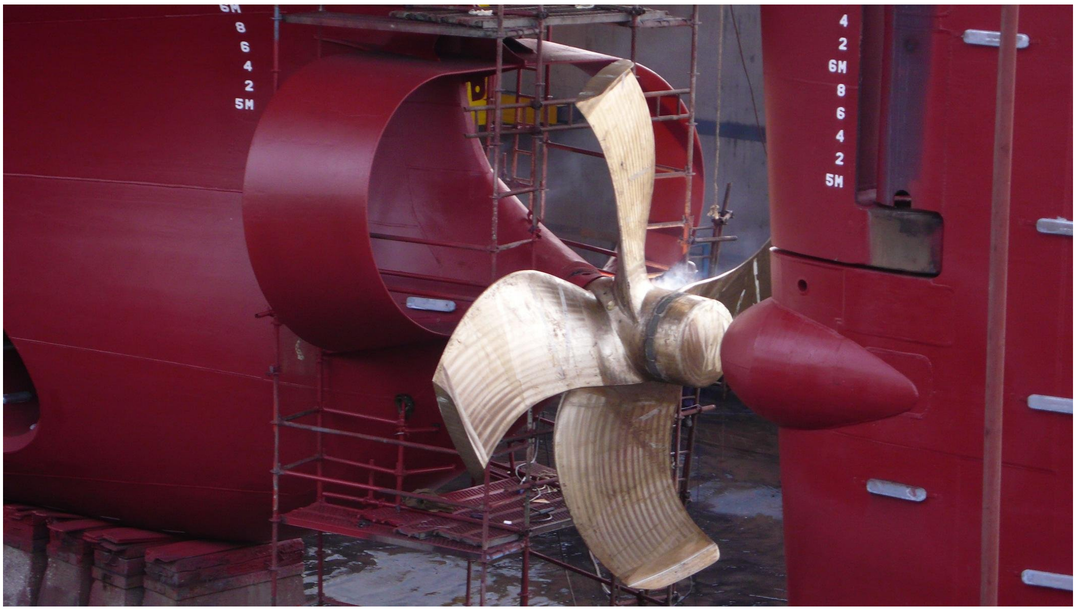
Studio di Ingegneria Navale e Meccanica

Unconventional Tip Shape Propellers



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ABSTRACT

The current market trend, the rising cost of fuel and the concern for pollution require ship propulsion systems to be the more and more efficient. Notwithstanding the above a large number of new buildings is still substandard in respect to propulsion efficiency and many of the so called “Green” or “Eco” designs can be further optimised.

Unconventional Tip Shape Propellers, have been installed in relatively high number at full scale (more than 300 vessels, from hydrofoils to bulk carriers, from Ro-Pax to VLCC) and have shown their superior characteristics when compared to conventional propellers. Despite this fact they are still unbeknown to most Ship Owners, Technical Managers, Ship Designers and Shipyards.

Unconventional Tip Shape Propellers are the current state-of-the-art in respect to ship propulsion. They are the dominant choice for new buildings and they are the most attractive retrofit to increase the propulsive efficiency of existing vessels to the large savings and short ROI.

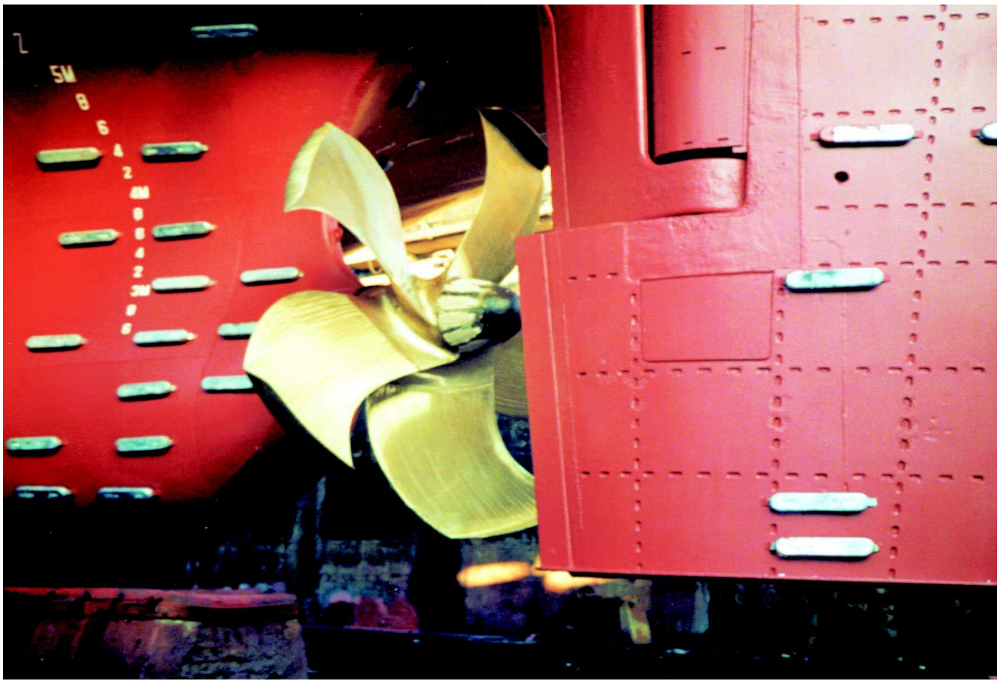

Figure 1. A 5 bladed FP CLT propeller installed on a containership.

INTRODUCTION

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

Efficiency, as a whole, is the results of three non intersecting matters:

- the generation of power: i.e. how efficient the prime mover is in converting the potential energy of the fuel into mechanical power;
- the usage of power: i.e. how efficient the vessel in using the minimum possible mechanical power to advance through the water;
- the operating envelope: i.e. how efficient the operators are in maximizing favourable operations and in minimizing operations in adverse conditions (such as ballast trips, sailing in adverse environmental conditions...).

In this context the focus is only on the second item, the first and the third been neglected.

Notwithstanding the above a large number of new buildings is still substandard in respect to propulsive efficiency and many of the so called "Green" or "Eco" designs can be further optimised.

The scenario for ships in service is, in general, even worse and it is possible to increase substantially the propulsive efficiency of existing vessels, both by means of propulsion improving devices (PID) and, foremost, by means of Unconventional Tip Shape Propellers.

Historically much has been achieved in the reduction of the advance resistance of the hull, naked and appended. In addition many Populsion 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 Unconventional Tip Shape Propellers.

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

Since then the Unconventional Tip Shape Propeller concept has been evolved continuously and nowadays two different types of Unconventional Tip Shape Propellers are available for ship propulsion: MAN Kappel propellers and SISTEMAR CLT® propellers.

From late 80's Unconventional Tip Shape Propellers, in particular of CLT type, have been installed in relatively high number at full scale (more than 300 vessels, from hydrofoils to bulk carriers, from Ro-Pax to VLCC) and have always shown their superior performance when compared to conventional propellers.

Despite this fact Unconventional Tip Shape Propellers are still unbeknown to most Ship Owners, Technical Managers, Ship Designers and Shipyards.

In this context it should be noted that Wartsila Tip Rake Propellers, STX Wide Tip Chord Propellers, Stone Marine New Profile Technology Propellers are conventional propellers in all respects. They can offer limited advantages over “standard” conventional propeller designs but they cannot rival the or propulsive efficiency of Unconventional Tip Shape Propellers.

In the present technical report paper a comprehensive technology review of Unconventional Tip Shape Propellers, and in particular of CLT propellers, is supplied with the aim of promoting their wide spread use, both for new building and as retrofit.

TVF PROPELLERS

Tip Vortex Free propellers (TVF) were developed between late 70's and early 80's by Prof. Gonzalo Perez Gomez who, at that time, was working for Astillers Españoles.

TVF propellers were characterised by Kaplan-like propeller blades ending with cylindrical end plates.

Figure 2. A TVF propeller blade and end plate.

In 1983 the results of an extensive research program carried out at full scale on a 35,000 DWT bulkcarrier, consecutively fitted with a conventional propeller and with the first TVF propeller ever built, and on a 270,000 DWT tanker consecutively fitted with a conventional propeller and with the second TVF propeller built at full size were published and analysed. Both installations showed very attractive power saving for the TVF propellers as compared with the corresponding conventional propellers.

CLT PROPELLERS

Contracted and Loaded Tip propellers (CLT) were developed from early 80's after the first full scale trials with the Tip Vortex Free propellers (TVF), when it was realized that:

- the part of the end plate located on the suction side was unnecessary and detrimental;
- the geometry of the tip plate had to be conformed according to the contraction of the fluid vein crossing the propeller disk.

Subsequently SISTEMAR, Madrid, was established with the purpose of developing designing and marketing CLT propellers.

Figure 3. The striking difference between a CLT and a state-of-the-art high skew conventional propeller blade designed for the same Ro-Pax vessel and for the same speed

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 thrust increases from the root to the tip of the blades.
- Low to moderate skew.

It should be noted that in CLT 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.

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.

Figure 4. FP CLT propellers installed on an hydrofoil.

The advantages of CLT propellers over conventional propellers have been proved by means of many full scale installations, full scale comparative sea trials and long term observations

CLT propellers offers the following advantages over equivalent conventional propellers:

- Higher efficiency (5 to 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 manoeuvrability.

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, PID, hull maintenance, slow steaming, exhaust gas treatment...).

The increase in efficiency granted by a CLT propeller over an alternative equivalent conventional propeller, and hence the fuel saving, depends on the type of vessel, being in principle higher for slow vessels with high block coefficient as tankers, bulk carriers, etc.

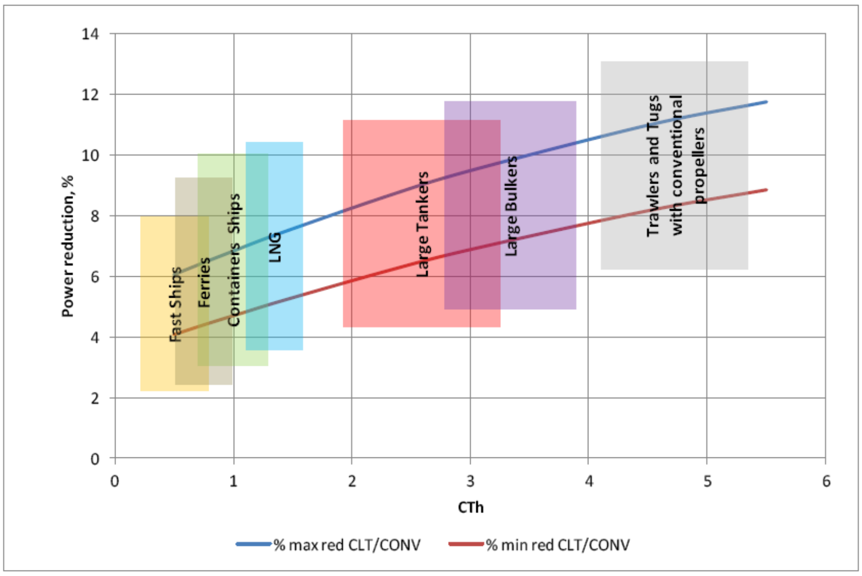

Figure 5. Maximum and minimum expected improvement due to CLT propeller installation, for different ship types and for different dimensional load.

CLT propellers can be applied both to new-buildings and ships in service, either in FP or CP type. The hub, for FP applications, and the blade flange, for CP applications, 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.

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.

KAPPEL PROPELLERS

The Kappel propeller concept was initially proposed by Prof. Jens J. Kappel and Prof. Poul Andersen in early 90's and it is based on the principle of non-planar lifting surfaces applied to the design of modern aircraft wings to obtain better lift to drag ratios. The first Kappel propeller was fitted in early 2000's on M/V Nordamerika within the EU funded Kapriccio R&D Project.

Kappel propellers might appear quite similar to conventional propellers, up to the point of being unrecognisable to the untrained eye, due to the fact that the winglet is fully integrated in the propeller blade. Kappel propellers are characterized by the following:

- A winglet is integrated in the propeller blade.
- The winglet is curved toward the suction side.
- The winglet is loaded.
- Low to moderate skew.

Figure 6. A CP Kappel propeller, note the winglet integrated in the blade and curling toward the suction side.

Prof. Jens. J. Kappel established a firm for the design of the Kappel propeller, MAN has acquired the Kappel propellers technology and know-how in 2012.

The advantages offered by Kappel Propellers are similar to the ones offered by CLT propellers, namely:

- Higher efficiency (3 to 5%)
    - Fuel saving
    - Reduced emissions
    - Saving on MM/EE maintenance
    - Higher top speed
    - Greater range
- Inhibition of the tip vortex
    - Less noise
    - Less vibrations
    - Lower pressure pulses
- Greater thrust
    - Smaller optimum propeller diameter

For Kappel propellers, as for any type of unconventional propeller, the advantages offered by the propeller alone add to what achieved by other means (e.g. hull form optimization, PID, hull maintenance, slow steaming, exhaust gas treatment...).

The increase in efficiency granted by Kappel over an alternative equivalent conventional propeller depends on the type of vessel, being in principle higher for slow vessels with high block coefficient as tankers, bulk carriers, etc.

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

SCALING OF UNCONVENTIONAL TIP SHAPE PROPELLERS

The scaling of model test of conventional propellers is, in general, carried out according to ITTC Recommended Procedures and Guidelines, document 7.5-02-03-01.4 “Performance, Propulsion 1978 ITTC Performance Prediction Method.”

Several researches have been carried out on the scaling of model tests of Unconventional Tip Shape Propellers, in particular for CLT propellers, and all agree that these propellers are subjects to higher scale effects than conventional propellers, therefore the standard ITTC procedures are not suited for the scaling of model tests of Unconventional Tip Shape Propellers. This issue has been the major drawback for the wide spread use of Unconventional Tip Shape Propellers.

This fact is highlighted in the “Final Report and Recommendations to the 27th ITTC” of the Propulsion Committee , where it can be read:

> *“It has been known that the CLT and Kappel type propellers, as well as the propeller boss cap fins, are subject to more severe scale effect, and the ITTC'78 procedure originally designed for conventional propellers might be no longer applicable to them.”*

In late 1990's SISTEMAR, recognizing the need for a scaling procedure for CLT propeller model tests, started a model and full scale research activity with El Pardo Model Basin, CEHIPAR, Madrid, which has resulted in the first standard procedure for the scaling of CLT propellers, such procedure was published in 2005. and it is based on ITTC'78. This procedure has become a standard for CEHIPAR and SISTEMAR.

In late 2000's SISTEMAR and SINM have started to working on a strip method extrapolation for CLT propellers. At the same time SISTEMAR has joined effort with VTT, Finland, and the University of Genoa for the use of CFD and panel codes for the scaling of CLT propeller model tests. The following paper, entirely dedicated on the scaling of CLT propellers will be presented at IHCD 2014, Singapore:

"Comparison of different scaling methods for model tests with CLT propellers" J. GONZÁLEZ-ADALID, M. PÉREZ SOBRINO SISTEMAR -A. GARCÍA GÓMEZ CEHIPAR - G. GENNARO SINM S. GAGGERO, M. VIVIANI UNIGE - A. SÁNCHEZ-CAJA , VTT."

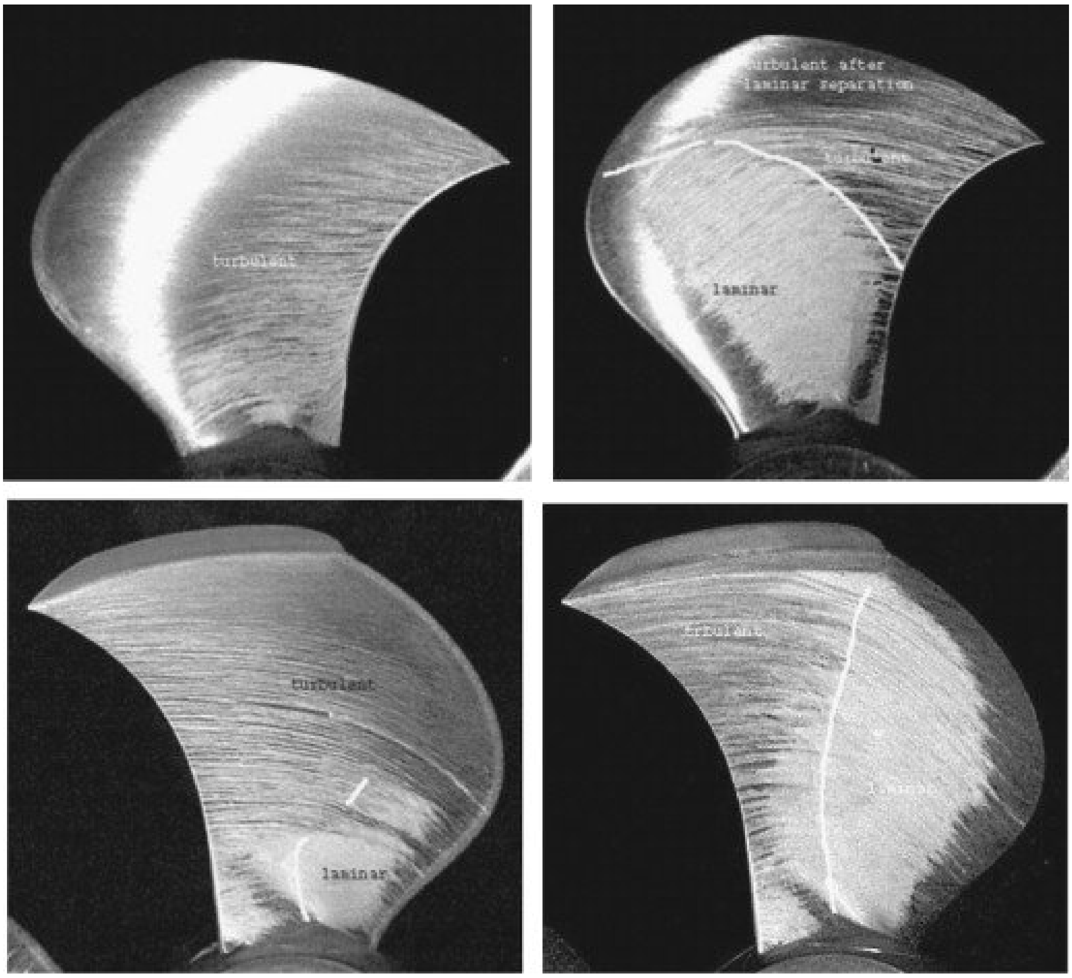

Figure 7. Model test streamlines from paint tests on the suction (up) and pressure (down) sides of the blade of a CLT propeller under design condition. Rough (left) and smooth (right) surfaces, in case of smooth surface suction side laminar separation is experienced.

The results of the different approaches to the scaling of CLT propellers confirm the presence of increased scale effects both in KT and in KQ and they are well described in the conclusions of the paper:

> *"CLT propellers are considered one of the most efficient and advanced propellers in order to obtain reductions of fuel consumption in maritime transportation with reliable applications to tankers, bulkers, containers and ferries. Design studies of CLT propellers can be performed based on model tests results as in the case of conventional propellers, but scaling of CLT propellers from model tests results to full scale predictions must be performed by specific procedures different from the ITTC'78 standards. The main difference can be reduced to the scaling of the Open Water model tests results. Several technical approaches have been applied in this report to a test case showing in all cases a better prediction than simply adopting ITTC'78 standard procedures. In particular Boundary Element/Panel methods (BEM) and other CFD method like the RANS solver FINFLO, presented in this report, show that the flow pattern developed on the blades of the CLT propellers are quite different than in the case of conventional propellers, being this fact probably the reason to need specific scaling procedures for this kind of propellers. The viscous effects in the end plate must be also taken into consideration. The complex phenomena present are correctly captured by semi-empirical approaches, thanks to the very large (and successful) database of data gathered during years, which allow for their suitable calibration."*

As far as the scaling of Kappel propeller little is known to the general public since the literature on the subject is extremely limited. It is known that MAN considers ITTC'78 scaling method inaccurate and that, as a consequence, MAN has developed their own scaling, however MAN has not published any information about their scaling method. Despite the above MAN insists on using ITTC'78 for the scaling of Kappel propellers.

In parallel to the above Prof. P. Andersen and HSVA, Hamburg, have worked on strip method scaling for tip plate propellers. Several papers have been published in this respect however the details of these methods are not known. In recent CLT propellers model tests activities it was found that the results of HSVA strip method scaling were similar to the results of both SISTEMAR standard scaling and SINM strip method scaling.

From all the above it can be stated that Unconventional Tip Shape Propellers suffer from greater scale effects than conventional propellers and that ITT'78 scaling is inadequate for the task, up to the point of possibly showing for Unconventional Tip Shape Propellers lower full scale efficiency than for the equivalent conventional propeller.

This fact is highlighted in the following chart, in which sea trials predictions based on model tests with conventional and CLT propeller are compared with full scale sea trials measurements performed in 2014 a CLT conventional propeller. In particular in the chart it can be observed that ITTC scaling of the CLT propeller (red) is pessimistic, up to the point of predicting a performance worse than for the equivalent conventional propeller (black), and that by using the CLT propeller standard scaling a very good agreement between trial predictions (blue line) and sea trial measurements (blue dots) is obtained.

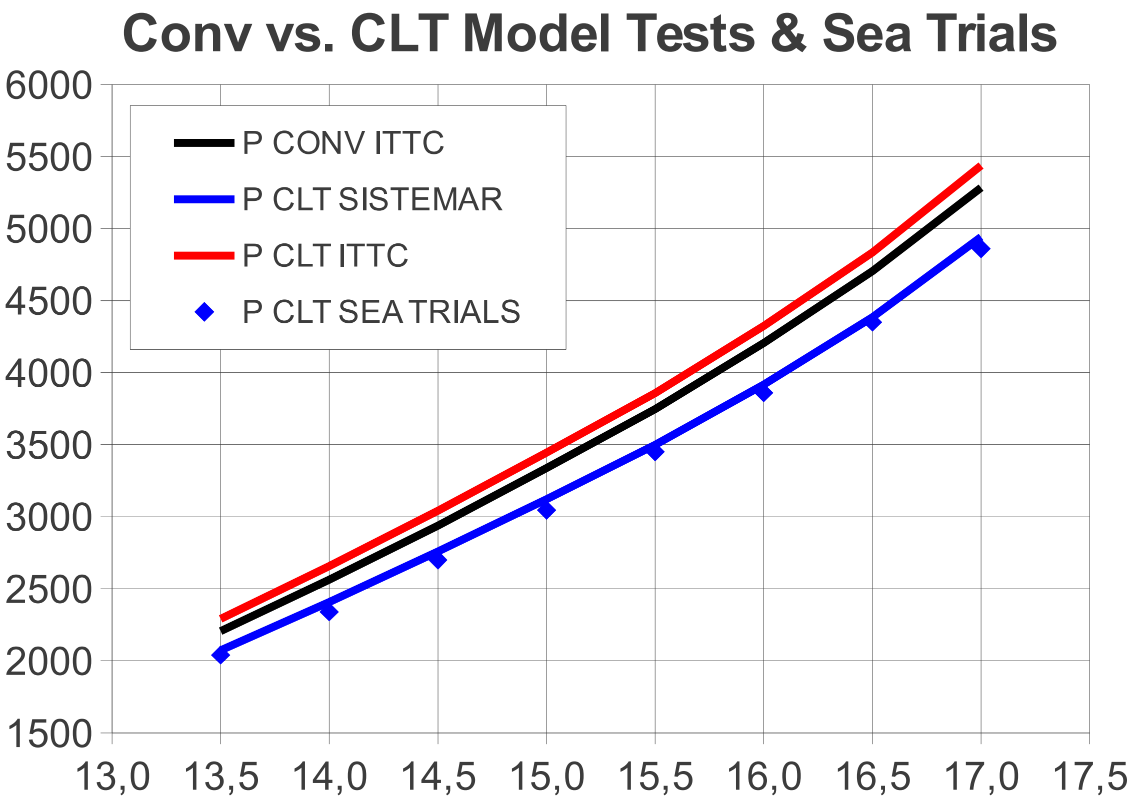

Figure 8. Sea trial predictions vs measurements, Power [kW] vs Speed [knots] curves

The need for generally accepted scaling procedures for Unconventional Tip Shape Propeller, capable of capturing the peculiar scale effects of each type of propeller is becoming more and more apparent. In this respect in the Final Report and Recommendations to the 27th ITTC of the Specialist Committee on Performance of Ships in Service the need for an ITTC standard is clearly stated:

> *"For both CLT and Kappel propellers, however, a standard* (ITTC) *procedure for the open water hydrodynamic characteristics scaling is still missing. Therefore, a recommendation to the full Conference could be addressed to look into this issue."*

CLT vs KAPPEL vs CONVENTIONAL PROPELLERS

The first and foremost merit of Unconventional Tip Shape Propellers is to allow a better spanwise circulation distribution compared to conventional propeller, thereby limiting the induced velocities and allowing the loading of the tip of the propeller blades (which is unloaded in conventional propellers) this, in turn, allows for a decrease of the propeller expanded area.

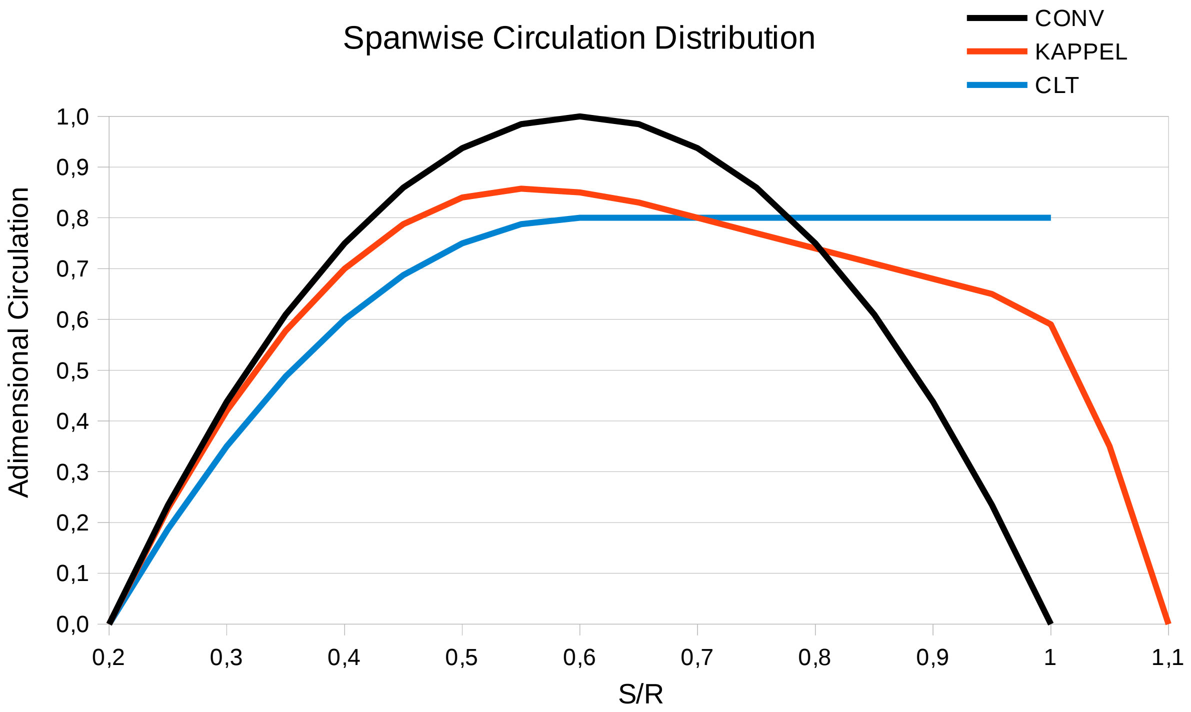

Figure 9. Spanwise Circulation distribution of conventional, Kappel and CLT propellers.

All the above results in the generation of a smaller torque for the same thrust, thereby increasing the efficiency of Unconventional Tip Shape Propellers in comparison to conventional ones.

The possibility of a direct comparison between CLT, Kappel and conventional propeller has been remote due to the very little literature on Kappel propellers, aside from MAN presentations that can be found on the web.

However in July 2014 the first back to back model tests of a CLT and a Kappel propellers have been performed, allowing the possibility of comparing CLT and Kappel propellers not on basis of general information, advertisement, brochure, conference papers... but on the basis of actual model tests of two propellers (three, considering also the conventional propeller) designed for the very same vessel and for the very same speed.

In the following table the full scale results of the a.m. tests are presented. Due to confidentiality reasons figures are given in an approximate and non dimensional manner.

	Conventional	**KAPPEL**	**CLT**	
Diameter	100	97	95	%
Developed Area	100	90	70	%
Blade number	4	4	4	-
Propeller design speed	100	100	100	%
Ship Design speed	100	100	100	%
Power at design speed	100	97	92	%
Speed increase at NCR	-	0.10	0.30	knots

The following considerations can be be made:

- The gains of the Kappel and of the CLT propeller over the conventional propeller are congruent with what claimed by MAN and SISTEMAR (about 3% and about 8% respectively). This item clarifies that the Unconventional Tip Shape Propellers are more efficient than conventional propellers.
- Both Kappel and CLT propeller have lower diameter than the conventional propeller (about -3% and -5% respectively). This item clarifies that the use of end plates allows to increase the circulation along the propeller blade, similarly to winglets in aviation.

- Both Kappel and CLT propellers have a lower expanded area than the conventional propeller (about -10% and -30% respectively). This item clarifies that the use of end plates allows for a more favourable circulation distribution along the propeller, also in respect with cavitation. However this matter is much more pronounced for CLT propellers, allowing for a sharp reduction of viscous losses.

It should be noted that during the above mentioned tests the rather small expanded area of the CLT propeller raised some eyebrow, however, as it will be discussed in the following, a survey of the published literature and references showed that this is a peculiar feature of CLT propellers.

Let us consider two well documented retrofitting of CLT propellers, one case concerning FPP and one case concerning CPP, in both cases the design point of the new CLT propeller was the same as for the original conventional propellers.

A.P. Moeller Maersk 35K DWT Tanker – Roy Maersk

Propeller characteristics			
	Conventional	CLT	
Propeller type	FP	FP	-
Diameter	5.65	5.25	m
Blade area ratio	0.56	0.48	-
Blade number	4	4	-

In this case the expanded area of the CLT propeller is about 74% of the original one.

Acciona Trasmediterranea 27K GT Ro-Pax Fortuny

Propeller characteristics			
	Conventional	CLT	
Propeller type	CP	CP	-
Diameter	4.600	4.368	m
Blade area ratio	0.714	0.520	-
Blade number	4	4	-

In this case the expanded area of the CLT propeller is about 65% of the original one.

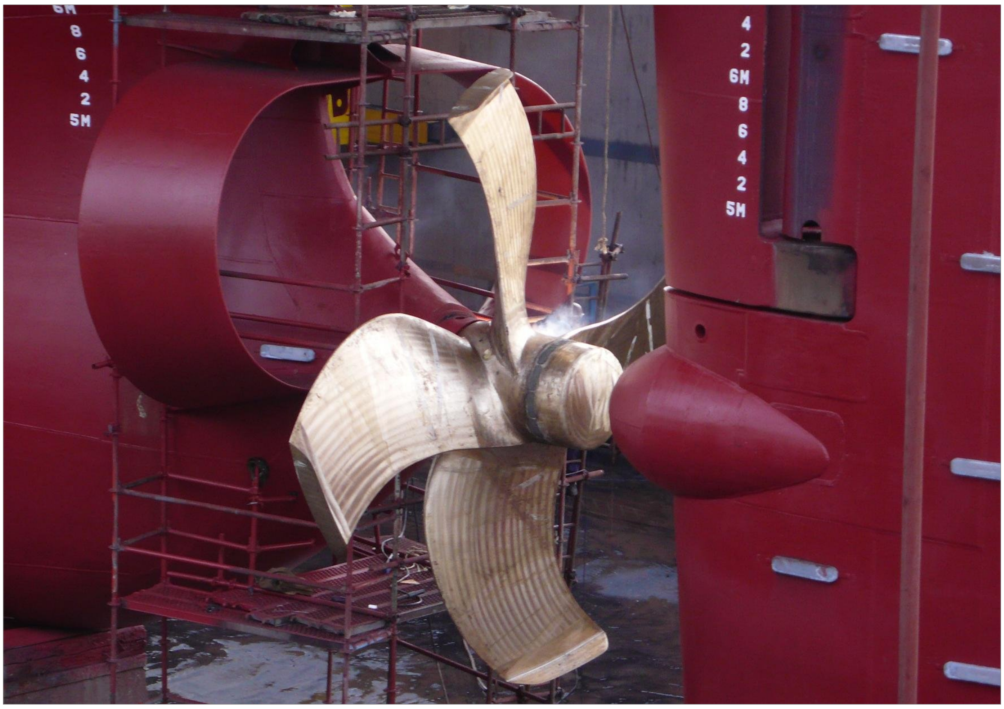

Figure 8. 35K DWT product tanker "Roy Maersk", the retrofitted CLT propeller with pre-existing WED and bulbed rudder.

The conventional and the CLT propeller blades of Ro- Pax Fortuny are portrayed, side by side, in Fig. 2.

In both cases, despite the much smaller developed area of the CLT propellers in comparison to the one of the conventional propeller, the vibration level on board decreased as a consequence of the retrofitting and no cavitation issues were experienced.

It should be finally mentioned that for CLT propellers the end plates do not contribute to the expanded area, while they do contribute to the expanded area of Kappel propellers. When incorporating the end plates in the calculation of the expanded area of a CLT propeller the expanded area increase of about 7%, which means that the CLT propeller surface is much smaller than the one of the equivalent conventional and Kappel propeller.

HYDRORAKE, CLT AND KAPPEL PROPELLERS

In the previous chapter it has been established that Kappel and CLT propellers, in the one and only back to back model tests, have performed according to the claims of the designers. It is now of interest to understand why CLT and Kappel propellers perform in a different way.

Reference is made to theroving Propeller Efficiency Throut Tip Loading", Michael Brown, Antonio Sánchez-Caja, Juan G. Adalid, Scott Black, Mariano Pérez Sobrino, Phillip Duerr, Seth Schroeder, Ilkka Saisto, to be published at 30th Symposium of Naval Hydrodynamics Hobart, Tasmania, Australia, 2-7 November 2014.

According to NSWCCD propeller blades with single-sided winglets do not lend themselves to traditional ITTC geometry definitions and therefore NSWCCD has introduced the concept of hydrorake, which is a rake-like displacement perpendicular to the local propeller pitch and it is defined as follows :

$$\text{Hydrorake} = (\text{ Total Rake} / D - 0.5 \text{ Skew } r/R \tan(\varphi)\ )\ \ \sin(90 - \varphi)$$

where R and D are propeller radius and diameter respectively, skew is projected skew in radians, r is local radius, and φ is local propeller pitch angle. Sistemar's CLT propeller is an example of positive hydrorake, while the Kappel propeller is an example of negative hydrorake.

NSWCCD has performed a design space exploration covering a series of spanwise circulation distributions, hydrorakes, advance coefficients, thrust loading coefficients and area ratios. The result of such exercise are as follows:

- Unconventional Tip Shape Propellers provides the greatest possible increase in efficiency for operating conditions of high thrust loading coefficient and high advance coefficient, in other words Tip Propellers allow for the greatest efficiency improvement in case of heavily loaded propeller turning at a low RPM.
- Positive hydrorake allows for a greater increase in efficiency than negative hydrorake.

The first item was well known and already highlighted for both Kappel and CLT propellers (in this respect reference is made to Figure 5).

The second item is more interesting and it requires some comments. The fact that positive hydrorake is better that negative hydrorake was apparent from the different claims about the efficiency gains of CLT and Kappel propellers.

A similar conclusion is described by Yasuhiki Inuaki in his paper "A development of a propeller with backward tip raked fin" presented at the Third International Symposium of Marine Propulsion, Australia, May 2013. In the paper it is explained that by bending the propeller tip toward the pressure side (i.e. positive hydrorake) it is also possible to reduce the the blade area without sacrificing the cavitation performance.

In other words the positive hydrorake, aside from giving the typical advantages of tip loaded propellers in terms of better radial distribution (i.e. use of the entire blade, for root to tip, to generate thrust and the consequent reduction of expanded area) it also allows for a subsequent sharp decrease of expanded area, and the consequent reduction of viscous losses.

In addition to the above it should be noticed that in case of positive hydrorake the tip, being bet backwards, is at the boundary between the pressure side and the external flow (which is at ambient pressure), therefore it is protected from harmful cavitation phenomena due to the high pressure. In addition, being a barrier between the pressure side and the external flow, it "protects" the pressure build up, this is the reason for the very high margin of CLT propellers in respect to face cavitation.

On the contrary in case of negative hydrorake the tip, being bent forward, is at the boundary between the suctions side and the external flow (which is at ambient pressure), therefore it is partly immersed in a low pressure region and, as a consequence, it is not protected from harmful cavitation phenomena. In addition the tip plate, being a barrier between the pressure side and the external flow, while impeding communication between the external flow and the suction side it allows communication between the pressure side and the external flow, resulting in a lower margin in respect to face cavitation when compared to CLT propellers.

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.

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 analysed by means of CFD calculations and model tests and have been identified as measure to decrease the noise and vibration levels on board.

2010 – 2013 "TRIple Energy Saving by Use of CRP, CLT and PODded Propulsion" (TRIPOD) ABB, VTT, AP MOLLER MAERSK, CEHIPAR, CINTRANAVAL-DEFCAR and SISTEMAR. The main goal of the project was the development and validation of a new propulsion concept for improved energy efficiency of ships through the combination of three existing propulsion technologies: podded propulsion (POD), CLT propellers and and counter-rotating propeller (CRP) principle. Different propulsion configurations for the 8.500 TEU's container vessel "Gudrun Maersk." were analysed: single screw ship with conventional propeller and CLT propeller, CRP arrangement with conventional and with CLT propellers.

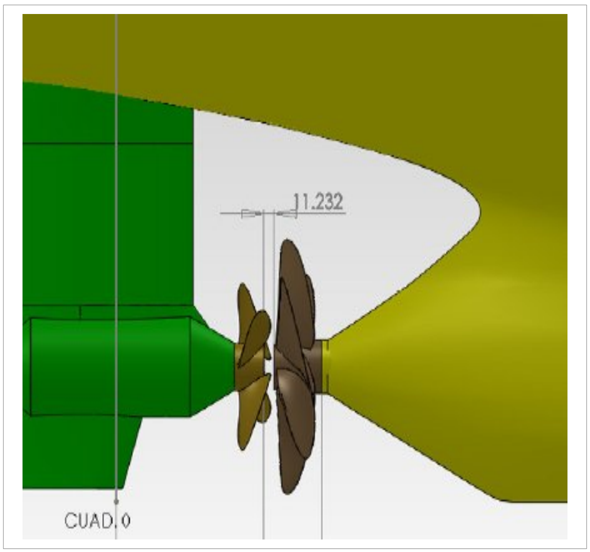

Figure 9. CRP-POD configuration (shown with conventional propellers)

The results of the TRIPOD project have been as follows:

- The application of the three principle results in the best propulsive efficiency, albeit at a substantial increase in the building costs and of the ROI.
- The use of a single CLT propeller results in a substantial increase of the propulsive efficiency and in the best ROI.

During TRIPOD several parameters pertaining the end plate geometry have been investigated by means of CFD, in particular endplate contraction, flap, sweep and cutting have been varied in a systematic manner and optimised. The results of this exercise have been published in "Scale effects on tip loaded propeller performance using a RANSE solver" A. Sánchez-Caja, J. González-Adalid, M. Pérez-Sobrino, T. Sipilä. 2014 Elsevier Ltd .

2012 – 2013 "Energy Efficient Contracted-Loaded Tip (CLT) Propellers for Naval Ships" U.S. NAVY (NSWCCD), SISTEMAR with CEHIPAR and VTT as subcontractors. The main goal of the project was to test a CLT propeller designed by SISTEMAR and a Tip Loaded propeller design by NSWCCD and to perform RANS calculations both at model and full scale.

Figure 10. SISTEMAR CLT propeller, left, and NSWCCD TLP propeller, right. Albeit independently designed the two propellers are very similar.

The results of this project will be published at 30th Symposium of Naval Hydrodynamics Hobart, Tasmania, Australia, 2-7 November 2014.

The collaboration between U.S. Navy and SISTEMAR is still ongoing in the form of a future full scale application based on an acquisition project.

2012 – 2013 “Design of new propellers for C/V Grand Princess”, CARNIVAL, PRINCESS CRUISES, HSVA, SISTEMAR, UNIVERSITY of GENOA, SINM. An initial “standard” CLT propeller design showed a markedly higher efficiency than the conventional propellers, however the performance of the conventional propellers in respect with pressure pulses was superior. A revised and updated CLT propeller design was able to retain the gain in efficiency while matching the performance of the conventional propellers in respect with pressure pulses.

This exercise has highlighted that CLT propellers, despite having in general superior performance to conventional propellers in respect to both propulsive efficiency and pressure pulses, need to be designed with particular attention to pressure pulses for application such as cruise vessels.

The lessons learned in this project is being incorporated not only in “sensitive” CLT propeller designs (such as passenger vessels and naval units), but also for standard ones.

PRESSURE PULSES AND CAVITATION CHARACTERISTICS

The pressure pulses and cavitation characteristics of Unconventional Tip Shape Propellers are, in principle, comparable if not superior to the ones of conventional propellers. However it is difficult to present a sound and comprehensive overview due to the extremely scant literature on Kappel propellers.

As far as pressure pulses the scenario for CLT propellers is as follows:

- The amplitude of the first harmonic is in principle of the same order of magnitude or a little higher than those of the equivalent conventional propeller.
- The amplitude of the higher order harmonics is very much lower than the amplitude of the first harmonic and much lower than those of the equivalent conventional propeller.

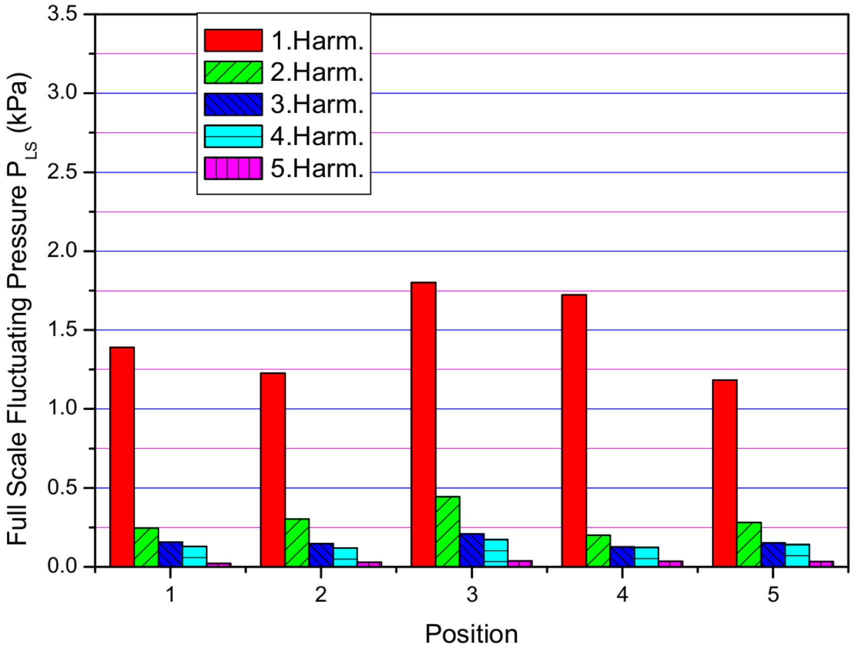

Figure 11. Typical pressure pulses of a CLT propeller for a single screw vessel

In addition, as a consequence of retrofits of CLT propellers, the vibration levels on board have decreased.

According to MAN brochures and presentation Kappel propellers allow for a drastic decrease in pressure pulses is present for first and second order harmonics.

As far as cavitation the scenario for CLT propellers is as follows:

- CLT propellers have a much larger margin against pressure side cavitation than conventional propellers.
- CLT propeller have a larger margin against suction side cavitation than conventional propellers.
- Sheet cavitation developed by CLT propellers in the wake peak is much more stable than for conventional propeller.

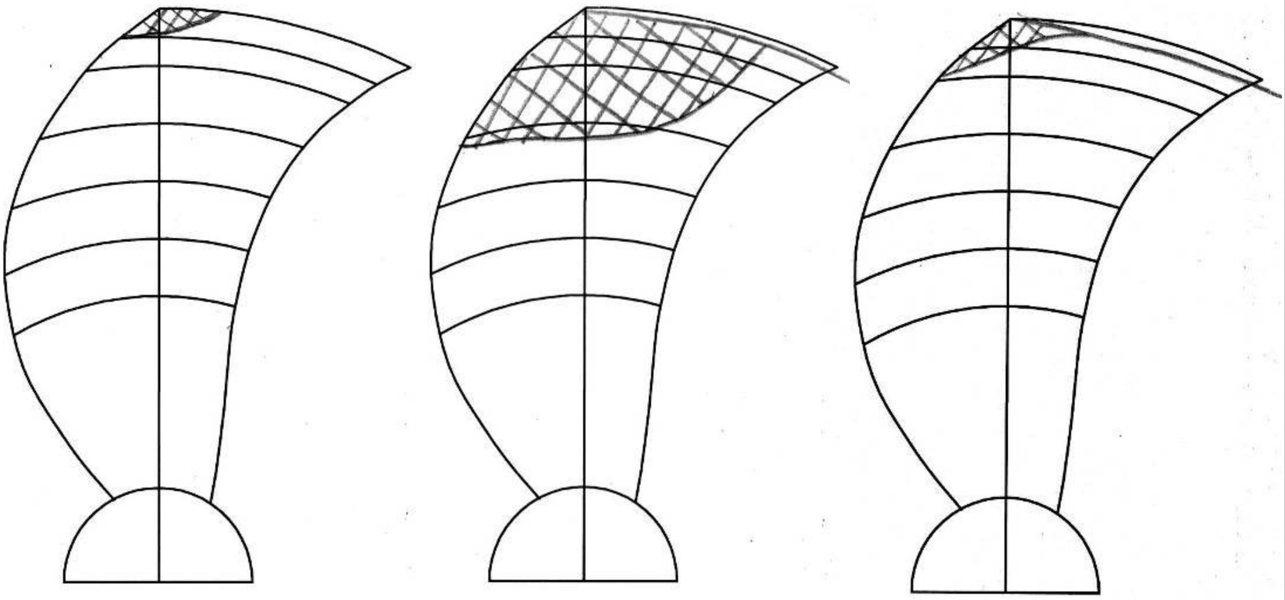

Figure 12. Typical Cavitation Pattern of a CLT propeller for a single screw vessel Design Draft (320°, 0°, 70°)

The following Kappel propeller cavitation pattern is taken from “Unsteady cavitation simulation on Kappel propeller with a hull wake field” Keun Woo Shin, Rasmus Møller Bering, MAN Diesel & Turbo , Frederikshavn, Denmark. It is believed that the cavitation pattern is for a 5.8 m Kappel propeller applied to a single screw 35K DWT Tanker.

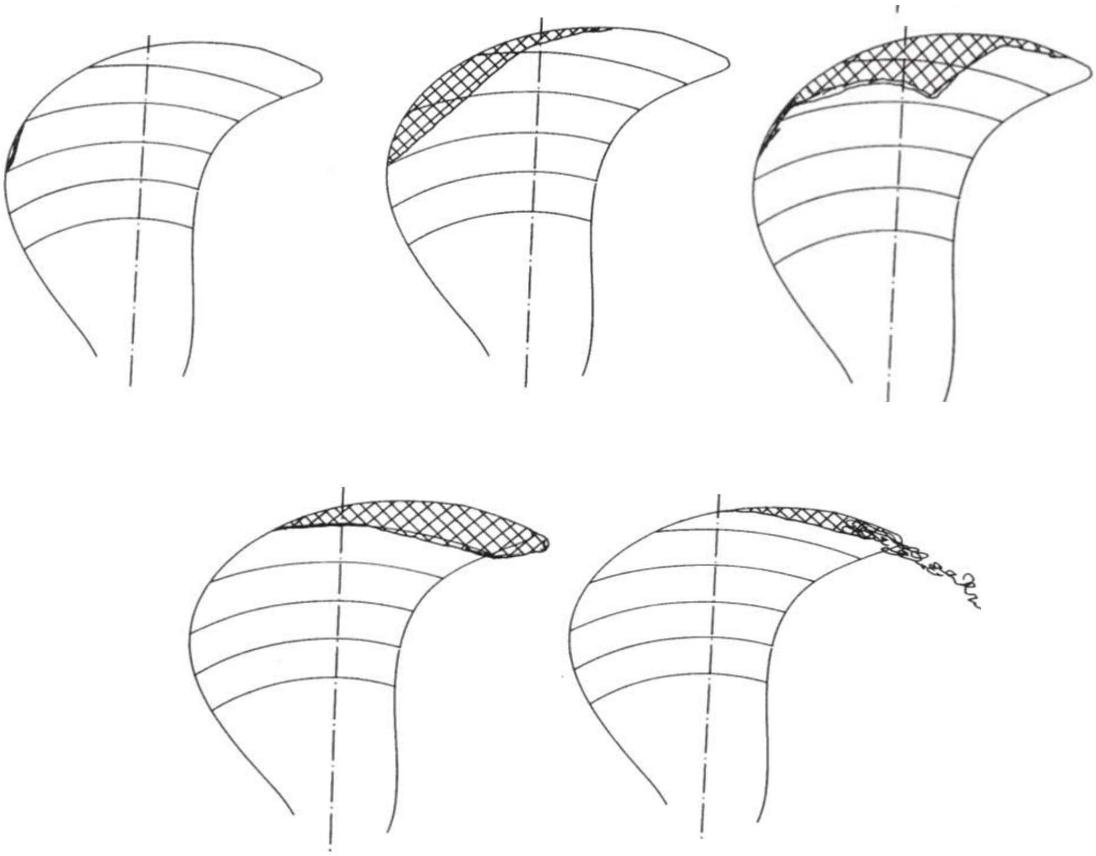

Figure 13. Kappel propeller Cavitation Pattern (320°, 340°, 0°, 20° 40°)

REPAIRS

The possibility of repairing Unconventional Tip Shape Propellers is very similar, if not identical to the one of conventional propellers. As a matter, in case of cropping, the need for correct alignment of the welded part is extremely important, regardless of the presence or absence of the end plate.

During the extensive collaboration between A. P. Moeller Maersk and SISTEMAR on CLT propellers it was asked Lloyd Register to check in their records for all “problems” involving ships equipped with CLT propellers. Lloyd Register ascertained that several ships had indeed suffered from either vibration or cavitation problems but BEFORE being retrofitted with CLT propellers. The only problems that had to do with CLT propellers were a pair of contacts with the bottom / buoys.

The author is not aware of any particular problem involving Kappel propeller either.

It should be finally noted that Unconventional Tip Shape Propellers, having a diameter smaller than the equivalent conventional propeller, the risk of a collision is diminished.

UNCONVENTIONAL TIP SHAPE PROPELLERS AND PIDS

Historically many Populsion 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.

In principle the careful optimization of the hull (main dimensions, bow and stern shape), followed by the selection of an Unconventional Tip Shape Propeller and of a bulbed and twisted rudder will guarantee a high propulsion efficiency (hence low EEDI and EEOI).

If the above is performed effectively, the use of further Propulsion Improvement Devices (PIDs) is likely to bring only marginal gains.

The exception are vessels with unfavourable main dimensions, large block coefficients and non optimized hulls, in such cases PIDs such as Flow Regulating Hull Fins (e.g. Grotheus Spoier or SHI Saver Fin) or as Pre Ducts (e.g. Sumitome Integrated Lammersen Duct or Mewis Duct) can help ameliorating the flow conditions on the stern, reorganizing the wake at the propeller disk, generating a pre rotation of the flow and increasing the propulsive efficiency.

As far as compatibility between PIDS and propellers it should be stressed that, in principle, all propellers are compatible with any kind of PID, while not all PIDs are compatible with one another.

In principle PIDs cab be divided in the following categories:

Before the propeller:

Flow Regulating Hull Fins, used to alleviate flows separation at the hull and to improve propeller inflow, in principle these device are use to “cure” problems arising from a “bad” hull.

Pre Ducts, used to improve propeller inflow and to create additional thrust.

Pre Swirlers, used to improve propeller inflow, also by adding a pre rotation.

Please note that Pre Ducts ad Pre Swirlers can be integrated, the Mewis Duct is a typical example of such integration, both in its standard and in its updated version (Becker Twisted Fin).

After the propeller:

Propeller cap, used to decrease eddy losses at the propeller hub.

Rudder Bulb, used to decrease viscous losses at the propeller hub.

Twisted Rudder, used to recover rotation losses.

Rudder Fins, used to recover rotation losses.

It should be noted that:

Propeller Caps are incompatible with Rudder Bulbs.

Twisted Rudders render the addition of Rudder Fins of very marginal usefulness.

It should be further noted propulsors arrangements, such as azimuthting propellers and contra rotating propellers, should not be confused with PIDs.

As far as PIDs it should be underlined the very large difference in flow at model and full scale due to the large difference in Reynold number and, consequently, viscous losses and boundary layer thickness. Due to such reasons the scaling of PIDs performance from model to full scale is still an issue.

Even thought PIDs installed after the propeller generate minimum effects on the propeller, be it conventional of of Unconventional Tip Shape Type, PIDs installed before the propeller can have a large influence on the propeller.

In any case the design of the propeller and of the selected PID must be integrated.

However, contrary to what some statements, this is not to say that propeller and PIDs must be designed by the same designer, quite the contrary, “packages” and off-the-shelf designs should be best avoided, preferring to select, independently, the best type of propeller and the best PIDs for the task.

REBLADING & RETROFITS STRATEGY

The possibility of retrofitting existing vessels with "modern" propellers and PIDs, also in view of an actual operating speed different from the original design speed of the vessel, is a clear strategy for the improvement of the propulsive efficiency and for the reduction of fuel oil consumption.

Also in this case the use of Unconventional Tip Shape Propeller is dominant, both in respect to the installation of a new conventional propeller or of a PID.

In addition, in case of retrofit, the gains to be expected are in principle higher than what normally quoted for new buildings, the difference lying in the fact that in case of new buildings the gains are calculated in respect of a state-of-the-art conventional propeller, while in the case of reblading and retrofits the term of comparison is, in general, an old-design propeller in conditions far from mint ones!

In addition in case of a change in design point, a further gain is to be expected, since the geometry of the old propeller is mismatched for the new design point (higher area ratio, high pitch...).

This is often the reason for the high gains often appearing in commercial brochure and advertisements: if the term of comparison is not very good two digit efficiency gains are possible even be installing state-of-the-art conventional propellers. However, installing Unconventional Tip Shape Propellers the gain would always be higher.

It should also be noted that in case or retrofits either the designer of the new propeller (be it conventional or not) knows the exact geometry of the old propellers (which is extremely unlikely, unless the designer is the same) or he will be conservative in giving the gains to be achieved due to the retrofit, since he knows how his new propeller will perform, but he can only make an educated guess about the performance of the old propeller.

This uncertainty is present also in case the complete original model tests and sea trials are available for perusal, but of course, in case the original model tests and sea trials are not available the uncertainty is much greater.

It should be finally noted that care should be exerted when retrofitting a PID without replacing the propeller, the risk is that the original propeller will become heavier, this risk is greater when the PID is located in front of the propeller and it is the norm in case the PID acts a pre swirler.

CONCLUSIONS

Unconventional Tip Shape Propellers are a mature technology and they represent the best solution in order to increase the propulsive efficiency of new buildings and of existing vessels.

The merits of Unconventional Tip Shape Propellers (higher efficiency, lower noise an vibration levels and better manoeuvrability characteristics) have been demonstrated in more than 300 full scale applications on very different ship types.

The efficiency increase (and hence the achieved fuel saving) is in the range of 3 – 5 %, for Kappel Propellers and 5 – 8% for CLT propellers when compared to an equivalente state-of-the-art conventional propeller. The efficiency is higher for slow vessels with high block coefficient as tankers, bulkers, etc...

From the above it follows that Unconventional Tip Shape Propellers 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 Unconventional Tip Shape Propellers are compatible with all PID currently offered, thereby allowing to achieve even higher energy efficiency when combined.

REFERENCES

- G. PEREZ GOMEZ. "Una innovación en el proyecto de hélices". Ingeniería Naval, October 1976.
- G. PEREZ GOMEZ; J. GONZALEZ-ADALID. "Tip Loaded Propellers (CLT). Justification of their advantages over high skewed propellers using the New Momentum Theory". SNAME – New York Metropolitan Section, Fiftieth Anniversary 1942-1992, 11th February 1993 and also at International Shipbuilding Progress nº 429, 1995.
- G. PEREZ GOMEZ; J. GONZALEZ-ADALID. "Optimisation of the propulsión system of a ship using the Generalised New Momentum Theory". WEMT Golden Metal Awards, 1997.
- G. PEREZ GOMEZ; J. GONZALEZ-ADALID. "Detailed Design of Ship Propellers". Book edited by FEIN (Fondo Editorial de Ingeniería Naval), Madrid 1998.
- G. PEREZ GOMEZ; J. GONZALEZ-ADALID. "Nuevo procedimiento para definir la geometría de las líneas medias de las secciones anulares de las palas de una hélice". Ingeniería Naval, September and December 1999.
- M. PEREZ SOBRINO; J.A. ALAEZ ZAZURCA; A. GARCIA GOMEZ; G. PEREZ GOMEZ; J. GONZALEZ-ADALID. "Optimización de la propulsión de buques. Un proyecto español de I+D", XXXVI Technical Sessions of Ingeniería Naval. Cartagena, 25th and 26th of November 1999.
- G. PEREZ GOMEZ; J. GONZALEZ-ADALID. "Scale effects in the performance of a CLT propeller". The Naval Architect, July/August 2000.
- M. PEREZ SOBRINO; E. MINGUITO CARDEÑA; A. GARCIA GOMEZ; J. MASIP HIDALGO; R. QUEREDA LAVIÑA; L. PANGUSION CIDALES; G. PEREZ GOMEZ; J. GONZALEZ-ADALID. "Scale Effects in Model Tests with

CLT Propellers”. 27th Motor Ship Marine Propulsión Conference. Bilbao, Spain, 27th-28th January 2005.

- “CLT: A Proven Propeller for Efficient Ships”. Supplement of the Naval Architect, July/August 2005 issue.
- G. PEREZ GOMEZ; J. GONZALEZ-ADALID; A. GARCIA GOMEZ; J. MASIP HIDALGO; R. QUEREDA LAVIÑA; L. PANGUSION, E. MINGUITO CARDEÑA, C. GALINDO, M. PEREZ SOBRINO; “Full scale comparison of a superferry performance fitted with both High Skew and CLT blades”. WMTC Conference. London, U.K, 2006.
- G. PEREZ GOMEZ; M. PEREZ SOBRINO; J. GONZALEZ-ADALID; A. GARCIA GOMEZ; J. MASIP HIDALGO; R. QUEREDA LAVIÑA; E. MINGUITO CÁRDENA; P. BELTRÁN PALOMO. “Un hito español en la propulsión naval: rentabilidad de un amplio programa de I+D+i”. Ingeniería Naval, June 2006.
- A. SANCHEZ CAJA, T. P. SIPILA, J.V. PYLKKANEN “Simulation of the Incompressible Viscous Flow around an Endplate Propeller Using a RANSE Solver” 26th Symposium on Naval Hydrodynamics Rome, Italy, 17-22 September 2006.
- P. ANDERSEN, J. J. KAPPEL, E. SPANGEBERG “Aspects of Propeller Developments for a Submarine”, First International Symposium on Marine Propulsors , SMP’09, Trondheim, Norway, June 2009
- G. GENNARO; J.G. ADALID; R. FOLSO. “Contracted and loaded tip (CLT) propellers. Latest installations and experiences”. 16th International Conference of Ship and Shipping Research, NAV 2009. Messina, Italy. November 2009.
- B. CERUP. SIMONSEN; J.O. DE KAT; O.G. JAKOBSEN; L.R. PEDERSEN; J.B. PETERSEN; T. POSBORG. “An integrated approach towards cost-effective operation of ships with reduced GHG emissions”. SNAME, 2010.

- H. HAIMOV; J. VICARIO; J. DEL CORRAL. "Ranse Code Application for ducted and endplate propellers in open water". 2nd International Symposium on Marine Propulsors SMP'11, Hamburg, June 2011.
- S. GAGGERO; S. BRIZZOLARA. "Endplate Effect Propellers: A Numerical Overview." XIV Congress of the International Maritime Association of the Mediterranean, IMAM 2011. Genoa, Italy. September 2011.
- J.G. ADALID; G. GENNARO. "Latest experiences with Contracted and loaded Tip (CLT) propellers." XIV Congress of the International Maritime Association of the Mediterranean, IMAM 2011. Genoa, Italy. September 2011.
- Y. INUKAI "A Development of a Propeller with Backward Tip Raked Fin." Third International Symposium on Marine Propulsors , SMP'13, Tasmania, Australia, May 2013.
- "Propulsion Committee Final Report and Recommendations." 27th International Towing Tank Conference, 27th ITTC, Copenhagen, Denmark, September 2014.
- "Specialist Committee on Performance of Ships in Service Final Report and Recommendations." 27th International Towing Tank Conference, 27th ITTC, Copenhagen, Denmark, September 2014.
- J. GONZALEZ-ADALID, M. PEREZ SOBRINO, A. GARCIA GOMEZ, G. GENNARO, S. GAGGERO, M. VIVIANI, A. SANCHEZ CAJA, "Comparison of Different Scaling Methods for Model Tests with CLT Propellers" 2014 International Conference on Hydrodynamics, ICHD2014, October 2014.
- M. BROWN, A. SANCHEZ CAJA, J. GONZALEZ-ADALID, S. BLACK, M. PEREZ SOBRINO, P. Duerr, I. SAISTO "Increasing Propeller Efficiency through Tip Loading", 30th Synposium on Naval Hydrodynamics, 30th SNH, Tasmania, Australia, November 2014.