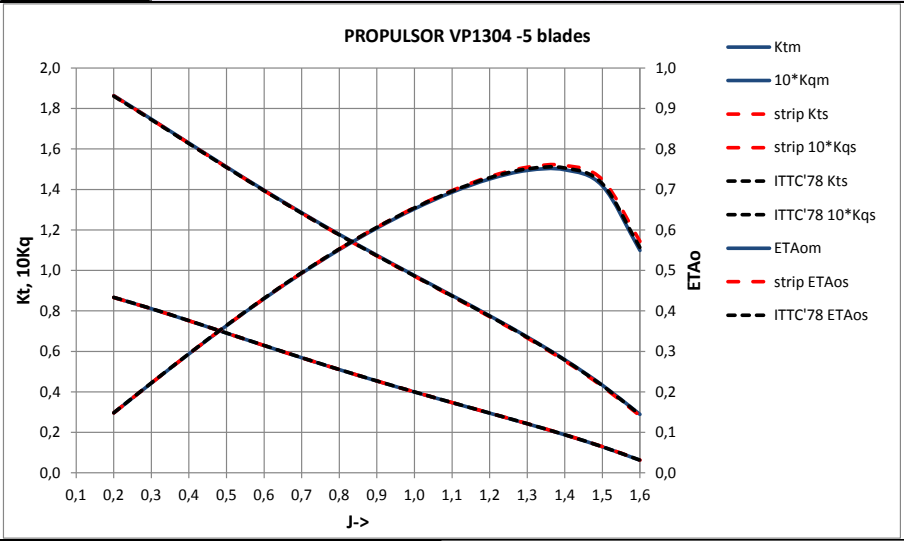
kp= 3,000E-05
CDs= 7,930E-03

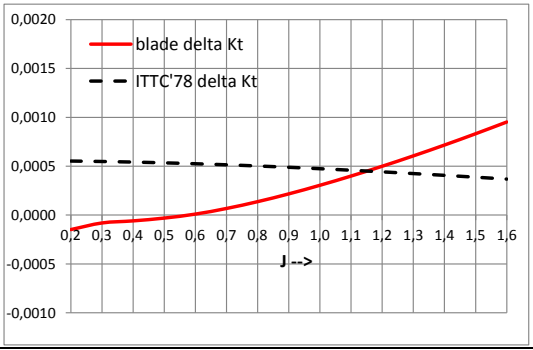
				ITTC'78	ITTC'78	ship			
Js	Rnm	CDm	delta CD	delta Kt	delta Kq	Kts	10*Kqs	ETAos	Kt/J2s
0,2000	8,795E+05	8,462E-03	5,312E-04	5,528E-04	-2,825E-04	0,8668	1,8610	0,1483	21,6702
0,3000	8,840E+05	8,457E-03	5,270E-04	5,484E-04	-2,802E-04	0,8113	1,7447	0,2220	9,0143
0,4000	8,902E+05	8,451E-03	5,212E-04	5,423E-04	-2,771E-04	0,7519	1,6264	0,2943	4,6994
0,5000	8,982E+05	8,444E-03	5,137E-04	5,346E-04	-2,732E-04	0,6907	1,5087	0,3643	2,7629
0,6000	9,079E+05	8,435E-03	5,048E-04	5,253E-04	-2,684E-04	0,6294	1,3937	0,4312	1,7482
0,7000	9,191E+05	8,425E-03	4,945E-04	5,145E-04	-2,629E-04	0,5690	1,2824	0,4943	1,1612
0,8000	9,320E+05	8,413E-03	4,828E-04	5,024E-04	-2,567E-04	0,5105	1,1754	0,5529	0,7976
0,9000	9,464E+05	8,400E-03	4,700E-04	4,890E-04	-2,499E-04	0,4541	1,0724	0,6065	0,5606
1,0000	9,621E+05	8,386E-03	4,559E-04	4,744E-04	-2,424E-04	0,3998	0,9725	0,6544	0,3998
1,1000	9,793E+05	8,371E-03	4,409E-04	4,588E-04	-2,345E-04	0,3472	0,8737	0,6958	0,2870
1,2000	9,978E+05	8,355E-03	4,250E-04	4,422E-04	-2,260E-04	0,2954	0,7738	0,7290	0,2051
1,3000	1,017E+06	8,339E-03	4,082E-04	4,248E-04	-2,171E-04	0,2429	0,6694	0,7508	0,1437
1,4000	1,038E+06	8,321E-03	3,907E-04	4,066E-04	-2,078E-04	0,1882	0,5568	0,7530	0,0960
1,5000	1,060E+06	8,303E-03	3,726E-04	3,877E-04	-1,981E-04	0,1289	0,4310	0,7141	0,0573
1,6000	1,083E+06	8,284E-03	3,540E-04	3,683E-04	-1,882E-04	0,0627	0,2869	0,5562	0,0245

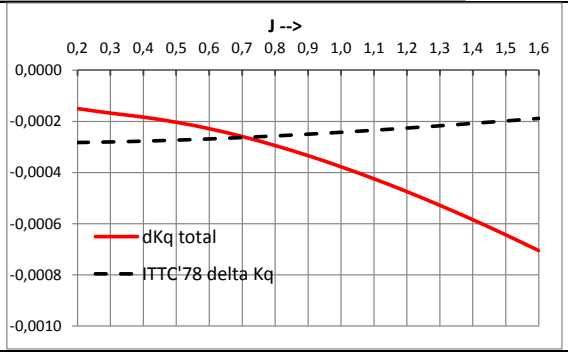
Calculation of Open Water corrections by present Strip Method:

OWT corrections according to present strip method

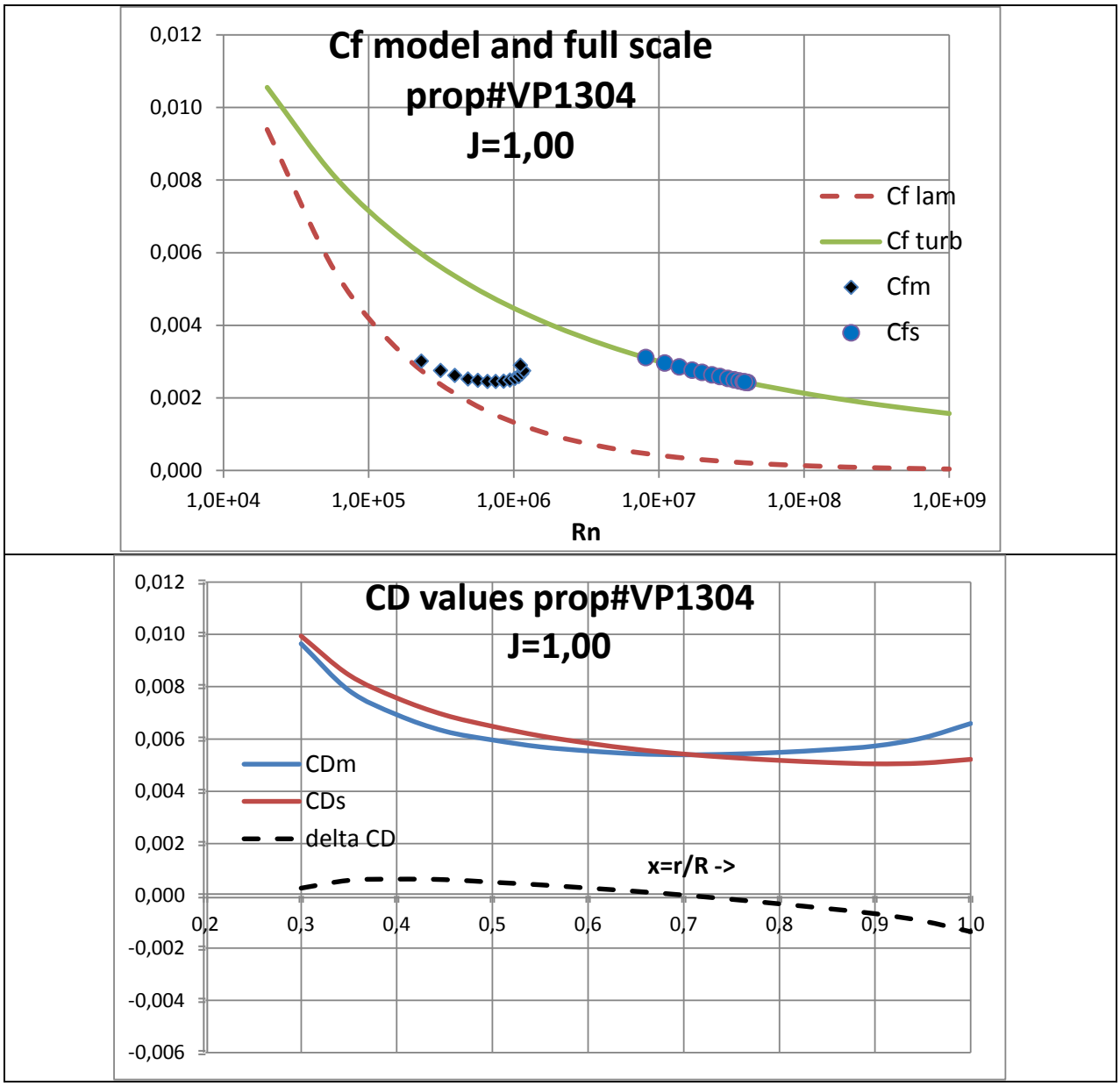
Js	blade delta Kt	blade delta Kq	strip blade Kts	strip blade 10*Kqs	strip blade ETAos
0,2000	-8,836E-05	-2,195E-04	0,8662	1,8616	0,1481
0,3000	-6,560E-05	-2,322E-04	0,8107	1,7452	0,2218
0,4000	-3,390E-05	-2,498E-04	0,7513	1,6267	0,2940
0,5000	7,529E-06	-2,723E-04	0,6902	1,5088	0,3640
0,6000	6,323E-05	-3,003E-04	0,6289	1,3934	0,4310
0,7000	1,278E-04	-3,329E-04	0,5686	1,2817	0,4942
0,8000	2,015E-04	-3,700E-04	0,5102	1,1743	0,5531
0,9000	2,839E-04	-4,114E-04	0,4539	1,0708	0,6071
1,0000	3,735E-04	-4,567E-04	0,3997	0,9703	0,6557
1,1000	4,697E-04	-5,057E-04	0,3472	0,8710	0,6979
1,2000	5,721E-04	-5,583E-04	0,2955	0,7705	0,7325
1,3000	6,801E-04	-6,141E-04	0,2432	0,6655	0,7560
1,4000	7,934E-04	-6,730E-04	0,1885	0,5521	0,7609
1,5000	9,114E-04	-7,348E-04	0,1295	0,4257	0,7260
1,6000	1,034E-03	-7,992E-04	0,0633	0,2808	0,5743







Detailed analysis of values of C_F and C_D of section profiles at model and full scale, at J=1.00:



Case study A3- Propeller CEHIPAR-1697, FP Propeller. 6 blades.

Propeller and Open Water tests data and Calculations of ITTC'78 Open Water corrections:

PROPELLER DATA		
Prop nº	CONV-1697	
Nº shafts=	1	
Nº blades=	6	
Diameter=	4,800	m
Ae/Ao=	0,800	
Scale=	21,500	
H/D(0.75R)=	0,8303	
c (0.75R)=	1,4113	m
t (0.75R)=	0,0594	m
t/c(0.75R)=	0,0421	

OPEN WATER TEST DATA	
General Data	OWT
Test nº	
Temp fresh water (ºC)=	15
Dens fresh water (Kg/m3)=	998,95
Visc fresh water (m2/s)=	1,1410E-06
Nº of J values	15
dens salt water (Kg/m3)=	1025,93
Visc salt water	1,1883E-06
Nº Reynolds mod.=	4,054E+05
rate of rev (rps)=	14,00

	CONV-1697		
X	H/D	Chord, m	Thickness, m
0,200	0,6979	0,9611	0,1890
0,250	0,7173	1,0385	0,1745
0,300	0,7353	1,1095	0,1600
0,350	0,7517	1,1740	0,1451
0,400	0,7667	1,2320	0,1310
0,450	0,7804	1,2838	0,1176
0,500	0,7926	1,3287	0,1050
0,550	0,8033	1,3666	0,0947
0,600	0,8126	1,3975	0,0852
0,650	0,8201	1,4166	0,0763
0,700	0,8260	1,4212	0,0677
0,750	0,8303	1,4113	0,0594
0,800	0,8329	1,3868	0,0512
0,850	0,8339	1,3263	0,0427
0,900	0,8331	1,1943	0,0340
0,950	0,8304	0,9590	0,0255
1,000	0,8250	0,0100	0,0194

Open Water Results - MODEL SCALE			
J	Ktm	10*Kqm	ETAom
0,100	0,3741	0,4744	0,1255
0,150	0,3553	0,4545	0,1866
0,200	0,3352	0,4332	0,2463
0,250	0,3139	0,4105	0,3043
0,300	0,2915	0,3866	0,3600
0,350	0,2681	0,3612	0,4135
0,400	0,2436	0,3346	0,4635
0,450	0,2181	0,3068	0,5091
0,500	0,1918	0,2779	0,5492
0,550	0,1648	0,2481	0,5815
0,600	0,1371	0,2177	0,6014
0,650	0,1088	0,1869	0,6022
0,700	0,0799	0,1558	0,5713
0,750	0,0503	0,1248	0,4811
0,800	0,0205	0,0943	0,2773

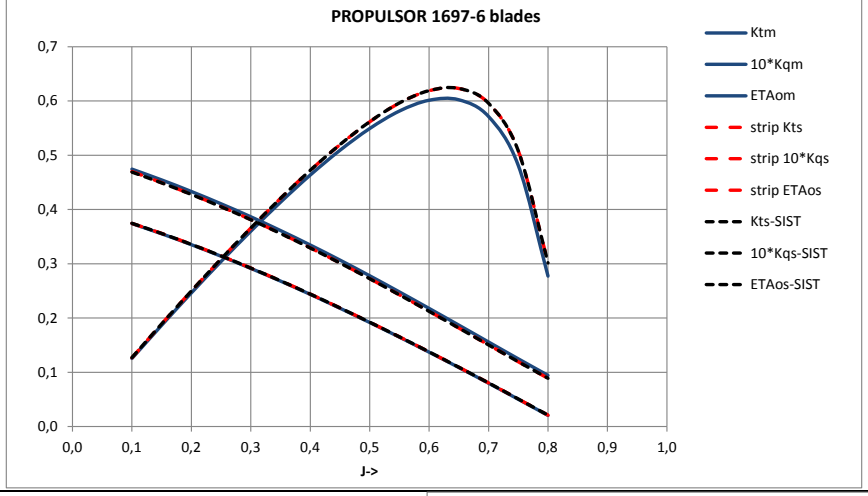
OWT corrections according to ITTC'78-PPM

kp= 3,000E-05
CDs= 7,879E-03

				ITTC'78	ITTC'78	ship			
Js	Rnm	CDm	delta CD	delta Kt	delta Kq	Kts	10*Kqs	ETAos	Kt/J2s
0,1000	3,958E+05	9,124E-03	1,244E-03	5,468E-04	-5,488E-04	0,3746	0,4689	0,1271	37,4616
0,1500	3,963E+05	9,123E-03	1,244E-03	5,465E-04	-5,485E-04	0,3558	0,4490	0,1892	15,8154
0,2000	3,971E+05	9,122E-03	1,243E-03	5,461E-04	-5,481E-04	0,3357	0,4277	0,2499	8,3937
0,2500	3,980E+05	9,121E-03	1,242E-03	5,456E-04	-5,476E-04	0,3144	0,4050	0,3089	5,0311
0,3000	3,991E+05	9,120E-03	1,240E-03	5,450E-04	-5,469E-04	0,2920	0,3811	0,3659	3,2449
0,3500	4,004E+05	9,118E-03	1,238E-03	5,442E-04	-5,462E-04	0,2686	0,3557	0,4207	2,1930
0,4000	4,019E+05	9,116E-03	1,236E-03	5,433E-04	-5,453E-04	0,2441	0,3291	0,4722	1,5259
0,4500	4,036E+05	9,114E-03	1,234E-03	5,424E-04	-5,443E-04	0,2186	0,3014	0,5196	1,0797
0,5000	4,055E+05	9,111E-03	1,232E-03	5,413E-04	-5,432E-04	0,1923	0,2725	0,5618	0,7694
0,5500	4,076E+05	9,108E-03	1,229E-03	5,401E-04	-5,420E-04	0,1653	0,2427	0,5964	0,5466
0,6000	4,099E+05	9,105E-03	1,226E-03	5,388E-04	-5,407E-04	0,1376	0,2123	0,6191	0,3823
0,6500	4,123E+05	9,102E-03	1,223E-03	5,374E-04	-5,393E-04	0,1093	0,1815	0,6232	0,2588
0,7000	4,150E+05	9,099E-03	1,219E-03	5,358E-04	-5,378E-04	0,0804	0,1504	0,5957	0,1642
0,7500	4,178E+05	9,095E-03	1,216E-03	5,342E-04	-5,362E-04	0,0508	0,1194	0,5080	0,0904
0,8000	4,208E+05	9,091E-03	1,212E-03	5,325E-04	-5,345E-04	0,0211	0,0890	0,3015	0,0329

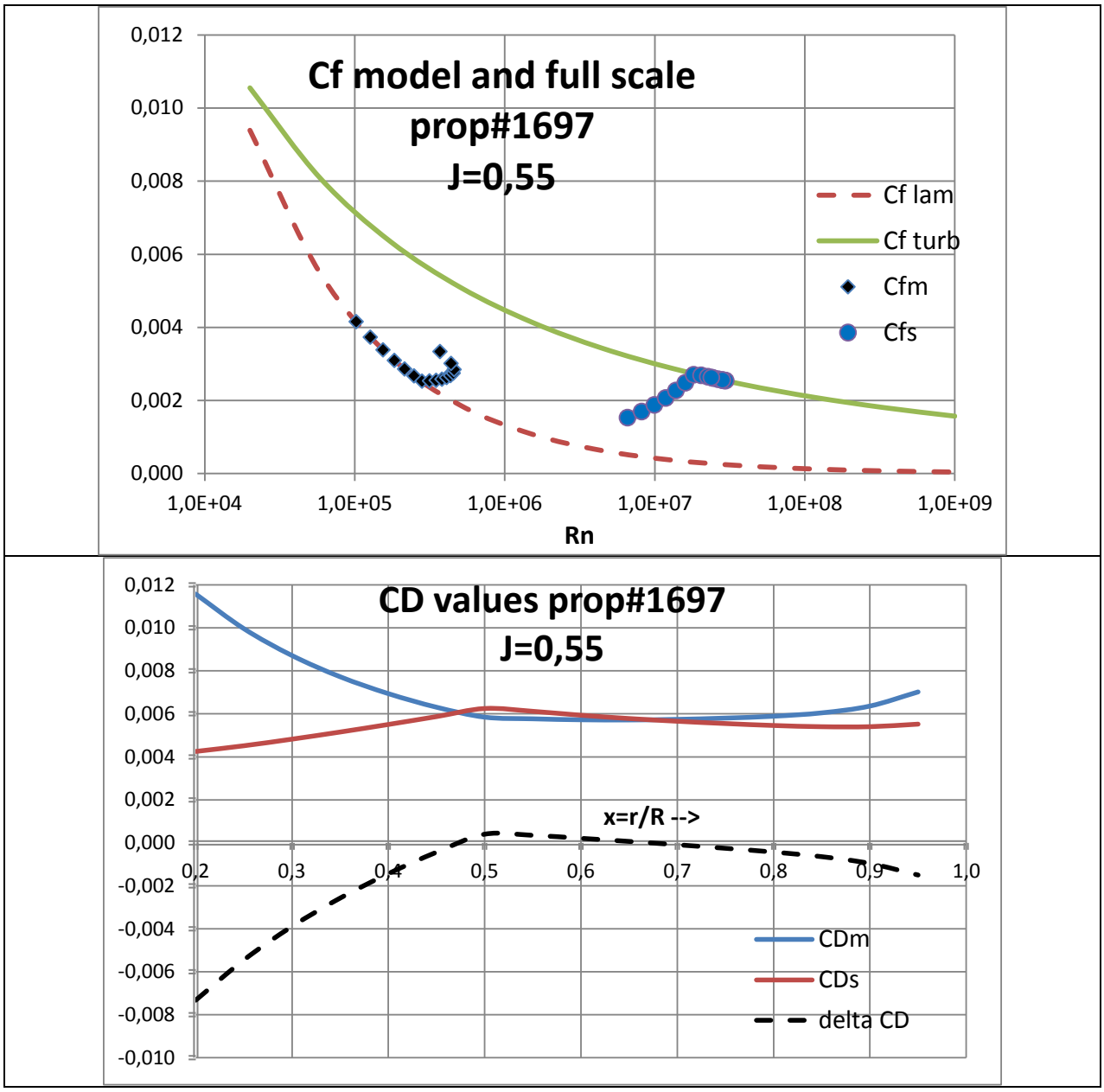
Calculation of Open Water corrections by present Strip Method:

	OWT corrections according to present strip method				
	blade	blade	strip blade	strip blade	strip blade
Js	delta Kt	delta Kq	Kts	10*Kqs	ETAos
0,1000	3,457E-04	-4,324E-04	0,3744	0,4701	0,1268
0,1500	6,797E-04	-5,216E-04	0,3560	0,4493	0,1892
0,2000	6,728E-04	-5,218E-04	0,3359	0,4280	0,2498
0,2500	6,641E-04	-5,220E-04	0,3146	0,4053	0,3088
0,3000	6,538E-04	-5,223E-04	0,2922	0,3814	0,3658
0,3500	6,420E-04	-5,227E-04	0,2687	0,3560	0,4205
0,4000	6,289E-04	-5,233E-04	0,2442	0,3294	0,4721
0,4500	6,146E-04	-5,240E-04	0,2187	0,3016	0,5194
0,5000	5,997E-04	-5,251E-04	0,1924	0,2726	0,5616
0,5500	5,846E-04	-5,269E-04	0,1654	0,2428	0,5962
0,6000	5,689E-04	-5,289E-04	0,1377	0,2124	0,6189
0,6500	5,546E-04	-5,322E-04	0,1094	0,1816	0,6230
0,7000	5,404E-04	-5,361E-04	0,0804	0,1504	0,5957
0,7500	5,260E-04	-5,405E-04	0,0508	0,1194	0,5081
0,8000	5,115E-04	-5,452E-04	0,0211	0,0889	0,3016



Other case of conventional propeller where OWT corrections calculated by present strip method and ITTC'78-PPM present a very good agreement.

Detailed analysis of values of C_F and C_D of section profiles at model and full scale, at J=0.7022:



APPENDIX B- Detailed calculations for Unconventional CLT propellers

Case study B1- LEG Carrier 12k cbm. This case is to be published in the 38th Motorship Propulsion & Emissions Conference to be held in Hamburg, 11-12 May 2016 (10).

Propeller and model tests faired raw data are:

PROPELLER DATA		
Prop nº	CLT1-pm5400	
Nº ejes=	1	
Nº palas=	4	
Diámetro=	5,400	m
Ae/Ao=	0,445	
Design RPM=	110,0	rpm
H/D(0.75R)=	0,9237	
c (0.75R)=	1,2126	m
t (0.75R)=	0,1017	m
t/c(0.75R)=	0,08387	
H @ 1.0R=	5,1670	m
H/D(1.0R)=	0,9569	
c (1.0R)=	1,0914	m
end plate width=	0,2000	m
end plate max thickness=	0,0200	m
m/c(1.0R)=	0,0101	

OPEN WATER TEST DATA	OWT
Test nº	P-19109
Temp fresh water (ºC)=	15,5
Dens fresh water (Kg/m3)=	998,83
Visc fresh water (m2/s)=	1,1245E-06
Nº of J values	15
dens salt water (Kg/m3)=	1025,81
Visc salt water	1,1883E-06
Nº Reynolds mod.=	3,82E+05
rate of rev (rps)=	18,000
Scale=	25,048

General Tests Data

	Resistance	Self-Prop.
Temp fresh water (ºC)	16,9	16,9
Dens fresh water (kg/m3)	998,64	998,64
Visc fresh water (m2/s)	1,084E-06	1,0844E-06

	CLT1-pm5400		
X	H/D	Chord, m	Thickness, m
0,200	0,7315	0,9806	0,2300
0,250	0,7865	1,0146	0,2176
0,300	0,8306	1,0479	0,2051
0,350	0,8636	1,0797	0,1926
0,400	0,8855	1,1096	0,1799
0,450	0,8965	1,1368	0,1671
0,500	0,9019	1,1608	0,1542
0,550	0,9074	1,1810	0,1412
0,600	0,9128	1,1968	0,1282
0,650	0,9183	1,2075	0,1150
0,700	0,9237	1,2126	0,1017
0,750	0,9292	1,2115	0,0884
0,800	0,9346	1,2036	0,0749
0,850	0,9401	1,1882	0,0613
0,900	0,9457	1,1648	0,0476
0,950	0,9513	1,1327	0,0339
1,000	0,9569	1,0914	0,0200

Open Water Results - MODEL SCALE

J	Ktm	10*Kqm	ETAom
0,250	0,3250	0,4492	0,2879
0,300	0,3080	0,4305	0,3416
0,350	0,2902	0,4105	0,3938
0,400	0,2717	0,3893	0,4443
0,450	0,2525	0,3668	0,4930
0,500	0,2324	0,3430	0,5392
0,550	0,2117	0,3180	0,5827
0,600	0,1902	0,2917	0,6227
0,650	0,1679	0,2642	0,6574
0,700	0,1449	0,2354	0,6858
0,750	0,1212	0,2053	0,7047
0,800	0,0967	0,1740	0,7076
0,850	0,0715	0,1415	0,6836
0,900	0,0455	0,1077	0,6051
0,950	0,0189	0,0726	0,3936

SHIP DATA	BALLAST	
Lpp=	134,500	m
Lwl=	134,400	m
Los=	135,000	m
B=	21,600	m
Tpr=	4,500	m
Tpp=	6,500	m
Vol=	11391	m3
Wetted Surf.	3369	m2
Append. Surf.	54	m2
AEV=	503	m2

Model measurements of reistance and self-propulsion tests

VS	RTm	THRUST mod	TORQUE mod	REV mod	Friction Ded.
nudos	N	N	Nm	rps	N
13,50	23,46	21,19	0,6697	7,03	6,09
14,00	25,33	23,14	0,7296	7,33	6,47
14,50	27,28	25,08	0,7895	7,62	6,86
15,00	29,24	27,04	0,8501	7,90	7,26
15,50	31,23	29,06	0,9131	8,18	7,67
16,00	33,35	31,21	0,9800	8,47	8,09
16,50	35,65	33,55	1,0528	8,77	8,52
17,00	38,12	36,15	1,1336	9,09	8,96
17,50	40,72	39,08	1,2243	9,43	9,41

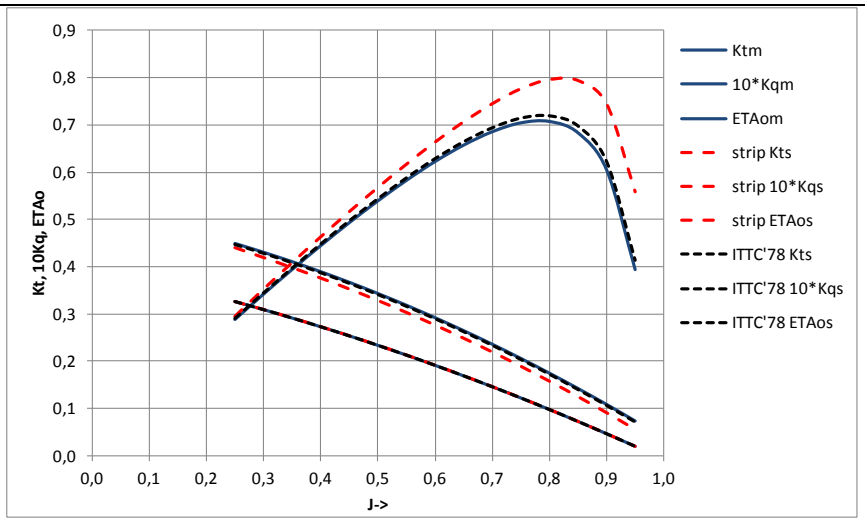
Analysis of OWT extrapolation (ITTC'78-PPM vs. present strip method):

OWT corrections according to ITTC'78-PPM

kp=	3,000E-05					SHIP			
CDs=	8,730E-03			ITTC'78	ITTC'78	ITTC'78	ITTC'78	ITTC'78	ITTC'78
Js	Rnm	CDm	delta CD	delta Kt	delta Kq	Kts	10*Kqs	ETAos	Kt/J2s
0,2500	3,698E+05	9,863E-03	1,132E-03	2,818E-04	-2,543E-04	0,3253	0,4467	0,2898	5,2045
0,3000	3,708E+05	9,861E-03	1,131E-03	2,815E-04	-2,540E-04	0,3083	0,4280	0,3439	3,4253
0,3500	3,720E+05	9,860E-03	1,129E-03	2,811E-04	-2,536E-04	0,2905	0,4080	0,3966	2,3713
0,4000	3,734E+05	9,858E-03	1,127E-03	2,806E-04	-2,531E-04	0,2720	0,3868	0,4477	1,6999
0,4500	3,750E+05	9,855E-03	1,125E-03	2,800E-04	-2,526E-04	0,2528	0,3643	0,4970	1,2483
0,5000	3,768E+05	9,853E-03	1,123E-03	2,794E-04	-2,521E-04	0,2327	0,3405	0,5438	0,9307
0,5500	3,787E+05	9,850E-03	1,120E-03	2,788E-04	-2,515E-04	0,2120	0,3155	0,5882	0,7008
0,6000	3,808E+05	9,847E-03	1,117E-03	2,780E-04	-2,508E-04	0,1905	0,2892	0,6290	0,5291
0,6500	3,831E+05	9,844E-03	1,114E-03	2,772E-04	-2,501E-04	0,1682	0,2617	0,6648	0,3981
0,7000	3,856E+05	9,841E-03	1,110E-03	2,764E-04	-2,493E-04	0,1452	0,2329	0,6944	0,2963
0,7500	3,882E+05	9,837E-03	1,107E-03	2,755E-04	-2,485E-04	0,1215	0,2028	0,7149	0,2160
0,8000	3,909E+05	9,833E-03	1,103E-03	2,745E-04	-2,477E-04	0,0970	0,1715	0,7199	0,1515
0,8500	3,939E+05	9,829E-03	1,099E-03	2,735E-04	-2,467E-04	0,0718	0,1390	0,6984	0,0993
0,9000	3,970E+05	9,825E-03	1,094E-03	2,724E-04	-2,458E-04	0,0458	0,1052	0,6230	0,0565
0,9500	4,002E+05	9,820E-03	1,090E-03	2,713E-04	-2,447E-04	0,0192	0,0702	0,4132	0,0212

OWT corrections according to present strip method

			strip	strip	strip
Js	dKt total	dKq total	Kts	10*Kqs	ETAos
0,2500	6,003E-04	-1,009E-03	0,3256	0,4391	0,2950
0,3000	7,720E-04	-1,227E-03	0,3088	0,4182	0,3525
0,3500	8,815E-04	-1,362E-03	0,2911	0,3969	0,4085
0,4000	9,538E-04	-1,452E-03	0,2727	0,3748	0,4631
0,4500	1,009E-03	-1,518E-03	0,2535	0,3516	0,5164
0,5000	1,051E-03	-1,567E-03	0,2335	0,3273	0,5675
0,5500	1,084E-03	-1,606E-03	0,2128	0,3019	0,6169
0,6000	1,112E-03	-1,638E-03	0,1913	0,2753	0,6636
0,6500	1,138E-03	-1,666E-03	0,1690	0,2475	0,7064
0,7000	1,161E-03	-1,691E-03	0,1461	0,2185	0,7448
0,7500	1,182E-03	-1,715E-03	0,1224	0,1882	0,7764
0,8000	1,203E-03	-1,736E-03	0,0979	0,1566	0,7958
0,8500	1,225E-03	-1,758E-03	0,0727	0,1239	0,7939
0,9000	1,247E-03	-1,779E-03	0,0467	0,0899	0,7447
0,9500	1,270E-03	-1,799E-03	0,0202	0,0546	0,5585



Sea Trials data and correlation with predictions computed using ITTC'78-PPM and using present strip method. In this case four sister ships were built of which sea trials data in ballast condition are available:

Ship#1		
Sea Trials Date:	Jun. 06 - 08, 2014	
VS knots	RPM	PS-Ship#1 kW
14,582	92,80	2789,8
16,032	103,00	3906,1
16,842	109,00	4675,1
17,397	113,30	5282,0

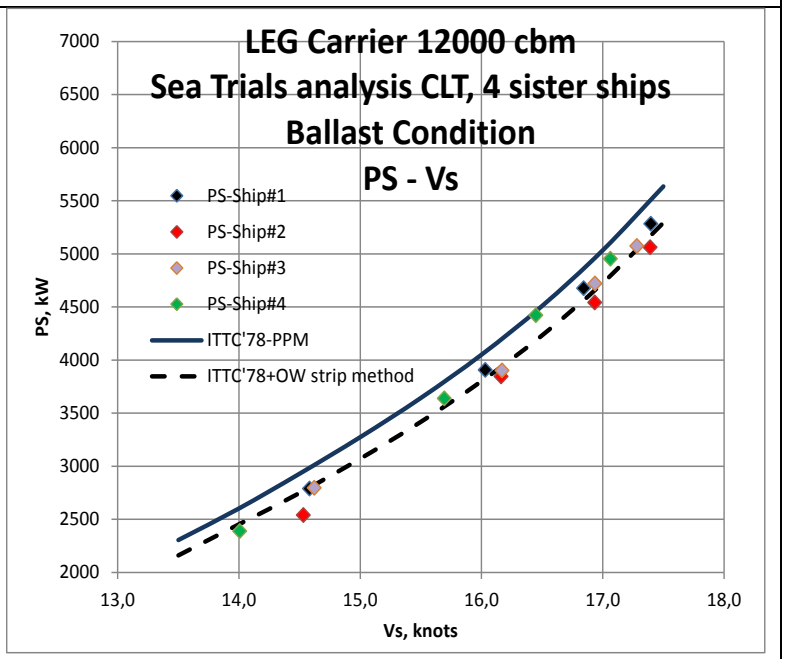
Ship#2		
Sea Trials Date:	July 28 - 31, 2014	
VS knots	RPM	PS-Ship#2 kW
14,531	91,20	2540,4
16,162	104,40	3846,2
16,934	109,60	4542,5
17,390	113,30	5062,0

Ship#3		
Sea Trials Date:	Sept 26-28, 2014	
VS knots	RPM	PS-Ship#3 kW
14,622	93,40	2795,1
16,169	103,90	3902,6
16,937	110,10	4720,4
17,282	112,70	5073,1

Ship#4		
Sea Trials Date:	Apr. 12-16, 2014	
VS knots	RPM	PS-Ship#4 kW
14,006	87,70	2389,3
15,693	100,30	3637,8
16,448	106,80	4422,1
17,063	110,60	4952,8

ITTC'78-PPM		
VS nudos	PS kW	REV rpm
13,50	2305	86
14,00	2602	89
14,50	2930	92
15,00	3274	96
15,50	3643	99
16,00	4050	103
16,50	4510	106
17,00	5034	110
17,50	5635	114

ITTC'78+OW strip method		
VS nudos	PS kW	REV rpm
13,50	2160	85
14,00	2453	89
14,50	2748	92
15,00	3071	95
15,50	3418	99
16,00	3801	102
16,50	4233	106
17,00	4726	109
17,50	5293	113



It is clear that using OWT corrections calculated according to present strip method the predictions at full scale match sea trials results much better than using OWT corrections according to ITTC'78-PPM.

Case study B2- Twin shafts Ferry "FORTUNY".

This case has been published in the 11th ICHD 2014, October 2014, Singapore, (11). It is a large Ferry propelled by two CPP propellers. In this reference detailed data of ship and propellers are given.

Propeller and OW test faired raw data are:

PROPELLER DATA		
Prop nº	CLT-2465Br	
Nº shafts=	2	
Nº blades=	4	
Diameter=	4,368	m
Ae/Ao=	0,520	
Scale=	17,9600	
H/D(0.75R)=	1,1080	
c (0.75R)=	1,5516	m
t (0.75R)=	0,0851	m
t/c(0.75R)=	0,05485	
H @ 1.0R=	5,1174	m
H/D(1.0R)=	1,1716	
c (1.0R)=	1,4056	m
end plate width=	0,2600	m
end plate max thickness=	0,0300	m
m/c(1.0R)=	0,0079	

OPEN WATER TEST DATA	OWT
Test nº	C-16567
Temp fresh water (ºC)=	18,2
Dens fresh water (Kg/m3)=	998,36
Visc fresh water (m2/s)=	1,0491E-06
Nº of J values	15
dens salt water (Kg/m3)=	1025,81
Visc salt water	1,1883E-06
Nº Reynolds mod.=	9,16E+05
rate of rev (rps)=	20,000
Scale=	17,960

	CLT-2465Br		
X	H/D	Chord, m	Thickness, m
0,324	0,9223	0,8600	0,2429
0,350	0,9538	0,8736	0,2310
0,400	1,0049	0,9225	0,2089
0,450	1,0432	0,9955	0,1879
0,500	1,0687	1,0858	0,1680
0,550	1,0815	1,1862	0,1492
0,600	1,0879	1,2900	0,1315
0,650	1,0943	1,3901	0,1150
0,700	1,1007	1,4796	0,0995
0,750	1,1080	1,5516	0,0851
0,800	1,1171	1,5991	0,0719
0,850	1,1281	1,6152	0,0598
0,900	1,1408	1,5930	0,0487
0,950	1,1553	1,5254	0,0388
1,000	1,1716	1,4056	0,0300

Open Water Results - MODEL SCALE			
J	Ktm	10*Kqm	ETAom
0,100	0,5228	0,8775	0,0948
0,200	0,4803	0,8146	0,1877
0,300	0,4361	0,7491	0,2780
0,400	0,3903	0,6811	0,3649
0,450	0,3668	0,6461	0,4066
0,500	0,3429	0,6104	0,4470
0,550	0,3185	0,5742	0,4856
0,600	0,2938	0,5373	0,5222
0,650	0,2686	0,4997	0,5561
0,700	0,2431	0,4615	0,5867
0,750	0,2171	0,4227	0,6131
0,800	0,1907	0,3832	0,6336
0,850	0,1639	0,3431	0,6463
0,900	0,1367	0,3023	0,6476
0,950	0,1091	0,2609	0,6320

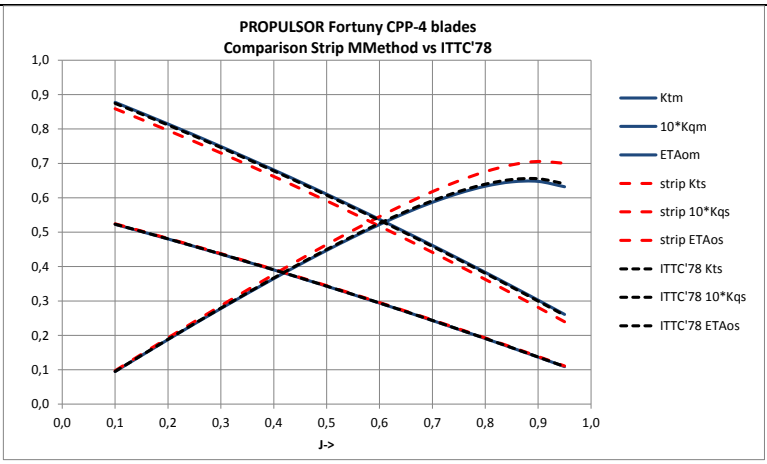
As all data can be found in (11), in this appendix only detailed calculations of OWT corrections will be presented to compare present strip method and ITTC'78-PPM.

Analysis of OWT extrapolation (ITTC'78-PPM vs. present strip method):

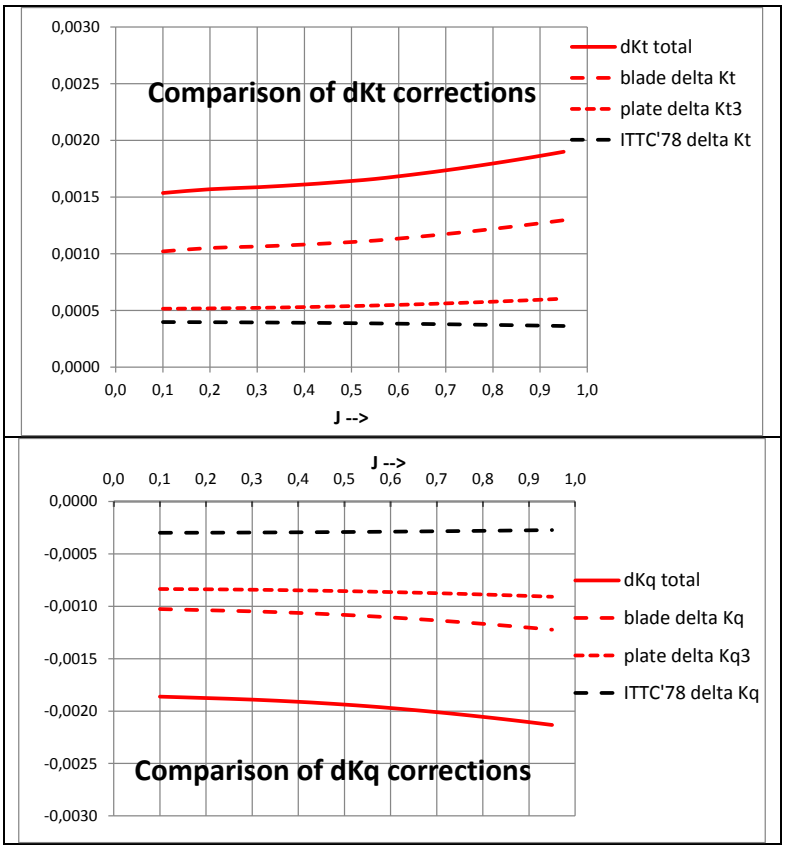
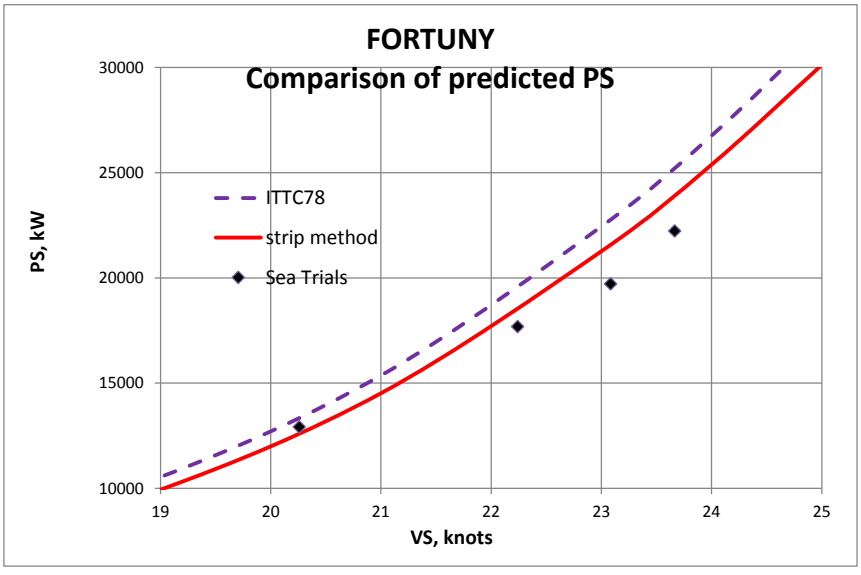
OWT corrections according to ITTC'78-PPM

						ship			
kp=	3,000E-05								
CDs=	7,924E-03			ITTC'78	ITTC'78	ITTC'78	ITTC'78	ITTC'78	ITTC'78
Js	Rnm	CDm	delta CD	delta Kt	delta Kq	Kts	10*Kqs	ETAos	Kt/J2s
0,1000	8,818E+05	8,765E-03	8,415E-04	3,975E-04	-2,989E-04	0,5232	0,8745	0,0952	52,3201
0,2000	8,845E+05	8,763E-03	8,388E-04	3,962E-04	-2,980E-04	0,4807	0,8116	0,1885	12,0170
0,3000	8,890E+05	8,758E-03	8,345E-04	3,941E-04	-2,964E-04	0,4365	0,7461	0,2793	4,8502
0,4000	8,953E+05	8,752E-03	8,284E-04	3,913E-04	-2,943E-04	0,3907	0,6781	0,3668	2,4419
0,4500	8,991E+05	8,749E-03	8,247E-04	3,895E-04	-2,930E-04	0,3672	0,6431	0,4089	1,8133
0,5000	9,033E+05	8,745E-03	8,207E-04	3,876E-04	-2,915E-04	0,3433	0,6075	0,4496	1,3730
0,5500	9,080E+05	8,740E-03	8,163E-04	3,855E-04	-2,900E-04	0,3189	0,5713	0,4887	1,0543
0,6000	9,131E+05	8,735E-03	8,114E-04	3,833E-04	-2,882E-04	0,2942	0,5344	0,5257	0,8171
0,6500	9,185E+05	8,730E-03	8,063E-04	3,808E-04	-2,864E-04	0,2690	0,4968	0,5601	0,6367
0,7000	9,244E+05	8,725E-03	8,007E-04	3,782E-04	-2,844E-04	0,2434	0,4587	0,5913	0,4968
0,7500	9,307E+05	8,719E-03	7,948E-04	3,754E-04	-2,823E-04	0,2174	0,4198	0,6182	0,3866
0,8000	9,373E+05	8,713E-03	7,886E-04	3,725E-04	-2,801E-04	0,1911	0,3804	0,6395	0,2985
0,8500	9,444E+05	8,706E-03	7,821E-04	3,694E-04	-2,778E-04	0,1643	0,3403	0,6530	0,2273
0,9000	9,518E+05	8,699E-03	7,753E-04	3,662E-04	-2,754E-04	0,1370	0,2995	0,6553	0,1692
0,9500	9,595E+05	8,692E-03	7,681E-04	3,628E-04	-2,729E-04	0,1094	0,2582	0,6408	0,1212

	strip	strip	strip
Js	Kts	10*Kqs	ETAos
0,1000	0,5243	0,8589	0,0972
0,2000	0,4819	0,7958	0,1927
0,3000	0,4377	0,7302	0,2862
0,4000	0,3919	0,6619	0,3769
0,4500	0,3684	0,6268	0,4210
0,5000	0,3445	0,5911	0,4638
0,5500	0,3202	0,5546	0,5053
0,6000	0,2955	0,5175	0,5452
0,6500	0,2703	0,4798	0,5829
0,7000	0,2448	0,4414	0,6178
0,7500	0,2188	0,4023	0,6493
0,8000	0,1925	0,3626	0,6758
0,8500	0,1657	0,3223	0,6956
0,9000	0,1385	0,2812	0,7056
0,9500	0,1109	0,2396	0,7003



It has to be noticed that corrections due to end plate are an important part of total corrections as it is represented in next figures:



Applying these corrections predictions at full scale are much more in line with sea trials measurements: