Green retrofitting through optimisation of hull-propulsion interaction – GRIP

H.J. Prins a, M.B. Flikkema a,*, B. Schuiling a, Y. Xing-Kaeding b, A.A.M. Voermans c, M. Müller d, S. Coache c, T.W.F. Hasselaar a, S. Paboeuf f

aMARIN, Haagsteeg 2, Wagenigen, 6708PM, The Netherlands
bHSVA, Bramfelder Strasse 164, Hamburg, D-22305, Germany
cWartsila Netherlands, Lipsstraat 52, Drunen, 5151RP, The Netherlands
dIMAWIS, Industriestrasse 8 Rostock, 18069, Germany
eVICUS DT, Avenida Beiramar 77-1°, 36202, Vigo, Spain
fBureau Veritas, 8 Avenue Jacques Cartier, Saint-Herblain, BP70279, France

Abstract

In the FP7 project GRIP, partners have extensively studied Energy Saving Devices which improve the propulsive efficiency of ships. The research has focussed on an early assessment of the performance, yard processes for the installation of an ESD, structural issues related to ESDs, and the hydrodynamical working principles of ESDs. All the work came together in the final demonstration of the efficiency gain of an ESD on Uljanik built bulk carrier MV Valvoline. To demonstrate the ESD design procedure and the potential performance gain of ESDs, a design competition was held between MARIN, HSVA and Vicus who designed a pre-duct, pre-swirl stator and rudder bulb respectively. Designs were evaluated based on the performance improvement, manufacturability and structural issues. The PSS designed by HSVA came out the best with a reduction of required propulsion power. CFD analysis has shown that the PSS creates a pre-swirl resulting in an increase of the propeller efficiency mainly affecting the upcoming blade trajectory. Speed trial procedures were evaluated by MARIN to come to a procedure to evaluate the performance change with a minimum uncertainty. Speed trials before and after installation of the PSS on the bulk carrier were performed in favourable environmental conditions resulting in a performance improvement of 6.8% at a speed of 16 knots.

This paper gives an overview of the work performed in the project by all partners resulting in the successful demonstration.

* Corresponding author. Tel.: +31(0)317493336; fax: +31(0)317493245.
E-mail address: M.Flikkema@marin.nl

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1. Introduction

A combination of factors such as emission reduction, regulations, increased environmental awareness and economically challenging times urge ship owners and operators to improve the speed–power performance of their vessels. For new built vessels designers are looking for efficiency in the design, while for existing vessels there is the possibility for easy and efficient retrofits. Propulsion of the ship is the single largest energy consumer on board. Reducing the energy required for propulsion will have a large effect on the total energy consumption of the ship, thus on the costs and the emissions.

The idea of Energy Saving Devices (ESDs) is not new. In the 1970s, during the oil crisis, a great deal of attention was paid to some devices and several patents resulted from these studies. The devices were tested in model basins and some of them showed great potential at model scale. The application to full scale was more difficult however, and trials often showed no significant benefit. For some devices, model tests showed no efficiency gain while manufacturers claimed that full scale tests, often performed by the manufacturer, were very successful. Before the ESDs were really commercially viable, fuel prices dropped so that investments into energy saving retrofits seemed less attractive. It should be noted that at that time environmental aspects such as emissions were not really an issue.

In the past various experiments with ESDs have been done to aim at reducing the required propulsive power. These experiments have however suffered from scale effects on model tests and uncertainty in the full scale validation trials. Back in the 1970s, when computational power was limited and numerical simulations were not possible, the designs only relied on model tests. With the increase of computational power and the wide availability of numerical codes, a more in depth study can be done on ESDs, their working principles and design methodologies.

With the above in mind, EU FP 7 project GRIP has set out in November 2011 to study the working principles of ESDs, to study the structural issues involved, to develop a tool for early assessment of the performance improvement of ESDs, to study the retrofitting process and finally to demonstrate the design and installation of an ESD for full scale.

The GRIP project concluded in March 2015 with good results and a full scale demonstrator of an ESD fitted to a bulk carrier. Dedicated speed trials were performed with high accuracy proving the energy saving of this selected ESD. This paper gives an overview of the work done in the GRIP project leading up to the demonstration on the bulk carrier.
2. Energy Saving Devices

Energy Saving Devices (ESDs) are appendages to the ship hull, the rudder or the propeller which affect the inflow or outflow of the propeller. ESDs are designed to prevent energy losses in the propulsion system or to recover some of these losses. An example of an ESD is shown in Fig. 1, the pre-swirl stator introduces rotation into the flow and redirects this flow to increase the propeller efficiency in the upcoming blade trajectory. A drawback of added devices to the hull or rudder is that they also increase the frictional resistance of the ship. The real benefit of any propulsion improvement device can only be exploited once a sound trade-off between additional resistance and improved propulsive efficiency can be obtained.

There are many devices which tackle the friction and hull / rudder interaction problems and are based on different energy recovery mechanisms. Basically these can be divided into two categories, upstream and downstream devices. An upstream ESD is mounted upstream from the propeller and influences the inflow of the propeller to increase the propeller efficiency. A downstream ESD is mounted downstream of the propeller and recovers mainly the rotation losses of the propeller.

Examples of upstream devices are the wake equalising duct, pre-swirl stator, Mewis Duct and flow improving fins and ducts. Downstream devices are either fixed to the rudder or to the propeller hub, examples are the propeller boss cap fin, Costa bulb, rudder fins and Wartsila high efficiency Rudder.

A third category of ESDs exists which does not influence the propulsive efficiency but influences the resistance of the vessel by either adjusting the flow in certain area’s or generating thrust. Probably the best known example of this is the bulbous bow. This category was not addressed in GRIP.

3. GRIP work

To achieve the GRIP objectives, the GRIP consortium has set out to investigate ESDs in detail looking at the working principles and detailed design using CFD. The work done is described here in the order of a regular design process, starting with an early assessment and RoI calculation followed by the ESD design and the final retrofitting and validation.

3.1. Early assessment

Before ship owners and operators invest in the design of an ESD, a quick scan of the expected performance improvement and costs needs to be made. In the GRIP project an Early Assessment Tool (EAT) was developed consisting of a benefit tool calculating the performance improvement of an ESD and a cost tool consisting of the costs for building and installing an ESD.

The flow chart of the benefit tool is given in Fig. 2. This shows that based on the vessel type and speed range a wake field is chosen from the database. This wake field is used as input for the calculation of the propeller performance. If an upstream ESD is selected, the wake field is adapted accordingly. Through the hub vortex model
the potential savings of a downstream ESD can be calculated. This will result in an estimate of the required propulsion power for the ship with ESD which is set against the original ship or a value for a reference ship in the database.

Fig. 2. Flow chart of ESD performance improvement (from Voermans and Cales (2016)).

An initial estimation of ESD costs is split between design, installation and material costs. As the dimensions of ESDs are often related to the propeller diameter, the propeller diameter will determine the scaling of ESD costs. Design costs are not scaled with the propeller diameter, the installation costs scale linearly with propeller diameter, while the material costs are scaled with a power of 2.5 of the propeller diameter.

Together the benefit tool and the cost tool make the EAT. Two versions of the EAT have been developed in GRIP, a basic publically available version to be found through: http://www.grip-ieat.eu/ and a more extensive version available for GRIP partners.

3.2. Ship geometry

For the optimal design of an ESD, it is important to know the geometry of the hull, propeller and rudder in detail. In case of retrofitting an ESD to an existing ship, often the geometry is not known making design optimisation difficult. Various reverse engineering methods were studied with which the relevant geometry can be determined. Methods studied were:

- Tachymeters are very precise technologies which are established in the industrial measurement, but they are very limited in their mobility and are normally high-priced.
- Laser scanners are appropriate to measure large surface or complex objects in a short time with a high degree of detail as well as a good accuracy.
- In-door GPS is a simple method for the detection of discrete points, if it is always measured in the same measurement environment and there is no shadowing.
- Photogrammetry and Photo modelling allow a simple and flexible detection of many object points in a short time. In case of the Photogrammetry, there is also very good accuracy possible but each measurement point must be signalled with a target.
Panoramic photography is a very new field in the 3D object measurement and primarily applicable for the fast capture of complex geometries with relatively low requirements concerning the accuracy.

A critical point in the evaluation of the various methods was the transfer of data to CAD systems or other evaluation software.

3.3. ESD design process

With the geometry known, the detailed ESD design can be made. The GRIP project has looked into the various numerical methods capable of predicting the performance change due to an ESD. Numerical uncertainty studies indicate that the different models for the hull-propeller-ESD modelling have their specific advantages and disadvantages. The most straightforward RANS-BEM (hull-propeller) model has short computational times, but does not completely capture the effect of an ESD. The most complete modelling is the RANS-RANS modelling using a sliding interface between the ship fixed grid and the rotating propeller fixed grid. But the smaller modelling error is to be paid for by preparation and computational time. An intermediate model is the so-called frozen rotor model, where the propeller is fixed in one position relative to the ship. This latter model was initially thought to be an efficient model in the design of the ESD-propeller configuration. Although it was not expected to give the highest possible accuracy of the absolute values, it was expected to be useful in indicating trends. However, it appeared that this simple model did not only lead to higher uncertainties, but could even lead to wrong conclusions for optimisation. Extreme care needs to be exercised when this Frozen Rotor model is used. The RANS-BEM model proves to be a useful tool in the design, whereas the RANS-RANS model with Sliding Interface is particularly suited for the final stages of the design where the accuracy of the absolute values becomes important.

One of the main challenges in ESD design is the structural assessment as there is a lack of knowledge on the dynamic loads in sailing condition and the dynamic behaviour of ESDs. From a classification point of view, today the ESD structure is not reviewed, only its attachment to the hull is considered. No rules are given on the method to validate the ESD design. Methodologies and tools have been developed by BV and VICUS in the GRIP project. Based on hydrodynamic software and the study of the local flow incidence variation, new methods, enabling the assessment of hydrodynamic forces have been introduced and tested on application cases. Concerning the dynamic behaviour, three types of flow induced vibrations have been investigated:

- Motion Induced Vibrations (MIV), or flutter
- Vortex Induced Vibrations (VIV)
- Turbulence Induced Vibrations (TIV)

Following these methods, cyclic loads can be defined and used to perform a fatigue analysis of the ESD.

3.4. Design for demonstrator

The design method developed in GRIP was applied as a demonstrator to an ESD for the Uljanik built bulk carrier MV Valvoline (see Table 1 for particulars). The challenge was taken up by MARIN, HSVA and VICUS to design a pre-duct, pre swirl stator and rudder bulb respectively. The results of these designs are extensively described by Xing-Kaeding et al. (2016) and Coache and Fernández (2016) for the PSS and Rudder Bulb respectively. On the design of the pre-duct no publicly available paper exists, however the design process is applied to a tanker by Schuiling and van Terwisga (2016).

MARIN has carried out the pre-duct design and optimisation for the GRIP validation bulk carrier. The positive effect of the pre-duct is the improvement of the propeller performance by reorienting the total force vector through pre-swirl. Besides a reduction of rotational losses, the pre-duct also uniform the thrust distribution of the propeller. To obtain a working ESD design, more than 10 ESDs were evaluated using Frozen Rotor. Based on these results, successful variants were chosen. In the end, two ESD designs were analysed in a fully time dependent fashion. The performance improvement is disappointing for the bulk carrier as the expectations from other applications were high. The difference was found in the full aft body which resulted in little space between the hull and the pre-duct resulting in a significant local resistance increase. Other test cases, where the gondola was less pronounced, showed a much better performance improvement due to the pre-duct.
Table 1. Demonstration vessel particulars.

|                         | Ballast | Design |
|-------------------------|---------|--------|
| Length between Perpendiculars $L_{PP}$ m | 182.00  | 182.00 |
| Overall Beam $B_{OA}$ m | 32.24  | 32.24  |
| Draught at forward perpendicular $T_F$ m | 4.6     | 11.00  |
| Draught at aft perpendicular $T_A$ m | 6.6     | 11.00  |
| Draught at midship $T$ m | 5.6     | 11.00  |
| Displacement volume moulded $\mathcal{V}$ m$^3$ | 25673  | 54530  |
| Wetted surface $S_S$ m$^2$ | 6292.3  | 8656.4 |
| Block Coefficient $C_B$ | 0.7173  | 0.8235 |

HSVA has carried out the pre-swirl stator design and optimisation for the GRIP validation bulk carrier. As the first step, BEM analysis for the propeller alone has been performed to obtain the circumferential averaged propeller blade circulation. Since it is not clear how many stator fins would actually be optimal to produce enough pre-swirl for the propeller while simultaneously not largely increasing the required thrust, two versions were considered: three stators on the port side with (V01) and without (V02) starboard stator blade. The subsequent RANS evaluations showed that the PSS V02 performs better in this case. Further design optimisation was done followed by a RANS evaluation of the final design compared to the ship without ESD.

VICUS has carried out the rudder bulb design and optimisation for the GRIP validation bulk carrier. Instead of performing a parametric analysis, several bulbs with different thickness, length, sharp leading edge bulb, different curvatures leading edge bulb, etc. were analysed. The different ESD designs were compared against the original by the net gain. The improvements achieved for all computations were not so high, always lower than 1%. After sharing the bulb geometry with the partners, a computation with finer mesh was performed (for cross check validation) leading to a new result: a deterioration of propulsive efficiency in respect to bare hull. Obviously, the medium mesh was not enough to retain all physical phenomena around propeller, rudder and ESD. More details on the design of the rudder bulb are given by Coache and Fernández (2016).

At a certain point in time which is derived backward from the installation and trial planning, the designs were frozen and the performance improvements were compared in order to select the ESD to be fitted to the vessel. In Table 2 the performance improvement results for each of these ESDs are shown. Based on this, the PSS was selected to be built and retrofitted to MV Valvoline. It should be noted that these results and this ranking is only valid for MV Valvoline, for other ships other ranking may occur.

Table 2. ESD performance evaluation results for MV Valvoline.

|                         | Power reduction |
|-------------------------|-----------------|
| Pre-duct                | 1.5-2%          |
| Pre-swirl stator        | 2.2%            |
| Rudder bulb             | -1.4%           |

Fig. 3. ESD designs for the validation vessel Pre-duct (left), PSS (middle) and Rudder Bulb (right) (from Xing-Kaeding et al. (2016)).
3.5. Structural evaluation

After the selection of the ESD and the fixed shape, the Ship Motion Methodology (SMM) developed by BV for the strength assessment of ESD in the design process was applied. It is based on hydrodynamic computations, using HydroStar, a Bureau Veritas software, and the study of fluid velocities and the profile angle of attack. From the ship motions Response Amplification Operators (RAO) and considering the scatter diagram of the sailing area of the ship, the forces applied on an ESD structure can be estimated. The design wave, leading to the maximum strength, is also determined with the SMM. In order to obtain more accurate estimations of loads applied on an ESD, CFD computations using the design wave determined by the SMM has been carried out in a further step. The methodology provides also cyclic loads for fatigue analysis and allows evaluating the probability of occurrence of the angle of attack of the ESD profile over a certain period.

In order to estimate the maximum forces applied on the PSS, the SMM has been performed considering 2 loading cases, ballast and full loads, and 3 ship speeds. The scatter diagram has been divided into 3 domains in order to adapt the ship speed to the sea state. The following operational conditions have been considered:

1. Wave height [0 m;5.5 m] and ship speed 15 knots;
2. Wave height [6.5 m;14.5 m] and ship speed 10 knots; and
3. Wave height [15.5 m; 21.5 m] and ship speed 5 knots.

The forces were determined for every fin: Fin 1, the horizontal fin; Fin 2, the upper fin and Fin 3, the lower fin, and at 3 positions along the fins, at the tip, at the middle and at the root of each. Finite Element Analyses have been performed to validate the scantling defined by the shipyard, using the loads obtained with the SMM and stresses have been compared with allowable stresses according to BV rules (see Fig. 4). From the methodology, it is possible to estimate the probability distribution of the ESD angle of attack over a period of time based on the scatter diagram. The study shows that the angle of attack of the PSS is less than 10° during 96.5% of the navigation time of the ship, in ballast condition, and during 99.4% of the navigation time of the ship in full load condition. Additionally, the angle of attack is greater than 15 °, which corresponds to the ESD stall angle, only during less than 1% of ship navigation in ballast or in full load condition.

In addition, vibration analyses have been performed to study the PSS behaviour in navigation. The effect of a surrounding fluid in the analysis of natural frequencies is to be incorporated by adding the added mass of the fluid. The added mass will lower the natural frequencies of the plate. The results show that the fins’ frequencies are out of range of the propeller excitation ones so the risk of vibration of the fins by the propeller excitation is very limited. The risk of vortex induced vibrations of the fins also appeared to be very limited. As far as flutter is concerned, the fluid speed leading to this phenomenon is higher than the ship speed range.

These results highlight that the efficiency of PSS is kept during the majority of the ship’s navigation life. More details on the evaluation method are given by Paboeuf and Cassez (2016).

Fig. 4. Stresses distribution in the Finite Element Model.
4. GRIP demonstration results

This chapter discusses the results of the demonstration of a dedicated ESD design for bulk carrier MV Valvoline, HSVA, MARIN and VICUS worked on the design of different ESDs after which the best performing ESD was selected to be built and retrofitted to the ship.

4.1. Ship and ESD geometry

Reverse engineering of the hull and ESD showed some difference between the original design and the installed configuration. The full hull and hull including PSS geometry were measured using laser scanning by IMAWIS. As also the hull including PSS were measured, a detailed CFD calculation of the final condition could be made for validation of the CFD calculations. HSVA performed new CFD calculations with the as built model to keep building accuracies out of the equation in the validation of the performance improvement. This resulted in a higher efficiency improvement than the original design, coming to 4.5% power reduction.

Also during the construction design phase of the PSS, structural reasons required to move the root sections of the PSS about 30 cm forward. There was little time left before the PSS should be actually built so that it was not possible to induced a new PSS design process. This problem has been solved by introducing some rake to the stator fins so that the sections at higher radii are still experiencing the similar flow field as before. Since parametric models have been developed for ESDs, this change can be easily realized making a quick adaption of the PSS design. More detailed of the design process can be found in Xing-Kaeding et al. (2016).

In order to perform the validation of the ESD installation process, only the assembly process of the ESD was considered for validation using simulation. The logistics involved in the retrofitting process in the shipyard is not considered in the simulation scenario studies, as its significance would be small and also logistics planning of Uljanik is being done on rough estimation. Both the reverse engineering and the assembly simulations are discussed in detail by Hübler et al. (2016).

4.2. Full scale demonstration

In order to validate the ESD design and the CFD calculations, dedicated speed trials were done before and after installation of the ESD. The objective of these speed trials was to accurately determine the speed – power relation for both conditions. During the docking in which the PSS was installed the hull was cleaned but that was judged to have only minor effect on the performance according to Hasselaar (2016) as the fouling condition was very good before cleaning. Hasselaar (2016) furthermore explores the uncertainty in full scale measurements to understand if the resulting performance difference is statistically significant. Based on this exploration, the following conclusions can be made for estimation of performance gains from an ESD using speed/power trials:

- Trials should be done on the same vessel with the same instrumentation to avoid yard uncertainties and large uncertainties in shaft power measurement.
- Trials should be conducted at the highest power setting possible to minimise the relative contribution of added wind and wave resistance to speed loss.
- Typical measurement uncertainties in wind, wave, draught, speed and power propagate to uncertainties in the corrected trial performance. In fair weather they can be as low as 1%. In sea state 4 this can increase to 5%, based on the assumption that wind speed is measured with an uncertainty of 15%, wave height 25% and draught is read with 3cm accuracy.
- A wave buoy should be deployed when wave height is larger than 1.0 meter to avoid wave estimation uncertainties.

The speed trials were performed following these conclusions.

Speed trials on the demonstration bulk carrier were done on April 5 and April 18, 2014 in the Adriatic Sea. Shaft power was measured by power measurement system using strain gauges on the propeller shaft. Data was sampled at 1000Hz to avoid aliasing. The system was zeroed in port prior to departure of the first trial and checked after the trials. For both trials, the same instrumentation and strain gauge on the propeller shaft was used. Position, course and
speed over ground were determined using a DGPS unit, which was installed on the bridge top. The relative wind speed and direction was obtained using a sonic anemometer positioned on the mast on top of the wheelhouse, at a location as high as possible to reduce the effects of wind distortion. Data was stored automatically with a sampling frequency of 10Hz on a PC on the bridge. Furthermore, the depth below the keel was recorded manually from the echo sounder indicator on the wheelhouse. To record the wave height, period and direction, a free floating Datawell Directional Wave Buoy of type DWR G4 was deployed. The trials without and with ESD were performed by the same trial team.

The uncorrected performance data has been analysed and corrected for the ideal weather and environmental conditions according to the ‘Direct power method’, described in ITTC (2012). The analysis has been performed using the IMO EEDI-certified program ‘STAIMO’ ITTC (2013). Both trial results have been corrected to no-wind, no-wave conditions and equal displacement. Corrections have been applied for wind, wave reflection and displacement differences. The difference in power at 16.0 kN between the two trials was 6.8% as shown in Fig. 4. Exceptionally fair weather conditions and the use of the same instrumentation during both trials resulted in a low uncertainty due to measurement errors of ±0.7%. The uncertainty from hull fouling remains difficult to determine with certainty. However, based on the fouling assessment in dock (only a very thin layer of transparent slime on patches on the hull was observed), the influence of the fouling is negligible. The power differences are considered to be caused by the PSS.

The predicted power-speed relations have been compared to the sea trial results for cases without and with the ESD respectively. This shows the trends of both curves have been predicted by CFD very well, however there is still a certain gap in absolute power for both cases without and with ESD. And the effect of the ESD has been somewhat under-predicted by CFD when compared to trial results.

For the evaluation of the ESD performance, relative difference between the condition with and without ESD is most relevant. The relative changes in power for this ESD using CFD is approximately 4.5% while the speed trial results show a difference of 6.8%. The difference in rotation rate is better predicted by CFD coming to 4.7% with the trial difference coming to 5.2%. This indicates that the torque difference is under predicted by CFD. According to Hasselaar and Xing-Kaeding (2016) this is caused partially by the blade roughness model used in CFD. Adapting the blade roughness model already improves the prediction of the performance improvement of the ESD using CFD.

A more detailed description of the speed trial and validation results is given in Hasselaar and Xing-Kaeding (2016).
5. GRIP conclusions

The GRIP project concluded successfully in March 2015 resulting in the following main project conclusions and achievements:

- It was an objective of GRIP to reduce the fuel consumption of ships with ESDs on average by 5%, with reductions for individual ships up to 10%. For the demonstrator vessel, a handymax bulk carrier, a fuel saving of 6.8% over the speed range was demonstrated during dedicated speed trials. This fuel saving is well above the projected average fleet wide fuel saving.
- With the Early Assessment Tool (EAT) a first estimate of the potential ESD fuel saving for a specific ship with given propeller details can be made. With the EAT and the calculation of the potential fuel savings, we are able to better estimate the RoI upon retrofitting the vessel with an ESD.
- Detailed investigations into the working mechanisms of various ESDs such as Propeller Boss Cap Fins (PBCF), Pre-Swirl Stators (PSS), hub-cup rudder bulb and rudder fins suitable for a large variety of vessels have led to a better understanding of these ESDs.
- As there are no regulations on ESD design, from a structural point of view, the structural issues are often challenging. Within GRIP the load variations, flutter, MIV, VIV and fatigue of ESDs have been studied and documented. Methods to evaluate the strength of both upstream and downstream ESDs have been developed.

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