Improving the Propulsion Efficiency by means of Contracted and Loaded Tip (CLT®) Propellers

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ABSTRACT

A large number of Propulsion Improvement Devices (PID) have been developed in the past and are routinely “reinvented” whenever the price of fuel increases; on the contrary propellers have undergone very few modifications.

Only tip propellers, most noticeably of CLT type, have been installed in relatively high number at full scale (about 300 vessels, from hydrofoils to bulk carriers, from Ro-Pax to VLCC), showing their superior characteristics when compared to conventional propellers.

Despite this fact, tip propellers are still unbeknown to most Ship Owners, Technical Managers and Shipyards. In addition their use has been curtailed by the need of different treatment at model scale when compare with conventional propellers.

The goal of the intended lecture / paper is to present an overview of about 30 years of development of tip plate propellers and to present the latest experiences and R&D projects on CLT propellers.

INTRODUCTION

The current market trend, the rising cost of fuel, the concern for pollution and the introduction of Energy Efficiency Design Index and Operational Indicator (EEDI and EEOI) are all factors that require propulsion systems to be the more and more efficient.

Historically much has been achieved in the reduction of the advance resistance of the hull, naked and appended. In addition many propulsion improving devices (PID) have been invented, later abandoned and then reinvented and reintroduced in conjunction with energy crisis. Nowadays the PID portfolio spans over pre-swirlers, swirl recoverers, ducts, hull fins, rudder fins, bulbed or twisted rudders, hub caps... either alone or combined one with the other.

On the contrary propellers have gone through very little innovation: little is worth mentioning apart from the introduction of high skew and a continuous improvement of the annular profiles.

At the same time two types of unconventional propellers have been developed: surface propellers, which bear little interest for commercial shipping, and tip propellers.

The first claims about the potential advantages of tip loaded propellers (Tip Vortex Free propellers, TVF propellers) were published in October 1976 in “Ingeniería Naval” by Prof. G. P. Gomez, later contributions by Klaren, Sparemberg, Anders, De Jong, Kappel... followed.

Since then the tip plate propeller concept has been evolved continuously and nowadays it is the dominant choice in respect with ship propulsion.

Currently two different types of tip propellers are available for ship propulsion: the Kappel propeller and the CLT propeller.

The Kappel propeller was developed by Mr. J. Kappel, his design company was recently incorporated by MAN.

In the Kappel propeller the tip is located on the suction side of the propeller, the transition between the blade and the tip is smooth, the tip is hydro-dynamically loaded and it is designed so as to contribute to the generation of lift and thrust.

About 10 Kappel propellers have been installed to date, the gain in efficiency, in respect to an equivalent state-of-the-art conventional propeller is reported as up to 6%.

CLT PROPELLERS

CLT propellers were developed after the first trials with the TVF propellers, when it was realized that the contraction of the fluid vein crossing the propeller disk was to be considered in defining the geometry of the tip plate. The name was consequential: Contracted and Loaded Tip Propeller.

Subsequently SISTEMAR was established with the purpose of designing and further developing CLT propellers.

SINM is a partner and a shareholder of SISTEMAR and it is also active in the development of CLT propellers.

Figure 1. The striking difference between a CLT and a state-of-the-art high skew conventional propeller blade for the same vessel

CLT propellers are characterized by the following:

- The tip chord is finite.
- An end plate is fitted at the blade tip, located on the pressure side.
- The blade tip bears a substantial load.
- The pitch increases from the root to the tip of the blades.
- Low to moderate skew.

It should be noted that in the CLT propeller, contrary to Kappel propellers, the end plates are unloaded and operate as barriers, avoiding the communication of water between the pressure and the suction side of the blades, allowing to establish finite load at the tip of the blade.

The fundamental goal of the CLT propeller is to improve the propeller open water efficiency by reducing the hydrodynamic pitch angle through the reduction of the magnitudes of induced velocities at the propeller disk.

In the new momentum theory the parameter ε is defined; ε is the ratio between the suction in front of the propeller disk and the pressure jump across the propeller disk.

In other words ε defines how the propeller thrust is obtained by combining the under-pressure existing at the suction side of the propeller blades:

$$(p_o - \varepsilon \Delta p)$$

with the over-pressure existing at the pressure side of the propeller blades:

$$(p_o + (1-\varepsilon)\Delta p)$$

In accordance with the new momentum theory, to reduce the magnitude of the induced velocities at the propeller disk it is necessary to reduce the value of ε, which means to reduce the suction for the same pressure jump across the propeller disk.

The non dimensional propeller specific load coefficient is defined as follows:

$$C_{TH} = T / (0.5\ \rho\ A\ V^2)$$

The ideal propeller efficiency can be expressed as a function of the non dimensional propeller specific load; according to the classic momentum theory the formulation is as follows:

$$\eta_0 = 2 / (1 + (1 + C_{TH})^{0.5})$$

The expression of the ideal propeller efficiency according to the New Momentum Theory is rather different:

$$\eta_0 = 1 / (1 + \varepsilon\ C_{TH})^{0.5}$$

In Figure 2 both formulations are plotted; the following comments can be made:

1. According to the new momentum theory η_0 increases when ε decreases;
2. The new momentum theory allows for greater ideal efficiency than classic momentum theory in case of ε parameter having a low value.

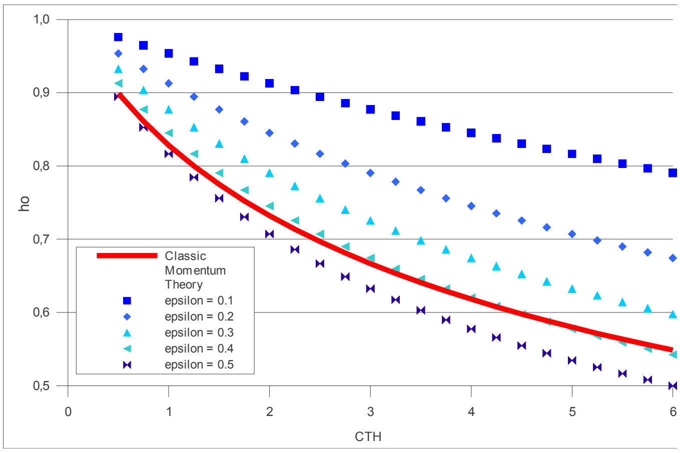

Figure 2. Ideal efficiency according to either the classic and the new momentum theory.

The ε coefficient depends on the type of propeller, its main characteristics (diameter, number of blades, blade area ratio, etc.) and on the radial load distribution.

For conventional propeller ε is in the range of 0.4, for a CLT propeller ε is in the range of 0.1.

ADVANTAGES OF CLT PROPELLERS

Up to date CLT propellers, both of fix and controllable pitch type, have been successfully installed on more than 280 vessels, of very different types:

Tankers, Product carriers, Chemical carriers, Bulk carriers, Cement carriers, General cargoes, Container ships, Reefers, Ro–Ro, Ro–Pax, Fishing vessels, Trawlers, Catamarans, Hydrofoils, Patrol boat, Landing crafts, Oceanographic ships, Yachts.

The application range has been extremely wide:

- Up to 300,000 DWT
- Up to 22 MW per propeller
- Up to 36 knots.

The advantages of CLT propellers over conventional propellers resulting from full scale installations and from several comparative full scale trials and long term observation are the following:

- Higher efficiency (between 5 - 8%)
  - Fuel saving
  - Reduced emissions
  - Saving on MM/EE maintenance
  - Higher top speed
  - Greater range
- Inhibition of cavitation and of the tip vortex
  - Less noise
  - Less vibrations
  - Lower pressure pulses
  - Lower area ratio
- Greater thrust
  - Smaller optimum propeller diameter
  - Better maneuverability.

Figure 3. FP CLT propellers installed on an hydrofoil.

It should be remarked that the advantages offered by CLT propellers in terms of reduced emissions and fuel consumption add to what achieved by other means (e.g. hull form optimization, hull maintenance, slow steaming, exhaust gas treatment...).

The percentage of efficiency improvement over an alternative conventional propeller and hence the fuel saving achieved depends on the type of vessel, being higher for slow vessels with high block coefficient as tankers, bulk carriers, etc.

CLT propellers can be applied both for new-buildings and ships in service,either in FP or CP type. The boss for FP applications and the blade flange for CP are interchangeable with the ones of the alternative conventional propeller/blades and the inertia is almost the same, therefore the installation of CLT propeller/blades does not introduce any modification in the shaft line neither for new-buildings nor retrofittings.

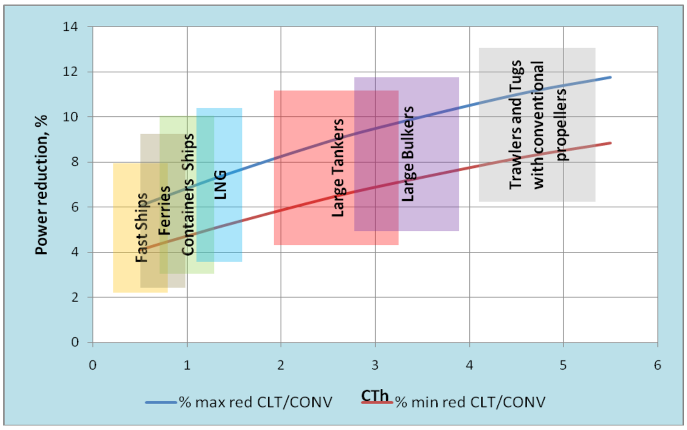

Figure 4. Maximum and minimum percentages of CLT improvement for different ship types

In case of CP applications there are additional advantages for CLT blades operating in off-design conditions at constant rpm derived from its special radial pitch distribution. For conventional blades the radial pitch distribution at design pitch setting is unloaded at the blade tip with the aim to reduce the risk of high pressure pulses. As a consequence, at low pitch setting, the pitch at the tip becomes negative and the outer sections of the blade provide negative thrust, thereby decreasing the propeller efficiency decreases and originating substantial broad band noise and pressure pulses due to cavitation.

This is not the case for CLT blades because the pitch at the blade tip is positive even at very low pitch setting, thereby maintaining a high efficiency also in off-design conditions and preventing broad band noise and large pressure pulses.

PAST R&D ON CLT PROPELLERS

In the past the following R&D activities were carried out on CLT propellers.

1997 – 2000 "Optimization of ship propulsion by means of innovative solutions including tip plate propellers." CEHIPAR, NAVANTIA, SISTEMAR. This R&D project resulted in the development of an ad hoc extrapolation procedure for open water tests of CLT propeller. The extrapolation is based on the ITTC-78 method adapted for CLT propellers by considering the presence of the end plates and the scale effects on lift forces.

During 1999 a new type of mean lines has been developed by SISTEMAR with the aim to improve further the efficiency of CLT propellers by reducing the under-pressure on the suction side and increasing the overpressure on the pressure side. These mean lines are characterized by a higher slope at the trailing edge compared to standard NACA mean lines.

2001-2003 "Research on the cavitation performance of CLT propellers, on the influence of new types of propeller blades annular sections and the potential application to POD's" CEHIPAR, NAVANTIA, SISTEMAR. This R&D project resulted in the development of a new procedure for cavitation tests and pressure fluctuation measurements with CLT propeller at model scale.

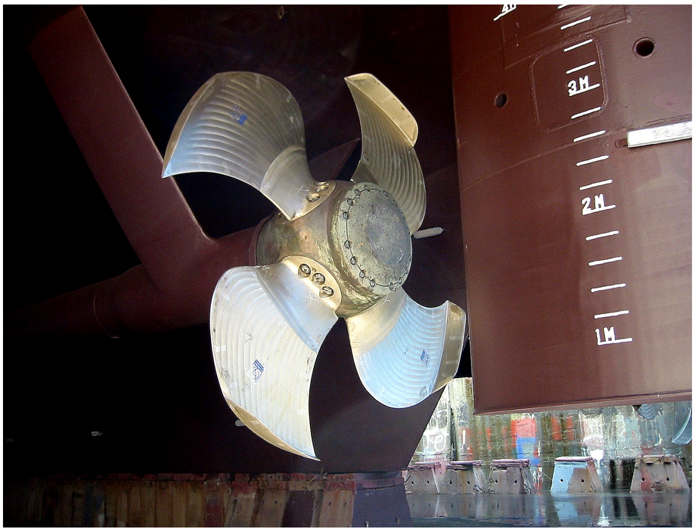

Figure 5. A CP CLT propeller installed in a modern Ro-Pax.

2003 – 2005 "Research on the performance of high loaded propellers for high speed conventional ferries" CEHIPAR, NAVANTIA, SISTEMAR, TRASMEDITERRANEA, TSI. The aim of this research was the full scale application of CLT propeller blades to a large and modern conventional Ro-Pax and a complete full scale measurement campaign, aimed at comparing the CLT propeller blades with state-of-the-art high skew conventional propeller blades.

2005 – 2008 "SUPERPROP: Superior Life Time Operation of Ship Propeller" an EU sponsored R&D project aimed at studying the influence of different maintenance policies on the hydrodynamical performance of tugs and trawlers. Within this project a CLT propeller was successfully retrofitted on a trawler.

In 2009 SISTEMAR has been invited by CEHIPAR and VTT to participate as subcontractor to the SILENV project, approved within the FP7 of the EU. CLT propellers have been analyzed by means of CFD calculations and model tests and have been identified as measure to decrease the noise and vibration levels on board.

THE ROY MAERSK PROJECT

In 2006 A.P. Moeller Maersk who, at that time, was conducting an internal evaluation of energy saving devices, selected CLT propellers as the single most promising device and a joint R&D campaign was launched.

CLT propellers were designed for a 2,500 TEU container vessel, a 35,000 DWT product tanker and a VLCC and were tested at model scale at HSVA, Hamburg. The CLT propeller for the 35,000 DWT product tanker was also tested at CEHIPAR and it was retrofitted on the M/S Roy Maersk at the end of October 2009.

LPP	162.0	m
B	27.40	m
D	17.30	m
T	9.75	m
Δ	35,300	t

	Conventional	CLT	
D	5.65	5.25	m
z	4	4	-
AeAo	0.563	0.490	-
H@07R	3.685	4.050	m

Table 1 and 2. Main characteristics of M/V Roy Maersk and of the conventional and CLT propeller

Full scale observations, comprising cavitation observations and pressure pulses measurements, have being conducted. Results are in good agreement with model tests and design calculations.

A. P. Moeller Maersk is currently considering further full scale experiments and installations.

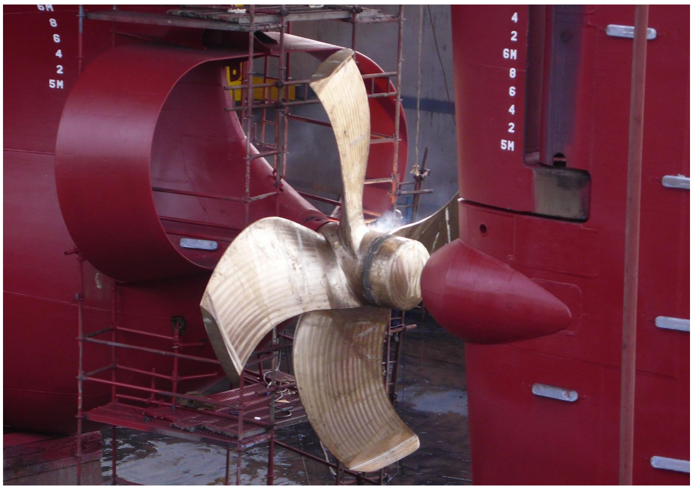

Figure 6. 35,000 DWT product tanker "Roy Maersk", the new CLT propeller with pre-existing WED and bulbed rudder.

EXPERIENCES WITH THE SPANISH NAVY

In the last few years CLT propellers have been installed on several units belonging to the Spanish Navy.

In October 2009 the sea trials of the m/v Cantabria (Buque de Aprovisionamiento en Combate, BAC Class), the new replenishment vessel of the Spanish Navy, were carried out.

The m/v Cantabria is equipped with the largest and most powerful CP CLT propeller manufactured to date (single screw, 5 blades, diameter 5.7 meter, MCR 21.8 MW).

Figure 7. The replenishment vessel A15 Cantabria.

The full scale performance of the CLT propeller was in line with both design calculation and model test predictions.

The Spanish Navy has programmed a series of 14 corvettes (Buques de Acción Marítima, BAM class) to be built by NAVANTIA. All the units of the BAM class will be equipped with CP CLT propellers (twin screw, 4 blades, diameter 3.45 meter, MCR 2 x 4.5 MW).

All the 4 units of the first batch have been already launched and the sea trials of the lead unit were performed in March 2011 with satisfactory results.

The next batch of BAM has been already announced by the Spanish Ministry of Defense but it has been delayed.

Figure 8. The launching of P41 Meteor, the lead unit of the BAM class

CLT PROPELLERS AND CFD

The development of numerical methods suitable to model the peculiar characteristics of tip plate propellers in general and of CLT propellers in particular has been a clear goal from the very beginning.

However more urgent matters were at hands in particular it was necessary to develop suitable model test procedure, model test extrapolations and to foster not only the installation of tip propellers but also full scale measurements and experiments.

Now that the CLT propeller technology is well established and that the advantages obtained at full scale over conventional propellers have been checked in a large number of cases it is possible to invest on numerical methods with the goal of refining the design of the CLT propellers and better to respond to stringent design requirements such as very low pressure pulses, cavitation extension and irradiated noise.

For such reasons several collaborations have started collaborating with a number of subject with important expertise in numerical methods and CFD in order to check to what extent the results, obtained with tools developed for conventional propellers, are also valid for CLT propellers and to devise a road-map for the creation of computational tools developed ad hoc for CLT propellers.

The first results that were obtained confirmed that the output by programs developed for conventional propellers are not satisfactory; in particular a number of calculations performed at model scale showed large deviations from the experimental results (up to 6.5% error on KT and 16.5% error on KQ).

In consideration of the difficulty (if not the impossibility) of a complete validation of the results at full scale it was immediately clear that such large deviations at model scale were a roadblock not easily circumvented.

Lately several calculations performed by CEHIPAR, VTT and the University of Genoa, with codes developed ad hoc codes for tip plate propellers were able to reproduce the model test results with a fairly good accuracy, in addition they also indicated scale effects ofsimilar magnitude to the measured ones.

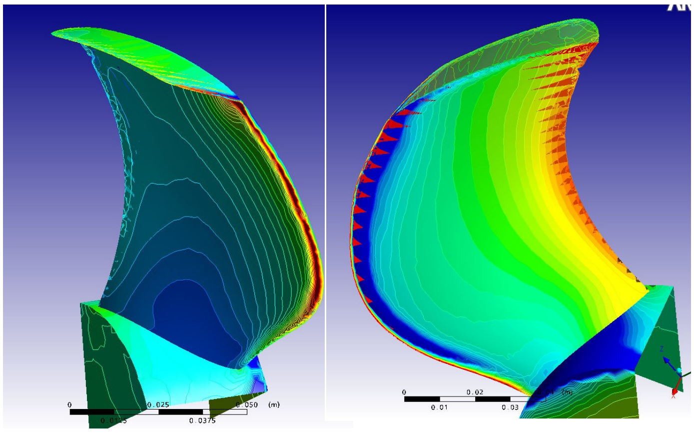

Figure 9. Pressure distribution on the pressures side (left) and on the suction side (right) of a CLT propeller blade computed by means of CFD.

Such promising results show that the current technology relevant to CFD and numerical methods in general can be successfully applied also to tip plate propellers but only after having considered their peculiar characteristics.

SISTEMAR and SINM are currently collaborating with CHEIPAR, VTT and with the University of Genoa for the development of numerical codes capable of predicting the performance of CLT propellers both at model and full scale, both in design and off-design conditions.

These codes will validated on the basis of the large body of knowledge accumulated in the past by SISTEMAR both at model and at full scale.

By means of these codes the quality of the design of the CLT propellers will be ameliorated and their already good characteristics will be further enhanced.

EEDI, EEOI, PROPELLERS AND PIDS

IMO, through MARPOL, is considering scrutinizing the propulsion efficiency of the vessels by means of both EEDI and EEOI.

In principle the careful optimization of the hull (main dimensions, bow and stern shape), followed by the selection of a tip plate propeller and of a bulbed and twisted rudder will result in a high propulsion efficiency (hence low EEDI and EEOI).

If the above is performed effectively, the use of further PIDS (e.g. pre or post stators) is likely to bring only marginal gains. The exception are vessels with unfavorable main dimensions and non optimized hulls, in such cases PIDS can help ameliorating the flow conditions on the stern and increase the propulsion efficiency.

It should be noted that propellers in general, and tip plate propellers in particular, are compatible with any kind of PID, while PIDS are not always compatible with one another.

In any case the design of the propeller and of the selected PID must be integrated; off-the-shelf designs will not be compatible with one another and should be best avoided.

For the same reason, in principle, to retrofit a PID on an existing vessels to increase the propulsion efficiency is bound to modify the wake on the propeller disk and the power absorption characteristics of the propeller. The net result is that part of the gains are curtailed by the fact that the original propeller will work in an off-design conditions. Therefore it is better to retrofit a high efficiency propeller, of tip plate type, and, eventually, retrofit a PID at the same time, rather than to retrofit a PID only and keeping the existing propeller.

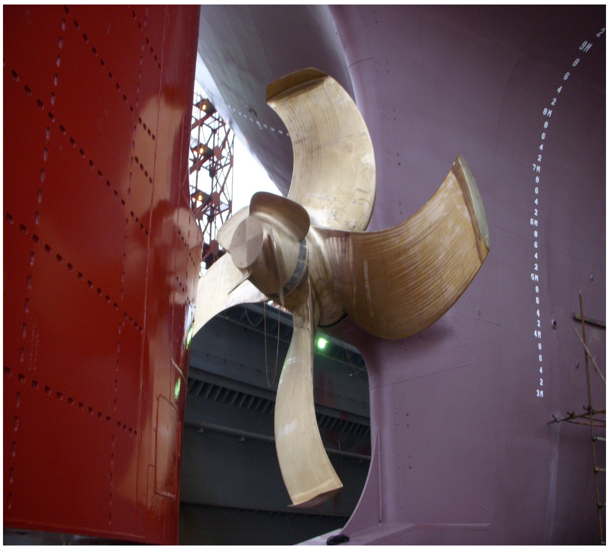

Figure 10. A CLT propeller installed on a bulker, in combination with PBCF and twisted rudder.

CURRENT R&D PROJECTS

Tripod Project

“TRIple Energy Saving by Use of CRP, CLT and PODded Propulsion” (TRIPOD) is a European FP7 project currently conducted by ABB and VTT from Finland, AP MOLLER MAERSK from Denmark and CEHIPAR, CINTRANAVAL-DEFCAR and SISTEMAR from Spain.

The main goal is the development and validation of a new propulsion concept for improved energy efficiency of ships through the advance combination of three existing propulsion technologies: podded propulsion (POD), CLT tip loaded end plate propellers and counter-rotating propeller (CRP) principle.

Different propulsion configurations of 8.500 TEU’s container vessel “Gudrun Maersk.”will be analysed: single screw ship with conventional propeller and CLT propeller, CRP arrangement with conventional and with CLT propellers.

Once finalised both numerical analysis and model tests for different propulsion arrangements, a concept validation will be performed in order to estimate the energy savings and the noise reduction for the CRP-CLT-POD concept as compared to the other propulsion arrangements.

A feasibility study for the introduction of the novel propulsion concept on new ship designs and for retrofitting on existing vessels from technical point of view will be performed as well as an economic analysis of the viability of the new propulsion concept for retrofitting and for new ship designs.

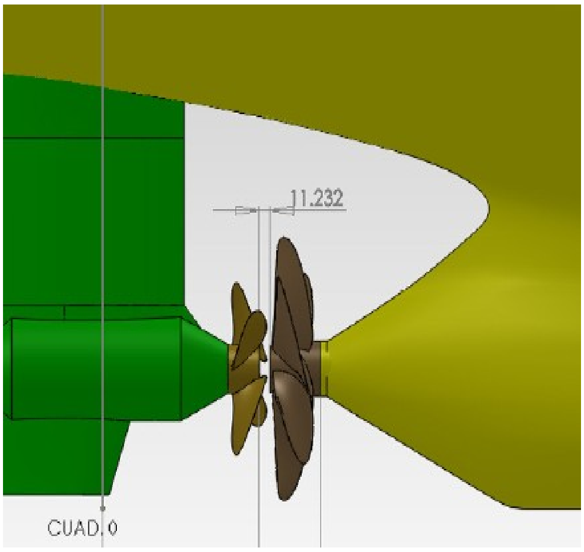

Figure 11. CRP-POD configuration (shown with conventional propellers)

Large energy savings and consequently, CO_2, SOx and NOx emission reductions as well as environmentally harmful noise mitigation are expected.

Nicop Project

Within the framework of the National International Cooperative Opportunities in Science and Technology Program (NICOP) the OFFICE OF NAVAL RESEARCH of the U.S. NAVY (ONR) has contracted SISTEMAR for a two years R&D project called "Energy Efficient Contracted-Loaded Tip (CLT) Propellers for Naval Ships"

The objectives of the project are two-fold:

1. To develop and to demonstrate that CLT-type propellers for naval ships can improve efficiency by an amount comparable to the one demonstrated for commercial ships (i.e. 6 - 8%) over conventional open propellers without sacrificing cavitation performance.
2. to develop a scaling method for full scale CLT propeller performance based on model-scale testing in the water tunnel.

SISTEMAR will design a CLT propeller and NSWCCD will design and alternative Tip Loaded Propeller; both propeller models will be manufactured and tested by CEHIPAR. Computations will be made both by NSWCCD and SISTEMAR/CEHIPAR for the two propeller designs using RANS methods at model and full-scale Reynolds numbers.
This project will provide the US Navy with direct experience on energy efficient tip plate propellers.

LATEST PROJECTS AND INSTALLATIONS

CARNIVAL CORPORATION has recently launched decided to investigate CLT propellers by mens of a series of model tests, the goal is to compare a state-of-the-art conventional propeller with a CLT propeller on basis the Grand Class.

Figure 12. C/V Gran Princess, the first unit of the Grand Class

The propulsion system is composed by two 21 MW Siemens electric motors, each driving a FP propeller via conventional shafting.

Resistance and self-proulsion model tests with will be performed by CEHIPAR while cavitation tests and pressure pulses measurements will be performed by HSVA (Hamburg) in the HYKAT.

The results of the complete experimental program will provide CARNIVAL CORPORATION very valuable informations on CLT propellers.

LPP	289.9	m
B	35.97	m
T	7.92	m
GT	109,000	-
Capacity	4,314	People
Built	1998	-

Table 3. Main characteristics of Grand Class

The Brazilian company EMPRESA DE NAVEGAÇAO ELCANO has signed a new building contract with ESTALEIROS ITAJAI shipyard for three 7,500 m³ LPGs to be chartered to PETROBRAS. The propulsion system will consist of a two stroke Diesel engine, MCR 4,400 kW, driving a 3.9 m CP CLT propeller. Model tests have been satisfactorily carried out at CEHIPAR, Madrid, in early 2011.

SISTEMAR is currently designing CLT propellers for a a wide range of vessels, including Kamsarmax Bulkers, Handysize Tankers, Gas Carriers and fast patrol boats.

CONCLUSIONS

Tip propellers in general and CLT propellers in particular are a a mature technology.

The merits of CLT propellers (higher efficiency, lower noise an vibration levels and better maneuverability characteristics) have been demonstrated in about 280 full scale applications on very different ship types.

The efficiency increase (and hence the achieved fuel saving) is in the range of 5 – 8 %, being higher for slow vessels with high block coefficient as tankers, bulkers, etc... making CLT propellers the most attractive device for increasing the propulsion efficiency and lowering the EEDI and the EEOI.

From the above it follows that CLT propellers are a dominant choice for new buildings due to the very short return of investment (3 to 6 months).

In addition they do not require any modification whatsoever to the vessel, therefore they can be introduced also as retrofits or for vessels the design of which has been already concluded.

Finally CLT propellers are compatible with most of the PID currently offered, thereby allowing to achieve even higher energy efficiency.

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