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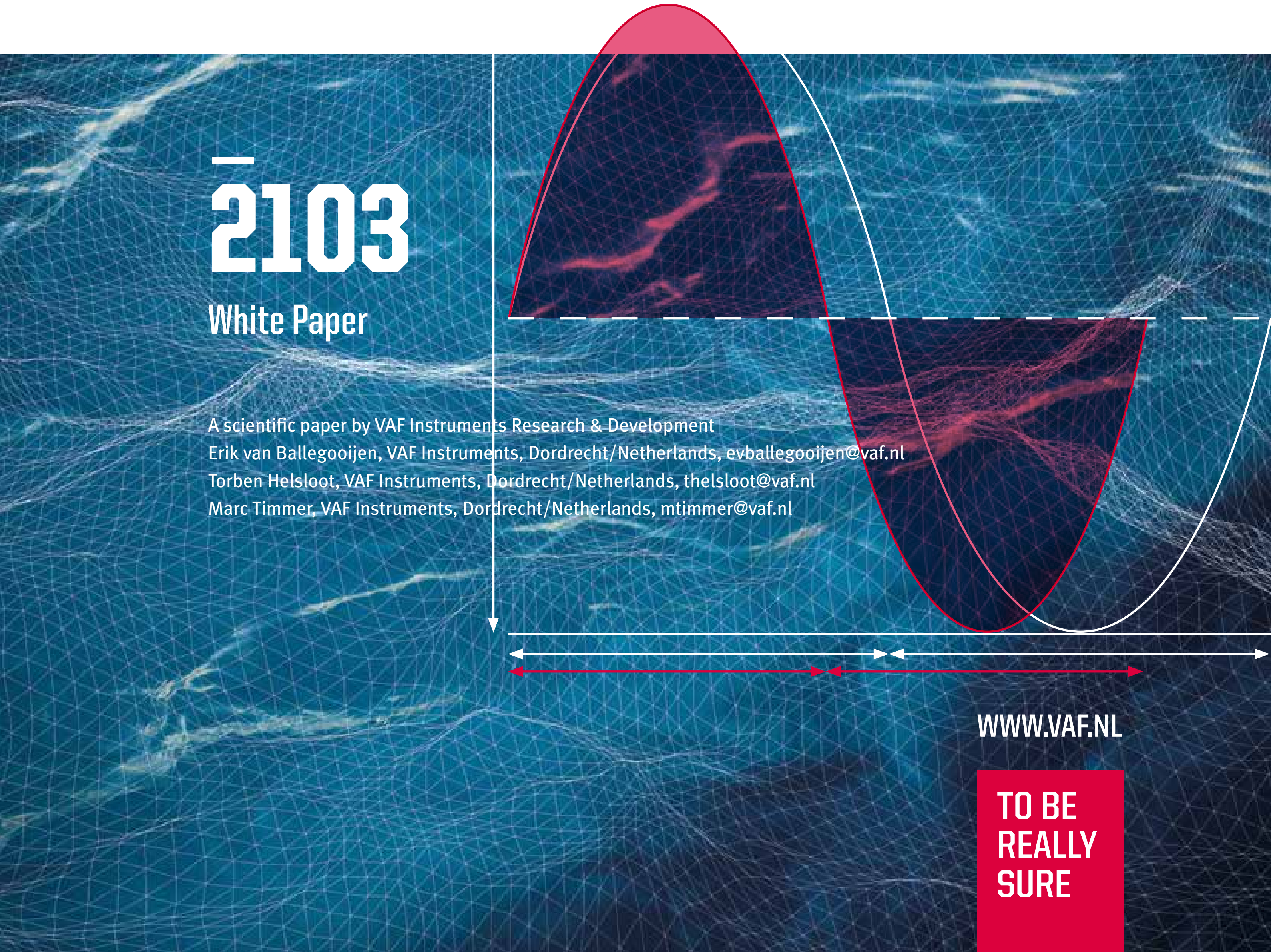
THE PROPELLER AS A SPEED LOG: USING FULL SCALE THRUST MEASUREMENTS TO QUANTIFY PROPELLER EFFICIENCY AND HULL FOULING



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White Paper

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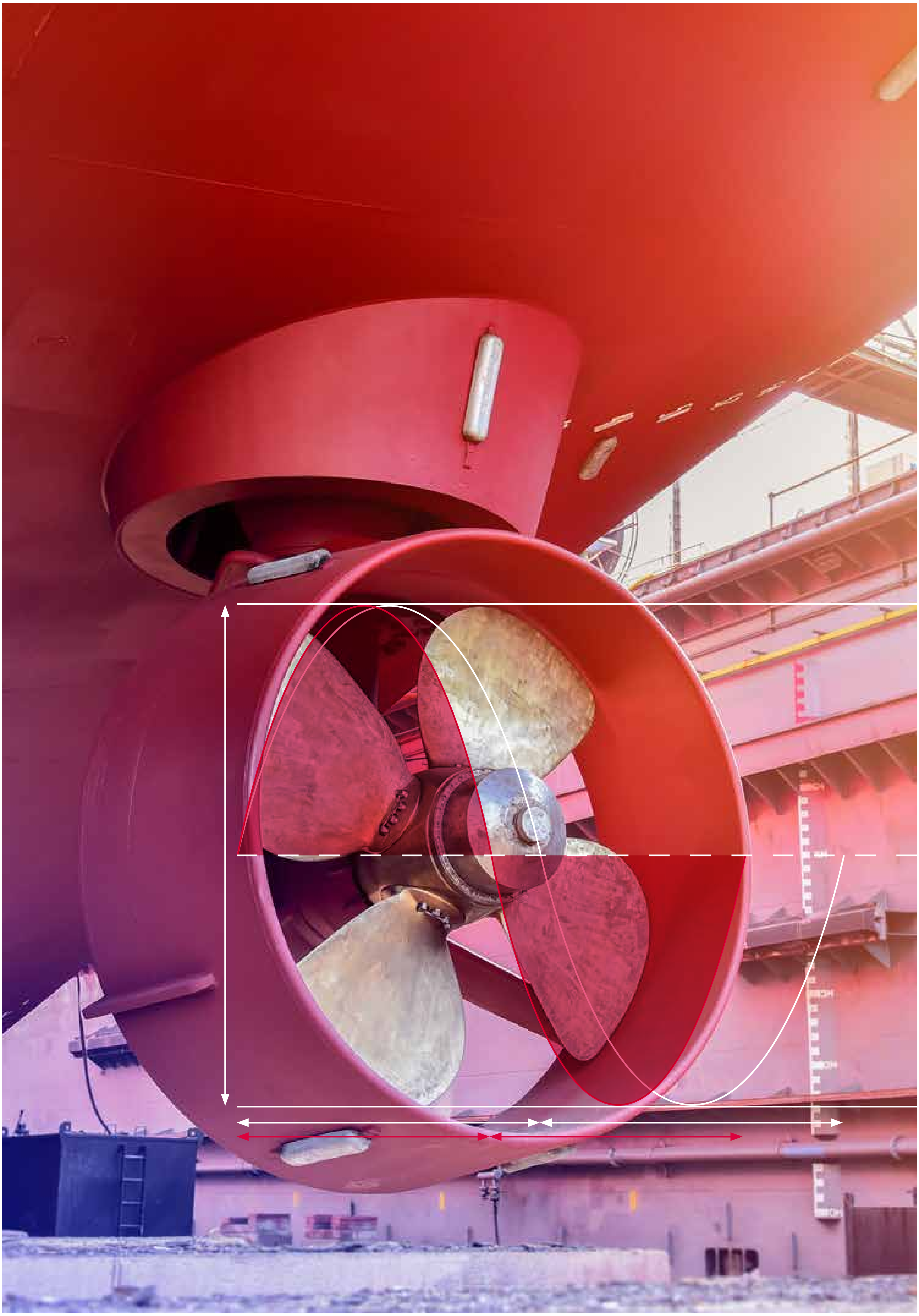
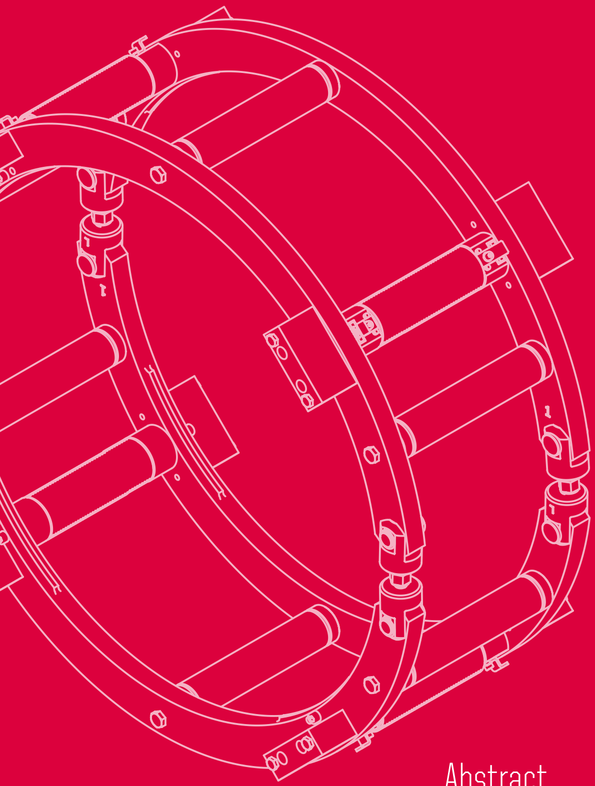
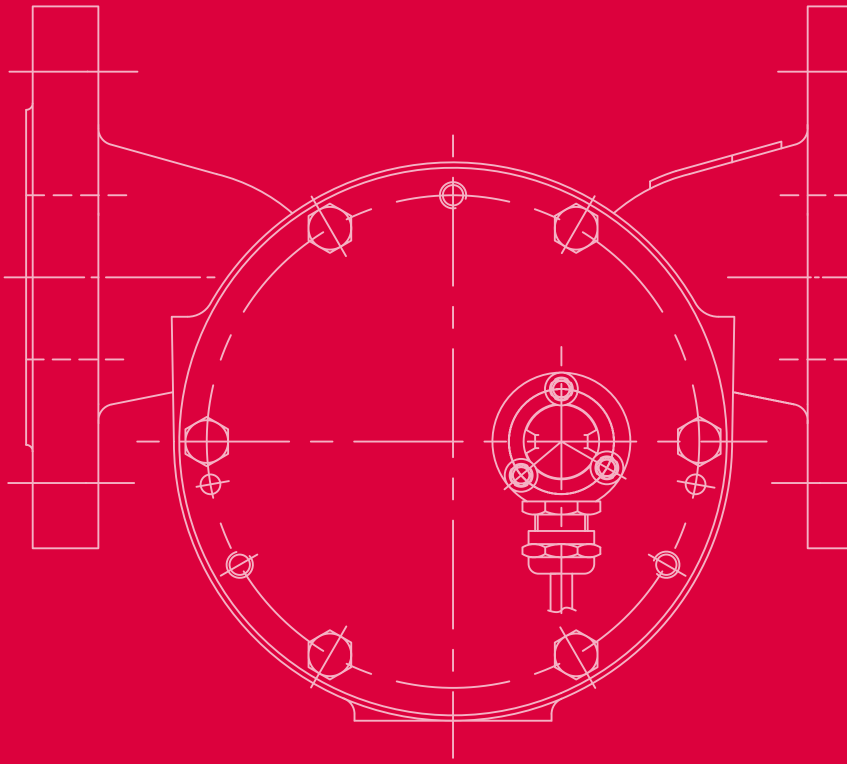




Abstract

Ships require less fuel when their hulls are clean and their propellers are smooth, so regular maintenance is needed to allow them to sail efficiently. To optimally plan maintenance to propeller and hull, the ship's hydrodynamic performance must be monitored. Full scale thrust measurements are a very useful input for such performance monitoring. Using thrust measurements a distinction can be made between efficiency losses related to the hull, and efficiency losses related to the propeller. Moreover, when a ship is equipped with a fixed pitch propeller the combination of propeller rotation rate and thrust can be used to estimate ship speed. This paper discusses a method to determine hull and propeller fouling separately, and a method to correct faulty speed log data using thrust measurements. A case study shows that the two methods successfully provide significant improvement to calculate changes in hull resistance and propeller efficiency.



1. INTRODUCTION

Ships require less fuel when their hulls are clean and their propellers are smooth. A ship operator can therefore save money and emissions by performing hull and propeller cleanings when they are needed. There is a trade-off between maintenance costs and costs incurred by hull and propeller fouling. This trade-off is not an easy one to make. Maintenance costs can be readily estimated, but the added costs of fouling are difficult to quantify. This can only be done by measuring changes in the hydrodynamic performance of a ship.

Over time, the surface of the propeller blades becomes more rough or damaged while biofouling accumulates on the hull. Biofouling causes a gradual increase in resistance and thus the required thrust increases (at equal ship speed). At the same time propeller roughness results in an increase in required torque (at equal thrust). By measuring thrust and torque over a period of time propeller fouling can be detected and separated from the effect of hull fouling.

The principle behind performance monitoring is relatively simple but in practice it has proven to be difficult. Three key challenges are:

- Collecting accurate measurements with long term stability in a harsh full-scale environment.
- Accounting for the large number of factors that influence torque and thrust that are not due to hull and propeller fouling.
- Separating hull fouling from increased propeller roughness.

This paper partly addresses the aforementioned challenges by presenting an approach to account for possible errors in speed measurements, as well as presenting an approach to separately determine the effects of hull fouling and propeller roughness. Both approaches are based on thrust measurements.

2. MEASURING THRUST

Thrust measurements are based on measuring the compression of the shaft under the influence of force. Reference [9] contains an insightful discussion of some successes and challenges regarding thrust measurements.

The thrust measurements used in this paper were done by the thrust and torque sensor developed by VAF Instruments called the TT-Sense®, shown in Figure 1. As discussed in [2], the TT-Sense® is an optical sensor that consists of two shaft-mounted clamp rings that can move independently. The rings carry detector arms equipped with four optical cells in total, that are sensitive to displacements down to 25 nm.

With the optical system strain is measured over a relatively large distance of 20 cm, resulting in a large signal for thrust. Another advantage of the TT-Sense® is that the shaft-mounted rings can move independently, which makes it straightforward to independently measure the compressive and torsionial displacement.

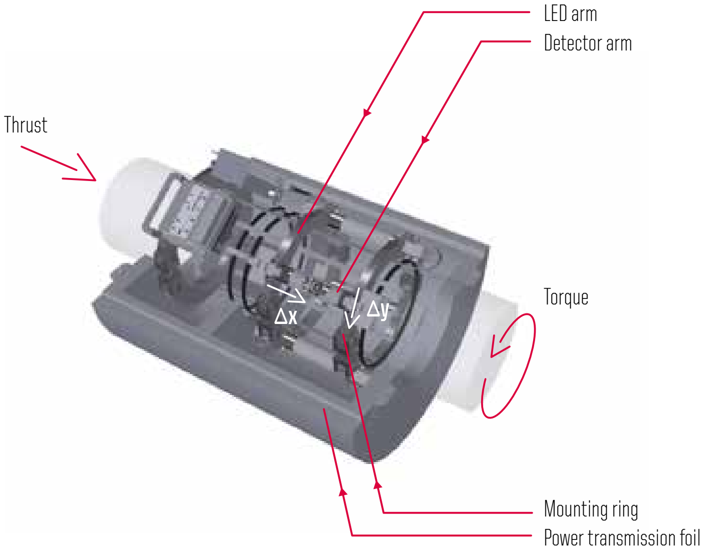


Figure 1: TT-Sense®, Thrust and Torque Sensor

3. SPEED THROUGH WATER

One of the vital pieces of information needed to monitor ship performance is the value of speed through water (STW). It is vital not only because the primary function of the propeller is to achieve a certain forward speed, but also because fuel costs are related to it with approximately the third power. Due to the strong dependency with fuel and also with thrust and torque, a small measurement error in STW will result in large errors in performance metrics.

3.1 Problems with speed logs

STW is measured by the ship's speed log, a sensor that most commonly works by measuring the doppler effect of transmitted sound waves reflected within the seawater. Because of their working mechanism doppler speed logs have a hard time dealing with air bubbles and ship motions, and are sensitive to the location and orientation in which they are installed. Air bubbles and ship motions can lead to temporary scatter in the measurements, whereas improper installation or calibration can lead to a permanent bias. Moreover, the speed of sound through water varies with temperature and salinity, the influence of which is not always properly accounted for.

Especially the slow variation in measurement errors caused by changes in seawater characteristics is a problem. It causes slow variations in performance metrics that are practically indistinguishable from the effects of fouling. Furthermore, speed logs are sometimes re-calibrated. When this is done the performance metrics that are based on speed can change suddenly.

The problems that arise in ship performance monitoring due to imperfect speed measurements are mentioned often in the literature [1][3][6], and have previously been addressed by combining more stable speed over ground (SOG) measurements with current estimates [3], or by combining several propulsion related inputs into a virtual sensor [1]. In this paper a different technique based on thrust measurements is proposed.

The goal of the proposed method is to provide an unbiased estimate of the speed through water that does not vary over time. Most importantly gradual variations due to seawater characteristics and sudden changes caused by e.g. recalibration should not occur in the new estimate. Scatter or imprecision is less of a problem for the specific purpose of performance monitoring, as long as it averages out in the longer run.

3.2 Speed estimation method

An age old method of determining speed through the water is based on propeller revolutions. Propellers are characterised by their pitch, the distance that they could theoretically travel in a single revolution if they behaved like a perfect cork-screw. By multiplying the propeller pitch by the number of revolutions per second one obtains a very optimistic estimate of ship speed.

In the era of the Titanic the position of a vessel could only periodically be accurately ascertained with the use of a sextant. With a known distance travelled between two moments in time and a known average propeller rpm an officer would be able to work out slip, the percental difference between the ideal 'cork-screw' distance and actual travelled distance. With rpm and slip known, the officer would then work out the speed of the ship. This made it possible to estimate the ship's position without taking new sights with the sextant, using dead reckoning.

The amount of slip however, depends on the amount of ship resistance that the propeller needs to overcome. In calm water conditions the propeller slip is mainly a function of rpm, but wind and waves cause added resistance so that propeller slip increases. Ship speed would be tabulated for a number of combinations of rpm and slip in a so-called slip table. Presumably, by making many observations of slip, an experienced crew would have some indication of the typical amount of slip in different weather conditions allowing them to make fairly accurate estimates of speed through water.

The proposed method in this paper also uses the principle of slip to determine ship speed. Where in the olden days manual observations could be made periodically, nowadays sensors and a continuous data logging system make the observations as often as once per minute, in which travelled distance (or SOG) and total revolutions (or rpm) can be used to calculate slip. Indispensably, also thrust is measured. Thrust is a strong predictor for slip because more thrust means that the propeller experiences a higher resistance, preventing it from achieving the ideal cork-screw distance. Rather than estimating ship resistance from wind, waves, draught, etc., the thrust force that actually causes slip is directly measured.

Using many data points, a statistical/machine-learning algorithm then learns the relations between thrust, rpm and slip so that the first two can be used to determine the latter. In this way the algorithm creates a modern successor of the slip table. In essence the propeller is thus turned into a speed measuring device.

A different way of thinking about this is to consider thrust as lift generated by the propeller blades. When rpm is kept constant the propeller blades can only generate more lift when the angle of attack increases. The angle of attack increases only when the inflow velocity to the propeller decreases. This means there is some unique relation between rpm, thrust and inflow velocity (which is strongly correlated to ship speed). Given enough data points this relation can be determined and used to estimate speed through water.

Figure 2 visualises the relation between thrust, rpm and speed through water in case of a well working speed log. Aside from some scatter there is a clear pattern. A nearly linear relation exists between rpm and speed, but at heavy propeller loads speed decreases and vice versa. The colour bar indicates the difference between the expected value of thrust and the measured thrust, with red denoting a heavily loaded propeller and blue a lightly loaded one.

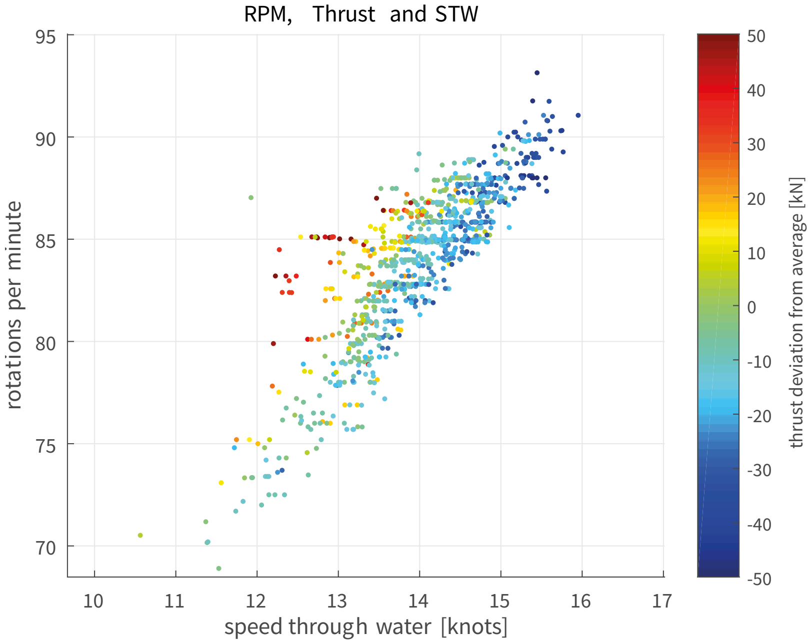


Figure 2: The measured relation between STW, rotation rate and thrust.

3.3 Possible objections to the method

There are a couple of assumptions that are made with the proposed method. When these assumptions are violated the results will be less accurate, so it is important to be aware of them. For the best results the following things must apply:

- The ship must be sailing in quasi-static conditions, in other words, the ship must not be accelerating or decelerating strongly.
- The propeller must not change much over time. Critically the lift-generating properties of the propeller blades must remain the same.
- When averaging over a significant period of time, mean speed over ground must be approximately equal to speed through water.
- The wake-fraction should not change much.

The method only works because thrust is strongly related to ship speed. When accelerating or decelerating quickly this is no longer true. As a consequence, the described method cannot be used as a general replacement for a speed log. For the performance monitoring application in this paper however, data points are selected at times during which the ship was in nearly equilibrium conditions. For these data points the method is valid. The amount of thrust generated by a propeller is mostly determined by non-viscous effects. Increasing roughness is not expected to change the lift-generating properties of the propeller blades much because it does not change the shape of the blades. At a given rate of rotation, roughness will increase friction and thereby the torque needed to rotate the propeller, but will not affect the generated thrust. Some evidence for this was found in [8], in which the graphs show that the thrust coefficient for a propeller changes negligibly between an equivalent sand roughness ranging from about 10 to 250 μm. A separate study [7], also shows no change in the thrust coefficient for the investigated roughness range. This is especially important because it shows that the speed estimation method will not be affected by polishing the propeller. However, if the propeller gets damaged or macro-fouling occurs the method will break down.

The assumption that average SOG is equal to average STW means that a ship encounters as much adverse currents as advantageous currents. For most ships this is a valid assumption, but when there is enough freedom to plan routes advantageous currents will be preferred. In this case there will be a long term difference between SOG and STW and the present method could have a slight bias.

Another assumption of the method is that the propeller inflow speed has a fixed relation with ship speed. Therefore the wake-fraction is not allowed to change much. This assumption is violated when a ship moves from shallow to deep water or vice versa. To improve accuracy in this case the method should be extended with an approximation for shallow water effects, but this has not been done for the results in this paper.

3.4 Results of the method

The results of the STW correction are presented to the end-user via the performance monitoring dashboard of the VAF IVY® website. This website is connected to a cloud storage containing sensor data that has been collected and processed on board of a ship. The data is automatically uploaded to the IVY® cloud storage, where the STW correction algorithm processes it and visualises the results.

Figure 3 shows the data of the original speed log signal. The data points represent quasi-static conditions. The difference between speed over ground and speed through water is plotted as an indication of speed log quality. Between May and December 2017 the speed log consistently indicates a lower speed than the GPS device. It is highly unlikely and inconsistent with other data that this is due to persistent advantageous currents.

Figure 4 shows the data of the corrected speed log signal. Again the data points represent the same quasi-static conditions, for which the speed through water has not been determined by the speed log, but was instead calculated according to the thrust method. The new data points are much more evenly distributed around the zero-line, signalling better correspondence with speed over ground. Moreover, the long term fluctuations are less severe in the corrected STW data.

This difference can best be seen in the comparison graph, Figure 5, where the moving averages of both the original and the corrected STW are shown in the same graph. From this graph it is apparent that the STW corrected with the thrust method has less bias and less long term variation. It would thus be advisable to use the thrust corrected STW in this case, because it is clearly better than the original speed log. The end-user can select both the original and the corrected speed to use for the ship performance analysis.

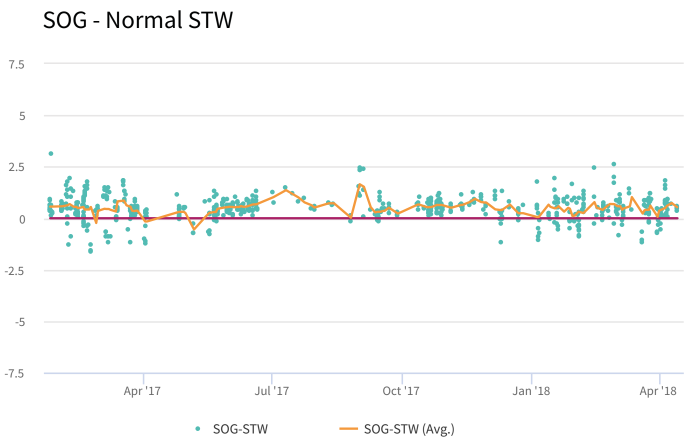


Figure 3: Original difference between SOG and STW in knots

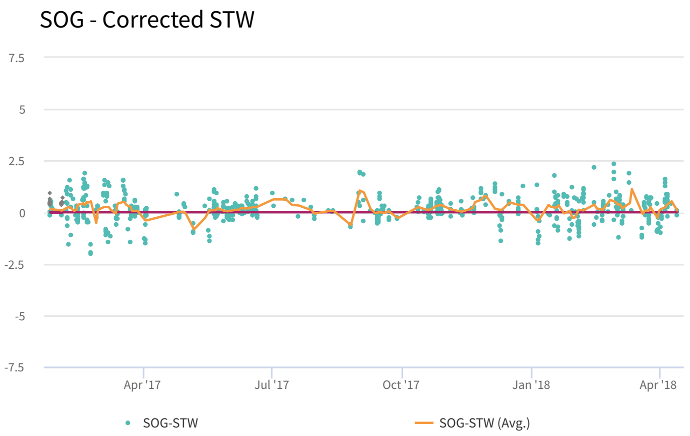


Figure 4: Corrected difference between SOG and STW in knots

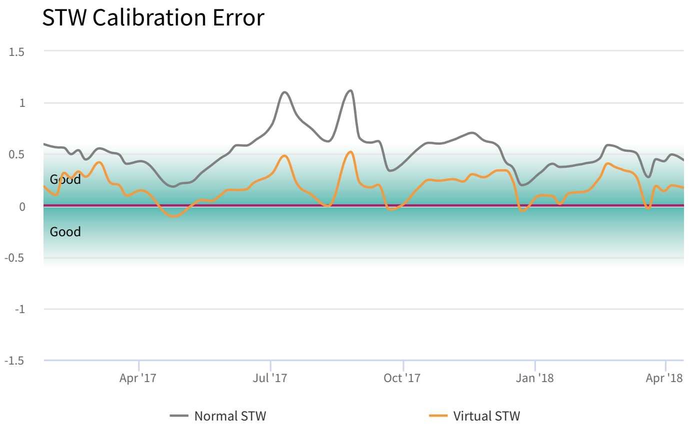


Figure 5: Moving averages of current in knots indicated by the original speed log and corrected STW.

4. SEPARATING HULL AND PROPELLER

Propulsion performance analysis can be done in many ways depending on the amount of data that is available. This is exemplified by the fact that even the ISO19030 standard on performance analysis contains a part concerning alternative methods [5]. The standard also notes: “If hull performance is to be separated from propeller efficiency, propeller thrust would also have to be measured.” [4]. Aside from this note, analysing ship performance with thrust measurements is outside the scope of ISO19030, so in this paper a slightly different methodology will be used.

Three KPI’s were designed to indicate changes in hull efficiency, propeller efficiency and propulsive efficiency (combined hull and propeller efficiency). The three KPI’s are:

- Propulsion KPI $\dfrac{\text{Expected Power}}{\text{Measured Power}}$ 100%
- Hull KPI: $\dfrac{\text{Expected Resistance}}{\text{Measured Resistance}}$ 100%
- Propeller KPI: $\dfrac{\text{Measured Propeller Efficiency}}{\text{Expected Propeller Efficiency}}$ 100%

The definition of these KPIs makes sure that downward trends denote a loss of efficiency and increases denote performance gains. The expected resistance, power and propeller efficiency rely on a prediction model that is based on the one described in [2]. For the measured quantities the following definitions are relevant:

- $\text{Power} = 2\,\pi\,\dfrac{\text{rpm}}{60}\,\text{Torque}$
- Resistance = Thrust (1 - thrust deduction)
- $\text{Prop.Efficiency} = \dfrac{\text{Thrust STW (m/s) (1-wake fraction)}}{\text{Power}}$

Thrust deduction and wake fraction account for the interaction between propeller and hull, but they are not precisely known, which introduces errors. It is expected that these errors are minor. Performance analysis regards relative changes in power consumption so that only the changes in the interaction terms are relevant.

Following the approach in the rest of this paper, data points for the performance analysis are chosen to represent quasi-static conditions. To isolate the effects of fouling from other influences filters are applied for low windspeeds, similar draft and deep water. The act of filtering the data makes sure that the difference between expected and measured power is most likely caused by fouling and not by other effects.

The filtered data points can be used to estimate the rate of deterioration of propeller efficiency, hull resistance and total propulsive efficiency. They can also be used to estimate the beneficial effect of cleanings on the aforementioned performance indicators.

4.1 Case study

To estimate the effect of cleanings it is customary to average performance indicators over a period of time before the maintenance event, and a period afterwards. The difference between these two averages indicates how effective the cleaning has been [4].

To accommodate a fair comparison it is important that the speed measurement does not differ between the before and after period. However, if the ship sailed in warm water (e.g. Mediterranean Sea) before the cleaning event and moved to colder water (e.g. Baltic Sea) after the event, this might affect the speed through water measurement to such an extent that the performance indicators become unreliable. The case study in this section serves as a real life example of this.

The ship under consideration is a large (⇢50,000GT) passenger vessel that underwent maintenance where both the hull and propeller were cleaned. The data used for this study encompasses 11 months, roughly 5.5 months before and 5.5 months after the maintenance. The KPIs are calculated as described, and averaged over the two maintenance periods. After filtering the following number of data points remain:

- Before cleaning: $N_{before} = 226$
- After cleaning: $N_{after} = 246$

In Figure 6 water temperatures are shown during the measurement period. Before the cleaning, denoted with a dashed line, the ship sailed for a large part in warm water, after the cleaning it sailed predominantly in colder water.

The average water temperature of the data before the maintenance events was 27 °C, the average temperature after was 19 °C. This difference in water temperature has had an effect on the accuracy of the speed log. A clear correlation exists between sea water temperature and the moving average of measured current, which suggests the speed log is temperature dependent. The effect that this has on ship performance analysis becomes apparent when the KPIs are calculated based on the original STW.

In Figure 7 the calculated KPIs are shown using the original speed log. The KPIs are supposed to quantify the effect of fouling on consumed power, resistance and propeller efficiency in percentages, where a percentage lower than 100 is an efficiency loss. By eye, the effect of the maintenance is hardly noticeable. Halfway between Month 5 and the dashed line, a visibly detectable change does occur, which seems to correlate with the decreasing sea water temperature.
The change in propulsive efficiency is not caused by the change in seawater properties itself. Although water temperature also has an effect on viscosity, which influences frictional resistance, this effect is already taken into account by including it in the expected power and resistance. Also, the change in KPI is of the opposite sign, because resistance increases in cooler water. The difference in resistance due to water temperature is not large, at 19 °C it is estimated to be almost 2 percent higher than at 27 °C.

Figure 8 shows the calculated KPIs for the same data points, but with the speed through water corrected with the thrust method. These graphs correspond much better with what can logically be expected from a cleaning event. The step halfway between Month 5 and the cleaning is now no longer visible, whereas the data points directly after maintenance have noticeably better KPIs. In addition, the scatter in the data has been reduced.

Table 1 contains a summary of the data. The data points are averaged to estimate the long term effects of the cleaning. The mean KPI values as well as the standard error of the mean (SEM) are displayed for the period before the hull and propeller cleaning and the period afterwards. The analysis with the original speed log shows a very small adverse effect of the wrong sign. The analysis using the corrected speed log shows a moderately large improvement in power consumptions, caused by improvements in both hull resistance and propeller efficiency. The standard errors are also smaller for all the averages that are computed over the corrected speed log, which means that scatter has been reduced.

Original STW	Mean (SEM) Before Cleaning	Mean (SEM) After Cleaning	Cleaning Effect
Propulsion KPI	99.6 (3.0e-2)	99.4 (3.3e-2)	-0.2 %
Hull KPI	99.6 (2.1e-2)	100.3 (2.4e-2)	0.7 %
Propeller KPI	99.8 (1.5e-2)	99.0 (1.1e-2)	-0.8 %
Corrected STW			
Propulsion KPI	100.4 (2.3e-2)	106.6 (1.8e-2)	6.1 %
Hull KPI	100.2 (1.9e-2)	104.7 (1.8e-2)	4.6 %
Propeller KPI	100.0 (1.3e-2)	101.3 (5.3e-3)	1.3 %

Table 1: KPI summaries using different STW inputs

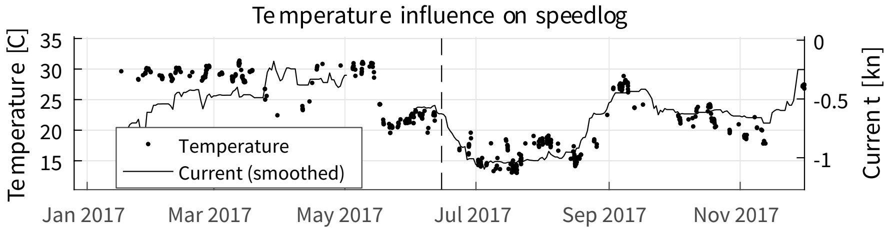


Figure 6: Sea water temperature during monitoring period

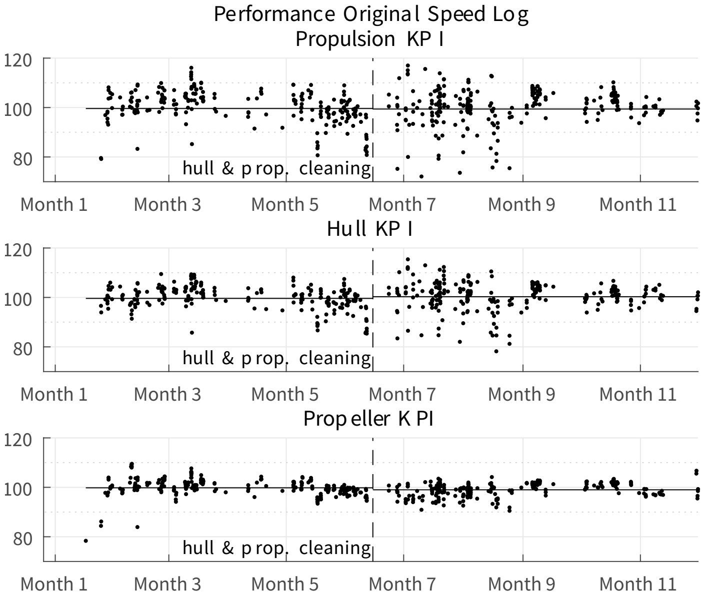


Figure 7: Performance metrics with the original speed through water measurements

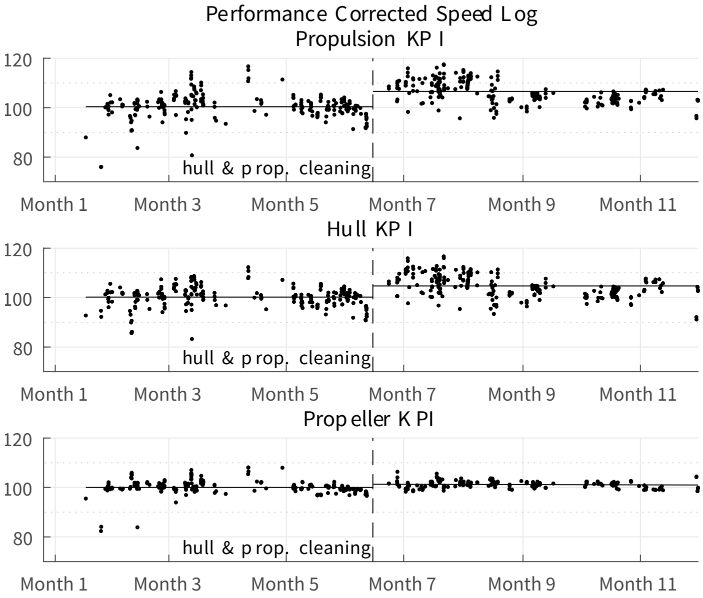


Figure 8: Performance metrics computed with corrected speed through water values

5. CONCLUSIONS

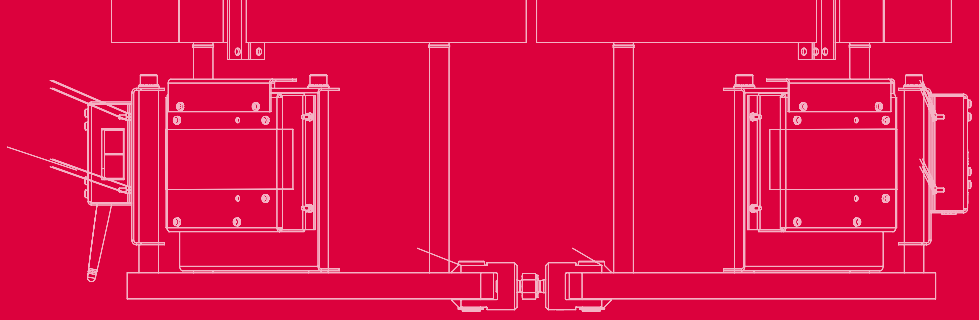
The accuracy of ship performance analysis is very much dependent on the accuracy of speed through water data. Ships are commonly equipped with doppler speed logs that can be slightly influenced by seawater temperature. In the presence of large temperature differences this heavily affects the outcome of performance analysis.

Through the use of thrust and rpm measurements propeller slip can be predicted. The measurement of thrust can therefore be used to provide a corrected estimate of speed through water. In the presented case study the method reduced bias and temperature dependency compared to speed log data.

Ship performance analysis based on corrected speed log data provided more credible results than analysis based on original speed log data, or speed over ground data. Additionally the corrected speed log favourably reduced variance in KPIs.

Using corrected STW data the maintenance effects of a combined hull and propeller cleaning were estimated. In this case study hull resistance was 4.6% lower after cleaning, while propeller efficiency saw a relative increase of 1.3%. This resulted in a 6.1% decrease in required propulsive power.

The case study has shown that thrust measurements can be used to improve ship performance analysis in two ways. Firstly, thrust measurements can be used to correct the signal of a faulty speed log. Secondly, thrust measurements allow the effects of a propeller cleaning and a hull cleaning to be separately determined.



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Authors biography

Erik van Ballegooijen holds the current position of R&D Director at VAF Instruments. He leads a multi-disciplinary team of data scientists, software developers, hydrodynamicists and electrical engineers. He has over 20 years of experience at VAF Instruments and Wärtsilä, leading innovations in propulsion design, hydrodynamic technology and software development. He is a regular speaker at shipping related conferences.

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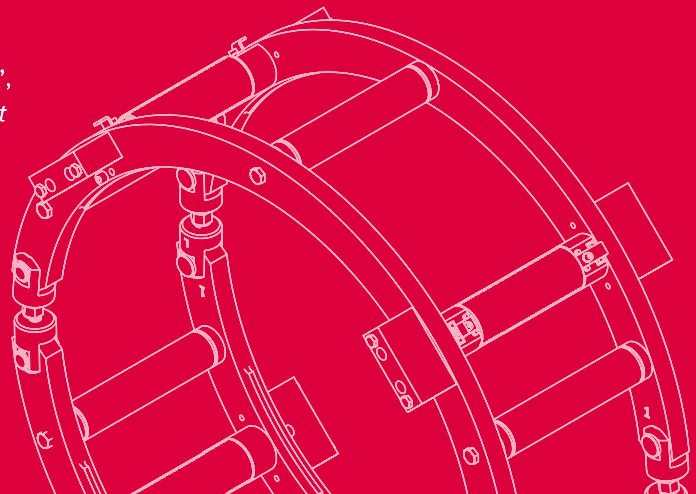

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