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A simplified method for calculating propeller thrust decrease for a ship sailing on a given shipping lane

Katarzyna Zelazny, Ph. D.,
West Pomeranian University of Technology Szczecin, Poland

ABSTRACT

During ship sailing on rough water, relative ship motions can be observed which make the propeller emerge from the water, and decrease its thrust as a consequence. The article presents a simplified method for calculating the thrust decrease and the time of propeller emergence from water for the ship on a regular an irregular wave. The method can be used for predicting the operating speed of the ship on a given shipping lane.

Keywords: ship motions on rough water; propeller emergence; thrust decrease

INTRODUCTION

As a direct effect of ship sailing on rough water, ship's heaving, rolling and pitching continuously take place in response to waves being their source. These motions can provoke other dangerous phenomena, such as accelerations and relative motions, which act continuously, and those occurring occasionally, like deck flooding, slamming, or propeller emergence from water. The latter phenomena result from, among other sources, relative ship motions, and in those cases the object of analyses is the frequency of their appearance in one hour or per 100 waves. The propeller emergence is dangerous for the entire ship propulsion system, in particular it is the source of thrust decrease which finally results in speed decrease of the ship sailing on rough water (this effect can also be caused by other causes) [6]. Calculating the ship thrust and speed decrease requires not only the information about the frequency of the propeller emergence, per hour for instance, but also on the scale and duration times of this emergence on a given shipping lane. Based on these data the thrust decrease can be calculated, and then the ship speed decrease caused by the propeller emerging from water.

The problem of propeller thrust decrease during ship sailing on rough water has been the object of study in numerous publications, for instance in [3] – a study of the effect of waves, but without propeller emergence, on the speed of the wake current and thrust, [2] – a study of thrust decrease during propeller emergence, and [4] – where the thrust decrease caused by the bow thruster tunnel emerging from water was examined. In Refs. [7] and [8] their authors also analysed the approximate effect of propeller emergence on the ship speed decrease. However, these publications do not provide information on the current value of the propeller thrust when the ship sails in given weather (sea) conditions and when its course is in certain relation to the direction of waves.

For the ship sailing on a given shipping lane the propeller emergence and thrust decrease take place when the wave is sufficiently high. Relevant analyses have revealed [8] that this situation occurs occasionally and the propeller thrust decrease leads to the decrease of operating speed of the ship by less than ten percent (which obviously depends on parameters of sea waves and navigating characteristics of the ship).

The article presents a simplified method for calculating the thrust decrease caused by the propeller emergence from water on regular and irregular wave. The presented method can be applied for predicting the operating speed of the ship sailing on a given shipping lane.

RELATIVE SHIP MOTION AND PROPELLER EMERGENCE ON REGULAR WAVE

Pitching, rolling, and heaving of the ship sailing on rough water generate its relative motions. The absolute vertical ship dislocation resulting from these motions is:

$$S_{zP}(t) = Z(t) + y_P\Phi(t) - x_P\Theta(t) \qquad (1)$$

while the relative dislocation is:

$$R_{zP}(t) = S_{zP}(t) - \zeta(t) \qquad (2)$$

where:

$Z(t)$, $\Phi(t)$, $\Theta(t)$ – ship heaving, rolling and pitching on regular wave,

x_P, y_P – coordinates of point P fixed to the ship, for which the relative vertical motion is calculated. In this case the point is situated at the propeller blade tip in its upper position, Fig. 2,

$\zeta(t)$ – ordinate of the regular sinusoidal wave which approaches the ship at the angle β_w (Fig. 1).

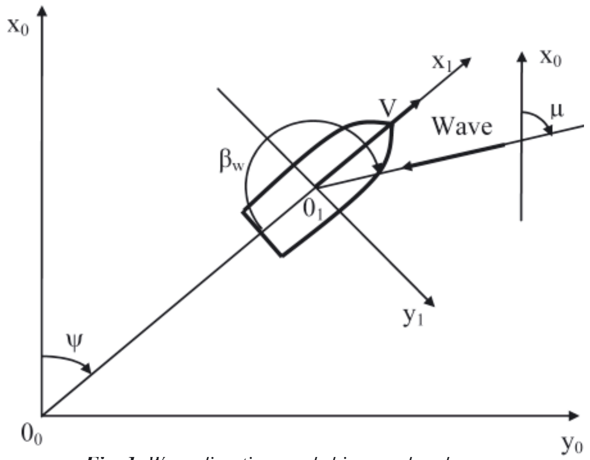

Fig. 1. Wave direction, and ship speed and course

The relative motion R_{zP} of the point P (propeller blade tip in its upper position - Fig. 2) is calculated based on the linear theory of ship motions, hence Equation (2) can have the form:

$$R_{zP}(t) = R_{zPA} \sin[\omega_E t - \delta_{RzP}(\omega_E)] \tag{3}$$

where:

R_{zPA} – amplitude of the relative vertical motion of point P,

$\delta_{RzP}(\omega_E)$ – phase shift angle between the ordinate of the relative motion and that of the wave motion.

Based on the relative motion, Equation (2) or (3), and the propeller position (more precisely: propeller blade tip – point P, Fig. 2) we can calculate when, to which height and for how long the propeller will emerge from water. The propeller emergence to the height h_{ws} will take place when:

$h_{ws}(t) = R_{zP}(t) - T_{zS}(t) > 0$ (4)

where:

T_{zS} – the draught of the propeller blade tip in its upper position:

$$T_{zS} = T_{P0} - 0.5D_P \tag{5}$$

T_{P0} – propeller shaft draught (Fig. 2),

D_P – propeller diameter.

A sample time-history of propeller emergence on regular wave, calculated for the ship having parameters given in Table 1, is shown in Fig. 3.

***Tab. 1.** Technical parameters and dimensions of the ship*

Length between perpendiculars	**L_{PP} = 138.0 m**
Width	B = 23.0 m
Draught	T = 8.5 m
Displacement	∇ = 21 411 m³
Speed	V = 14.24 w
Propeller diameter	D_P = 5.0 m
Propeller revolutions	n_P =110 rpm
Propeller shaft draught	T_{P0} = 5.9 m
Position of the propeller disc with respect to ⊗	x_P = -68.16 m

The time-history of the ordinate of the propeller blade tip emergence $h_{ws}(t)$ has made the basis for calculating its average value $h_{(ws)śr}$ (Fig. 3):

$$h_{(ws)śr} = \frac{1}{T_{ws}} \int_{t_1}^{t_3} h_{ws}(t)dt \tag{6}$$

where:

$$h_{ws}(t) = \begin{cases} R_{zP}(t) & \text{for} \in (t_1, t_2) \\ 0 & \text{for} \in (t_2, t_3) \end{cases} \tag{7}$$

t_1, t_2 – beginning and end of propeller blade tip emergence, Fig. 3,

t_3 – end of relative motion time period $R_{zP}(t)$, Fig. 3.

The average propeller emergence was calculated for different amplitudes ζ_A and frequencies ω of the regular wave, different directions of wave approach with respect to the ship, and different assumed ship speeds. Fig. 4 shows one of the analysed cases. The differences of the average propeller emergence values (Fig. 4) which are observed for different

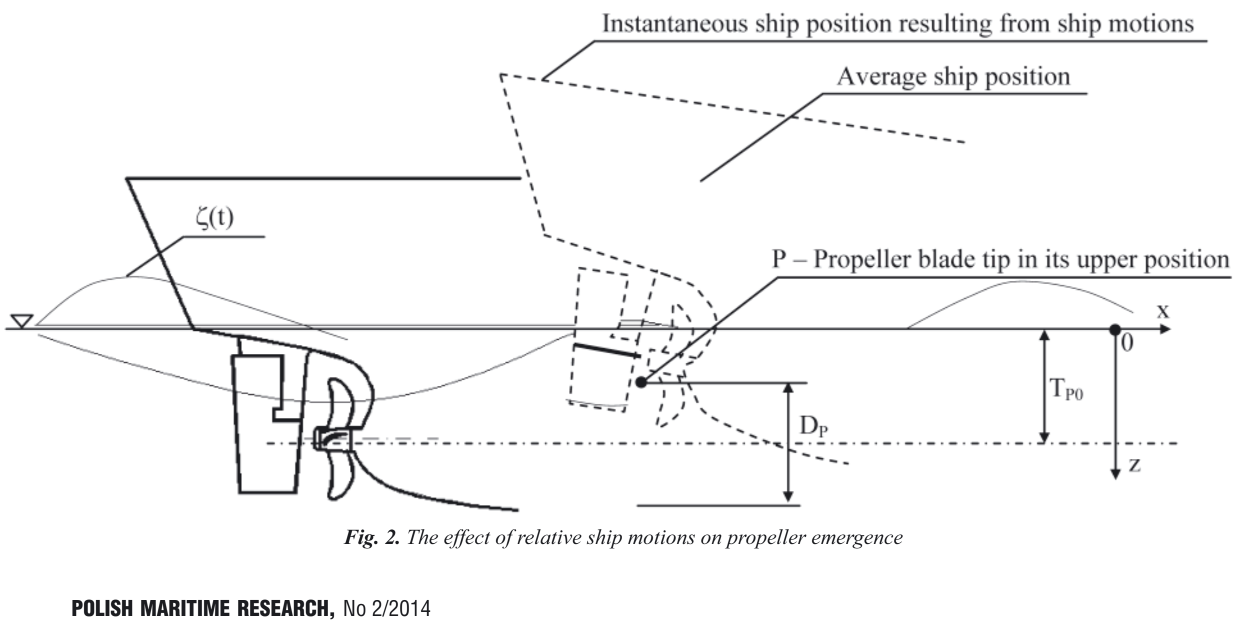

Fig. 2. The effect of relative ship motions on propeller emergence

wave frequencies ω result from amplitude characteristics of ship motions on regular wave (Table 1) for which the calculations were performed.

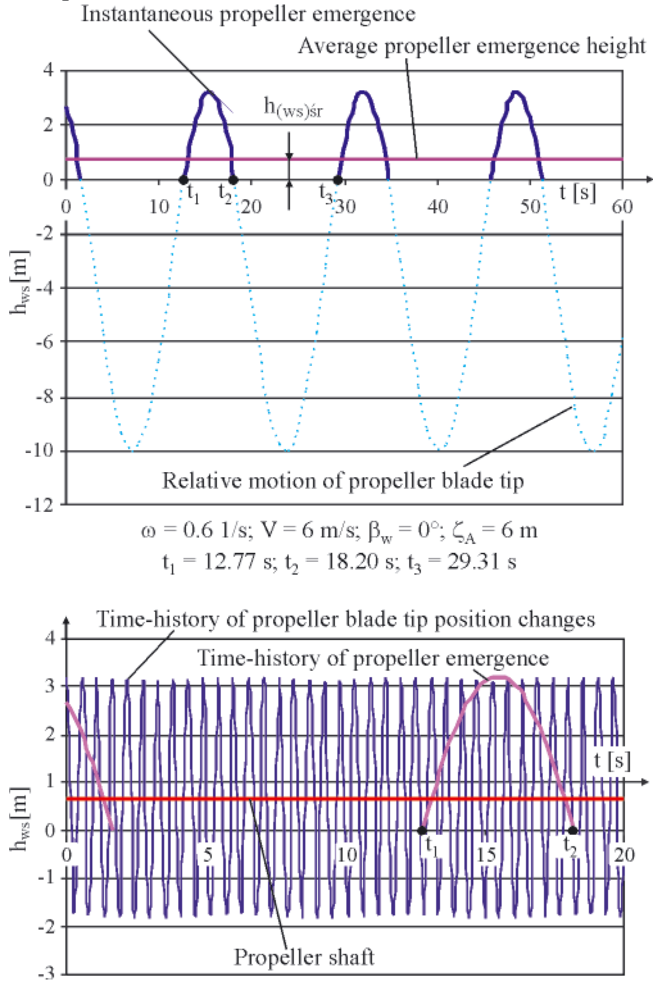

Fig. 3. Relative motion, emergence height, and the time-history of position changes of the propeller blade tip in its upper position

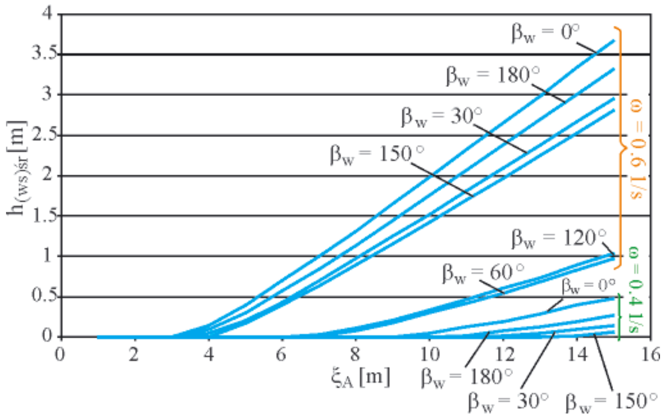

Fig. 4. Average propeller emergence height on regular wave for different wave amplitudes ζ_A and directions β_w with respect to the ship (V = 6 m/s)

APPROXIMATE METHOD FOR CALCULATING THRUST DECREASE DURING PROPELLER EMERGENCE

When the propeller emerges from the water, part of the surface of its blades is in contact with the air and not with the water. As a consequence, the lifting force and thrust of these blades will be different than that of the blades totally submersed in water, and will be in practice close to zero. The resultant thrust of the propeller gradually emerging from the water will decrease with respect to that of the propeller totally submersed.

The rotational speed of the analysed ship is n = 110 [rpm] (Table 1). The motion of the propeller tip during the emergence process taking place at this speed is shown in Fig. 3. Based on the time-history of position changes of the propeller blade tip we can conclude that when emerging from water, the propeller can accomplish about twenty full revolutions. For a given emergence height h_{ws}, the surface of the emerging propeller during its rotations undergoes small changes resulting from the shape of the propeller outline. In order to simplify the problem it was assumed that for about ten revolutions the average surface of the propeller part emerging from water is proportional to the average emergence height $h_{(ws)śr}$ (6), Fig. 3.

The surface of the propeller blades is defined using the expanded blade area ratio:

$$a_E = A_E/A_0 \tag{8}$$

where:
A_E – expanded area of propeller blades,
A_0 – propeller disc,

while for the emerging propeller the coefficient a_E^* is defined in the form:

$$a_E^* = 1 - \left(\frac{A_{Ew}}{A_0}\right) \tag{9}$$

which depends on the ratio (h_{ws}/D_P). This coefficient was calculated using the emerged propeller surface A_{E0} (Fig. 3).

The effect of the propeller emergence process on the area of its emerged segment is shown in Fig. 5.

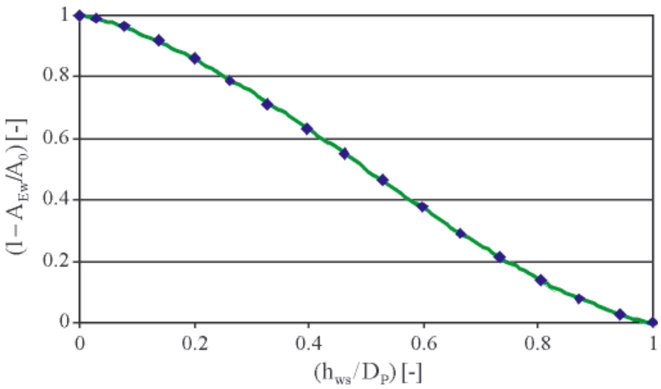

Fig. 5. Emerged propeller segment area vs. emergence height

THE EFFECT OF PROPELLER EMERGENCE ON REGULAR WAVE ON PROPELLER THRUST

The hydrodynamic characteristics of the propeller having basic parameters given in Table 1 and totally submersed in water are shown in Fig. 6.

The thrust of the propeller partially emerged from water was calculated using the vortex surface theory based algorithm [5] which can be used for calculating the thrust on a propeller blade segment in different angular positions of the segment. This approach provides opportunity to calculate the thrust distribution on the propeller blade (Fig. 7). The calculations making use of the above algorithm were performed based on the following simplifying assumptions:

- the thrust decrease results from reducing to zero the thrust distribution over the blade surface part emerging from water,
- neglected is the effect of the division surface between the water and the air on the propeller blade,

− neglected is the water density change resulting from its saturation with air during entering of the propeller blade into water and leaving it.

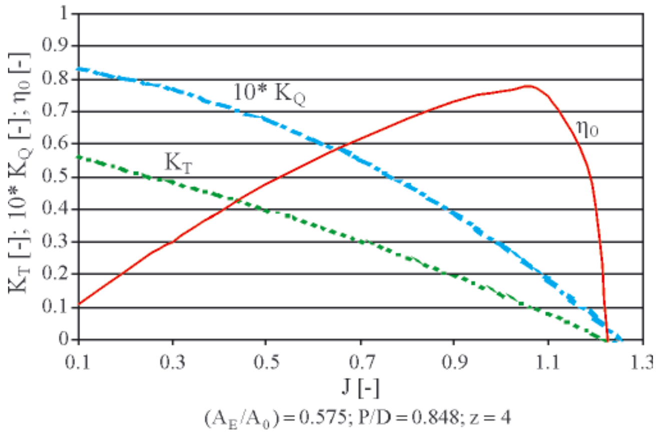

Fig. 6. *Hydrodynamic characteristics of the isolated propeller (totally submersed in water)*

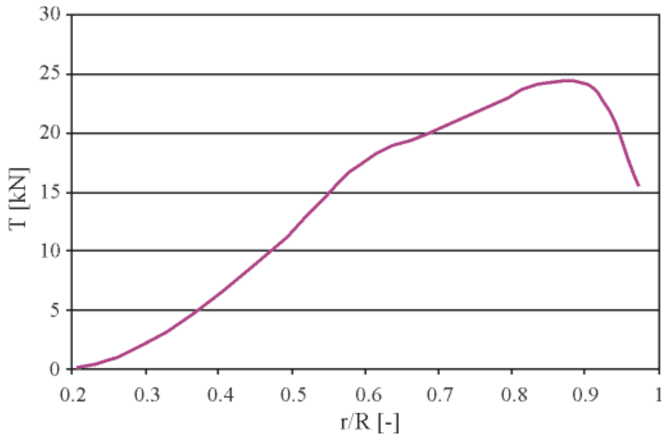

Fig. 7. *Thrust distribution on the blade of the totally submersed propeller vs. relative radius r/R*

Area changes of the propeller blade segment emerged from the water for different emergence heights and angular positions are shown in Fig. 8.

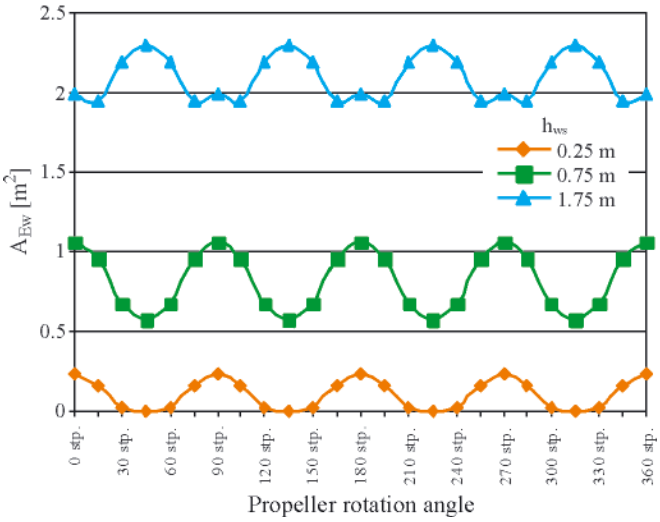

Fig. 9. *The area of the emerged propeller blade segment at different angular positions and three emergence heights (one full propeller revolution)*

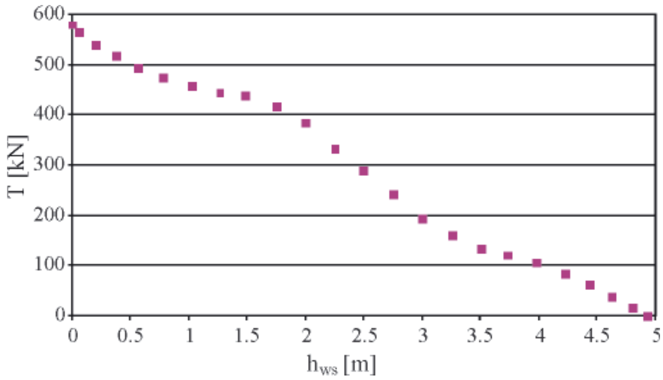

Fig. 10. *Average propeller thrust vs. propeller emergence height (D_p = 5 m)*

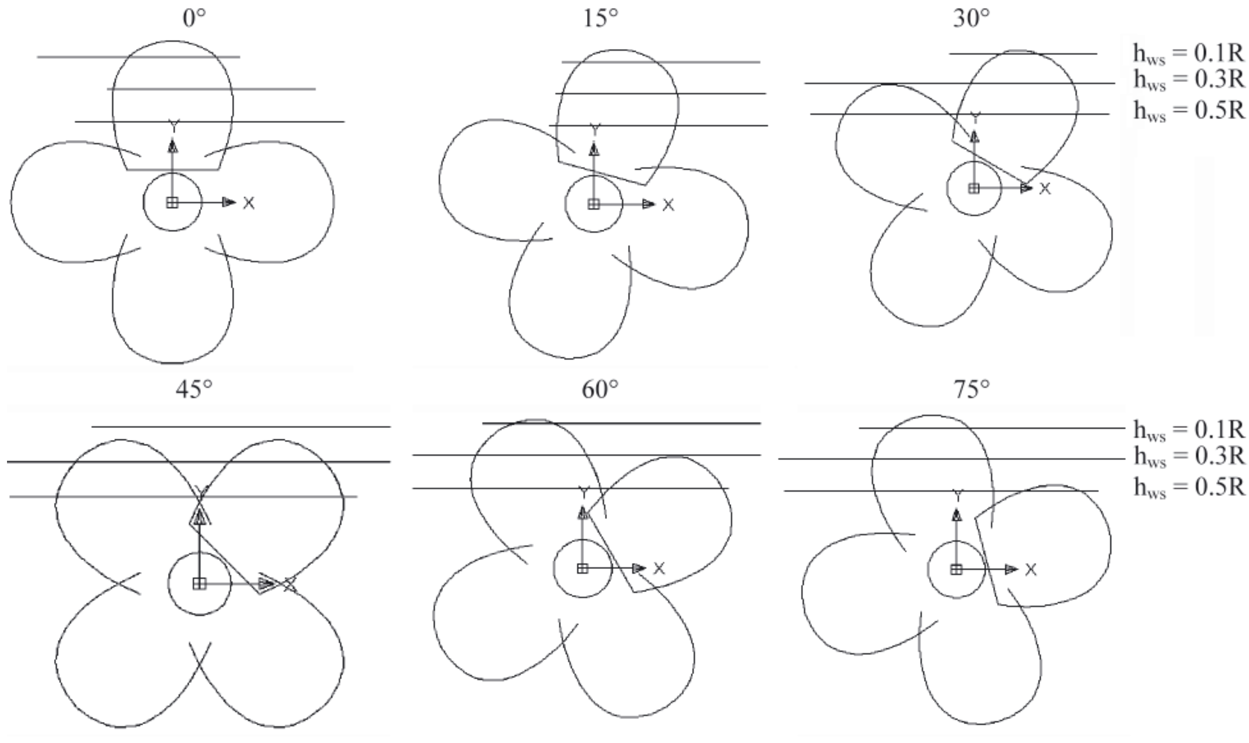

Fig. 8. *Area changes of the propeller blade segment emerging from water during blade revolutions at different emergence heights*

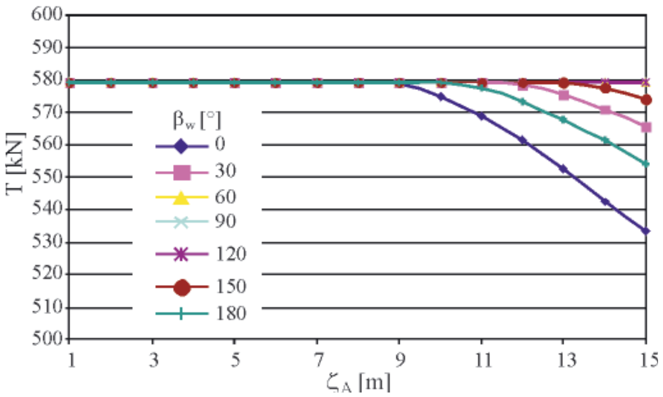

Fig. 11. *Sample results of calculations of thrust changes during propeller emergence process on regular wave for wave frequency ω = 0.4 1/s and different wave amplitudes ζ_A and directions β_w with respect to the ship (V = 6 m/s)*

The time-history of the area changes of the emerging propeller blade segment is shown in Fig. 9. For a given level of propeller emergence the thrust will change in the same way. The average total thrust values for different propeller emergence values are shown in Fig. 10, while Fig. 11 shows the effect of the parameters and ship-related direction of the regular wave, being the cause of propeller emergence, on the thrust.

PROPELLER EMERGENCE ON IRREGULAR WAVE

When calculating the relative ship motion on irregular wave we have to take into account the phase shift between the ordinate $\xi(t)$ of the irregular wave and that of the irregular ship motion $u_{(l)}(t)$, as well as the phase shifts between particular forms of ship motions composing its relative motion. The theory of pulse transmission function can be used for this purpose [9].

With the aid of the pulse transmission function the potential damping $[b_{(k,l)}(t)]$ of ship motions on irregular wave can be written as:

$$[b_{(k,l)}(t)]\{\dot{u}_{(l)}(t)\} = \int_0^\infty [K_{(k,l)}(\tau)]\{\dot{u}_{(l)}(t-\tau)\}d\tau \qquad (10)$$

$$k, l = 1, 2, \ldots 6$$

and the hydrodynamic masses $[m_{(k,l)}(t)]$ have the following form:

$$[m_{(k,l)}(t)] = [m_{(k,l)}(\tilde{\omega})] + \frac{1}{\tilde{\omega}} \int_0^\infty [K_{(k,l)}(t)\sin(\tilde{\omega}t)]dt \qquad (11)$$

$$k, l = 1, 2, \ldots 6$$

where:
- $[K_{(k,l)}]$ – matrix of pulse transmission functions,
- $[m_{(k,l)}(\tilde{\omega})]$ – matrix of generalised hydrodynamic masses from the regular wave with frequency $\tilde{\omega}$,
- $\tilde{\omega}$ – arbitrarily selected frequency of the regular wave,
- τ – time interval.

The form of the function $K_{(k,l)}(t)$ for the watercraft has been given in [11] as:

$$[K_{(k,l)}(t)] = \frac{2}{\pi} \int_0^\infty [b_{(k,l)}(\omega)\cos(\omega t)]d\omega \qquad (12)$$

$$k, l = 1, 2, \ldots 6$$

where $[b_{(k,l)}(\omega)]$ is the matrix of generalised coefficients of potential ship motion damping on regular wave.

Taking into account Equation (10), the ship motions on irregular wave can be described by the following equation system:

$$\begin{aligned} &([M_{(k,l)}] + [m_{(k,l)}(t)])\{\ddot{u}_{(l)}(t)\} + \\ &+ \int_0^\infty [K_{(k,l)}(\tau)]\{\dot{u}_{(l)}(t-\tau)\}d\tau + \\ &+ [C_{H(k,l)}(t)]\{u_{(l)}(t)\} = \{F_{(k)}(t)\} \end{aligned} \qquad (13)$$

$$k, l = 1, 2, \ldots 6$$

where:
$[m_{(k,l)}(t)]$ and $[K_{(k,l)}(\tau)]$ are given by Eqs. (11) and (12), respectively,
- $[C_{H(k,l)}]$ – matrix of generalised hydrostatic coefficients of restoring forces,
- $\{\ddot{u}_{(l)}\}$ – vector of generalised accelerations generated by ship motions on irregular wave,
- $\{\dot{u}_{(l)}\}$ – vector of generalised velocities generated by ship motions on irregular wave,
- $\{u_{(i)}\}$ – vector of generalised dislocations generated by ship motions on irregular wave,
- $\{F_{(k)}(t)\}$ – vector of generalised wave excitation forces generated by ship motions on irregular wave.

A solution method for Equations (13) and calculation of ship motions (and relative motions) on irregular wave are given in Ref. [12].

SAMPLE CALCULATIONS OF PROPELLER EMERGENCE ON IRREGULAR WAVE

The relative ship motion calculations were performed for the irregular wave defined by the wave energy spectral density function acc. to ITTC:

$$S_{\zeta\zeta}(\omega) = A \cdot \omega^{-5} \cdot \exp\left(-\frac{B}{\omega^4}\right) \qquad (14)$$

where:

$$A = 173\frac{H_S^2}{T_1^4}; \; B = \frac{691}{T_1^4}$$

- H_S – meaningful wave height,
- T_1 – average characteristic time period.

The relative vertical motion on irregular wave is the following:

$$R_z(t) = S_z(t) - \zeta(t) \qquad (15)$$

where:
- $\zeta(t)$ – ordinate of the irregular wave,
- $S_z(t)$ – ordinate of the absolute vertical motion:

$$S_z(t) = Z(t) + y_p\phi(t) - x_p\theta(t) \qquad (16)$$

while $Z(t)$, $\phi(t)$, $\theta(t)$ are the ordinates of ship heaving, rolling and pitching on irregular wave for time t.

The results of computer simulations of the time-histories of the random wave ordinate, and the absolute and relative ordinates of the motion of the propeller blade tip, as well as the time-history of the propeller blade tip emergence process on irregular wave are shown in Figs. 12 ÷ 15.

The time-history of the propeller blade tip emergence height $h_{ws}(t)$ (Fig. 15) has made the basis for calculating its average value $h_{(ws)śr}$ for the time interval equal to 3 hours (T = 10800 s):

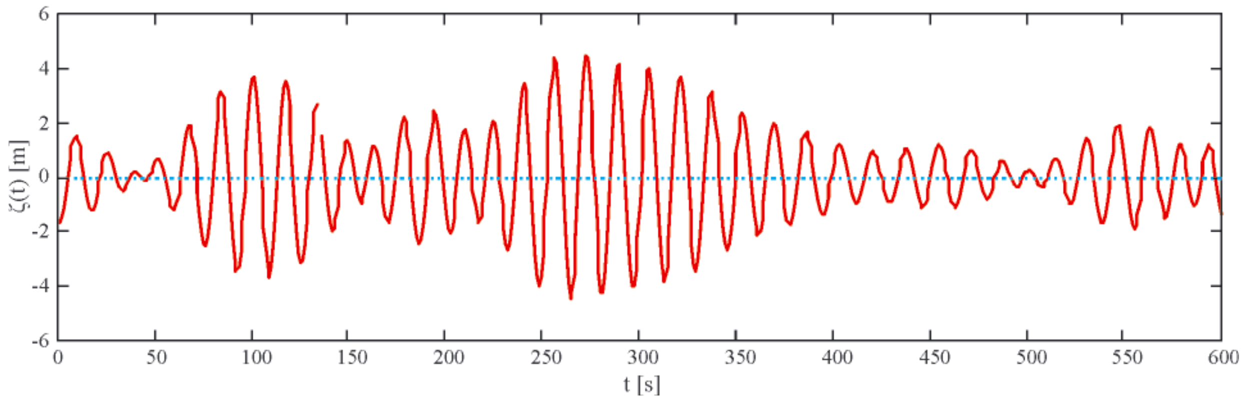

Fig. 12. *Time-history of the random ordinate of the irregular wave for 8°B (H_S = 5.25 m, T_1 = 8.5 s) and β_w = 0°*

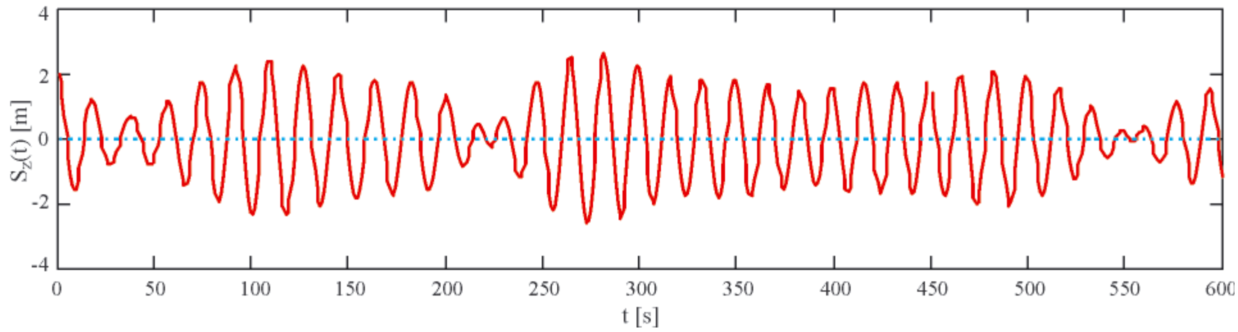

Fig. 13. *Time-history of the ordinate of the absolute propeller blade tip motion on irregular wave for 8°B (H_S = 5.25 m, T_1 = 8.5 s) and β_w = 0°*

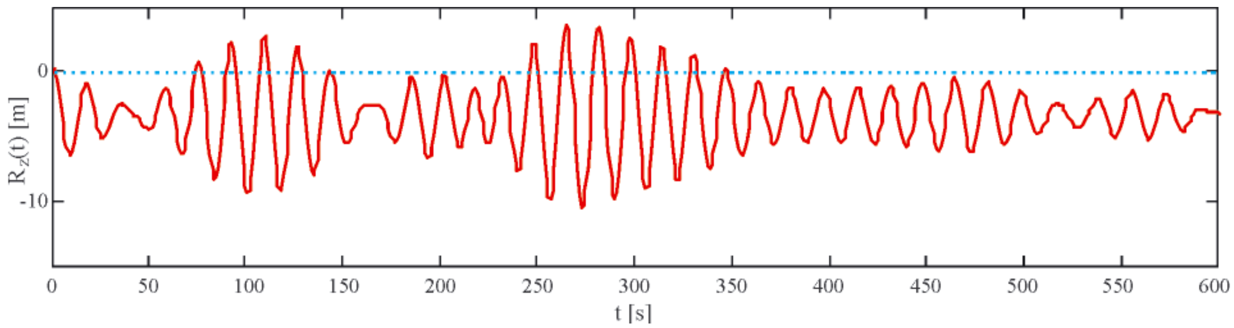

Fig. 14. *Relative vertical motion of the propeller blade tip on irregular wave for 8°B (H_S = 5.25 m, T_1 = 8.5 s) and β_w = 0°*

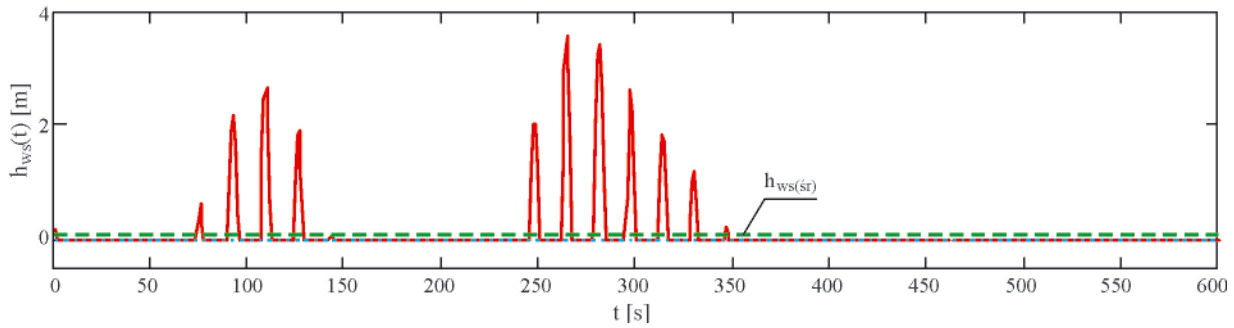

Fig. 15. *Propeller blade tip emergence on irregular wave for 8°B (H_S = 5.25 m, T_1 = 8.5 s) and β_w = 0°, $h_{ws(śr)}$ = 0.03 m*

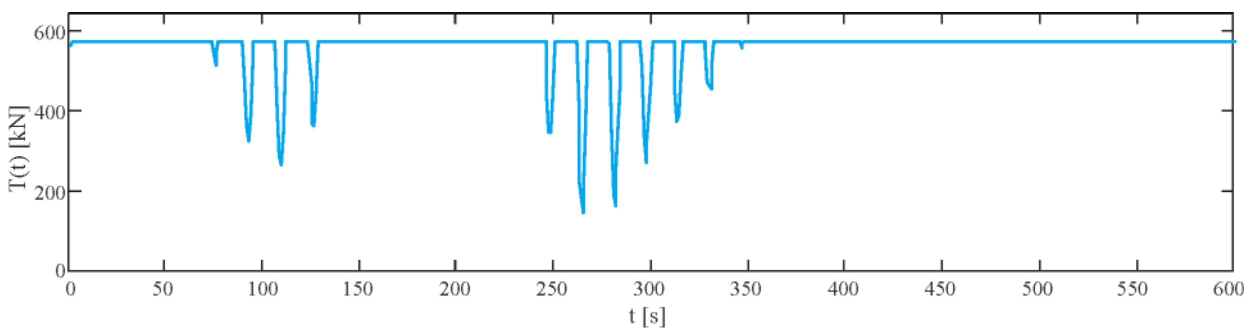

Fig. 16. *Time-history of propeller thrust changes on irregular wave for 8°B (H_S = 5.25 m, T_1 = 8.5 s) and β_w = 0°*

$$h_{(ws)śr} = \frac{1}{T}\int_0^T h_{ws}(t)dt \qquad (17)$$

where:

$$h_{ws}(t) = \begin{cases} R_{zP}(t) \text{ for } R_{zP}(t) \geq 0 \\ \text{otherwise} \end{cases}$$

Like in case of the regular wave, the time of propeller emergence on irregular wave (Fig. 15) is sufficiently long for the propeller to accomplish a number of full revolutions (Fig. 3). The instantaneous propeller thrust decrease on irregular wave was also calculated in the way similar to that used for the regular wave (Fig. 16).

The average propeller thrust decrease on irregular wave was calculated for different sea conditions and different wave directions with respect to the ship, and for the assumed ship speeds. Figure 17 shows sample results obtained for one of the analysed cases.

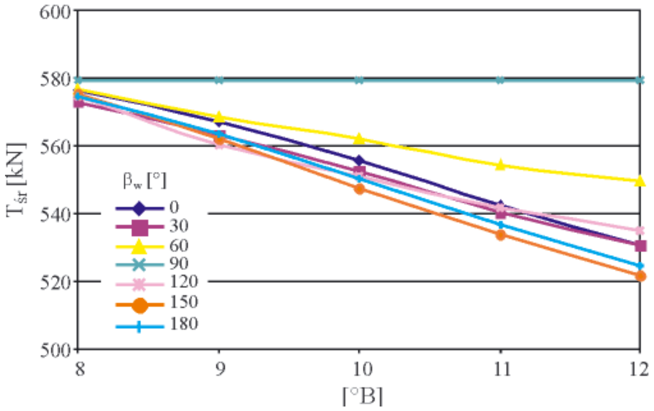

Fig. 17. *Thrust changes during propeller emergence on irregular wave for different sea conditions and wave directions β_w with respect to the ship (V = 6 m/s)*

The obtained results referring to the propeller thrust decrease during ship motions (Table 1) have been compared with those presented in Ref. [10], Fig. 18. That publication presents only the propeller thrust decrease as a function of propeller emergence, without any information on parameters of the ship and the propeller. In this context an opinion seems to be reasonable that the results given in Ref. [10] have been averaged for different ships and propellers. Despite the adopted simplifying assumptions, the here presented results reveal sufficient accuracy

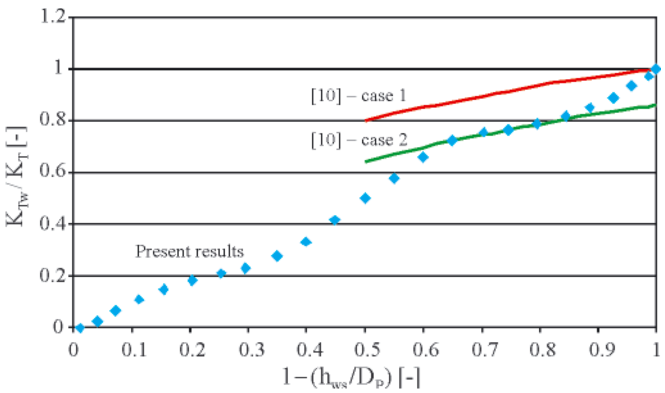

Fig. 18. *Comparing results of present calculations of propeller thrust decrease during propeller emergence with those published in Ref. [10];* ***case 1*** *– thrust decrease only resulting from propeller emergence;* ***case 2*** *– thrust decrease resulting from: propeller emergence, generation of stern wave system and varying lift on propeller blade;* K_{Tw} *– thrust coefficient for the emerging propeller;* K_T *– thrust coefficient for the totally submersed propeller*

in propeller thrust decrease evaluation for known geometric parameters of both the ship and the propeller.

CONCLUSIONS

- During preliminary ship design, a crucial task is to predict accurately the operational ship speed on a given shipping lane. This speed is affected by, among other factors, the propeller thrust decrease resulting from propeller emergence during ship motions on rough water.
- The article presents a simplified method for evaluating propeller thrust decrease during ship motions on regular and irregular wave. This method makes it possible to calculate the propeller thrust decrease for an arbitrary ship and propeller, and for given wave parameters occurring on the shipping lane.
- Despite certain simplifications, the presented method gives satisfactory results (they were compared with relevant results available in the literature), the accuracy of which is sufficiently high to use it for predicting the operating speed of the ship on an arbitrary shipping lane at the preliminary design stage.

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CONTACT WITH THE AUTHOR

Katarzyna Żelazny, Ph. D.,
Faculty of Marine Technology,
Szczecin University of Technology
Al. Piastów 41
71-065 Szczecin, POLAND
e-mail: katarzyna.zelazny@zut.edu.pl
phone: (91) 449 41 26