ISSUES WITH ENERGY SAVING DEVICES AND THE WAY FORWARD

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ABSTRACT

The introduction of regulatory requirements in the marine industry to limit ship emissions has been a major concern in recent years. This has motivated and directed research to improve the energy efficiency of a vessel. One particular area that has been given attention and developed in recent years is Energy Saving Devices (ESDs). These technologies are installed as a means to improve the hull-propeller interaction and maximize the propulsion efficiency of a vessel. This paper presents a review of the most typical energy saving technologies together with the different ESD measuring methods as well as their associated issues. It continues to explain the reason for finding different magnitudes of gains presented in the literatures for the same ESD. These contrasting benefits might raise concerns in their credibility and are a result of issues relating to the various methodologies carried out for the investigation. A standard procedure for ESD analyses that is briefly outlined in this paper, is currently being developed and will be proposed explicitly as an extension of this study. This can be then used as the bases for other technology investigations, making energy efficiency improvement comparisons more meaningful by taking the same approach.

Keywords: Energy Saving Devices (ESDs), Retrofitting Devices, Energy Efficiency and EEDI.

1. INTRODUCTION

With the introduction of recent marine regulations, industry focus has turned to the reduction of ship pollution and emissions, energy efficiency improvements and enhancement of safety requirements. The need for reducing carbon emissions and improving energy efficiency for environmental benefits are expected to have a strong influence on the design and operation of merchant ships. Knowing that ships are the most efficient mode of bulk transport, the International Maritime Organisation (IMO, 2009) carried out a study identifying the potential energy efficiency improvements that could be attained using technologies or operational methods. The Marine Environmental Protection Committee (MEPC) who are a specialised group of the IMO, have thus developed the Energy Efficiency Design Index (EEDI) (IMO MEPC, 2011) as a mandatory technical measure requirement to help control and lower ship Green House Gas (GHG) emissions. This is done by restricting the designed energy efficiency of ships before built by providing a calculation that predicts the carbon emissions compared to the transport work done by the ship (i.e. tonnes of cargo transported per nautical mile). This is generally verified by model tests and ship speed sea-trial tests by classification companies. The EEDI value requirements are assigned according to ship type and size. These regulations were enforced on 1st January 2013 and a phased implementation plan will see the restrictions become more stringent over the coming years. In view of voyage and operational efficiency for ships in service, an Energy Efficiency Operational Indicator (EEOI) (IMO MEPC, 2009) was introduced as a voluntary technical measure. Vessels complying with the legislations will be awarded with a new International Energy Efficiency Certificate (IEEC) that outlines particulars related to the ship's energy efficiency. Not surprisingly, the ambition to increase energy efficiency is shared with shipping companies seeking to reduce fuel costs and operational expenses.

Ship energy consumption depends on the performance of a ship system; one significant component being the ships' hydrodynamic system comprising of hull resistance, propulsion efficiency and hull-propeller interaction. For new buildings, an initial effective measure to minimise hull resistance is to choose suitable main dimensions that comply with construction and operational route constraints; such as the Panama Canal, Bayonne Bridge, ports and arctic areas. This is generally followed by hull form optimization that is performed to improve both resistance and propulsive efficiencies. These procedures are generally carried out for new builds since it is very hard to modify the main dimensions or the hull form of a vessel in service. This being said, some form of modifications can be carried out; a typical example would be the replacement of the bulbous bow based on the optimization of the operating profile (Kim and Park, 2015) together with the consideration of slow steaming (Banks et al., 2013) and in-service performance.

Meanwhile, Energy Saving Devices (ESDs), also known as 'retrofitting devices' focus on improving the propulsion and hull-propeller interaction efficiencies. They can be installed on optimised new hulls as well as existing vessels by means of refitting (Hansen et al., 2011). Recently a large amount of ESD research has been carried out experimentally and numerically. Studies (Kawamura, et al., 2012; Hansen, et al., 2011; Patience & Atlar, 1998; Schuiling, 2013) suggest that the installation of ESDs on a ship can result in a significant improvement in energy efficiency. As specified by Hooijmans et al. (2010), ESDs are designed to improve the flow around the hull, improve the wake/propeller inflow and can also be designed to recover energy leaving the ship system. Ongoing research focuses on maximising the energy efficiency potential of these devices through design improvements. With the increased availability of computational power and advances in numerical tools and modelling software, the use of optimisation procedures are becoming more and more popular to identify the energy efficiency saving potential of ESDs. Nevertheless, the availability and reliability of many ESDs that can be used to reduce the EEDI value and increase energy efficiency remains yet uncertain. There is a lack of confidence about their use within the industry because efficiency gains are small and extremely difficult to assess, not only by full-scale measurements but also by model tests.

This paper first introduces how ESDs affect the EEDI of a vessel. It then presents a literature review of the most commonly used devices highlighting their benefits and disadvantages. In addition, the various measuring ESD impact methods are outlined and their problematic issues indicated. The reason for finding different magnitudes of gains for the same ESD are then explained and an ESD analyses procedure is proposed to reduce the possibilities of such differences.

2. ENERGY EFFICIENCY DESIGN INDEX

2.1 EEDI EQUATION

The EEDI is a simple formula that estimates the carbon emission of a vessel per tonne mile. It is an index developed to allow for the preliminary assessment of a ship's performance at the design stage. Compliance is attained by comparing the attained EEDI of the vessel to corresponding baseline values that have been stated by the IMO. As can be seen in the EEDI equation (1) below, the numerator represents carbon emissions that also take into consideration innovative machinery and energy efficient technologies whilst the denominator denotes the transport work done.

$$\frac{\text{Main Engine Emissions} + \text{Aux Engine Emissions} + \text{Shaft \& Motor Emissions} - \text{Energy Efficient Technologies}}{f_i \ \text{Capacity} \ V_{ref} \ f_w} \tag{1}$$

f_i and f_w are correction factors that account for the capacity adjustment and the speed reduction due to weather conditions respectively. Capacity is the deadweight tonnage rating of a vessel and V_{ref} is the ship speed in the condition corresponding to the capacity in deep and calm water conditions with no wind and waves. The speed of the vessel in particular, has a significant impact on the EEDI and fuel consumption because the speed is exponentially related to the required propulsive power. Significant savings make it easy to understand why there is substantial interest in slow steaming, especially when fuel prices escalate. This being said, it should be noted that the ship speed varies according to the market demands and expectations and should be thus reconsidered regularly to reflect realistic ship operations since it has a direct impact on the EEDI. To help meet EEDI requirements and reduce the fuel oil consumption, the installation of ESDs can maximise design speed for a specific power or decrease the power required for the specific speed of vessels taking into account the general improvement of the total propulsive efficiency (η_D). A wide range of ESDs have been developed through the years with different features, types and working principles. Devices to improve propulsive efficiency can generally be classified into three different categories; Pre-swirl, Post-swirl and added features to the propeller. Various authors have reviewed ESDs in the past, (Blaurock, 1990), all outlining various improvements and gains achieved by the different technologies that seem quite promising. However, since ESDs tend to produce minor improvement, there is some doubt whether they can be achieved in operations. Therefore, the reliability and guarantee of energy savings for such devices remain an issue and continuous research should be carried out to support their reliability.

3. ENERGY SAVING DEVICES REVIEW

3.1 PRE-SWIRL DEVICES

Pre-swirl devices are energy saving devices installed upstream of the propeller. These are designed to improve the wake flow into the propeller plane in such a way that the inflow to the propeller is faster and more uniform or made to rotate in the opposite direction to that of the propeller imposing a better angle of attack on the propeller blades helping the flow leave the propeller plane with less circumferential momentum thus requiring less kinetic energy to produce forward thrust.

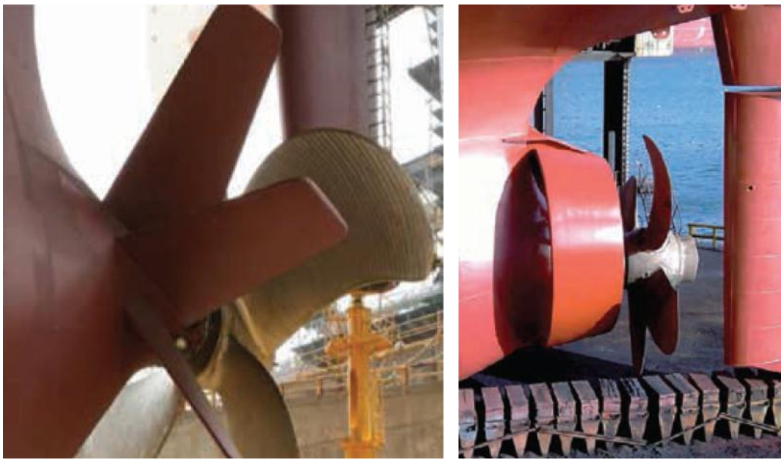

Figure 1: Pre-swirl stator (left) and Becker Mewis Duct (right) (ABS)

3.1 (a) Pre-Swirl Stator

A vessel with a single propeller suffers from significant rotational losses in the slip stream. The function of a pre-swirl stator (Figure 1) is to recover that energy by reducing the rotational losses incurred by the propeller. In general, this ESD consists of four stator blades that are mounted on the stern boss ahead of the propeller in order to re-direct the flow. It generates a swirling flow in the direction opposite to that of the rotating propeller increasing the load through which the delivered thrust per unit of power is increased. Due to the uneven vertical distribution of the wake on either side of the vessel, the number of fins and their orientation are not always symmetrical to port and starboard sides of the ship thus requiring a tailored design for each ship. A typical configuration generally involves three fins on the port side and one on the starboard side because reducing the upcoming flow on the port side requires more effort than trying to re-enforce the flow downward on the starboard. The technology itself increases resistance. However, it also improves the propulsion efficiency and hull-aft interaction. Therefore, systems should be designed in such a way that the gain in propulsion outweighs the added resistance to result in a positive gain. Such a technology can offer savings of up to 4.5% (Zondervan, et al., 2011) and is adequate for ships with heavy loaded propellers where no flow acceleration is required but only the re-direction of the flow. These devices can be considered to be simple, robust and cost effective. It can also be also be coupled with a duct to accelerate the flow into the propeller.

3.1 (b) Ducts

The Wake Equalizing Duct (WED) is made up of two aerofoil sectioned half ring designs that are integrated into the stern of the ship hull and are positioned in front of the upper region of the propeller. The stern hull form of a vessel generally results in slower flow velocity towards the top of the wake compared to the lower region. The WED is therefore designed to accelerate the flow at the top of the wake improving uniformity to increase propeller efficiency. The foil generates a lift that accelerates the flow and increases the thrust. It also helps reduce the flow separation at the aft end to minimise the thrust reduction factor. This being said, the duct itself creates additional resistance, therefore, the device needs to be optimised to generate a higher thrust than its drag resulting in a beneficial impact. Important design characteristics of the WED are duct angles, longitudinal positions, inner diameters, profile section shapes, lengths and angles of sections. The report (ABS) identifies that the propeller tip clearance and load, influence the duct efficiency. Accelerated and straightened flow into the rudder also improves steering qualities. In summary, this ESD reduces aft flow separation, generates additional thrust, reduces propeller vibrations and improves manoeuvrability. The Schneekluth duct was installed on over 1500 vessels and has been claimed to produce fuel savings of around 5% and reduce vibration by up to 50% (Lambos Maritime Services LTD, 2013). The Mewis Duct (Figure 1), developed by Becker Marine systems, consists of an integrated duct with fins configuration. It combines two working ESD principles; that of the contra-rotating propeller and of the wake equalizing duct to enhance the propeller inflow and reduce rotational losses. More than 20 Mewis ducts have been installed on different vessels with analyses estimating that the technology results in a mean power reduction of around 6.5% and also reduces vibration excitation and pressure pulses by up to 80% (Mewis & Guiard, 2011). It is most effective for ships that run at lower speeds generally under 20 knots and that have high block coefficients (Hollenbach & Reinholz, 2010).

3.2 UNCONVENTIONAL PROPELLERS

Not many unconventional propellers have been developed through the years. Other than skew and annular profile modification, propellers have been designed through very little innovative development. The most common are the tip propellers, namely Kappel, Contracted and Loaded Tip (CLT) and Contra-Rotating Propellers.

Figure 2: Kappel (left), CLT Propellers (centre) (Gennaro & Gonzalez-Adalid, 2012) and CRPP (right) (Kluijven, et al.)

3.2 (a) Contracted and Loaded Tip (CLT) Propeller

CLT propellers (Figure 2), which are most effective for slower speed vessels with a higher block coefficient, are installed with end plates at the blade tips located on the pressure side to reduce the tip vortices. The tips are therefore bent sharply towards the rudder. They are designed to enhance propeller open water efficiency by minimising the induced velocities at the propeller disk to reduce the hydrodynamic pitch angle. They have been extensively tested on full scale trials showing 5-8% better efficiency as well as cavitation reduction while also providing a higher thrust due to the smaller optimal propeller diameter (Gennaro & Gonzalez-Adalid, 2012).

3.2 (b) KAPPEL Propeller

The Kappel propeller was designed with a modified blade tip and developed to supress the tip vortex, generate lift and thrust to improve the overall efficiency. The tip (Figure 2) is located on the suction side of the propeller featuring a smooth transition between the blade and the tip. The gain in Efficiency is reported to be around 6% (Gennaro & Gonzalez-Adalid, 2012).

3.2 (c) Contra-Rotating Propeller (CRP)

CRPs come in two different configurations both of which work with the same principles. One arrangement, commonly known as the Coaxial Contra-Rotating Propeller (CCRP), involves two-contra rotating propellers on a single shaft that is mechanically complex. On the other hand, the Contra Rotating Propeller Pod (CRPP) is a regular conventional propeller with a pod propeller that rotates in the opposite directions just. A regular conventional propeller produces a rotational flow aft of the propeller. Other than just producing a forward thrust, the screw generates an undesirable sideway force due to the swirling flow more commonly known as the 'wheel effect' resulting in a loss of energy (Kluijven, et al.). The CRP is therefore used to neutralise this rotation minimising the sideway force to reduce the energy leaving the hydrodynamic system of the ship causing a higher forward thrust. The CCRP (Figure 2) can reduce cavitation and torque to improve the propulsion efficiency. A study (Rutundi, 1934) comparing CRP with a conventional propeller for a 3500 ton naval training ship claims an 18% improvement in the propulsive performance even though mechanical shaft issues were raised when applied to larger merchant vessels due to the associated higher power (Ghassemi, 2009). IHI has developed a contra-rotating propeller system for large ships and installed it on a 37,000 DWT vessel. Sea trials indicated a 15% power improvement together with less cavitation and noise (Nishiyama & Sakamoto, 1990). CRPP has drawn attention in recent years due to its beneficial impact, hydrodynamic performance and significant savings. One study (Kluijven, et al.) indicated that the CRPP resulted in 8% less fuel consumption. In addition, the POD is able to rotate by 360 degrees improving vessel manoeuvrability.

3.2 POST-SWIRL DEVICES

Post swirl devices are generally installed downstream of the screw and are used to condition the flow aft of the propeller. They can be designed to recover the rotational flow and use that energy to enhance axial flow. They can also reduce or divert the flow in order to improve rudder efficiency. They are particularly suitable for cases where energy losses in the slipstream are expected to be significant i.e. applications with medium to high propeller loads.

Figure 3: PBCF (left) (Hansen et al., 2011), Asymmetric Rudder (centre) and Rudder Bulb (right) (Becker Marine Systems)

3.2 (a) Grim Vane Wheel

The Grim Vane wheel is a freely rotating device located behind the propeller, consisting of a number of blades that are larger than the propeller. The inner radii of the vane wheel blades are designed with a pitch such that they act as an impeller and are driven by the wake of the propeller. The extended tips of the blades are designed with a different pitch such that they act as a propeller on rotation thus producing additional thrust. This energy saving device is therefore designed to recover energy from the propeller slipstream and convert it to additional thrust. Ghose and Ghose (2004) have outlined that the vane wheel should be designed with a 25% increase in diameter and have a higher number of blades than the front propeller. They add that the tip clearance to the hull need not be high since the technology is lightly loaded and that it should rotate at an rpm of 30-50% of the propeller in the same direction. It has been claimed that this ESD provides additional thrust and reduces propeller loading to enhance propeller performance by around 5 – 10% (DNV GL, 2015). The reduced propeller load results in smaller propeller diameter requirements and reduced cavitation thus improving the propeller efficiency. Although a few studies focusing on Grim Vane wheels have been carried out in the past, (Kehr, 1986) and (Blaurock, 1983), this technology was not given the attention it deserves because of its failure during sea trials when installed on the QE2 cruise ship (Chen, et al., 1989) giving off a bad first impression that lasted years.

3.2 (b) Stator Fins

These are fins installed aft of the propeller designed to produce an additional thrust and recover rotational energy. They deflect the flow from the propeller and convert the rotational energy to useful axial flow. They tend to be most effective when mounted on the rudder imposing a horizontal rotation resulting in around 5-8% energy gains (Celik & Guner, 2007). Compared to the pre-swirl stator, the post stator is relatively moderate in size (less than 80% of the propeller diameter) and does not have any effect on propeller cavitation (Hollenbach & Reinholz, 2010).

3.2 (c) Propeller Boss Cap Fins (PBCF)

The PBCF (Figure 3) are post–swirl fins that are installed onto the boss cap of the propeller. As water passes through the propeller disc area, it is accelerated and twisted. These effects are prominently dominant near the down-flow just after a blade's trailing edge. The vortices produced at the root of each blade combine together resulting in a very strong vortex at the end of the boss cap. This phenomenon is known as hub vortex which reduces the propeller efficiency and may cause rudder corrosion. As explained by Ghassemi (2012), the strength of such phenomena is dependent on the hub geometry as well as the axial load distribution of the propeller. The aim of installing a PBCF is to minimise this hub vortex to reduce rudder cavitation and increase propeller efficiency. With the addition of a PBCF, the rotating fluid flow coming off the propeller hub is rectified, and thus the energy lost from the hub vortex is recovered. Gearhart and McBride (1989) performed a detailed experimental analysis of a PBCF retrofitted model propeller behind a hull including a rudder. The report concluded that out of the total 6% gain in efficiency, 2% was due to a thrust increase, and 4% was due to a decrease in torque. The total gain in efficiency may also be reduced due to the additional frictional drag from the fins. Nojiri et al. (2012), Hansen et al. (2011) and Atlar et al. (1998) all come to the common agreement about the beneficial effects of PBCF technology resulting in a reduction in shaft power and subsequent increase in fuel efficiency.

3.2 (d) Hub Vortex Vane (HVV)

The HVV was jointly developed by SVA Potsdam and Schottel. The HVV is a small vane propeller fixed to the tip of a cone shaped boss cap. The vane's diameter is limited to where the tangential velocities due to the hub vortex are greater than those due to the propeller. The small vane propeller diverts the high tangential velocities in the direction of the jet to generate additional thrust. Another effect of the HVV is the diverting torque of the vortex assisting engine torque, meaning drive power savings. A detailed report by Schulze (1995) claims an increase in propeller efficiency of 3% on full-scale trails.

3.2 (e) Asymmetric Rudder

Asymmetric rudders have been used to avoid rudder cavitation such as erosion and gap cavitation. In contrast to the conventional blades, they are designed to reduce low pressure peaks on the rudder blades. Asymmetric rudders (Figure 3) have aerofoil profiles with separate portions of the rudder above and below the propeller axis optimised to work in the wake of the propeller. Therefore, they generally feature a twisted leading edge, sometime merging in a Costa bulb and stators just behind the propeller hub. These types of rudders also take advantage of the rotational flow behind the propeller but this effect is normally used to improve the rudder efficiency rather than create significant additional thrust. A study (Khorasanchi, et al., 2013) indicated 1.25% power savings using numerical simulations.

3.2 (f) Rudder Bulb

The rudder bulb (Figure 3) is a streamlined bulb that is attached to the leading edge of the rudder. The transition between the bulb and the propeller hub can also be bridged by a fairing cap. The rudder bulb attempts to condition the radial distribution of the flow behind the propeller plane at the hub, to reduce losses associated with high rotation and to minimise the generation of a strong hub vortex. The Costa bulb can accelerate the flow past the rudder to improve rudder efficiency. If a Costa bulb is mounted on the rudder rather than its horn, it is important to take into account the effect of rudder rotation on its efficiency and its interaction with the propeller.

4. METHODS TO MEASURE ESD IMPACT

Although, optimally designed installed ESDs have showed contribution to the reduction of resistance and improved propulsion efficiency, some aspects of uncertainties such as scale effects and discrepancies between analysis methodologies raises concerns and lack of credibility. In this section, the methodologies used to measure the gains of ESDs are presented with the investigation and comparison of their characteristics.

4.1 MODEL TESTS

Usually ship hydrodynamics and performance have been tested, analysed and confirmed by experimental fluid dynamics (EFD, model test) such as resistance and propulsion test, propeller open water, cavitation and noise/vibration test, flow line test, and wake, local and global measurement tests. The basic idea of model test is to experiment with a smaller model ship with geometrical similarity to extract information which can be scaled to a real ship. Although hull performance has been successfully estimated over the years, full-scale predictions based on model test data tend to result in slight discrepancies when compared to sea trial results. These extrapolation methods are based on the ITTC performance prediction method and correlation factors. Issues with model tests are that they are unable to satisfy both dynamic similarities of Froude number (Fn) and Reynolds number (Rn) with the prior being related to the ratio between inertia and gravity and the other related to the ratio between inertia and viscous forces. As shown in equations (2) and (3), the model speeds required to achieve equivalent Rn are too high.

$$\frac{Inertia\ force}{Gravity\ force} \propto \frac{\rho U^2 L^2}{\rho g L^3} = \frac{U^2}{gL}\ ,\ Fn = \frac{U_M}{\sqrt{gL_M}} = \frac{U_F}{\sqrt{gL_F}}\ ,\ U_M = \frac{U_F}{\sqrt{\lambda}} \tag{2}$$

$$\frac{Inertia\ force}{Viscous\ force} \propto \frac{\rho U^2 L^2}{\mu UL} = \frac{\rho UL}{\mu}\ ,\ Rn = \frac{\rho_M U_M L_M}{\mu_M} = \frac{\rho_F U_F L_F}{\mu_F}\ ,\ U_M = U_F \lambda \tag{3}$$

In practice, model speeds according to Fn are applied, which are able to model wave resistance phenomena correctly. For example, for a 7,500TEU container with length between perpendiculars (Lpp) of 286m, at 22 kts, Fn is about 0.214 for both model and full-scale ship, whilst Rn are 9.563×10^6 and 2.712×10^9 respectively, which means that Rn is considerably higher for the ship than it is for the model.

Generally, ESDs make scaling more difficult because they are operated largely or wholly within the full-scale boundary layer and are strongly affected by viscous effects such as differences in boundary layers, flow separation and vortex formation. The ITTC 1978 performance prediction method is proved to work properly for hulls without appendages, unconventional propulsors and ESDs. Therefore, the ITTC 1999 method was proposed to consider ESDs with the availability of computing power and advances in numerical simulation, particularly computational fluid dynamics (CFD). The principal concept of the ITTC 1999 method is that the ratio for the wake fraction of the model to the full-scale ship without ESDs must be the same as that with ESDs as can be seen in equation (4).

$$\frac{1-w_{w/o\ ESD,\ full\ scale}}{1-w_{w/o\ ESD,\ model\ scale}} = \frac{1-w_{w/\ ESD,\ full\ scale}}{1-w_{w/\ ESD,\ model\ scale}} \tag{4}$$

To apply this method for cases with or without ESDs, model tests or computations for the model-scale ship and numerical simulations for the full-scale ship have to be carried out. This does not exclude the fact that further studies and developments of model tests and analysis methods are needed to measure the exact impact of ESDs both at model and full scale scenarios. Park et al. (2015) proposed a propulsive performance prediction method for full-scale ships with ESDs compared with those by the existing extension methods (ITTC 1978 and ITTC 1999) and by full-scale CFD computations predicting the performance of KVLCC2 with a pre-swirl stator.

4.2 SEA TRIALS

After the design and construction of vessels, the official sea trial is conducted to confirm ship performance. Sometimes, full-scale operation trial is performed in service by request of ship owners. Once the sea trial is carried out, the results, that are in terms of ship speed, power and propeller shaft speed, are corrected to the calm (no wind and no wave) sea condition according to the guidelines such as ISO 15016 (ISO 15015:2015) to verify the satisfactory attainment of a ship speed stipulated by EEDI regulations and/or contract. Sea trials should be carried out in ideal calm water conditions as far as practically possible allowing proper measurements and also noting the current, tide and drift experienced throughout the test.

The impact on efficiencies and fuel oil consumption (FOC) due to ESDs fitted to real ships can be analysed and evaluated from the available data sets of sea trials and ships in service. The first approach is the official sea trial. However, unless the official sea trial is conducted repeatedly before and after fitting the ESDs, the impact can only be confirmed by comparing sea trial results of a vessel installed with ESDs with model test results with or without ESDs. Another approach would be to carry out the full-scale trial in an actual voyage of ship service, which is conceptually simple and direct avoiding any scale effect issues such as wake fraction and flow separation. This can be performed with close support of engineering staff to evaluate the efficiency improvement of ESDs although there would be the considerable cost of ship off-hire and the difficulty of measuring and verifying small improvements. Also, it is extremely difficult to separate and identify the effect of ESDs on fuel consumption from other factors like speed, draft, trim, sea condition, wind, tide or current, etc. Hansen et al. (2011) conducted full-scale trials on an Aframax tanker with and without Propeller Boss Cap Fins (PBCF) which are considered to be suitable retrofitting devices for existing ships. The technology was fitted on the vessel afloat in the Mediterranean Sea with good weather conditions without the need of dry dock installation. A reduction in shaft power and fuel efficiency was confirmed.

4.3 CFD

Traditionally, potential flow theory has been used with panel methods to predict ship performance and is still considered a popular method for research areas focusing on seakeeping, global wave load and propeller design. This is because potential codes are easy, robust and well developed requiring less computational time. These methods assume the flow is inviscid and non-rotational, neglecting any frictional forces and turbulent flows. However, thanks to the rapid development of CFD that is now capable of simulating viscous flows, the working principles and scale effects of ESDs are becoming clearer than before (Çelik, 2007 and Heinke et al., 2011). Dang et al. (2011) investigated three ESDs, the pre-duct with a supporting stator, the pre-swirl stator and PBCF by means of CFD simulations and self-propulsion model test including local flow measurements using Particle Image Velocimetry (PIV) techniques. They calculated the nominal wake at the propeller plane as shown in (Figure 4) which clearly indicates that the full scale wake significantly differs from the model scale prediction because of the scale effects.

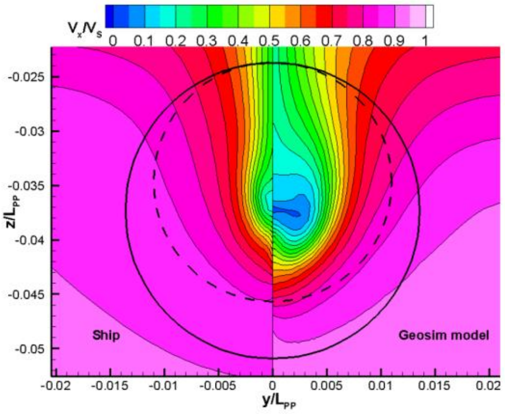

Figure 4: Comparison of calculated nominal wake field for model-scale and full-scale (Dang et al., 2011)

Therefore, CFD simulations and ESDs studies should be performed at full-scale because of the uncertainties associated with extrapolation of viscous flows from model to full scale. In addition, CFD provides guidance on ESD designs so that their performance can be optimized even for full-scale conditions and flow separation.

5. ISSUES WITH ESDS

In this section, issues with ESDs are identified and discussed to measure and estimate their impact and efficiency. Firstly, scale effects issues are of concern since the Reynolds number is considerably higher for the ship than it is for the model. Some researches (Hansen et al., 2011 and Kawamura et al., 2012) have shown that ESDs are more efficient at full-scale than those determined from model tests. The main scale effects are as below:

- The boundary layer is relatively thinner in full-scale flows than in model test conditions. The wake fraction is therefore larger in model tests than in full scale. ESDs within the boundary layer result in different behaviour between both scales.
- Flow separation is generally delayed in full scale and vortices encounter higher damping. Thus, ship wakes in the propeller plane are significantly changed. Vortices from bilge or struts are much weaker sometimes vanishing in full-scale simulations.

Secondly, when installing a combination of ESDs, for example, a pre-swirl device with a post-swirl device, it should be noted that the total energy efficiency is not cumulative. This is because some ESDs affect the flow regimes of others and can reduce the total effectiveness. The efficiency of one ESD cannot be easily subtracted or added from the total efficiency. However, various ESDs are compatible with each other and can be considered and used to obtain a higher benefit.

Thirdly, it is important to consider the beneficial or detrimental side effect that ESDs can have. These effects should be studied and investigated by model tests and numerical simulations at the design stage to avoid any unwanted deleterious effects, such as the reduction of manoeuvring capability, or in turn improve and enhance favourable criteria such as the limitation of cavitation and vibration problems. For example, a full-spade asymmetry rudder could deteriorate seakeeping capabilities. ESDs should be therefore optimised based on the wake field to improve the propeller efficiency but also limit any cavitation, noise and vibration.

Finally, ESD gains are small and extremely difficult to evaluate not only by model tests but also during sea trial measurements. Improper extrapolation of model tests due to scaling issues together with the correction factors associated with sea trial testing and the disconcertingly great natural variation between the performances of sister ships result in an uncertainty of establishing proper gain figures. With regards to numerical simulations, CFD methods have their own assumptions and simplifications that can produce significant differences in the results and thus verification and validation procedures are required in order to justify the accuracy of the method and gains achieved. This being said, with progress in computing power and parallel computing technology full-scale CFD simulations may reduce the present uncertainty of ESD savings.

6. THE WAY FORWARD

Savings claimed and predicted by ESD developers and manufacturers are very promising yet the gains achieved from some of the technologies would not be as promising as those published in the literature. In this section, ways to maximize ESDs efficiencies and improve analysis methods will be discussed.

Initially, at the design stage, the ship main dimensions are selected and the hull form is optimized based on calm water as well as operating conditions by applying the design spiral focusing on maximizing economic and fuel efficiencies for given requirements. Regarding propeller design, the number of propeller blades, revolutions per minute (RPM) and propeller diameter are investigated to improve the propulsive efficiency (Hooijmans et al., 2010) whilst also considering propeller clearance, cavitation, vibration and best engine performance. After these basic design procedures, ESDs would be selected to improve ship efficiencies further.

Before investigating and designing ESDs, resistance and propulsion power components and ratios have to be considered also understanding the physical phenomenon and reasons for efficiency losses depending on ship type and size. Figure 5 indicates resistance components ratios for tankers and containers. It can be clearly seen that the wavemaking and air resistance are more prominent for containerships having a larger portion of the total resistance. Therefore, it would be more efficient if ESDs are investigated and designed to target components of resistance and propulsion power.

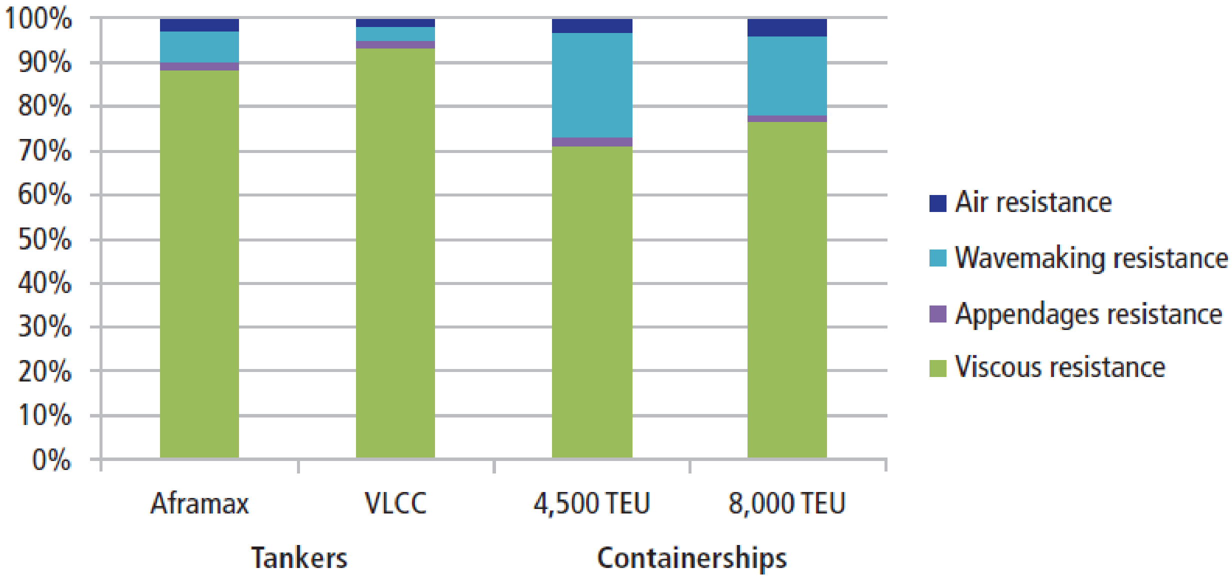

Figure 5: Components of hull resistance in calm water conditions at design speed (ABS)

Rapid advancements in the development of EFD and CFD provide the necessary tools for realisation of simulations for design of ESDs. However, calibration and validation with international collaboration between institutes for model validation data (Larsson, et al., 2003) are also required for model tests and CFD simulations with regard to status and future uses and requirements. Model test analysis methods will have to be reconsidered regularly to evaluate the ship performance with ESDs considering viscous scale effects, extrapolation and in some cases, if possible, feedback from official sea trials, full-scale trials or operations in service.

All methodologies to assess the impact of ESDs are interrelated and complementary to each other. Firstly, in the absence of model tests, CFD would have not been developed quantitatively even though there still are some minor differences in the results and some challenging problems such as complex breaking waves, fluid-structure interactions of wave impact, slamming and sloshing. Whenever possible, model tests for ESDs analysis are required for CFD validation and verification. If the CFD output shows good agreement with model test results, there would be no problem in continuing to simulate other cases by CFD and saving extra model tests costs. Secondly, with the help of CFD, once the model simulations are verified and validated, more accurate full-scale performance could be predicted avoiding any associated scaling issues. Data sets or information from sea trials have also proven useful in developing correlation factors to extrapolate model test data to estimate resistance and propulsive coefficients at full scale. Sea trial analysis methods to estimate speed and power performance require further development to evaluate ESDs efficiencies more correctly and validate the impact of the energy efficient technologies in the EEDI formula. In addition to the official sea trial, real time data and automated data analysis with guidance on ship draught, speed, trim, fuel oil consumption and weather conditions are important to isolate and find the effect of ESDs efficiently and improve them further.

Therefore, the fruitful combination of these analysis tools; dedicated model tests, CFD and full-scale sea trial considering realistic ship operating conditions altogether offer a robust and reliable method to successfully apply fuel saving devices on merchant ships.

7. DISCUSSION CONCLUSIONS

In this paper, most commonly used ESDs have been reviewed outlining their principles and benefits. Other technologies not covered in this paper that are worth mentioning are grothues spoilers, ducted propellers and controllable pitch propellers. While carrying out the review for ESDs, differences in efficiency gains have been identified between various studies analysing the same ESD.

Numerous issues with some points to note for designing ESDs have been investigated with respect to the different procedures conducted by different studies. When investigating ESDs, researchers tend to analyse their efficiencies and benefits by means of model tests, full scale sea trials or CFD simulations or a combination of these methods. All these approaches have their pros and cons, are interrelated and complementary as previously outlined in the paper. Model tests give rise to scaling issues, full-scale sea trials are carried out in environmental conditions introducing the need of correction factors that might increase the uncertainty in the results, and accurate numerical simulations require state of the art software together with knowledge and expertise to operate. All these inconsistent criteria lead to different sources stating different magnitudes of benefit even for the same technology.

Therefore, a standard procedure for ESD analyses should be developed to allow ESD investigations to follow the same approach enabling different sources to compare their devices based on a standard procedure developed through collaborative studies and verifications. Gains between different studies can be then directly compared giving a better overall picture of these technologies and how they benefit the overall efficiency of a vessel and their impact on the EEDI and environment. A standard ESD procedure is currently being developed by the authors and can be considered to be an extended study of this paper. Explicit details cannot be disclosed yet; however an overview of the concept will be briefly presented.

The best controlled environment for experimentation are the model scale tests carried out in model basins avoiding problems with weather conditions and other inconsistent criteria associated with full-scale sea trials. Such methods also avoid any numerical prediction discrepancies and any need of special numerical calculations. However, these give rise to scaling issues when extrapolating the results and do not accurately identify the impact of the ESD not to mention the limited designs that can be studied due to the expensive resources required. With the advancement in computational power and state of the art CFD methods, numerical predictions can produce consistent and accurate results that can be considered satisfactory post validation and verification studies. They can also simulate full-scale conditions in any required environments avoiding any problems with extrapolations and viscous effects in model scale.

Therefore, it is proposed that ESDs are analysed using CFD methods due to the consistent procedures, controllable environments and full-scale simulations that can be developed. A more explicit procedure will be presented in future works highlighting an accurate standardised way of analysing ESDs that can be used as bases for other technology investigations. A couple of case studies will be performed to complement and support the recommended procedure proposed.

ACKNOWLEDGEMENTS

This research has been funded by the Engineering and Physical Research Council (EPSRC) through the project, “Shipping in Changing Climates. All supports are greatly appreciated. EPSRC grant no. EP/K039253/1.

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