POLISH MARITIME RESEARCH 4(54) 2007 Vol 14; pp. 18-23
DOI: 10.2478/v10012-007-0035-8

Mean long-term service parameters of transport ship propulsion system

Part I
Screw propeller service parameters of transport ship sailing on a given shipping route

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ABSTRACT

During ship sailing on a given shipping route in real weather conditions all propulsion system performance parameters of the ship change along with changes of instantaneous total resistance and speed of the ship. In this paper results of calculations are presented of distribution function and mean statistical values of screw propeller thrust, rotational speed and efficiency as well as propulsion engine power output and specific fuel oil consumption occurring on selected shipping routes. On this basis new guidelines for ship propulsion system design procedure are formulated.

Keywords: thrust, efficiency and rotational speed of screw propeller, long-term prediction, shipping route, design working point of screw propeller

INTRODUCTION

A crucial element of design process of transport ship propulsion system is selection of its design parameters, i.e. determination of a speed value for which screw propeller should be designed and determination of a thrust value which should be developed by this propeller at the assumed speed. Correct selection of the design speed is specially important for ships fitted with fixed pitch propellers (most often applied to transport ships) as only at that design speed such propeller is able to use full engine power output.

The service speed at which the designed ship has to operate in real weather conditions on a given shipping route, should be assumed as the design speed.

The way of calculation of the mean long-term service speed and the mean long-term resistance of the ship is presented in [1, 2, 3].

The design working point of screw propeller is associated with the following design parameters : ship speed and propeller thrust. Selection of such point is very important with a view of correct operation of propulsion system. In this point screw propeller efficiency should reach as - high - as possible value. For screw propellers interacting with piston combustion engines the design point is usually placed half way between the points A and B (Fig. 1), that generally ensures correct operation of the propulsion system in the point B, i.e. in service conditions (real weather conditions).

Instantaneous service speed of ship and its total resistance depend on instantaneous weather conditions occurring on a given shipping route. Hence working parameters of the screw propeller designed and applied to propel the ship will be changeable depending on weather parameters and assumed criteria of propulsion system control [4]. Knowing statistical data on wind and waves occurring on a given shipping route as well as long-term distribution function of ship speed [3] on the route, one can determine long-term distribution functions of working parameters of the screw propeller and hence mean statistical location of its working point on a given shipping route.

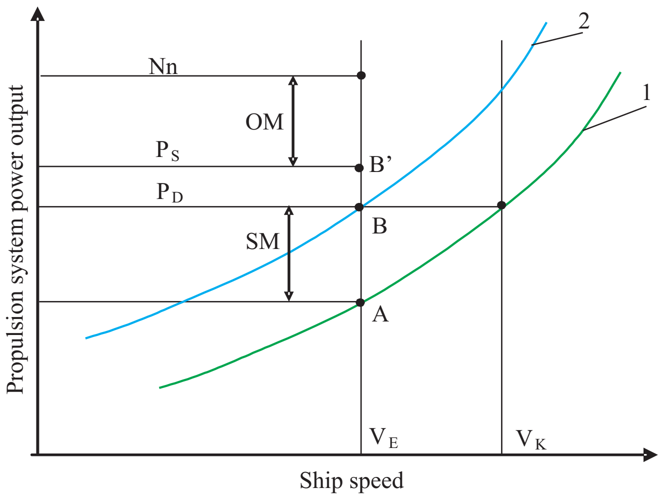


Fig. 1. *Predicted service speed of ship*
Nn *– nominal power output of engine,* P_S *– shaft-line power,* P_D *– power delivered to propeller cone,* V_K *– contractual speed of ship,* V_E *– predicted service speed of ship,* ***1*** *– still-water propeller curve for clean ship hull,* ***2*** *– predicted propeller curve with service margin, in real conditions,* ***OM*** *– operational margin,* ***SM*** *– service margin.*

Therefore this paper presents calculations - performed for designed ships and their propulsion systems together - of long-term service parameters of screw propeller and mean service location of its working point as well as discussion on how it would influence its design working point.

SERVICE PARAMETERS OF SCREW PROPELLER

The service parameters of screw propeller to be calculated for a ship sailing on a given shipping route are the following:

- ⇨ the propeller thrust T
- ⇨ the propeller rotational speed n_p
- ⇨ the free-propeller efficiency η_0.

The thrust of the behind-the-hull propeller is expressed as follows :

$$T = \frac{R_C}{1-t} \quad (1)$$

where:

R_C – total resistance of ship to motion in waves
t – thrust deduction.

The free-propeller thrust can be calculated by using the formula :

$$T = K_T \rho_w D_p^4 n_p^2 \quad (2)$$

where:

D_p – propeller diameter,
n_p – propeller speed,
K_T – thrust ratio which – for typical B-Wageningen screw propellers of given parameters : (P/D) (A_E/A_0), (Z) – is approximated with the use of the expression:

$$K_T = A_0 + A_1 \cdot J + A_2 \cdot J^2 + A_3 \cdot J^3 \quad (3)$$

where:

A_0, A_1, A_2, A_3 – coefficients of polynomial approximating propeller thrust characteristic, dependent on (P/D), (A_E/A_0), (Z)
J – advance ratio:

$$J = \frac{V[1-w(V)]}{D_p \cdot n_p} \quad (4)$$

where:

w(V) – wake fraction dependent on the ship speed V.

On the propeller in operation the torque Q is generated:

$$Q = K_Q \rho_w D_p^5 n_p^2 \quad (5)$$

where:

K_Q – torque ratio which – for a given propeller – can be expressed as follows:

$$K_Q = B_0 + B_1 \cdot J + B_2 \cdot J^2 + B_3 \cdot J^3 \quad (6)$$

where:

B_0, B_1, B_2, B_3 – coefficients of polynomial approximating propeller torque, dependent on the propeller parameters : (P/D), (A_E/A_0), (Z).

The free-propeller efficiency (free of ship hull) is equal to:

$$\eta_0 = \frac{K_T}{K_Q} \cdot \frac{J}{2\pi} \quad (7)$$

During calculations of the propeller service parameters, propeller thrust changes due to ship's rolling motion and resulting excitations to propeller were taken into account; the influence of ship roll on propeller thrust decrease was presented in [2].

The behind-the-hull propeller loads its propulsion engine with the torque (5). The relationship between the propeller torque and propulsion engine output is as follows:

$$Q = \frac{P_D}{2\pi n} \quad (8)$$

where:

P_D – power delivered to the propeller
n – engine speed (for slow-speed engines where a reduction gear is not applied : $n = n_p$), and :

$$P_D = N \cdot \eta_{LW} \cdot \eta_R \cdot \eta_P \quad (9)$$

N – engine power output
η_R – rotative efficiency
η_{LW} – shaft-line efficiency
η_P – efficiency of reduction gear (if applied).

The calculations of the service parameters of screw propeller were performed for the propulsion engine whose working area is limited by its characteristics [2].

PREDICTION OF MEAN STATISTICAL SERVICE SPEED OF SCREW PROPELLER OF SHIP SAILING ON A GIVEN SHIPPING ROUTE

Instantaneous values of propeller service parameters

During ship sailing in waves the ship is loaded by additional resistance components due to wind, waves, sea surface currents, and possible rudder blade deviations [1]. The additional resistance forces make propeller speed and thrust changing; new values of propeller speed and thrust are searched for in such a way as to keep engine working point within its working area. Searching for the working point at given criteria, e.g. at maintaining a given ship speed or reaching the maximum one without engine overloading, is performed in the same way as the searching for of instantaneous ship speed [2, 3].

On the basis of the solution of the non-linear set of equations presented in [2], at first instantaneous values of propeller speed and ship speed are determined and if all criteria are satisfied then instantaneous values of propeller thrust and efficiency are calculated.

Mean statistical values of screw propeller service parameters of ship sailing on a given route

In the case of screw propeller - like in calculating the mean statistical value of ship service speed - its parameters depend on statistical parameters of waves and wind, and assumed ship course angles and speeds on a given shipping route. Therefore the probability of ship being in a given situation while sailing in waves on a given shipping route is the following :

$$p_w = f_A \cdot f_S \cdot f_\mu \cdot f_{HT} \cdot f_V \cdot f_\psi \quad (10)$$

where:

f_A – probability of staying the ship in the sea area A
f_S – probability of staying the ship in the sea area A during the season S
f_μ – occurrence probability of the wave direction μ in the sea area A during the season S
f_{HT} – occurrence probability of wave of the parameters (H_S, T_1), propagating from the direction μ
f_V, f_ψ – probability of the event that ship will sail with the speed V and the course angle ψ, respectively.

For each situation for which the probability p_w is calculated, the instantaneous working point of propeller, determined by the instantaneous ship speed V_i and the instantaneous propeller speed n_{pi}, is calculated. Different instantaneous values of V_i and n_{pi} may yield the same value of the advance ratio J_i acc. (4) and - in consequence - instantaneous values of the thrust T_i and the propeller efficiency η_{0i}.

The total occurrence probability P_T of given values of propeller thrust and efficiency is as follows :

$$P_{TT} = \sum_{A=1}^{n_A} \sum_{S=1}^{n_S} \sum_{\mu=1}^{n_\mu} \sum_{H,T=1}^{n_{HT}} \sum_{V=1}^{n_V} \sum_{\psi=1}^{n_\psi} p_{T_i}[T_i(\Delta R_i)] \qquad (11)$$

where:

P_{TT} – total occurrence probability of a given value of the thrust T_i
$T_i(\Delta R_i)$ – instantaneous value of the propeller thrust in function of the instantaneous additional resistance
n_A, n_S, n_μ, n_{HT}, n_V, n_ψ – number of : sea areas crossed by the ship, seasons of the year, values of wave direction, wave parameters and ship course angle, respectively.

All instantaneous values of propeller service parameters are grouped into classes (intervals of a width appropriate to a given parameter and number of its calculation results).

Calculating the distribution function of occurrence probability of instantaneous propeller thrust, $f(T_i)$, or that of occurrence probability of instantaneous propeller speed, $f(n_{pi})$, or that of occurrence probability of instantaneous propeller efficiency, $f(\eta_{0i})$, one can determine the mean, long-term value of propeller thrust (or – analogously – propeller speed and efficiency) for a given shipping route :

$$\overline{T} = \frac{\sum_{i=1}^{n_T} P_{TT} \cdot T_i(\Delta R_i = \text{const})}{\sum_{i=1}^{n_T} P_{TT}} \qquad (12)$$

where:

n_T – number of intervals containing similar instantaneous values of propeller thrust.

From the expressions similar to (12) the mean, long-term value of propeller speed, $\overline{n}_p$, or that of propeller efficiency, $\overline{\eta}_0$, can be calculated.

PARAMETERS OF THE SHIPS AND SHIPPING ROUTES FOR WHICH THE CALCULATIONS WERE PERFORMED

The calculations of the mean statistical service parameters of screw propeller were performed for the ships and shipping routes whose parameters were given in [3].

RESULTS OF CALCULATIONS

Results of the calculations for the selected ship and shipping routes are presented in the form of :

- histogram of propeller thrust and its mean statistical value
- histogram of propeller speed and its mean statistical value
- histogram of propeller efficiency and its mean statistical value
- mean statistical propeller working point,
- probability distribution function of long-term occurrence of given values of propeller rotational speed and ship service speed.

All the calculations were performed under the assumption that engine's power output reaches at most 0.9 N_n.

In the below attached figures the calculation results are presented for K1 containership [3] and the two very different shipping routes : 5b - "easy" one and 2b - „difficult" one - in the sense of occurrence of long-term weather parameters.

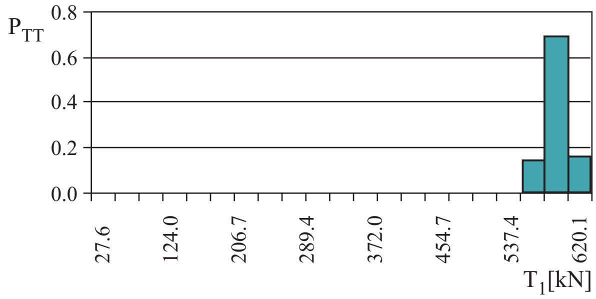
MEAN STATISTICAL WORKING POINT OF SCREW PROPELLER

Presented in Fig. 2, the histograms of propeller thrust, speed and efficiency show that propeller service parameters depend to a large extent on shipping route weather parameters. The most interesting is the distribution of the free-propeller efficiency η_0, the mean statistical value of propeller efficiency on a given route, $\overline{\eta}_0$, and its comparison with that in still water, η_0, Fig. 3 and 4.

Ship: K1 - assumed service speed = 8.44 [m/s]
- probability of maintaining the assumed speed P_{VE}

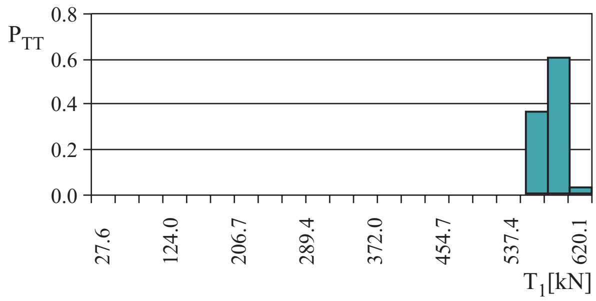
Thrust histograms

Route no. 2b - P_{VE} = 0.50



Thrust in still water T = 579 [kN]
Mean thrust $\overline{T}$ = 593 [kN]

Route no. 5b - P_{VE} = 0.83



Mean thrust $\overline{T}$ = 582 [kN]

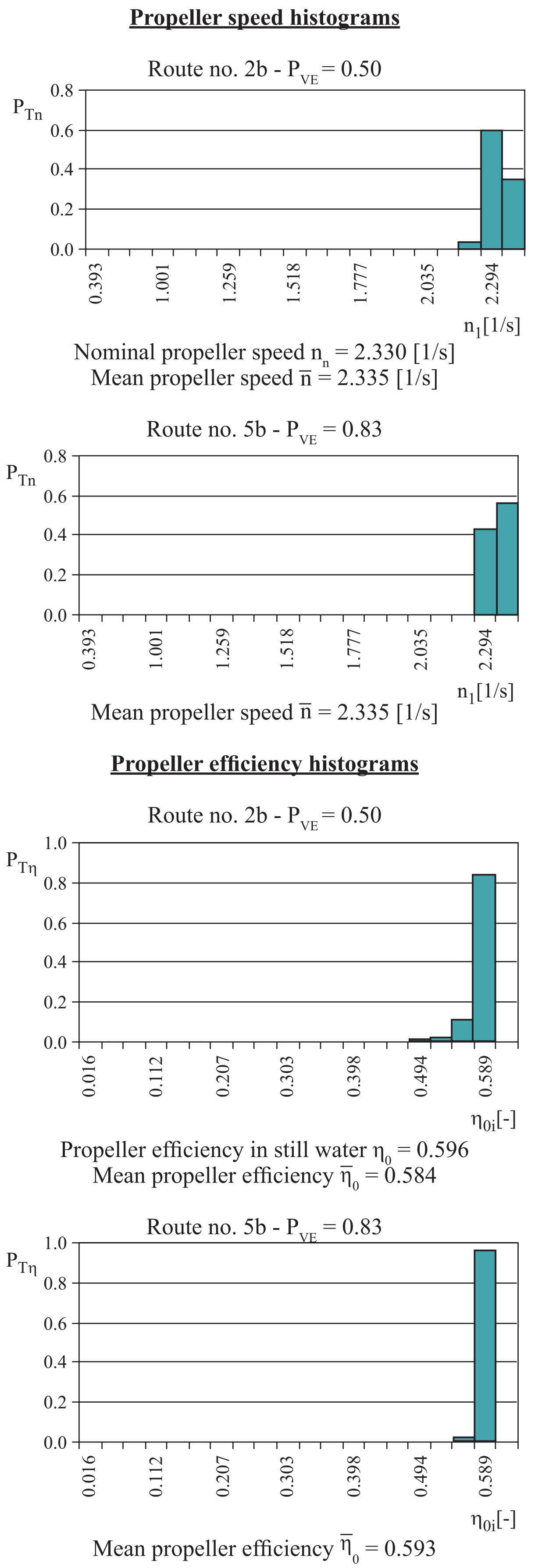


Fig. 2. *Histograms and mean statistical values of thrust, speed and efficiency of propeller for K1 ship sailing on 2 b and 5 b shipping routes*

The enlarged fragment of the propeller efficiency characteristic together with the depicted mean statistical values of propeller efficiency for various shipping routes makes it possible to determine values of propeller design parameters for a selected ship sailing on a given route. For ship which sails on many shipping routes appropriate mean efficiency value can be calculated from mean statistical efficiency values for the ship on particular shipping routes.

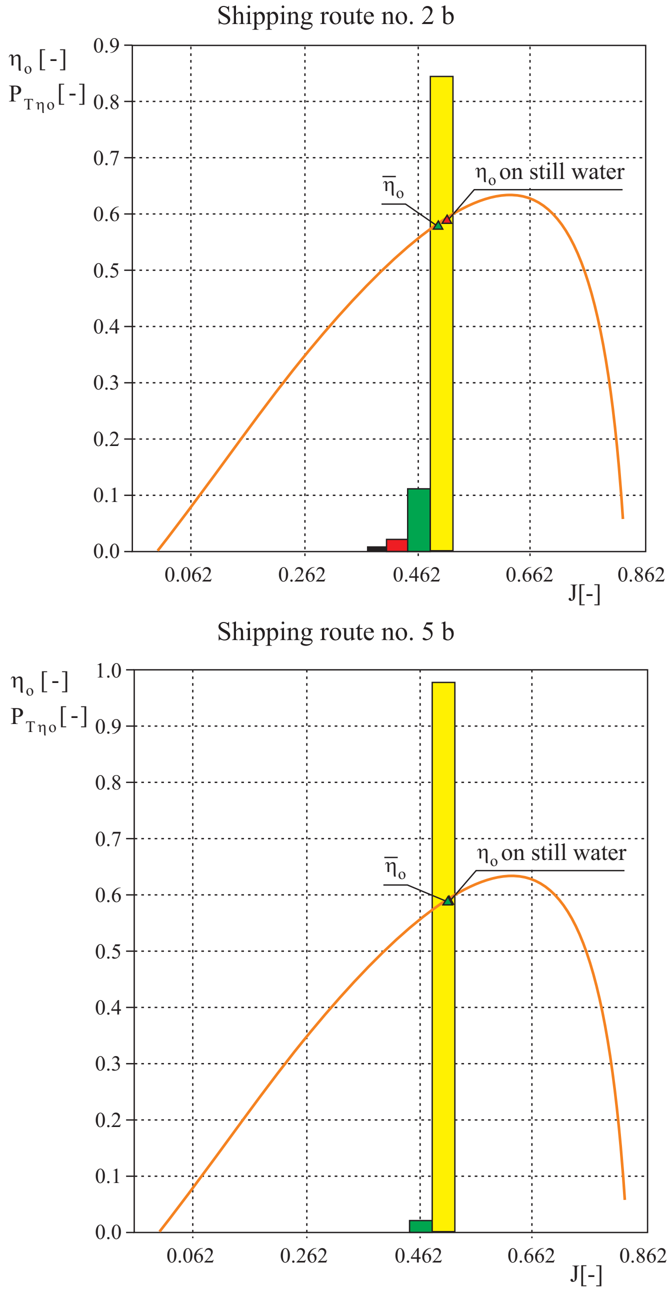


Fig. 3. *Histogram, mean statistical value of propeller efficiency on a given shipping route and propeller still-water efficiency for K1 ship*

On the basis of the calculation results of the mean statistical values of propeller efficiency (Fig. 4), were calculated the mean statistical working points of the propeller, presented on the power output – ship speed diagram (Fig. 6). On comparison of Fig.6 and Fig. 1 it can be clearly stated that the design working point is not only located between the points A and B (Fig. 1) but also its location depends on the mean statistical service speed of ship on a given shipping route hence it also depends on statistical weather parameters on the shipping route in question These problems are planned to be further investigated so as to make it possible to elaborate design guidelines for screw propeller of ship sailing on a given shipping route. The presented figures yield one important information, namely :

it is rather improbable that during ship sailing on a given route in real weather conditions the advance ratio J could reach a value greater than that in still water conditions.

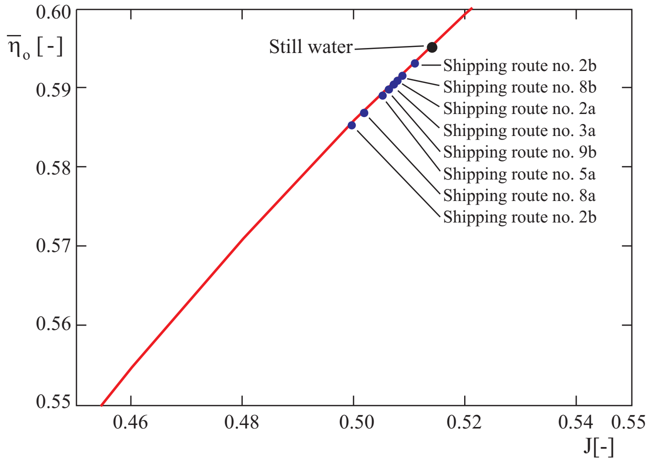


Fig. 4. Influence of shipping route [3] (weather parameters on a given shipping route) on mean statistical value of propeller efficiency for K1 ship

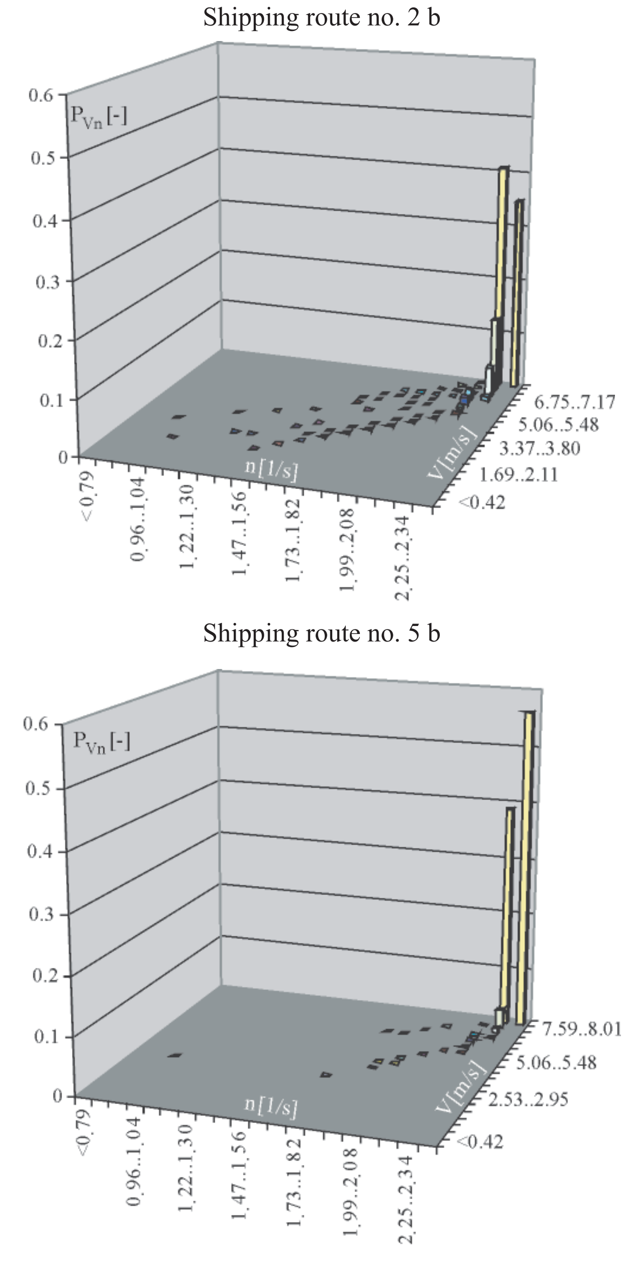


Fig. 5. Occurrence probability of given values of propeller speed and ship speed on a given shipping route for K1 ship

Efficiency of a given screw propeller depends on its rotational speed and ship speed (advance ratio J). Fig. 5 shows which is the occurrence probability of the pairs of propeller rotational speed – ship speed values for two selected shipping routes.

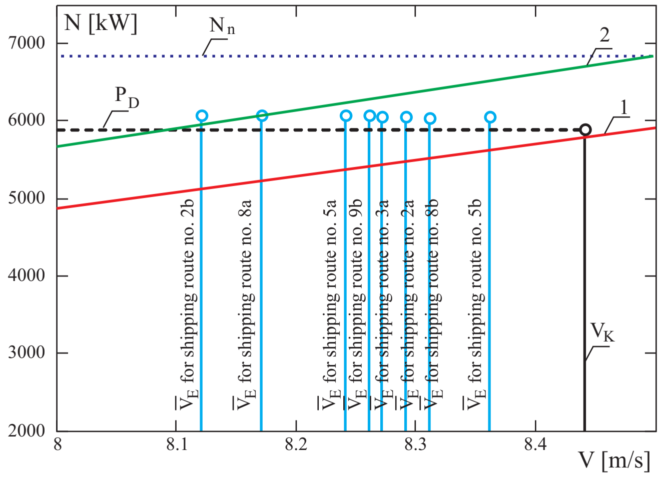


*Fig. 6. Mean statistical working point of K1 ship propeller, depending on the mean statistical ship service speed $\overline{V}_E$ on various shipping routes. **1** – still-water propeller curve; **2** – propeller curve containing the service margin SM = 15%; $\boldsymbol{P_D}$ – power delivered to propeller cone at ship's contractual speed in still water conditions; $\boldsymbol{N_n}$ – nominal power output of propulsion engine; $\boldsymbol{\overline{V}_E}$ – mean statistical long-term value of ship service speed on a given shipping route; $\boldsymbol{V_K}$ – contractual speed of ship*

NOMENCLATURE

- (A_E/A_0) – coefficient of developed area of propeller blades
- A_0, A_1, A_2, A_3 – coefficients of polynomial approximating propeller thrust characteristic
- B_0, B_1, B_2, B_3 – coefficients of polynomial approximating propeller torque characteristic
- D_p – propeller diameter
- f_A – probability of staying the ship in the sea area A
- f_{HT} – occurrence probability of wave of the parameters (H_S, T_1), propagating from the direction μ
- f_S – probability of staying the ship in the sea area A during the season S
- f_V, f_φ – probability of the event that ship will sail with the speed V and the course angle ψ, respectively
- f_μ – occurrence probability of the wave direction μ in the sea area A during the season S
- H_S – significant wave height
- J – propeller advance ratio
- J_i – instantaneous advance ratio
- K_T – propeller thrust ratio
- K_Q – propeller torque ratio
- N – propulsion engine power
- N_n – nominal propulsion engine power
- n – propulsion engine speed
- n_p – propeller (rotational) speed
- n_{pi} – instantaneous propeller speed
- $\overline{n}_p$ – long-term, mean statistical propeller speed
- $n_A, n_S, n_\mu, n_{HT}, n_V, n_\psi$ – number of : sea areas crossed by the ship, seasons of the year, values of : wave direction, wave parameters and ship course angle, respectively
- P_D – power delivered to propeller cone
- P_S – shaft-line power
- P_{Vn} – occurrence probability of given values of propeller speed and ship speed
- P_{VE} – probability of maintaining a given value of ship speed
- P_{Tn} – occurrence probability of a given value of propeller speed
- P_{TT} – occurrence probability of a given value of propeller thrust T_i
- $P_{T\eta 0}$ – occurrence probability of a given value of propeller efficiency

p_w – probability of being the ship in a given situation
Q – propeller torque
R_C – total ship resistance to motion
T_i – instantaneous thrust of propeller
$\overline{T}$ – long-term mean statistical value of propeller thrust
t – propeller thrust deduction
V – ship speed
V_E – ship service speed
$\overline{V}_E$ – mean statistical ship service speed
V_K – contractual ship speed
Z – number of propeller blades
w – wake fraction
η_0 – free -propeller efficiency
η_{0i} – instantaneous propeller efficiency
$\overline{\eta}_p$ – long-term mean statistical propeller speed
η_R – rotative efficiency
η_{LW} – shaft-line efficiency
μ – geographic direction of wave
ρ_w – water density
ψ – geographic angle of ship course.

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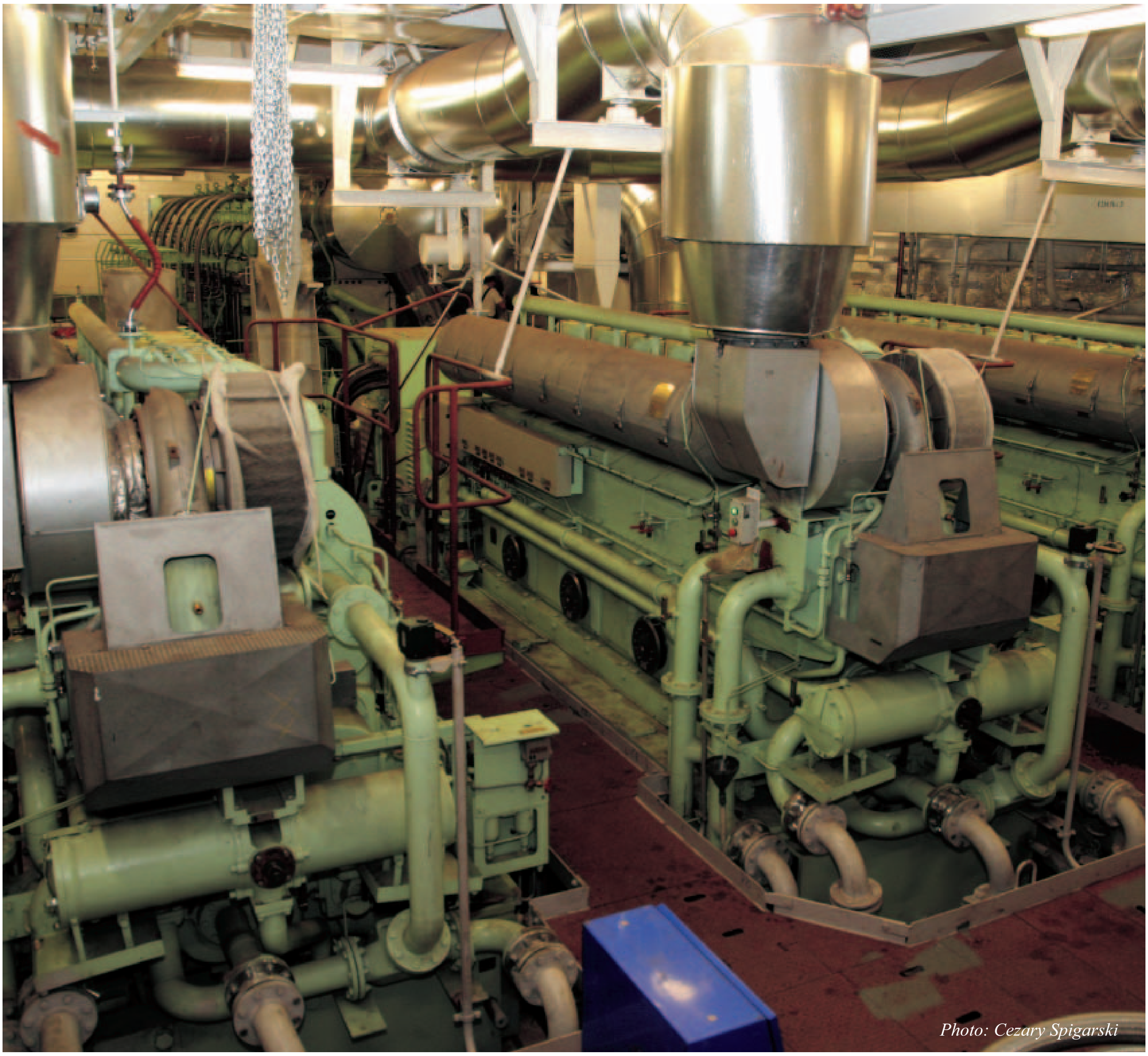
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