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Four Points of View on the Designation of the Navigation Area for Yachts

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Abstract: Usually, the need for research arises when there is a discrepancy between the theoretical and practical data. For example, the RINA (Registro Italiano Navale) Rules describe two navigation areas for yachts: unrestricted navigation and a navigation area with a significant wave height of not more than 4 m. In the GL (Germanischer Lloyd) Rules, it is proposed to assign the maximum wave height that a ship can meet, taking into account its speed and design features. The CCS (China Classification Society) Rules consider five categories of yachts for different navigational conditions. The significant wave height range is from 0.5 m to 6 m, and the distance from the place of refuge is from 5 to 200 nautical miles or more. Directive of the European Parliament and of the Council does not consider the distance from the place of refuge for the ship, and significant wave heights from 0.3 m to 4 m or more are proposed. In practice, the following situations may arise: it is necessary to determine the maximum value of the wave height at which the ship will be able to move against the wave or a possible decrease in the speed of the ship; to determine the height of the wave at which the wetness of the deck will begin; to study the relationship between the allowable values of the design accelerations and technical characteristics of the ship; to determine the distance from the emergency ship to the mooring place of the rescue ship; and calculate the minimum time to render assistance to people. These four situations will be considered in the article by using the energy wave criterion *EWC*, the recommendations of classification societies, and modeling the behavior of a vessel on a head wave.

Keywords: energy wave criterion (EWC); navigation area; yachts; towing tank tests; safety

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1. Introduction

Three yacht projects with different sizes and relative speeds were selected for the study. The rules of various classification societies [1–3] and the Directive [4] propose to assign a navigation area to ships depending on the distance from the port of refuge and the height of the wave. Using the energy wave criterion *EWC*, wave heights were determined at which yachts are able to move toward the wave [5]. Such a possibility of vessel movement will qualitatively characterize a particular vessel project. The ability to move against the wave as well as the prediction of a decrease in speed on the head wave is also extremely important for rescue ships performing a rescue operation, since the time to save people is limited. This period depends on the temperature of the sea water and the time during which a person can survive in sea water. In some rules, for example, in [6], the rescue operation time is limited to four hours. Thus, the navigation area of the vessel will be determined not only by the height of the wave, but also by the period of time during which the rescue vessel will be able to approach the sinking vessel, moving toward the head wave, with a loss of speed.

The bow height of the ship must be taken into account when assigning a navigation area in order to prevent the wetness of the deck. Insufficient bow height, and, accordingly, insufficient reserve buoyancy of the fore end can lead to an emergency. For a simplified assessment, it is possible to use the summation method. It is necessary to determine the dominant sum of the wave height and the pitching amplitude of the ship. This can be, for example, the sum of half of a sea wave and the pitch amplitude or pitch amplitude and the height of the formed wave during high-speed movement in calm weather.

The designation of the navigation area is directly related to parameters such as the distance of the ship from the port of refuge and the wave height in the region. When moving on a sea wave, additional accelerations occur, which must be taken into account when designing structures. A method to designate the area of navigation, which takes into account the size of the vessel, the relative speed, and the permissible values of design accelerations, must be developed. In this paper, the authors wanted to validate the method, and they decided to apply the method to the area around the main islands of Italy and Greece, in consideration of the fact that for large yachts such as the ones examined, this is the most used. In fact, for the most part, yachts in the size range investigated (30–65 m) usually spend the navigation time in the Mediterranean and uses different means of transportation such as yacht carriers if they need to move to other destinations such as the Far East or Caribbean.

2. Materials and Methods

Description of the Main Research Tools and Yacht Parameters

The criterion EWC was applied to solve the task of determining the maximum value of the wave height at which the ship will be able to move against the wave and for the evaluation of the value of the decrease in the speed of the rescue ship.

The criterion $EWC = \frac{\gamma g k_w h_w^3 B}{4.4 m v^2}$ contains the following parameters: water density γ; acceleration of gravity g; coefficient $k_w = \frac{L_w}{h_w}$ relating to the length L_w and height h_w of the wave; ship width B; speed v; and mass displacement of the vessel m. This criterion was derived from the inequality containing the wave energy $E_w = \frac{\gamma g k_w h_w^3}{8} B$ and the kinetic energy of the ship (vessel parameters: block coefficient c_b, length L, width B, and draft d) with the added masses of water $E_s = 1.1 \frac{m v^2}{2} = 1.1 \frac{\gamma c_b L B d v^2}{2}$. The coefficient EWC is similar to Newton's criterion $Ne = \frac{P L_N}{m v^2}$; in this equation, P is the force and L_N is the linear size [7].

The relationship between the design acceleration values, ship characteristics, and the maximum wave height that the ship can meet during the voyage is based on the GL [2] and RINA [8] formula $H_{sm} = 5 \frac{a_{CG}}{v} \frac{L^{1.5}}{6+0.14L}$. As quoted from [2]: "For craft with type of service "Passenger, Ferry, Cargo" an acceleration greater than a_{CG} = 1.0 g may not be adopted for the purpose of defining limit operating conditions". The calculation was conducted following the scheme. Froude number values and ship length options were given. The speed of the ship was then determined, which corresponded to these Froude numbers and the lengths of the ship. Using the iteration method, the length of the vessel and the Froude numbers were determined, which corresponded to a given wave height and to the condition a_{CG} = 1.0 g.

The requirements on the minimum bow height of the ship are included in the texts of the International Convention on Load Lines (the old version and new). Furthermore, in these normative documents, the purpose of the minimum bow height of the ship is not taken into account in the velocity of the ship.

When the vessel moves, formed waves arise, which is one of the components of water resistance. The height of these waves must be taken into account when assigning the bow height of the vessel (Figure 1). Several calculation options are possible. The first option is the summation of the height of the formed wave and the pitch amplitude. In this case, the ship moves with high relative speeds in calm water and is additionally subjected to an action of external forces. This may be due to the movement of cargo, the impact of wind, or a single wave from passing ships. The second option to calculate the bow height is the summation of half the sea wave height and the pitch amplitude.

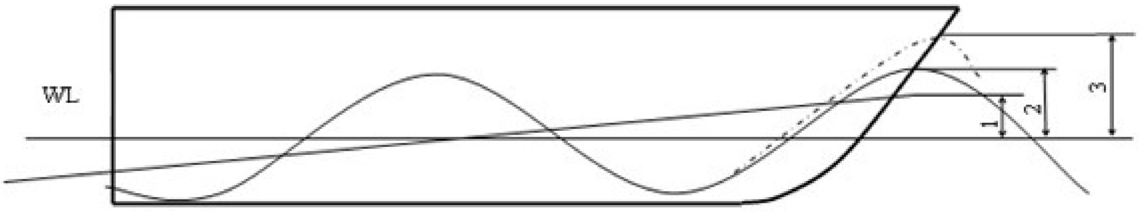

Figure 1. Three parts of the submersion of the bow: 1—pitch; 2—sea waves; 3—formed waves.

For small passenger vessels, on a wave of up to 4 points, the amplitude of the pitching can reach 7°, and the minimum value is 3° [9]. Bureau Veritas offers values for the amplitude of pitching $A_r \leq 0.2$ radian. For the selected yachts, it was assumed that the amplitude φ was about 3°, taking into account that the ship has good maritime qualities. Trim t is calculated from the expression $t = L \times tg\varphi$. Immersion of the bow, as a result of pitching will be equal to half the trim.

An empirical Tasaki formula $h_{fw} = 0.75B\frac{Fr_L^2}{l_e}$ is designed to calculate the height of the formed waves. The height of the formed waves will depend on the relative velocity, the width of the hull B, and the relative entrance length $l_e = \frac{L_e}{L}$.

The yachts have a high relative speed Fr_L (from 0.34 to 0.45) and therefore a high formed wave may occur during their movement. The main parameters of the vessels are presented in Table 1 and the general arrangement of one of them is shown (Figure 2).

Table 1. The main dimensions of the yachts.

Length L_{pp}, m	Width B, m	Draft d, m	Displacement, t	Block Coefficient	Speed v, kn	Power of Main Engines, kW
34	7.48	2.57	310.1	0.462	16	2 × 1000
48	10.09	2.68	590	0.4435	16.5	2 × 1200
64.51	12	4.16	1412	0.4274	16.5	2 × 1500

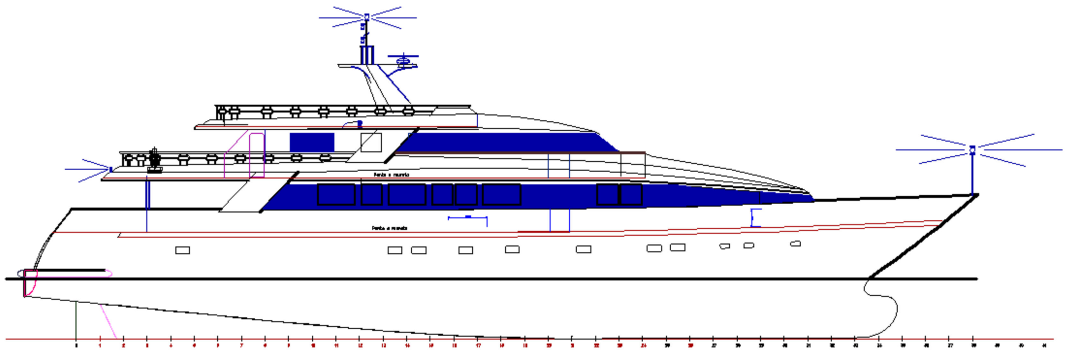

Figure 2. Part of the general arrangement of a yacht (length 34 m).

3. Results

Practical Application of the Main Research Tools

The criterion $EWC = \frac{\gamma g k_w h_w^3 B}{4.4mv^2}$ was applied to solve the above tasks. Figure 3 shows the dependence of the speed reduction in the head wave on the criterion EWC and plotted a point characteristic of the yacht (length 48 m). The formula $Speedr\ reduction$ (%) $= 180EWC^3 - 522EWC^2 + 496EWC - 54$ describes this dependence, which was obtained on the basis of tests in towing tanks. Tests were carried out in several towing tanks [9,10] on a regular wave at various ratios of height and wavelength as well as at various ratios of vessel length and wavelength. In addition to the test results of the three ship models in two tanks, Figure 3 shows the calculation results for two ships. It can be assumed that such test results can be extended to study the behavior of a ship on an irregular wave. The assumption of the possibility of extending the test data of models on a regular wave, with different ratios of the length and height of the wave, to an irregular wave is sometimes used in research.

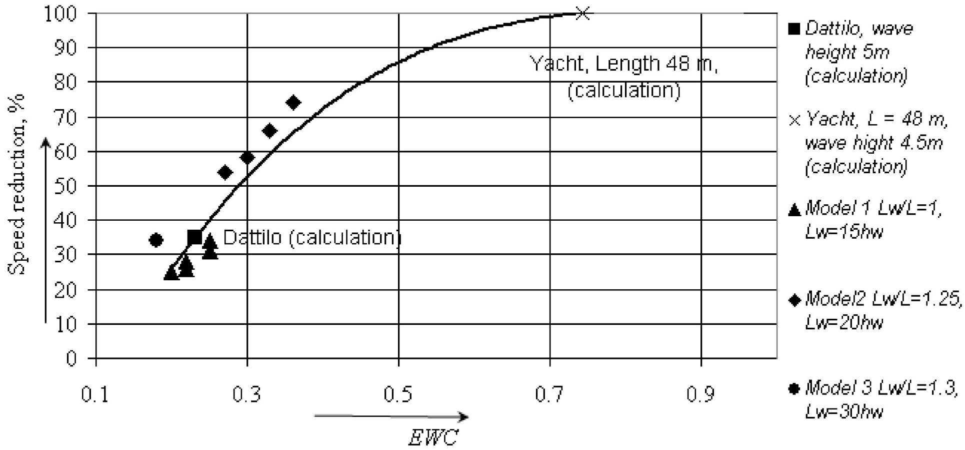

Figure 3. The dependence of the decrease in the speed of the ship in the head wave on the criterion *EWC*: Model 1 and Model 2—data [9]; Model 3—data [10].

For a yacht (length 48 m) with a wave height $h_{3\%}$ = 4.5 m, which corresponds to $h_{1/3}$ = 3.4 m, the speed of the ship will be close to zero. The same situation exists for yacht with a length of 34 m and a yacht with a length of 64.51 m at wave heights of $h_{3\%}$ = 4 m and $h_{3\%}$ = 5.5 m, respectively. Figure 3 shows the data for the rescue ship "Dattilo" (length 80 m, speed 18 knots). The wave height was assumed to be 5 m, and the ratio of the wave length L_w to its height $h_{3\%}$ was $\frac{L_w}{h_{3\%}} = 15$. Such a wave height was chosen for the third region of the Mediterranean Sea (Figure 4). A wave height of $h_{3\%}$ from 4 to 5 m ($h_{1/3}$ from 3 to 3.76 m) has a probability of less than 10% during the year.

Figure 4. The geographic area taken for the calculations.

Figures 5–7 show the results of the calculation using the equation $1.1\frac{\gamma c_b LBdv^2}{2} = \frac{\gamma g k_w h_w^3}{8}B$, which is the basis of the criterion *EWC*. This equation relates the kinetic energy of the vessel with the added masses of water and the energy of the wave. The kinetic energy of the vessel with the added masses of water $E_s = 1.1\frac{\gamma c_b LBdv^2}{2}$ is spent to overcome the barrier and in accordance with the principle of change in the kinetic energy, the speed of the vessel is reduced to zero.

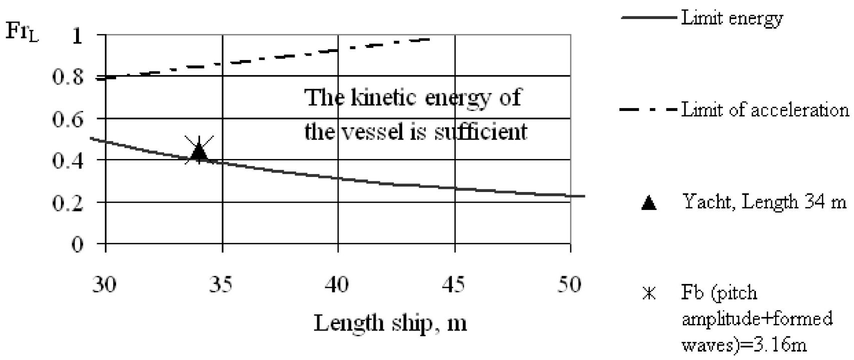

Figure 5. A comparison of the energies of the yacht (length 34 m) and the energy of a wave with a height $h_{3\%}$ = 4 m ($h_{1/3}$ = 3 m).

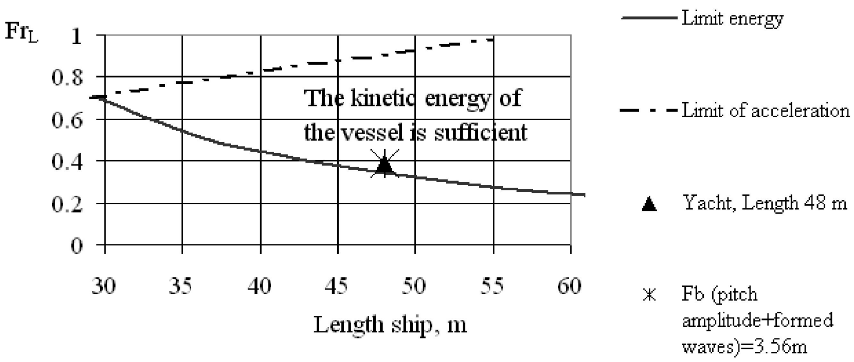

Figure 6. A comparison of the energies of the yacht (length 48 m) and the energy of a wave with a height $h_{3\%}$ = 4.5 m ($h_{1/3}$ = 3.4 m).

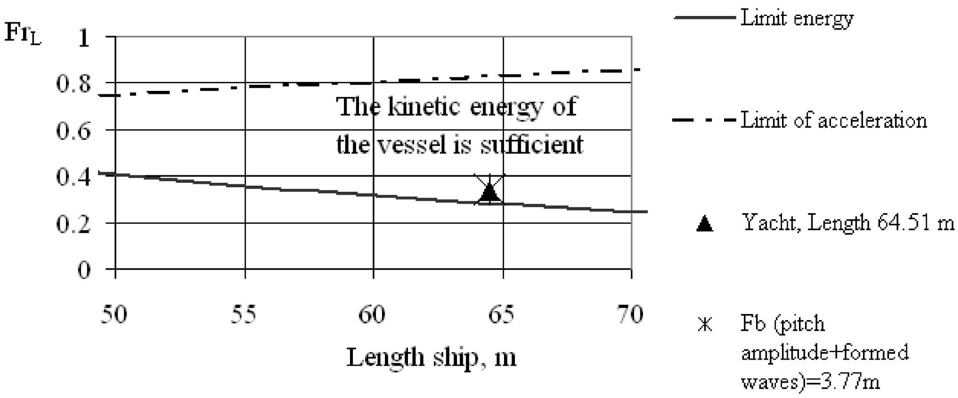

Figure 7. A comparison of the energies of the yacht (length 64.51 m) and the energy of a wave with a height $h_{3\%}$ = 5.5 m ($h_{1/3}$ = 4.1 m).

It can be seen from the figures that the movement of the yachts toward a wave with heights of $h_{3\%}$ = 4 m, 4.5 m, and 5.5 m, respectively, is possible with almost a complete decrease in speed. This was confirmed by the data in Figure 3.

The points for the characteristic of yachts were located above the line, showing the sufficiency or insufficiency of the vessel's energy. In these cases, the ships have the kinetic energy necessary for movement, with such a wave. Additionally, the figures show the line for the limit of permissible design accelerations. These lines were built on the basis of the RINA and GL requirements for the maximum wave height that the ship can meet during the voyage $H_{sm} = 5\frac{a_{CG}}{v}\frac{L^{1.5}}{6+0.14L}$ [2,8]. The calculation was made following this scheme. The Froude number values and ship length options were given. The speed of the ship was then determined, which corresponded to the Froude numbers and the lengths of the ship. Using the iteration method, the length of the vessel and the Froude numbers were determined, which corresponded to the wave heights, subject to the condition a_{CG} = 1.0 g.

Figures 5–7 and Table 2 contain information about the recommended bow height when the ship is moving in a given region at a given speed. Two cases for each yacht were considered. The first case was associated with the formation of a formed wave, at a relative speed Fr_L and the occurrence of pitch amplitude due to external influences (wind, waves from passing ships, cargo movement, etc.). The second case was based on the summation of the pitch amplitude and half the sea wave height. Calculations of the height of the formed wave were made using the empirical Tasaki formula $h_{fw} = 0.75B\frac{Fr_L^2}{l_e}$.

Table 2. The bow height F_b of the yachts.

Name	F_b, Pitch Amplitude and Formed Waves, m	F_b Pitch Amplitude and $h_{3\%}$, m	F_b Real Value, m
Yacht (length 34 m) $h_{3\%}$= 4 m	3.16	2.89	3.55
Yacht (length 48 m) $h_{3\%}$= 4.5 m	3.56	3.51	3.55
Yacht (length 64.51 m) $h_{3\%}$= 5.5 m	3.77	4.44	5.7

As can be seen from the data in the table, all three projects corresponded to the selected navigation areas, in terms of the selected wave height. For yacht with a length of 34 m and a yacht with a length of 48 m, the option of summing the formed wave and the pitch amplitude will be dominant.

To determine the navigation area for the yacht, taking into account the time of human survival in the water, it is necessary to have information about the average water temperature in a given area and the survival time of a person in water at such a temperature. In region 3, in July, the average water temperature is about 25 °C. A person, at this temperature, can survive in water for about 20 h. This period of time should be taken for further calculations as the period during which people should be helped. During this time, assistance must be provided by a rescue vessel.

One modern vessel is the offshore patrol vessel "Dattilo", where the maximum capacity for rescued people is about 600 people, the vessel length L = 80 m, width B = 16.6 m, and speed v = 18 knots. The wave height in region 3, as above-mentioned, is from 4 to 5 m and has a probability of less than 10% during the year. With a wave height of $h_{3\%}$ = 5 m, the rescue ship "Dattilo" will lose about 35% of speed (Figure 3) and will move at a speed of 11.7 knots. In 20 h, the "Dattilo" will cover about 230 nautical miles. Such a distance from where the rescue ships are based may be assigned to these yachts during the summer. In winter, the survival time of a person in cold water is shorter, and the distance from the base of the rescue ship will be less.

4. Conclusions

The conducted research confirms the possibility of using the criterion EWC for assigning a navigation area to ships. The navigation area is usually associated with the height of the wave and the distance from the port of refuge. The considered options for yacht projects can be operated at wave height $h_{3\%}$ from 4 m to 5.5 m, depending on the length of the vessel and relative speed. At these wave heights, the speed of the yachts on the head wave will be reduced to zero and the yachts will not be able to overcome the wave with a given energy. The boatmaster can change the course of the vessel or drift, but these measures limit the range of effective use of the vessel.

The prevention of deck wetness was tested for the same values of the wave heights for the two options. The first option was related to the summation of the formed wave that occurs when the ship is moving in calm water and the pitch amplitude that occurs due to external influences (wind, waves from passing ships, cargo movement, etc.). The second option was based on the summation of the pitch amplitude at a given sea wave height. As the calculations showed, the dominance of one or the other option is possible. In general, the bow height of the vessels corresponded to the operating conditions at the selected sea wave heights.

A forecast of the decrease in the speed of the rescue vessel "Dattilo" during the rescue operation, taking into account the height of the wave, was made in this article. The speed of this vessel will decrease to 11.7 knots when moving against a $h_{3\%}$ = 5 m high wave. Consequently, in 20 h, during the maximum time of the rescue operation in the summer, the rescue ship will be able to cover about 230 nautical miles, which will be the boundary of the navigation area for the investigated vessels. In winter, the period of survival of a person in cold water is shorter, and the distance from the port of refuge will be less.

Design accelerations offered by classification societies do not exceed the allowable limits. Corresponding lines are plotted on the graphs, which limit the accelerations depending on the size of the vessel, the height of the wave, and the relative speed of the yacht.

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