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# Energy efficiency audits on ships: Hydrodynamic aspects for energy efficiency improvements

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*Abstract*—**The very first step for reducing the fuel bill on a ship, is to carry out an energy efficiency audit; this way the owner can know the details on how the energy is used on board and prepare an action plan. There exist on the market different solutions for improving the energy efficiency of ships and some of them are outlined in this article. Since the propulsion is the main energy consumer of the vessel, the focus is on the hydrodynamic aspects.**

***Keywords: Energy efficiency, ship propulsion, hydrodynamics, ship energy efficiency audit.***

## I. SEA TRANSPORTATION

Sea transport has historically been the most important mean of transporting goods, mainly due to the ability to get to places unreachable by road and the amount of cargo loaded on each trip. Despite the technological developments achieved on road, train and air transport, sea transport has remained unbeatable when it comes to move large amounts of cargo at low cost. If we compare the cost per ton-mile, it can be seen that sea transportation is 80 times more efficient than air transport; this is something pretty clear to everybody, but we still notice that sea transportation can be almost 30 times more efficient than moving goods by truck.

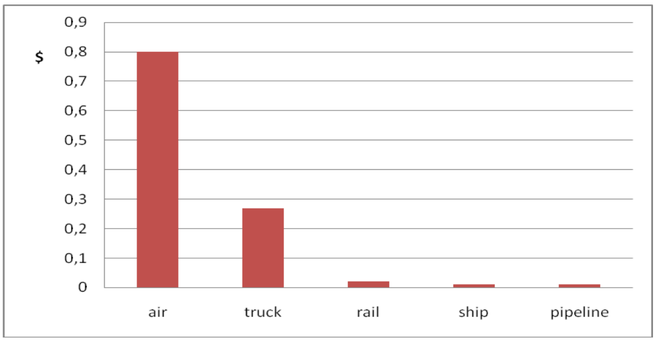


Figure 1. National Transportation Statistics , 2009 (Source: US Department of Transportation)

It is true that the efficiency, both in terms of energy consumption and operating costs, of aircrafts, trucks and trains is being improved continuously due to the evolution of the technology, but so is doing the shipping and shipbuilding industry, so its leading position is going to last.

Furthermore, there is no other mean of transportation offering the flexibility of shipping to suit different boundary conditions such as traffic, speeds, loads, etc. The potential for a vessel to adapt to new environments has no equivalent among the other means of transport. For example, a vessel may be elongated, retrofitted, converted to move a different cargo or duty, and can achieve great improvements in energy efficiency incorporating the latest technologies. All this can be applied to ships even older than forty years.

Based on the above considerations, we can be confident that shipping will remain as the main mean of transportation of goods for a long time. The promotion of transport and maritime technology should be a key aspect into the R&D strategic plans and infrastructure development of our governments.

## II. KNOWING THE PROBLEM. ENERGY AUDITS

### A. *Purpose of the energy audit*

The goal of energy audits is to identify and analyze how energy is transformed and used onboard a ship, in order to make suggestions for improvements that reduce fuel consumption. Through an energy audit the energy consumption profile of the vessel and the potential for improvement in each field can be quantified.

The energy balance in a typical vessel normally involves a propulsion engine as a primary consumer and several diesel generators as secondary fuel consumers, existing combinations of drive solutions for the power plant and ancillary equipment (shaft generators, hydraulics, etc.).

While the primary consumer is the engine of the ship, we must not forget that this engine uses energy to drive a propeller, which in turn must overcome the resistance of the hull and interact with it and its appendages (nozzle, rudder, etc.). This is why it is essential to focus the audit not only as a collection of data but a detailed analysis which also assess the hydrodynamics of the ship. There are small low-cost actions (such as new designs of bulbs, keels, stern flaps, flaps, nozzles, rudders, etc.) that improve the performance of the vessels significantly. Small investments can lead to big savings over the medium term. There is also drive and control technology that can improve the generation and use of electric power on board.

### *B. Benefits to the owner*

We can cite now some of the advantages justifying why an energy efficiency audit is very interesting and beneficial to the ship owner:

- Immediate fuel savings derived from the knowledge of the consumption profile detecting inefficient work conditions and avoiding malpractice.
- Identification of potential engine problems (excessive consumption, poor combustion, etc.)
- Hydrodynamic characterization of the entire ship (main energy consumer)
- A study of potential improvements and technical and economic impact of those receiving advice on their implementation.
- The energy audit supports and opens the door to future requests from the administration regarding emission reductions such as the EEOI (Energy Efficiency Operational Index) or for sailing on controlled areas for reduced emissions (ECA's).
- The implementation of the proposed improvements, typically have a low payback time and enhance profitability from day one.

### *C. Audit Phase*

We can distinguish the following stages in an energy audit of a ship:

1) Initial contact and situation analysis.

This stage requires a number of contacts with the owner and his technical team and crew in order to know the current status of the vessel to be audited in relation to the fuel consumption, identified weaknesses, etc. The compromise of the technical staff and crew is essential in the audit process, so that its results are satisfactory.

2) Technical data collection

For a proper analysis, it is crucial to study both the ship and its installed machinery, having available as much technical information as possible. The technical information and drawings are normally available from the owner own files or can be requested at the technical design offices or shipyards involved in the construction (and subsequent repairs if any) of the vessel. It is obvious that the greater the amount of technical information and best quality of it, the more accurate the analysis; there are however a number of drawings that are fundamental to the analysis of propulsion, these are the hull form, propeller and rudder.

3) Data acquisition onboard

One of the critical tasks of the energy audit is the data acquisition onboard, this is a complex task that normally requires the involvement of specialized engineers, but can also be supplemented with measurements and records made by the crew itself. From the information obtained here we will know how the vessel is operating, in terms of power demand as a function of time, obtaining an operational profile which should be as detailed as possible (usually these operating conditions do not match any of the analyzed and optimized in the design stage). Below, different methods of data collection are listed, usually used in combination for higher accuracy:

a) Permanent monitoring system:

This is the ideal case, where the owner installs a permanent system for energy efficiency monitoring (like the PEMS system www.pems.com). Such systems record several parameters related to energy use on board such as:

- Real power at the propeller shaft with torque meter
- Main engine fuel consumption
- Diesel generator sets fuel consumption
- Generators electric power
- Consumers electric power
- Pressures and use of hydraulic systems
- Temperatures
- Water flow on the cooling systems
- Speeds
- Etc.

All this information is usually transmitted to land on a regular basis, since it is stored in a database, and further analysis is very easy.

b) Monitoring system temporarily installed:

An alternative to installing a permanent system is the installation of a portable system for a given period of time. This system has virtually the same capabilities as the fixed one but with the advantage that it is not necessary to purchase the equipment (though there is an installation cost) and the disadvantage that the recorded data frame covers a much smaller period of time.

c) Individual measurements:

In a normal case, it is necessary to conduct a comprehensive set of measurements in actual operating conditions of the ship, boarding a team of engineers with specialized instruments. Ideally, the measurements are made for several days, for example sailing in a route between two ports and varying operating conditions of the ship emulating the usual working conditions. If the ship has a dedicated monitoring system, this point would be covered by analyzing data collected by this system as stated in the previous section.

d) Data collected by the crew:

Additionally to all the above measures, the use of work sheets for data collection by the crew can be an option. The engine room staff typically keeps quite complete records of the operating parameters of the machine and we can take advantage of it. On the other hand, specific guidance can be provided to the crew in order to collect additional data both at the engine room and wheelhouse during specific time periods.

4) Data Analysis

Given the large amount of data collected in previous stages, it is necessary to use specialized software for filtering the data and draw conclusions, identifying the main consumers of energy and inefficient processes and practices

5) Simulations

a) Hydrodynamic Analysis:

Since the propulsion is the largest energy consumer in the ship, it is essential to conduct a detailed analysis of the hydrodynamics of the hull, propulsion and maneuvering system. The use of CFD tools can accomplish this task with a reasonable cost and high accuracy. Standard analysis include the study of the hull resistance, orientation of appendages, propeller design and operation of the rudder. The analysis includes both the situation and response in the original condition of the vessel and the response in "off design" conditions as well as evaluation of those possible geometric changes to improve performance.

b) Machine Simulation:

Modeling the operation of machinery supplements the measurements and data taken on board, allowing predictions of consumption in different working conditions or after having modified or replaced gear or working modes. A global model of the ship's machinery should include the main engines, auxiliary engines, generators and main consumers.

6) Economic Survey

The economic study assesses the current performance of the installation, making proposals for improvement. Different scenarios are presented, based on variations in the operation of ships and oil price perspectives for the future; each of the scenarios is evaluated with various improvements combinations in machinery, including both upgrading and complete replacement of systems. All investments must be evaluated based on ROI (return of investment), taking into account interest rates, fuel price scenarios, etc.

7) Solutions implementation

The energy audit report evaluates the costs and procedures associated with each action, in such a way that its implementation steps are clearly defined to avoid unpleasant surprises.

Normally different solutions of different depth and complexity are found, from simple changes in habits or configuration of equipment at no cost, to large changes requiring long dry docking periods with significant investments. Normally a higher investment means greater reduction in fuel consumption, but each owner must evaluate different alternatives and scenarios according to his needs and expectations of use of the vessel and fuel price scenarios.

## III. SHIP ENERGY CONSUMPTION AND EFFICIENCY. WORKING AREAS

For a proper energy efficiency methodology it is important to classify the energy use on board in different areas:

### *A. Hydrodynamics*

Typically, the majority of energy in the vessel is used to propel it, overcoming the drag of the hull by means of a propeller. The performance and interaction among hull, propeller and rudder is the key issue on the propulsive efficiency improvements. Other aspects of the hydrodynamic response of a vessel are the course stability and seakeeping.

### *B. Propulsion Machinery*

When we speak about ship’s propulsion machinery, we normally refer to diesel engines driving the propellers directly or through a gearbox since this is the most common arrangement. We are not going to enter in this paper into the discussion on the different alternatives such as diesel electric, “father and son” or auxiliary PTI arrangements.

The diesel engines are responsible for converting chemical energy stored in fuel into mechanical energy (torque and rotation), which is transmitted to the propeller through the propeller shafts. 40% could be considered as an average efficiency value of diesel engines, though of course each machine has its own performance curves, which are significantly affected by environmental factors such as working conditions, load profile, aging components, etc. For overpowered installations, the de-rating of an engine must be carried out by specialized personnel, adjusting and/or modifying the turbo charger, injection timing, etc., offering significant savings at a very low cost. Needless to say that the maintenance of the diesel engine must be carried out with care and on a regular basis, since a small percentage of efficiency means a huge amount of money over the year.

Based on the above, it follows that the analysis of propulsion engines for the purpose of energy efficiency requires a thorough study for each ship, bringing together different operating conditions. Another option arising on the market is for instance the recovery of a part of the huge amount of energy wasted as heat, either through the exhaust gas or cooling water (ORC Organic Rankine Cycle, TEG Thermo Electric Generators, Stirling engines, etc…) but this is material for a different paper.

### *C. Electrical power generators*

After propulsion, power generation is the most important energy conversion process on the ship (except on passenger cruise vessels, where it is often the largest fuel consumer). Power generation is actually a simple process of transforming the chemical energy contained in fuel into electrical energy to be distributed in the network of the ship, but despite simple, is a key process as the inefficiencies here are paid very expensive, since they affect all energy consumed on board (while the inefficiencies located in the consumer only affect each consumer individually). Without going too much into detail, we may briefly review some aspects of the most common power generation systems, shaft generators and diesel-generating sets.

1) Shaft generators

They are widely used for power generation on ships equipped with controllable pitch propeller. From the point of view of energy efficiency, its greatest advantage lies in taking advantage of the fact that the mechanical power generated by the main engine is usually more efficient in terms of specific fuel consumption that the use of diesel-generators. On the other hand, the main limitation is the imposition of a fixed rotation speed of the entire drive train (in order to maintain the frequency), which significantly reduces the efficiency of the propeller, especially in regimes away from the design point, while working with a  pitch and rpm away from the optimum value.

2) Diesel generator sets (DG sets)

The use of DG sets is the normal electrical power generating system on ships fitted with fixed pitch propeller, and as an additional, harbour or back-up system in vessels equipped with shaft generator.

Among the main problems identified in this type of equipment, we normally found that they are used with loading rates below 60%, using simultaneously several diesel generators with low load.

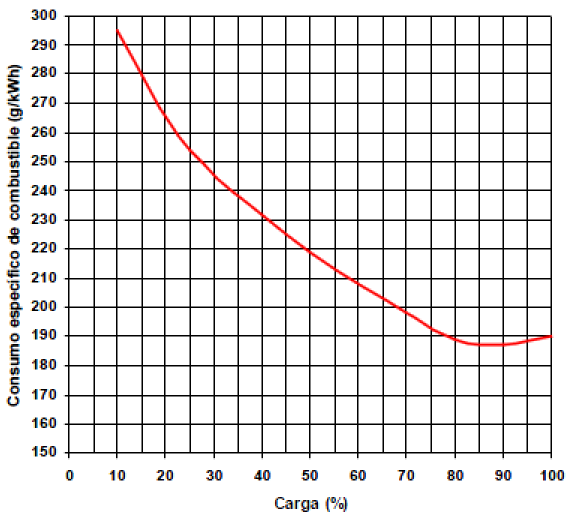


Figure 2. Specific consumer graphics depending on the load on DG sets.

3) V – F Control

The great progress made by the power electronics in recent years has facilitated the development of innovative solutions to improve the operating range of synchronous generators. SHYMGEN system is a device that allows the operation of a variable speed synchronous generator in a network with constant voltage and frequency, as in the case of a ship. This system, installed between the generator output and the network, acts on the current generated by adapting it to that required by the network, thus enabling the generator to work at variable speed. This has advantages as:

- In shaft generators. The diesel engine is allowed to work in a more favorable area of the curve for part load operations. The propeller hydrodynamic performance is also increased significantly.
- In DG sets. Diesel engine performance is improved at partial load operations.

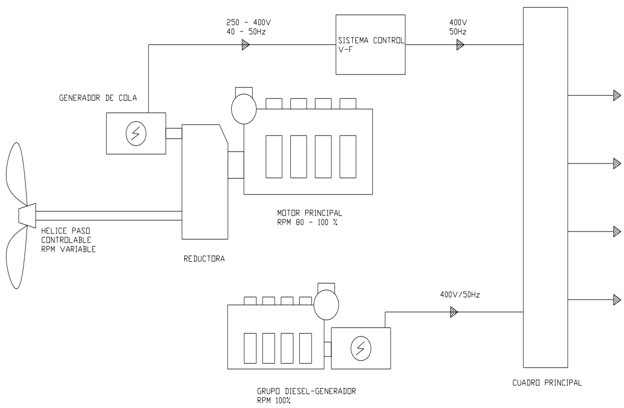


Figure 3. SHYMGEN System allows the main engine to drive a shaft generator at variable speed.

4) Variation of the power factor by capacitor bank

There are different solutions on the market for power factor correction in naval installations; while power factor correction is a very mature technology and widely used in land, using it in vessels is not so interesting, mainly due to the low losses incurred in the transport of electrical energy in the vessel network. The percentage of energy efficiency improvement of the system is low, which affects the return of investment, and it is therefore more interesting to focus on more profitable systems.

5) Consumers

There are many energy consumers onboard and we cannot analyze each of them here for obvious space limitation; we are only going to cite some of the most important and also the most common ways to act over them.

Improving the energy efficiency of the consumers can occur through changes in their operation profile, adjustment or replacement by more efficient equipment.

a) Lighting

While lighting is a small percentage of the total energy consumed, in the case of vessels equipped with large lighting installed power (usually spread over many small power lamps, such as on cruise ships) it can be a large consumer. It is recommended to optimize times of use and replace old lamps by more efficient technologies.

b) Refrigerating plant and A/C units.

It is advisable to optimize the use and to change settings and modes of operation of any type of refrigeration system. An option in some cases is the operation of compressors and condenser cooling pumps at variable speed.

c) Centrifugal pumps

The main improvement in cooling pumps is the variable speed drive, controlled by the temperature of the cooling system.

d) Ventilation

Fans are another player into the energy efficiency equation, not very powerful but operating continuously. Running the fans at variable speed and controlling them based on the temperature of the engine room and engine load is always advisable. On the other hand, analyzing the design of the engine room and ducts for a proper cooling with low pressure drop is also important.

e) Oil-hydraulic systems

Variable speed operation and replacement by electric drive systems. We should check if the sizing of the circuit is adapted to the loads.

## IV. USES IN HYDRODYNAMICS FOR ENERGY EFFICIENCY IMPROVING IN EXISTING SHIPS

As previously mentioned, for the vast majority of existing vessels most of their energy is consumed in the propulsion. On this basis, it is clear that hydrodynamics has a great potential for reducing fuel consumption, both in reducing the drag in the improvement of propulsion.

The following graph shows the breakdown in components of the drag of a ship.

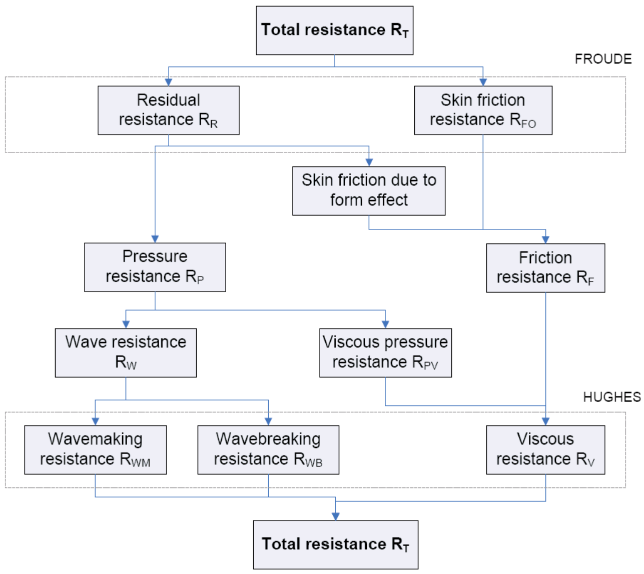


Figure 4. Resistance components

### A. *Operation*

1) Optimal speed

For each ship there is an optimal operation speed, it has to do with the wave length at each speed and Froude number. This is something you must take care of when designing the ship and choose length and speed. For existing ships, at least the user should concern about the upper recommended speed limit; this is especially important for ships operating at high Froude number, i.e. short vessels.

The common sense dictates that we should avoid the very steep areas of the resistance curve, as can be seen in the following figure, shifting the speed by one single knot from 12 to 13 knots increases the effective power by 44%.

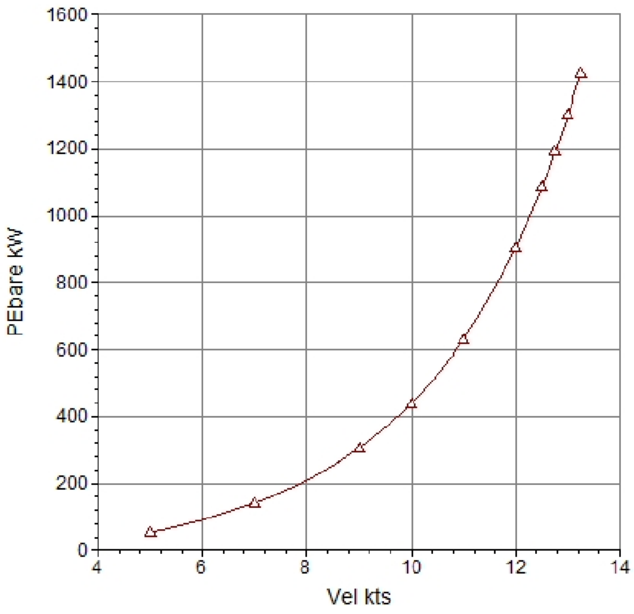


Figure 5. Power-speed curve

2) Optimal trim

Another important aspect is adopting the best trim for each displacement: trimming the ship can offer significant gains at no cost. The prediction of the optimal trim can be done by means of CFD tools and can be incorporated on a database onboard.

This is especially useful in larger vessels fitted with ballast tanks and capability to modify the trim.

3) Other aspects

Last but not least, the autopilot settings should be analyzed and optimized for optimal course keeping, also route analysis taking into account currents and sea states can save money on the fuel bill.

### B. *Reduced frictional resistance*

The weight of the frictional resistance on the total resistance varies greatly depending on the type of vessel. Based on the Froude number, the percentage of frictional resistance on the total varies from 50% for a tanker of 300,000 dwt to 10% in a tug operating at Froude numbers of 0.35.

Decreasing the frictional resistance of the hull implies reducing the friction coefficient over the hull or in a specific area of it. There exist on the market paints based on fluoropolymer or silicones, which reduce the frictional resistance, while decreasing the time between dockings, resulting in a cleaner hull for a longer time. For an adequate analysis of the return of investment, it is necessary to provide the service profile of the ship and its hydrodynamic characteristics, docking costs, docking periods, etc.

### C. *Design bow area*

For ships sailing at high Froude numbers, wave making is the main component of resistance: to reduce it on a retrofitting project, a classical approach is the lengthening of the vessel, usually by adding an additional section in main body, thus decreasing the resistance and winning at the same time capacity. Another cheaper option is the redesign of the bow, working on the design of the bulbous bow (or adding one if the ship did not have it.) The use of CFD tools can achieve unimaginable improvements in designs of bulbs that were already considered optimized a few years ago, needless to say that improvements can be dramatic in vessels designed for over a decade or vessels without bow bulb. Combining this with an energy audit, the design of the bulb can be adapted to the actual operating conditions, since a bulb optimized for project condition may not be optimal for the real drafts and speeds at which the ship operates

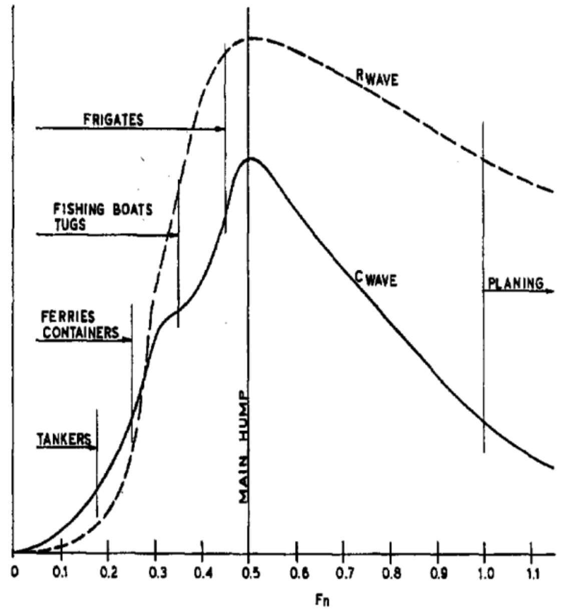


Figure 6. Typical wave resistance components

### D. *Appendages Optimization*

In this section we discuss the potential of change and reorientation of appendages, except those located in the aft area to be analyzed in the next section. The design and positioning of appendages such as bilge keels, sonar domes and tunnels, among others, enables significant improvements with small investments, which guarantees recovery times via reduced investment.

In the case of bilge keels orientation, in accordance with the streamlines calculated in the CFD, this work can be done in a few hours of work in a scheduled docking, with little or none material cost. The improvement may be between 1 and 5%, depending on the original design.

In the case of other appendages such as speed log or ultrasonic sensors housing, these are usually replaced by other more streamlined design, or integrated within the hull.

Another element to consider is the replacement, as far as possible, of sacrificial anodes for an impressed current system. The hydrodynamic force on a sacrificial anode is small, but their overall contribution is not negligible if we take into account the total number of elements in a ship.

Sea chests and other openings like transverse tunnels need special attention requiring a detailed analysis of the local flow in order to improve their design.

### *E. Stern area design*

Redesign and modifying the stern on existing ships is more complicated than the changes of the bow, mainly due to the presence of the propulsion and auxiliary machinery that limits the possible steel work.

1) Decreased resistance of appendages at the stern

This component is mainly on improving the design of ships struts in two shaft lines and skeg design.

2) Improved wake

By improving the wake configuration, the rotative-relative efficiency is increased, improving the performance and decreasing noise and vibration levels, it also facilitates the redesign of a new propeller wake-adapted to the real operating conditions. The improvement of the wake on existing ships is not an easy task, given the limitations arising from the hull geometry, though some improvements can be achieved through the use of appendages to guide the flow, obtaining a better distribution.

3) Relative position among propeller, rudder and hull.

There is always an optimal position for the above mentioned items, it can be found iterating with several CFD calculations, combining good hull efficiency with rudder energy recovery and rotative-relative efficiency.

### *F. Propeller redesign*

Design and construction of a new propeller is always a worthwhile investment. The minimum realizable improvement is usually around 5%, with the upper limit of up to 25% in certain cases where a new full drive train (changing diameter and rotational speed) is installed. There exist multiple combinations, but we can outline some of them below:

- Redesign of a propeller with new CFD tools, keeping unchanged all other parameters (such as speed, area ratio, thickness, etc.). This development takes advantage of the potential of CFD tools to better understand of the flow over the blades and slightly modify their design, achieving improvements starting from 5%.
- Adapting the propeller to the real operating conditions, reducing design power or reduction of ICE Class. If an energy audit process has determined that the propulsion plant is oversized, you can improve performance by redesigning a new propeller for a lower engine power (and speed maybe). In the case of a ship with an ICE class propeller, but not sailing in these areas, we can act on the blade design reducing the thickness of the profiles, thus improving their characteristics. The owner can keep the original propeller as a spare one and for future changes in the ship's operating zone.
- Adjusting the cavitation margins. The extensive use of advanced hydrodynamic simulation tools allows us to optimize cavitation margins for a given design, adjusting the geometry of the blade.
- Setting the optimum rpm and diameter. This change usually involves a great investment because it may involve the complete replacement of the drive train (or at least reduction gear and propeller shaft); however it can lead to a huge performance improvement, achieving an interesting ROI.

### *G. Devices in front of Propeller*

Some margin for energy recovery is kept in the flow before the propeller. Devices such as fins (that recover rotational energy and reduce pressure pulses), wake equalizing duct (duct preventing the separation of flow) or swirls, can lead up to a 10% improvement in certain cases.

Figure 7. Fins (Source: Daewoo shipbuilding)

### *H. Devices located in the propeller*

For certain vessels equipped with highly loaded propellers, adapting the propulsion by adding a nozzle is an alternative used successfully on multiple occasions. The use of nozzles does not need to be restricted to tugs and trawlers, but it is interesting to study for any ship with propeller operating at Kt/J2 values greater than 1. For installation, you must keep in mind that for optimal operation it is necessary to adjust the engine rpm (lower), and a redesign of the blades with a new load distribution. The design of the nozzle can be optimized for each application, allowing an additional performance; this optimization is done solely through the use of CFD tools and requires detailed modeling of the propeller working behind the ship.

Regarding paints, the use of coatings to reduce water friction on the blades of the propeller is a solution available in the market, using the same paints based on silicone or fluoropolymers available for the ship's hull. Although the surface of the propeller is very small compared to the wet surface of the ship, we must not forget the high linear velocities that occur on the surface of the blade, usually ranging between 20-40 m/s, hence the impact of this measure. Alternatively, we strongly recommend frequent polishing of the propeller blades as it produces an improvement in performance at a very low cost.

There are some alternatives such as cover plates located at the tip of the blades, like the Spanish patented propeller CLT, which in certain cases can produce a performance improvement.

*I. Devices located aft of propeller*

The propeller is perhaps the biggest source of losses, as consequence, most of the special devices for energy saving are designed thinking on the propeller. One goal is to increase the recovery energy ratio from the propeller losses and for this we can take advantage of the rudder, since it is located downstream of the propeller.

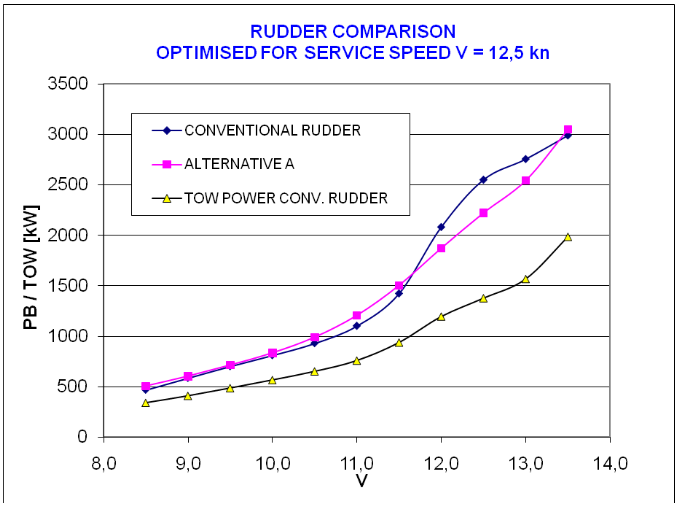


Figure 8. Power reduction on a multipurpose cargo vessel by using a tuned rudder designed by VICUSdt

The rudder itself is a major energy recovery device, but the amount of energy recovered can be improved. A good solution is to twist the rudder blade so it acts like a stator, recovering the rotational energy on the water flow leaving the propeller. Aft appendages are normally added to the rudder blade, among others we can mention the “Costa bulb” and the "Additional thrust fins" of Ishikawajima Heavy Industries. The Grim vane wheel can be installed on the propeller shaft or on the rudder and is shown in figure 7. These modifications are intended to get an increase in propulsive efficiency and recover some of the propeller losses (wake fraction increase, vortex reduction, etc.).

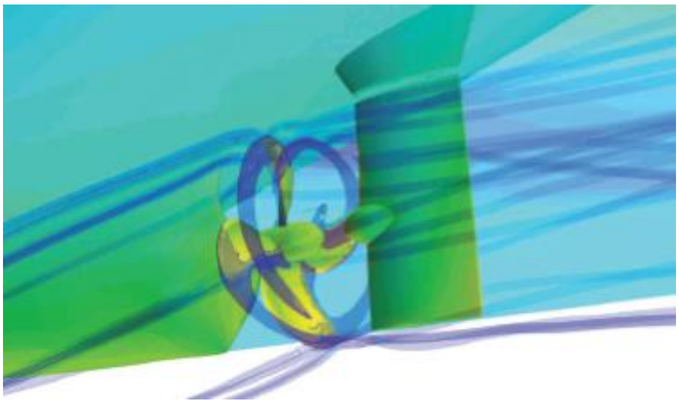

Figure 9. Rudder propeller interaction

Figure 10. Twisted rudder installed on ship. This simple aproach reduced fuel consumption by 4%

There exist many other alternatives and configurations of devices, but is impossible to list all of them since would need a whole book about *"propulsion improvement devices"*.

### *J. Stern wedge*

The ducktail is an extension of "virtual" vessel length, improving the resistance of wave formation. Interceptors and "trim wedges" are devices placed in the transom or aft part of the ship leading to a high pressure area, promoting trim change and thus reducing drag.

## V. OTHER PROJECTS.

On the website www.vicusdt.com, information on energy efficiency audits and how to improve energy efficiency in ships can be found. There are many projects and developments running at the same time, but the trends for ships are to look for hybrid drive trains, variable speed generators and using the thermal energy waste from diesel engines.

We will be glad to answer all your questions at info@vicusdt.com.

## ACKNOWLEDGMENT

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