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Conventional propellers in CRP-POD configuration. Tests and extrapolation.

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ABSTRACT

A CRP-POD propulsion system concept is explained and the challenges related to testing at model scale are presented. CRP-POD configuration includes two different propulsors arranged in line with a short distance in between them, and consequently a high interaction is expected. The full power is divided into two parts.

Each unit provides a percentage of the total power. It is quite common 60-80% for the main engine and 40-20% for the POD unit.

Hull resistance test is carried out in the same way than in any other propulsion configuration because this propulsion system is considered as a unit.

Several open water tests (OWT) must be carried out to know the thrust and torque of both propellers in different situations. POD unit resistance is also deduced from OWT. K_T and K_Q parameters are defined in a different way by considering that the rpm of both propellers are different.

To carry out OWT and self propulsion tests in the towing tank two independent dynamometers are necessary. Specific devices have been designed and manufactured to carry out the model tests. The paper describes these tests and the device arrangement developed and manufactured at CEHIPAR necessary to test the unit in a towing tank.

A general extrapolation method with conventional type propellers is presented and applied in detail to a case studied in a R&D project funded by EU FP6.

Keywords

Propulsors, CRP-POD system, POD housing, model testing, scaling procedure.

1 INTRODUCTION

The so called CRP-POD which is a contra-rotating propellers configuration including two different propellers arranged in the same geometrical shaft with a short distance in between them and rotating in opposite sense but with a specific driven system.

During the last decade the interest on CRP-POD units has increased. In particular a case of CRP-POD system was used in the R&D project supported by the EU-FP6, TRIPOD "(Sánchez Caja et al 2013)", that was developed from 2010 to 2013 and all necessary tests were carried out at CEHIPAR facilities. It was necessary to design and manufacture specific devices to carry out the model tests. Part of these developments has been already presented in 10^{th} ICHD "(Quereda et al, 2012)". The complete procedure to test this kind of unit is presented in this paper including device arrangements, model testing method, extrapolation procedure, test results and extrapolation application.

Existing ITTC procedures have been taken as a basis to develop a new extrapolation method allowing the prediction of the performance of a real ship propelled with this propulsion system.

Main numerical data of one case included in TRIPOD is also presented here to facilitate the comprehension of the new testing and extrapolation procedure proposed. It corresponds to a model of an 8,500 TEU container ship tested in TRIPOD project at the scale of 38.913.

2 CRP-POD SYSTEM DESCRIPTION

A CRP-POD configuration includes two different propellers driven by separated engines and arranged in line with a very short distance in between them, and consequently a high interaction must be considered. The main engine drives the forward propeller and the aft propeller actuates separately and it is driven by an electrical engine arranged inside the POD unit and rotating in opposite sense. As in other CRP systems the aim is to recover in the aft propeller the rotational energy losses of the main propeller.

This system allows reaching higher power on vessels splitting the full power into two parts. Each unit provides a percentage of the total power. It is quite common 60-80% for the main engine and 40-20% for the POD unit.

A CRP-POD system has intrinsically more degrees of freedom than a conventional propulsion system mainly depending on the engines and driving arrangements.

In the case studied here the electrical motor, driving the POD propeller is connected to an electrical generator (PTO) allowing to establish a fixed relation of rpm between main and POD propellers. In this case the value of 10/14 was established.

The POD UNIT tested is the so called RUDDER-POD developed by ABB which has not the possibility of rotation around its vertical axis. Ship manoeuvrability will be attained by means of a large flap acting as a rudder installed in the POD unit.

3 TEST PROGRAM

The test program includes resistance, open water with different configurations and self propulsion tests. To carry out the tests in the CEHIPAR towing tank, it was necessary to design and manufacture specific devices, as shown in figures 1 and 2. The whole propulsion system is considered as a unit.

To carry out OWT and self propulsion tests in the towing tank two independent dynamometers are necessary. The dynamometer corresponding to the main propeller will measure the thrust, torque and rpm of the main propeller, while the dynamometer of the POD unit "Figure 1" will measure the thrust, torque and rpm of the POD propeller and an additional load cell allows to measure the total thrust of the unit, T_{mUNIT}.

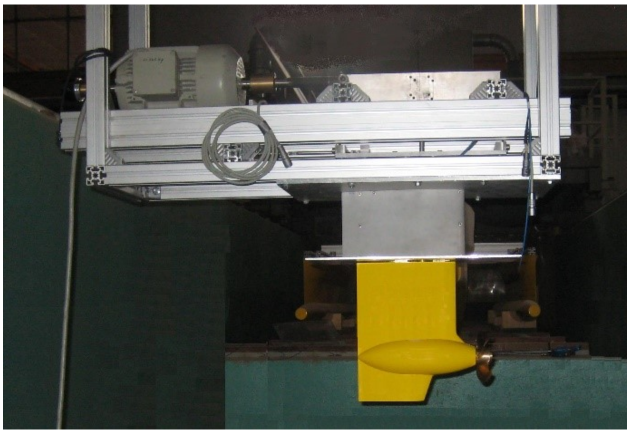

Figure 1. POD housing and POD dynamometer.

The arrangement of POD dynamometer to carry out self propulsion tests is shown in "Figure 2".

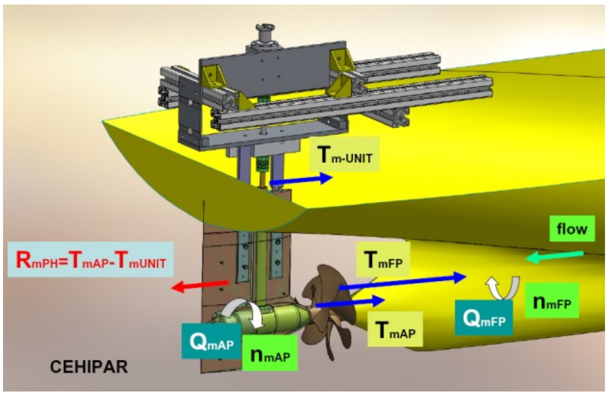

Figure 2. Arrangement to carry out self propulsion test.

Self propulsion tests were carried out maintaining constant the ratio of the rpm between main and POD propeller at each velocity. Load varying tests were conducted to determine the self-propulsion operation point.

3.1 Resistance Test

The resistance test has been carried out without the POD unit, in bare hull condition, see "Figure 3", as it is recommended in the ITTC procedure, because the POD housing is a part of propulsion system and it is not considered as an appendage. So, this test is carried out following the standard procedure included in ITTC`78-PPM.

The form factor k has been determined according to Prohaska's method by using the resistance of the model measured at low Froude number values.

The residual resistance coefficient C_R is obtained from the calculated total resistance coefficient of the model C_{Tm} and frictional resistance coefficient C_{Fm} which is calculated according to ITTC-57 friction line.

$$C_R = C_{Tm} - (1+k)C_{Fm} \quad (1)$$

The total resistance coefficient C_{TS} is obtained from the calculated friction resistance coefficient C_{FS} according to ITTC-57, the residual resistance coefficient C_R obtained from Equation (1), the skin friction correction ΔC_F and the coefficient C_{AA}.

$$C_{TS} = (1+k)C_{FS} + C_R + \Delta C_F + C_{AA} \quad (2)$$

Figure 3. Stern of the ship model to carry out resistance test. Without appendages.

3.2 Open Water Test

In summary, a CRP-POD system is composed of the main propeller and the POD unit; this, in turn, consists of POD housing and POD propeller.

Different Open Water Tests (OWT) must be carried out to determine the propulsion system characteristics of each individual propeller, their interactions and the influence of the POD housing. Below it is explained all the OWT with main and POD propellers in different configurations.

In all OWT the shaft of the propellers must be immersed 1.5 times the diameter of the main propeller.

3.2.1 Main propeller alone

In "Figure 7" the configuration of the CRP-POD system in Open Water condition shows that main propeller is tested in reverse flow comparing with standard OWT. In order to check if the shaft of the propeller dynamometer can have any influence, main propeller has been tested in both condition, normal and reverse flow, "Figure 4". It was concluded that being the shaft large enough there was not influence on the K_T and K_Q values for J values close to the design point, so small wake field effect has been neglected.

Sub-Index $_{FP}$ is used to be referred to the main propeller, m has been used for the model and super index ^{o} is used to indicate that the propeller has been tested alone, as it is shown in “Figure 4”. Non-dimensional parameters obtained from this test are:

$$J^{o}_{mFP} = \frac{V_m}{n_{mFP} D_{mFP}} \quad (3)$$

$$K^{o}_{TmFP} = \frac{T^{o}_{mFP}}{\rho_m n^2_{mFP} D^4_{mFP}} \quad (4)$$

$$K^{o}_{QmFP} = \frac{Q^{o}_{mFP}}{\rho_m n^2_{mFP} D^5_{mFP}} \quad (5)$$

$$\eta^{o}_{omFP} = \frac{J^{o}_{mFP}}{2\pi} \frac{K^{o}_{TmFP}}{K^{o}_{QmFP}} \quad (6)$$

Where J means advance coefficient, V_m velocity of the model, n model propeller rps, D propeller diameter, K_T thrust coefficient, T thrust measured, K_Q torque coefficient, Q torque on the propeller axis and ρ water density. η_o is the open water efficiency.

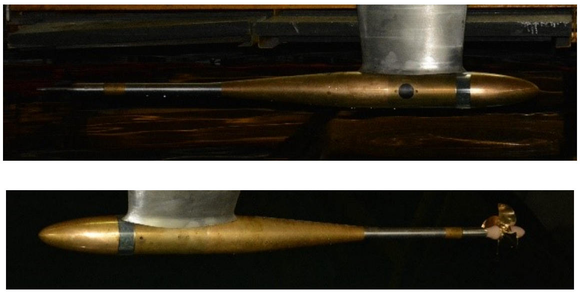

Figure 4. Fore propeller. Open water tests.
Up, normal position; down, reversed flow.

3.2.2 POD propeller alone

Sub-Index $_{AP}$ is referred to the POD propeller, or after propeller in this configuration, only tested in normal position, as it may be observed “Figure 5”.

Figure 5. Open water test. Aft propeller.

$$J^{o}_{mAP} = \frac{V_m}{n_{mAP} D_{mAP}} \quad (7)$$

$$K^{o}_{TmAP} = \frac{T^{o}_{mAP}}{\rho_m n^2_{mAP} D^4_{mAP}} \quad (8)$$

$$K^{o}_{QmAP} = \frac{Q^{o}_{mAP}}{\rho_m n^2_{mAP} D^5_{mAP}} \quad (9)$$

$$\eta^{o}_{omAP} = \frac{J^{o}_{mAP}}{2\pi} \frac{K^{o}_{TmAP}}{K^{o}_{QmAP}} \quad (10)$$

3.2.3 POD propeller and POD housing

As the POD housing is a part of the POD unit, an OWT of the POD unit as a whole must be carried out. The POD propeller should rotate at the same rpm than in the open water carried out with the POD propeller alone.

Figure 6. Open water test. Aft propeller in the POD housing.

The POD housing is located downstream of the POD propeller during the test. The plate situated over the POD housing, “Figure 1”, must be over the water surface, so the arm must be large enough to permit that the model propeller be immersed 1.5 times the diameter of the main propeller.

The POD dynamometer allows to measure the POD propeller thrust T^*_{mAP} and the total thrust of the POD unit T^*_{mUNIT}. The drag of the POD housing R^*_{mPH} is deduced as the thrust produced by the POD propeller T^*_{mAP} minus the total thrust of the POD UNIT T^*_{mUNIT}. Super-index * means that propeller and POD housing have been tested together.

$$R^*_{mPH} = T^*_{mAP} - T^*_{mUNIT} \quad (11)$$

$$J^*_{mAP} = \frac{V_m}{n_{mAP} D_{mAP}} \quad (12)$$

$$K^*_{TmUNIT} = \frac{T^*_{mUNIT}}{\rho_m n^2_{mAP} D^4_{mAP}} \quad (13)$$

$$K^*_{QmAP} = \frac{Q^*_{mAP}}{\rho_m n^2_{mAP} D^5_{mAP}} \quad (14)$$

$$\eta^*_{omUNIT} = \frac{J^*_{mAP}}{2\pi} \frac{K^*_{TmUNIT}}{K^*_{QmAP}} \quad (15)$$

3.2.4 Main and POD propeller with POD housing

One last open water test must be done. The main propeller and CRP-POD propeller will be placed in the CRP configuration. In this test it is necessary to maintain the same rpm ratio than in self propulsion condition.

In the case studied in this paper, the POD propeller rotates at the same rpm than in the open water test mentioned in *3.2.3* and the main propeller rotates in opposite sense at 1.4 times the rpm of the POD propeller.

The main propeller has been used as the reference to calculate the parameters on the CRP-POD system performance of the open water test carried out with both propellers. Super index ^{ow} has been used.

$$J_m^{ow} = \frac{V_m}{n_{mFP} D_{mFP}} \quad (16)$$

A new parameter, $K^{ow}{}_{Tm}$, has been defined taking into account the total thrust of the system referred to the rpm and diameter of the main propeller.

$$K_{Tm}^{ow} = \frac{T_{mFP}^{ow} + T_{mUNIT}^{ow}}{\rho_m n_{mFP}^2 D_{mFP}^4} \quad (17)$$

Another new parameter, $K^{ow}{}_{Qm}$, has been defined taking into account the power of both propellers referred to the rpm and diameter of the main propeller.

$$K_{Qm}^{ow} = \frac{n_{mFP} Q_{mFP}^{ow} + n_{mAP} Q_{mAP}^{ow}}{\rho_m n_{mFP}^3 D_{mFP}^5} \quad (18)$$

$$\eta_{om}^{ow} = \frac{J_m^{ow}}{2\pi} \frac{K_{Tm}^{ow}}{K_{Qm}^{ow}} \quad (19)$$

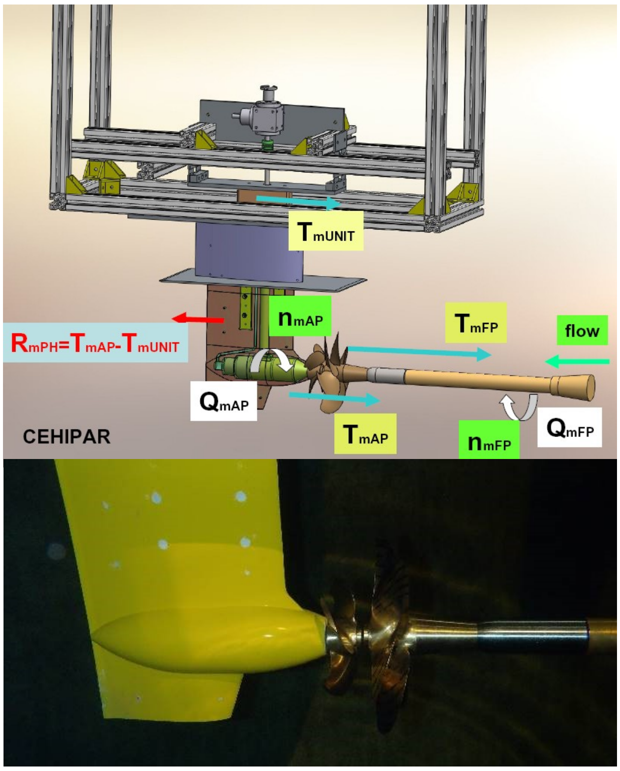

Figure 7. Arrangement to carry out OWT. Main propeller is acting in reverse flow.

As in the case of Equation (11):

$$T_{mUNIT}^{ow} = T_{mAP}^{ow} - R_{mPH}^{ow} \quad (20)$$

To calculate the POD housing model device resistance, $R^{ow}{}_{mPH}$, Equation (20) written before, may be used.

$$R_{mPH}^{ow} = T_{mAP}^{ow} - T_{mUNIT}^{ow} \quad (21)$$

Rpm ratio of main and POD propellers for the test case is:

$$n_{mAP} = \frac{10}{14} n_{mFP} \quad (22)$$

3.3 Self Propulsion Test

During self propulsion test the real rpm ratio between main and POD propellers will be maintained, as it is in the case studied, being the power developed at each propeller a result of the test.

Figure. 8. Model ship to carry out self propulsion test.

During the self propulsion test the values of POD propeller thrust and POD housing thrust are measured. The POD housing drag may be deduced.

$$R_{mPH} = T_{mAP} - T_{mUNIT} \quad (23)$$

Load variations are produced by varying the main propeller rpm n_{mFP}; maintaining the rpm ratio, the POD propeller rpm n_{mAP} is established. Both independent dynamometers allow measuring rpm and torque on each propeller Q_{mFP} and Q_{mAP} at each model velocity.

A minimum of three values of n_{mFP} are used for each hull model speed to establish the load variation of the propellers.

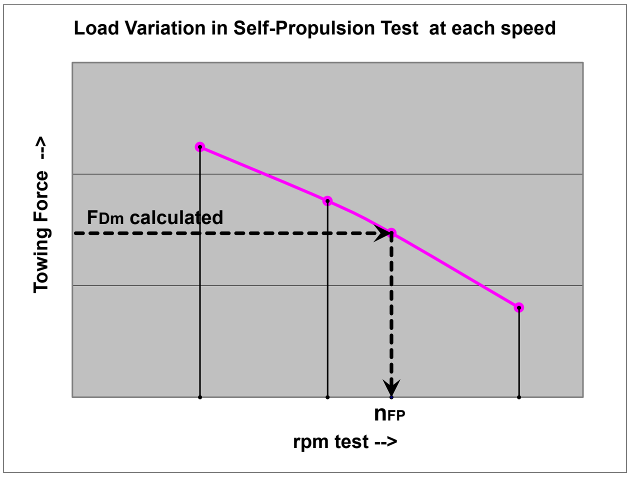

Figure 9. Load Variation Test.

The self propulsion point is determined interpolating in the measured data of the load variation test. The frictional deductions due to hull model F_{DHULL} and POD housing F_{DPH} must be considered to calculate the total frictional deduction.

$$F_{Dm} = F_{DHULL} + F_{DPH} \quad (24)$$

$$F_{DHULL} = \frac{\rho_m S_m V_m^2}{2} \left[(1+k)(C_{Fm} - C_{Fs}) - \Delta C_F \right] \quad (25)$$

C_F is the friction resistance coefficient. C_{FS} for ship and C_{Fm} for model, ρ means density and λ is the scale factor. *Sm* is the hull model wetted surface. C_{FS} for ship and C_{Fm} for model are determined according to ITTC'57.

Deduction fraction on POD housing F_{DPH} is calculated taking into account the friction resistance coefficients $C^{PH}{}_{FS}$ and $C^{PH}{}_{Fm}$ for the POD housing. Reynolds number is calculated at the same height than the *0.75R* section of the POD propeller over the shaft.

$$F_{DPH} = R_{mPH}(1 - \frac{C_{Fs}^{PH}}{C_{Fm}^{PH}}) \quad (26)$$

The total thrust of this propulsion system is supplied by the thrust on the forward propeller T_{mFP} "Figure 2", which is measured by the carriage dynamometer and the thrust of the POD unit T_{mUNIT} which is measured by the POD dynamometer at each model velocity.

$$T_{mT} = T_{mFP} + T_{mUNIT} \quad (27)$$

Where T_{mT} is the total thrust at model scale and the meaning of T_{mUNIT} has been explained in Equation (23).

$$1 - t = \frac{R_{Tm} - (F_{DHULL} + F_{DPH})}{T_{mFP} + T_{mUNIT}} \quad (28)$$

Where R_{Tm} is the model resistance measured during the resistance test in accordance with "Figure 3", when the hull model has not installed the propulsion system.

F_{DHULL} and F_{DPH} have been calculated according to the Equation (25) and Equation (26), respectively. T_{mFP} is the thrust corresponding to the main propeller and T_{mUNIT} is the thrust of the POD unit.

The model thrust coefficient K_{Tm} is computed at each velocity while self propulsion test is carried out and it is referred to the main propeller rpm and diameter.

$$K_{Tm} = \frac{T_{mFP} + T_{mUNIT}}{\rho_m n_{mFP}^2 D_{mFP}^4} \quad (29)$$

The model torque coefficient K_{Qm} corresponding at the self propulsion test is calculated at each velocity. It is referred to the main propeller rpm and diameter.

$$K_{Qm} = \frac{n_{mFP} Q_{mFP} + n_{mAP} Q_{mAP}}{\rho_m n_{mFP}^3 D_{mFP}^5} \quad (30)$$

To calculate w_{Tm} the K_{Tm} parameter is obtained from self propulsion test results, Equation (29) and with the K_{Tm} value, the advance coefficient J_{Tm} corresponding at thrust coefficient identity, is read off from the open water model test curves with the propulsion system, Equation (16) and Equation (17).

$$w_{Tm} = 1 - \frac{J_{Tm} D_{mFP} n_{mFP}}{V_m} \quad (31)$$

Once determined the J_{Tm} value, the non dimensional parameter $K_{Qm}{}^{ow}$ is read off from the open water model test curves with the propulsion system, Equation (16) and Equation (18).

Taking into account the $K_{Qm}{}^{ow}$ coefficient from open water model test curves and the K_{Qm} value obtained from the self propulsion test, Equation (39), corresponding to J_{Tm} value, the rotative-relative coefficient could be determined.

$$\eta_{Rm} = \frac{K_{Qm}^{ow}}{K_{Qm}} \quad (32)$$

4 EXTRAPOLATION METHOD

The proposed extrapolation procedure is based on ITTC standard procedures and it is applicable to CRP-POD system with conventional propellers.

4.1 Scaling of POD Housing Drag

CRP-POD propulsion system is a combination of 3 elements: 2 propellers and one passive POD housing structure. A part of the POD housing is operating in the accelerated propeller slipstream flow and other part is operating in the surrounding flow. All these 3 element characteristics must be corrected to take into account the scale effects and each model basin has its own method to do it. A simple method is proposed here, based on the ITTC'78-PPM extended to the new elements that are present in the CRP-POD configuration.

Open water results of both propellers are individually corrected according to ITTC'78-PPM. POD housing drag, which is the difference between POD propeller thrust and POD unit thrust, is extrapolated from the model self propulsion and resistance test results.

$$R_{SPH} = \frac{C_{Fs}^{PH}}{C_{Fm}^{PH}} R_{mPH} \frac{\rho_s}{\rho_m} \lambda^3 \quad (33)$$

Where R_{mPH} is obtained from self propulsion test results at each tested velocity, "Figure 2", by applying Equation (23).

4.2 Scaling of Open Water Characterisitcs

Main propeller thrust coefficient is used to calculate the thrust of the propeller.

$$T_{SFP} = (K_{TmFP}^{ow} + \Delta K_{TFP}^{ow}) \rho_S n_{SFP}^2 D_{SFP}^4 \quad (34)$$

Where $\Delta K^{ow}{}_{TFP}$ is calculated according with ITTC'78-PPM correction for conventional propellers.

$$T_{SUNIT} = (K_{TmUNIT}^{ow} + \Delta K_{TAP}^{ow} + \Delta K_{TPH}^{ow}) \rho_S n_{SAP}^2 D_{SAP}^4 \quad (35)$$

Where $\Delta K^{ow}{}_{TAP}$ for conventional propellers is calculated according to the ITTC'78-PPM, and

$$\Delta K_{TPH}^{ow} = \frac{R_{mPH}^{ow}}{\rho_m n_{mFP}^2 D_{mFP}^4} (1 - \frac{C_{Fs}^{PH}}{C_{Fm}^{PH}}) \quad (36)$$

The thrust coefficient of ship propulsion system is calculated according to Equation (34), Equation (35), ITTC'78-PPM corrections on conventional propellers thrust coefficients and Equation (36).

$$K_{TS} = \frac{T_{SFP} + T_{SUNIT}}{\rho_S n_{SFP}^2 D_{SFP}^4} \quad (37)$$

In the same way, torque coefficient has been calculated. Ship propellers torque is calculated taken into account the ITTC'78-PPM to obtain $\Delta K^{ow}{}_{QFP}$ and $\Delta K^{ow}{}_{QAP}$.

$$Q_{SFP} = (K^{ow}_{QmFP} + \Delta K^{ow}_{QFP})\rho_S n^2_{SFP} D^5_{SFP} \tag{38}$$

$$Q_{SAP} = (K^{ow}_{QmAP} + \Delta K^{ow}_{QAP})\rho_S n^2_{SAP} D^5_{SAP} \tag{39}$$

According with Equation (38) and Equation (39) and corrections on conventional propellers torque coefficient ITTC'78-PPM the torque coefficient of the ship propulsion system is calculated.

$$K_{QS} = \frac{Q_{SFP} n_{SFP} + Q_{SAP} n_{SAP}}{\rho_S n^3_{SFP} D^5_{SFP}} \tag{40}$$

$$J_S = \frac{V_S}{n_{SFP} D_{SFP}} \tag{41}$$

The parameters J_S, K_{TS} and K_{QS}, Equation (41), Equation (37) and Equation (40) allow obtaining the open water curves of the propulsion system for the ship.

4.3 Performance Prediction

To extrapolate the self-propulsion test results, it is considered that the thrust deduction fraction t has the same value for model and full scale ship, *t(model)=t(ship)* and consequently it has not sub index.

The effective wake fraction for the ship w_{TS} based on thrust identity is extrapolated according with the ITTC'78-PPM

$$w_{TS} = t + (w_{Tm} - t)\frac{(1+k\ )C_{FS} + \Delta C_F}{(1+k\ )C_{Fm}} \tag{42}$$

It is necessary to point out that the 0.04 coefficient has been neglected because there is not rudder effect.

As in the ITTC'78-PPM, it is considered that the rotative-relative coefficient is not affected by scale effects.

$$\eta_{RS} = \eta_{Rm} \tag{43}$$

Taking into account the wetted surface of the selected ship, S_S, the load of the full scale propeller is obtained.

$$\frac{K_{TS}}{J^2_{TS}} = \frac{S_S}{2D^2_{SFP}}\frac{C_{TS}}{(1-t)(1-w_{TS})^2} \tag{44}$$

With this $K_{TS}/J^2{}_{TS}$ as input value the full scale advance coefficient J_{TS}, thrust coefficient K_{TS} and torque coefficient K_{QS} are read off from the full scale propeller characteristics and the following quantities are calculated.

$$n_{SFP} = \frac{(1-w_{TS})V_S}{J_{TS} D_{SFP}} \quad \text{(rps)} \tag{45}$$

Thrust, T_S.

$$T_S = (\frac{K_{TS}}{J^2_{TS}})J^2_{TS}\rho_S n^2_{SFP} D^4_{SFP} \quad \text{(N)} \tag{46}$$

The delivered power.

$$P_{DS} = 2\pi\rho_S n^3_{SFP} D^5_{SFP}\frac{K_{QS}}{\eta_R}10^{-3} \quad \text{(kW)} \tag{47}$$

The total propulsive efficiency.

$$\eta_D = \frac{\frac{1}{2}\rho_S V^3_S S_S C_{TS}}{P_{DS}} \tag{48}$$

5 APPLICATION CASE

A container ship has been selected as test case. Propulsion system CRP-POD has been designed.

5.1 Model characteristics

Hull model and two conventional propeller models with scale factor *λ=38.913* were manufactured at CEHIPAR, Spain, to carry out the model testing program.

5.1.1 Hull model characteristics

Length between perpendicular, LPP.	9031.7 mm
Moulded beam	1099.9 mm
Mean draught at ballast condition	204.3 mm
Block coefficient	0.594
Wetted surface	9.080 m^2

5.1.2 Main propeller model characteristics

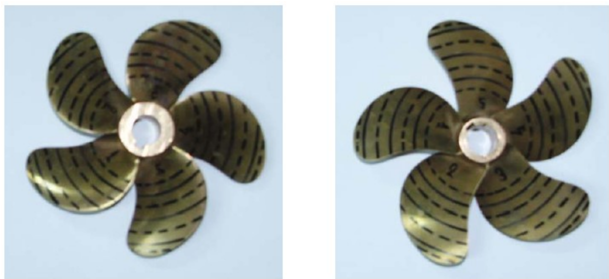

Figure 10. Main propeller model.

Diameter.	212.01 mm
Pitch at 0.75 R.	214.79 mm
Pitch/Diameter ratio at 0.75R	1.027
Number of blades.	5
AE/A0	0.780
Chord length at 0.75 R.	73.86 mm
Thickness at 0.75 R.	2.34 mm

5.1.3 POD propeller model characteristics

Figure 11. POD propeller model.

Diameter.	182.46 mm
Pitch at 0.75 R.	276.21 mm
Pitch/Diameter ratio at 0.75R.	1.524
Number of blades.	4
AE/A0	0.500
Chord length at 0.75 R.	50.86 mm
Thickness at 0.75 R.	1.77 mm

5.2 Test results

Hull and propeller models have been tested according to the proposed procedure and the measurement data are presented below.

5.2.1 Resistance test. Ballast condition

Bare hull model test results at ballast condition are presented in “Table 1”.

Table 1. Model Resistance.

V	R_{Tm}
knots	N
18.0	34.95
19.0	38.66
20.0	42.59
21.0	46.78
22.0	51.25
23.0	56.04
24.0	61.23
25.0	66.88

5.2.2 Open water test

Different open water tests have been carried out as has been indicated in 3.2 and results are presented from “Table 2” to “Table 5”.

Table 2. Open water test. Main propeller alone.

J^o_{mFP}	${K_T}^o_{mFP}$	$10{K_Q}^o_{mFP}$	${\eta_o}^o_{mFP}$
0.300	0.3706	0.5511	0.321
0.400	0.3210	0.4875	0.419
0.500	0.2696	0.4215	0.509
0.600	0.2167	0.3530	0.586
0.700	0.1627	0.2817	0.643
0.750	0.1355	0.2450	0.660
0.800	0.1081	0.2076	0.663
0.850	0.0807	0.1694	0.644
0.900	0.0533	0.1304	0.585
0.950	0.0259	0.0906	0.432

Table 3. Open water test. POD propeller alone.

J^o_{mAP}	${K_T}^o_{mAP}$	$10{K_Q}^o_{mAP}$	${\eta_o}^o_{mAP}$
0.500	0.4635	0.9810	0.376
0.600	0.4217	0.9044	0.445
0.700	0.3786	0.8286	0.509
0.800	0.3345	0.7519	0.566
0.900	0.2896	0.6725	0.617
1.000	0.2439	0.5885	0.659
1.050	0.2207	0.5445	0.677
1.100	0.1972	0.4988	0.692
1.150	0.1733	0.4514	0.703
1.200	0.1490	0.4022	0.707
1.250	0.1241	0.3508	0.704
1.300	0.0984	0.2971	0.685
1.350	0.0717	0.2406	0.641
1.400	0.0438	0.1808	0.540
1.450	0.0142	0.1168	0.280

Table 4. Open water test. POD propeller with POD housing.

J^*_{mAP}	${K_T}^*_{mUNIT}$	$10{K_Q}^*_{mAP}$	${\eta_o}^*_{mUNIT}$
0.500	0.4722	0.9309	0.404
0.600	0.4313	0.8574	0.480
0.700	0.3883	0.7891	0.548
0.800	0.3433	0.7243	0.603
0.900	0.2964	0.6602	0.643
1.000	0.2478	0.5931	0.665
1.050	0.2229	0.5573	0.669
1.100	0.1976	0.5194	0.666
1.150	0.1720	0.4794	0.657
1.200	0.1460	0.4370	0.638
1.250	0.1197	0.3923	0.607
1.300	0.0931	0.3455	0.557
1.350	0.0662	0.2970	0.479
1.400	0.0390	0.2475	0.351
1.450	0.0115	0.1979	0.134

Table 5. Open water test. Propulsion CRP-POD system.

J^{ow}_m	${K_T}^{ow}_m$	$10{K_Q}^{ow}_m$	${\eta_o}^{ow}_m$
0.300	0.4422	0.6794	0.311
0.400	0.3880	0.6098	0.405
0.500	0.3322	0.5362	0.493
0.600	0.2744	0.4586	0.571
0.700	0.2145	0.3767	0.634
0.800	0.1524	0.2906	0.668
0.850	0.1204	0.2460	0.662
0.900	0.0878	0.2002	0.628
0.950	0.0546	0.1534	0.538
1.000	0.0206	0.1054	0.311

5.2.3 Self propulsion test. Ballast condition

Self propulsion tests have been carried out as has been indicated in 3.3 and results are presented from “Table 6” to “Table 8”.

Table 6. Self propulsion test. Coefficients.

V	C_{Fs}	C_{Fm}	t	w_{Tm}
knots	10^{-3}	10^{-3}		
18.0	1.359	2.909	0.153	0.253
19.0	1.351	2.882	0.163	0.247
20.0	1.343	2.857	0.172	0.243
21.0	1.335	2.834	0.176	0.242
22.0	1.328	2.812	0.176	0.246
23.0	1.321	2.791	0.172	0.251
24.0	1.315	2.771	0.164	0.254
25.0	1.309	2.752	0.156	0.248

Table 7. Self propulsion test. Propulsion system measurements.

V	n_{mFP}	T_{mFP}	Q_{mFP}
knots	rps	N	N. m
18.0	6.980	17.933	0.633
19.0	7.448	20.366	0.705
20.0	7.899	22.877	0.780
21.0	8.320	25.447	0.855
22.0	8.704	28.037	0.931
23.0	9.060	30.627	1.005
24.0	9.415	33.187	1.077
25.0	9.831	35.679	1.144

Table 8. Self propulsion test. POD unit measurements.

V	n_{mAP}	R_{mPH}	Q_{mAP}	T_{mUNIT}
knots	rps	N	N . m	N
18.0	4.987	7.426	0.248	0.216
19.0	5.321	7.799	0.264	0.392
20.0	5.643	8.299	0.284	0.598
21.0	5.943	9.035	0.308	0.785
22.0	6.218	10.124	0.335	0.883
23.0	6.472	11.644	0.367	0.883
24.0	6.726	13.606	0.405	0.814
25.0	7.022	15.873	0.458	0.873

5.3 Extrapolations

Hull model and propeller models had been manufactured and tested to predict the ship performance by using the proposed extrapolation procedure.

5.3.1 Open water test

Considering "Table 5" and Equation (37), Equation (40) and Equation (41) and the ITTC'78-PPM, values of K_{TS} and K_{QS} have been calculated.

Table 9. Open water test. Ship propeller prediction.

J_s	K_{T_S}	$10K_{Q_S}$	η_{o_S}
0.300	0.4618	0.6695	0.329
0.400	0.4076	0.6000	0.432
0.500	0.3516	0.5264	0.531
0.600	0.2936	0.4488	0.623
0.700	0.2334	0.3670	0.707
0.800	0.1710	0.2809	0.773
0.850	0.1389	0.2363	0.793
0.900	0.1062	0.1905	0.795
0.950	0.0729	0.1437	0.762
1.000	0.0389	0.0958	0.641

5.3.2 Self propulsion test

By the application of the extrapolation procedure presented in the paper, the ship performance has been stablished.

Table 10. Ship performance.

V_S	W_{TS}	T_S	P_{ES}	P_{DS}
knots		kN	kW	kW
18.0	0.200	1442.2	11326.7	16744.1
19.0	0.202	1623.1	13287.8	19211.2
20.0	0.205	1816.2	15491.4	22000.1
21.0	0.208	2018.0	17976.6	25163.3
22.0	0.209	2226.0	20774.7	28742.6
23.0	0.209	2439.9	23943.4	32795.7
24.0	0.206	2664.8	27556.1	37437.7
25.0	0.199	2916.0	31704.2	42923.4

The splitting on power obtained for a fixed rpm ratio has been calculated and it is presented on "Figure 12".

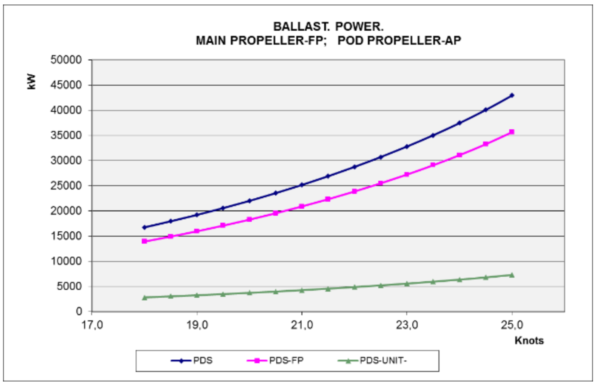

Figure 12. Power curves of different elements.

CONCLUSIONS

A model testing procedure for CRP-POD system for a fixed rpm ratio between main and POD propeller has been developed. This procedure may be applied to any power/rpm combination. It is necessary to develop independent dynamometers allowing the measurements of individual rpm, thrust, torque and POD housing drag in open water and self propulsion conditions.

An extrapolation method for this CRP-POD system based on the guidelines of the existing ITTC standard procedures has been proposed. The extrapolation procedure has been applied successfully to a container ship tested at model scale and predictions for full scale have been calculated.

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DISCUSSION

Question from Taegoo Lee

Where can we get the frictional resistance coefficient? Resistance of pod housing is measured at the propeller with pod open water test and self propulsion condition. In full scaling, the resistance of POD housing in self propulsion condition is used, and frictional coefficient comes from the ITTC's flat plate friction line.

Author's closure

Yes, we confirm that for extrapolation purposes frictional resistance coefficient of POD Housing, both in Open Water condition and in Self Propulsion tests, is calculated according to ITTC-57 formula.

Question from Artur Nerman

Efficiency benefit compared to single stern propeller.

Author's closure

Only a case has been analysed deeply, a container ship with a conventional propeller of 8.950 m, diameter. In the CRP-POD configuration the main conventional propeller diameter was 8.250 m, and the conventional Pod propeller diameter were 7.100 m.

In ballast condition, there was obtained a mean benefit of 4% in power in the frame 18 to 23 knots.