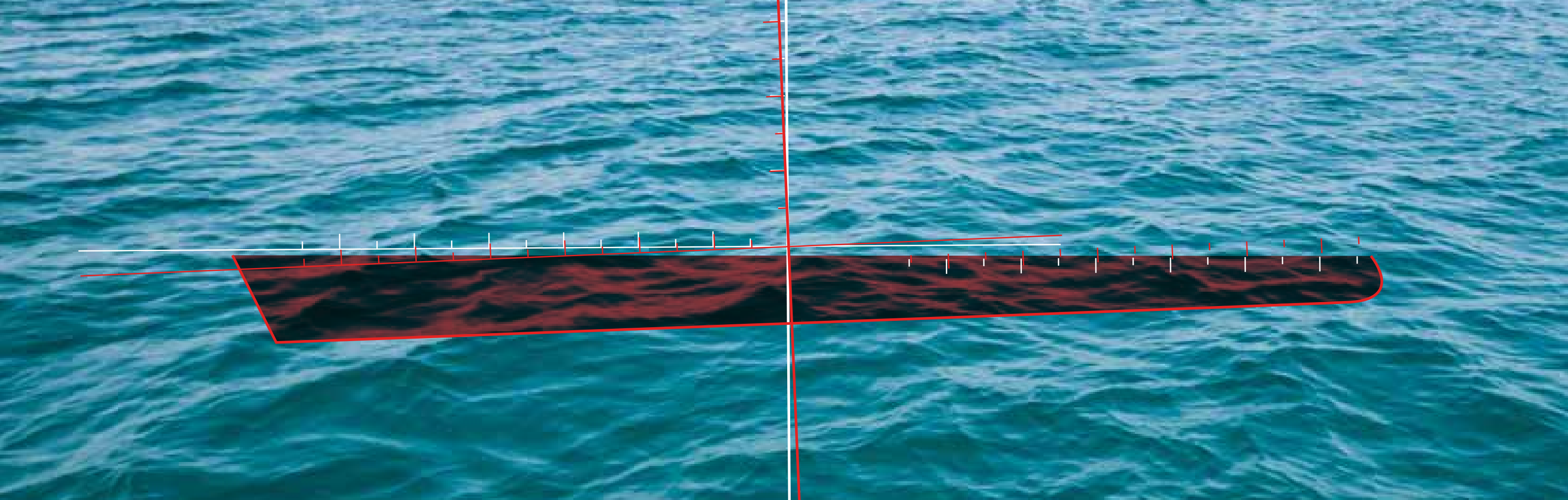
EXPERIENCE WITH FULL SCALE THRUST MEASUREMENTS IN DYNAMIC TRIM OPTIMISATION



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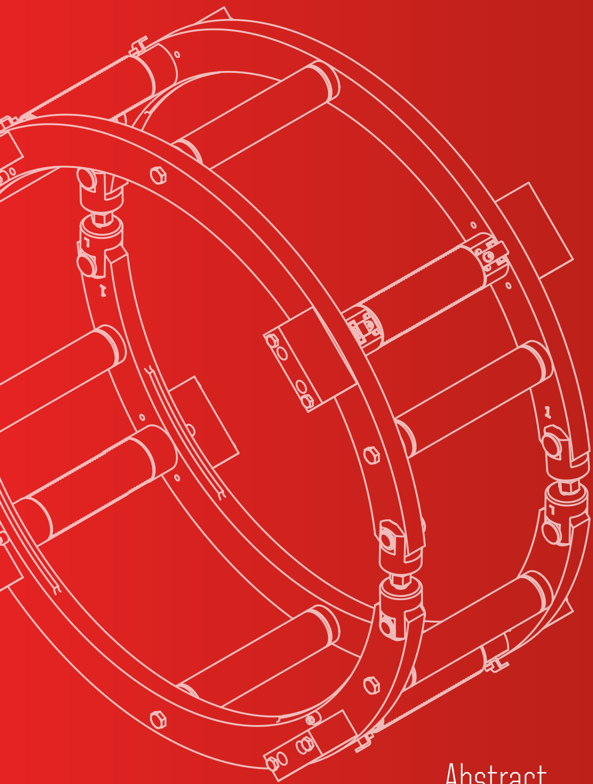
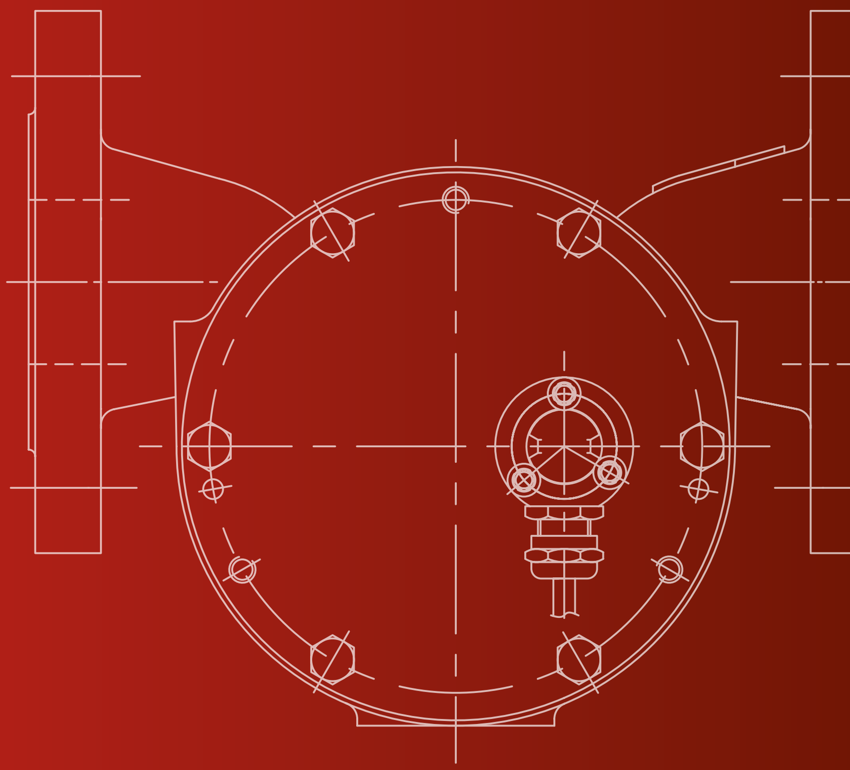


Abstract

This paper presents an explorative study on the role that thrust measurements can play in trim optimisation. Currently data-driven trim optimisation solutions rely on a shaft power meter, but it will be demonstrated that also thrust measurements are a valuable input. A better understanding of the subject is gained by discussing the effects of trim and assessing different approaches to trim optimisation. Possible improvements that thrust measurements can bring to the data-driven method are suggested and investigated with the help of a case study. In this case study continuously monitored data of a ship that was equipped with a thrust sensor and power meter is presented. With the help of the thrust measurements insight is given in how the hull and propeller separately respond to changes in trim. Through further analysis of the full-scale data it is shown that there is a promising potential for improving data-driven trim optimisation by incorporating thrust measurements in addition to power measurements.



1. INTRODUCTION

The trim of a ship is the difference between its forward and aft draught. Trim can be influenced relatively easily. Before the start of a voyage it can be altered by carefully choosing the weight distribution of cargo, and during the voyage by changing the levels in the ballast tanks. Fuel savings can be achieved by choosing the right trim in the right circumstances, and therefore the subject of trim optimisation is of high interest to the maritime industry

Changing the trim changes a ship's resistance, even when all other variables are kept the same. As such there is an optimal trim value, at which fuel consumption is lowest. The optimal trim value is different in different operating conditions because it is dependent on other variables, most importantly speed through water and draught, see e.g. *Bertram* (2014).

To be able to sail as efficiently as possible the optimal trim should be known at all times. Sailing at any draught and at any speed, the ship's crew should be able to select the amount of trim for which the required power is minimal. This means that the power should be determined for a large number of different combinations of trim, speed and draught. Determining this has traditionally been done with full-scale trials and/or model tests, *SSPA* (2009). More recently the capabilities of computational fluid dynamics (CFD) have progressed far enough so that it is economically viable to compute the influence of trim for a large array of speeds and draughts, *Hansen and Freund* (2010). Even more recently the maritime industry has become increasingly data driven, enabling the advent of data-driven trim optimisation, in which machine learning algorithms deduce the relation between trim and power by learning from data measured when a ship is in service, *Ignatius et al.* (2013).

Technological progress has increased the options and potentially improved the accuracy of trim optimisation. In this paper the role that another innovation, thrust measurements, can play in further improving trim optimisation is discussed. VAF Instruments has developed the TT-Sense®; a device that in addition to being a torque and power meter, is able to measure the thrust provided by the ship's propellers. Information regarding thrust is of large added value because it is measured at the shaft, in between the propeller and the thrust bearing (see Figure 1), allowing the hull and propeller to be analysed separately.

It is therefore expected that thrust data can be a valuable input for data-driven trim optimisation. The application of the TT-Sense® with regard to trim optimisation had already been envisioned by its designers. Now that the sensor has been on the market for several years the first steps to making this a reality are presented.

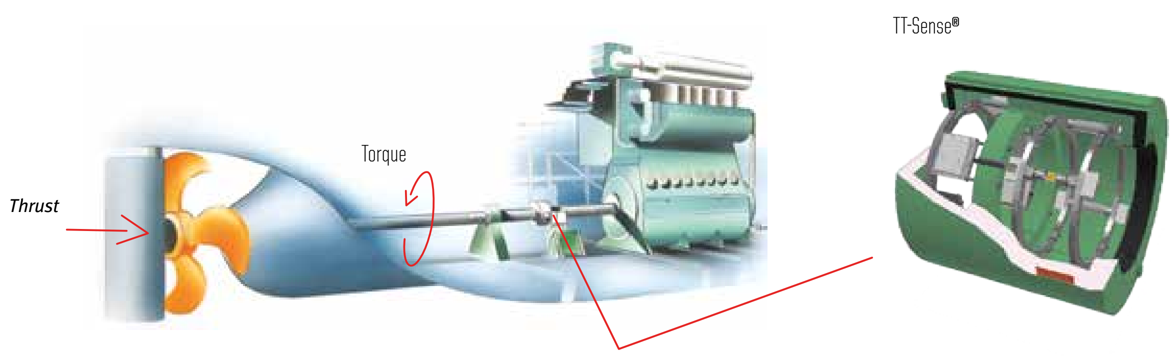


Figure 1: Measuring hull and propeller performance with the TT-Sense®

2. THE EFFECTS OF TRIM

Trimming changes the shape of the submerged part of the hull and because of this different hull shape almost every resistance and propulsion related aspect is affected by trim. As discussed by *Reichel et al.* (2014), the most important influences on the required propulsive power are the change in residual resistance of the ship and the change in propulsive efficiency.

The residual resistance changes primarily due to a change in the wave pattern that is generated by the ship. Especially when a bulbous bow is present the effect of trim on the wave pattern can be large. A favourable trim will result in a favourable wave pattern in which less energy is dissipated.

The propulsive efficiency is affected because the flow around the hull changes with trim. This causes the thrust deduction factor and wake fraction to change resulting in a changed hull efficiency (η_h). Moreover the propeller starts to operate in a different wake and therefore the propeller efficiency (η_o) changes. These two effects result in a changed propulsive efficiency. A favourable trim will result in a favourable flow pattern around the hull so that less power is lost by the propeller and by hull-propeller interaction.

An important distinction has to be made between static and dynamic trim. The trim before the start of the voyage is referred to as static trim. *Gourlay and Klaka* (2007) discuss that when underway, the flow around the hull and the influence of the active propeller change the pressure distribution beneath the hull which, amongst other factors, causes the actual trim to change with respect to the static value. The trim as measured during a voyage is referred to as dynamic trim. When the operating conditions of a voyage are known in advance, it is possible to predict the dynamic trim based on the static trim, and vice versa. Trim optimisation software can both give a static trim advice before the voyage commences, and a dynamic trim advice while sailing. Whenever trim is mentioned in this paper it should be understood as dynamic trim.

3. PREDICTING THE EFFECTS OF TRIM

To predict the effects of trim it is most important that the change in (residual) ship resistance and the change in propulsive efficiency are correctly determined. The resistance has to do with the hull, whereas propulsive efficiency is the domain of the propeller (forgetting for a moment about interaction effects). Therefore, to have a good prediction of the effects of trim, both the hull and propeller need to be correctly captured. In the next few paragraphs three methods of modelling that were mentioned in the introduction will be briefly discussed, addressing the uncertainties involved with them. The three methods are; the model test approach, the CFD approach and the data-driven approach.

3.1. Model tests

In the model test approach self-propulsion tests will need to be performed to take into account both the hull and the propeller. To account for viscous scale effects corrections will have to be made, translating the model results to full scale. Because the hull and propeller adhere to different scaling laws they will have to be treated separately. The full-scale corrections are the biggest source of uncertainty with model scale tests. Another contribution to the uncertainty of model tests results from imprecision and bias in sensors, but because of the controlled laboratory environment of a towing tank this uncertainty can be kept to a minimum. It has been observed that different experimental approaches can lead to differences in the predicted optimal trim, *Reichel et al.* (2014).

3.2. Computational Fluid Dynamics

CFD computations can be done at full-scale, which eliminates the influence of scale effects. However different CFD models use different approximations to model viscous effects, which means that there are modelling uncertainties involved. Moreover the use of numerical methods introduces a numerical uncertainty. The propeller is often separately modelled from the hull, and the models are coupled e.g. in the approach taken by *Hansen and Freund* (2010). Just as in the model test approach the hull and propeller are thus treated separately.

3.3. Data-driven approach

The focus of this paper lies on the data-driven approach, which uses full-scale data measured during regular ship service. This alleviates the problems of scale-effects and numerical uncertainty. However, the conditions in which these measurements are made are quite the opposite of a laboratory environment, and hence the data is more scattered than model test data. The sensors operate in harsh conditions and the data is dependent on a lot of changing external factors (wind, waves, temperature etc.) that are not present during a model test. This introduces uncertainty. The trim optimisation that is done based on the full-scale measured data relies on machine-learning algorithms that are able to cope with noisy and uncertain data that depends on many variables. There are many choices to make in the selection of the machine learning model and the relevant parameters it takes into account (feature selection). Those choices may influence the optimal trim predicted from the same data, which means there is also an uncertainty involved in the model selection for the data-driven approach, *Pétursson* (2009).

3.4. Pros and Cons

When using CFD computations and model tests the influence of trim on the hull and the propeller can be separated. This is not the case for the data-driven approach when it relies on the power meter only. Even though the optimal trim can be predicted based on power only, it does take away the additional insight that the other two methods can give.

Another weakness that the data-driven approach arguably has, is the problem of data scarcity. When conducting experiments or computations a predetermined matrix of draught, speed and trim can be accounted for such that there is a knowledge base covering all operational conditions of a ship, even though it rarely encounters. A trim optimisation model that learns 'on the job' from data obtained in service may not accurately predict in newly encountered conditions simply because it does not yet have the data to do so. These considerations are more elaborately discussed by *Bertram* (2014).

To cope with data scarcity it is also important to mitigate what is known as the 'curse of dimensionality'. This is a problem that occurs with high-dimensional data because with an increase in dimensions the volume spanned by those dimensions rapidly becomes larger, effectively making the data more scarce. If the dimensionality of data (in other words the amount of relevant variables) can be reduced, this can improve the optimal trim prediction of the machine-learning model, *Pétursson* (2009).
Each of the methods to predict the relationship between trim and fuel consumption has its own strengths and weaknesses. Which method is most accurate or most cost-effective is an interesting question that will not be discussed in this paper. Instead it will be investigated if some of the challenges in the data-driven method can be addressed by incorporating additional information in the form of thrust measurements.

4. ADVANTAGES OF USING THRUST MEASUREMENTS IN TRIM OPTIMISATION

In the previous sections it was discussed that trimming can be used to optimise the resistance of the hull as well as the performance of the propeller. It was also addressed that when using a power meter, the data-driven trim optimisation methodology only optimises the system as a whole (i.e. total propulsive power) without giving any insight into the contribution of the separate components. In addition it was mentioned that it is favourable to reduce the number of relevant variables that are used as an input for machine-learning models. Taking into account these considerations, it will be discussed in this section how the measurement of thrust can be used to the advantage of data-driven trim optimisation.

4.1. Separating hull and propeller

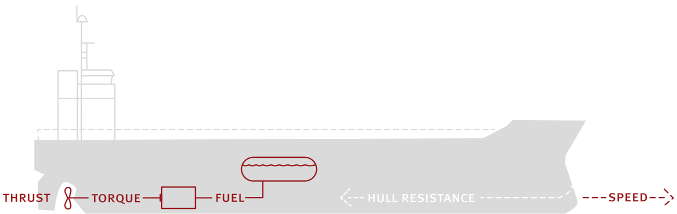
Suppose that a ship is continuously sailing at exactly the same speed. When the hull resistance increases because of the adoption of a sub-optimal trim, the power required to propel the ship will increase. The thrust delivered by the propeller will also have to increase to match the increased resistance.

Now suppose that only the efficiency of the propeller decreases due to a sub-optimal trim. The required power will increase as well, but because the hull resistance does not increase the propeller will not have to deliver a larger amount of thrust. In both cases the power demand increases, but only if the hull resistance increases does the thrust increase. This is why thrust measurements are needed to make a distinction between the performance of the propeller and the hull.*

When thrust measurements are available the effect that trim has on hull resistance can thus be separately analysed from the effect that trim has on propeller efficiency. In Section 5 this will be demonstrated with real in-service data.

4.2. Reducing relevant parameters

The ability to separate hull resistance and propeller efficiency can be beneficial when there are influences aside from trim that influence the one but do not affect the other. An example will be given in the following paragraphs.



In reality there are interaction effects between propeller and hull that make matters more complicated, and one would need to measure flow speeds in the ship's wake to resolve this. As this is not practical the pragmatic approach is chosen to apportion the increase in required power that can be linked to an increase in thrust to the hull, and the remainder to the propeller.

Figure 2: Only by measuring thrust propeller efficiency can be separated from hull resistance

Some ships are equipped with a propeller of which the blade angles (pitch) can be adjusted during sailing. This type of propeller is called a controllable pitch propeller (CPP). In contrast to a conventional propeller, a CPP can deliver the same amount of thrust at different rotation rates by using a different pitch. The efficiency of the propeller will depend on the chosen pitch and will therefore affect the power needed to propel the ship, see Figure 3.

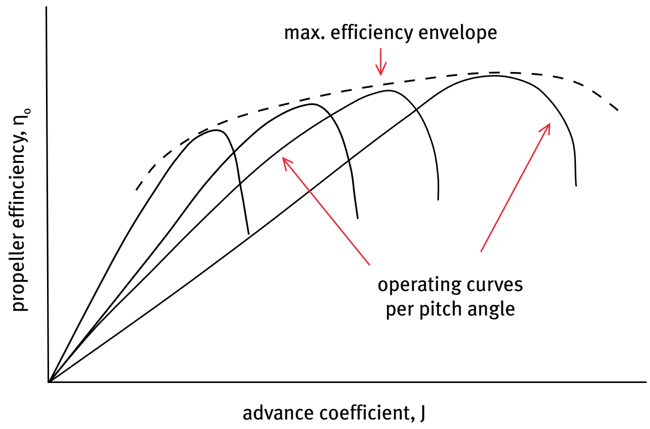


Figure 3: Schematic graph of propeller efficiency and pitch (CPP)

To illustrate how this can affect trim optimisation suppose the following scenario takes place: A ship sails with a speed of 14 knots and a draught of 6 meters. It does so with a low value of trim and consumes a relatively low power. This data point is provided to the trim optimisation software which learns from the experience. Two weeks later the ship sails again with 14 knots at a draught of 6 meters. It now has a high value of trim and consumes a relatively high power. However, its CPP now has a different pitch and efficiency than it did a week before. Now the increase in power cannot be ascribed to the high value of trim, because it may have been caused by the difference in propeller pitch. Therefore, when power measurements are used to optimise trim the change in propeller pitch (efficiency) must be taken into account.

Suppose now that this same ship had used thrust measurements to optimise trim. At a low value of trim it turns out a relatively low thrust was needed to overcome the resistance of the ship. Two weeks later when it sailed at a higher trim it turns out that an even lower amount of thrust was needed to propel this hypothetical ship, in other words, its hull resistance had decreased. When thrust measurements are used to optimise trim, the CPP efficiency is no longer relevant and there are less variables to take into account.

A sensibly designed ship will have an optimised hull shape equipped with a propeller that has been optimised to operate behind that same hull. In general one can expect the propeller to operate most efficiently in those cases where the hull resistance is lowest (taking into account some limiting factors such as propeller submergence). The optimal trim value can thus be found relying on thrust measurements. Some evidence for this will be presented in Section 5.

4.3 Increasing reliability

The assumption that the trim value that minimises the required thrust and the trim value that minimises the required power are approximately equal, leads to the possibility of consolidating those two values. In doing so a greater reliability can be achieved by the trim optimisation software.

Ideally the machine learning model is able to learn realistic relationships between speed, draught, trim and thrust or power, while taking into account the relevant external conditions. If it has successfully done so the model can predict the optimal trim even when the ship sails in new, unseen conditions. Conditions for which no data is available yet.

However there is a risk that the model predicts wrong, and overfits certain parameters in such a way that the model output corresponds to observations within the current set of available data, but makes bad predictions when the results are extrapolated to predict certain conditions that are void of data, *Pétursson* (2009). Overfitting can be detected when two models are trained to find the optimal trim, one based on thrust, the other based on power. If the two models predict roughly the same optimal value it is pretty safe to say that it is close to the truly optimum trim. If the two models predict entirely different values it may be an indication that overfitting has taken place.

5. CASE STUDY

The previous sections introduced the concept of data-driven trim optimisation, and discussed the possibility of using thrust measurements instead of or in addition to power meter readings. To demonstrate that thrust measurements are indeed a useful input, some full-scale TT-Sense® data is presented within this case study.

In this section data is shown in order to compare the effect of trim on power with the effect that trim has on thrust. The case study encompasses a month of continuously monitored data that, to protect the interests of our clients, is completely anonymised. The vessel in question has a length between 200 and 300 meters and is equipped with a fixed pitch propeller. No machine-learning algorithms will be used in the case study, instead a more perspicuous approach is chosen so that the results can be more clearly understood.

5.1 Relevant variables

The variables that are used in the case study are:

- Thrust
- Power
- Trim
- Speed through water
- Draught
- Wind speed
- Water depth

Thrust and power were measured by the thrust and torque sensor developed by VAF Instruments called the TT-Sense®. As discussed by Ballegooijen and Muntean (2016), the working principle of the TT-Sense® is based on measuring shaft compression and torsion. Optical sensors detect the small displacements over the shaft length, in both axial and tangential directions, corresponding to the compression (thrust) and torsion (torque) of the propeller shaft. The used optical measurement principle allows for an independent measurement of both the thrust and the torque. Torque, combined with the measured rotation rate, is used to compute power, see Figure 4.

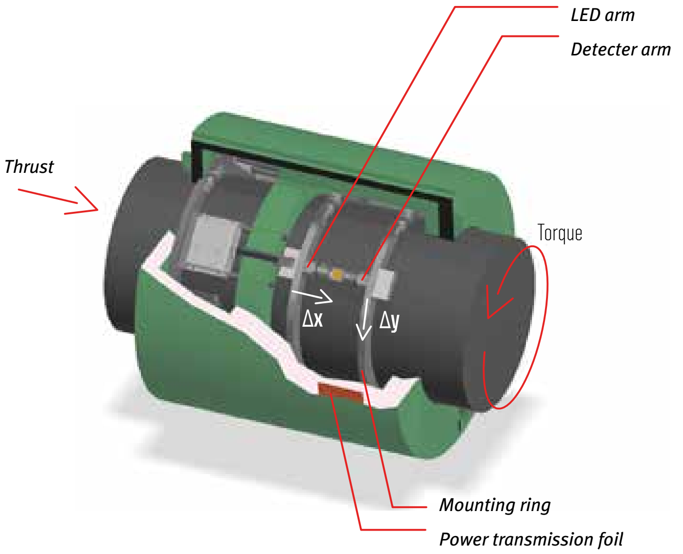


Figure 4: TT-Sense®, Thrust and Torque Sensor

Trim is measured by two draught sensors near the bow and the stern of the ship. Unfortunately this is not the most accurate way of measuring trim, since the sensors are sensitive to variations in speed. In the ensuing analysis the results will be presented in very narrow ranges of ship speed, which will mitigate this problem. However, for future studies it is preferable to use a dedicated instrument to measure trim, such as an inclinometer or real time kinematic (RTK) GPS technology.

Speed through water is measured by the speedlog. It is a known problem that the speedlog is not always a reliable instrument. Fortunately, the speedlog data used did not show any obvious signs of faultiness.

Draught sensors located near midship are used to measure the draught of the ship. Wind speed is measured with an anemometer and water depth with a depth gauge.

The values of these variables have been logged on board of the vessel with a sampling interval of one second. The average value of each minute was stored and sent to shore. The minute averaged values are used in the ensuing analysis.

5.2 Data preparation

In order to isolate the effect of trim on power and thrust, the effects of external influences should be minimal. To ensure this is the case the data is filtered. Firstly data is only used from those periods in time during which the ship was sailing at a near constant speed. In other words, data from periods of time during which the ship was accelerating and not in physical equilibrium are removed from the data set. Moreover, the data set is filtered for deep water and low wind speeds so that the influences of shallow water effects, waves and wind are small. For the sake of clarity and transparency no corrections or alterations have been applied to the data.

From the filtered set of data of which external influences have been mitigated, three subsets are selected of narrow ranges in draught and speed. For each of these subsets both the draught and speed are only allowed to vary within +-2% of their mean value. This ensures that the influence of draught and speed variations is small in those subsets, so that only the relation between trim and thrust and power remains.
Even with the narrow speed range a noticeable dependency of power on speed was observed. This is to be expected, considering power relates roughly to the cube of speed. In order to further remove the influence of speed, the power was therefore made adimensional with the cube of speed. Analogously the thrust was made adimensional using speed squared. In order to compare the influence of trim on both power and thrust in the same graph they need to share the same axis. This has been achieved by dividing the adimensional power and thrust of each individual data point in a subset, by the average of the adimensional power and thrust of all data points within that subset. The resulting variables are:

$$P^* = \frac{\frac{P}{V^3}}{\left\langle \frac{P}{V^3} \right\rangle} \qquad T^* = \frac{\frac{T}{V^2}}{\left\langle \frac{T}{V^2} \right\rangle}$$

P* indicates a relative power, T* indicates a relative thrust. A data point having a P* of 1 needed the expected, average amount of power. A data point with a P* of 1.05 needed 5% more power than the average, and with a P* of 0.95, 5% less. The same goes for thrust. When it is approximated that effective towing power is linearly related to thrust, a 5% increase in T* equates to a 5% increase in towing power. If both P* and T* increase with 5%, that means the propeller efficiency stayed equal, and the increase in power can be ascribed to an increase in hull resistance entirely. If for a certain trim the increase in P* is larger than the increase in T*, that means the propeller has also become less efficient.

5.3 Results

In this section measured thrust and power data from the TT-Sense® will be shown as a function of trim. This will be done for three operating conditions. For all three operating conditions the draught is the same, but they have different speeds; 14, 14.5 and 18 knots.

The figures show the measured values of thrust and power, converted to the adimensional values T* and P* respectively. All values were sampled while the ship sailed in very similar conditions, calm weather, deep water, and with only +-2% variation both in ship speed and draught. With the influence of all other parameters mitigated, the thrust and power are only dependent on trim. The figures can be used to estimate the dependency for the applicable operating condition.

In Figures 5, 7 and 9 the thrust and power values are shown side by side. In Figures 6, 8 and 10 the exact same data points are shown again within the same graph. For the latter set of figures a polynomial fit has been drawn through the datapoints in order to highlight the differences between them. The polynomial fits are purely indicative, they are meant to show the general trend that is followed by the data points.

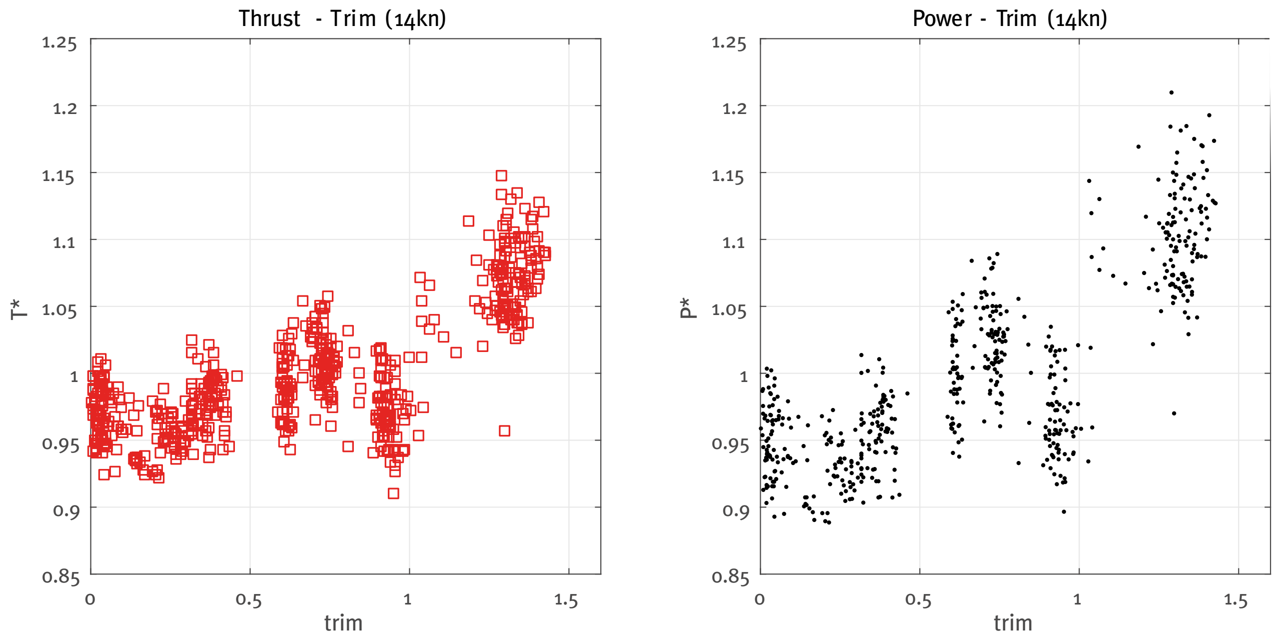


Figure 5: Side by side display of thrust and power at 14 knots

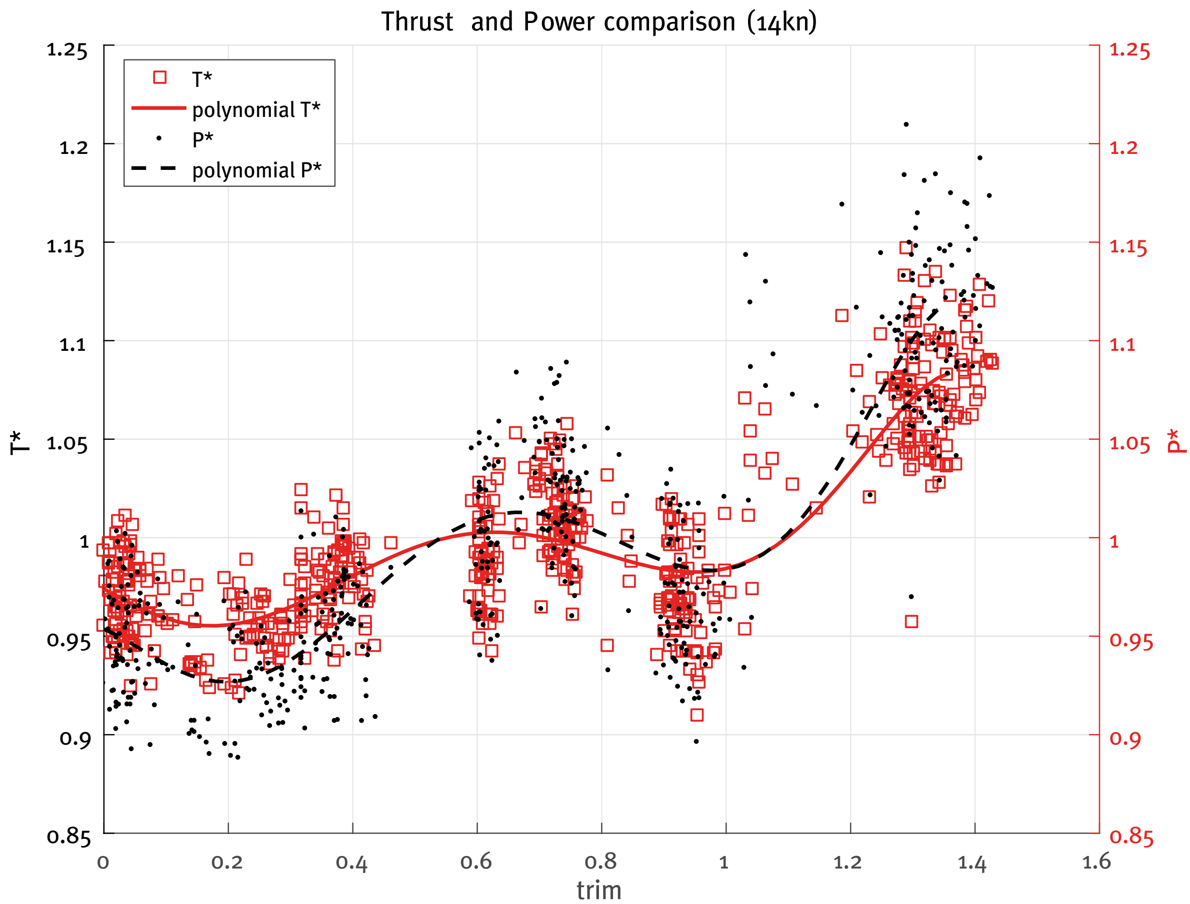


Figure 6: Direct comparison of thrust and power at 14 knots

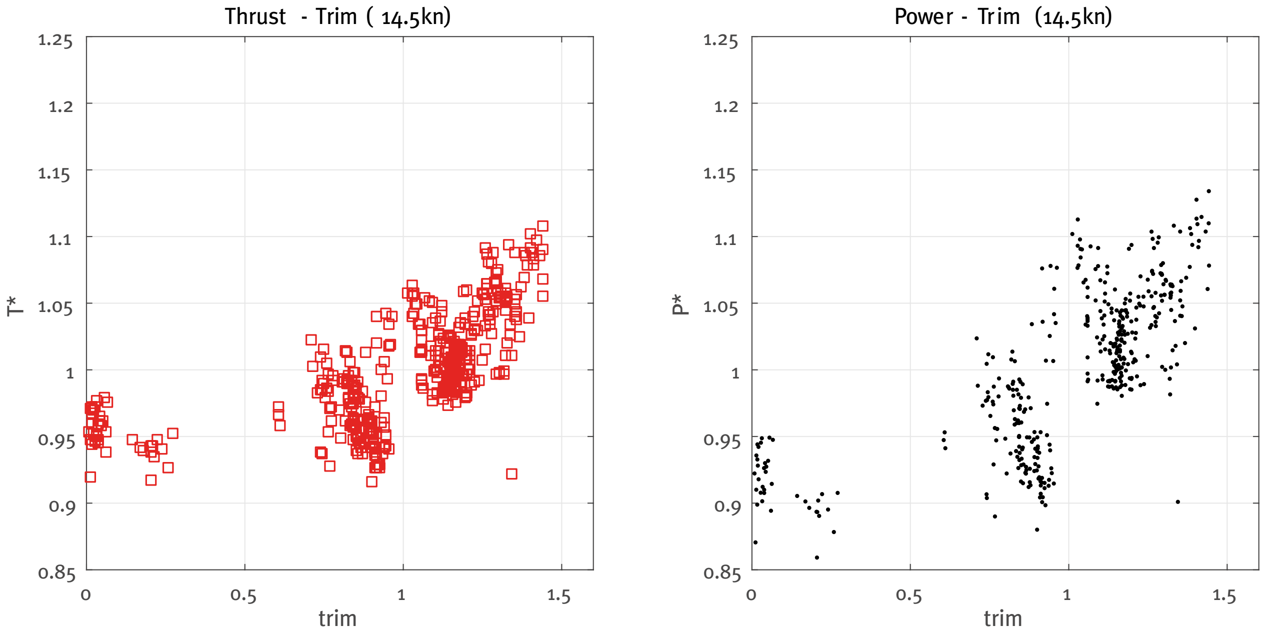


Figure 7: Side by side display of thrust and power at 14.5 knots

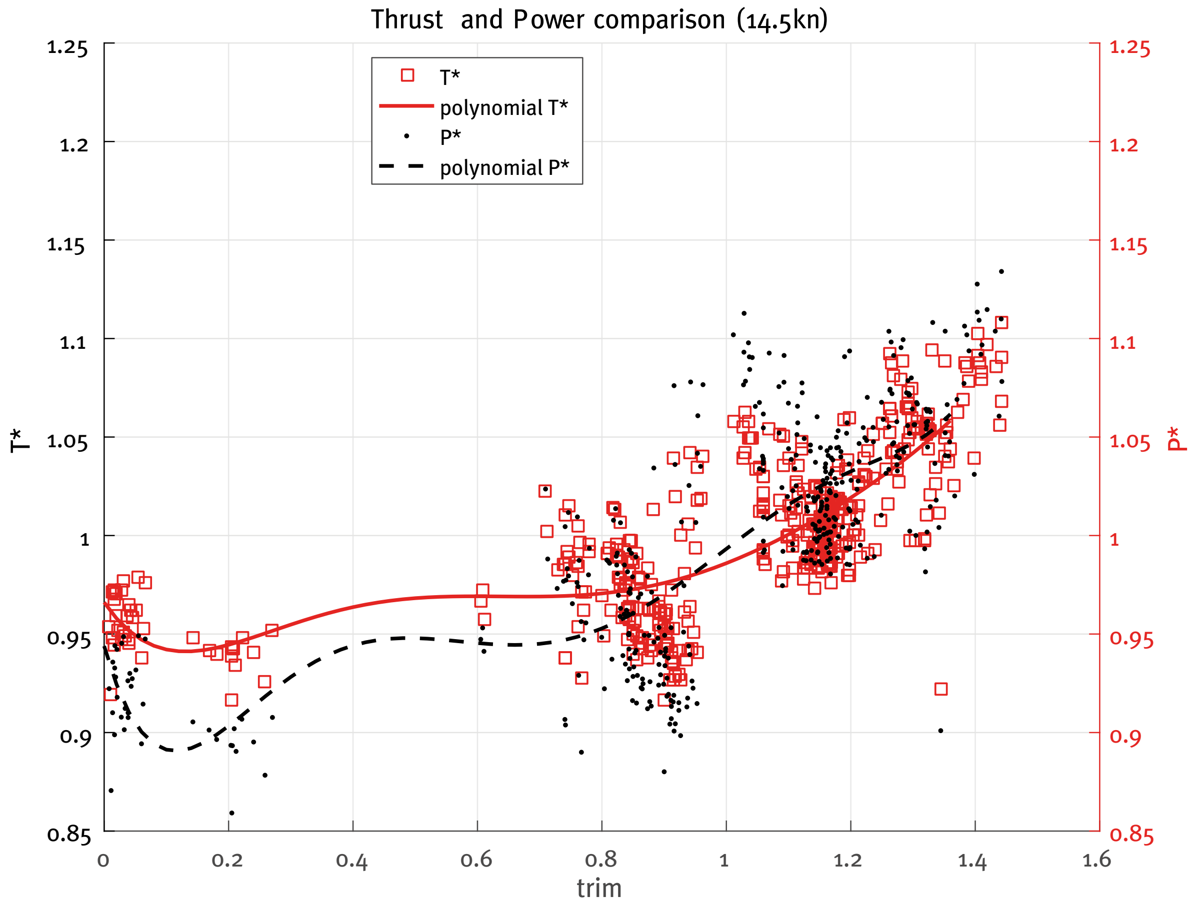


Figure 8: Direct comparison of thrust and power at 14.5 knots

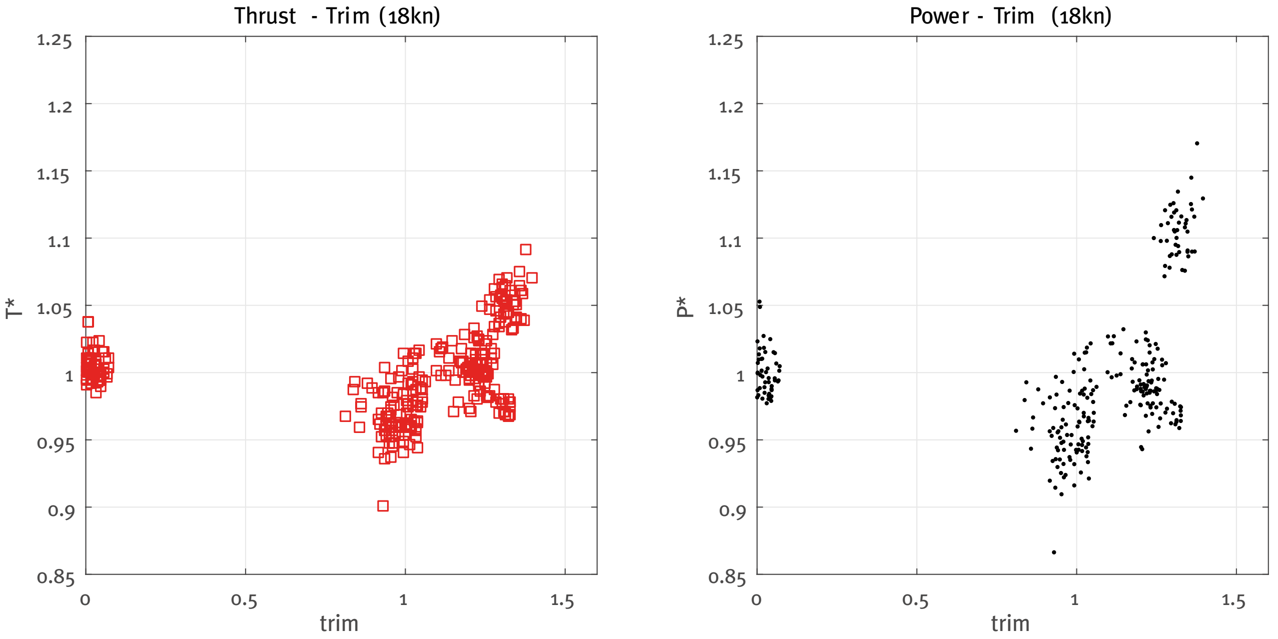


Figure 9: Side by side display of thrust and power at 18 knots

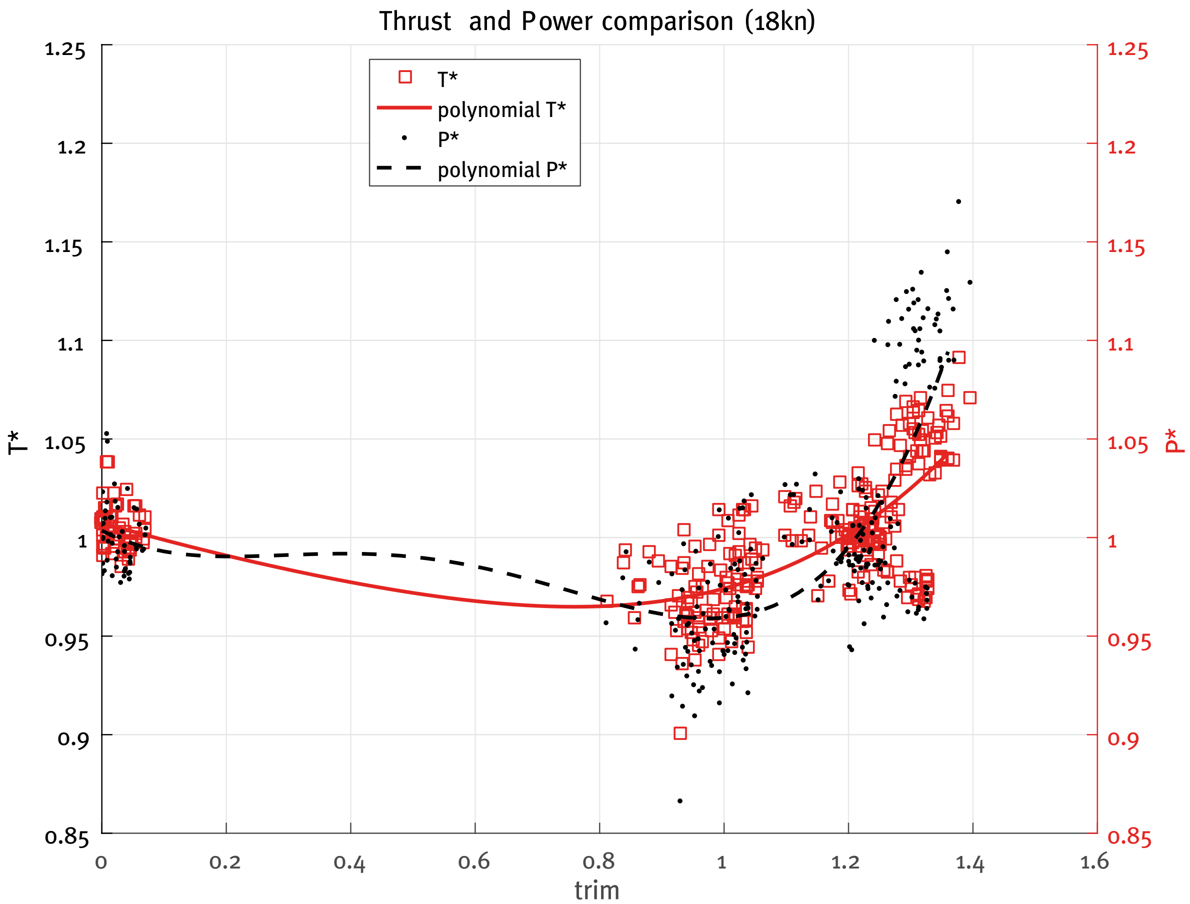


Figure 10: Direct comparison of thrust and power at 18 knots

5.4. Discussion

The quality of the measurements in this case study is found to be sufficient for data-driven trim optimisation. The measurements of power and thrust show a very similar relationship to trim in the three investigated cases. Moreover, the derived relationships between trim, thrust and power are plausible, demonstrating the capabilities of the TT-Sense® as a measuring device.

The trim value where thrust is smallest is almost the same as the trim where required power is smallest. However, where T* has a low value, P* has an even lower value. This means that the decrease in required power cannot be explained only by the decrease in hull resistance, but that the propeller is more efficient in those cases as well. As was hypothesised in Section 4.2 the propeller appears to be most efficient when the hull resistance is smallest. At least for the investigated draught. The reverse also applies, when T* is large P* is even larger, indicating that the propeller experiences an unfavourable wake when hull resistance is largest.

Even though the polynomial estimation suggests even lower values, the lion's share of the data indicates a most optimal P* of about 0.95. This means that by always sailing at the most favourable trim the ship under investigation can save about 5% in propulsive power consumption compared to how it is currently trimming. This seems to roughly agree with values reported by commercial parties (see SSPA (2009), Ignatius et al. (2013), Hansen and Freund (2010) and the overview given in McMillan and Jarabo (2013)). It must be taken into account that it is not always possible to adopt the optimal trim in practice.

For the operating condition at 14 knots there is a good amount of data spanning the entire range of trim. For the other two operating conditions however, there is data missing for certain values of trim. This is simply because the ship never sailed in such a condition. In Figure 10 between 0.1 and 0.8 meter trim the polynomials for thrust and power predict opposing trends, without there being any data to justify this. It nicely exemplifies the problem of data scarcity. Even though trim optimisation software will make a much more sophisticated estimate than a simple polynomial, a generalisation will inevitably be made without there being data to validate it.

6. CONCLUSION

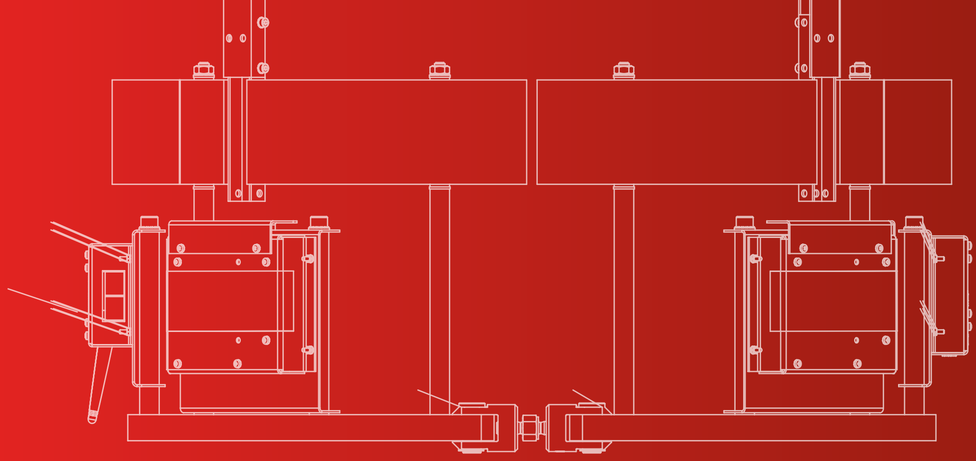
There is a promising potential for improving data-driven trim optimisation by incorporating thrust measurements in addition to power measurements. In a case study it was shown that the TT-Sense® provided thrust data of a good quality. The information on thrust allowed for a separate measurement of trim effects on the hull and the propeller. This separation can especially be helpful when dealing with controllable pitch propellers.

The conventional propeller investigated in the case study seems to perform best when the hull resistance is low and worse when hull resistance is high. As a consequence the trim value that minimises hull resistance is very close to the trim value that minimises total power.

During the period of continuous monitoring, the ship did not sail at every possible combination of trim and speed. This caused gaps in the data. When trim optimisation software tries to predict what happens in these data gaps there is a risk of overfitting. This was demonstrated with simple polynomial fits. When such fits are based both on thrust and power measurements, it can be checked whether they do not deviate too much.

> By incorporating thrust measurements into data-driven trim optimisation software, its reliability can thus be improved.

An interesting next step would be to build a proof of concept of trim optimisation using thrust data. Additional research with more data of ships (with CPPs) would be supportive in this.



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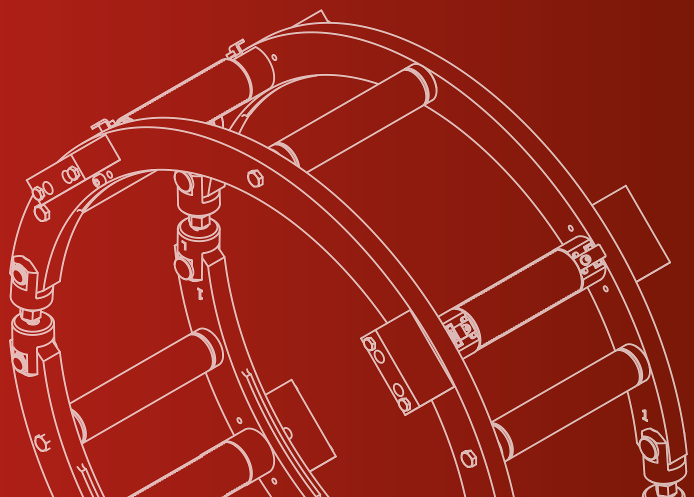

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