STUDY OF THE EFFECT OF TRIM ON SHIP POWERING PERFORMANCE

ИЗСЛЕДВАНЕ НА ВЛИЯНИЕТО НА ДИФЕРЕНТА ВЪРХУ ХОДОВИТЕ КАЧЕСТВА НА КОРАБА

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Abstract: *The recently issued IMO requirements for reduction of GHG emissions for shipping reinforced the attempts to increase the energy efficiency of ships.*

One of the measures prescribed by IMO is Ship Energy Efficiency Management Plan (SEEMP). This, among other things, involves trim optimization.

Trim i.e. difference between the draft at the bow and the stern is controlled parameter worthy of attention with respect of fuel usage and GHG emissions while the ship is cruising. It is shown in this paper that the powering performance of vessels varies with different trim conditions.

The main objective function of the trim optimization is the powering performance (resistance and propulsion).

The objective of this paper is to analyze the physics behind the effect of varied trim on ship resistance and propulsion, to detect the origin of this effect.

In particular are examined the change of total resistance depending on the change of some parameters such as length of waterline (hence frictional resistance), submerged surface , change of the residual resistance, wave making/breaking at the bow and ~~analyzed in terms of and~~ viscous - pressure resistance (form-factor). Also examined are parameters influencing the powering performance as: thrust deduction, wake fraction, relative rotative efficiency, and propeller efficiency when the ship is trimmed.

This analysis has been based on experimental data of particular ships.

KEYWORDS: *ENERGY EFFICIENCY, SEEMP, TRIM OPTIMIZATION*

1. *Introduction*

Energy efficiency of ships has ever been an important issue for ship-owners and ship operators due to entirely economic reasons.

Lately, however, this interest has been revived and reinforced by the environmental concerns of mankind in all fields of our life.

The recently issued IMO Marine Environment Protection Committee (MEPC) requirement for reduction of GHG emissions from shipping reinforced the attempts to increase the energy efficiency of ships.

One of the measures the IMO introduced regarding reduction of GHG emitted by shipping [4] is SEEMP (Ship Energy Efficiency Management Plan). SEEMP is mandatory to exist onboard every ship but voluntary in contents. Table 1.1 shows SEEMP related measures.

Table 1.1 *SEEMP related measures*

No.	Energy Efficiency Measure
1	Engine tuning and monitoring
2	Hull condition
3	Propeller condition
4	Reduced auxiliary power
5	Speed reduction (operation)
6	**Trim/draft monitoring and optimisation**
7	Voyage execution
8	Weather routing
9	Advanced hull coating
10	Propeller upgrade and aft body flow devices

The topic of this paper is trim/draft optimization and more specifically analysis of the physics behind its effect on ship powering performance, effect of flow and resistance when draft and trim vary.

2. *Physics behind the effect of varied trim on ship powering performance*

FORCE Technology, Denmark [3] investigated what causes the change in propulsive power when a vessel is trimmed. The possible explanations may relate to changes in the following parameters: wetted surface area; water line length; form-factor; residual resistance coefficient; thrust deduction; wake fraction; propeller efficiency and relative rotative efficiency.

The objective of this section is to try decompose the effects of trim on the above parameters. All discussions are based on the results of powering model tests of 320 000 DWT VLCC at one speed (The trim optimization test matrix included four practicable ballast conditions- 1 m, 2 m, 2.4 m and 3 m trim aft, without systematic variation of mean draught).

Trim is defined as the difference between the draft at aft perpendicular (T_A) and the draft at fore perpendicular (T_F):

$$TRIM = T_A - T_F \quad (2.1)$$

The physical effects that reduce delivered power when the ship is trimmed can relate to ship resistance and propulsive efficiency, as shown in the formula to determine the delivered power (2.2):

$$P_D = \frac{R_T.V}{\eta_D} \quad (2.2)$$

i.e. the scope to reduce the power are reducing the ship resistance (R_T) and/or increasing the propulsive efficiency (η_D).

2.1. Resistance

The total resistance coefficient, according to ITTC [1] is:

$$C_T = C_R + (1+k).C_F + C_A \quad (2.3)$$

The correlation allowance C_A usually is assumed constant for all trim conditions, except in case of major changes in draft

Change in the friction resistance coefficient C_F, according to ITTC-57 is:

$$C_F = \frac{0{,}075}{(\log_{10}(\mathrm{Re})-2)^2} \quad (2.4)$$

Where Re is Reynolds number defined by:

$$\mathrm{Re} = \frac{V.L_{WL}}{\nu} \quad (2.5)$$

The kinematic viscosity of sea water (ν) is constant for the same temperature.

From the above formulas, it follows that the frictional coefficient depends on the length on waterline.

Table 2.1 *Change in power due to waterline length at Vs=14kn for 320k VLCC*

Trim	**1**	**2**	**2,4**	**3**	**4**
Cases	**B1**	**B2**	**B3**	**B4**	**Ballast**
ΔL_{WL} [%]	0,6%	0,7%	0,3%	0,2%	0%
ΔPD_{LWL} [%]	-0,06%	-0,07%	-0,07%	-0,07%	0%

From above table can be seen that the effect of waterline length changing is negligible.

When the vessel is trimmed, the wetted surface area varies as shown in Table 2.2.

Table 2.2 *Change in power due to wetted surface area at Vs=14kn of 320k VLCC*

Trim	**1**	**2**	**2,4**	**3**	**4**
Cases	**B1**	**B2**	**B3**	**B4**	**Ballast**
ΔS [%]	0,44%	-0,61%	-0,97%	1,74%	0,44%
ΔPD_S [%]	0,44%	-0,61%	-0,97%	1,74%	0,44%

The saving in power due to wetted surface area varies not so little as due to waterline length. The delivered power varies proportionally to the wetted surface variation.

The residual resistance coefficient (C_R) is often claimed to be the quantity most affected by trim.

In Table below are shown the savings due to changes in C_R

Table 2.3 *Change in power due to C_R at Vs=14kn of 320k VLCC*

Trim	**1**	**2**	**2,4**	**3**	**4**
Cases	**B1**	**B2**	**B3**	**B4**	**Ballast**
ΔC_R [%]	107,9%	-47,1%	-13,6%	-48,3%	0%
ΔPD_{CR} [%]	3,28%	-1,43%	-1,43%	-1,43%	3,28%

From table 2.3 it can be seen that the C_R changing in all cases is high. Its effect on the delivered power is more than this due to previously mentioned parameters.

The summing up of all the saving due to resistance components to propulsive power gives the following results:

Table 2.4 *Change in propulsive power due to total resistance at Vs=14kn of 320k VLCC*

Trim	**1**	**2**	**2,4**	**3**	**4**
Cases	**B1**	**B2**	**B3**	**B4**	**Ballast**
ΔPD_{LWL} [%]	-0,06%	-0,07%	-0,07%	-0,07%	0%
ΔPD_S [%]	0,44%	-0,61%	-0,97%	1,74%	0%
ΔPD_{CR} [%]	3,28%	-1,43%	-1,43%	-1,43%	0%
ΔPD_{RT} [%]	**3,66%**	**-2,11%**	**-2,47%**	**0,24%**	**0%**

2.2. Propulsion

The propulsive efficiency is also affected when the vessel is trimmed. It is composed of the hull efficiency:

$$\eta_H = (1-t)/(1-w) \quad (2.6)$$

The relative rotative efficiency (η_{rr}) and the propeller efficiency (η_0) as shown in the formula below, according to ITTC [2]:

$$\eta_T = \eta_H.\eta_{rr}.\eta_O \quad (2.7)$$

The hull efficiency is a function of thrust deduction (t) and wake fraction (w). The thrust deduction is a function of total resistance and propeller thrust:

$$t = (T - R_T)/T \quad (2.8)$$

It has already been said that the total resistance changes when ship is trimmed. Propeller thrust will change also.

The wake fraction is defined as a ratio of effective wake velocity (V-Va) and ship speed (V), where (Va) is propeller inflow velocity:

$$w = (V - V_A)/V \quad (2.9)$$

When the ship speed is kept constant, the wake fraction changes due only to propeller inflow velocity.

Propeller efficiency is defined from open water test, not in the wake of the vessel. The open water curve is a function of the advance ratio (J), which is a function of propeller inflow velocity, propeller revolutions and diameter:

$$J = V_A/n.D \quad (2.10)$$

So the propeller efficiency is affected by trim also due to V_A

The relative rotative efficiency is defined as a ratio of propeller torque in open water (Q_{ow}) and behind the ship(Q_{ship}):

$$\eta_{rr} = Q_{ow}/Q_{ship} \quad (2.11)$$

The summing up all power saving from propulsive efficiency components to propulsive power gives the following results:

Table 2.5 *Change in propulsive power due to propulsive effects at Vs=14kn of 320k VLCC*

Trim	**1**	**2**	**2,4**	**3**	**4**
Cases	**B1**	**B2**	**B3**	**B4**	**Ballast**
ΔPD_t [%]	-0,64%	2,89%	0,51%	0,13%	0%
ΔPD_w [%]	-0,91%	-3,84%	-0,91%	-1,10%	0%
ΔPD_{ETAR} [%]	0,72%	0,31%	0,51%	0,72%	0%
ΔPD_{ETA0} [%]	0,68%	1,73%	0,00%	0,68%	0,0%
ΔPD_{ETAT} [%]	**-0,14%**	**1,09%**	**0,11%**	**0,44%**	**0,0%**

The saving from changes in total resistance and propulsive coefficients are shown in Table 2.6.

Table 2.6 *Change in propulsive power due to trim at Vs=14kn of 320k VLCC*

Trim	**1**	**2**	**2,4**	**3**	**4**
Cases	**B1**	**B2**	**B3**	**B4**	**Ballast**
ΔPD_{RT} [%]	3,7%	-2,1%	-2,5%	0,2%	0%
ΔPD_{ETAT} [%]	-0,14%	1,09%	0,11%	0,44%	0%
ΔPD [%]	**3,52%**	**-1,02%**	**-2,35%**	**0,68%**	**0%**
ΔPD (MT) [%]	**1,79%**	**-1,93%**	**-3,35%**	**3,62%**	**0%**
Diff [%]	**1,73%**	**0,91%**	**1,00%**	**-2,94%**	**0%**

It can be seen that in some of the cases the difference is high (e.g. case B4), but the direction of the change due to trim is the same compared to the values from model tests.

From the results shown in Table 2.6 it can be concluded that the most affected factor due to trim is the total resistance. Still, the propulsive coefficients change effects to the total sum of change due to trim are significant and they should not be neglected.

3. Effect of bow bulb close to or intersecting the free surface

All discussions in this section are based on observations of model tests with 19 000 TDW tanker (a matrix of three drafts, three trims each, has been tested), 320 000 DWT VLCC and 50 000 DWT Product Carrier (three trims of 50k Product Carrier have been tested with one mean draft and displacement, i.e. systematically varied)

Fig. 3.1 and Fig.3.2 shows a sample photo of the wave pattern related to the wave resistance coefficient curve for one of the cases of model tests with 19 000 DWT tanker (Fig.3.1) and one of the cases of model tests of 50k Product Carrier (Fig.3.2).

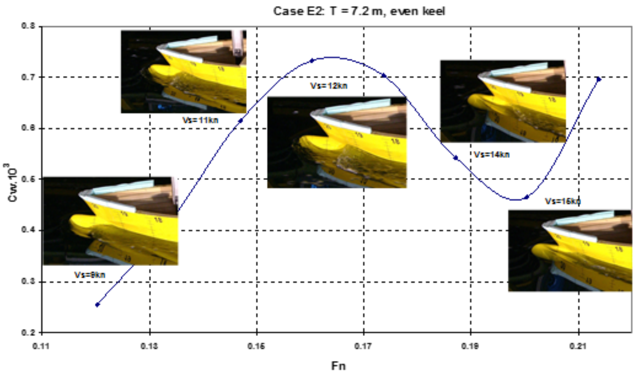

Fig.3.1 *Photo of wave pattern related to the wave resistance coefficient curve of 19000 DWT tanker*

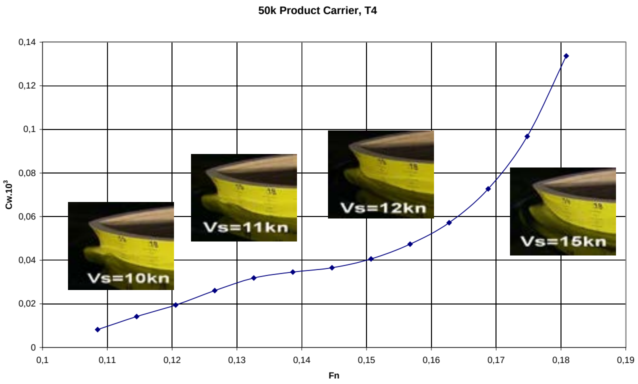

Fig.3.2 *Photo of wave pattern related to the wave resistance coefficient curve of 50k Product Carrier*

It can be seen that when the bulb is intersecting the free surface at still water with increasing Froude number there occurs wave breaking in front of the blunt part of the bulb and a single overturning wave immediately behind the bulb where flow meets the main hull. At certain Fn these events are most intensive that corresponds to a local maximum of the wave resistance coefficient. Only when the dynamic pressure gets high enough to raise the water over the bulb and smoothly flow downstream there is a local minimum of the wave resistance coefficient. This phenomenon is more obvious for the case of 19000 DWT tanker.

The previous assertion is not valid for 320 000 DWT VLCC due to the fact that water does not cover the bow bulb, in all trim cases it is not submerged and there are no peaks in wave resistance coefficient curve (Fig.3.3).

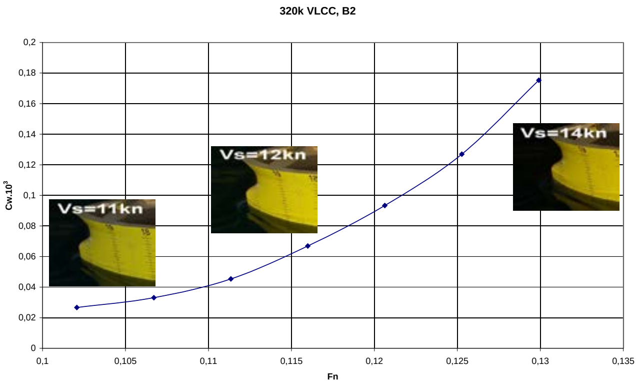

Fig.3.3 *Photo of wave pattern related to the wave resistance coefficient curve of 320k VLCC*

The location and magnitude of these local extrema probably depend on the height from the still waterline to the level above the bulb and the bluntness of the bulb shape.

Using 4th order polynomial curve-fit the local maximum and minimum of the effective wave resistance $Cw=C_T-(1+k).C_F$ and their location on the Fn axis have been determined.

From physical considerations and common sense, the following assumption was made:

Assumption The observations illustrated with Fig. 3.1 and Fig. 3.2 suggest that the local minimum of the wave resistance curve occurs when the flow covers completely the bow and smoothly continues downstream. Theoretically, by virtue of Bernoulli's equation, the free surface elevation at the stagnation point is:

$z=\frac{1}{2}\frac{V^2}{g}$ (3.1) or non-dimensionally $\frac{z}{L}=\frac{1}{2}Fn^2$. (3.2)

That means that if the height needed to cover the bow bulb is Zup this will happen at

$$Fn_{min}\approx\sqrt[2]{\frac{Z_{UP}}{L}} \qquad (3.3)$$

As a representative height *Zup*, was accepted the distance between the crossing point of the still waterline with the bulb profile and the level of the design waterline.

Fig. 2.4 and Fig 2.5 shows the relation Fn_{min} (z/Lwl)

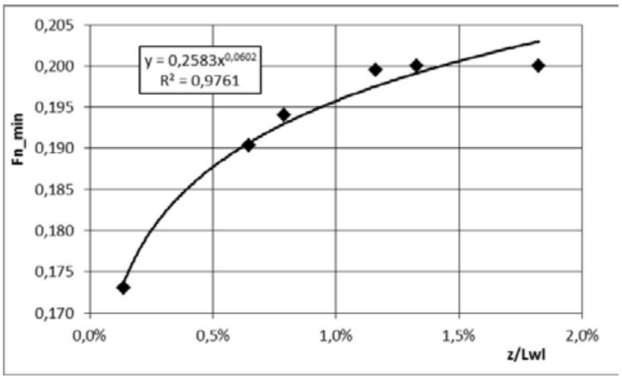

Fig.3.4 *Relation between Fn of local minimum* C_W *and the height to the top of the bulb of 19k tanker*

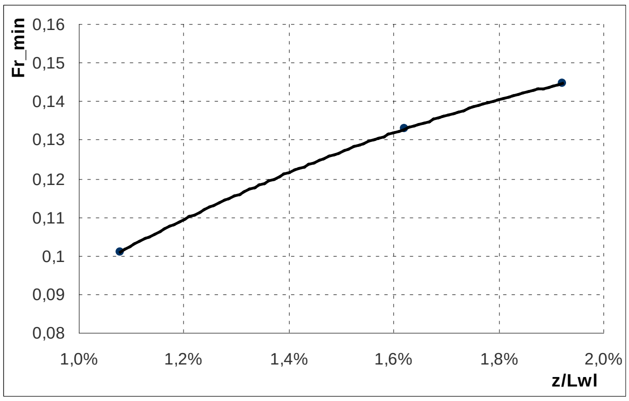

Fig.3.5 *Relation between Fn of local minimum* C_W *and the height to the top of the bulb of 50k Product Carrier*

A trend line, approximating the observations with satisfactory determination coefficient, really has the behavior of the square root function (3.3).

4. *Effect of trim on viscous resistance*

Viscous resistance is affected by trim in two ways. First, wetted length (hence Reynolds number) and wetted surface change with trim but this is a minor effect. Equally minor is the effect of trim on windage area and air resistance.

The more important effect of trim is on viscous-pressure resistance, i.e. the form-factor.

The data analyzed in this section are based on two powering model tests of a 320 000 DWT VLCC and 50 000 DWT Product Carrier.

After trying to relate different geometrical parameters to form-factor values, the best try was the curvature of the run shoulder of the sectional area curve.

Fig. 4.1. and Fig. 4.2 shows the prismatic curves for the two tested models.

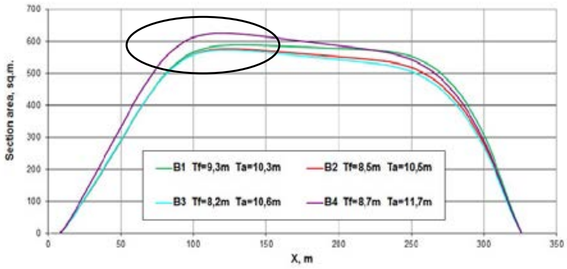

Fig.4.1 *Prismatic curves for investigated trim condition of 320k VLCC*

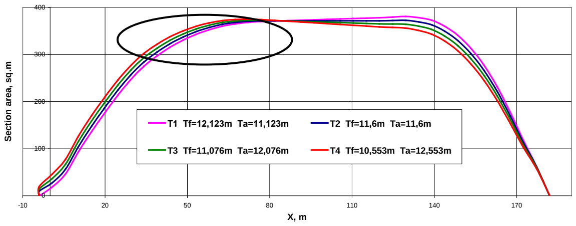

Fig.4.2 *Prismatic curves for investigated trim condition of 50k Product Carrier*

The curvature of the prismatic curve in the area outlined in Fig. 4.1 and Fig.4.2 was calculated for the same x-values in all cases for model according to the classical formula:

$$k = \frac{y''}{(1 + y'^2)^{3/2}} \qquad (4.1)$$

These values were related to the corresponding values of 1+k (Fig. 4.3).

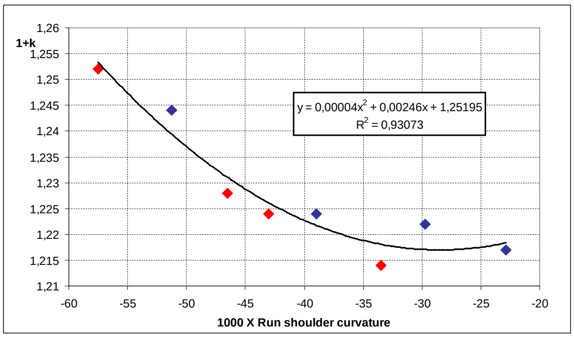

Fig.4.3 *Relation of form-factor vs. run-shoulder curvature for 320 000 DWT VLCC and 50k Product Carrier*

The figure shows an excellent fit of the investigated variables.

5. *Summary and conclusion*

On the basis of specific model test results the physics behind trim effect on ship powering performance, the flow around the hull and ship resistance components have been analyzed to find that:

- The most affected quantity by trim is the total resistance.
- The propulsive coefficients change effects to the total sum of change due to trim are significant and they should not be neglected.
- With bow bulbs intersecting the free surface the flow features wave breaking followed by a smooth flow around the bulb which result in a hump and hollow of the wave resistance curve. It has been established that they and their Fn position depend on the depth of the bulb of the still-water line. The viscous resistance, specifically the form-factor, of an investigated case relates quite definitively to the curvature of the stern run shoulder of the prismatic curve.

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