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The propeller thrust and speed reduction as a result of the propeller emergence on a given ocean route

Spadek naporu i prędkości statku w wyniku wynurzania się śruby napędowej na danej linii żeglugowej

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Abstract
During ship navigation on waves its relative motions occur which result in propeller emergence. This, in consequence, causes the propeller thrust drop. The article presents the results of calculations of the propeller thrust drop and ship service speed reduction on a preset ocean route where specific mean statistic weather parameters occur.

Słowa kluczowe: kołysania statku na fali, pionowy ruch względny

Abstrakt
Podczas pływania statku na fali powstają m.in. ruchy względne, które powodują wynurzanie się śruby napędowej, a w konsekwencji spadek naporu. W artykule przedstawiono algorytm obliczania spadku naporu śruby w wyniku kołysań statku na fali o zadanych parametrach: wysokość znacząca H_s, okres T_1 i kierunek geograficzny.

Introduction

During ship navigation on waves the relative motions of a ship occur, which may result, *inter alia*, in propeller emergence. Depending on the extent of emergence, it will cause a propeller thrust drop and, consequently, ship's speed will decrease. The article [1] presents an algorithm for calculating the propeller thrust drop depending on the propeller emergence value. The calculation results of the propeller thrust drop and ship speed drop on a given ocean route make use of average statistic weather parameters prevailing on that ocean route. Hence the obtained results of the ship thrust drop and resultant ship speed drop are also average statistic values for a given ship and for a given ocean route.

Ship and weather parameters on an ocean route

The calculations have been performed for the ship K1 (container ship, table 1) and for the ocean route no. 2 from Western Europe to the USA (Fig. 1) which runs through ocean areas for which the average statistical parameters of waves are included in the atlas [2].

The atlas [2] includes for particular water areas (Fig. 1) mean statistical values of the significant wave height H_S the period T_1 and the geographical direction μ as well as probability of occurrence of these values (example values are presented in table 2).

Table 1. Parameters of the container ship
Tabela 1. Parametry kontenerowca

Length between perpendiculars	L [m]	140.14
Breadth	B [m]	22.30
Draught	T [m]	8.25
Displacement for T	∇ [m^3]	17 300
Contractual speed	V_K [m/s]	8.44
Propeller diameter	D_P [m]	5.2
Propeller pitch	P [m]	3.9
Nominal power of the main engine	N_n [kW]	6930
Nominal r.p.m. of the main engine	n_n [1/s]	2.33
Ship resistance in calm water for T and V_K	R [kN]	461.3
Sea margin assumed in the ship propulsion	$K_ż$ [%]	15

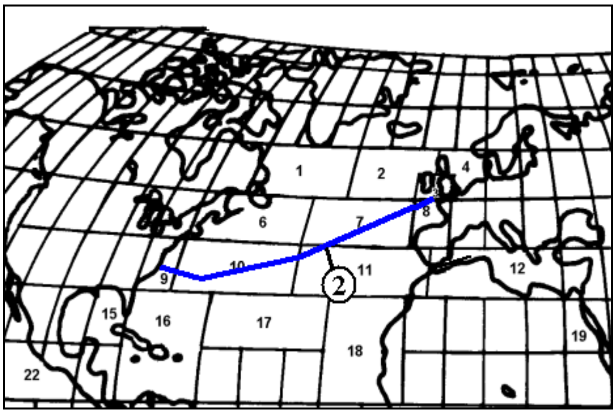

Fig. 1. the ship's route
Rys. 1. Przebieg trasy żeglugi statku

The instantaneous ship service speed on waves

The instantaneous ship service speed on a given wave having parameters H_S, T_1 and μ will be developed by the ship when the total ship resistance is balanced by the propeller thrust, taking into account its potential drop caused by the emergence, and when the moment on the propeller is equal to the main engine moment. These conditions are written in form of two nonlinear equations:

$$\begin{aligned} T \cdot \beta_T - \frac{R_C}{1-t} &= 0 \\ Q - \frac{N \cdot \eta_S \cdot \eta_R \cdot \eta_G}{2\pi n} &= 0 \end{aligned} \qquad (1)$$

where: T – separated propeller thrust given in equations (16), (17) and (18) in [1]; β_T – ship thrust drop coefficient as a result of the propeller emergence during ship navigation on waves (the method of the coefficient calculation is presented in (1); R_C – total ship resistance, dependent on the ship speed V, ship course ψ, waves parameters H_S, T_1, μ and wind parameters V_A, γ_A; t – thrust deduction factor, Q – torque on the separated propeller; N – power of the main engine; η_S – shaft line efficiency; η_G – efficiency of the gear (if installed, otherwise $\eta_G = 1$); η_R – rotational "efficiency"; n – nominal r.p.m. of the main engine.

Table 2. Probability of occurrence of wave height H_S and period T_1 for a given direction μ at a given water area [2]
Tabela 2. Prawdopodobieństwo wystąpienia fali o wysokości H_S i okresie T_1 dla danego kierunku μ na danym akwenie [2]

Water area: 1
Season of the year: December – February (winter)
Direction of waves: μ = 000 deg

T_1 [s] / H_S [m]	calm	< 5	6–7	8–9	10–11	12–13	14–15	16–17	18–19	20–21	> 21
0.25		0.023									
0.5		0.011	0.011	0.011							
1.0		0.091	0.023	0.011	0.011						
1.5		0.023	0.045	0.057		0.023					
2.0			0.057		0.034						
2.5		0.011	0.057	0.045	0.034						
3.0			0.011	0.034	0.023	0.011					
3.5			0.011	0.045	0.057						
4.0				0.011	0.011	0.045	0.011	0.011			
4.5				0.045	0.023		0.011	0.011			
5.0					0.011						
6.0				0.011							
6.5				0.011	0.023						
7.5					0.011						

The method of calculating the total ship resistance on waves R_C and the torque of the propeller Q as well as the main engine power N from the motor / engine operation area are presented in [3] and [4].

The solution of the non-linear equations (1) for each set of data concerning:

- ship movement: V, ψ;
- waves: H_S, T_1, μ;
- wind: V_A, γ_A;
- gives the instantaneous ship speed V_i.

The mean long-term ship service speed on a given ocean route

During a ship voyage on a given ocean route where parameters of wave and wind shall be changing as well as the ship course and preset ship speed, the ship resistance on waves shall be changing, its motions and relative movements and thus propeller emergence and possible thrust drop.

That is why the ship thrust drop and the ship service speed on a given ocean route depend on:

- route of navigation and probability of ship's sailing in particular sea areas;
- statistical parameters of waves (H_S, T_1, μ) wind (V_A, γ_A) and probability of occurrence of these parameters in given areas;
- the probability of occurrence of the ship movement parameters, i.e. speed V and course ψ (the speed V should first be assumed, so that it could be later calculated and so that its assumed value could be corrected).

The probability of the ship remaining in a given situation during navigation in wavy waters along the preset navigation route is as follows:

$$p_w = f_A \cdot f_S \cdot f_\mu \cdot f_{HT} \cdot f_V \cdot f_\psi \tag{2}$$

where: f_A – frequency (probability) of the ship sailing at a given water area A; f_S – frequency (probability) of the ship sailing in a given season of the year S at a given water area A; f_μ – frequency (probability) of occurrence of wave direction μ in a given season of the year S at a given water area A; f_{HT} – frequency (probability) of occurrence of waves having parameters H_S and T_1 from direction μ; f_V, f_ψ – frequency (probability) of the ship sailing at speed V and on course ψ.

The values of additional resistance due to wind and values of the propeller thrust drop due to the ship motions on waves depend on random parameters of waves and wind. Therefore the same (identical) values of additional resistance and values of the propeller thrust drop can occur for different values of parameters V_A, γ_A, H_S, T_1, μ, V, ψ. For each value of additional resistance and the propeller thrust drop thus calculated the ship speed is calculated.

The total probability P_{TV} of the ship reaching the speed V at the occurrence of additional resistance ΔR and the propeller thrust drop ΔT having a specific value is equal to:

$$P_{TV} = \sum_{A=1}^{n_A}\sum_{S=1}^{n_S}\sum_{\mu==1}^{n_\mu}\sum_{H,T=1}^{n_{HT}}\sum_{V=1}^{n_V}\sum_{\psi=1}^{n\psi} P_{Vi}\left[V_i\left(\Delta R_i, \Delta T_i\right)\right] \tag{3}$$

where: $V_i(\Delta R_i, \Delta T_i)$ – instantaneous ship service speed versus instantaneous additional resistance and instantaneous thrust drop of the propeller; n_A, n_S, n_μ, n_{HT}, n_V, n_ψ – numbers of sea areas through which the ship is sailing, seasons of the year, wave directions (angles), waves parameters, ship speeds and courses.

From calculations of the distribution function $f(V_i)$ of the probability of occurrence of instantaneous ship speed $f(V_i)$ it is possible to calculate the long-term ship service speed for the preset navigation route:

$$\overline{V} = \frac{\sum_{i=1}^{n_V} P_{TV_i} \cdot V_i\left(\Delta R_i = \text{const}, \Delta T_i = \cos nt\right)}{\sum_{i=1}^{n_V} P_{TV_i}} \tag{4}$$

where n_V is the number of ranges including instantaneous ship service speeds of approximate values.

Results of calculations of the propeller thrust drop and the ship speed drop on a given ocean route

The calculations of propeller thrust drop as a result of the propeller emergence and of the developed ship service speed have been performed for the container ship (Table 1) crossing an ocean route from Western Europe to the USA (Fig. 1). The obtained results have been compared with identical calculations assuming that the propeller does not emerge and there is no thrust drop.

Figure 2 shows a bar chart and probability distribution function of propeller immersion depth [draught] (100% means total immersion / draught of propeller). Figure 3 presents a bar chart (a) without taking the propeller emergence into account and (b) taking the propeller emergence on a given ocean route into account. After taking into account the emergence of propeller due to ship motions, on the same ocean route the mean statistical value of the propeller thrust has been reduced by approximately 1%. Figure 4 displays a bar chart of the probability

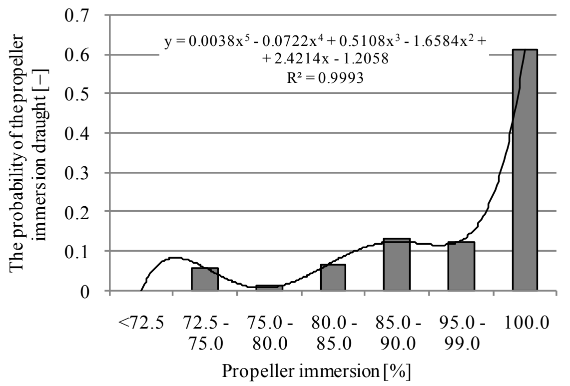

Fig. 2. The bar chart and probability distribution function of ship propeller immersion on Western Europe – USA ocean route

Rys. 2. Histogram i funkcja rozkładu prawdopodobieństwa zanurzenia śruby napędowej statku na linii żeglugowej EZ–USA

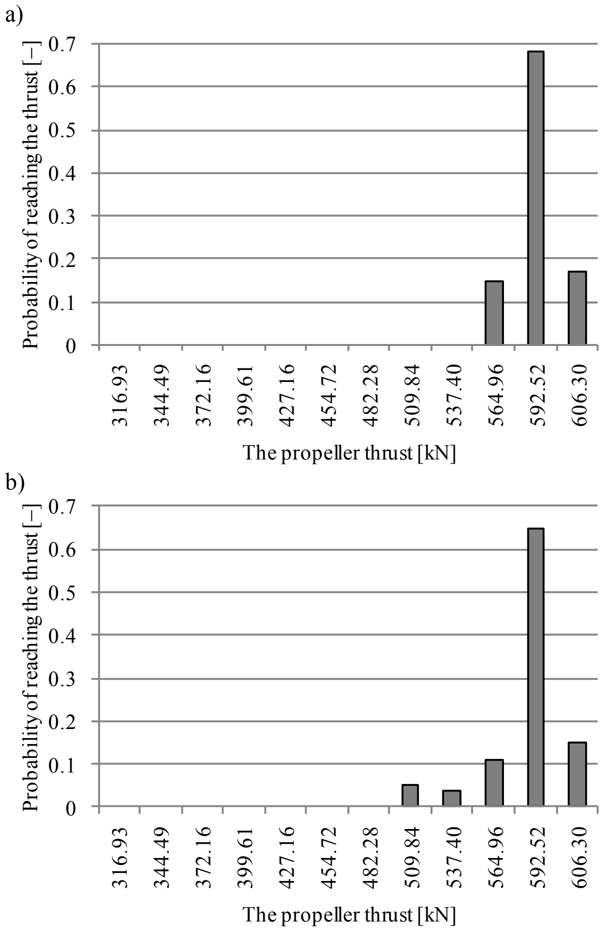

Fig. 3. The bar chart of the K1 ship propeller thrust on the Western Europe – USA ocean route: a) without taking the propeller emergence into account, b) with taking the propeller emergence into account

Rys. 3. Histogram naporu śruby napędowej: a) bez uwzględnienia wynurzania się śruby, b) z uwzględnieniem wynurzania się śruby

of reaching ship service speed with and without taking the propeller thrust drop into account. In this case the drop of the mean long-term ship service speed was equal to 0.02 m/s.

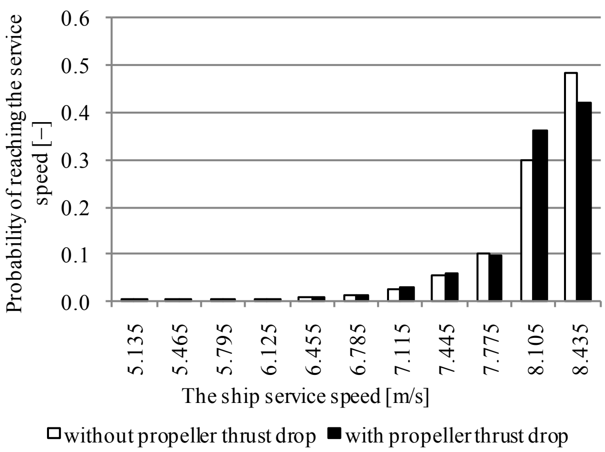

Fig. 4. The bar chart of probability of reaching ship service speed with [black colour] and without taking the propeller thrust drop due to ship motions into account

Rys. 4. Histogram prawdopodobieństwa osiągnięcia prędkości eksploatacyjnej statku z uwzględnieniem (kolor czarny) i bez uwzględnienia spadku naporu śruby od kołysań statku

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