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Published in:
Transport Research Arena (TRA) 2014 Proceedings

Published: 01/01/2014

Document Version
Early version, also known as pre-print

Please cite the original version:
Sánchez-Caja, A., Pérez-Sobrino, M., Quereda, R., Nijland, M., Veikonheimo, T., González-Adalid, J., Saisto, I., & Auriarte, A. (2014). Triple Energy Saving by Use of Contra Rotating, Tip Loaded and Podded Propulsion Technology. In *Transport Research Arena (TRA) 2014 Proceedings*

Triple Energy Saving by Use of Contra Rotating, Tip Loaded and Podded Propulsion Technology

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Abstract

The TRIPOD project deals with energy saving in waterborne transport. It explores the feasibility of a novel propulsion concept resulting from the integration of two promising technologies (podded propulsion and tip loaded endplate propellers) in combination with energy recovery based on counter rotating propeller (CRP) principle. New ways of saving energy are studied to improve ship operational costs. The paper describes the main objectives and the different phases of the project, including the design activities, validation of the concept by model testing and numerical computations, and the economic analysis of main results. The main focus is on the development of a tool for the assessment of the overall energy balance in the ship design phase and on the application of the new propulsion concept to several ship fleets. Energy savings and consequently emission reductions are derived from the use of the analysis tool.

Keywords: Contrarotating propeller (CRP); CLT propeller ; Pod propulsion ; CFD ; model test ; Tip Loaded ; Economic analysis ; Saving energy;

Résumé

Le projet TRIPOD traite des économies d'énergie dans les transports maritimes. Il explore la faisabilité d'un concept de propulsion novateur intégrant deux technologies prometteuses (propulsion de type POD et chargement de l'hélice en bout de pale) combinées à la récupération d'énergie selon le principe d'hélice contra-rotative (CRP). De nouvelles voies d'économie d'énergie sont étudiées pour améliorer les coûts d'exploitation des navires. Le document décrit les objectifs principaux et les différentes phases du projet, incluant la conception, la validation du concept par des essais sur des modèles et par des simulations numériques ainsi que l'analyse économique des résultats. L'objectif principal porte sur le développement d'un outil d'évaluation de l'équilibre énergétique global durant la phase de conception du navire et sur l'application de ce nouveau concept de propulsion à plusieurs types de navires. L'utilisation de cet outil d'analyse permet de prédire les économies d'énergie et par voie de conséquence les réductions des émissions de gaz.

Mots-clés: hélice pales chargées, hélice contra-rotative, POD, simulation de la dynamique des fluides, essais sur modèles, analyse économique, réduction énergétique.

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Nomenclature

CRP	contra-rotating propeller
CLT	endplate propeller (Contracted and Loaded Tip propeller)

1. Introduction

There is a need for fast ship transportation that is both efficient and non-polluting. Conventional propellers are known to have low efficiency. As an indicative example, most of ship propellers installed on cargo vessels waste about 40 percent of the energy in the form of rotational losses in the wake, vortex generation, noise production, cavitation, etc. The recovery of such losses is one of the major ways to contribute to a more rational, environmentally-friendly use of energy.

The main objective of the TRIPOD project is the development and validation of a new propulsion concept for improved energy efficiency of ships. The ship propulsion efficiency is optimized through the combination of three existing propulsion technologies. In particular TRIPOD explores the feasibility of a novel propulsion concept resulting from the integration of two promising EU grown technologies (podded propulsion and tip loaded endplate propellers) in combination with energy recovery based on counterrotating propeller (CRP) principle. The three existing technologies have been used separately and are known to improve the overall ship propulsion efficiency as compared to conventional propulsion. However, they have never been combined together in a single propulsion package. TRIPOD contemplates two types of propulsive innovations:

- Using CLT propellers in combination with pods
- Using CLT propellers in connection with CRP propulsion and with pods

As a result of the investigation tools have been developed to assess the optimal use of propulsive energy from environmental and economic viewpoints both for new designs and for the retrofitting of existing ships with the novel propulsion concept. In particular, an existing cargo ship with conventional propulsion has been selected and the propulsion unit has been redesigned. First, the ship was retrofitted with a podded contrarotating CLT solution without introducing any hull modifications. In a second phase, hull modifications were allowed, the hull geometry was optimized from the propulsion standpoint and a new CRP-CLT pod unit was designed. The energy savings were quantified for both cases and economic analysis was performed to study the viability of the concept for new ship designs and for retrofitting existing cargo ships. The project findings were used to develop tools to assess the overall energy balance of the new propulsion concept in the ship design phase.

2. Concept Exploration

A reference ship and a reference propulsion system were initially selected for the evaluation of the new propulsion concept from the standpoint of energy savings. APMoller-MAERSK identified Gudrun Maersk as the reference vessel with waste heat recovery and spare electrical power. The length between perpendiculars was 351 m and the displacement 120000 cubic meters. The engine output is 68640 kW MCR at 102 rpm and the original propeller has 8.950 m in diameter and 6 blades. The technical and economic information concerning the ship including route and operation conditions, propulsion efficiency, fuel consumption over fleet operating lives, working life estimations, maintenance and reparation costs, ageing effects impacts on costs, etc. were collected.

In order to keep the CRP pod unit cheap, compact and reliable, ABB decided to use a pod concept called RudderPod, which was further developed to meet the design constraints of the reference vessel. It consists of a non-rotatable pod working as the aft-propeller of a CRP unit, being the ratio of main propeller to the pod propeller RPMs fixed. The after propeller is acting as a slave for the main propeller and follows the main propeller RPM. Steering is achieved by the use of flaps on the strut of the RudderPod.

3. Hydrodynamic Design

The design activities have been performed in two phases called “retrofit scenario” and “new building scenario”, respectively.

Retrofit Scenario. In this scenario the reference ship hull form was kept untouched. A first design of an equivalent CLT propeller was initially made (CLT1). Next, the original horn rudder was removed and a Rudder-Pod designed and installed. The main conventional (CONV1) propeller (fore-propeller) was now the same as that in original vessel; two alternative designs (aft-propeller) were developed to work in contra-rotating mode (CRP) as pod propellers: one of conventional type (CONV3) and the other of CLT type (CLT3).

New Building Scenario. A new optimized hull design for the CRP unit is developed. New propellers designs are made and tested in full load and ballast conditions in order to evaluate the possible advantages of the new propulsion system. Both types of propellers were designed: conventional and CLT propellers. Ship performance calculations including numerical CFD calculations to optimize new hull were carried out and detailed propeller designs were made for the following propulsion configurations:

- CRP-POD configuration with optimum conventional propellers for both the main and the Rudder-Pod propellers (CONV2+POD/CONV4),
- CRP-POD configuration with optimum CLT propellers for both the main and the Rudder-Pod propellers (CLT2+POD/CLT4)

4. Numerical Analysis

CFD tools were used to evaluate different design options from the standpoint of efficiency, scale effects, cavitation and unsteady forces. Additionally, they allowed reducing the number of cases to be experimentally tested that are needed in order to assess the performance of the new designs. RANS code FINFLO was mainly used in the computations.

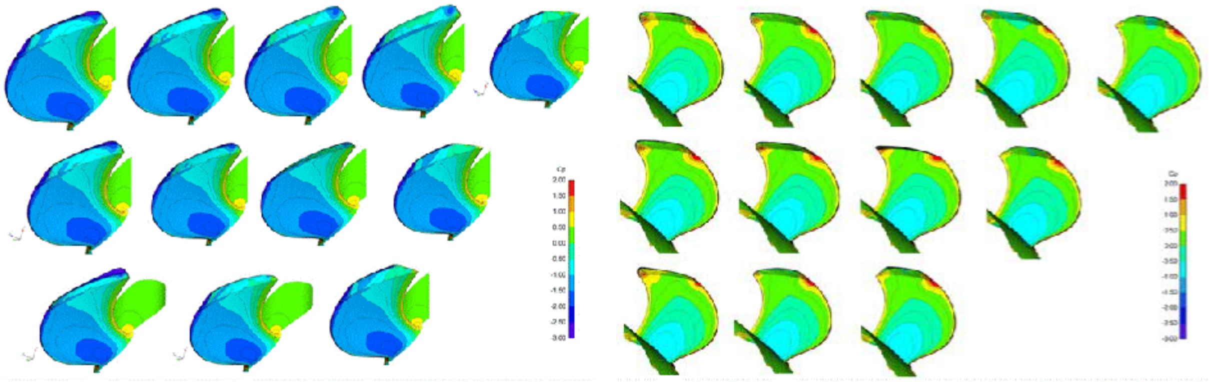


Figure 1. Pressure distribution on the suction (left) and pressure (right) sides of a series of CLT propeller blades with different endplate shapes.

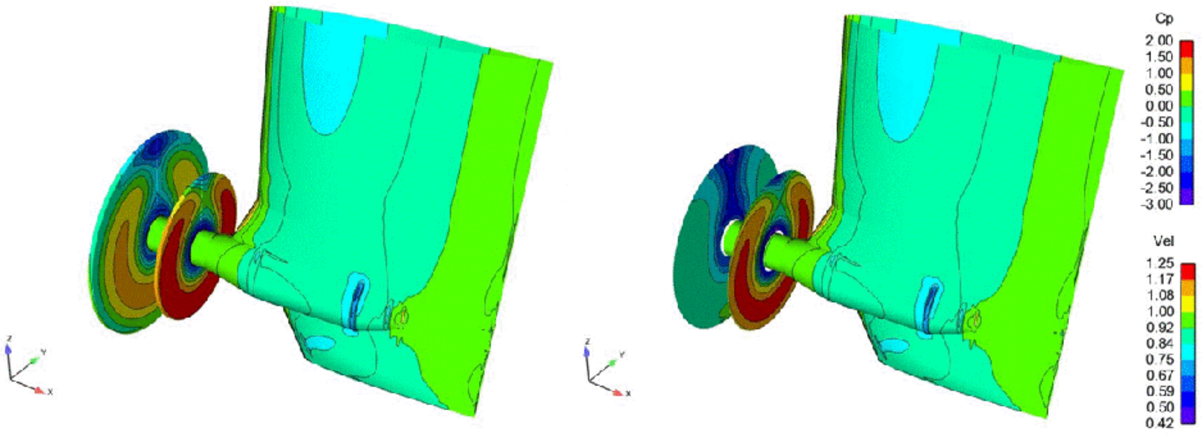


Figure 2. Total non-dimensional velocities (left) and effective wakes (right) at the CRP propeller disks. The colours represent pressures on the pod surfaces and velocities on the propeller disks. New building scenario.

The computations were made for the evaluation of different pod housing geometries, endplate propeller blades shapes and hull form. Additionally, a procedure was developed for the estimation of effective wakes. Figure 1 shows a study made on different CLT propeller shapes, which was reported in Sánchez-Caja et al. (2012, 2013). Figure 2 illustrates computations made for the estimation of the effective wakes, Sánchez-Caja et al. (2014).

5. Model Tests

The propeller designs are checked by model tests. The main objectives of the model tests were:

- Performing complete propulsion tests of the ship models for the cases of both retrofitting and new hull design. The tests allowed evaluating the new propulsion concept from the standpoint of energy saving.
- Performing cavitation and pressure fluctuation tests to assess the impact of the new propulsion concept on noise radiation.
- Finding the ship hull flow to the propeller both for the original hull and for the one optimized from the CRP-CLP-pod propulsion standpoint.
- Additionally the test measurements were used to validate CFD computations.

A new procedure for the extrapolation of the model tests results was introduced for this new system consisting of a main propeller and a POD propeller in a CRP configuration. The method includes a procedure based on the ITTC-78 and related ITTC recommendations to perform model tests (Quereda et al., 2012).

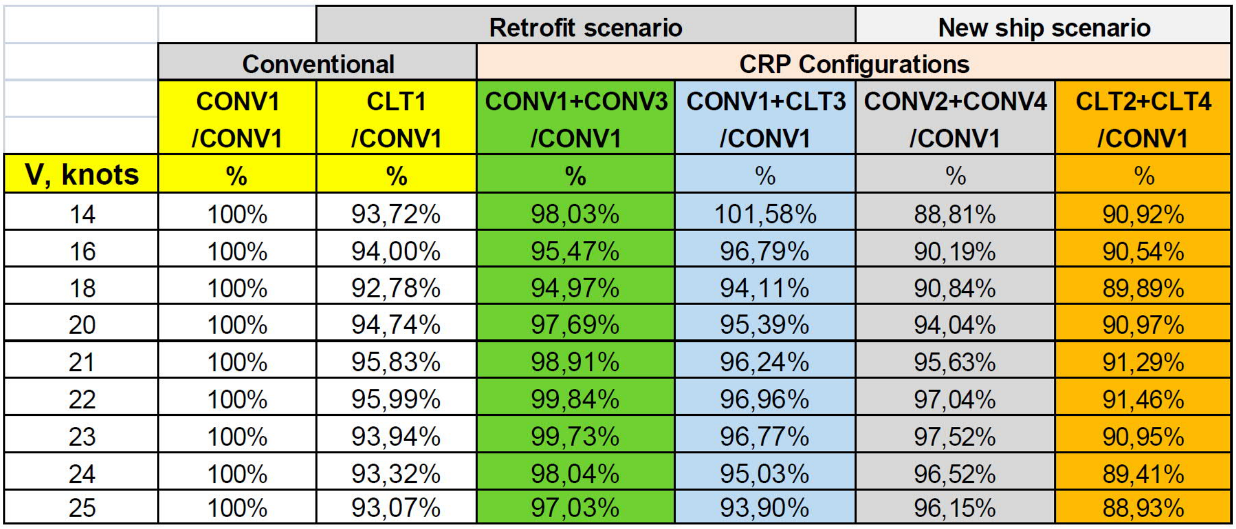
Five programs of tests were scheduled. Each program of tests includes:

- Construction of required models: hull, propellers, pod housing.
- Resistance tests with and without pod housing.
- Open Water tests (propellers alone, pod + conventional propeller open water test, POD+CLT open water test, CRP open water test [main propeller + pod propeller]).
- Propulsion tests
- Cavitation observation tests including pressure fluctuation measurements.

6. Concept validation

An existing cargo ship, the GUDRUN MAERSK, of more than 350 meters length between perpendiculars, was selected to validate this concept. It is operating to full satisfaction of the owner and is propelled with a 6 bladed optimum conventional propeller (CONV1) well adapted to the wake-flow of a carefully studied hull form. To improve the propulsive performance of this ship is a true challenge for a novel propulsion concept.

Table 1. Relative power improvements of tested alternatives with respect to reference propeller



		Retrofit scenario			New ship scenario	
	Conventional		CRP Configurations			
	CONV1 /CONV1	CLT1 /CONV1	CONV1+CONV3 /CONV1	CONV1+CLT3 /CONV1	CONV2+CONV4 /CONV1	CLT2+CLT4 /CONV1
V, knots	%	%	%	%	%	%
14	100%	93,72%	98,03%	101,58%	88,81%	90,92%
16	100%	94,00%	95,47%	96,79%	90,19%	90,54%
18	100%	92,78%	94,97%	94,11%	90,84%	89,89%
20	100%	94,74%	97,69%	95,39%	94,04%	90,97%
21	100%	95,83%	98,91%	96,24%	95,63%	91,29%
22	100%	95,99%	99,84%	96,96%	97,04%	91,46%
23	100%	93,94%	99,73%	96,77%	97,52%	90,95%
24	100%	93,32%	98,04%	95,03%	96,52%	89,41%
25	100%	93,07%	97,03%	93,90%	96,15%	88,93%

The new concept CRP-POD-CLT propulsion system has also several advantages derived from the split of the power into two mechanically independent propellers, for example the redundancy in propulsion. But the focus of TRIPOD project is to improve the propulsive efficiency and consequently, the amount of emissions to the atmosphere.

As explained in section 3 the tests have been oriented to obtain the best knowledge about the possible energy saving in two realistic scenarios: the retrofitting of the propulsion system in the existing ship and the new building of a ship.

Using as reference the power prediction for CONV1 propeller, the results of several tested alternatives are reflected in Table 1 in relative percentages. The CRP-POD system has proved to be more efficient than a state of the art optimum conventional propeller. All the alternative CRP-POD systems developed have improved the ship propulsion power, (Pérez-Sobrino et al., 2013).

6.1. Economic Analysis

Economic criteria to analyze investment proposals are usually not written in stone. Hence the real economic criteria to evaluate business proposals vary from project to project, from business case to business case and from market situation to market situation. Acceptable payback times are very dependent on the global economic outlook and the business situation. This means that proposals will need to be evaluated on their specific arguments, and on a case-to-case basis. Sometimes an investment proposal can be approved, provided that it creates value consisting of new knowledge, or future applications which might have a lower investment. Such arguments can be found in the various scenarios in the TRIPOD project as well.

Operational profiles of the existing ships like the reference ship used in TRIPOD project are changing in these years but not too much, so there are not a lot of differences expected when performing the economic analysis for 2010 or 2013.

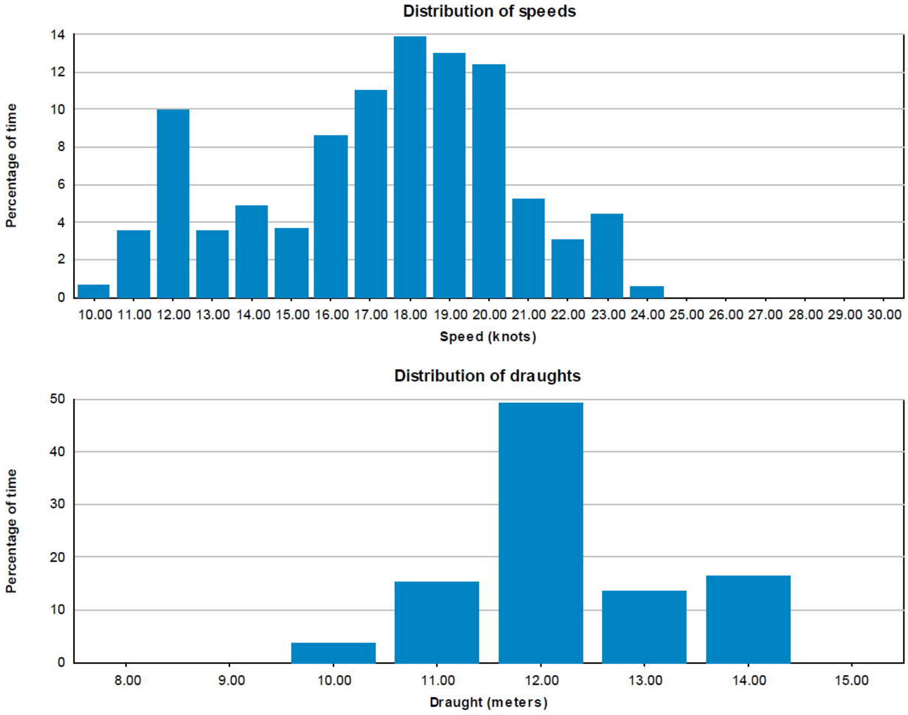


Figure 3. - Operational profile Gudrun class in 2010.

Comparing fuel savings with required CAPEX, it can be concluded that CLT alone is the most promising scenario with today's price levels. For a new building project, the payback time is around 0.3 years, which is quite short. However for a retrofit, the payback time is around 3 years which is relatively long already.

The payback times for different RudderPod new building scenarios are between 6.9 and 8.5 years and for retrofit scenarios beyond the economic life of the ship. In case of a higher average vessel speeds, the new building scenarios for RudderPod become more attractive, especially the CLT2 + CLT4 scenario.

It must however be noted, that the tested propulsion configuration in TRIPOD is considered a state-of-the-art solution, which is technically very promising. It has a high potential in fuel savings and emission reductions. Especially for future new building projects of the Maersk Group, it will be an interesting propulsion concept. And if the investment level can be brought down, obviously in close cooperation with the relevant specialist suppliers, Maersk will be interested to explore further installation opportunities in new building projects of large container ships.

6.2. Pre-design tool

In the process of ship basic design, the propulsion system is one of the most important parts to be defined. The main objective in this phase is the estimation of the propulsive efficiency, which in turn allows to determine the required power and to select the main engine.

If conventional propulsion is selected, there are several alternatives to study with different values of relevant parameters, such as maximum diameter, nominal rpm, position of the propeller in the stern, etc. For the selection of a CRP-POD unit, the number of variables or degrees of freedom is even larger.

In this section a new procedure will be explained to address the main aspects and parameters that must be defined for the selection of a CRP-POD system in the preliminary phase of design. The data required for the estimation of the parameters that differ from those of conventional propellers will be presented.

6.2.1 ASSUMPTIONS TO DEVELOP AN EARLY DESIGN TOOL

Our main assumption is that the new propulsion system (CRP-POD type) is to be installed in a merchant ship that usually has conventional propulsion, i.e., a low speed diesel engine connected to a single shaft line with a conventional propeller.

The expected output is an estimation of the power improvement that can be obtained with a CRP-POD unit compared to the power needed for a conventional propeller. In other words, we are interested in relative improvements in efficiency rather than in absolute values of energy consumption for the different propulsion alternatives. The accuracy of the absolute values of the preliminary data and of the several estimations to be made is consequently, of relative importance, provided that these estimations are made in a consistent way not distorting the final results. The design of a conventional optimum propeller is not an easy task and several methods can be used from the simplest ones like the use of systematic series or lifting line theory to the lifting surface and CFD or panel methods. Here for this qualitative assessment any method can be useful assuming that the same method is employed to analyze each propulsion alternative.

6.2.2 PROCEDURE FOR PRELIMINARY DESIGN OF A CRP-POD SYSTEM

Using the analysis and the assessment of the propulsive coefficients performed in the TRIPOD project, the procedure developed consists of the following steps (Table 2):

Table 2. Preliminary design procedure

Step 1	
Collect Main data	General dimensions of the ship: Main engine data: Main conventional propeller data: Reference propulsion data:
Step 2	
Design conventional propeller.	Conventional propeller must be designed for the same conditions as the propellers of the CRP-POD unit. Use a propeller design method of your choice; here we will use the simplest method based on the systematic BB series developed by MARIN for all these propellers; in this way the qualitative assessment is not influenced by the propeller design method in use.
Step 3	
Decide power share for CRP-POD system.	In CRP-POD configuration the power of POD propeller should not be very large because the mechanical/electrical losses are higher than those of the main propeller. It is recommendable to analyze several alternatives of power sharing between the main and POD propellers. A good practice would be to scan for instance 20%, 30% and 40% in each case, selecting the optimum. Calling: Developed power in Main propeller: $P_{D1} = P_{S1} \times \eta_{m1}$ Developed power in POD propeller: $P_{D2} = P_{S2} \times \eta_{m2}$ Where: $P_{S1} + P_{S2} = P_S$ (Total power shaft) = NOR The configuration used in TRIPOD has been quite well optimized being the respective transmission losses η_{m1}= 0.985 and η_{m2}= 0.94; so the mechanical + electrical losses of power in the case of the POD propeller are more than 4% higher than in the case of the main propeller.
Step 4	

RPM ratio assessment.	To establish an optimal ratio of RPMs between the main and POD propellers the next step is to design the main propeller.
Step 4.1 - Design main propeller for CRP-POD system.	The main propeller is directly matched to the main engine so the rpm of the main propeller are fixed. To be in the conservative side, it is assumed that in the case of CRP-POD system the main engine will be the same that in case of conventional propeller, so using the same value of RPM; (in principle, it could be possible to rate the engine to smaller rpm with the same diameter)
Step 4.2 - Design POD propeller.	POD propeller is electrically driven and there is some degree of freedom to select the rpm of the electrical motor. To be as much close to the optimum as possible the best approach is to fix the diameter in a value slightly smaller of the diameter of the main propeller and to carry out a design for optimum rpm. The number of blades of the POD propeller must be also chosen taking into account the number of blades of main propeller to avoid resonances in the blade passing frequency.
Step 5	
Combine main and POD propeller.	To obtain the OW efficiency of the CRP-POD system it is necessary to account for the added resistance of the POD housing, that has been called R_{mPH} at model scale and R_{sPH} at ship scale. But to make a correct comparison P_S values must be used or, what is equivalent, values of ETA_T (η_T) must be compared: $\eta_T = \eta_D \cdot (\eta_{m1} \cdot \frac{P_{S1}}{P_S} + \eta_{m2} \cdot \frac{P_{S2}}{P_S})$
Step 6	
Estimation of power saving.	
Step 6a - Case of CONVENTIONAL propellers.	The global value of ETA_T compared with the value obtained in step 2 gives the improvement obtained in power absorbed at the same speed and as a consequence the power and gas emissions that can be saved. This finalizes the procedure for conventional propellers.
Step 6b - Case of CLT propellers.	The procedure is also applicable to CLT propellers although the design method for this kind of propellers is different from that of conventional propellers. According to SISTEMAR this improvement over the case of a conventional propeller can be estimated in terms of the load coefficient of the propellers in the following way: $\eta_0(CLT - CRP) = \eta_0(CONV - CRP) \cdot f_\eta$ $f_\eta = -0.00096 C_T^2 + 0.0155 C_T + 1.032$ These expressions must be applied to each propeller and combined in terms of the absorbed power by each one to obtain the global OW efficiency improvement in the case of using CLT propellers. $\eta_{0-TOTAL} = \eta_{01} \cdot \frac{P_{S1}}{P_S} + \eta_{02} \cdot \frac{P_{S2}}{P_S}$

6.3. Application to Ship Fleets

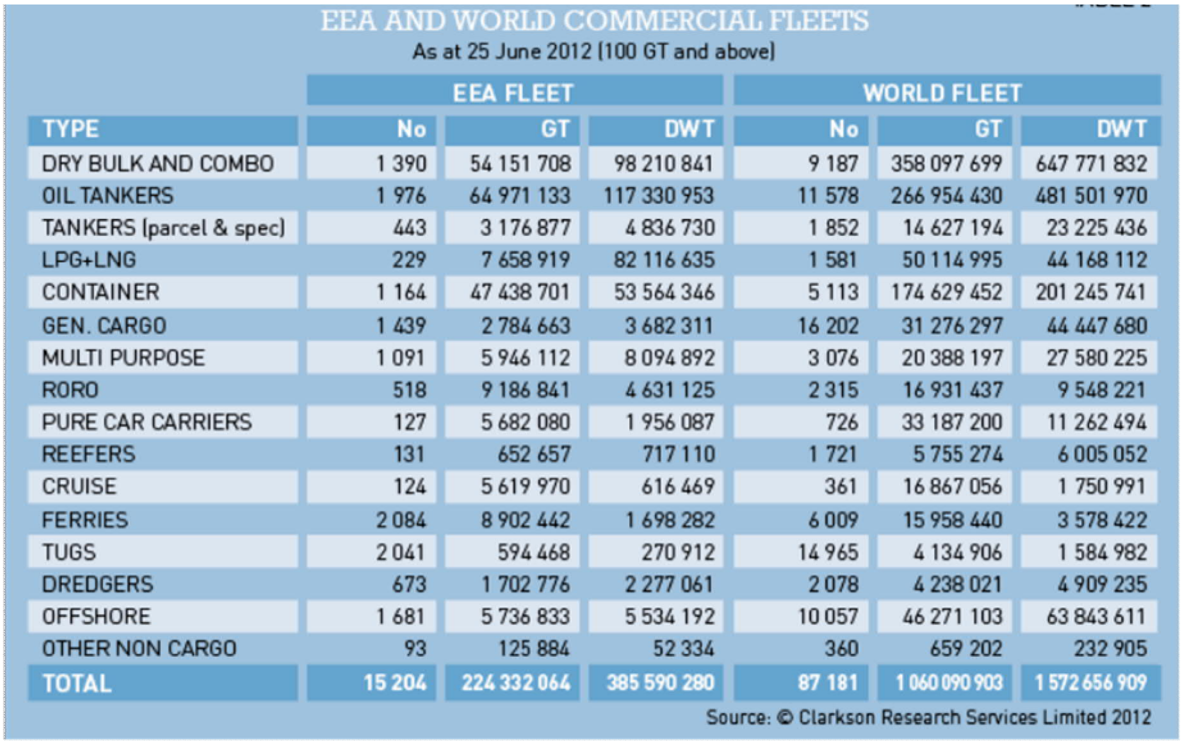
This section deals with the analysis of the possibilities to reduce the fuel consumption of a fleet and consequently the gas emissions by the application of the CRP-POD propulsion system developed in this project.

6.3.1. SUMMARY OF RELEVANT OVERALL DATA OF WORLD FLEETS OF TANKERS, BULK-CARRIERS AND CONTAINER SHIPS

From a commercial and regulatory point of view, the size and type of ships are two criteria of relevance for the classification. Therefore, a simple overview of the world merchant fleet will be given in this summary. Ships are usually grouped by size into four categories:

1. Small ships 100 GT to 499 GT
2. Medium ships 500 GT to 24.999 GT
3. Large ships 25.000 GT to 59.999 GT
4. Very Large ships ≥60.000 GT

The small ship size category reflects the main tonnage threshold for merchant ships to comply with the SOLAS Convention. This category also includes many ships which do not trade internationally and therefore are not covered by the International Conventions or the Port State regimes. Many classifications by types of ships can be found in the open data bases and statistics, but there are not significant differences for the purpose of this exercise. In the annual report of ECSA 2012, Figure 4 can be found.



EEA AND WORLD COMMERCIAL FLEETS

As at 25 June 2012 (100 GT and above)

	EEA FLEET			WORLD FLEET		
TYPE	No	GT	DWT	No	GT	DWT
DRY BULK AND COMBO	1 390	54 151 708	98 210 841	9 187	358 097 699	647 771 832
OIL TANKERS	1 976	64 971 133	117 330 953	11 578	266 954 430	481 501 970
TANKERS (parcel & spec)	443	3 176 877	4 836 730	1 852	14 627 194	23 225 436
LPG+LNG	229	7 658 919	82 116 635	1 581	50 114 995	44 168 112
CONTAINER	1 164	47 438 701	53 564 346	5 113	174 629 452	201 245 741
GEN. CARGO	1 439	2 784 663	3 682 311	16 202	31 276 297	44 447 680
MULTI PURPOSE	1 091	5 946 112	8 094 892	3 076	20 388 197	27 580 225
RORO	518	9 186 841	4 631 125	2 315	16 931 437	9 548 221
PURE CAR CARRIERS	127	5 682 080	1 956 087	726	33 187 200	11 262 494
REEFERS	131	652 657	717 110	1 721	5 755 274	6 005 052
CRUISE	124	5 619 970	616 469	361	16 867 056	1 750 991
FERRIES	2 084	8 902 442	1 698 282	6 009	15 958 440	3 578 422
TUGS	2 041	594 468	270 912	14 965	4 134 906	1 584 982
DREDGERS	673	1 702 776	2 277 061	2 078	4 238 021	4 909 235
OFFSHORE	1 681	5 736 833	5 534 192	10 057	46 271 103	63 843 611
OTHER NON CARGO	93	125 884	52 334	360	659 202	232 905
TOTAL	**15 204**	**224 332 064**	**385 590 280**	**87 181**	**1 060 090 903**	**1 572 656 909**

Source: © Clarkson Research Services Limited 2012

Figure 4. - Data of European and World fleets.

The table clearly shows that the major tonnage, both in terms of GT or DWT, of the world fleet correspond to DRY BULK CARRIERS, OIL TANKERS and CONTAINER SHIPS, representing the 84.6% in terms of DWT of the world fleet (respectively 41.2%, 30.6% and 12.8%). Consequently, these ship types have been selected for the study. LNG Carriers have been also included because they are large ships and their fleet is also representative in terms of GT; in total the ship types selected represents the 87.4% of total DWT.

Other ships types like Large Fast Ferries and Ro-Ro/Ro-Pax ships are considered suitable for a CRP-POD system, but their propulsion characteristics are very different from the reference ship used, so the findings of TRIPOD perhaps cannot be applied directly to such ship types. More research will be needed for them. Moreover, the main purpose of TRIPOD is to develop a new system with potential for reducing the exhaust emissions through the improvement of the propulsive efficiency of ships. It is obvious that the three selected ship types have the maximum potential for power savings because they represent a large percentage of the world fleet.

6.3.1. ASSESSMENT ON THE POSSIBILITIES OF FUEL SAVINGS

To assess the expected fuel savings connected to the TRIPOD concept, preliminary designs of CRP-POD units were made for representative ships of the four most significant ship types in the world maritime transport fleet:

- TANKERS: Cases 1 to 3 (VLCC, SUEZMAX and Product Tanker)
- BULKCARRIERS: Cases 4 to 6 (large size (about 160.000 dwt), medium size -80.000 dwt, general cargo – smaller, about 35.000 dwt)
- CONTAINERS: Cases 7 and 8 (aprox 15000 TEU’s, aprox 5000 TEU’s)
- LNG carriers: Cases 9 and 10 (145.000 cm, 175.000 cm)

The exercise predicts the fuel savings for each case by applying the procedure explained in preceding section. In some way it will be also a validation exercise for the concept. Anyway, it should be clearly pointed out that even today, the accurate prediction of propulsive characteristics of any new ship cannot be obtained without performing model tests, especially when dealing with a new propulsion system like this CRP-POD. Combining predicted energy savings with the fleet numbers, a global reduction of fuel consumption will be obtained assuming that a part (5%) of these fleets installs CRP-POD-CLT system. The main dimensions for each ship type have been chosen to be representative of the existing ships. Of course there is not a unique design for each type and size of ship but the qualitative assessment will not change appreciably by a small variation in any dimension.

Following the procedure explained in section 6.2 and the same propeller design method for all the ship cases, the consistency of the performance estimations is guaranteed from the standpoint of comparing different alternatives.

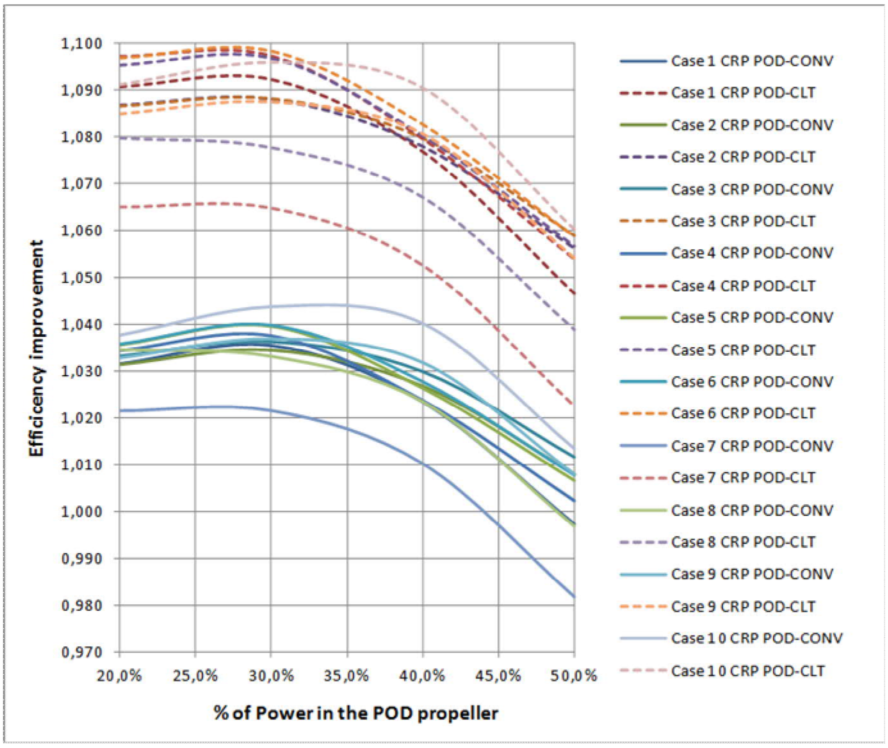


Figure 5. - Results of ten cases studied.

Gathering together all the results obtained after applying the new tool to different ship types and sizes (Figure 5), it can be concluded that the new CRP-POD system for single shaft ships (case 7 is twin shaft) could improve the propulsion efficiency in a mean value of about 4% in case of using conventional propellers and up to a 9% when using CLT propellers.

In all cases studied and for this specific arrangement, the estimations have shown that the optimum savings can be obtained when the installed power in the POD engine is between 20% and 30% of the total power. The optimization of the POD propeller looking for optimum operating rpm is very important to obtain a positive improvement capable of compensate their relatively larger mechanical losses.

Acknowledgements

This work has been made within the European Union TRIPOD project under the 7th framework program (Grant # 265809).

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