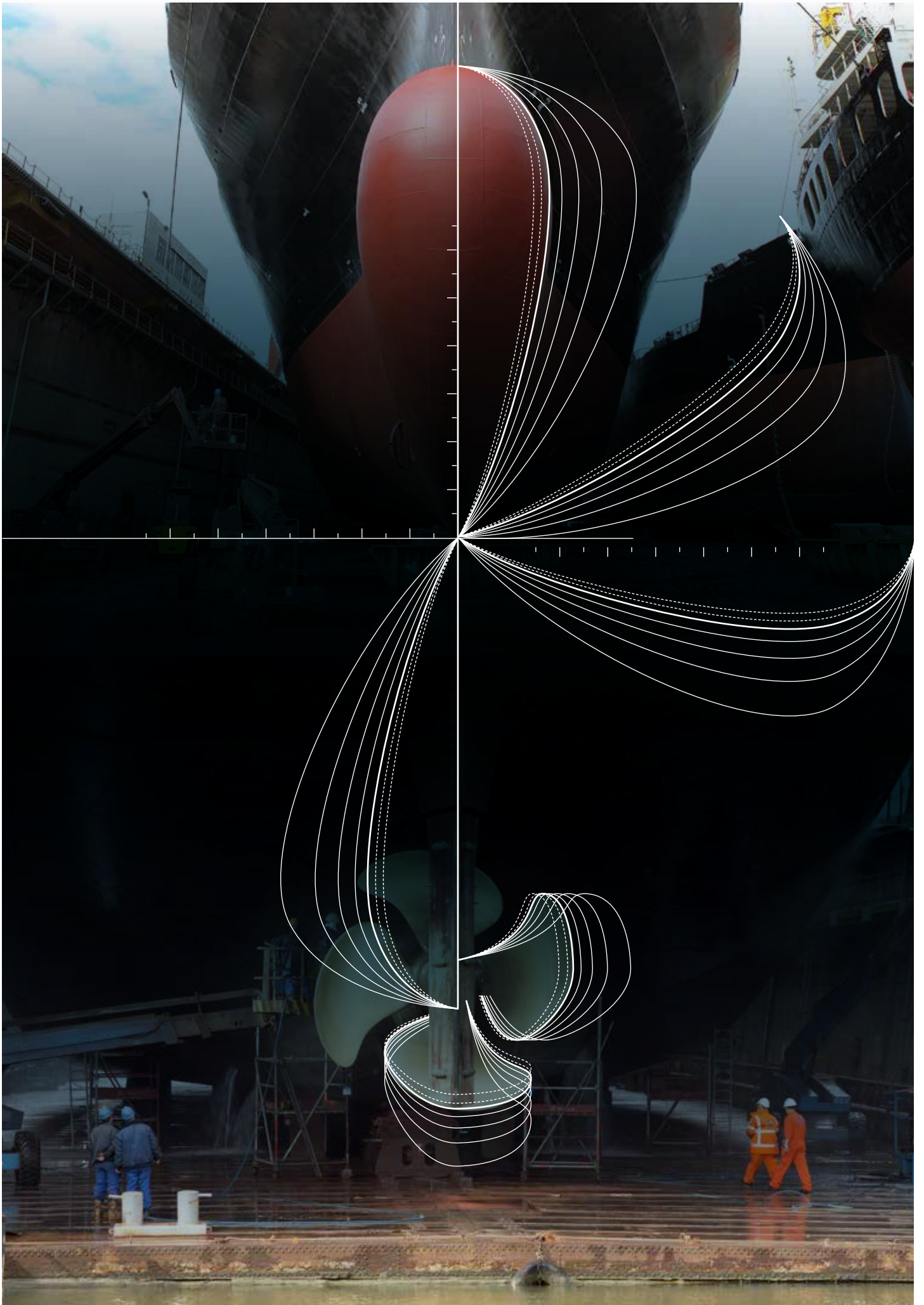


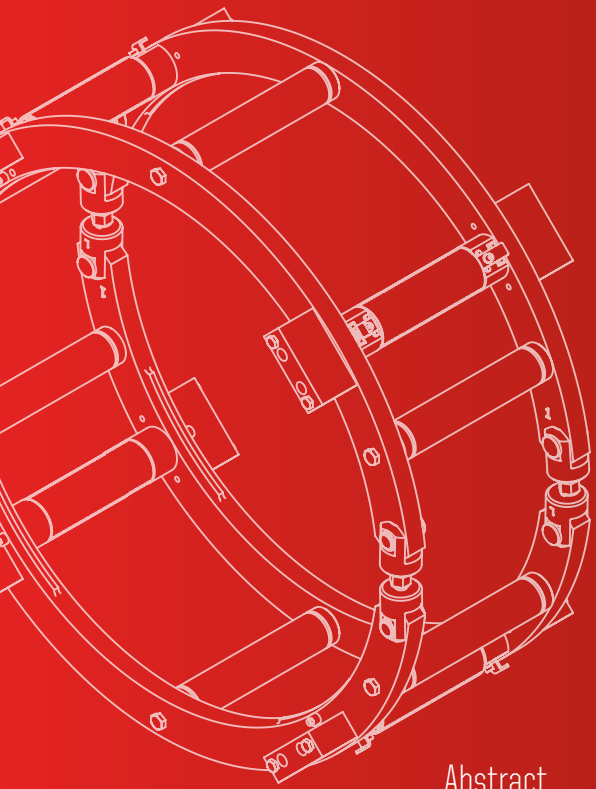


MEASURING THE FULL SCALE PERFORMANCE OF A PROPELLER AND BULBOUS BOW **RETROFIT** VIA PROPELLER THRUST MEASUREMENTS

A scientific paper by VAF Instruments Research & Development
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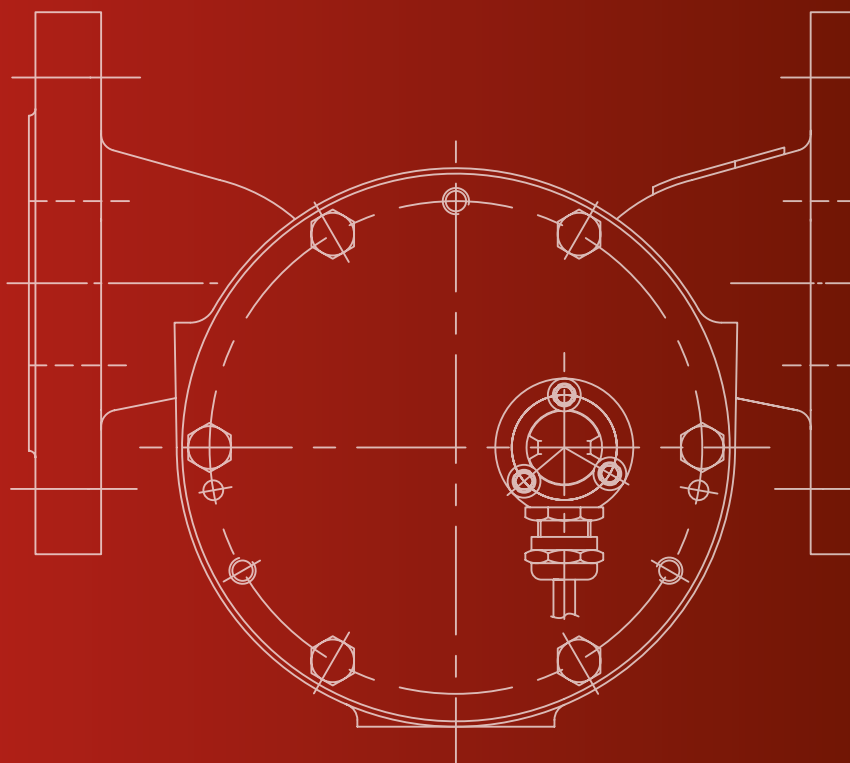
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Abstract

This paper presents the possibilities offered by full scale measurements of propeller thrust (and torque), for fuel saving potentials and emission reductions due to the retrofit of a new propeller design and a new bulbous bow design on a large TEU container vessel. It will be explained how via full scale measurements of propeller thrust, in relation to other parameters like ship speed, the change in propeller efficiency and the hull resistance can separately be measured. Herewith the ship owner will be able to evaluate the effects of the retrofit on reducing fuel consumption and emissions. In addition an example will be shown of the measurement results of the propeller thrust and torque measurements on an actual large TEU container vessel in service, before and after the vessel has been retrofitted with a new propeller design, and a new bulbous bow design.



1. INTRODUCTION

In general there is a large interest in the maritime world for ship propulsion efficiency. This has several reasons related to either cost savings, legislation, and/or environmental concern. In this respect also the upcoming MRV and IMO regulations on respectively CO₂ emissions and fuel consumption play an important role. Next to legislation the focus on fuel consumption has also a direct operational (fuel) cost reduction benefit.

In view of the above fuel consumption reduction, the concept of slow steaming has been introduced on for instance container vessels. This in general resulted in significant fuel savings. But since the earlier container vessels have mainly been designed for higher ship speeds and therewith engine powers, the propeller and hull designs might not be optimum anymore for the new operational conditions when applying slow steaming. In order to further benefit from slow steaming, applying a retrofit to the vessel is considered as an option. The retrofit could exist of several modifications such as:

1. A new propeller design which is optimized for the new slow steaming operational condition of lower power and RPM. This might increase the propeller efficiency.
2. A new bulbous bow design which is optimized for the new slow steaming operational condition of lower ship speed, and possible lower draught, and therewith an improved wave pattern of the ship's bow. This might reduce the hull resistance.

As both modifications imply a considerable amount of investment costs, the expected to be achieved fuel savings via increased propeller efficiency and/or reduced hull resistance need to be verified after the retrofit in order to verify if the predicted improvements are really achieved.

To determine the increase in propeller efficiency, and the reduction in hull resistance, before the actual retrofit, use can be made of calculations (like CFD), and/or model tests in a model basin. For determining the improvements of propeller and hull after the retrofit on the actual ship, full scale measurements need to be performed. In order to be able to identify the improvement of the propeller separate from the improvement of the ship's hull, next to shaft power and RPM, also propeller thrust should be measured. If one is only relying on measurements of propeller shaft power or even only engine fuel consumption, the distinction between propeller and hull improvement can not be made. This hampers a proper comparison of the actual improvements against the predicted improvements based on CFD and/or model tests.

This paper provides a more detailed description on the full scale propeller and hull performance measurements, and an example of the measurement results achieved on a large TEU container vessel in service prior and after it has been retrofitted with new propeller and bulbous bow designs.

2. THEORETICAL APPROACH FOR PROPELLER AND SHIP HULL PERFORMANCE MEASUREMENT

When looking at the performance of the propeller and ship hull retrofits, it is important to be able to separately measure the propeller performance from the hull resistance. In order to be able to do this it is needed to measure next to propeller power, also the propeller thrust.

In order to measure the performance of the propeller and the ship hull (resistance), in practice several ways are used as are shown in Figure 1, based on either:

- Engine Fuel consumption (1st route in Figure 1)
- Torque (2nd route in Figure 1)
- Thrust (3rd route in Figure 1)

As can be seen, the 3rd route, where propeller thrust is measured (next to torque), is the only way at which the propeller performance can be separately measured from the hull performance (resistance). If in addition the fuel consumption of the propulsion engine is measured, also the efficiency of the engine can be determined separately.

2.1. Propeller performance determination

When looking at propeller theory the propeller efficiency (η_{p-o}) is clearly defined as the ratio between dimensionless propeller thrust (K_t) and dimensionless propeller torque (K_q), where J is the advance ratio of the propeller through the water:

$$\eta_{p-o} = J K_t / 2 \pi K_q$$

This formula is valid for both Fixed Pitch Propellers (FPP) as well as Controllable Pitch Propellers (CPP), and indicates that both thrust and torque need to be measured in order to measure the propeller efficiency. As such the only proper way to measure the performance of the propeller separately from the performance / resistance of the hull, is via measuring thrust.

2.2. Hull resistance determination

A direct measurement of the hull performance is the amount of propeller thrust (T_{prop}) needed to overcome the hull resistance (R_{hull}) at a certain ship speed. For this the following function applies:

$$T_{prop} = f(R_{hull})$$

If for instance only the propeller power is used to “measure” hull resistance (2nd route in Figure 1), there is an underlying assumption that the conversion of power to the propeller into thrust from the propeller is always a non changing constant. This is not the case in reality, as the propeller conversion from power to thrust is clearly related to the efficiency of the propeller, which changes over time and also per sailing condition like for instance for a fixed RPM CPP.



Fig.1: Three ways to monitor the ship propulsion performance, and the involved detailed efficiencies.

3. FULL SCALE MEASUREMENT LAY OUT USED

In order to determine the propeller and ship hull condition via measurements, several parameters need to be taken into account and measured. In addition the measured data need to be enriched in order to be able to subtract the relevant data points for a proper comparison of the propulsion performance. In the next paragraph a general overview of the used measurement parameters and data enrichment is shown. Special attention is paid to the propeller thrust measurement via the TT-Sense® sensor, and the used data enrichment via the IVY® Propulsion Performance Management solution.

3.1. Parameters to be measured

In order to determine the propeller and ship hull condition, several parameters need to be taken into account and measured. A typical list of to be measured parameters consists of:

- Propeller thrust
- Propeller torque
- Propeller RPM
- Speedlog (STW)
- GPS location
- Ship draught
- Seastate
- Wind

The majority of these parameters is already measured and available on board of a ship via dedicated sensors, and / or log reports. Propeller power, via torque and RPM, is nowadays a rather

common measurement on board of a ship. But in order to be able to separate the propeller performance from the ship hull performance, the propeller thrust needs to be measured as well. This asks for an additional propeller thrust sensor.

For this, VAF Instruments (the Netherlands), a well known supplier of measurement systems for the maritime market, has developed the TT-Sense® thrust and torque sensor, as is shown in Figure 2. The sensor, which is already on the market for more than four years, has been used by VAF Instruments R&D department to quantify vessel performance and to track the changes in vessel performance over time. Until now experience is gained on many types of vessels from small cargo vessels towards 14000 TEU container vessels, as well as on navy vessel shaft lines. The working principle of the TT-Sense® sensor is based on, separately measure the torsion (torque) and compression (thrust) of the propeller shaft via very accurate optical sensors.

With the TT-Sense® sensor it is possible to separately measure the propeller efficiency of the actual propeller at full scale behind the vessel, next to the actual resistance of the vessel's hull. See also [BALLEGOOIJEN, van, W.G.E.; MUNTEAN, T.V. (2016)], for more details.

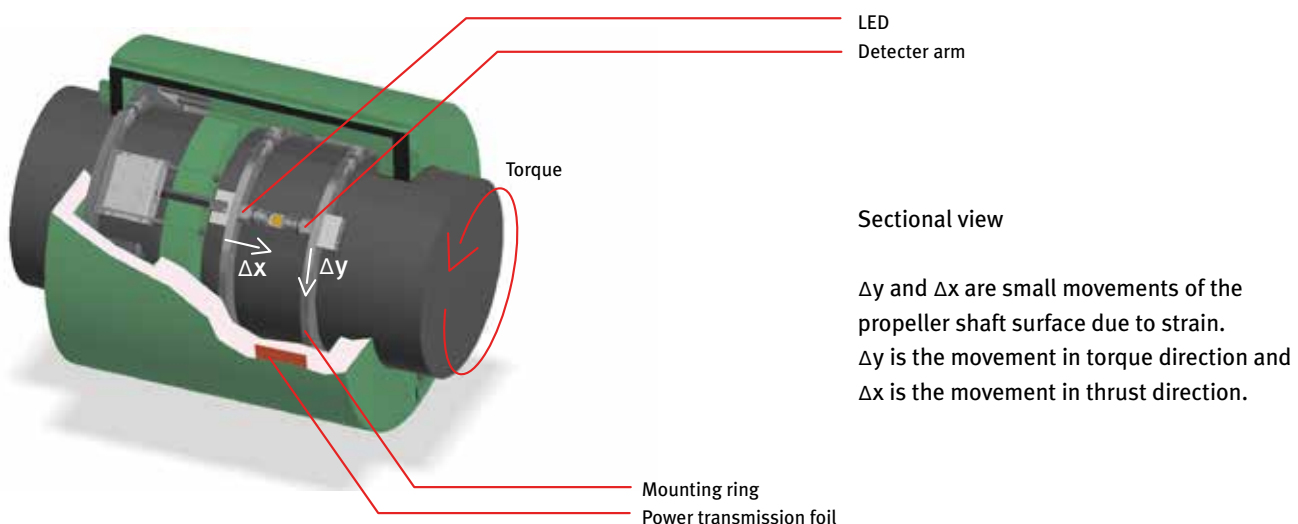


Fig.2: General working principle of the TT-Sense® Thrust and Torque sensor

3.2. Handling of measured data

VAF Instruments developed in addition the IVY® Propulsion Performance Management solution. This is a dedicated software solution that among others enriches the data from the TT-Sense® and translates it into easy to access dashboards with KPIs and graphs, showing the actual performance of the propeller and the ship hull separately. A typical example of the IVY® dashboard can be seen in Figure 3. where the measured performance over time of the propeller and the ship hull is shown.

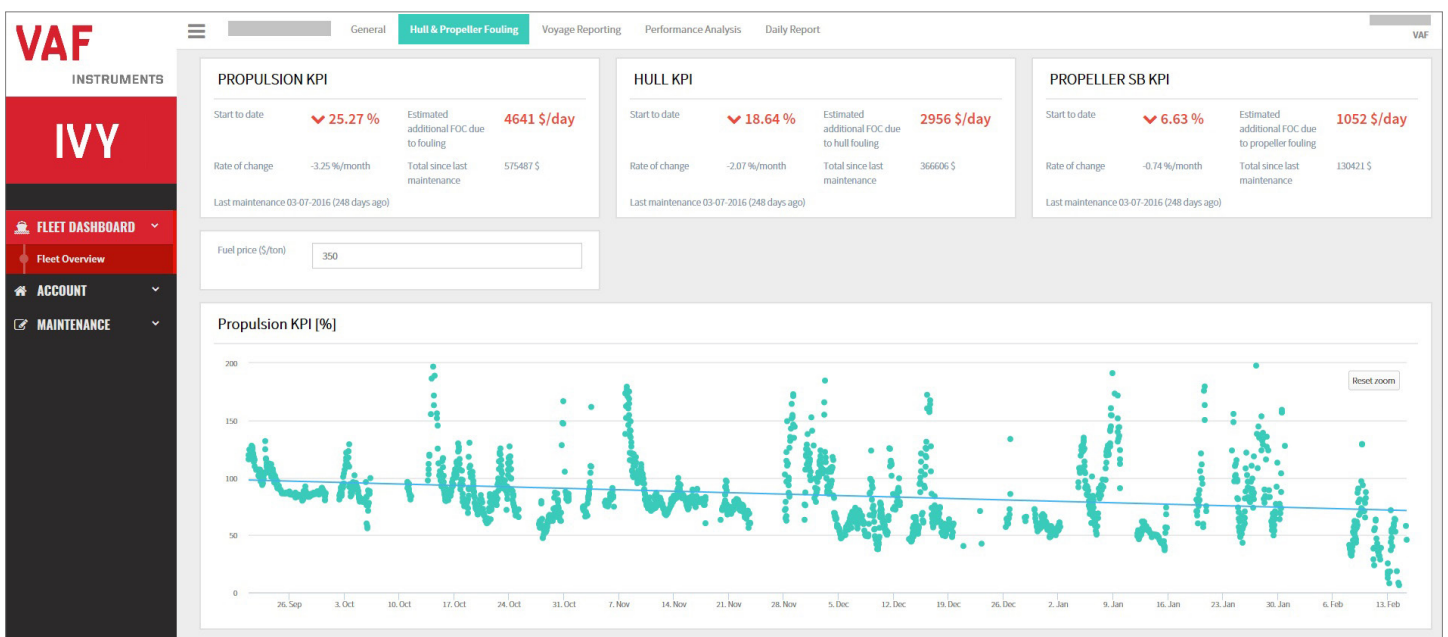


Fig.3: A typical example of the IVY® Propulsion Performance Management solution where the TT-Sense® measured propeller and hull performance is shown over time.

4. FULL SCALE MEASUREMENTS ON A LARGE TEU CONTAINER VESSEL

The full scale measurement results for a large TEU container vessel which has been retrofitted with both a new propeller design and a new bulbous bow design, are presented in this paper. Measurements of the separate propeller performance and the hull resistance are performed via the use of the VAF Instruments TT-Sense® sensor, and the IVY® Propulsion Performance Management solution.

The measurements as shown in Figure 4 are performed based on the TT-Sense® thrust measurements.

The full scale measurements with the VAF Instruments TT-Sense® thrust sensor on board of this large TEU container vessel comprise a period of more than 2½ years. About the first 1½ years are with the original propeller and original bulbous bow design. After the actual retrofit of the vessel when the vessel was equipped with the new propeller design and the new bulbous bow design, the full scale measurements with the TT-Sense® thrust sensor continued for about ½ a year.

	Light draught	Design draught
Original propeller design	x	x
Original bulbous bow design	x	x
New propeller design	x	x
New bulbous bow design	x	x

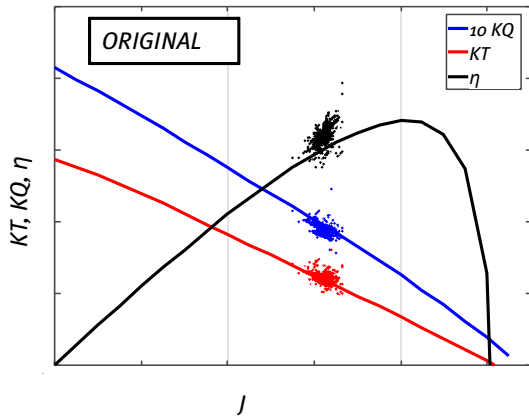
Fig.4: Full scale conditions for measurements performed with the TT-Sense® thrust sensor

4.1 Full scale propeller performance based on thrust measurements with the TT-Sense®

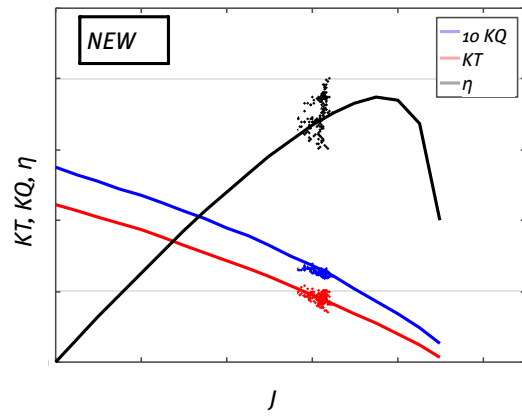
For predicting the possible performance improvements of the new propeller design, which will be applied at the retrofit of the vessel, model tests have been performed at a model test basin with both the original propeller and the new design propeller. The model tests predicted significant performance improvements for the new propeller design at the various ship speeds and for both light draught and design draught conditions. The new propeller performance improvements are rather insensitive to draught conditions and ship speed.

From the model tests, the propeller open water curves are available of both the original and the new propeller design. In addition there is 1½ year of full scale propeller efficiency (thrust and torque) measurements done via the VAF Instruments TT-Sense® sensor for the original propeller design. Next to that there is for ½ a year of full scale propeller efficiency (thrust and torque) measurements done via the TT-Sense® sensor for the new propeller design. Measurements are split into light draught and design draught conditions.

In Figure 5, full scale TT-Sense® measurement results of the original propeller design and the new propeller design for the light draught condition of the vessel are shown. In the graphs a good comparison is seen between the full scale measurements via the TT-Sense® thrust and torque sensor (dots), and the model test predicted open water curves (lines). This good comparison applies for both propeller designs (original and new). Herewith a good indication of the accuracy and the long term stability of the thrust and torque measurements is shown.



Original propeller, before retrofit
Light draught conditions

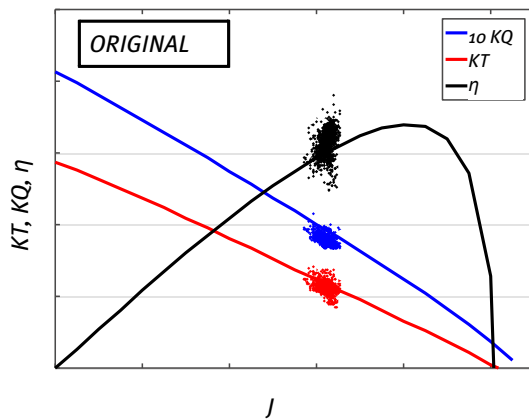


New propeller, before retrofit
Light draught conditions

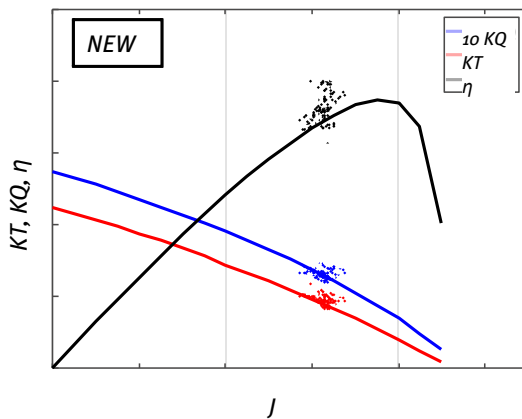
Fig. 5: Light draught: full scale measurements with TT-Sense® sensor (dots) of the original propeller (left) versus new propeller (right), compared to model test open water curves (lines)

In Figure 6, the results of the full scale propeller performance measurements via TT-Sense® sensor (dots) for the design draught conditions of the vessel are compared to the model test predicted open water curves (lines) of both the original propeller design and the new propeller design.

Figure 6 shows that also for design draught conditions a good comparison between the model test predicted propeller performance, and the full scale measured propeller performance, is found. In addition herewith a good indication of the accuracy and the long term stability of the thrust and torque measurements via TT-Sense® is shown.



Original propeller, before retrofit
Design draught conditions



New propeller, before retrofit
Design draught conditions

Fig. 6: Design draught: full scale measurements with TT-Sense® sensor (dots) of the original propeller (left) versus new propeller (right), compared to model test open water curves (lines)

As can be seen from Figures 5 and 6, the model test predicted performance improvement of the new propeller design correlates fairly well with the full scale measurements of the new propeller. Next to the model tests, also the full scale measurements point towards an improvement in efficiency by retrofitting the new propeller, as is shown in Figure 7. Here the relative performance improvement in %, of the new propeller design compared to the original design, is plotted against 3 different slow steaming ship speeds. The ship speed (V_s) is shown as a fraction of the original vessel design speed (V_{design}).

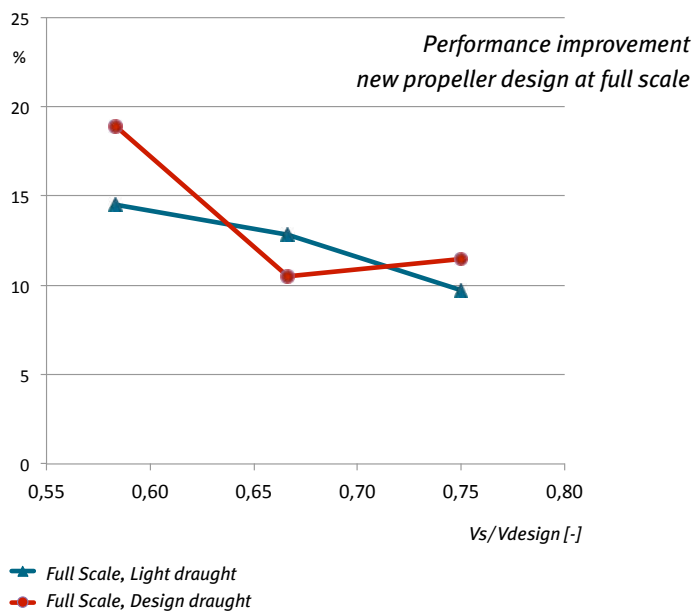


Fig. 7: Full scale new propeller design performance improvement compared to original design, based on thrust measurements via the TT-Sense® sensor.

4.2. Full scale bulbous bow performance improvements via TT-Sense® thrust measurements

Since at the vessel the propeller thrust is measured via the TT-Sense® thrust sensor, herewith also the total hull resistance is measured. Based on these measurements the possible resistance improvement of the new bulbous bow design can be measured. In Figure 8 the full scale measured improvement in resistance due to the new bulbous bow design (compared to the original design) is shown for the various ship speeds and the 2 draughts.

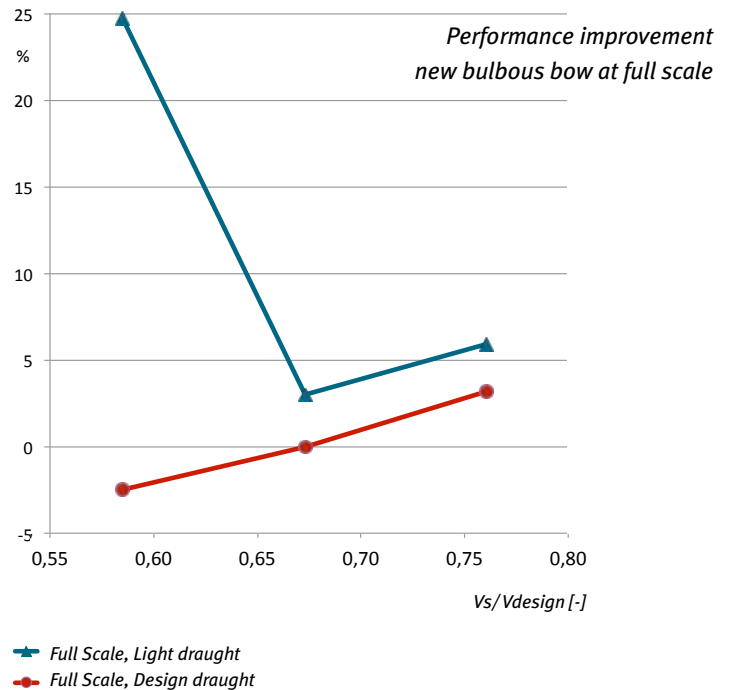


Fig. 8: Full scale new bulbous bow design performance improvements compared to original design, based on thrust measurements via the TT-Sense® thrust sensor.

Figure 8 shows that the improvement in full scale hull resistance due to the new bulbous bow design is highly depending on the ship speed and the draught of the vessel. Especially at the design draught, the improvement in hull resistance compared to the original design, is measured to be limited.

4.3. Full scale propeller and bulbous bow performance improvement measured by thrust

When combining the measured full scale performance improvements of the new propeller design, with the performance improvements of the new bulbous bow design, the total performance improvement of the retrofit can be determined. Since the individual performance improvements of the new propeller design and the new bulbous bow design can be measured only via the full scale thrust measurements, the full scale measured performance improvements of both, as shown in paragraph 4.1. and 4.2. are combined. The total full scale measured performance improvement of the retrofit, based on the TT-Sense® thrust measurements, is shown in Figure 9.

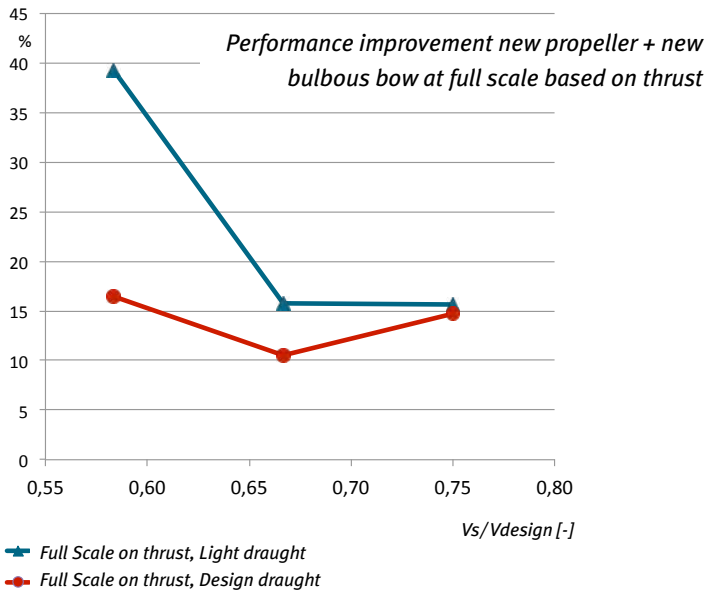


Fig. 9: Total full scale retrofit performance improvement measured via TT-Sense®

As can be seen from Figure 9, the full scale measurements indicate towards a total performance improvement due to the retrofit.

As indicated these full scale measurements are based on thrust measurements. In order to further investigate the measured performance improvements, in the next paragraph the measurements are compared to full scale measurements based on torque (power), and on fuel consumption of the main engine. As is shown in Figure 1, only via thrust measurements a distinction between propeller performance and hull resistance can be measured. When measuring the performance improvement of the retrofit via torque (power), the individual performances of the propeller and the hull are summed and can not be measured separately (the 2nd route in Figure 1).

Finally when measuring the performance improvement of the retrofit via measuring the propulsion engine fuel consumption also the propulsion engine performance is summed together with the propeller and hull performance (the 1st route in Figure 1), and no distinction between engine, propeller, and hull performance can be made.

Nevertheless, next to the thrust measurement route, a comparison is made with the torque (power) measuring route and the propulsion engine fuel consumption route, in the next paragraphs. This to provide insight in the correlation and accuracy of the thrust measurements. Especially since the measurement of thrust, torque and fuel consumption are 3 independent measurements.

4.4. Full scale propeller and bulbous bow performance improvement measured by torque (power)

In this paragraph the full scale measurements based on torque (power) are shown. In Figure 10 the total full scale performance improvement due to the retrofit as measured via the propulsion power is shown.

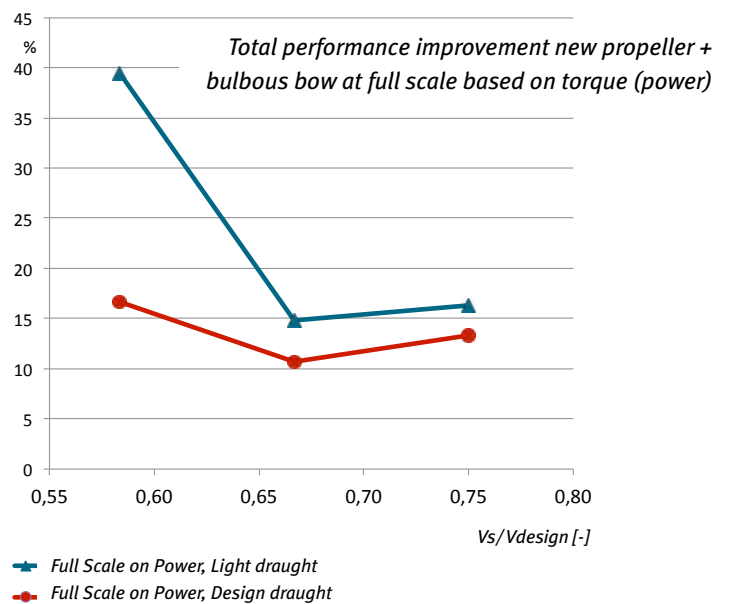


Fig. 10: Total full scale retrofit performance improvement based on torque (power) measurements

As can be seen from Figure 10, the full scale total performance improvement based on the torque (power) measurements is nearly identical to the total performance improvement based on thrust, which provides an indication of the value of both (independent) measurements.

4.5. Full scale propeller and bulbous bow performance improvement measured by engine fuel consumption

The third way to compare the full scale propulsion improvements of the retrofit is via measurements of the actual fuel consumption of the propulsion engine. When measuring the fuel consumption of the engine, not only the change in performance of the new propeller design and the new bulbous bow design is summed, but now the engine efficiency is incorporated as well. This is shown in the 1st route of Figure 1.

Based on earlier investigations the engine efficiency is changing over time due to for instance engine deterioration, changes in caloric value of the fuels used, and operational conditions of the engine like the RPM dependability of the efficiency of the engine. Variations in engine efficiency of several percent are seen from past data. As such the measurements of the propulsion engine fuel consumption provide just an indication of the overall performance improvement of the propeller and bulbous bow retrofit. In addition, when measuring only engine fuel consumption, no split in efficiency improvements between engine, propeller and hull can be made, in contrary to when measuring thrust.

The full scale measured propulsion engine fuel consumption is shown in Figure 11. The trend in the fuel consumption measurements, is comparable to the trends as seen in the full scale thrust and power measurements as shown in the previous paragraphs. The differences seen between the full scale performance improvements based on engine fuel consumption, compared to thrust or torque, are expected to be highly related to variations in the engine performance and fuel quality as described above. As such the measurements of the performance improvement of the retrofit via the engine fuel consumption measurements is less accurate when compared to the torque or thrust measurements (where the thrust measurements provide the most detailed insights via the split in propeller and hull performance).

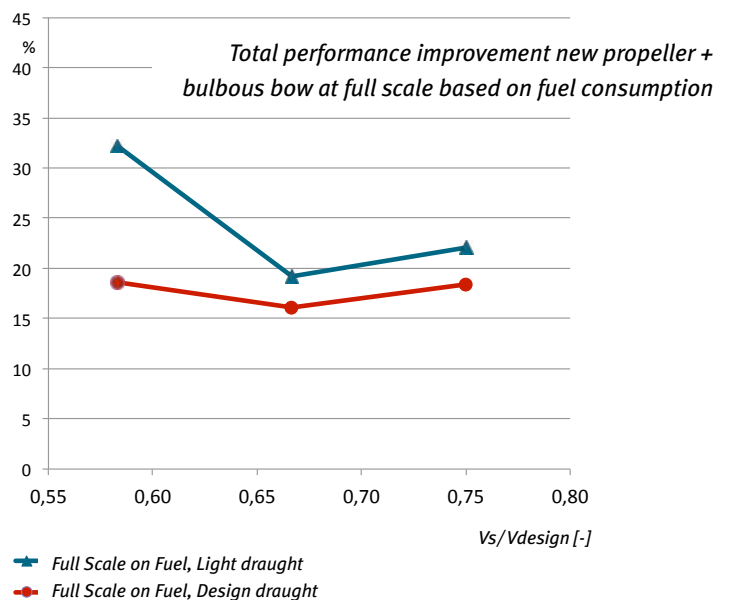


Fig. 11: Total full scale retrofit performance improvement based on engine fuel consumption measurements

5. CONCLUSIONS OF THE FULL SCALE PROPELLER AND BULBOUS BOW RETROFIT PERFORMANCE IMPROVEMENT MEASUREMENTS ON A LARGE TEU CONTAINER VESSEL

The full scale performance improvements by the retrofitting of a new propeller design and a new bulbous bow design are measured via 3 different routes (as is shown in Figure 1). First via the thrust measurements with the TT-Sense® sensor, secondly via torque (power) measurements, and third via the engine fuel consumption measurements.

Only via measuring the propeller thrust, the separate performance improvements by the new propeller design and the new bulbous bow design, can be determined. Also a comparison is made with the full scale measurements based on torque (power), in order to verify the full scale results based on thrust. Disadvantage of the measurements based on torque is that there can be made no distinction between the individual performance improvements of the new propeller design and the new bulbous bow design.

Also the engine fuel consumption improvement is measured and compared to the torque and thrust results. This is the least accurate way of measuring the propulsion performance improvement by the retrofit, as next to the improvements by the new propeller design and the new bulbous bow design, also the changes in engine performance (SFOC, fuel quality, etcetera) are measured. No distinction between the engine performance, propeller performance and hull performance can be made, when measuring engine fuel consumption.

The results of the full scale measurements via thrust, torque and fuel consumption are split for the light draught conditions and the design draught conditions. In Figure 12, the total results of the full scale performance improvements for the light draught conditions are shown. In Figure 13, the total results of the full scale performance improvements for the design draught conditions are shown.

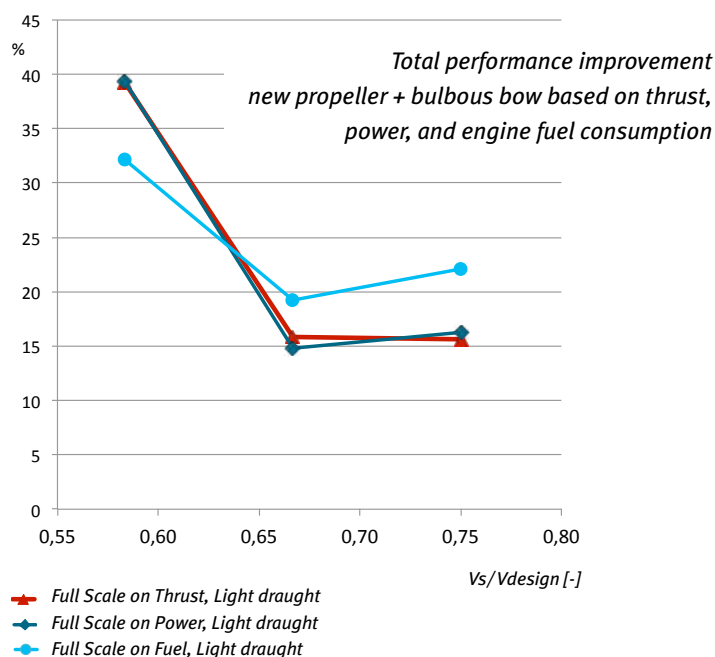


Fig. 12: Total full scale performance improvements based on thrust, torque (power), and engine fuel consumption measurements, for light draught conditions.

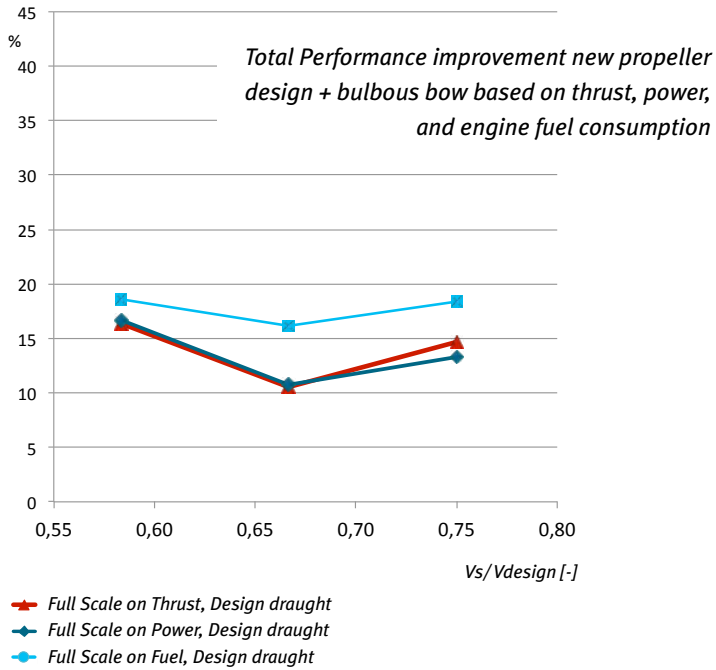
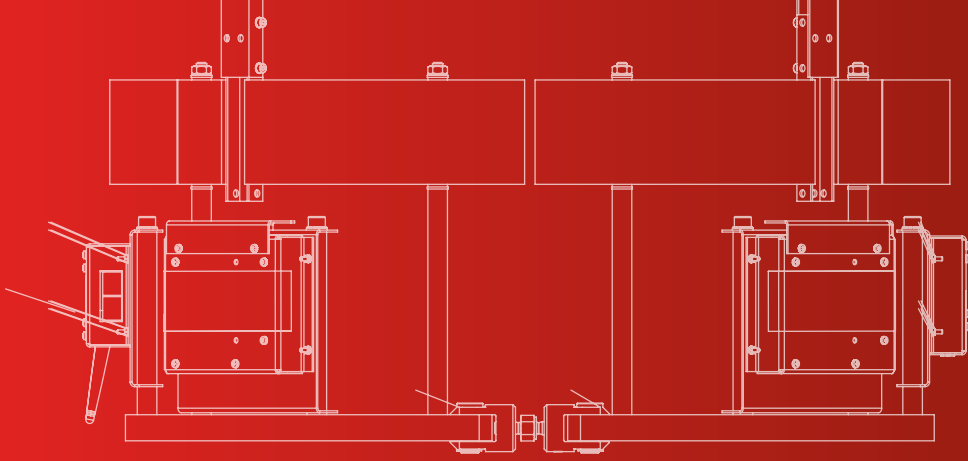


Fig. 13: Total full scale performance improvements based on thrust, torque (power), and engine fuel consumption measurements, for design draught conditions.

The full scale measurement results of the complete retrofit are very similar for both torque and thrust method. In addition also the improvements based on fuel consumption show a comparable trend with the thrust and torque measurements. The full scale measurement results are based on three different (independent) measurement principles. These three measurement principles provide comparable values (thrust and torque), and comparable trend (fuel consumption). The comparable values and trend indicate that thrust is an accurate method to measure performance improvements in propulsion.

The full scale performance measurements based on the TT-Sense® measurements of the complete retrofit, provide the most detailed insights into the individual performance improvements of the new propeller design, and the new bulbous bow design.





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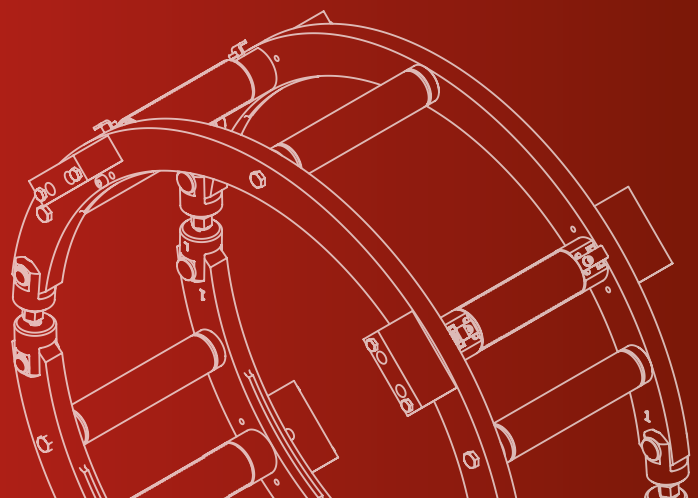
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