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CRP propulsion system for merchant ships. Past, present and future.

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ABSTRACT

The objective of this work is to disclose the advantages of the CRP-POD propulsion system in comparison with the traditional propulsion, based on the analysis of the results of the tests carried out with models in the CEHIPAR facilities.

In recent years, the incorporation of the aft propeller in a POD unit not only avoids mechanical problems related to co-axial shafts but also allows the POD housing to act as a rudder. Consequently, the traditional rudder has disappeared, the efficiency has increased and better manoeuvrability has been obtained in both azimutal-POD and rudder-POD configurations.

At present, advanced propellers design methods, based on numerical calculations, permit to obtain high efficiency propellers, as tip rake, CLT propeller among others. They may be used in the CRP-POD configuration which will achieve additional energy saving. Future merchant ships, provided with CRP-POD propulsion system, will produce low CO_2 emissions to the environment.

Conclusions and advantages are established.

Keywords

CRP-POD, rudder-POD, POD unit, contra-rotating, PTO, low emission, energy saving, merchant ships, efficiency.

1 INTRODUCTION

CRP propulsion systems consist of two different propellers arranged in line rotating in opposite directions. The aft propeller is located downstream the main propeller to recover part of the energy of the slipstream, increasing in this way the propulsive efficiency of the system. These results in significant energy savings during ship navigation. The first developments of the CRP configuration were based on coaxial contra-rotating shafts with special gearboxes.

The mechanical installation was very complicated and expensive, requiring high maintenance costs. For these reasons, CRP units has been installed in few full-scale ships in the past.

The contra-rotating configuration of the propulsion (CRP) and its advantages have been known for many years, and it was implemented with mechanical transmission that entails operational problems in large vessels. In the last fifteen years, the propellers have been installed in a POD with electric motors in different types of vessels. As established by the ITTC Specialist Committee on Propulsion Systems with POD, 2008, "POD propellers have been treated as a new propulsion system on many types of ships, opening a new page in marine propulsion".

Aware of the importance of this propulsion system, the European Union has funded projects with electric propulsion with POD, being considered as one of the most promising technologies.

The basic foundation of this propulsion system is its suitability for the segment of cargo ships in which economic activity has a great importance.

With reference to newly built vessels, where it would be convenient to install this modern propulsion system, there are Ro-Ro, tankers, gas tankers (LNG), container ships, freighters, for the great advantages derived from higher performance and lower emission of polluting waste.

Some applications of this propulsion system had been made in Japan, as HAMANASU and AKASHIA Ro-Pax "(Ueda et al 2004)" and a tanker ship, SHIGE-MARU, launched in 2007 in NIIGATA.

The CRP-POD propulsion system combines the CRP concept and propulsion with POD. The electric motor that drives the secondary propeller is incorporated in the POD. This makes mechanically simple the distribution of power between propellers, which is also a new parameter whose optimization can provide advantages for the ships of the future. Avoiding flying buttresses and even other complex mechanical elements, propulsive performance is improved and emissions of polluting gases are reduced, which benefits to the future ships that will be provided with this propulsion system.

2 CRP CONCEPT

This propulsion system includes two propellers located with the axis in the same line and the aft propeller in the downstream the main propeller. At the beginning, both propellers were located in a single shaft, figure 1.

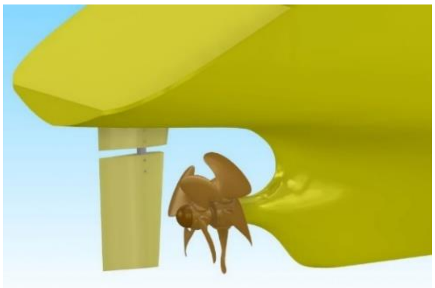

Figure 1. Contra Rotating Propeller.

The main propeller causes circulation in the water. The aft propeller rotating in opposite direction neutralizes the circulation. This effect causes a bigger forward thrusting force and the propulsion efficiency is increased.

2.1 CRP configuration

The configuration of both propellers located in a single shaft, but turning in opposite directions, originates a lot of mechanical problems. The inner shaft causes frictional forces resulting in a lot of wear. The lubricating of the inner shaft is very hard to establish. That mechanical loses are difficult to avoid and they were the motive why this propulsion system was not extended too much.

2.2 CRP-POD characteristics

CRP-POD propulsion system configuration is based on two propellers with the axis in the same line and the aft propeller acting on the downstream the main propeller. The POD propulsion and CRP concept are combined.
Both propellers are driven by independent engines and they rotate, synchronized, in opposite direction in all the ship operational navigation conditions. The mechanical problems are avoided because the axes are independents, as it can be observed in figure 2.
The aft propeller is incorporated in the POD and it is driven by an electrical motor. In this way the share of power is simple from a mechanical point of view.
The distribution of power between propellers is a new parameter whose optimization can provide advantages for the ships of the future; the flying buttresses and other complex mechanical elements are eliminated and the propulsive performance is improved and, consequently, the emissions of polluting gases are reduced.

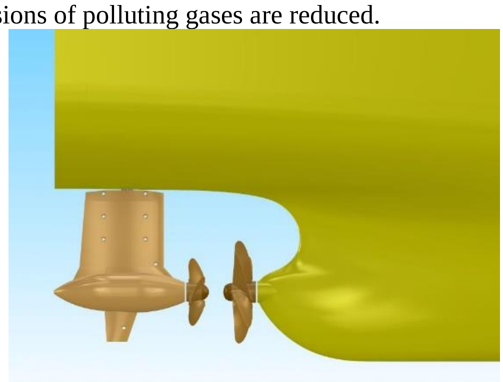

Figure 2. Azimutal-POD.

The POD occupies the position of the rudder of conventional propulsion, so it must also replace its effects. The original design of the POD is an azimuthal system that can rotate 360º, as can be observed in figure 2; in this case the axial separation between the two propellers must be sufficient to allow the rotation without interferences; this alternative provides an improvement of the maneuverability of the ship since the transverse force that the POD with its propeller can generate is much greater than that of a conventional rudder.
Due to the induced velocities, the fluid vain generated by the main propeller is contracted so that, in general, the POD propeller must have a smaller diameter than the main propeller, to avoid the risk of erosion of the POD propeller if any type of cavitation is developed on the main propeller.
There is another alternative in which the POD acts as "rudder-pod"; its azimuthal character is lost and consists of a fixed part "pod housing + rudder" or casing plus the rudder. In this case, the "pod housing" is fixed and carries inside the electric motor that drives the aft propeller, while the rear, "rudder", can rotate, acting as a rudder, darker brown zone in the figure 3. In this case, the separation between the two propellers can be smaller and the hydrodynamic interaction between both propellers is more effective.

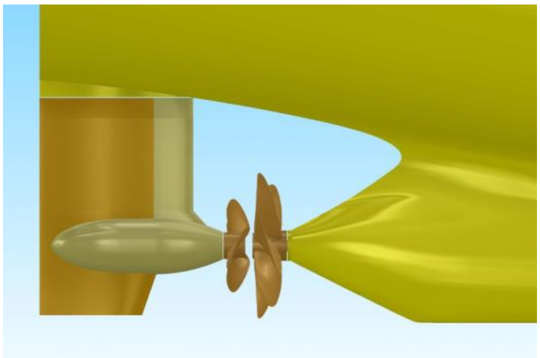

Figure 3. Rudder-POD.

Comparing with a conventional propulsion system, the CRP-POD system allows, conceptually, several alternatives and different degrees of freedom according to the selected option, giving rise to different configurations of the entire propulsion system. A first set of alternatives results from the operation of the two propellers; they can be designed driven by diesel engines, electric motors or mixed solutions.
The power distribution between both propellers is a new degree of freedom whose optimization may depend on the selected drive alternative. It must be considered that the diesel engine directly coupled to a propeller is the solution that presents lower losses in the transmission of power from the engine to the propeller, while the electric transmission of the power, from its generation to the engine that drives the propeller, can have a considerable percentage of losses. Later, it is explained how to focus the hydrodynamic optimization of diameters and speeds of rotation of the propellers according to the power distribution selected.
It has been investigated in depth the most suitable CRP-POD configuration to install this system in an existing vessel with conventional propulsion, in order to cause the lowest possible cost, from the necessary investment point of view, within the framework of a R&D project, named TRIPOD, supported by European Community. The goal of the project was to achieve a short period of return on investment that could be attractive to shipowners and applicable to all ships whose propulsion consists of a diesel engine directly coupled to a propeller.
Advanced propellers design methods, based on numerical calculations, including CFD analysis, permit to obtain high efficiency propellers, as tip rake, CLT propeller among others. They may be used in the CRP-POD configuration leading to the achievement of additional energy savings. "(Sánchez-Caja et al 2012)"
The finally selected configuration of the TRIPOD project is shown schematically in figure 4. It consists in maintaining the main engine and replacing the rudder with a "rudder-pod" system consisting of a POD with electric motor, mounted in housing with a fixed part and a "flap" type rudder, coupled to the housing or "pod housing". This type of "rudder-pod" requests a lower investment than the standard POD, but loses its azimutal character.
For the electrical drive of the POD motor, a solution with

great advantages consists of installing a generator of alternating current PTO, geared to the main engine, and connected to the electric motor of the POD, directly, without transformers, or converters, which causes the lowest percentage of losses due to electrical transmission, especially if it is done at medium or high voltages. Thus, the speed of rotation of the propeller of the POD is determined as a proportion of the speed of rotation of the main engine, and therefore of the propeller, fixed by the ratio of the number of poles of the PTO alternator and of the POD engine.

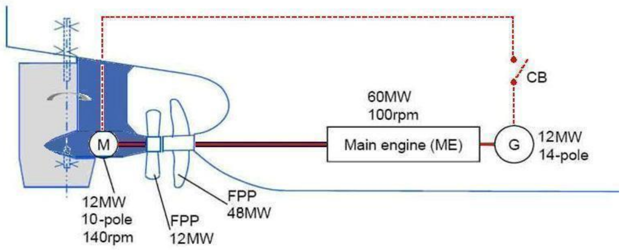

Figure 4. CRP-POD configuration.

This configuration allows many alternatives such as, for example, the connection to be made through the main electrical panel of the vessel, allowing the POD engine to be fed from the auxiliary generators. The installation is complicated, but in case of emergency due to failure of the main engine, auxiliary propulsion is available. 14 poles were configured in the PTO generator and 10 poles in the electric motor of the POD, thus maintaining the ratio of revolutions of both propellers in the 10/14 ratio constant.

This solution, changing the propulsion system in an existing merchant ship, means that the number of elements to be modified is minimal, and a degree of freedom difficult to control in other configurations is eliminated, as is the ratio of rpm between propellers, main and POD. For the power optimization calculations, the performance in the electrical and mechanical transmission of the POD propeller has been established by 94%, while with the main propeller 98.5% is adopted, as mechanical performance of the transmission from the engine principal. Consequently, the losses in the transmission with the POD exceed by 4.5% those of the main propeller. This handicap, inherent in the electro-mechanical transmission, must be compensated with the best hydrodynamic performance of the CRP-POD system.

In the CRP-POD propulsion system, the power distribution must be decided, taking into account that the power, assigned to the POD propeller, must not be excessively large, since the electrical and mechanical losses in the transmission are greater than those they take place in the main propeller.

In the case that the CRP-POD system is selected for a newly constructed vessel, practically only the stern forms of the hull must be adapted for the new configuration, and in this case a slight hydrodynamic improvement of the vessel can be achieved. The decrease of the resistance of the vessel, which will hardly exceed 2%, also contributes to increasing energy savings and reducing the emission of polluting gases.

In the case of ships that originally were already configured with electric diesel propulsion, such as cruise ships, introducing a new CRP-POD configuration would also improve their navigation characteristics, since the transmission losses would be the same in both cases, but the propulsive performance of the CRP-POD system is greater and, in addition, it benefits from the advantages of power sharing.

Another additional advantage, which can be considered, for the ships that install this CRP-POD propulsion system in the future, and according to the configuration that is decided, is a consequence of the possible smaller space needed for the engine room, as it needs less power and be divided into two engines. This available space allows a greater load capacity.

3 TESTS

The propulsion system is considered as a package, so the POD is not treated as an appendix when carrying out the tests. The resistance, open water and self-propulsion tests are necessary. "(Quereda et al 2012)"

The CRP-POD, used in all tests conducted with this propulsion system, is composed of a main propeller and the unit that includes the housing, "pod housing", and the rudder, which, to facilitate the development of the tests, has been manufactured as a monobloc, and the aft propeller, figure 3. This whole set that works behind the main propeller, has been referred to as "UNIT" in this work.

3.1 Resistance tests

It is necessary to carry out a resistance test to determine the bare hull resistance.

The propulsion equipment, formed by the main propeller and the POD with the secondary propeller, is considered the propulsion system in the CRP-POD configuration, so it is not included in the resistance test, because it is not an appendix.

Consequently, this test is carried out with the bare hull, since the rudder is incorporated in the POD, as can be seen in figure 3. The test is carried out in the traditional way established by the ITTC. With this test, the effective power is determined and the form factor (1 + k) is established.

3.2 Open water tests

The configuration of the CRP-POD propulsion system requires carrying out different open water tests to know the behaviour of the main and secondary propellers, acting alone and, also, in the arrangement they carry when working on the ship they propel.

All the open water tests that should be realized with this system of propulsion, must be done with the axis of each propeller submerged 1.5 times the diameter of the main propeller.

Different types of open water test must be carried out. Both propellers alone, main propeller in reverse flow, the aft propeller with POD and the CRP-POD system as it is installed at full scale. In this paper, we explain how the open water test of the whole system is carried out, that is, main propeller and aft propeller in POD.

To know the operating characteristics of both propellers, two dynamometers must be used, which requires a test configuration different from the traditional, when testing a single propeller.

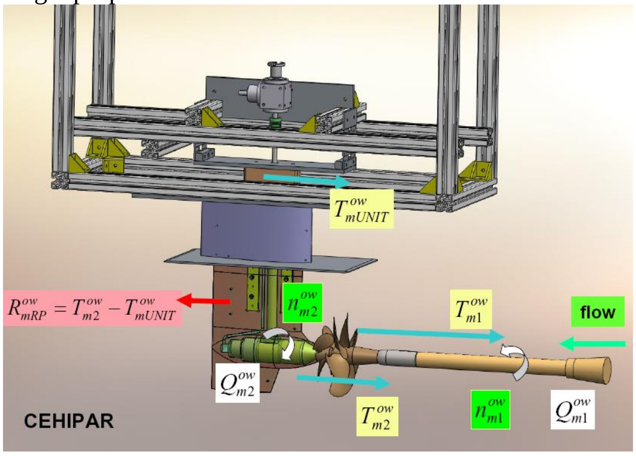

Figure 5. Open water test device.

The carriage dynamometer measures the characteristic magnitudes of the main propeller. The second dynamometer allows measuring the magnitudes of the aft propeller. The thrust of the whole POD unit is measured in the tray, T^{ow}_{mUNIT}, in figure 5.

In this test there are two propellers running synchronized, rotating in opposite directions. It can be affirmed that this open water test is the most important and indispensable for the analysis of this CRP-POD propulsion system, for this reason the ^{ow} nomenclature has been employed in all superscripts for this propellers test.

The decision is made to make reference to the characteristics of the main propeller, rpm and diameter, for the definition of all the parameters, the advance coefficient of the system, J_m, the thrust coefficient of the whole CRP-POD system, K_{Tm}, and the torque coefficient, K_{Qm}. That is why all these parameters are referred, in their definition, to the rpm, n_{m1}, and diameter of the main propeller, D_{m1}.

$$J^{ow}_{m} = \frac{V_m}{n_{m1} D_{m1}} \tag{1}$$

$$K^{ow}_{Tm} = \frac{T^{ow}_{m1} + T^{ow}_{mUNIT}}{\rho_m n^2_{m1} D^4_{m1}} \tag{2}$$

Analysing this equation 2, it can be concluded that the thrust of the whole system has been defined by the sum of the thrust of the main propeller, T^{ow}_{m1}, and the thrust measured in the tray, T^{ow}_{mUNIT}. However, the coefficient of thrust of the secondary propeller, K^{ow}_{Tm2}, is also determined, based on its own characteristics. A parameter named torque coefficient of the aft propeller, K^{ow}_{Qm2}, should be defined.

The definition of the coefficient of torque of the system, K^{ow}_{Qm}, is made taking as reference the diameter and the revolutions of the main propeller to adimensionalize the sum of power contributed by each propeller, equation 3.

$$K^{ow}_{Qm} = \frac{n_1 Q^{ow}_{m1} + n_2 Q^{ow}_{m2}}{\rho_m n^3_{m1} D^5_{m1}} \tag{3}$$

Maintaining the usual nomenclature, the performance of the entire system is defined.

$$\eta^{ow}_{m} = \frac{J^{ow}_{m}}{2\pi} \frac{K^{ow}_{Tm}}{K^{ow}_{Qm}} \tag{4}$$

3.3 Self propulsion test

During the performance of the self-propulsion test it is necessary to measure the operating characteristics of propellers, thrust, torque and rpm, so it will be necessary to use two dynamometers, as well as the thrust of the entire UNIT that is measured in the cell load in the tray above the POD. The propellers rotate synchronized, in opposite directions, and keeping constant the ratio of the rotational speeds of both propellers.

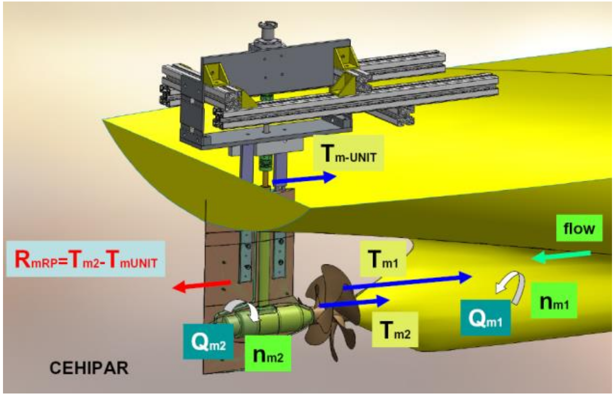

Figure 6. Self-propulsion test scheme.

For the performance of the self-propulsion test, it is necessary to specify the value of the deduction fraction, F_{Dm}, value that is calculated, adding the contribution of the whole rudder-pod housing, F_{DRP}, to the deduction fraction of the hull, F_{DHULL}, as it is defined in equation 5.

$$F_{Dm} = F_{DHULL} + F_{DRP} \tag{5}$$

The value of the deduction fraction of the fairing, F_{DHULL}, is determined considering the traditional resistance test and the form factor, 1 + k, calculated as indicated in the proceeding of ITTC.

$$F_{DHULL} = \frac{\rho_m S_m V^2_m}{2} \left[(1+k)(C_{Fm} - C_{Fs}) - \Delta C_F \right] \tag{6}$$

S_m is the wet surface of the model hull, C_{Fm} and C_{Fs} are, respectively, the model and ship friction resistance coefficients, which are calculated as a function of the Reynolds number, and ΔC_F is the roughness correction coefficient.

The deduction fraction of the "rudder-pod" is determined according to equation 7, in which the friction coefficients of the model and ship "rudder-pod", are defined according to the hydrodynamic characteristics of the POD and its geometry, are involved.

$$F_{DRP} = R_{mRP} \left(1 - \frac{C^{RP}_{Fs}}{C^{RP}_{Fm}}\right) \tag{7}$$

F_{DRP} is calculated taking into account the coefficients of friction resistance in the shell, C^{RP}_{Fm} and C^{RP}_{Fs}, calculating the Reynolds number with the velocity of the flow and with the length of the section of the POD located at the height of 0.75R of the main propeller above the axis.

For each test speed, the load is varied, by using three different values of the rpm, and the measurement of the magnitudes represented in the scheme of figure 6 is made, so that three different values of all the magnitudes are recorded, even of the friction deduction, F_{Dm}, a lower one, another with a value close to that of the deduction fraction calculated by equation 5 and another with a higher value. The valid point of the test is obtained by interpolating the values measured during this test with the deduction fraction calculated by equation 5.

$$R_{mRP} = T_{m2} - T_{mUNIT} \quad (8)$$

Since the resistance value of the POD housing, R_{mRP}, is calculated with the self-drive test data, and taking into account its dependence on the thrusts measured with the POD dynamometer, it is necessary to make successive iterations until achieving the convergence value with the two quantities that are written in equation 8, thrust of the POD propeller, T_{m2}, and thrust of the unit, T_{mUNIT}.

The final result of the interpolations and iterations made with the measurements taken during the self-propulsion test, allows establishing the values of the magnitudes described in the scheme of figure 6, n_{m1}, T_{m1}, Q_{m1}, n_{m2}, T_{m2}, Q_{m2} and T_{mUNIT} at each tested velocity.

Because there is no procedure in the ITTC to extrapolate the tests results with this propulsion system, SISTEMAR-CEHIPAR have developed a procedure that allows to know the navigation characteristics of a ship provided with the CRP-POD system. "(Quereda et al 2017)"

4 MERCHANT SHIPS APPLICATIONS

In the TRIPOD project, knowledge was generated about the behaviour of the propulsive coefficients of the CRP-POD propulsion system, both in the case of using conventional or unconventional type propellers, such as CLT. "(Sánchez-Caja et al 2014)"

Based on this, it has been possible to develop a design tool to estimate the benefits that can be achieved by applying this CRP-POD system to different types of vessels.

As the commitment acquired with the environment is growing, new rules and norms to comply with maritime transport have arisen. Chapter 4 of Annex VI of the MARPOL Convention establishes mandatory technical and operational energy efficiency measures, called in their abbreviated form:

• EEDI. Energy efficiency design index. Measurement of the energy efficiency of a ship.

• SEEMP. Energy efficiency management plan for the ship. Mechanism that allows a ship to improve energy efficiency during its navigation and port operations.

• EEOI. Operational indicator of the ship's energy efficiency. Reference level for greenhouse gas emissions.

This chapter of the Convention was made compulsory for all ships of new construction, covering different aspects of the efficiency of ships in terms of construction and operation during their useful life.

It is the first instrument on climate change, after the adoption of the Kyoto Protocol in 1997, where rules on energy efficiency are introduced for a sector of international scope. CO_2 emissions are obtained from the vessel's consumption, taking into account propulsion, auxiliary systems and the carbon content of the type of fuel it uses.

The reports of the Official Organizations that carry out the statistics of the distribution of the world fleet, "Review of Maritime Transport 2017", establish that the vessels of the Oil tanker, Cargo, and Container ship type represent more than three quarters of the world fleet. The fleet of LNG has, also, an increasing importance. These four types of vessels have been chosen with the aim to carry out a study of application of the CRP-POD propulsive system. This vast majority of ships have propulsion systems based on a main engine, which drives a propeller through an axis with its corresponding supports and horn. It is what is called conventional propulsive system.

4.1 CRP-POD propulsion system design procedure

Determination of the main data of the project in its preliminary status.

• Overall dimensions of the ship.

• Data of the main engine.

• Data for the design of the CRP-POD system.

It is necessary to optimize the two propellers of this system, considering the following degrees of freedom, added to those that have the design of a conventional propeller:

• Selection of the optimal power distribution between both propellers.

• Selection of optimum diameters and rpm of both propellers.

• Selection of the number of blades of both propellers.

Optimization is done through the total propulsive performance of the system (η_T):

$$\eta_T = \eta_D \eta_m \quad (9)$$

η_m, the mechanical performance of the shaft line; It must be borne in mind that the electric transmission has its own losses that reduce this performance.

This factor, η_m, is the most important parameter to establish the share of power, taking into account the different mechanical transmission loses in both propellers.

The parameter η_D, quasi-propulsive efficiency may be calculated as a function of different coefficients.

$$\eta_D = \eta_0 \eta_R \eta_H \quad (10)$$

Being, as usual in Naval Architecture:

η_o, ideal efficiency, open water.

η_R, the relative-rotational efficiency.

η_H, the hull efficiency, (1-t)/(1-w).

1-t, the thrust deduction coefficient.

1-w, the wake coefficient.

With these considerations and with the optimal distribution of the power between the two propellers, it is possible to proceed with the design of the CRP-POD system propellers.

First, we proceed to design the main propeller of the CRP-POD system.

In order to finalize the design of the propulsion system, in particular the aft propeller, its effective wake coefficient must be determined, for which the velocities induced by the fore propeller have to be taken into account. The following expression is used:

$$w_2 = w_1 - \Delta w \quad (11)$$

Next, it is necessary to proceed to the POD propeller design, aft propeller, of the CRP-POD system.

It is recommended to fix the diameter of the POD propeller, D_2, with a value close to 90% of the diameter of the main propeller, D_1, to maximize the contra-rotating effect. Taking into account these values, the optimal propeller for the POD, including its optimum rpm, is determined.

Combination of the main and POD propellers. It is necessary to determine the own resistance of the housing of the POD unit, R_{sRP}, which really is a reduction of the total thrust supplied by both propellers. $T_{s1} + T_{s2} - R_{sRP}$.

Selection of propellers. The propellers can be designed as conventional propellers or other advanced designs, as would be the case with the CLT propellers, which are also evaluated in this document.

4.2 Analysis and comparison

The most representative ship types of the world maritime transport have been selected in order to analyse the idea of the saving of the consumptions and, consequently, the reduction of emission of exhausted gases. The following cases have been studied:

• Tankers: Three types. VLCC, SUEZMAX, Products Tanker. (Cases 1, 2 and 3).

• Cargo ship: Three types. CAPESIZE of 160,000 t, PANAMAX of 80,000 t and a HANDY SIZE of 35,000 t. (Cases 4, 5 and 6).

• Container ship: Two types. 15000 TEU with 2 axes and 5000 TEU with 1 axle. (Cases 7 and 8).

• Gas, LNG: Two types. Standard of 145000 m^3 and new trend of 175000 m^3. (Cases 9 and 10).

Case	4	5	6
Ship type	BULKCARRIER		
Size	Capesize	Panamax	Handysize
Lpp	280.0	220.0	181.0
Beam	47.0	32.25	30.5
Depth, H	25.0	21.0	16.5
Design draft, T	17.80	12.50	11.00
dwt at design draft	172,000	65,000	43,000
Cb	0.837	0.832	0.828
total PS, MCR in kW	21,000	11,500	8,000
RPM	90.0	105.0	127.0
Design speed, kn	15.0	15.0	14.5
Dmax	8.6	7.3	6.2
Number of shafts=	1	1	1
NOR (%MCR)	85.0%	85.0%	85.0%
ETAm=	0.990	0.985	0.985

Figure 9. Bulk-carrier and ship characteristics.

In this paper, to avoid calculation repetitions, bulkarriers application is presented in detail. The main data can be observed in figure 9, ships characteristics.

An optimized conventional 4 blades propeller has been designed and used as traditional propulsion system for comparisons.

For the case 4, the diameter of the conventional propeller designed is 8.6m, and 4 blades. The efficiencies obtained are: η_T = 0,6352 and η_D = 0,6416.

Table 1. Propellers characteristics.

Main prop design	Case 4			
Power main prop, %=	80.0%	70.0%	60.0%	50.0%
PS1, kW=	16800	14700	12600	10500
ETAm1=	0.990	0.990	0.990	0.990
PD1, kW=	14440.1	12635.1	10830.1	9025.1
rpm=	90.0	90.0	90.0	90.0
V=	15.0	15.0	15.0	15.0
D/L=	0.0289	0.0280	0.0271	0.0263
w1=	0.377	0.381	0.385	0.390
z=	4	4	4	4
D=	8.138	7.928	7.631	7.328
H/D=	0.671	0.674	0.691	0.703
Ae/Ao=	0.456	0.440	0.430	0.413
ETAo=	0.520	0.527	0.534	0.543
T1 (kN)=	1560	1394	1218	1040
CT1=	2.528	2.411	2.308	2.170
delta w=	0.345	0.332	0.321	0.306

POD prop design	Case 4			
Power POD prop, %=	20.0%	30.0%	40.0%	50.0%
reduction D=	90%	90%	90%	90%
PS2, kW=	4200	6300	8400	10500
ETAm2=	0.940	0.940	0.940	0.940
PD2, kW=	3356	5034	6712	8390
V=	15.0	15.0	15.0	15.0
w2=	0.032	0.049	0.064	0.084
z=	3	3	3	3
D=	7.324	7.135	6.868	6.595
rpm=	46.2	70.1	84.9	99.9
H/D=	1.800	1.105	0.984	0.902
Ae/Ao=	0.374	0.394	0.431	0.472
ETAo=	0.745	0.7325	0.6979	0.6608
T2 (kN)=	335	502	649	784
CT2=	0.277	0.455	0.656	0.895
RPM ratio=	0.5133	0.7789	0.9433	1.1100
RsPH (kN)=	3.216	3.170	3.125	3.079
T-UNIT=	331	499	645	781

Table 1 presents the main values of the parameters used to analyse a bulk-carrier, type “Capsize”, including different sharing of power, by using two conventional propellers, main and POD.

Table 2. Sharing of power. Two conventional propellers versus two CLT propellers.

Efficiency in configuration CRP-POD with different power share								
Propeller	CONVENTIONAL				CLT			
Power share, %	80.0%	70.0%	60.0%	50.0%	80.0%	70.0%	60.0%	50.0%
	20.0%	30.0%	40.0%	50.0%	20.0%	30.0%	40.0%	50.0%
ETAo=	0.511	0.512	0.504	0.492	0.542	0.541	0.531	0.518
ETAH=	1.249	1.258	1.267	1.277	1.249	1.258	1.267	1.277
ETAr=	1.050	1.050	1.050	1.050	1.050	1.050	1.050	1.050
ETAD=	0.670	0.676	0.670	0.660	0.711	0.715	0.707	0.694
ETAT=	0.657	0.659	0.650	0.637	0.697	0.697	0.686	0.669
ETAD comparison =	1.045	1.054	1.045	1.028	1.108	1.114	1.102	1.081
ETAT improvement=	**1.034**	**1.038**	**1.024**	**1.002**	**1.097**	**1.097**	**1.080**	**1.054**

To define optimal sharing of power, different percentage considerations have been analysed. The calculation results of the CRP-POD configuration with two conventional propellers, green columns, and two CLT propellers, blue columns, including the efficiency raising, has been presented in table 2. Last two lines have been calculated using η_T = 0,6352 and η_D = 0,6416 as reference.

Once the analysis has been concluded with both types of configurations, two conventional propellers versus two CLT propellers, a relevant power saving has been obtained. The values obtained by the tests results with models and the extrapolation procedure must be validated by means of full-scale data. "(Quereda et al 2017)"

The saving energy obtained can be observed in the values of the total efficiency, η_T, presented in the last line of the table 2. The total efficiency of the bulk-carrier ship with a traditional propulsion system has been adopted 100% as reference. In the same way, as the bulk-carriers, other types of ships have been analysed.

It should be noted that the increase of benefits that can be achieved with this propulsion system, due to eliminate the flying buttresses and the rudder, which represents the decrease in effective power of the order of 2%, has not been taken into account in the calculations made.

The total efficiency, η_T, has been used to compare CRP-POD configuration with a conventional propulsion system. In the figures below the value (η_T=1.0) has been adopted for the traditional propulsion system and different figures have been represented.

The values presented in table 2 for bulk-carrier, case 4, type Capsize, have been represented in figure 10. Dot line in brown colour corresponds to CLT propellers, while the blue line corresponds to conventional propellers, both in CRP-POD configuration.

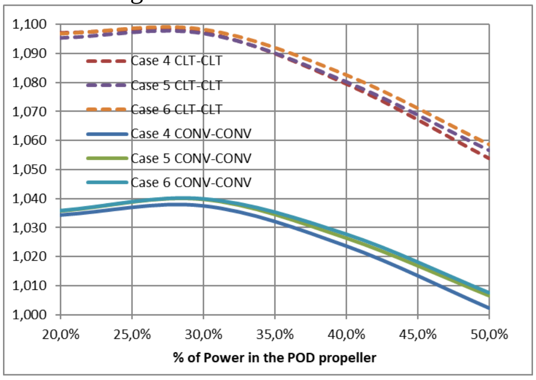

Figure 10. Energy saving in Bulk-carrier.

By using the same procedure for Panamax, case 5, and Handy size, case 6, obtained results have been presented in different colours as indicated in the figure 10. It can be concluded that 25% to 30% of power in the POD produce the maximum efficiency and CLT propellers permits about 6% better efficiency than two conventional propellers, and about 9 to 10% in comparison with the traditional propulsion system, η_T=1.0, adopted as reference to develop this comparative analysis.

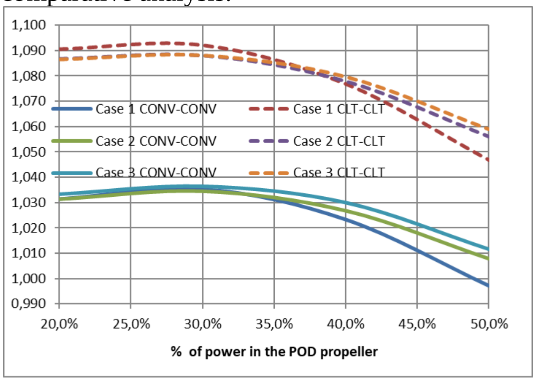

Figure 11. Energy saving in Oil tankers.

The values obtained for tanker by using the same procedure than for bulk-carriers have been represented in figure 11.

VLCC, case 1, Suezmax, case 2 and Products, case 3, obtained results have been presented in different colours as indicated in the figure 11. It can be concluded that close to 30% of power in the POD produce the maximum efficiency and CLT propellers permits about 5,5% better efficiency than two conventional propellers.

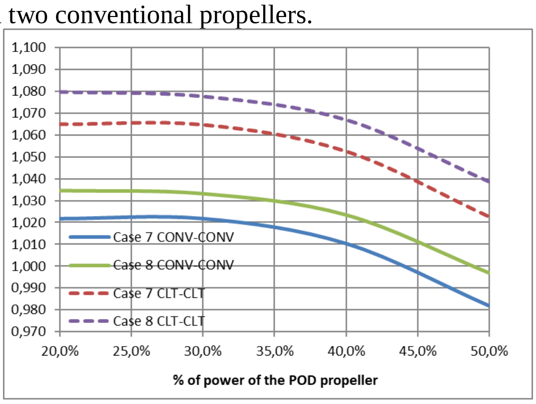

Figure 12. Energy saving in Container ships.

The values obtained for container ships by using the same procedure than for bulk-carriers have been represented in figure 12.

The results obtained for ships corresponding to about 15,000 TEU with two shafts, case 7, and ship around 5,000 TEU with 1 shaft, case 8, have been presented in different colours as indicated in the figure 12. It can be concluded that 22% to 25% of power in the POD produce the maximum efficiency and two CLT propellers permits about 4,5% better efficiency than conventional propellers.

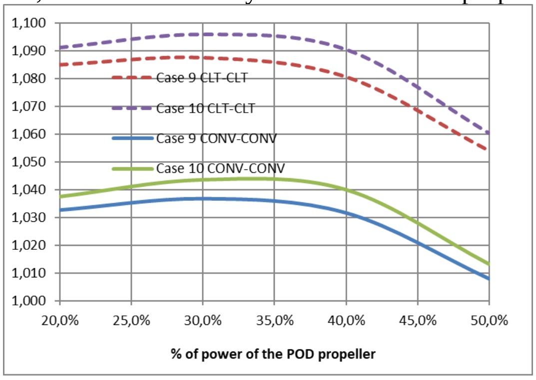

Figure 13. Energy saving in LNG ships.

The values obtained for LNG ships by using the same procedure than for bulk-carriers have been represented in figure 13.

Ships corresponding to Standard 145,000 m^3, case 9, and new trend, 175,000 m^3, case 10, obtained results have been presented in different colours as indicated in the figure 13. It can be concluded that 30% to 35% of power in the POD produce the maximum efficiency and two CLT propellers permits about 5% better efficiency than two conventional propellers.

5 CONCLUSIONS

1. The propulsion system formed by contra-rotating propellers, CRP, improves the propulsive performance, due to its hydrodynamic characteristics. This concept has been incorporated into the CRP-POD system. The methods of testing, the extrapolation of the results and the design of the CRP-POD system have been satisfactorily resolved in this work.

2. The system studied here, CRP-POD, represents an important technological advance, because it simplifies the mechanical configuration of the CRP system, relying on a mixed electric propulsion that could also be applied to a total electric propulsion

3. The CRP-POD system, depending on the solution adopted, can allow the elimination of flying buttresses and complex mechanical elements, reducing resistance and improving performance.

4. The CRP-POD propulsion system needs less power, and is divided into two engines, so the space needed for the engine room is smaller, enabling a greater load capacity.

5. There is great concern worldwide about the emissions of gases into the atmosphere that are derived from the technological activity of the human being. It has been demonstrated that performance improvements can be generated, that lead to lower consumption and, in the same

way, lower gas emissions, through the application of the CRP-POD system, combined, or not, with advanced design propellers, such as the CLT propeller.

6. This new system can be applied to the vast majority of ships that are used in practice for maritime transport.

However, currently, it only applies to a small minority of them, excusing their use, in most cases, for the higher investment cost that it represents. This excess cost, distributed over the life of the vessel, represents a negligible increase in the unit freight cost for each vessel. And, even if the return period of the investment were longer than ideal, all its advantages, including the reduction of gas emissions, should be considered sufficient to install the CRP-POD propulsion system, assuming the disadvantage of a higher manufacturing cost.

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