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Trim Optimisation - Theory and Practice

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ABSTRACT: Force Technology has been working intensively with trim optimisation tests for almost last 10 years. Focus has primarily been put on the possible power savings and exhaust gases reduction. This paper describes the trim optimisation process for a large cargo vessel. The physics behind changed propulsive power is described and the analyses in order to elaborate the optimum trimmed conditions are presented. Different methods for prediction of required power in trimmed conditions are presented and results are compared against each other. The methods with their advantages and disadvantages are discussed. On the basis of power prediction, a trim guidance with dedicated SeaTrim® software for ship master is made and presented.

1 INTRODUCTION

Trim optimisation is one of the easiest and cheapest methods for ship performance optimisation and fuel consumption reduction. It does not require any hull shape modification or engine upgrade. The optimisation can be done by proper ballasting or choosing of proper loading plan.

Although trim optimisation tests are considered less important than standard power performance model tests they can provide substantial savings and a return on investment between one and six months, depending on vessel type, operation and number of vessels in the series. The energy savings as a result of trim optimisation have been proven also by Hansen and Freund (2010), where the influence of water depth on possible gains has also been described.

The trim optimisation can be made by means of model tests or by means of computational fluid dynamics (CFD). Some results of possible power gains proven by CFD methods have been reported by Hansen and Hochkirch (2013) and a brief comparison of CFD methods with model tests at model and full scale have been presented by Hochkirch and Mallol (2013). These studies showed that generally both methods agreed well with each other concerning the trends in power requirement with respect to trim.

FORCE Technology is a leading consultant in the trim optimisation, where trim tests have been performed for almost 300 vessels including tankers, container vessels, LNG carriers, Ro-Ro vessels, ferries with the majority being however container vessels. Testing made so far shows possible fuel savings of up to 15% at specific conditions compared to even keel. In overall fleet operations, typical savings can be as high as 2 to 3%.

Extensive R&D campaign has been made at FORCE Technology to understand the physical effects that reduce the propulsive power. Lemb Larsen et al. (2012) presented a comprehensive analysis of resistance and propulsive origin factors and their influence on power requirement. It has been concluded that the power gain is mainly of resistance origin, but changes in the propulsive coefficients are also a part of performance change.

The trim optimisation guidelines made by FORCE Technology and procedure described in this paper do not take into account operational constraints which have to be considered during shipping, i.e. slamming and green water on deck, crew comfort zone, strength and stability, manoeuvrability and overall safety.

2 TRIM OPTIMISATION IN THEORY

Trim is defined as the difference between the draught at AP (T_A) and the draught at FP (T_F).

$$\mathrm{Trim} = T_A - T_F \tag{1}$$

This results in positive trim to the aft. Furthermore when a vessel is trimmed, the displacement and speed are kept constant, i.e. no extra ballast added and the power consumption varies if the resistance is changed when trimmed.

The trim optimisation objective is to minimise the required power at vessel specific displacement and specific speed. The physical effects that reduce the propulsive power (P_D) when a ship is trimmed can relate primarily to the hull resistance (R_T) and to the total propulsive efficiency (η_D) as shown in the formula below:

$$P_D = \frac{R_T \cdot V}{\eta_D} \tag{2}$$

The ship speed (V) is from definition kept constant, so it is obvious that the aim is to reduce the resistance and/or increase the total efficiency in order to gain from trimming.

2.1 *Resistance reduction*

The still water ship resistance is, according to ITTC standards, described by the following formula:

$$R_T = ½ \cdot \rho \cdot V^2 \cdot S \cdot C_T \tag{3}$$

Changes in vessel resistance can be therefore a function of the wetted surface area (S) and/or the total resistance coefficient (C_T), and both parameters have to be reduced in order to gain from the trim.

The wetted surface area is calculated for the vessel at rest, i.e. without dynamic sinkage and trim. The variation in wetted surface area due to trim relates in most cases to the large flat stern area and is relatively small. It can reach up to ±0.5% of the even keel wetted surface and therefore the total resistance varies the same due to linear proportionality.

The reduction of the total resistance coefficient, see eq. (4) below, can be achieved by reducing all its components.

$$C_T = C_R + (1+k) \cdot C_{F0} + C_A \tag{4}$$

The allowance coefficient (C_A) is normally however kept constant unless for vessels with large variation in the draught, e.g. a VLCC in loaded/unloaded condition.

The frictional resistance coefficient (C_{F0}) varies, according to the ITTC standards, with the Reynolds number (Re) for the flow along the hull:

$$C_{F0} = \frac{0.075}{\left(\log_{10}(\mathrm{Re}) - 2\right)^2} \tag{5}$$

where Re is the Reynolds number defined by:

$$Re = \frac{V \cdot L_{wl}}{\nu} \tag{6}$$

From (5) and (6) it can be derived that the frictional resistance coefficient is a function of the water line length (L_{wl}), and that they are inversely proportional.

Although the water line length in most cases can vary ±5% from the even keel condition, the inverse proportionality results in an increase/decrease in the propulsive power of only ±0.5%. The effect compared to the overall possible savings is minimal.

The form factor (1+k) is often kept constant at each draught in order to optimise the cost of the experimental program in the towing tank. So in practice this factor does not influence on the resistance changes for different trimmed conditions. This assumption, will be investigated in the presented case study below, where the form factor has been calculated separately for each trimmed condition.

The residual resistance coefficient (C_R) is often claimed to be the parameter most affected by trim. From previously analysed cases it can be seen that the residual resistance coefficient at trimmed conditions may vary up to ±150% from the even keel condition values. That can reflect in changes of power requirement up to ±20%.

It can be then concluded that the major part of the reduction in propulsive power, from resistance reduction point of view, is caused by changes in the residual resistance coefficient.

2.2 *Increase of total propulsive efficiency*

The propulsive efficiency is a product of the hull efficiency (η_H), the open water propeller efficiency (η_O) and the relative rotative efficiency (η_{rr}).

$$\eta_T = \eta_H \cdot \eta_O \cdot \eta_{rr} \tag{7}$$

None of these three contributions are necessarily constant when the vessel is trimmed.

The hull efficiency is a function of the thrust deduction (t) and the effective wake fraction (w).

$$\eta_H = \frac{1-t}{1-w} \tag{8}$$

So it is obvious that the thrust deduction should decrease and the effective wake fraction increase in order to gain from trimming. The thrust deduction is a function of the propeller thrust (T) and the hull resistance.

$$t = \frac{T - R_T}{T} \tag{9}$$

As mentioned before the hull resistance changes when the vessel is trimmed and naturally, the propeller thrust will change also as the speed is kept constant. However, the relation is not constant.

The thrust deduction changes with the trim and sometimes a peak, when the propeller submergence decreases to a critical level, can be observed. The location of the peak depends also on the dynamic sinkage and stern wave.

The changes in thrust deduction can achieve values of up to 15% and can result in significant changes in the propulsive power of up to 3%. However, changes in the thrust deduction must be seen relative to changes in the effective wake.

The effective wake fraction is a function of the vessel speed and the propeller inflow velocity (V_A).

$$w = \frac{V - V_A}{V} \tag{10}$$

As the vessel speed is kept constant, changes in the effective wake fraction can only relate to the propeller inflow velocity. As expected, the effective wake fraction increases for bow trim conditions and decreases for stern trim conditions. The increase of wake fraction for bow trims can be up to 20% and the decrease for stern trims can be up to 10%. The differences in wake fraction can therefore change the power demand of up to 5%.

Both thrust deduction fraction and wake fraction for bow trim balance each other and can result in a power gain up to 2%.

The propeller open water efficiency depends on the advance ratio (J), i.e on the water inflow velocity to propeller (V_A) and on the revolutions (n):

$$J = \frac{V_A}{n \cdot D} \tag{11}$$

where D is the propeller diameter.

As already concluded the propeller inflow velocity is affected by the trim. Since the open water curve for the propeller efficiency is inclined for the actual advance ratio, even minor changes in the advance ratio result in a changed propulsive power. These changes can reach up to 2% of the even keel power demand.

The relative rotative efficiency is defined as the ratio between the open water propeller torque coefficient (KQ_{ow}) and the propeller torque coefficient behind the ship (KQ_{ship}).

$$\eta_{rr} = \frac{KQ_{ow}}{KQ_{ship}} \tag{12}$$

It can vary up to 2% from even keel condition and the same way influence the power requirement.

2.3 *Total power gain*

From the theory and percentage values presented above can be concluded that the residual resistance coefficient is the factor most affected by trim. However, the propulsion affects the results at a level detectable in model tests and should not be neglected.

3 TRIM OPTIMISATION IN PRACTICE

Taking into account the theory presented above, several methods for determining the optimum trim, which are based on different practical approach may be used during optimisation process. The experimental methods in general can be divided into three options:

3.1 *Full resistance and self-propulsion model tests*

Model tests performed in this method consist of full set of resistance and self-propulsion model tests for each trimmed condition.

Each condition is treated as an independent propulsion prediction case, i.e. prediction to full scale is made according to FORCE's procedure. This approach fully accounts for variation of form factor, residual resistance coefficient and propulsive factors (effective wake, thrust deduction and relative rotative efficiency) with displacement/trim variation. Practical drawback is the relative high experimental matrix with associated increased cost.

3.2 *Self-propulsion model tests with constant form factor and constant thrust deduction fraction*

In this method the resistance tests are performed for reference conditions only, which in 90% of cases means the even keel condition for each tested displacement. Form factor and thrust deduction fraction are taken from the reference case and are kept constant during trimmed conditions analyses. The self-propulsion tests performed for trimmed conditions are the basis for calculation of wake fraction and propulsive coefficients on a basis of reverse approach. Advantages of this approach is somewhat reduced experimental cost, but with the disadvantage of losing the trim effect on form factor and thrust deduction.

3.3 *Direct power measurements*

The prognosis to full scale is made on the basis of torque and revolutions measured during the self-propulsion tests at ship self-propulsion point, i.e. including the additional towing force for compensation of frictional resistance between ship and model. The full scale prognosis is made according to Froude similarity law. This is the most straightforward approach, simulating the full scale ship trial procedure. There is no need of resistance, form factor, propeller open water data, neither propulsive factors measurement. In this approach, however, the effective wake scaling is neglected, which would influence propeller loading coefficient and subsequently propeller thrust, torque and shaft power prediction.

4 CASE STUDY PRESENTATION

Below the results of trim optimisation for a large cargo ship are presented. All three methods were used and results of all methods are presented. Some detailed analysis of form factor, residuary resistance coefficient, wake fraction, thrust deduction fraction, relative rotative and open water efficiencies is made.

Results of trim optimisation are presented in two-ways, as a matrix of possible power savings at tested trimmed conditions and as an optimum trim at specific displacement.

4.1 *Reference vessel*

The vessel chosen for this study is a large container vessel. The hull form represents a typical container vessel with a pronounced bulbous bow, slender hull and a centre skeg with one propeller.

Table 1. Main particulars of reference vessel

	Ship	Model
Length, L_{PP}	330.00	8.648
Breadth, B	42.80	1.122
Max draught (tested), T_{max}	11.50	0.301
Volume at max draught, V_{max}	104166	1.875
Block coefficient at max draught, CB_{max}	0.654	0.654

The vessel was chosen due to its well-documented resistance and self-propulsion performance by several model tests at FORCE Technology. Earlier it has been tested in numerous combinations of draughts, speeds and trims. In this study, only one partly loaded draught and speeds corresponding to a Froude number between 0.128 and 0.201 is described. Ten different trims have been investigated ranging from -2.5m to 2.0m in steps of 0.5m.

4.2 *Model tests results*

Figures 1-3 present the detailed comparison of form factor, thrust deduction and wake fraction between two methods, i.e full resistance and self-propulsion model tests for all trimmed conditions [act ff act t] and self-propulsion model tests with constant form factor and constant thrust deduction fraction with resistance tests only at reference draught [const ff const t].

Figure 1 presents markers representing thrust deduction fraction in method with full resistance, self-propulsion tests and a solid line, which represents the constant thrust deduction fraction in function of vessel speed from method with resistance tests only for reference trim.

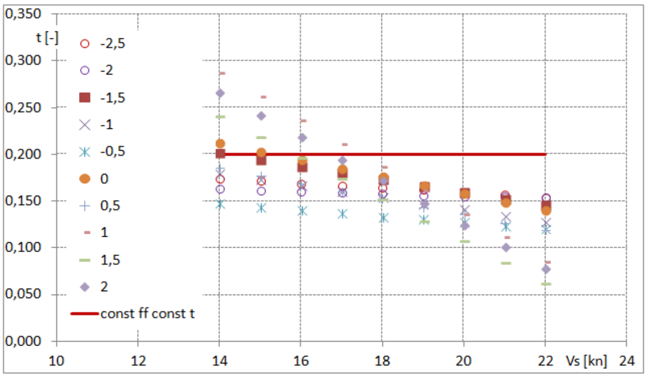

Figure 1. Thrust deduction fraction in different methods

It can be seen that the thrust deduction fraction for all tested trim conditions decreases with speed and has rather large scatter. Furthermore, there is a pronounced trim influence with deviations (relative to the constant t value) of up to 100%.

Figure 2 shows the relation between form factors measured at different trimmed conditions and constant form factor taken into account in method with resistance tests made only at reference trim. In that figure also the thrust deduction fraction from both methods for design speed is shown

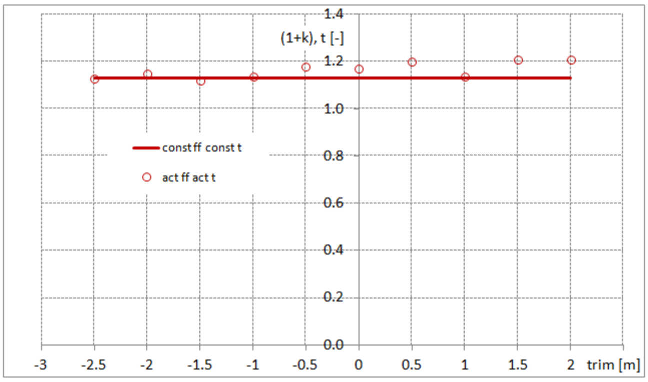

Figure 2. Form factor used in different methods

It is clearly visible that the form factor increases with the trim, i.e. with more submerged aft part. The deviation varies between 1.13 and 1.21. However not large it is still influential on the final power prediction because they may lead to effective power variations in the range o 6-7%.

Figure 3 presents the propeller open water efficiency derived from analysed methods. The efficiency is presented as a relation between calculated from full resistance and self-propulsion tests at each trimmed condition and calculated from constant thrust deduction method.

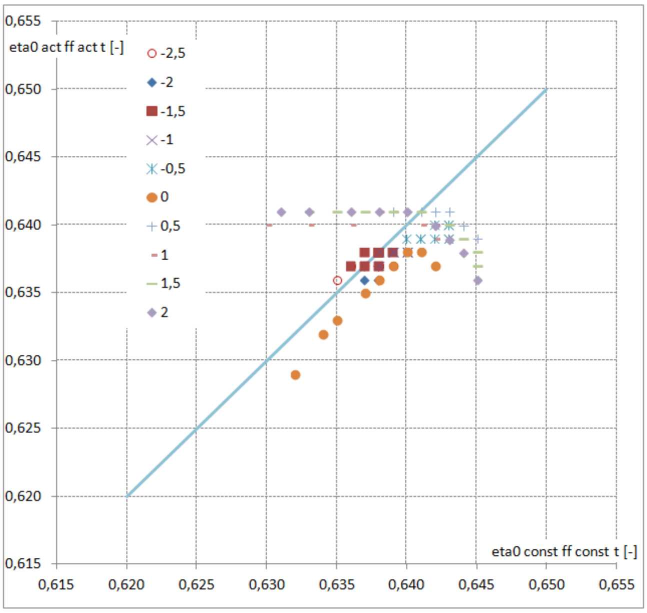

Figure 3. Relation of propeller efficiency from different methods

The propeller efficiency received from analysed methods can be in general treated as comparable, the maximum difference received is about 1.6% for the trim to aft and decreases with trimming to bow.

Figure 4 presents the optimum trim received from different methods in function of speed.

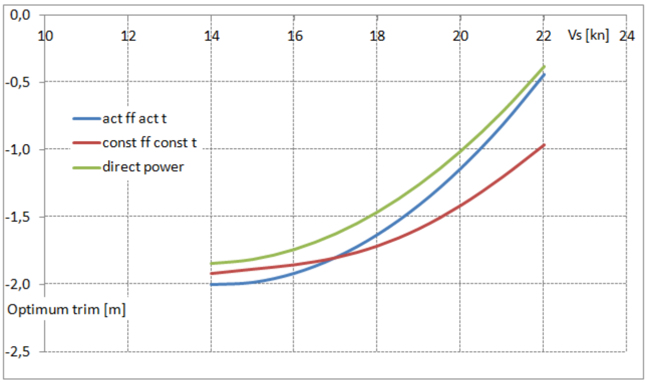

Figure 4. Optimum trim from different methods

Figure 4 shows that all three methods follow similar trend regarding the vessel speed and show the optimum trim reduces with increased speed. It can be seen however that the optimum trim for any specific speed may differ, e.g. for 18 knots was found -1.7m for the constant form factor and constant thrust deduction fraction and -1.6m for actual form factor and actual thrust deduction fraction, while for direct power method the optimum trim is about -1.5m.

Figure 5 presents the overall comparison of predicted power savings received from three analysed methods.

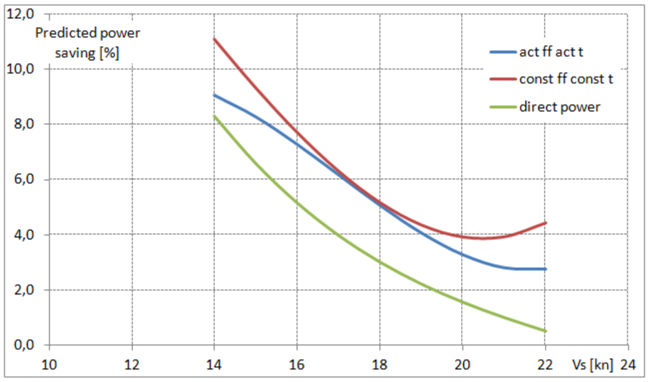

Figure 5. Predicted power savings from different methods

Like in case of optimum trim, the trend of possible power savings received from analysed methods is very similar. The difference in values of predicted possible power savings between the highest and lowest possible saving received from different methods is almost constant and equal to about 2.7%.

5 CONCLUSIONS ON THE OPTIMISATION METHODS

The final conclusions may be presented in two aspects, i.e. showing the effect of the investigated analysis method on the determination of the optimum trim condition and showing the effect of the investigated analysis method on the possible power savings.

If taking into account the first aspect it appears that in the low to medium speed range (14 to 18 knots) the methods with full resistance and self-propulsion tests (act ff act t) and the one with resistance for a reference trim only (const ff const t) give similar results (see Figure 4). For the top speed range, however, the act ff act t method is preferable for its better account of the thrust deduction and 1+k deviation with speed (see Figure 1). The direct power method follows the same trend as the indirect methods giving however the values of trim with a small offset.

Regarding the possible power savings it should be concluded that for the medium speed range (16 to 18 knots) the two methods, i.e. act ff act t and const ff const t indicate similar power savings, while for the low and top speed ranges deviations reach up to 2%. Thus, again, the actual t and (1+k) method could be recommended for better power saving prediction in the entire speed range. In the direct power method, the predicted power levels do not consider wake scale effect and correlation allowance coefficient. Therefore, the predicted power savings are generally lower, but exhibit the same trend as the two other methods.

A general comment may be concluded that the choice on which method to use is a compromise between possible resources both in time, in facilities utilisation or in software, when numerical methods instead of model tests will be used, and a satisfying level of accuracy. However all three methods could be used to predict certain power savings coming from trim optimisation.

6 SEATRIM® SOFTWARE

Force Technology has elaborated a decision support tool, which is designed to provide a quick and safe guidance in selection of the right trim in relation to the loading condition and planned speed.

Only three parameters are necessary to evaluate the influence of actual trim of the vessel and make optimum trim suggestions. These parameters are: Draught forward and aft (typically taken from ship loading computer) and the planned vessel speed (from vessel route planning). The program will then advise the user about the trim situation and will, by simple colour codes and reduction/ increase in power, advise the user if the trim is optimal. Should the trim not be optimal, the tool gives quick guidance to where the optimum trim can be found. The user can then use his cargo or ballast water to obtain the best possible trim before leaving the port.

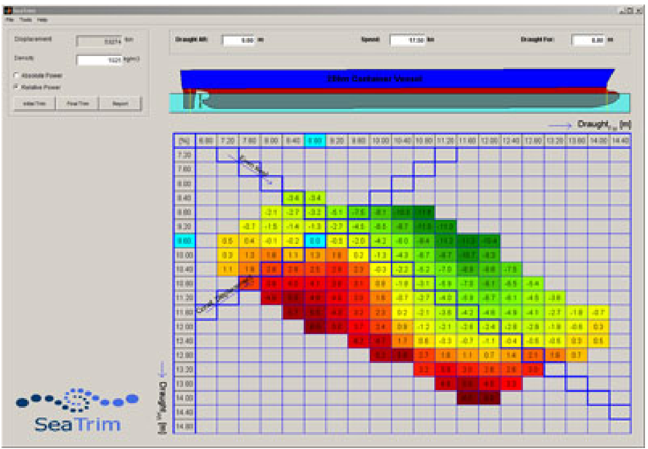

Figure 6. SeaTrim® software

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