Calculation of the mean long-term service speed of transport ship

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Part II
Service speed of ship sailing
on regular shipping route in real weather conditions

Tadeusz Szelangiewicz
Katarzyna Żelazny
Szczecin University of Technology

ABSTRACT

Service speed obtainable by a ship in real weather conditions when sailing on a given shipping route, is one of the major parameters which have great impact on ship operation costs. The so far used, very approximate method of service speed prediction based on "service margin", is very little exact. In this paper a new method based on additional ship resistance dependent on mean statistical parameters of wave and wind occurring on a given shipping route, is presented. The mean long-term service speed is calculated on the basis of the calculated additional resistance and the screw propeller and propulsion engine parameters. Also, a new definition of service margin and a way of its calculation is presented apart from the results of the mean service speed calculation depending on ship's type and size and shipping route.

Keywords : ship service speed, wind, waving, shipping route, service margin, long-term prediction.

SHIP PROPULSION SYSTEM

Screw propeller

Ship propulsion system is represented first of all by a propeller cooperating with propulsion engine. To calculate instantaneous ship service speed it is necessary to know hydrodynamic characteristics of the propeller (derived from model tests or calculated by using approximate methods) and the characteristics which describe engine load area.

In the calculations were used the characteristics of B-Wageningen screw propellers [4,5], from which propeller's thrust and torque were calculated.

Thrust of the propeller placed behind the ship hull is expressed as follows :

$$T = \frac{R_C}{1 - t} \qquad (27)$$

where :

R_C − total resistance of ship sailing in rough waters
t − thrust deduction factor.

Thrust of free propeller can be calculated from the formula :

$$T = K_T \rho_w D_p^4 n_p^2 \qquad (28)$$

where :

D_p − propeller diameter
n_p − propeller rotational speed

K_T − thrust coefficient which − for typical B-Wageningen propellers of given values of the pitch ratio (P/D), blade area ratio (A_E/A_0), number of blades (Z) − is approximated by using the expression :

$$K_T = A_0 + A_1 J + A_2 J^2 + A_3 J^3 \qquad (29)$$

where :

A_0, A_1, A_2, A_3 − coefficients of the polynomial describing thrust characteristics, depending on (P/D), (A_E/A_0), Z
J − advance coefficient :

$$J = \frac{V[1 - w(V)]}{D_p n_p} \qquad (30)$$

$w(V)$ − wake fraction depending on the ship speed V.

The propeller − when working − generates the torque Q :

$$Q = K_Q \rho_w D_p^5 n_p^2 \qquad (31)$$

where :

K_Q − torque coefficient which − like the thrust coefficient − can be expressed for a given propeller in the following form :

$$K_Q = B_0 + B_1 J + B_2 J^2 + B_3 J^3 \qquad (32)$$

where :

B_0, B_1, B_2, B_3 − coefficients of the polynomial describing torque characteristics, depending on (P/D), (A_E/A_0), Z.

Free-propeller efficiency (free from ship's hull) is equal to :

$$\eta = \frac{K_T}{K_Q} \cdot \frac{J}{2\pi} \qquad (33)$$

The hydrodynamic characteristics of propeller achieved from model tests [4,5] are determined for a given Reynolds number and propeller surface state. In order to use the characteristics for the behind-the-hull propeller were introduced relevant corrections associated with influence of Reynolds number and real state of propeller surface, which makes it possible − together with knowledge of ship hull surface state − to investigate influence of ship and propeller ageing on ship service speed.

The expressions (27) and (28) for propeller thrust are valid for ship sailing in still and rough waters provided its oscillating and relative motions are so small that propeller emerging does not occur. During sailing in waves at large oscillating and relative motions the propeller operates in highly aerated water or emerges. It generates thrust variations and drop of mean effective thrust value relative to that in still water (even if the ship goes at constant speed and number of propeller rotations).

The thrust decrease is caused a.o. by an influence of water particles being in oscillating motion, on wake, as well as by propeller emerging resulting from large relative motions of the ship in waves. The thrust decrease due to ship motions in waves has been discussed in various publications where approximate formulae for estimating the influence of relative motions on operational parameters of propeller are included [3].

The propeller thrust decrease due to ship relative motions in waves is defined by means of the following coefficient [3] :

$$\beta_T = \frac{K_{Tw}\left(\dfrac{h_p}{R}\right)}{K_T} \qquad (34)$$

where :

$K_{Tw}\left(\dfrac{h_p}{R}\right)$ − thrust coefficient of emerging propeller (the quantities h_p and R are shown in Fig.11)

K_T − thrust coefficient of fully immersed propeller.

Changes of values of the coefficient β_T

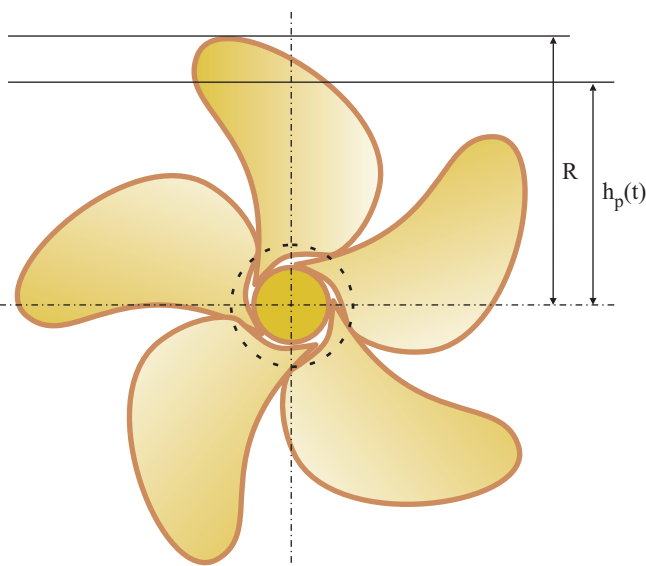in function of $\left(\dfrac{h_p}{R}\right)$ are shown in Fig.12, [6].

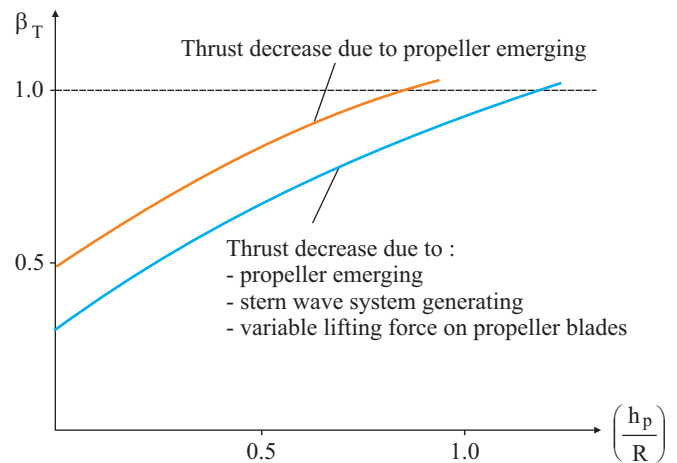*Fig. 11. The propeller draught h_p as defined in the equation (34) .*

Fig. 12. Thrust decrease during propeller emerging [6] .

In simulative propeller thrust calculations, the influence of wave parameters on propeller operation effectiveness was taken into account (detailed analysis of the phenomenon is given in [9]) whereas the propeller emergence was mitigated by intentional reduction of ship speed.

Propulsion engine

The behind-the-hull propeller loads the ship engine with its torque (31). The relation of the propeller torque and propulsion engine output power is as follows :

$$Q = \frac{P_D}{2\pi n} \qquad (35)$$

where :

P_D − power delivered to the propeller
n − rotational speed of engine (for slow-speed engines if no reduction gear is applied : $n = n_p$) :

$$P_D = N \cdot \eta_{LW} \cdot \eta_R \cdot \eta_P \qquad (36)$$

N − propulsion engine output power
η_R − relative rotative efficiency
η_{LW} − shaft-line efficiency
η_P − reduction gear efficiency, if applicable.

Engine output power for a designed ship is so selected as to obtain the propulsion system working point of the value equal to $0.85\,N_n$ at the design (contractual) speed in still water. In real weather conditions, when wind and waves affect the ship and the additional resistance ΔR appears, then the propulsion system working point changes its location within the propulsion engine's load area. By controlling fuel charge (and this way also rotational speed of engine and propeller) the working point can be positioned in the maximum continuous rating area or the limited rating area for engine overloading (Fig.13).

Therefore, in order to find an instantaneous speed at which a given ship would sail in considered weather conditions it is necessary to know the engine load area which is constrained by relevant characteristics. This area indicates where the propulsion system working point is to be located. For instance the area of a Sulzer engine is shown in Fig.13.

The particular areas are limited by the engine performance characteristic curves in the following form :

$$N = k_m \cdot n^m \qquad (37)$$

where :

N − engine output power
k_m − coefficient for a given characteristic curve
n − engine rotational speed

m − exponent depending on a type of engine of a given
producer :
- e.g. for SULZER RTA 52, RTA 62, RT 72, RTA 84
slow speed engines it is equal to :

m = 0 − for constant rated or maximum output power
m = 1 − for constant torque characteristic curve
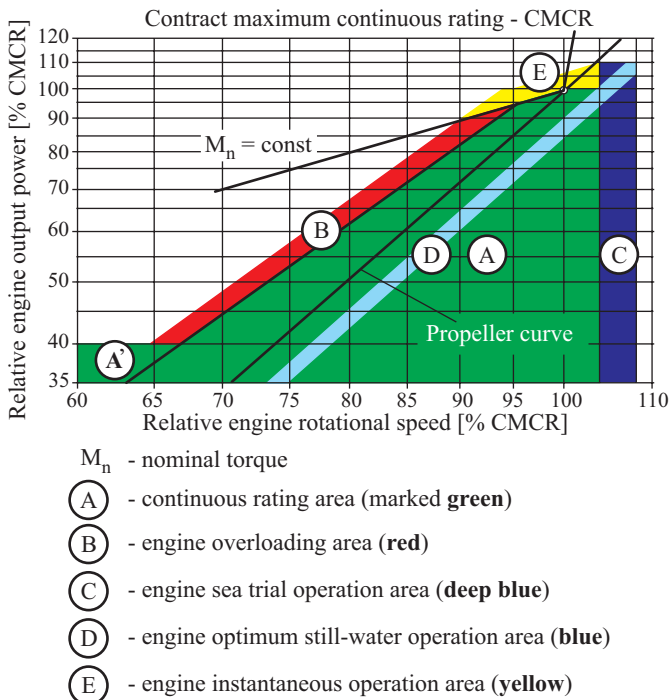m = 2.45 − for overloading characteristic curve.

Fig. 13. *The load area of an example Sulzer propulsion engine [2] .*

M_n - nominal torque

Ⓐ - continuous rating area (marked **green**)

Ⓑ - engine overloading area (**red**)

Ⓒ - engine sea trial operation area (**deep blue**)

Ⓓ - engine optimum still-water operation area (**blue**)

Ⓔ - engine instantaneous operation area (**yellow**)

Service speed of ships fitted with engines of other producers
can be calculated if engine characteristics limiting
its load area are known.

The searching for of a working point of propulsion system
and its parameters can be effected by taking into account vario-
us criteria e.g. that for maintaining a given or maximum speed,
or also by using the criterion for minimum fuel consumption
or maximum efficiency of whole propulsion system.

Intentional reduction of ship speed in view of hazardous wave-generated phenomena

During ship sailing in rough water ship's oscillating mo-
tions and their derivatives i.e. velocities and accelerations are
the direct effect of waves. The secondary phenomena which
accompany the oscillating motions are : shipping of water on
deck, propeller emerging, pounding of wave to ship bottom
and sides (slamming), worsening of ship stability and ma-
noeuvrability, additional dynamic loads on hull structure. The
oscillating motions and accompanying phenomena depend on
parameters of ship hull and waves as well as the ship speed V
and course relative to waves (the angle β_w). The phenomena,
especially if very intensive, may lead directly to averages and
disasters at sea. It is possible to mitigate the phenomena, e.g.
ship rolling - by changing ship's course relative to waves (the
angle β_w), reducing ship's speed V, or simultaneous changing
ship's course and speed.

In predicting the mean service speed was made the assump-
tion that ship's speed reduction will be performed if :

$$\overline{U}_Z > \overline{U}_{Zdop} \qquad (38)$$

where :

$\overline{U}_Z$ − mean statistical value of the wave-generated phe-
nomenon Z considered hazardous to ship

$\overline{U}_{Zdop}$ − permissible value of the wave–generated pheno-
menon Z, at which the sailing ship is still safe.

In the performed calculations the ship course relative to
waves was kept unchanged (though its changing is always
possible), since in predicting the mean long-term ship service
speed it was assumed that the ship heads the course resulting
from the selected shipping route.

In assessing ship performance in waves and making deci-
sion on possible reduction of its speed, the following pheno-
mena were taken into consideration: rolling, pitching, vertical
accelerations, horizontal transverse accelerations, shipping of
water on deck, slamming, propeller emerging. The calculation
methods of the phenomena and the assumed acceptance criteria
are presented in [1, 5, 8].

The points at which values of the parameters of ship sea-
-keeping qualities were calculated, are presented in Fig. 14, and
in Fig.15, in the polar diagrams is shown an influence of ship
speed and wave direction relative to ship on some phenomena
induced by waves. The zone of unsafe intensity, i.e. where the
sea-keeping criteria are exceeded , is marked red; yellow colour
warns about a real hazard; green colour means the safe zone.
It can be observed that reducing the speed one can mitigate
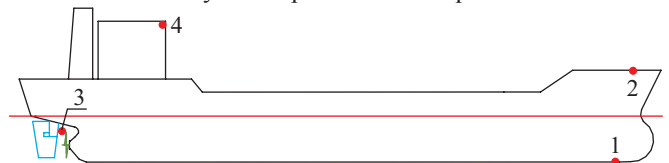intensity of the phenomena in question.

Fig. 14. *The points at which ship sea-keeping parameters were calculated :
1 – for slamming, 2 – for water shipping onto deck, and bow accelerations,
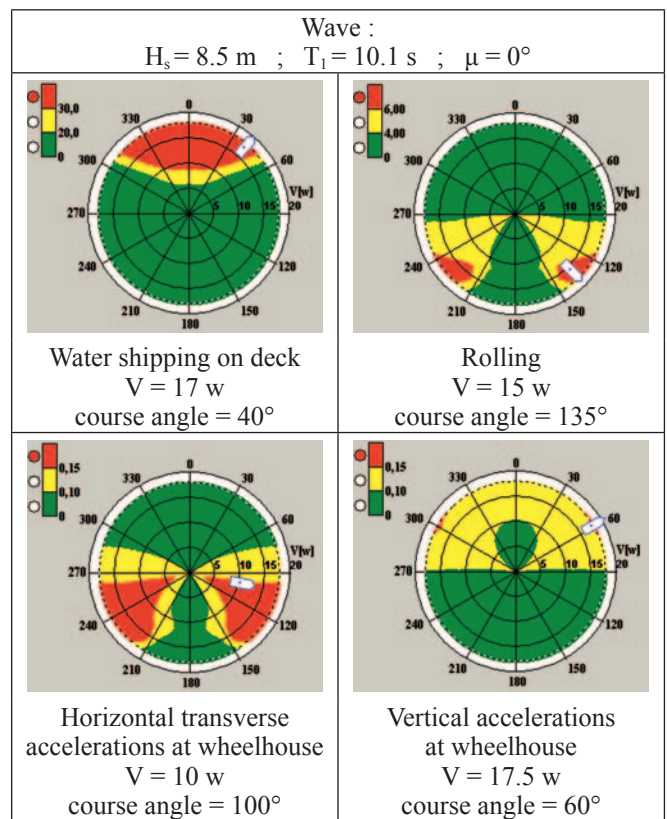3 – for propeller emerging, 4 – for accelerations at wheelhouse.*

| Wave : |
| $H_s = 8.5$ m ; $T_1 = 10.1$ s ; $\mu = 0°$ |

Water shipping on deck
V = 17 w
course angle = 40°

Rolling
V = 15 w
course angle = 135°

Horizontal transverse
accelerations at wheelhouse
V = 10 w
course angle = 100°

Vertical accelerations
at wheelhouse
V = 17.5 w
course angle = 60°

Fig. 15. *Influence course angle and speed of K1 ship on its selected sea-
keeping qualities. **Green** - safe operation of ship. **Yellow** - warning on a real
hazard (lower value of a relevant criterion is exceeded). **Red** - ship's safety
is endangered (upper value of a relevant criterion is exceeded) .*

A METHOD FOR PREDICTING MEAN STATISTICAL SERVICE SPEED OF A SHIP SAILING ON A GIVEN SHIPPING ROUTE

Instantaneous service speed of ship

During ship motion in rough water, apart from still-water resistance also additional forces due to wind, waves and possible surface sea current act on the ship. These actions generate, apart from an additional resistance, a transverse force and a moment tending to rotate the ship around its vertical axis. The transverse force results in ship drifting, and the moment – in ship course changing. Ship's passive rudder is to be laid appropriately to keep ship course constant under action of the external rotating moment. Under the assumption that the ship course has to be maintained , from the solution of the following non-linear equations :

$$Y_A(V) + Y_W(V) + R_y(V, \beta) + Y_R(V, \beta, \delta_R) = 0$$
$$M_A(V) + M_W(V) + M_z(V, \beta) + M_R(V, \beta, \delta_R) = 0 \qquad (39)$$

together with the relevant equations describing additional resistance forces, (presented below), for given values of the ship speed V, course angle ψ, wind parameters (V_A, γ_A), wave parameters (H_S, T, μ) and possible sea current parameters (V_C, γ_C), the following quantities can be obtained :

β − ship drift angle
δ_R − ship passive rudder angle
ΔR − additional ship resistance due to wind, waves, current and passive rudder
R_C − total ship resistance to motion.

Schematic diagram of the complete calculation algorithm of β, δ_R and R_C for given values of the ship motion parameters (V, ψ), wind parameters (V_A, γ_A), wave parameters (H_S, T, μ) and current parameters (V_C, γ_C), was presented in [9].

The instantaneous ship service speed in variable weather conditions is calculated from the solution of the set of non-linear equations in such a way as to obtain the propulsion system working point laying within the engine continuous rating zone when total ship resistance and propeller thrust , as well as propeller torque and driving engine torque become equal to each other, respectively . Making use of the equations (4), (5), (27 ÷ 36) one obtains the set of two non-linear equations :

$$(A_0 + A_1 J + A_2 J^2 + A_3 J^3) \rho_w D_p^4 n^2 - \frac{R_C}{1-t} = 0$$

$$(B_0 + B_1 J + B_2 J^2 + B_3 J^3) - \frac{N \eta_{LW} \eta_R \eta_P}{2 \pi \rho_w D_p^5 n^3} = 0 \qquad (40)$$

where :

J − advance coefficient (30)
R_C − a function of total ship resistance, depending on the ship speed V, ship course angle ψ, wave parameters H_S, T, μ and wind parameters V_A, γ_A
N − driving engine output power determined by its characteristics valid within respective intervals of its rotation number n.

To solve the set of equations (40) and determine instantaneous ship service speed it is necessary to know the total ship resistance R_C which depends not only on the statistical parameters of waves and wind occurring on a given shipping route but also on current ship speed, course and drift angle. Since all the quantities depend on random parameters of waves and wind the total ship resistance should be calculated for all

statistical parameters of waves and wind occurring on a given shipping route. The calculation algorithm of instantaneous ship speed is presented in [9].

Mean statistical service speed of ship sailing on a given shipping route

During the long-term sailing of ship on an assumed shipping route the additional resistance due to wave action will depend not only on a wave height (and period) but also on geographical directions: of wave, μ , and ship course , ψ. Also the additional resistance due to wind will depend, apart from the wind speed V_A, on the directions γ_A and ψ . It means that the additional resistance and also ship speed will depend on the values of the parameters of waves (H_S, T_1, μ), wind (V_A, γ_A) and ship motion (V, ψ), which may occur on a given shipping route within a long period of time.

In the case in question the surface sea current is considered to be a determinate phenomenon of the mean speed V_C and direction angle γ_C. If a ship is assumed to enter a region of large-scale surface currents then the current action will be included into ship still-water resistance.

Therefore the occurrence probability of the additional resistance ΔR of a given value, as well as the speed V which can be reached at occurrence of that additional resistance, depends on :

⊃ shipping route and probability of staying the ship in particular sea areas
⊃ the statistical parameters of waves , (H_S, T_1, μ), and wind, (V_A, γ_A), and probability of occurrence of the parameters in given sea areas
⊃ probability of occurrence of the ship motion parameters (V, ψ).

The probability of being the ship in a given situation when sailing in waves on a given route, is as follows :

$$p_w = f_A \cdot f_S \cdot f_\mu \cdot f_{HT} \cdot f_V \cdot f_\psi \qquad (41)$$

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 − probability of occurrence of the wave direction μ in the sea area A during the season S
f_{HT} − probability of occurrence of the wave of the parameters (H_S, T_1), propagating from the direction μ
f_V, f_ψ − probability of the event that the ship moves with the speed V and heads the course ψ, respectively.

In a similar way can be expressed the probability p_A of being the ship in a given situation associated with wind state. In the calculations of additional resistance due to wind and waves it was assumed that wind speed and wave height are mutually correlated, hence $p_w = p_A$. As the event of being the ship in a given situation described by (41) will result in generating an additional resistance and achieving a determined speed, hence :

$$p_w = p_R = p_V \qquad (42)$$

where :

p_R − partial occurrence probability (in given conditions) of additional resistance
p_V − partial occurrence probability (in given conditions) of instantaneous ship service speed.

Values of the additional resistance due to wind, R_{XA}, and that due to waves, R_{XW}, depend on random parameters of wind

and waves. Therefore the same values of R_{XA} and R_{XW} can occur for different values of the parameters V_A, γ_A, H_S, T_1, μ, V, ψ. For each of the values of this way calculated additional resistance, a value of ship speed is calculated (the criteria concerning sea-keeping qualities are simultaneously examined to execute possible speed reduction in order not to violate them at given wave and wind conditions).

The total probability P_{TV} of achieving the ship speed V at a given value of the additional resistance ΔR, is as follows :

$$P_{TV} = \sum_{A=1}^{n_A} \sum_{S=1}^{n_S} \sum_{\mu=1}^{n_\mu} \sum_{H,T=1}^{n_{HT}} \sum_{V=1}^{n_V} \sum_{\psi=1}^{n_\psi} P_{Vi}[V_i(\Delta R_i)] \quad (43)$$

where :

$V_i(\Delta R_i)$ − instantaneous ship service speed in function of instantaneous additional ship resistance

n_A, n_S, n_μ, n_{HT}, n_V, n_ψ − numbers of sea areas (crossed by a given ship), seasons, wave directions, wave parameters, ship speeds and courses, respectively.

By calculating the distribution function of occurrence probability, $f(V_i)$, of the instantaneous ship speed V_i the mean long-term ship service speed for a given shipping route, can be determined as follows :

$$\overline{V}_E = \frac{\sum_{i=1}^{n_V} P_{TV_i} V_i(\Delta R = const)}{\sum_{i=1}^{n_V} P_{TV_i}} \quad (44)$$

where :

n_V − number of intervals containing similar values of the instantaneous ship service speeds.

On the basis of the presented calculation formula for the mean ship service speed, (44), were performed relevant calculations and analyses for example ships and shipping routes, whose results will be presented in the 3rd part of the paper.

NOMENCLATURE

$\left(\dfrac{A_E}{A_0}\right)$ − propeller blade area ratio

A_0, A_1, A_2, A_3 − coefficients of the polynomial describing thrust characteristics

B_0, B_1, B_2, B_3 − coefficients of the polynomial describing torque characteristics

D_p − propeller diameter

f_A − probability of staying the ship in the sea area A

f_{HT} − probability of occurrence of the 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_ψ − probability of the event that the ship moves with the speed V and heads the course ψ, respectively

$f_{\gamma A}$ − probability of occurrence of a given wind direction

H_S − significant wave height

J − advance coefficient

K_T − thrust coefficient

K_{Tw} − thrust coefficient of emerging propeller

K_Q − torque coefficient

k_m − coefficient of a given characteristic curve of engine performance

N − propulsion engine output power

N_n − nominal output power of propulsion engine

n − rotational speed of engine

n_n − nominal rotational speed of engine

n_p − rotational speed of propeller

$\left(\dfrac{P}{D}\right)$ − propeller pitch ratio

P_D − power delivered to propeller

P_{TV} − combined probability of reaching a given value of instantaneous ship service speed at occurrence of a given value of instantaneous additional ship resistance

p_w − partial probability of staying the ship in a given situation

p_R − partial occurrence probability of instantaneous additional resistance (in given conditions)

p_v − partial occurrence probability of instantaneous ship service speed (in given conditions)

Q − propeller torque

R_C − total ship resistance to motion

R_{xA}, R_{yA}, M_{zA} − mean wind-induced forces exerted to going ship (R_{xA} - additional ship resistance due to wind)

R_{xR}, R_{yR}, M_{zR} − passive rudder forces (R_{xR} - additional ship resistance due to rudder)

R_{xW}, R_{yW}, M_{zW} − mean wave-induced drift forces (R_{xW} - additional ship resistance due to waves)

T − free-propeller thrust

T_1 − mean characteristic wave period

t − thrust deduction factor

U_z − mean statistical value of the wave-induced phenomenon Z

V − ship speed

V_A − wind speed

V_C − sea current speed

$\overline{V}_E$ − mean statistical ship service speed

w − wake fraction

Z − number of propeller blades

β − ship drift angle

β_T − coefficient of propeller thrust decrease

γ_A − geographical direction of wind

γ_C − geographical direction of sea current

ΔR − additional ship resistance due to weather conditions

δ_R − passive rudder angle

η_0 − free-propeller efficiency

η_P − reduction gear efficiency

η_R − propeller rotative efficiency

η_{LW} − shaft-line efficiency

λ − rudder aspect ratio

μ − geographical direction of wave

ρ_w − water density

ψ − geographical direction of ship course

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