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Comparative analysis of two optimization methods of ship's speed distribution during voyage

SUMMARY

Ship speed and fuel consumption calculations were performed based on foreign ship operation investigations and on the use of two ship speed distribution optimization methods. One of them was elaborated by Technical University in Berlin by means of the calculus of variations, the other by Maritime Institute in Gdańsk using the differential calculus.

A comparison of the calculation results indicated that both methods are equivalent and revealed differences less than 0.2%; moreover the latter method is far simpler. Fuel consumption savings which can be achieved in relation to a ship operated in the traditional way were also confirmed.

INTRODUCTION

In recent years, along with a growing interest to rational energy use, various saving-oriented efforts are undertaken in many developed countries, which are controlled by the national governments in cooperation with international organizations. In shipping more and more attention is paid to improving energy efficiency of ships by operational means, one of the visible results of which is ship speed optimization allowing to decrease fuel consumption up to 10%.

Following the results obtained abroad [1] the author carried out the work [2, 3] in which his own optimization method of ship speed distribution, hereafter called IM method, was presented. Different simplifying assumptions accepted in particular methods influence their accuracy and applicability. Consequences of the simplifications should therefore be assessed and compared. This is the aim of this paper which is based on the work [5].

PROBLEM FORMULATION

Two optimization problems: of mean ship speed and of ship speed distribution can be distinguished. The mean ship speed optimization based on the maximum profit criterion in dependence upon ship's speed and various cost components has been quite thoroughly investigated and described. If a mean ship speed in a given operational situation is determined, the problem appears of ship speed selection for given operational conditions (hydrologic, weather and loading conditions, sea currents etc) in such a way as to maintain the set mean speed. One could try to sail with the mean speed in any situation, but it would be economically unprofitable and often impossible due to a limited engine moment and speed. When the operational conditions get substantially worse, the fuel consumption seriously increases and it is reasonable to reduce temporarily ship's speed and to make up for lost time in good conditions. During longer ship voyages such changes can be frequent and the problem arises of selecting ship's speed for particular segments of ship route in such a way as to attain the possibly best economic result of ship's transportation task. Investigations on the problem undertaken in the 80 led to preparation of an optimization model called the TUB model following the name of the Technical University in Berlin where it was elaborated [1].

The model is a general prescription for preparation of the formulas by which the optimum ship speed distribution for given operational conditions can be calculated. An advantage of the model is, due to its general form, the accounting for a.o. sea current velocity. However it is not straightforward and clear for users due to the advanced methods of calculus of variations used in its creation. Moreover it requires a constant value to be determined by means of an iterative process.

The referenced author's investigations made preparation of a new model possible, which is substantially simpler and does not contain any constant calculated with the use of iterative methods. Its development is based, apart from calculation of function derivatives, on clear algebraic transformations which make the problem and its solution more understable to a user. Its drawback is not accounting for sea current velocity.

A simplified analytical comparison of both models revealed their high structural analogy, but it was impossible to quantitatively estimate discrepancies of their results without a detailed numerical verification. Such verification was performed [5] on the basis of a typical ship service voyage to determine values of ship speed and fuel consumption discrepancies yielded by different variants of the models. This was aimed at the determination of a possible range of their practical applications.

DETERMINATION OF REFERENCE CONDITIONS

The TUB model with the assumed non-zero sea current velocity v_p is taken as the basic one which other calculation variants will be related to due to its higher degree of generic extent. In this way consequences of any simplification applied in the IM model and its features could be disclosed and estimated. In order to do it results of appropriate experimental investigations should be selected. The investigation results published by Grabellus in [4] and referred in detail in [2] were found most useful for that purpose from among various considered results of investigations of ships in operation. The paper [4] contains, apart from experimental and other necessary data, the results of ship speed optimization by using TUB method. The results were used to test own computer programs.

The experimental data were collected during a service voyage of m/s „ Monte Sarmiento ", whose route of s = 7000 nautical miles and lasting time T = 450 hours was divided, for consistency of conditions, into 5 segments with appropriate propeller characteristics assigned to each of them (the relation of ship power versus ship speed).

- Values of the coefficients and index exponent of the characteristics are as follows:

A_1 = 1.3033
A_2 = 1.1892
A_3 = 0.8755
A_4 = 0.9931
A_5 = 0.8390
B = 1.92012

- Average values of the propulsion system performance parameters:

P_0 = 7500 kW
v_0 = 17 kn
$\overline{v}$ = 15.555 kn

- Values of the coefficients of the fuel consumption - propulsion power relationship (4) :

C_F = 2.568×10^{-5}t×h/g×day
C_0 = 238 g/kW× h
C_1 = -9.24×10^{-3}g/kW^2×h
C_2 = 6.2×10^{-7} g/kW^3×h

- Length of voyage route segments:

s_1 = 1800 Nm
s_2 = 1500 Nm
s_3 = 950 Nm
s_4 = 1000 Nm
s_5 = 1750 Nm

- Values of sea current velocity while passing each route segment:

v_{p1} = -0.6 kn
v_{p2} = -0.8 kn
v_{p3} = 0 kn
v_{p4} = 0.5 kn
v_{p5} = 0.8 kn

Note: The sign „-" denotes sea current velocity opposite to ship speed.

CALCULATION PROCEDURE

TUB method

Application of the TUB method consists in the calculation of the ship speed v_{di} in respect to the sea bed by means of the following set of equations, each of them established for the ship route segment s_i , i = 1, 2,..., 5 :

$$C_F\left[C_0P_0A_i\left(\frac{v_{di}-v_{pi}}{v_0}\right)^{B}+C_1P_0^2A_i^2\left(\frac{v_{di}-v_{pi}}{v_0}\right)^{2B}+C_2P_0^3A_i^3\left(\frac{v_{di}-v_{pi}}{v_0}\right)^{3B}\right]-v_{di}C_F\frac{P_0A_iB}{v_0}\left[C_0\left(\frac{v_{di}-v_{pi}}{v_0}\right)^{B-1}+2C_1P_0A_i\left(\frac{v_{di}-v_{pi}}{v_0}\right)^{2B-1}+3C_2P_0^2A_i\left(\frac{v_{di}-v_{pi}}{v_0}\right)^{3B-1}\right]+K=$$ (1

Analytical solution of the equations is not possible due to cor founded searched variable and unknown value of the constant K Therefore an approximate iterative procedure is applied. The procedur consists in assuming an arbitrarily small value of the initial speed v_{p0} an the initial value of K constant, k_0, and checking the sign of the differenc (k_0 - k_i) where k_i is calculated from the equation (1) for i = 1. Assumin a value of the ship speed increment Δv the calculations are performed fo (v_d + Δv) again and again until the sign of the difference is changed. The the calculations are drawn back one Δv increment and continued with th Δv/10 increment. The procedure of drawing-back and repetition o calulations with the decreased ship speed increment is performed till th assumed calculation accuracy $\varepsilon_v = 10^{-3}$ kn is obtained. The process i repeated for each consecutive ship route segment. Then the difference o the set voyage time and sum of route segment times is checked. Th calculations are repeated assuming some value of Δk increment till th sign of the difference is changed. Then the calculations are drawn back on Δk value and continued with the use of Δk/10 increment until the assume voyage time accuracy $\varepsilon_t = 10^{-1}$h is reached. This is the end of the calculation and the following output data are printed:

- searched values of the ship speed v_{pi}
- fuel consumption per hour
- total fuel consumption
- passing time of each route segment t_i
- K constant value.

The algorithm of the method was programmed for the Hewlett-Packard HP-9820 electronic calculator by means of which the further described calculations were performed.

IM method

Own determination method of ship speed distribution is described by the following formula:

$$v_{di}=\overline{v}\,\frac{\sum\sigma_i\sqrt[B]{A_i}}{\sqrt[B]{A_i}} \qquad (2)$$

where:

$$\sigma_i = s_i/s \qquad (3)$$

and

s- total length of ship's voyage route (from port to port)

An accuracy measure of the verified method is the difference of the total voyage fuel consumption calculated by means of the method and that by TUB method assumed as a reference model. Daily fuel consumption values are calculated for particular route segments by means of the following formula:

$$F_{di}=C_F\left[C_0P_0A_i\left(\frac{v_{di}-v_{pi}}{v_0}\right)^{B}+C_1P_0A_i^2\left(\frac{v_{di}-v_{pi}}{v_0}\right)^{2B}+C_2P_0^3A_i^3\left(\frac{v_{di}-v_{pi}}{v_0}\right)^{3B}\right] \qquad (4)$$

The total fuel consumption for a given route segment is as follows:

$$F_i = F_{di}\ t_i \tag{5}$$

where:

$$t_i = \frac{s_i}{v_{di}} \tag{6}$$

and

$$\sum t_i = T \tag{7}$$

The total voyage fuel consumption is:

$$F = \sum F_i \tag{8}$$

The calculation technique is straightforward and selfevident and needs no comment.

COMPARATIVE ANALYSIS

The ship speed distributions based on the voyage data of m/s „Monte Sarmiento" were at first calculated by both TUB and IM methods. Results of the calculations are presented for particular route segments in Tab. 1.

The optimum speed values given there are related to the sea bed. To reach the speed values a ship has to move, in both methods, with a speed relative to the water, defined by the following formula:

$$\bar{v} = v_d - v_p \tag{9}$$

From Tab. 1 it results that the discrepancies of both optimum speed and fuel consumption values for particular voyage route segments are small and equal on average to -0.13% and -0.15% respectively. The corresponding standard deviation values are 1.01% and 0.88%. In both considered cases the ship reaches the port of destination practically in the same time with the total fuel consumption differing by 0.03 t only which is within a rounding error value. Therefore the same results can be obtained when using both IM and TUB method to optimize ship speed distribution, and thus the same fuel consumption savings.

Tab. 1. Optimization results of ship speed distribution calculated for real voyage data of m/s „ Monte Sarmiento " by using TUB and IM methods

	TUB method				IM method				Discrepancies	
i	v_{di} [kn]	t_i [h]	F_{di} [t/day]	F_i [t]	v_{di} [kn]	t_i [h]	F_{di} [t/day]	F_i [t]	Δv_{di} [%]	ΔF_i [%]
1	13.80	130.43	37.17	202.00	13.90	129.50	37.66	203.19	0.72	0.59
2	14.43	103.95	37.76	163.54	14.58	102.88	38.47	164.91	1.04	0.84
3	17.18	55.30	35.09	80.84	17.10	55.56	34.79	80.52	-0.47	-0.40
4	16.21	61.69	33.56	86.30	16.13	62.00	33.26	85.92	-0.49	-1.34
5	17.75	98.59	32.85	134.96	17.49	100.06	31.94	133.15	-1.46	-1.34
Sum	-	449.96	-	667.66	-	449.99	-	667.69	mean -0.13	mean -0.15

Tab. 2. Optimization results of ship speed distribution calculated for m/s „Monte Sarmiento " voyage data at no-current conditions by using TUB and IM methods

	TUB method				IM method				Discrepancies	
i	v_{di} [kn]	t_i [h]	F_{di} [t/day]	F_i [t]	v_{di} [kn]	t_i [h]	F_{di} [t/day]	F_i [t]	Δv_{di} [%]	ΔF_i [%]
1	13.90	129.50	34.79	187.70	13.91	129.40	34.83	187.81	0.07	0.06
2	14.58	102.88	34.79	149.13	14.59	102.81	34.83	149.22	0.07	0.06
3	17.10	55.56	34.79	80.52	17.12	55.49	34.86	80.60	0.12	0.40
4	16.13	62.00	35.26	91.08	16.03	62.38	34.85	90.59	-0.62	-0.54
5	17.49	100.06	34.81	145.12	17.50	100.00	34.85	145.19	0.06	0.05
Sum	-	449.99	-	653.54	-	450.09	-	653.41	mean -0.06	mean -0.05

In Tab. 2 the results of analogical calculations for an ideal situation of no-current conditions are given. In this case the discrepancies between results obtained from the two methods are even smaller, as follows:

- that of optimum speed: - 0.06% of the average value and 0.31% of the standard deviation value
- that of fuel consumption at the particular voyage route segments: - 0.05% and 0.27 % respectively.

The total voyage fuel consumption given in Tab. 2 is different from that in Tab.1 although the total voyage time is equal, because the voyage conditions are different ($v_p = 0$).

It can be observed, when comparing the daily fuel consumption values, that the speed distribution optimization leads to a more uniform engine loading especially when sea currents are small or none. The engine load oscillations are about 6% in the considered case of active sea currents, but if there are no currents the oscillations are 0.6%.

Therefore a hypothesis stated in [2] is confirmed that, in the case when it is impossible to perform the speed distribution optimization, the most advantageous way of ship handling is to maintain a constant engine power in different operation conditions, viz. maintaining the fuel consumption per hour or day constant in such a way as to reach the port of destination in a given time.

In Tab. 3 results are additionally given of the voyage simulation for the same real conditions as in Tab. 1, but keeping traditionally ship's speed constant and equal to that average of the entire voyage. The fuel consumption difference is about 9.1 t , i.e. ca 1.4%. The value is obviously dependent on actual operation conditions and, generally, it is on average about 4% but can reach even 10%.

Tab. 3. Results of the voyage simulation for the same real conditions as in Tab. 1, but without optimization and with ship's speed kept constant and equal to that average for the entire voyage

i	v_{di} [kn]	t_i [h]	F_{di} [t/day]	F_i [t]
1	15.56	115.71	46.62	224.78
2	15.56	96.43	43.38	174.31
3	15.56	61.07	29.27	74.48
4	15.56	64.28	31.07	83.21
5	15.56	112.50	25.61	120.02
Sum	-	449.99	-	676.79

CONCLUSIONS

● The comparative numerical analysis of the two optimization methods of ship speed distribution showed that both TUB and IM methods are equivalent as far as ship speed choice in different operation conditions and fuel consumption is concerned. The revealed differences are less than 0.2%.

● IM method is substantially simpler because it is more understable for its user due to the applied simple calculation techniques and a pocket calculator and short time only is necessary to perform calculations which is very important from the point of view of ship operation practice.

● The hypothesis, stated in the earlier investigations, is confirmed that the way of ship operation at a constant engine power (constant fuel consumption per time unit) is reasonable in the case when it is impossible to perform the speed distribution optimization. Today this is a usual situation as using propulsion characteristics correlated to ship operation conditions and assessing those conditions is not sufficiently spread in practice.

● The calculation results confirmed that obtaining economic gains from ship speed distribution optimization is possible which should encourage ship operators to take into account the conclusions and to undertake actions for implementation of a ship operation method close to the optimum one. Several per cent of fuel consumption savings without any additional financial expenditure, apart from other profits e.g. lesser tear-and-wear of engine parts, is worthwhile to be observed.

● The results of the work should be also implemented, perhaps in the first order, in the education of future and acting ship personnel.

NOMENCLATURE

A_i	-	coefficients in the relation of the ship propulsion power versus relative-to-water speed for i-th voyage route segment
B	-	index exponent of the relation of the ship propulsion power versus relative-to-water speed, constant for all voyage route segments
C_F, C_0, C_1, C_2	-	coefficients in the relation of the fuel consumption versus ship propulsion power
F	-	total fuel consumption during the entire voyage
F_{di}	-	daily fuel consumption during i-th voyage route segment
F_i	-	total fuel consumption during i -th voyage route segment
ΔF_{di}	-	difference between daily fuel consumption values obtained from IM and TUB methods
i	-	number of the successive voyage route segment, $i = 1, 2, ..., N$
k_0	-	initial value of K during successive iteration
Δk	-	increment of K during computations
K	-	constant value for a given voyage
N	-	chosen number of voyage route segments
P_0	-	rated propulsion power
s	-	voyage route length
s_i	-	i-th voyage route segment length
T	-	voyage time
t_i	-	i-th voyage route segment time
v	-	relative-to-water ship speed
v_0	-	relative-to-water ship service speed
$\overline{v}$	-	set average ship voyage speed
v_{di}	-	relative-to-sea-bed ship speed during i-th voyage route segment
v_{pi}	-	sea current speed during i-th voyage route segment
Δv	-	ship speed increment during computations
Δv_{di}	-	difference between ship speed values obtained from IM and TUB methods
ε_v	-	assumed accuracy of ship speed calculations
ε_t	-	assumed accuracy of voyage time calculations
σ_i	-	i-th voyage route segment relative length

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Miscellanea

PURPOSEFUL AND FRUITFUL COOPERATION

The contemporary shipbuilding industry is more and more demanding in the field of ship design and shipbuilding technology. That is why some ship classification societies develop their own research divisions and on the other hand tighten cooperation with the technical universities whose scientific activity can support classification issues.

An example of that is the cooperation of the Ship Structures and Mechanics Department, Ocean and Ship Technology Institute, Technical University of Szczecin with several classification societies, viz. Bureau Veritas, Det Norske Veritas, Lloyd's Register and Polish Register of Shipping (PRS). There are also sporadic contacts with other classification societies such as American Bureau of Shipping, Germanischer Lloyd or Registro Italiano Navale.

Department's cooperation with Bureau Veritas is the most intensive which started in the middle of the eighties. Results of it are a.o. the following:

- publication of results of the Department research dealing with standardization criteria for permissible fabrication deformations of ship structures in „ Bulletin Technique du Bureau Veritas"
- technical reports and articles about reliability of submersibles and statistical investigations on shipbuilding steel mechanical properties, elaborated during scientific trainings of Department's personnel at Centre de Recherches et Development nearby Paris
- elaboration of backgrounds for common research on ultimate capacity of ship hull structure which resulted in the RESULT computer program, a part of the CAD computer system for hull structures, offered by BV as MARS system
- mutual exchange of specialists who participate in lecturing and scientific seminars, held both in Poland and France, on e.g. fatigue strength of ship structures, development of a new system, VERISTAR, of the CAD and structural safety control of ships in service, or the ultimate strength, structural reliability and hydromechanic problems of fast ships.

On the other hand the scientific trainings in Norway within Department's cooperation with Det Norske Veritas were utilized for preparing research works on load carrying capacity of ship plates and some ship hydrodynamic problems.

Department's staff took part in the activity of technical committees of the International Ship and Offshore Structures Congress as well as of the DnV-PRS Technical Committee.

In the past year contacts of the Department with Lloyd's Register revived and in consequence prospects of common works on the basis of SHIP RIGHT computer program system for fatigue analysis of ship structures emerged. Exchange of testing results of the system is expected.

LR representative presented a paper about ship structure fatigue analysis procedure at the conference on „ Ship Structure and Mechanics " organized by the Department.

Earlier, several years ago in London , prof. M. Kmiecik gave a lecture on standardization of fabrication deformations of ship plates in the light of their ultimate capacity criterion.

The Department made several research works for PRS on the ultimate strength of ship plates and strength of screw propellers and continued contacts within PRS Scientific- Technical Committee. The Department staff was sporadically engaged in revising some parts of PRS rules dealing with hull structure and materials and participated in seminars organized by PRS. Planning common research works on a few issues is underway.

The long practice showed that such cooperation of the Ship Structures and Mechanics Department with the classification societies is purposeful and can yield results fruitful for both sides and therefore it should be maintained and developed in compliance with actual demands.