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# The influence of wind, wave and loading condition on total resistance and speed of the vessel

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ABSTRACT

*Optimising the ship route is one of the most important tasks related to the operation of the vessel, its safety, and economic aspects of transport. Nevertheless, from a mathematical point of view, this problem has not been solved yet sufficiently precisely due to very high complexity of the model to be used to describe the motion of the ship along the shipping line, and time- and space-dependent average values of statistical weather parameters recorded during ship sailing. That is why various approximate methods are used, which, among other procedures, utilize ship speed characteristics, having the form of very simple relations between basic dimensions of the ship and the expected speed decrease at the assumed weather parameters. The paper presents a new method of calculating the speed decrease depending on technical and operating parameters of a given vessel. A computer code prepared based on this method is used for research on forecasting ship speed in real weather conditions.*

**Keywords:** optimization of route navigation of the vessel, vessel's speed calculation

## INTRODUCTION – REMARKS ON SHIP ROUTE OPTIMIZATION

Selecting the optimal route is one of most important tasks concerning the operation of a transport vessel. When choosing the optimal route, one or more criteria are taken into account including:

- minimum travel time,
- minimum fuel consumption for a given travel time,
- safety of the ship and cargo,
- passenger comfort during the trip.

The last criterion is generally used for cruise ships and does not apply to transport vessels.

The minimum travel time can be achieved by minimising the length of the route and/or maximising the speed of the ship.

The minimum fuel consumption can be achieved by minimising the length of the route and/or maintaining optimal operating parameters of the drive engine. In still water conditions (no wind and wave) these parameters define a point of engine operation which corresponds to constant speed of the vessel [9]. When the vessel floats on waves, searching for minimum fuel consumption (and the resultant optimum speed in given weather condition) may be associated with certain course changes resulting in a change of length of the route and extension of time [9]. The safety of the ship and cargo is associated with negative effects of the wind and waves acting on the ship (rocking, acceleration, slamming, flooding of the deck, propeller emergence). Reducing the impact of these phenomena during the operation of the vessel is associated with speed reduction and/or course changes. Both of these manoeuvres will result in elongation of the route and time of shipping, which leads to the increased fuel consumption. Selecting the optimal shipping route is very complex and despite the use of different methods [8], there is no certainty that the chosen route will be optimal, due to the fact that statistical average wind and wave parameters are random variables in both time and space. This means that during the trip, the statistical average weather parameters can change. Therefore the shipping route selected as optimal for the weather parameters observed at the beginning of the trip does not have to turn out optimal when the ship reaches the destination port, because weather parameters can change during the trip.

## BASIC APPROACH TO THE ROUTE SELECTION

Finding the optimal route for ship navigation can be reduced to two steps:

1. developing a mathematical model to describe the movement of the vessel in the marine environment,
2. determining the optimal route for the vessel.

Determination of the optimal route consists in the application of an algorithm that makes use of a mathematical model of ship motion and one or more criteria for selecting the optimal route. This issue was discussed in a number of publications [8], [9], [10].

Mathematical description of ship motion can have a form of differential equations of motion, containing full ship dynamics (forces of inertia and damping), the model of the propulsion and steering system (propeller, drive engine, and rudder fin), and the model of excitation forces (wind, wave, surface sea currents). Depending on the adopted model of the excitation forces, wave motion for instance, the model of the ship can be more or less complicated, which affects the adopted solving method and the use of the model in the algorithm for searching the optimal navigation route. Difficulties in the use of a complex but, on the other hand, accurate model of ship motion for optimizing shipping routes, were a motivation for widespread use of vessel speed characteristics. These characteristics have the form of relatively simple relations of the speed of the vessel vs. basic parameters of the vessel and average statistical parameters of waves, wind, and surface currents. These relations are presented as nomograms or simple formulas prepared on the basis of measurements or calculations performed for many ships. In these relations, geometric parameters of the vessel are frequently replaced by one or two numerical coefficients which characterize the vessel. These speed characteristics make the basis for calculating vessel's speed in assumed statistical average weather conditions, or more precisely: the speed decrease resulting from additional resistance in relation to the speed in still water (no wind and waves).

On the wave, the above speed decrease is accompanied by other dangerous phenomena (rolling, acceleration, slamming, etc.), and when they are too intense they may endanger the safety of the vessel and cargo. To reduce these risks, we can deliberately reduce the speed of the vessel (the storm fall speed) and/or change the vessel course. These phenomena are also presented in the form of simple universal nomograms. Due to their simplicity, the speed characteristics formulas are not very accurate. The article presents a more accurate method of calculating the instantaneous speed of the vessel in given weather conditions.

## INSTANTANEOUS SPEED OF THE VESSEL IN GIVEN WEATHER CONDITIONS

During ship sailing on rough water, its standard still water resistance changes due to the action of other forces generated by wind, waves and surface sea currents. Beside contributing to drag increase, these forces give rise to the creation of the lateral force and the torque which rotates the vessel about the vertical axis. The lateral force provokes the drift of the ship, while the torque changes the vessel course. For the vessel course to be kept constant in a given water region at the presence of the active external torque, the passive rudder fin is to be inclined.

Assuming that local changes of vessel speed, resulting from swaying on waves for instance, are negligibly small, the instantaneous operating speed of the ship is reached when its total drag $R_C$ is balanced by the pressure thrust $T_S$ of the propeller:

$$R_C(P_P, P_G) = T_S(P_{GS}, P_P, P_{SN}) \cdot (1-t)$$

where:
$P_P$ - weather parameters,
$P_G$ - geometric parameters of the hull of the vessel,
$P_{GS}$ - geometric parameters of the propeller,
$P_{SN}$ - parameters of the drive engine,
t - suction factor which takes into account additional resistance of the hull induced by the ship propeller.

To determine the vessel speed available at a given propeller thrust $T_S$, the total resistance $R_C$ which occurs when the vessel sails in real weather conditions should be known.

As can be seen from equation (1), weather parameters of ship sailing affect not only the total resistance but also the thrust of the propeller. Large wave swings and resultant relative motions of the vessel will lead to, among other effects, emerging of the propeller and trust decrease, which in turn will result in vessel speed decrease.

A mathematical model to calculate the total resistance of a ship in given weather conditions, and a model to calculate the thrust of the propeller (taking into account characteristics of the drive engine installed on the vessel) were presented in [6]. Substituting the equation (1) with three ship associated equations, separately for the X, Y, and Z axes in the rectangular coordinate system, and solving the system of equations created in this way enables to evaluate the speed of the vessel with the installed propulsion system in given weather conditions. The algorithm for solving the equation system and calculating the instantaneous operating speed is shown in [7]. If the still water speed is subtracted from the calculated speed, we get the ship speed decrease due to waves, wind and current.

## SHIP SPEED REDUCTION DUE TO DANGEROUS PHENOMENA CAUSED BY WAVES

When the ship sails on wavy water, a direct effect of waves is rolling of the ship and its derivatives: velocity oscillations and acceleration. Secondary phenomena which accompany the ship rolling are flooding of the deck, emergence of the propeller, wave hitting against the bottom and sides of the ship (slamming), worsened stability and manoeuvrability, and/or additional dynamic loads of the hull. Rolling of the ship and the accompanying phenomena depend on the parameters of the ship hull and the waves, as well as on the ship speed V and direction with respect to the wave (angle $\beta_W$). These phenomena, especially when intensive, can be a direct cause of a disaster at sea. Reducing the scale of these phenomena, lateral rolling for instance, is possible by changing the direction of ship sailing in relation to waves (angle $\beta_W$), the reduction of speed V, or simultaneous change in direction and speed.

When forecasting the average service speed, an accepted principle says that if:

$$\overline{U}_Z > \overline{U}_{Zdop}$$

where:
$\overline{U}_Z$ - average statistical value of the phenomenon Z caused by waves and considered hazardous to the ship

$\overline{U}_{Zdop}$ - acceptable value of the phenomenon Z caused by waves, at which the ship can still swim safely,

then the vessel speed is to be reduced and/or course changed in such a way that:

$$\overline{U}_Z \le \overline{U}_{Zdop}$$

To assess the behaviour of the ship on waves and to make a decision whether the ship speed and/or course is to be reduced, the following aspects are to be taken into consideration:

- rolling
- pitching,
- vertical acceleration,
- transverse horizontal acceleration,
- flooding of the deck,
- slamming,
- emergence of the propeller.

These phenomena are usually considered, or recommended to be taken into account, in assessing sea keeping properties of the vessel, or when determining the cost efficiency of the vessel [1], [2], [3], [4], [5].

The algorithm for calculating wave induced phenomena which are dangerous for the ship was given in [4].

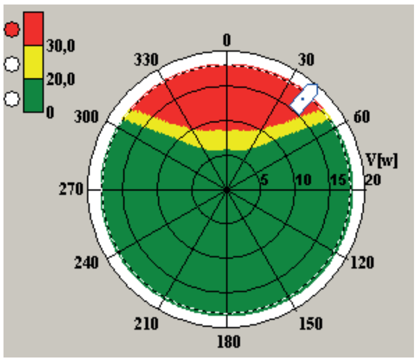
To test the condition (3), and possibly to correct the ship speed and/or course, we need to define certain criteria, which usually have the form of the permissible limits of wave induced phenomena at which the ship can still sail safely.

Years of observation and experience have made the basis for defining permissible limits for ship rolling and other accompanying phenomena, above which the safety of the ship and the crew or equipment working on the ship is endangered, which is equivalent to reducing the transport mission. The level of the permissible limits depends, among other factors, on the type and size of the ship. A sample set of criteria for the selected seagoing qualities is shown in table 1.

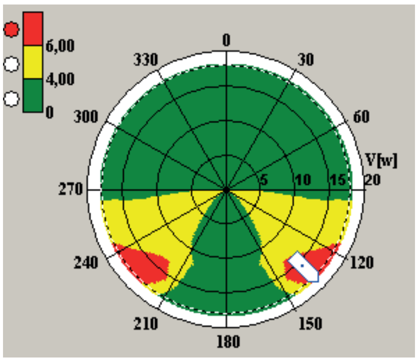
**Table 1** Criteria for selected seagoing qualities [2]

| | commercial vessels | warships | fast small units |
|---|---|---|---|
| Vertical accelerations at the bow (RMSD) | 0,275 g small<br>0,1 g large | 0,275 g | 0,65 g |
| Accelerations in the wheelhouse (RMSD) | 0,15 g | 0,2 g | 0,275 g |
| Horizontal lateral acceleration (RMSD) | 0,12 g | 0,1 g | 0,1 g |
| Swaying (RMSD) | 6,0° | 4,0° | 4,0° |
| Slamming (probability of occurrence for 100 waves) | 0,03 small<br>0,01 large | 0,03 | 0,03 |
| Flooding the deck (probability of occurrence for 100 waves) | 0,05 | 0,05 | 0,05 |

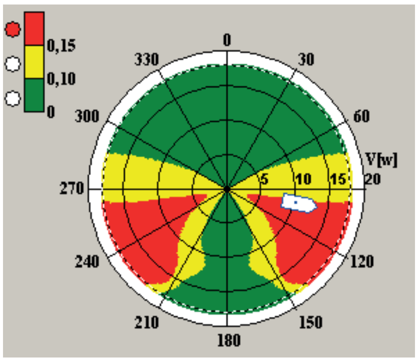
Figure 1 shows sample simulations of ship security threats caused by surge phenomena, calculated using the algorithm [4] and criteria from Table 1 for different vessel speeds and courses at selected weather parameters.



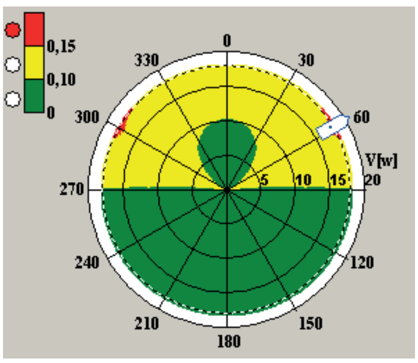

flooding the deck, V = 17 w, course = 40$^0$



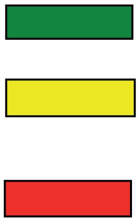

lateral rolling V = 15 w, course = 135$^0$




horizontal lateral acceleration in the wheelhouse V = 10 w, course = 100$^0$




vertical acceleration in the wheelhouse V =17,5 w, course = 60$^0$



- the ship sails securely

- warning about dangers (lower limit of the relevant criterion exceeded )

- threat to the safety of the ship (upper limit of the relevant criterion exceeded)

**Fig. 1.**Sample simulations of security threats for a container (Fig. 2) on the wave of parameters:
$H_S = 8{,}5$ m; $T_1 = 10{,}1$ sec; $\mu = 0^0$

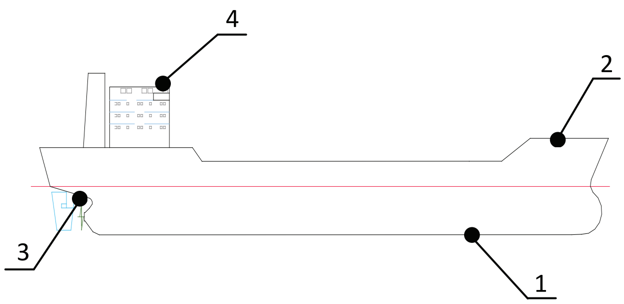



**Fig. 2.** Points for which the seakeeping characteristics shown in Figure 1 were calculated using the criteria from Table 1

1 - slamming, 2 - deck flooding and bow accelerations, 3 – propeller emergence, 4 - accelerations in the wheelhouse

## CALCULATING SHIP SPEED DECREASE IN SELECTED WEATHER CONDITIONS

### The computer code PRESTAT

The mathematical model and the solution of the model algorithm presented in [6], [7] have made the basis for working out a computer code to calculate the ship speed in selected weather conditions. The code bearing the name of PRESTAT was written in Delphi and run in the Windows environment. This code is intended to be used for the investigating ship route optimization, and along with the ship speed it can calculate such parameters as: power and speed of the drive engine, propeller speed (on ships without gear: engine speed = propeller speed), marine environment generated forces acting on the ship, seagoing qualities. All these parameters are displayed on the computer screen (Fig. 3).

Data for the program

The data are entered to the program in two forms:

- as a batch file with all geometric dimensions of the vessel and necessary characteristics concerning: still water resistance coefficients, aerodynamic drag coefficients, wave drift force coefficients, and the characteristics of the propeller and the drive engine;
- as the data entered from the keyboard directly to the user's interface.

The data entered from the keyboard relate mainly to weather parameters, vessel traffic parameters, and selecting the mode of operation of the drive engine.

Specified weather parameters:

- waves

$H_S$ = ... [m] - significant height 0,0 ÷ 20,0 m
$T_1$ = ... [sec] - time period 0,0 ÷ 30,0 sec
$\mu$ = ... [deg] - $\gamma$ geographical direction 0 ÷ $360^0$
$\mu = 0^0$ - northern wave
$\mu = 90^0$ - eastern wave

- wind:

$V_A$ = ... [m/sec] - average speed 0,0 ÷ 50,0 m/sec
$\gamma_A$ = ... [deg] - geographical direction 0÷$360^0$
$\gamma_A = 0^0$ north wind
$\gamma_A = 90^0$ east wind

- current surface:

$V_C$ = ... [m/sec] - average speed 0,0 ÷ 2,0 m/sec
$\gamma_C$ = ... [deg] - geographical direction 0÷3600
$\gamma_C = 0^0$ - current flows in the northerly direction
$\gamma_C = 90^0$ - current flows in the easterly direction

Operating state of the drive engine - the engine is running in the continuous operation mode, or is allowed to be overloaded or operated in the temporary operation mode.

Specified vessel course:

$\psi$ = ... [deg] (0÷$360^0$)
$\psi$ = 00 northern course
$\psi = 90^0$ eastern course.

After entering and confirming the above data, the calculations are performed and the following results are displayed on the screen:

wave parameters :

$H_S$ – significant height [m]
$T_1$ – time period [sec]
$\mu$ – geographical direction [deg]

wind parameters:

$V_A$ - average speed [m/sec]
$\gamma_A$ - geographical direction [deg]

sea current parameters:

$V_C$ – average speed [m/sec]
$\psi_C$ – geographical direction [deg]

operating parameters of the vessel:

$\psi$ - specified course of the vessel [deg]
$V_E$ - calculated instantaneous operating speed [knots]
$\delta_R$ - rudder angle [deg]
$n_S$ - engine RPM [1/sec] (specified by the slider, or calculated)
$N_S$ - engine power [kW]

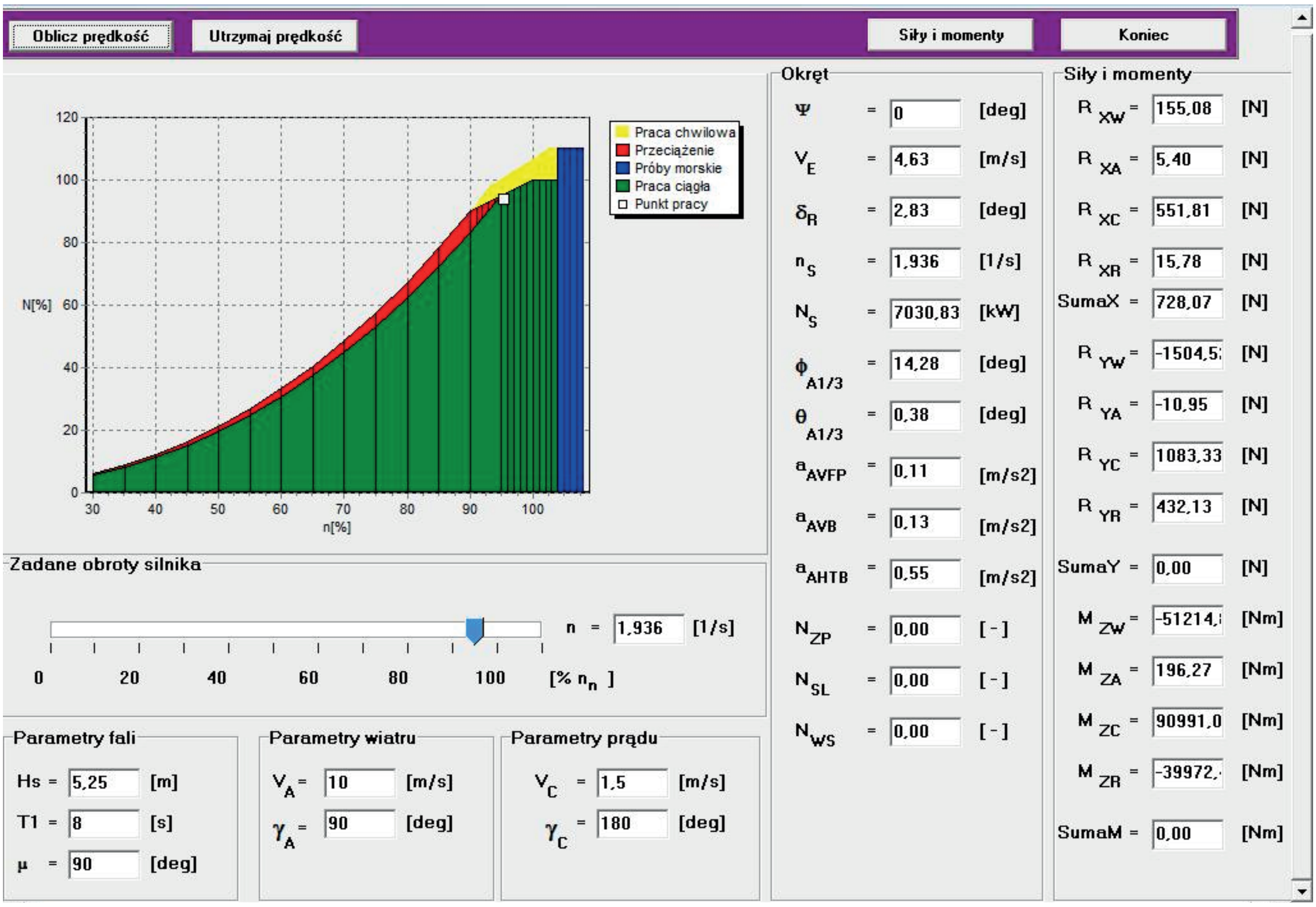



**Fig. 3.** Data entered from the keyboard, and the results of calculations displayed on the screen

Significant oscillation and acceleration amplitudes, and the frequencies of other phenomena for selected points of the ship to $V_E$, y, m, [m/s²]:

$\phi_{A1/3}$ – significant amplitude of ship rolling for $V_E$, ψ, μ, [deg]
$\theta_{A1/3}$ – significant amplitude of ship pitching for $V_E$, ψ, μ, [deg]
$a_{AVFP}$ – component of vertical acceleration on the forward perpendicular,
$a_{AVB}$ – component of vertical acceleration in the wheelhouse,
$a_{AHTB}$ – component of transverse horizontal acceleration in the wheelhouse,
$N_{ZP}$ – flooding frequency (number of times per hour) for $V_E$, ψ, μ, [-]
$N_{SL}$ – frequency of slamming for $V_E$, ψ, μ, [-]
$N_{WS}$ – frequency of propeller emergence for $V_E$, ψ, μ, [-]

Note: Data on possible ship safety threats from waves can be displayed on a separate screen in the form shown in Figure 1.

External forces and moments generated by the marine environment:

$R_{XW}$, $R_{YW}$, $M_{ZW}$ – force and moment generated by the wave,
$R_{XA}$, $R_{YA}$, $M_{ZA}$ – power and moment generated by the wind,
$R_{XC}$, $R_{YC}$, $M_{ZC}$ – power and moment generated by the water (including the current when VC≠0)
$R_{XR}$, $R_{YR}$, $M_{ZR}$ – power and moment generated by the rudder

## Influence of weather parameters on the vessel speed decrease

The code PRESTAT calculates the instantaneous average operating speed $V_E$ of the vessel in the selected conditions. By subtracting this speed from the speed V of the ship in still water we get the speed decrease which is used to forecast the optimal route of the ship.

By introducing different values of weather parameters we can investigate the influence of these parameters on the speed decrease at a given course (if the course is to be maintained), or look for the maximum speed $V_E$ (or minimal speed decrease) when the course of the ship is changed.

The computer code was designed in such a way that the speed of vessel sailing in the selected weather conditions can be calculated assuming different working scenarios of the drive engine, such as maintaining constant RPM or engine power, constant specific fuel consumption, or constant ship speed in changing weather conditions.

The code also displays the calculated parameters of ship rolling and other hazardous phenomena (Fig. 2). The computer code does not automatically reduce the speed of the ship when the permissible limits of wave induced ship rolling are exceeded (Tab. 1), and it is only the navigator who can reduce deliberately the speed of the vessel.

## Verification of calculations and vessel speed decrease

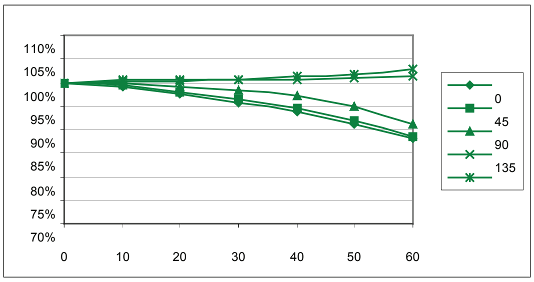
The presented sample calculations were performed for a bulk carrier with parameters shown in Table 2, and compared with measurements made on a similar ship (Tab.2).

**Tab. 2.** Parameters of compared vessels

| | $L_{PP}$ [m] | $B$ [m] | $T$ [m] | $\nabla$ [m³] | $C_B$ [-] | $V$ [nodes] ([m/sec]) |
|---|---|---|---|---|---|---|
| Bulk carrier for which calculations were performed | 185,0 | 25,3 | 10,6 4 | 0831 0 | ,820 | 14,6 (7,51) |
| Bulk carrier of "Diana" series, on which measurements were made | 186,4/177,0 3 | 0,0 | 11,46/6,23 | 41260 0 | ,812/0,800 | 13,5/14,5 (6,9/7,5) |

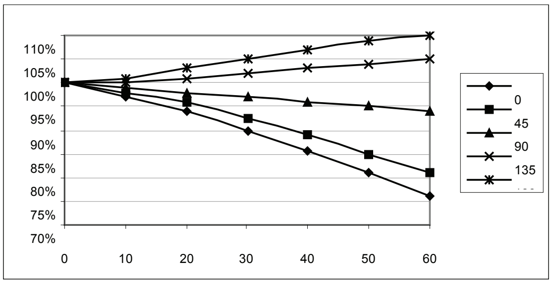
Figure 4 shows the speed decrease of the bulk carrier calculated for different parameters, and different wave and wind directions with respect to the vessel, while Fig. 5 presents rolling and other seagoing qualities, along with the selected criteria.

a)



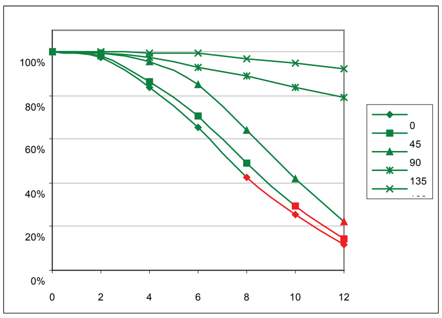

Bulk carrier LPP =185,0 m

a)



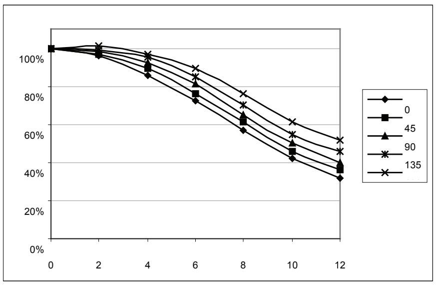

Bulk carrier of „Diana" series LPP =186,0/177,0 m

b)



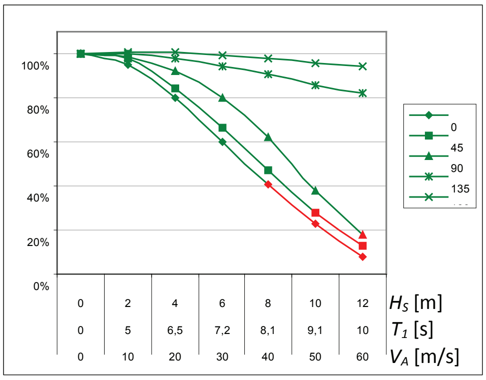

Bulk carrier LPP =185,0 m

b)



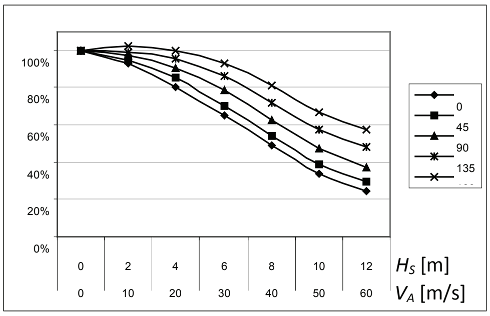

Bulk carrier of „Diana" series LPP =186,0/177,0 m

c)




Bulk carrier LPP =185,0 m

c)




Bulk carrier of „Diana" series LPP =186,0/177,0 m

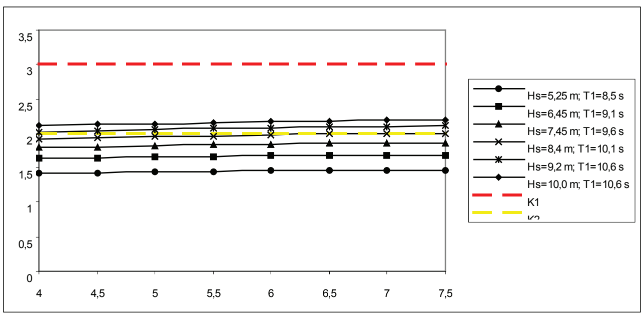
**Fig. 4.** Speed decrease for different parameters and wave and wind directions: the vessel course $\psi = 0^0$ (green – continuous operation without overload, red – engine overload, Figure 3)

a) impact of wind

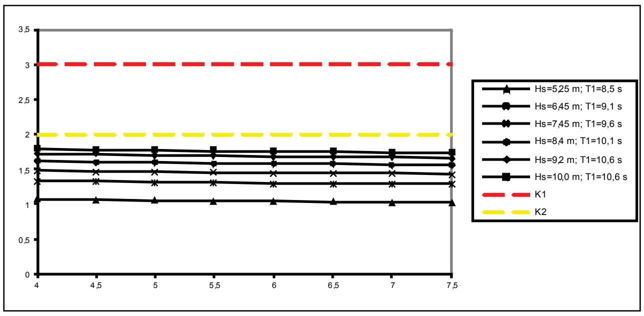
b) impact of waves

c) combined impact of wind and waves

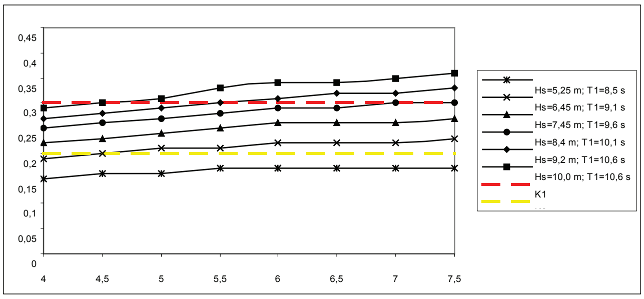
Pitching ($\beta$ w = 180$^0$) - the average standard deviation



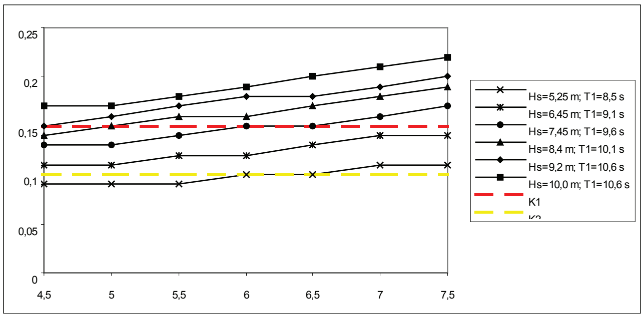
Pitching ($\beta_w$=0$^0$) - the average standard deviation




Vertical acceleration at bow ($\beta_w$=180$^0$)




Vertical acceleration in the wheelhouse ($\beta_w$=180$^0$)




Slamming ($\beta_w$=180$^0$)

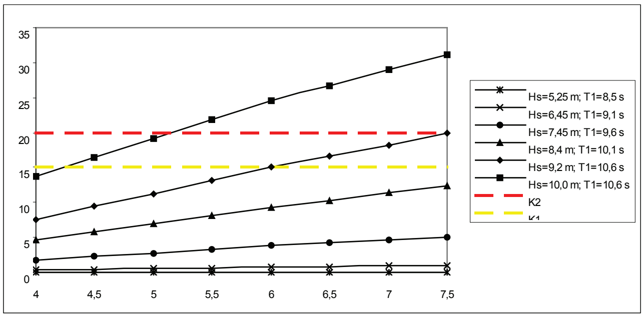



**Fig. 5.** Seagoing qualities of the vessel, with the marked selected criteria for bulk carrier LPP = 185.0 m (criterion K1 - warning of danger; criterion K2 - exceeding the permissible limit of seagoing qualities)

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