A Framework for Energy Saving Device (ESD) Decision Making

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Introduction

For those making decisions regarding either new builds or vessel refits, there are a myriad of considerations. The economic case for energy/fuel saving is here to stay and will increasingly become a decisive competitive factor.
This paper aims to raise awareness of the issues around energy saving and, in particular, the hydro (wet) parts of the ship. Guidance is provided on gaining increased confidence about the usefulness of a given investment. All ships, cargos and trading patterns differ substantially and the particular circumstances should be central to decision making. No easy solutions exist!

Background

Work on ESDs began as far back as the first half of the 20th century, gaining momentum in the late seventies/early eighties due to the oil crisis.

Many types of devices were investigated, and almost as many were ultimately rejected – with the possible exception of propeller ducts. Understanding why so many devices failed can assist current decision-makers by providing focus on the relevant issues.

At least four technical aspects contributed to the vanishing ESDs:

- *Structural failure*. Unforeseen vibration caused excessive fatigue on many of the larger devices such as ducts, spoilers, Grim or vane wheels, leading to their failure. (Of course, the vibrations themselves were also a source of unpopularity.)
- *Lack of accuracy in full-scale measuring capability*. Historically, due to a lack of transparent and accurate measuring systems/procedures, the energy-saving potential of the devices could not be verified in ship trials. Without proof of their financial viability, the often large investments could not be justified.
- Lack of transparency of the savings in actual operational conditions. Ships hardly, if ever, sail in the ideal conditions assumed during ESD calculations. In reality, differences occur in actual speed, draft (trim), water depth and wind and wave conditions that were, historically, unknown.
- *Limited insight into the detailed working principles of the devices* and therefore a lack of ship-specific design capability. One has to understand the world prior to trying to improve it! This is particularly true for the complex flow around a ship, which increases in complexity where it counts most i.e. the interaction at the stern of the vessel between ship, device and propulsor.

Another important, albeit less scientific reason, is the lack of ownership accountability. The highly fragmented nature of the shipping industry means the ownership, use and operation of the ‘steel’ (ship) is split in such a way that fuel efficiency is a scattered responsibility item. This certainly also hampers the ambitions defined around us by the various governmental organizations and ultimately by the public.

The good news

In recent years the capabilities for visualization and, hence, interpretation of the physical forces affecting ship resistance have improved significantly. New tools, such as Computational Fluid Dynamics (CFD), which calculates the detailed flow around the ship, show quickly and easily the potential for resistance reduction and/or propulsive efficiency improvements.

At the same time, on-board measuring and monitoring systems now produce copious data regarding events at sea and ship performance, thereby contributing to knowledge about ships' operational profiles.
Operational profiles are an important parameter in decision making around ESD's. Recently, new procedures have been agreed, strictly describing tools and methods for performance measurement trials, in order to eliminate arbitrariness.
Finally, the technique of Finite Element Analysis combined with agreed acceptable cavitation in the propeller, allows improved calculation of strength and stiffness of the proposed devices.

The ideal world
The application of energy saving devices (ESDs) either recovers original design losses at retrofit or avoids them at new-build.

The main losses are:

1. Generation of waves at the 'pressure peaks' along the hull, typically around the bow, fore and aft shoulders and stern.
2. Generation of flow (lost kinetic energy) due to the friction of the hull and propeller.
3. Propulsion losses due to the propeller, and generation of flowing water (lost kinetic energy).

Ad. 1. The design of bulbous bows with the further tuning of other pressure peaks by changes in the shoulder positions typically form part of the overall hull form design. The high-energy transverse waves generated at the stern are more difficult to flatten out (no 'ship' left to reduce them). It is here that some solutions focus, by reducing the sharp pressure changes in that area.

Ad. 2. Many measures aim at avoiding friction through lubrication, either by air or special paints or other hull/surface treatments.

The second category of measures uses the generated flow behind the ship to regain some of the kinetic energy, either directly or indirectly, through improvement of the pressure field and/or flow field (wake) behind the ship. The latter then will improve the efficiency of the propeller (see next item).

Ad. 3. The propeller is the most complicated 'device' in the ship system. The maximum efficiency of the propeller has physical limitations given its working principle. Devices can 'condition' the inflow into the propeller and so enhance the working of the propeller itself. Others directly improve the efficiency or extend the optimum into a wider working range. The plane devices (pre- or post-swirl stators) are put behind or in front of the propeller to recover/balance some of the generated rotational flow.

The ideal hull form, which won't transport a lot of cargo, would to a certain degree avoid the above losses. But vessel designs are compromises. Full ships (with high block coefficient) carry more cargo but create high resistance and likely bad propulsion characteristics. Transom immersion is often needed for sufficient (course) stability but can significantly increase resistance. In general it can be said that the 'better' the design, the fewer retrofits are needed to 'repair' some of the compromise design solutions. It also explains why no definite gains can be claimed but only ranges (see also in this guide) as they can differ substantially (including non-performance) from ship to ship.

The ideal ship would run on a fixed trade, so the designer would know the exact operational profile in terms of ship speed, vessel draft and operational circumstances. This would enable a point design matching these conditions. In real life, this data can be diverse and difficult to distill into a clear profile for use in the initial design process and for retrofit choices. In certain cases retrofits could be prohibited because of specific operations: for instance in ice or in frequent extreme sea states.

How to approach …..
In the retrofit selection process no easy solutions exist. First of all many devices, notwithstanding their success, still await a detailed physical explanation, which is needed to adjust them effectively for each specific vessel design and related operational profile. Almost no ready-to-use ESDs exist and if they do, they will bring you lower or uncertain returns. Most suppliers realize this and offer as part of the deal a serious design program including calculations and model testing where appropriate; this is probably the case for every appendage-type device.

Below a typical approach is suggested for the selection and verification of ESD options:

- Select retrofit using data indicated by the owner/supplier;
- Optimize by applying CFD & check viability;
- Model test to validate;
- Trial to confirm.

Select retrofit using data indicated by the owner/supplier

The first assessment is important to avoid disappointments at a later stage. The first assessment takes as a starting point:

- the type and details of the hull form,
- the ship speed(s),
- the variations in draft/trim and
- the relevant operational circumstances.

In the case of an evolving design, the normal vessel type and more specific design aspects are taken into account. Thereafter the first principles governing the working of the devices are used to assess the feasibility of the total solution. Often questions about the redesign of local hull form, the propeller and/or other appendages can then come into discussion.

As many effects are involved and the flow (for instance at the aft ship) is very complex, an assessment does not necessarily provide final answers, but can rule out obvious non-performers for that particular ship or operation.

Optimize by applying CFD & check viability

The reason for applying CFD and using its much improved capability to its full extent is threefold:

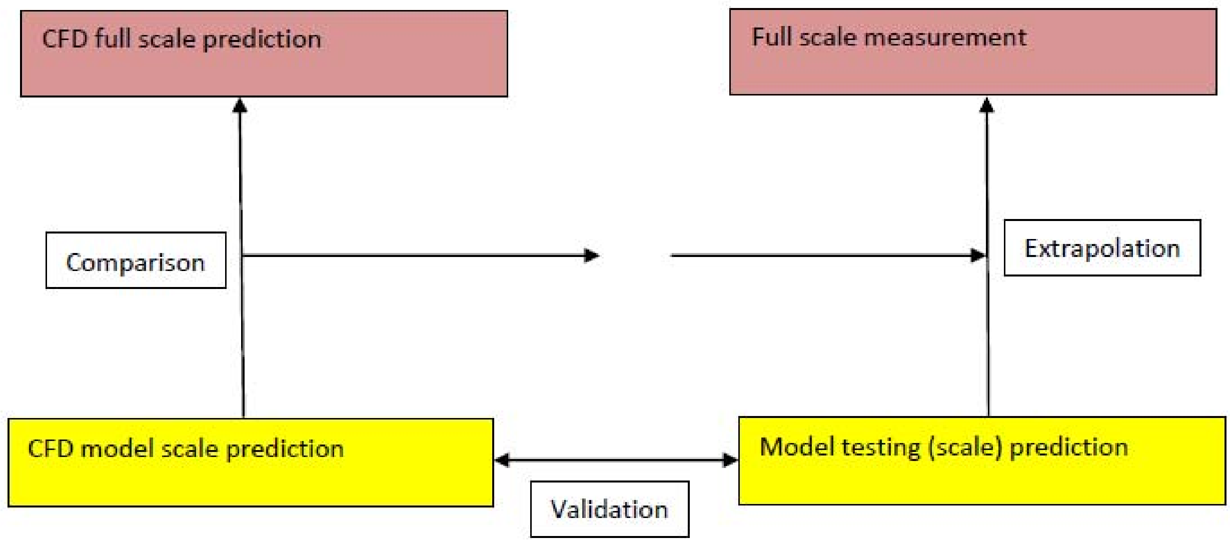
- Getting confidence in the proposed ESD as a real energy saver.
- Tuning the design of the ESD (and eventually its surroundings, including the propeller) for the particular ship and its operation.
- Preparing for the interpretation of the efficiency gain predictions derived from model tests.

Typical outcomes refer to the dimensioning and positioning of the devices based on calculated local flow and even to the orientation and form of the lift-generating profiles on struts, stators, rudders, ducts, spoilers, wedges, etc. CFD can also offer detailed insights into the resulting flow around the propeller, which can be used for the redesign of the propeller itself. Of course, the outcome could also be to rule out the device altogether.

The use of CFD to assist model testing is a more sophisticated application. As discussed in the next section, model testing is a sensible thing to do if initial results are positive. However, model testing also shows it weakness here, due to scale effects. Most devices operate around the stern of the ship, where the scale effects of model testing are most pronounced. In some examples, savings predicted by a small model can be only half of those revealed by a large model, and only a third of those achieved in full-scale sea trials. But beware, these figures can be the other way round! Exactly this fact explains the confusion in the late seventies in the application of ESDs.

Powerful CFD solves this problem. CFD offers the capability to compare model-scale results with full-scale results by making calculations for both cases. The comparison then gives ample support for extrapolations from model test predictions to trial conditions (see diagram below). This feature is extremely important in avoiding misinterpretation and over-optimistic (or pessimistic) predictions. The two calculations can also highlight whether flow separation occurs, which is devastating in real life as well as for the reliability of model test results in extrapolations.

In short, retrofitting relatively small devices around the stern of the ship is greatly enhanced by CFD model-scale and full-scale calculations. This is even more true if model testing experience with the devices is lacking.



These CFD calculations are relevant for all geometrical devices. Savings options concerning detailed lubrication aspects, which often focus on boundary layer flow, are currently beyond commercial CFD application. In configuration studies for air lubrications systems, however, CFD could be relevant.

Model test to validate
To date, model testing in combination with the CFD calculation proposed above is the most reliable way to assess the expected return on investment. The main reason for model testing is simply to prove that the device is doing what it should do, and to make the savings quantitatively available. Such testing can easily fit with the normal model testing process and in some cases can add to detailing of the propeller characteristics and the device itself.

In essence, even if both CFD and model testing don't give the final answer, together they come close.

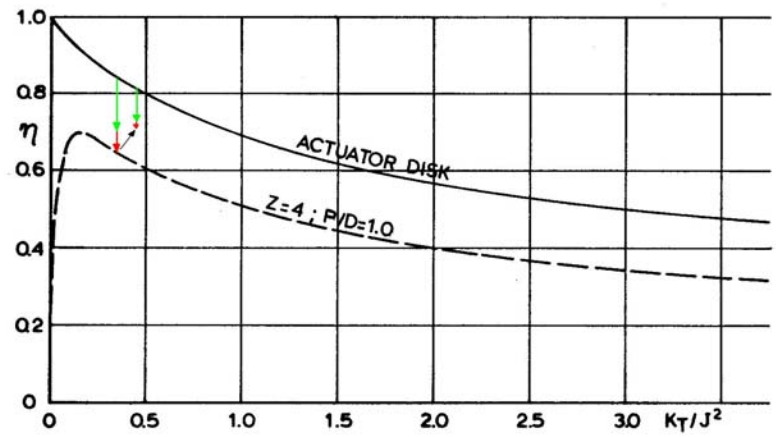
Trial to confirm
The performance of an accurate, standardized full-scale trial is of course extremely useful. The ideal would to be to compare the clean ship with and without the device but this is usually impractical in real life – although in 2011 MARIN launched the REFIT2SAVE project, which aims at this unique possibility for some devices. The next best and more feasible option is a comparison between sister ships, both cleaned before trial. Last and maybe least is a trial on the ship alone, with data compared to predictions which are themselves related to statistical references of similar ships.

Propulsion improvement
As seen above renewed interest is seen in fitting fuel saving devices (regularly called energy saving devices or ESDs) both in newbuildings and in existing ships to improve the propulsive efficiency.

The propulsive efficiency η_D is the ratio between the effective power (the power required to pull the ship forward by a tow rope) and the power absorbed by the propulsor. The propulsive efficiency η_D is divided into the propeller efficiency, η_p, and the hull efficiency η_H, with η_H= (1-t) / (1-w). The propeller efficiency η_p is divided into a propeller open-water efficiency η_{po} and the "*relative-rotative efficiency*", η_R. Indices "o" refer to open-water conditions in uniform flow.

$$\frac{P_E}{P_D} = \eta_D = \underbrace{\frac{J K_{To}}{2 \pi K_{Qo}}}_{(\eta_{po})} \underbrace{\frac{K_{Q_o} K_T}{K_Q K_{T_o}}}_{(\eta_R)} \underbrace{\frac{1-t}{1-w}}_{(\eta_H)}$$

The relative-rotative efficiency is by its definition the change of the propeller efficiency when going from open-water to the behind-ship condition. In the case of pronounced radial wake distributions (found in high block ships), the relative-rotative efficiency expresses to which extent the distribution of the radial load of the propeller blades has been properly matched to the radial wake distribution (wake-adapted). The η_R is also affected by the shape and size of the hub. For small hubs of usual shape the thrust produced by the propeller blades is about equal to the thrust transferred to the ship by the propeller shaft. For thick hubs the blade thrust depart.
Improvement of the propulsion by means of ESD's is either be a matter of the improving the performance of the propulsor itself, or of the hull-propulsor interaction, or both. This makes the design and optimisation of ESD's quite complicated. From the point of the propulsor consisting of a propeller and an ESD it remains a good approach to compare the propulsor efficiency with the actuator disc efficiency, the ideal efficiency η_i



Propeller efficiency in relation to efficiency of an actuator disc (illustration only)

From basic actuator disk theory it can be easily learned that for an ideal propeller, without any energy losses, the highest (ideal) efficiency is achieved for the lowest possible thrust loading. In reality it is known that the efficiency of well-designed single propellers is about 0.155 to 0.175 below the ideal efficiency (indicated by the dashed line). This difference is composed of the well-known list of energy losses such as rotational and viscous flow losses, non-optimum radial loading distribution and finite number of propeller blades.
ESDs can influence these energy losses and their relative importance in the design of the propulsor system. For instance if a device is able to reduce the rotational losses (red contribution in the above figure) this energy loss component becomes less important in the optimization of the propeller-ESD combination and therefore the optimization will concentrate more on minimizing the viscous flow losses (green contribution in the figure). This explains why the optimum diameter of contra-rotating propeller systems is smaller than that of their single propeller equivalent. Therefore, although the thrust loading (KT/J2) will increase and ideal efficiency reduce, still very substantial efficiency gains are possible.
Of course ESDs bring additional resistance (effective power) penalties and can influence the interaction with the hull. But in a comparison with the ideal efficiency it can often be made clear what a particular ESD design aims for.

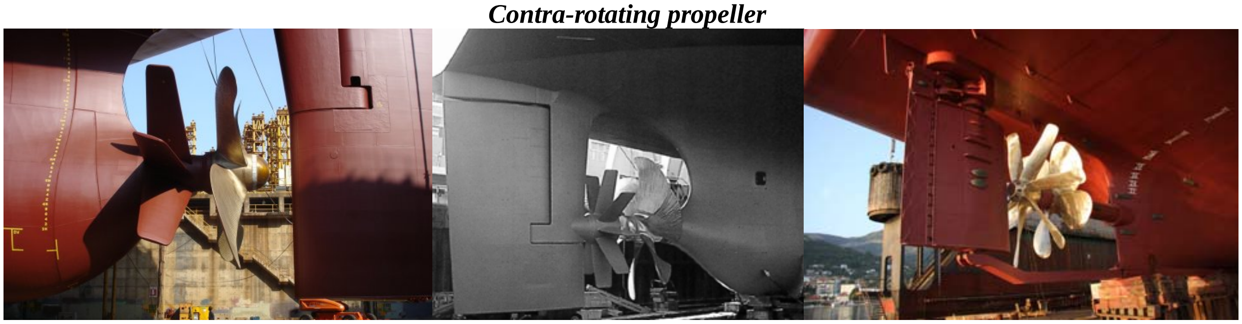
Underwater noise
Besides saving fuel, ESDs can also fulfill an interesting role as noise reducing devices. By influencing the flow into the propeller, ESDs can likely be designed such that load variations of the propeller blades are reduced. The related reductions of angle attack variations provide increased opportunities to reduce cavitation and related underwater noise. In particular it is thought that pre-swirl stators can be used to generate 'engineered' inflow fields for ship propellers.

Practical application
Swirl generating devices
Contra-rotating propellers and pre- and post-swirl stators (rudder fins included) all aim at recovering rotational energy losses. Besides swirl recovery, however, the optimum dimensions of these propulsion systems are smaller than that of a single propeller leading to lower propeller tip velocities and an additional reduction of viscous energy

losses. For each propulsion concept the many details and limitations of ship and engines will ultimately determine their potential. Studies have indicated that pre-swirl stators can provide efficiency gains in the order of 5 per cent both for single-screw as well as twin-screw vessels. Contra-rotating propellers can attain savings in the range of 10 to 15 per cent when the rate of revolution can be lowered significantly.

A special case is the Grim vane wheel. This device is composed of an inner part that operates as a turbine extracting energy from propeller slipstream and using this energy to power the outer part of the device that acts as a slow turning large diameter propeller. Instead of the contra-rotating propeller the thrust loading of the system is reduced and the ideal efficiency is increased when compared to the equivalent single propeller.

Contra-rotating propeller

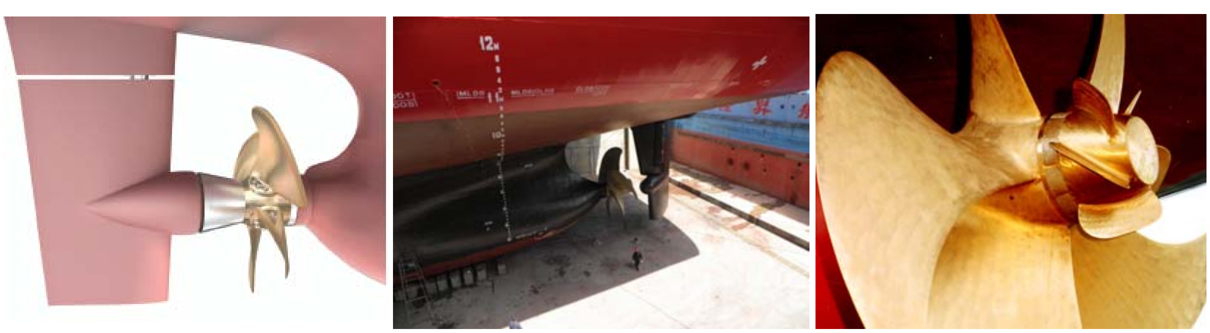


Pre- and post-swirl devices

Propeller hub devices

Energy saving devices mounted on or behind the propeller hub aim at recovering rotational energy leaving the propeller at the inner radial blade sections and possibly by reducing the pressure drag of the hub. For the first mechanism to work, the propeller must indeed produce these rotational energy losses. Because these losses are usually minimized by optimization of the radial loading distribution of the propeller blades the potential for recovery is not obvious. The second mechanism would work best for a large propeller hub in combination with a strong hub vortex.

Regarding area of application one should look for ‘compromise’ propellers with high tip unloading due to vibration and noise requirements and controllable pitch propellers with relatively large hubs.



Nozzles

With the Kort nozzle developed as early as the 1930's, nozzles are very well-known components of ship propulsion systems today. Propellers with nozzles outperform open propellers when the propeller suction is strong enough (thrust coefficient CT > 1.5 – 2.5) that the nozzle is starting to generate significant amounts of forward thrust exceeding its own added resistance. However, the proper integration of the nozzle with the hull is a major factor influencing the energy saving potential of propeller nozzles.

A different class of nozzles are the semi-circular pre-nozzles that are mounted upstream of the propeller. When the pre-nozzle is mounted in the close vicinity of the propeller the nozzle will perform in a similar way as a nozzle at the propeller plane. An additional benefit can be that the action of the nozzle concentrates the hull wake more towards the propeller disk, increasing the wake fraction and thus the hull efficiency. When mounted more closely to hull a pre-nozzle influences more directly the flow around the hull and can influence the viscous and even wave resistance of the hull. When fitted with guiding vanes the pre-nozzle can be designed to align the flow in axial direction or even generate pre-swirl to be absorbed by the propeller. Pre-nozzles are wrongfully called wake-equalizing ducts which is not what they do. They are also claimed to prevent flow separation, which is already unlikely for well designed hulls.

The above indicates that the working mechanisms of pre-ducts are complex and depend strongly on their design and mounting position. As a wake concentrator, pre-nozzles require a high wake to be effective, and thus these devices are found on high block vessels.