

## The speed characteristics adaptation of Polish Steamship Company's dry bulk vessels to SPOS

### Adaptacja charakterystyk prędkościowych statków masowych PŻM do systemu SPOS

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**Key words:** ship's speed, wave and wind, statistical measures, correlations

#### **Abstract**

The cumulative impact of wave and wind on vessel speed are presented. In theory, the influence of wind on ship has been separated including appropriate speed and wind direction. Greater impact on the overall loss rate has been assigned to ship waving. Determination of separate influence of wind and wave calculation was adopted to SPOS.

**Słowa kluczowe:** prędkość statku, falowanie i wiatr, miary statystyczne, korelacje

#### **Abstrakt**

W artykule zaprezentowano łączne oddziaływanie falowania i wiatru na prędkość statku. Teoretycznie wydzielono wpływ wiatru na statek, uwzględniając odpowiednie prędkości i kierunki wiatru. Większy wpływ na ogólne straty prędkości statku przypisano falowaniu. Określenie oddzielnego wpływu wiatru i falowania adoptowano do programu obliczeniowego SPOS.

#### **Introduction**

The ship's speed in calm water with no wind and wave action ( $V_0$ ) is already determined during the design phase of a vessel, then checked for speed and manoeuvring trials after ship launching and finally refined during exploitation. The corresponding value of the velocity  $V_0$  is determined by the captains as the ship's service speed on calm water with no waves and wind.

A more complex problem is to determine the loss of ship's speed due to waves and wind ship's speed prediction in ice. The speed characteristic is necessary for the vessel's predicted position calculations per day, 2 days, even at 9 days of travel. This characteristic is the basis for programming the routes of ships at sea and ocean along with weather data and impacts the selection of routes, selecting the most suitable route for a given criterion, subject to constraints [1, 2, 3].

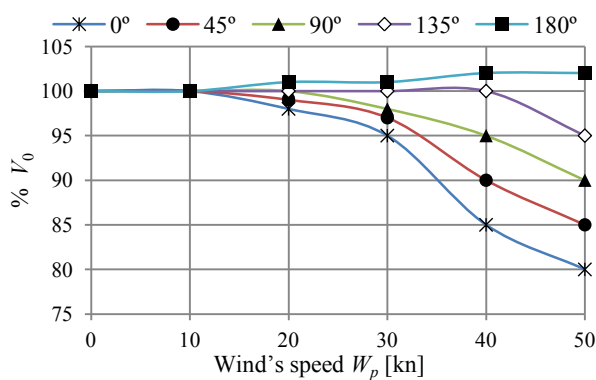
SPOS (Ship Performance Optimisation System) proposed a unreliable coefficients matrix, so called "default" characteristic speed without specifying size and type of vessel, its seaworthiness without distinguishing between loaded or ballast conditions. SPOS approach is not suitable to any dry bulk vessel of Polish Steamship Company (Fig. 1).

Polish Steamship Company operates SPOS on all of their ships. The system should fulfill two functions:

- providing digital weather information to the appropriate captain's order. From the SPOS module a graphical mode can be opened and a weather chart analysis is possible; this function is well used on ships and meet the expectations of operators;
- aid in the navigational calculation (e.g.: distance, time, navigation, point of return, the ETA parameter (Estimated / Expected Time of

Arrival) and other calculations for the purpose of programming the voyage. This function is not well implemented by SPOS and thus does not inspire trust among the ships' operators due to bad choice of vessel speed characteristics.

Wind's speed $W_p$ [kn]	Wind's angle on the bow				
	0°	45°	90°	135°	180°
0	100	100	100	100	100
10	100	100	100	100	100
20	98	99	100	100	101
30	95	97	98	100	101
40	85	90	95	100	102
50	80	85	90	95	102



Wave's height $h$ [m]	Wave's angle on the bow				
	0°	45°	90°	135°	180°
0	100	100	100	100	100
2	98	98	100	100	100
4	90	90	95	100	100
6	85	85	90	90	95
8	65	70	80	85	90
10					

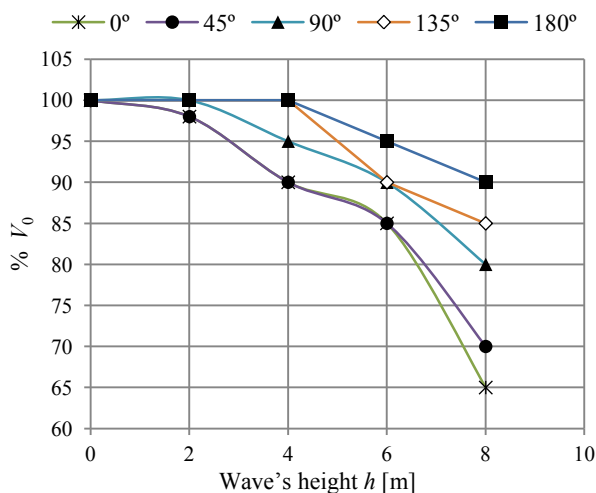


Fig. 1. The default vessel's speed characteristics in SPOS (based on data in tables a) and b) by SPOS [4])  
 Rys. 1. Domyślna charakterystyka prędkościowa statku w systemie SPOS (opracowano na podstawie danych w tabelach a) i b) według SPOS [4])

Graphic image analysis of results listed in SPOS table shows that they do not have sufficient grounds and have a little credibility among Polish Steamship Company's captains (due to inaccurate calculation of travel time and ETA, the dubious choice of route).

For the individual consistent wind direction and speed the ship wave curves are shown in figure 2. They confirm the dubious choice of the speed characteristics. The ship's speed curves should not be crossed, there is no symmetry between them and there is no data for wind speed of 50 knots and wave height of 10 m while vessels sail in these conditions.

Cumulative wind's and wave's coefficients in % $V_0$						
$W_p$ [kn]	$h$ [m]	0°	45°	90°	135°	180°
0	0	100.0	100.0	100.0	100.0	100.0
10	2	98.0	98.0	100.0	100.0	100.0
20	4	88.2	89.1	95.0	100.0	101.0
30	6	80.8	82.5	88.2	90.0	96.0
40	8	55.3	63.0	76.0	85.0	91.8
50	10					

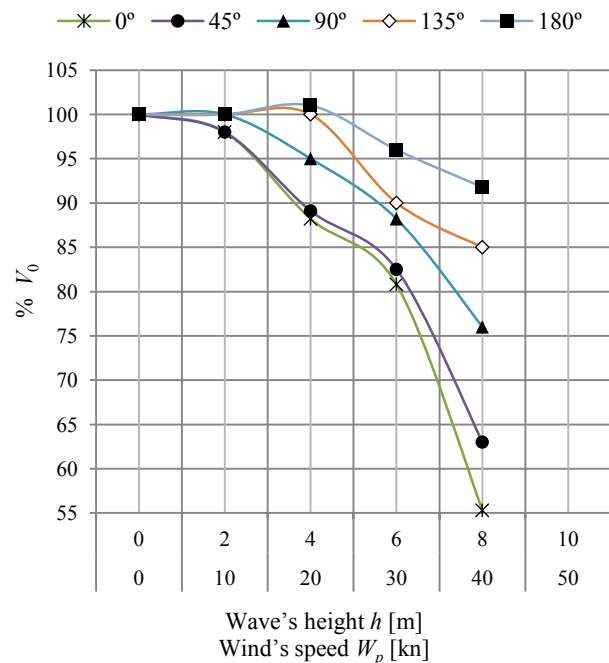


Fig. 2. SPOS vessel's speed curves according to the combined impact effect of wave and wind from consistent directions with their impact on ship (based on data by SPOS [4])  
 Rys. 2. Krzywe prędkości statku według SPOS dla łącznego oddziaływania wpływu fali i wiatru ze zgodnych kierunków ich oddziaływania na statek (opracowano na podstawie danych według SPOS [4])

The object of this publication is to build up speed characteristics for the selected type of Polish Steamship Company's ships and adapt it to the navigation calculation in SPOS and to present the methodology of study.

## Research scope and methodology

For the major types of Polish vessels' speed characteristics have been identified, depending on the combined action of waves and wind to comply with consistent directions of their effects, which are the most often at sea ( $\Delta K \leq 30^\circ$ ). The most valuable for the navigation practice were characteristics that have been developed based on actual measurements and observations from ships operating conditions [5, 6, 7, 8, 9, 10, 11, 12, 13, 14]. They also take into account the loss of ship speed, which resulted from the effects of excessive slamming, sea spray on deck, excessive propeller, run propulsion system overload, conditions similar to the dangerous resonance oscillations. Measurements include so called natural and forced loss of ship speed from the wave and wind, and speed reduction due to the dangerous tension in the drive, or speed reduction made by the captain during weathering, etc. These characteristics were determined for the fully loaded condition and ballast condition. Their verification and analysis are complemented by a series of 4065 measurements from 55 Polsteam's ships voyages and included in paper *The integrated programming paths of ships on the oceans in terms of safety of the vessel, cargo and people* – report *Vessels speed characteristics data bank* [15], and previous observational data of 63 ships' voyages from the B series, No. 7 [12, 15].

Observations and measurements collected on board of newly built Polsteam's ships (2010–2012) have been verified and speed characteristics determined:

- the main statistical for measured values (mean, standard deviation, extreme values);
- Pearson's linear correlation between the vessel and wind speeds and wave heights. The statistical significance of the correlation coefficient was tested at a significance level of  $p < \lambda$  where  $\lambda = 0.05$ ;
- partial correlation; allows to define the linear correlation coefficients, measuring the strength of the relation between two variables with the exclusion of third variable impact (variable still used). Partial correlation coefficient  $r_{12.3}$  is expressed by the following formula [16, 17]:

$$r_{12.3} = \frac{r_{12} - r_{13}r_{23}}{\sqrt{(1 - r_{13}^2)(1 - r_{23}^2)}} \quad (1)$$

where  $r_{12.3}$  is the correlation between variables  $X_1$  and  $X_2$  with the disengaged variable  $X_3$ . For the analyzes in this study for the variable  $X_1$  assumed vessel speed and for variable  $X_2$  and  $X_3$

separately wind speed and wave height were adopted;

- 4 degree polynomial – fit for the data in an  $XY$  scatter chart. For the set of points in the  $XY$  coordinate system on a scatterplot in the Statistica program a curve defined fourth-degree polynomial was matched. This is a polynomial of one independent variable  $x$ . The function of one independent variable is usually denoted as:

$$y = f(x) \quad (2)$$

This polynomial can be written as:

$$y = b_0 + b_1x + b_2x^2 + b_3x^3 + b_4x^4 \quad (3)$$

where  $b_0, b_1, b_2, b_3, b_4$  are the polynomial coefficients.

In report analyzes the dependent variable  $y$  assumed vessel speed  $V$  (in knots) depending on the wave height  $h$ , which was adopted as the independent variable  $X$ . In this way, the set of polynomial equations of five-vessel speed for the angles:  $0^\circ, 45^\circ, 90^\circ, 135^\circ$  and  $180^\circ$ . Graphical interpretation of this polynomial is a curve in the  $xy$  coordinate system (where  $x$  is the height of the  $h$  wave and  $y$  – vessel speed  $V$ );

- Square polynomial of 2 independent variables – fit for the data in  $XYZ$  scatterplot. For the set of points in the coordinate system  $XYZ$  for 3D scatterplot in the Statistica program a surface defined as second-degree polynomial (square) was matched. This is a polynomial of two independent variables:  $x$  and  $y$ . The function of two variables it usually denotes as:

$$z = f(x, y) \quad (4)$$

This polynomial can be written as:

$$y = b_0 + b_1x + b_2x^2 + b_3x^3 + b_4x^4 \quad (5)$$

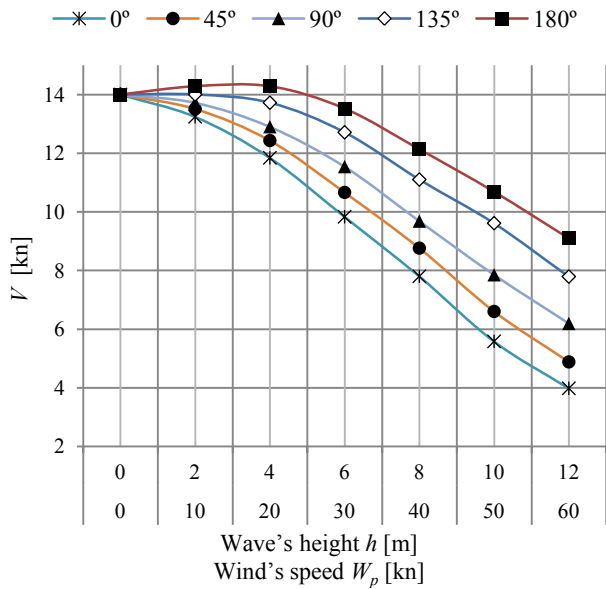
where:  $x$  and  $y$  are independent variables, while  $a, b, c, d, e$  and  $f$  are the polynomial coefficients (any number).

In this paper, a square polynomial of two independent variables was used in determining the vessel speed  $V$  (% of  $V_0$ ) depending on the effect of wave height  $h$  (variable  $x$ ) and the wave angle on the bow (variable  $y$ ) and in determining the vessel speed  $V$  (% of  $V_0$ ) depending on the effect of wind speed (variable  $x$ ) and the wind angle on the bow (variable  $y$ ).

In this way, the corresponding static distributions were matched to a series of actual observations made on ship's board. Equations were established for the consistent directions of waves impact and wind impact, and the corresponding wave

height and wind speed. Using the Statistica program, the equation between speed and combined effect of wave height and ship wind speed was established.

Figure 3 presents the cumulative impact of wave height and wind speed for the “Jawor” ships series [15].



$W_p$ [kn]	$h_f$ [m]	Wave's period [s]	0°	45°	90°	135°	180°
0	0	0	14.00	14.00	14.00	14.00	14.00
10	2	5	13.24	13.51	13.72	14.00	14.28
20	4	6.5	11.84	12.43	12.90	13.72	14.28
30	6	7.2	9.83	10.66	11.54	12.71	13.52
40	8	8.1	7.80	8.76	9.68	11.10	12.13
50	10	9.1	5.58	6.60	7.85	9.61	10.68
60	12	10.2	3.98	4.88	6.19	7.79	9.09
$W_p$ [kn]	$h_f$ [m]	Wave's period [s]	0°	45°	90°	135°	180°
0	0	0	100.0	100.0	100.0	100.0	100.0
10	2	5	94.6	96.5	98.0	100.0	102.0
20	4	6.5	84.6	88.8	92.1	98.0	102.0
30	6	7.2	70.2	76.1	82.5	90.8	96.6
40	8	8.1	55.7	62.6	69.1	79.3	86.7
50	10	9.1	39.8	47.2	56.1	68.6	76.3
60	12	10.2	28.4	34.9	44.2	55.7	64.9

Fig. 3. The speed curves of “Jawor” ships series depending on wind and wave height (according to impact directions), with the data (in knots and % of  $V_0$ ) (own work based on: [11, 15, 18])

Rys. 3. Krzywe prędkości statku z serii „Jawor” w zależności od wiatru i wysokości fali (zgodnie kierunki oddziaływania) wraz z danymi (w węzłach i % od  $V_0$ ) (opracowanie własne na podstawie: [11, 15, 18])

The existing characteristics of the designated speed in knots converted to ratios relative to the

speed  $V_0$ . To adapt the speed characteristics to SPOS vessels’ speed had to be determined separately in relation to wind and wave and expressed in %  $V_0$ .

From speed characteristics described collectively as the effect of wind and wave (their complaisant propagation directions) speed impact effect and wind angle on the bow were isolated and calculated by Rudiajey’s theoretical method, where following formula was used [11, 18]:

$$\Delta V_w = V_0 - \sqrt{\frac{V_0^2(1+k_q) - k_q W^2}{1+k_q}} + \frac{k_q W}{1+k_q} \cos q_w \quad (6)$$

where:

$$k_q = \frac{C_q S}{800 E \Omega} - \text{ship's wind factor;}$$

$S$  – area of the ship above water, projected to diametrical plane,  $m^2$ ;

$\Omega$  – submerged vessel surface,  $m^2$ ;

$V_0$  – vessel’s speed in calm water, m/s;

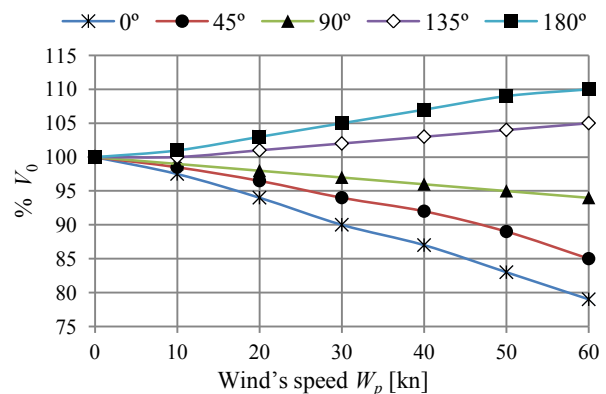
$C_q$  – drag coefficient corresponding to the specified wind angle on the bow;

$W$  – true wind speed, m/s;

$E$  – water drag coefficient;

$q_w$  – wind angle on the bow.

Ship speed curves (% of  $V_0$ ) depending on wind speed and angle on the bow is presented in figures 4 and 5.



$W_p$ [kn]	0°	45°	90°	135°	180°
0	100	100	100	100	100
10	97.5	98.5	99	100	101
20	94	96.5	98	101	103
30	90	94	97	102	105
40	87	92	96	103	107
50	83	89	95	104	109
60	79	85	94	105	110

Fig. 4. “Jawor” ships series speed curves depending on the wind with the data (own work based on: [11, 15, 18])

Rys. 4. Krzywe prędkości statku z serii „Jawor” w zależności od wiatru wraz z danymi (opracowanie własne na podstawie: [11, 15, 18])

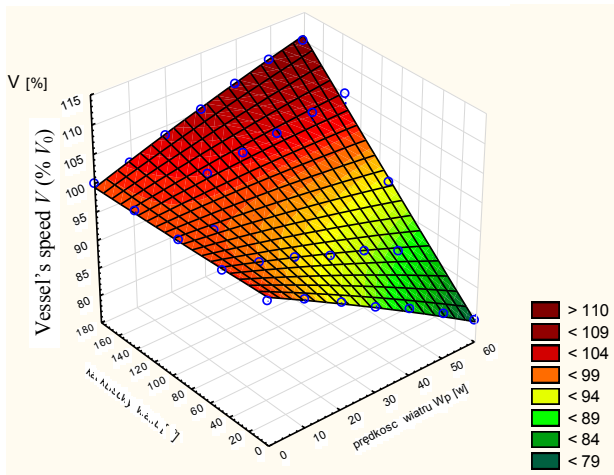


Fig. 5. Vessel's speed  $V$  ( $\% V_0$ ) depending on wind speed and direction ("Jawor" ships series with the load) (own work based on: [11, 15, 18])  
 Rys. 5. Prędkość statku  $V$  ( $\% V_0$ ) w zależności od prędkości i kierunku wiatru (statek serii „Jawor” z ładunkiem) (opracowanie własne na podstawie: [11, 15, 18])

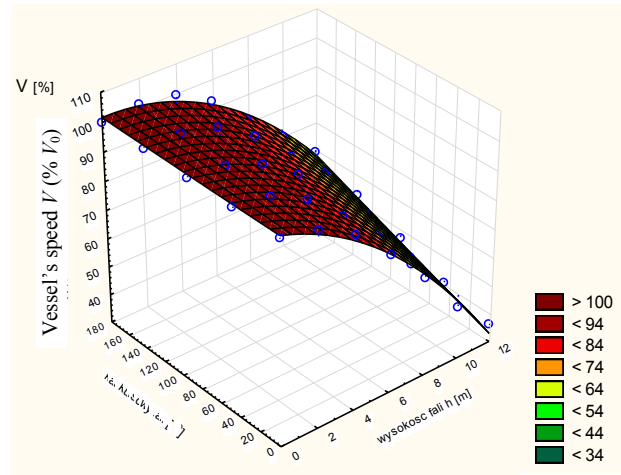
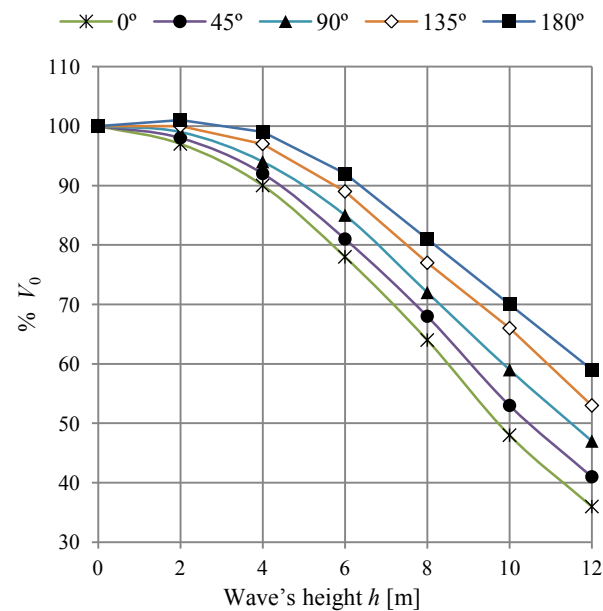


Fig. 7. Vessel's speed  $V$  ( $\% V_0$ ) depending on height and direction of wave ("Jawor" ships series with the load) (own work based on: [11, 15, 18])  
 Rys. 7. Prędkość statku  $V$  ( $\% V_0$ ) w zależności od wysokości i kierunku fali (statek serii „Jawor” z ładunkiem) (opracowanie własne na podstawie: [11, 15, 18])

The remaining part was attributed to the wave effect (Figs 6 and 7).



$h$ [m]	0°	45°	90°	135°	180°
0	100	100	100	100	100
2	97	98	99	100	101
4	90	92	94	97	99
6	78	81	85	89	92
8	64	68	72	77	81
10	48	53	59	66	70
12	36	41	47	53	59

Fig. 6. "Jawor" ships series speed curves depending on wave with the data (own work based on: [11, 15, 18])  
 Rys. 6. Krzywe prędkości statku z serii „Jawor” w zależności od fali wraz z danymi (opracowanie własne na podstawie: [11, 15, 18])

### Results

Figure 3 presents the cumulative impacts of wave and wind speed on vessel at the consistent angles on the bow noted on the ship. The wind effect has been theoretically separated for the respective ranges of wind speed and wind directions. Remaining was the part of speed losses attributed to wave effect thereby generating results that can be adapted to SPOS (Figs 4 and 6).

Wind obviously slightly increases the vessel speed from the stern sectors and reduces the vessel speed of bow sectors. However, the wind effect is several times smaller than the impact of waves especially from bow and traverse angles. Starting at 4 m wave height vessel speed clearly decreases due to roll, a continuous change of wetted surface during ship's pitching, rolling and heaving. This also applies to sailing at the stern wave directions at higher waves. This is consistent with actual observations performed during ship voyages. This is also confirmed by the results described in the methods (Figs 3–7).

### Discussion of results

Discussions of results can be carried out by comparing effect of determining ship speed curves depending on wave and wind with other characteristics, i.e. the default SPOS characteristics and calculations performed by PRESTAT program. The comparison result is advantageous for measurement data collected from the vessel and produced statistically (high correlation coefficients).

It is considered that SPOS proposal with default vessel's characteristics is the only non-binding

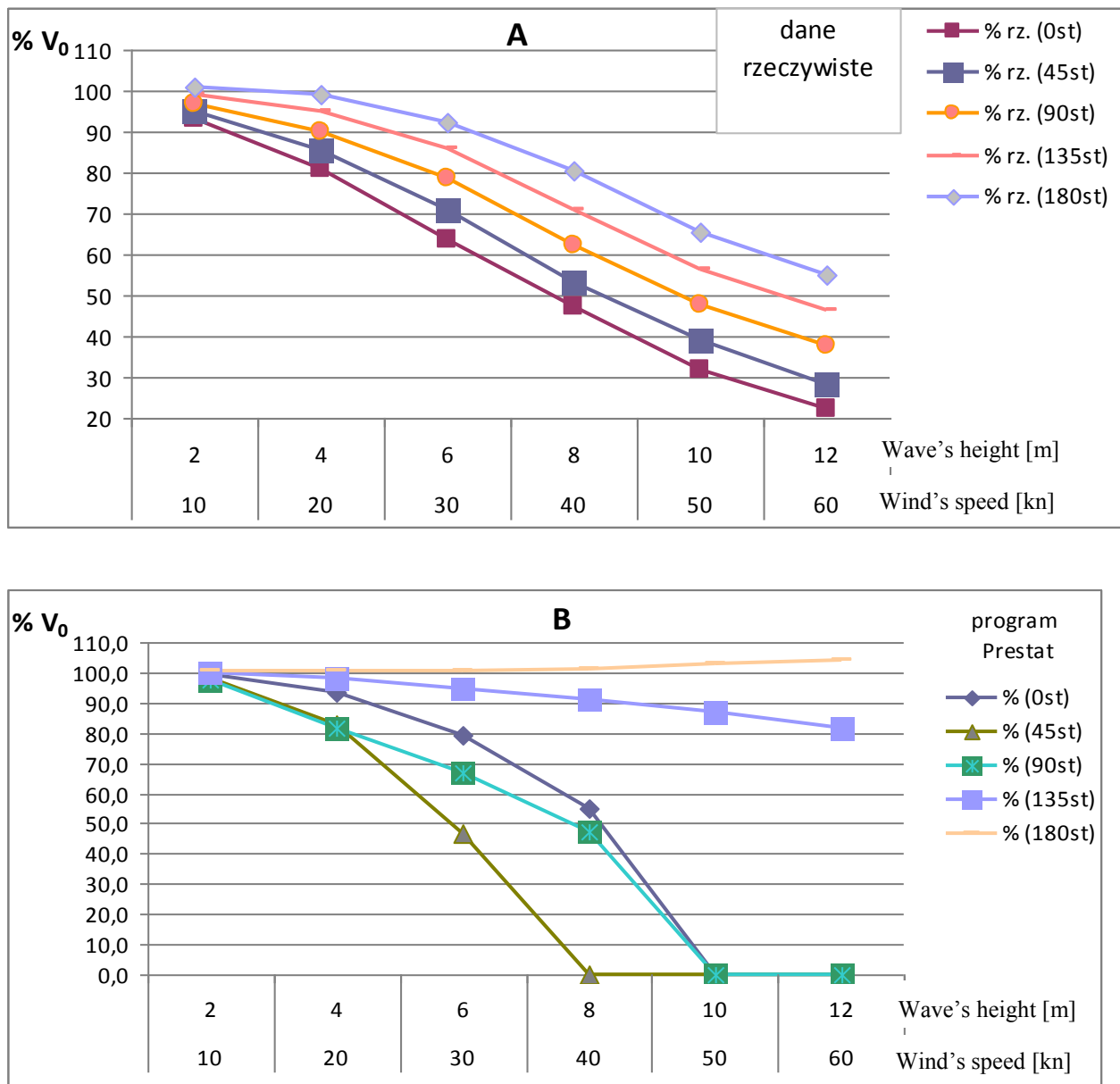


Fig. 8. Comparison of average ship's speed (33–44 thousand DWT) determined from actual observations (A) and the calculated by PRESTAT program (B) (own work based on: [11, 15, 18, 19])

Rys. 8. Porównanie wyników prędkości statku średniego (33–44 tys. DWT) określone z obserwacji rzeczywistych (A) oraz obliczonych programem PRESTAT (B) (opracowanie własne na podstawie: [11, 15, 18, 19])

proposal. The same applies to PRESTAT for which ship's speed chart comparison was presented.

It is expected that the theoretical calculation programs such as PRESTAT can be corrected for the actual observations done at sea. This allows the determination of mathematical model for calculating losses of vessel speed due to wave, wind and current including vessel stability conditions.

## Conclusions

The paper presents an example of dry bulk ship's speed characteristics development and its adaptation to SPOS. The aim is to use the other functions of SPOS – the adaptation of the real ves-

sel's characteristics to determine the different variants of routes in terms of safety, voyage time and calculation of the ETA parameter. This is expected to increase the credibility of SPOS for Polish Steamship Company's ships in service.

These vessel's speed characteristics due to the impact of waves and wind are better in comparison with the existing ones because they can separately consider the effect of wind and waves. At high seas the direction of waves is not always consistent with the direction of wind. These are the cases of simultaneous occurrence of wind wave and swell, rapid changes in wind speed and direction, swell only conditions, etc.

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