ТЕОРІЯ І ПРОЕКТУВАННЯ КОРАБЛЯ

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SOME QUESTIONS ABOUT GENERAL STRENGTH, PROPULSION AND ENERGY EFFICIENCY OF DEADRISE HULLS

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Abstract

Introduction. *When a high-speed vessel is moving in the transitional mode loads increase from the interaction of the bottom of the vessel and the waves. Accordingly increase adverse effects health of the passengers and crew. Hull structures and equipment may also be damaged. Modern requirements of classification societies significantly raise the level for permissible accelerations on board high-speed vessels. Various methods are used to reduce shock loads. One of them is an increase of deadrise angle . A decrease in resistance is possible by increasing the relative length of the vessel, which can lead to problems in ensuring general strength. To determine the maximum possible value of the relative length requires knowledge of the relative section modulus. The lack of information about the relative section modulus of an equivalent girder of the vessel occurs during various studies. The choice of the relative length of the vessel is associated with such quality as propulsion and many others. And sometimes, the shipbuilder's desire to reduce water resistance, by increasing this parameter, is limited by the difficulties of ensuring general strength. In this study, a try will be made to combine the requirements for general strength, propulsion and energy efficiency in order to create new and improve existing ships.* ***Purpose.*** *The goals of this work are to determine: the value of relative section modulus of an equivalent girder for a small vessel, the method for determining the maximum value of the relative length of a small high-speed vessel, the way for reducing the value of the factor EEDI.* ***Results.*** *The value of the relative section modulus of an equivalent girder for a small vessel of transitional mode is defined in this article. Graphic solution of two equations proposed in the article: equation of general strength, taking into account wave acceleration and the equation for the relative section modulus, taking into account the geometry of the hull. The result of this decision is the value of relative section modulus of an equivalent girder for a small vessel of transitional mode. This parameter is required to determine the limiting value of the relative length and finding solutions to reduce the coefficient EEDI. Comparative analysis of the obtained data with the data about* *strength and weight of the H-girder with length similar to the ship was conducted. The formula for determining the limiting value of the relative length was obtained from the equation of general strength. The way to reduce the energy efficiency factor EEDI, by increasing the relative length, was proposed in this article and demonstrated on the example for a real small high-speed vessel.* ***Conclusions.*** *Improvement of existing technologies may lead to the appearance of new technologies. The software is based on algorithms. The creation of such algorithms is necessary for new programs or for "one digital" assessment of the project, at the beginning of making design decisions. The algorithm proposed in this article can be used to achieve such goals.*

Key worlds: *section modulus, energy efficiency factor, small high-speed vessel.*

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ДЕЯКІ ПИТАННЯ ЗАГАЛЬНОЇ МІЦНОСТІ, ХОДОВОСТІ ТА ЕНЕРГЕТИЧНОЇ ЕФЕКТИВНОСТІ КІЛЮВАТИХ КОРПУСІВ

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Анотація

В цій роботі визначено значення відносного моменту супротиву перерізу еквівалентного брусу для малого судна перехідного режиму. Перехідний режим руху до теперішнього часу не дуже добре вивчений, тому ця сфера експлуатації суден потребує додаткової уваги. Малі швидкісні судна – це група плавзасобів, для яких притаманні специфічні характерні, тільки для них риси. Правила різноманітних міжнародних конвенцій дуже часто поширюються на судна, довжиною менше ніж двадцять чотири метри, що створює додаткову потребу для вивчення сфери малих суден. В цій роботі розглянуті питання загальної міцності малого швидкісного судна, що рухається на схвильованій поверхні моря. Графічне рішення двох рівнянь, запропоновано у статті: рівняння загальної міцності корпусу судна, з урахуванням перевантажень від впливу хвиль та рівняння для моменту супротиву перерізу еквівалентного брусу, з урахуванням геометрії корпусу. Результатом цього рішення є значення відносного моменту супротиву еквівалентного брусу для малого судна перехідного режиму. Цей параметр необхідний для визначення граничного значення відносної довжини та пошуку рішень для зменшення значення коефіцієнта EEDI. При русі в перехідному режимі, супротив води та повітря значно збільшується, що веде до додаткових витрат палива та заподіяння шкоди навколишньому середовищу, тобто збільшенню значення коефіцієнта енергоефективності EEDI. Зменшити вплив цього явища можливо за рахунок більшого значення відносної довжини судна. Але збільшувати відносну довжину судна можна не безкінечно, тому й виникла потреба в оцінці максимального значення цього показника. Проведено порівняльний аналіз отриманих даних з даними про міцність і вагу двотаврової балки, довжиною подібною до довжини судна.

Формула для визначення максимального значення відносної довжини судна отримана з рівняння загальної міцності. Спосіб зменшення коефіцієнта енергоефективності шляхом збільшення відносної довжини був запропонований та продемонстрований на прикладі для малого швидкісного судна.

Ключові слова: *момент супротиву перерізу еквівалентного брусу, коефіцієнт енергоефективності, мале швидкісне судно.*

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НЕКОТОРЫЕ ВОПРОСЫ ОБЩЕЙ ПРОЧНОСТИ, ХОДКОСТИ И ЭНЕРГЕТИЧЕСКОЙ ЭФФЕКТИВНОСТИ КИЛЕВАТЫХ КОРПУСОВ

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Аннотация

В этой работе определено значение относительного момента сопротивления сечения эквивалентного бруса, для малого судна переходного режима. Графическое решение двух уравнений, предложено в статье: уравнения общей прочности корпуса судна, с учетом перегрузок от воздействия волн и уравнения для момента сопротивления поперечного сечения эквивалентного бруса, с учетом геометрии корпуса. Результатом этого решения является значение относительного момента сопротивления эквивалентного бруса для малого судна переходного режима. Этот параметр необходим для определения максимально допустимого значения относительной длины и поиска решений для уменьшения коэффициента EEDI. Проведен сравнительный анализ полученных данных с данными о прочности и весе двутавровой балки, длиной равной длине судна. Формула для определения максимального значения относительной длины судна получена из уравнения общей прочности. Способ уменьшения значения коэффициента энергоэффективности, путем увеличения относительной длины, был предложен и продемонстрирован на примере для малого скоростного судна.

Ключевые слова: *момент сопротивления сечения эквивалентного бруса, коэффициент энергоэффективности, малое скоростное судно.*

NOMENCLATURE

$\Delta = \gamma V$ – displacement of the ship
γ – density of water
β – deadrise angle, degrees
Fr_V – volume Froude number
W – section modulus
$\frac{W}{\Delta}$ – relative section modulus

$\frac{L}{\sqrt[3]{V}}$ – relative length

$EEDI$ – energy efficiency index
D – depth of the ship
B – width of the ship
d – draft of the ship
c_b – block coefficient
n – overload
σ_a – allowable compression stress for material
t – thickness of plating
Ω – area of cross section of ship
$C_\Delta = \frac{\Delta}{\gamma B^3}$ – load coefficient
R – total resistance
$\frac{R}{\Delta}$ – relative total resistance
R_o – residual resistance
$\frac{R_o}{\Delta}$ – relative residual resistance

Introduction

When a high-speed vessel is moving in the transitional mode, with volume Froude number $1 \leq Fr_V = \frac{v}{\sqrt{g\sqrt[3]{V}}} \leq 3$, loads increase from the interaction of the bottom of the vessel and the waves. Accelerations increase accordingly, which adversely affects health of the passengers and crew. Hull structures and equipment may also be damaged. The limit acceleration that is considered to be acceptable from a physiological point of view, limited to the value 0,2g. In reality, the acceleration on board of the high-speed vessel reaches high values. Modern requirements of classification societies significantly raise the level for permissible accelerations on board high-speed vessels. Various methods are used to reduce shock loads. One of them is an increase of deadrise angle β. Vessels with deadrise angle $\beta > 20°$ are often called "monohull deep V".

In the transitional mode, the water resistance increases significantly. A decrease in resistance is possible by increasing the relative length $\frac{L}{\sqrt[3]{V}}$ of the vessel, which can lead to problems in ensuring general strength. To determine the maximum possible value of the relative length requires knowledge of the relative section modulus. The lack of information about the relative section modulus of an equivalent girder of the vessel $\frac{W}{\Delta}$ occurs during various studies. The choice of the relative length of the vessel is associated with such quality as propulsion and many others. And sometimes, the shipbuilder's desire to reduce water resistance, by increasing this parameter, is limited by the difficulties of ensuring general strength. There was a need to find the limiting values of the relative length, ensuring the strength of the vessel, while maintaining acceptable propulsion. The value $\frac{L}{\sqrt[3]{V}}$ is associated with propulsion, or rather with the relative resistance of water $\frac{R}{\Delta}$. And this indicator has an impact on the energy efficiency index $EEDI$. Thus, in this study, a try will be made to combine the requirements for general strength, propulsion and energy efficiency in order to create new and improve existing ships.

Undoubtedly, a change in the relative length of the vessel will affect the other qualities of the vessel: manoeuvring, seakeeping capacity and other. In this article it is impossible to consider the change of all parameters; therefore, the main, from the point of view of the author, questions are considered: general strength, propulsion and energy efficiency.

Problem statement and analysis of recent research and publications

Values characterizing various types of girders are sometimes given in different literature. For example, the book (Lesyukov, 1982) proposes a coefficient of the structural quality of a girder $\frac{W}{F}$, as the ratio of the section modulus W to the area of its cross section F. In the source (Barabanov, 1969), the dependence of the weight of one linear meter of the girder on the section modulus is presented. From the graph it is clear that for each type of beams is characterized by its own dependence. For research, it is possible to apply knowledge about section modulus of the small vessel, given in (Dormidontov & Kalmychkov, 1966). The minimum section modulus of a small vessel (with deadrise angle β=0, depth D, width B, thickness of plating t) is described by the formula $W = D(B + \frac{D}{3})t$.

As noted above, deadrise hulls are widely used in transitional motion. In this paper, the forms with deadrise angle will be considered, in Figure 1.

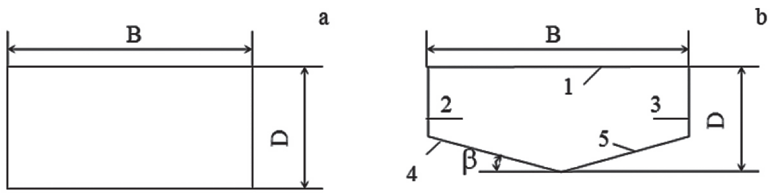

Fig. 1. Sections of the hull.
Source: Own elaboration

Writing the elements in the table, Figure 2, it is possible to obtain a formula for the section modulus of hull with deadrise angle $\beta = 25^o$.

$$W = (0,33D^2 + 0,015B^2 + 0,82DB - 0,028\frac{B^3}{D})t \quad (1)$$

When applying in the calculations the value of the deadrise angle $\beta = 0^o$, the formula was obtained

$$W_{\beta=0} = (0.33D^2 + DB)t \quad (2)$$

This formula is similar to the formula presented in (Dormidontov & Kalmychkov, 1966) and mentioned above in this article.

Numbers of elements correspond to figure 1b	Area, F	The distance between the center of gravity of the element and the central axis, z
1	2	3
1	tB	$\frac{D}{2}$
2, 3	$(D-\frac{B}{2}tg\beta)t$	$\frac{B}{2}tg\beta$
4, 5	$\frac{Bt}{2\cos\beta}$	$\frac{D}{2}-\frac{B}{4}tg\beta$

Fig. 2. Elements of the cross section of the vessel, in Figure 1b. Source: Own elaboration

Equations of a similar type for deadrise angles from 0º to 30º were obtained and are presented in the paper. (Kanifolskyi, 2010). The results of the calculations were used to determine of the coefficient of the profile u, in the formula $W=\frac{u}{2}D\Omega$, that includes the depth D and the area of cross section of ship Ω, after equating the right sides of the equations described above. Using this data, it is possible to find out how the section modulus of the deadrise hulls differs from flat bottom. The graph from the article is presented in the Figure 3.

Sometimes, in the early stages of a project, when there is no complete data on the projected vessel, the need to assess the general strength of the vessel arises. In such cases, some simplifications are applied in the calculation, and the cross-section of the vessel appears as the cross-section of an equivalent H-girder. In these cases, the formula $W=\frac{u}{2}D\Omega$ is usually used.

For calculations, it is assumed that the position of the central axis passing through the center of gravity of the cross section of the vessel is in the middle of the depth. This assumption is based on the fact that the bottom deadrise will shift the position of this axis towards the deck, and the stronger and heavier construction of the bottom will lower the axis towards the bottom. In (Germanischer Lloyd, 1996) it is noted that the minimum thickness of deck plating should be not less than 2.5 mm. The thickness of the bottom plating should be at least $t_{bp}=1,35L^{1/3}\geq 2,5$. For example, the thickness of the plating of the bottom

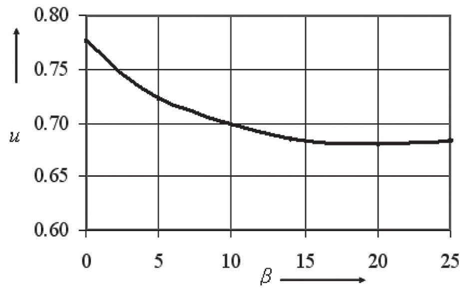

Fig. 3. The dependency of the coefficient of the profile u on the deadrise angle. Source: Own elaboration

for the vessel, $L = 24$ m, will be equal to 3.9 mm. This is 1.56 times greater than the minimum thickness of the plating of the deck. This thickness is adopted to justify the position of the central axis of the cross section. Accordingly, the central axis will move from the middle of the depth, towards the bottom. Another factor, affects the position of the central axis, is deadrise hull. Since the center of gravity half of the bottom constructions lies approximately at a distance of $0{,}25\,B$ from the middle line plane, the displacement of the center of gravity of the bottom structure towards the deck is $0{,}25\,B\,tg\beta$. The displacement of the central axis from the middle of the depth towards the deck will occur.

Sometimes in assessing the general strength, simplification is used to find the minimum acceptable value. The thickness of the girders is distributed over the thickness of the vessel plating.

For further calculations, the thickness of the steel plating is assumed to be 6 mm, as an average value for transitional mode vessels with a length of about 30 m.

The goals of this work are to determine:

– the value of relative section modulus of an equivalent girder for a small vessel;

– the method for determining the maximum value of the relative length of a small high-speed vessel;

– the way for reducing the value of the factor $EEDI$ and therefore reduces carbon dioxide emissions into the atmosphere.

Information about the structural quality of a girder $\frac{W}{F}$ can be projected on the calculations of the relative section modulus of an equivalent girder for a vessel $\frac{W}{\Delta}$. In approximate calculations of strength, the shape of the profile, which corresponds to the equivalent girder of vessel, is an H-girder, Figure 4, and, taking into account the direct dependence of the cross-sectional area on the length of the vessel, we can assume the presence of such a value of the relative section modulus $\frac{W}{\Delta}$, which is characteristic for a specific type of ships. This value retains approximately the same value for ships of the same type; the same hull material and speed mode.

Formula (2) can be represented in the form,

$$\frac{W}{\Delta} = \frac{D(B + \frac{D}{3})t}{\gamma c_b LBd} = \frac{k_D t(1 + 0.07k_D)}{\gamma c_b L}, \quad (3)$$

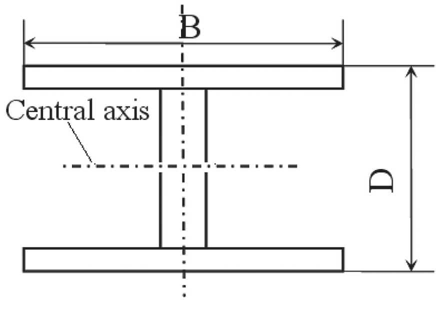

Fig. 4. The equivalent girder for calculation of section modulus of the ship (H-girder). Source: Own elaboration

taking into account the geometry of the hull and the fact $k_D = \frac{D}{d}$, $\frac{B}{d} = 4.7$ (last corresponds to the minimum of water resistance in the speed range $2 \le Fr_V = \frac{v}{\sqrt{g\sqrt[3]{V}}} \le 3$, NPL data). In this formula, c_b – block coefficient, γ – density of water, all other parameters are defined above.

The relative section modulus, in m^3/t, can also be found from the equation of general strength, based on the bending moment and section modulus, $\sigma_a \geq \frac{\Delta L}{Wk} n$, taking into account the additional acceleration at speed on the wave

$$\frac{W}{\Delta} = \frac{L}{k\sigma_a} n, \tag{4}$$

where n is overload, L – vessel length in m, σ_a – allowable compression stress for material of the hull in t/m^2 and k is coefficient characteristic for the type of vessels.

Allowable compression stress is assumed to be equal to 0.8 of the yield strength of the material, in this case, steel.

The researcher can apply the materials and the requirements of any rules chosen by him to solve the task in the proposed method.

Overload is the ratio of the vertical acceleration in the cross section of the vessel, caused by forces, when meeting a wave, to the acceleration of gravity.

For calculations, data on overloads was chosen from Rules (Bureu Veritas, 1990), in which it is proposed to take the overload factor regardless of the speed range: for passenger ships n=2, for pleasure boats n = 2.3. The value of the coefficient k is assumed to be 21. More detailed information on this subject is presented in (Kanifolskyi, 2010). The above article analyzes the various rules of classification societies and the work of scientists in the field of defining a bending moment.

In the calculations, a fixed value n = 2 was adopted, recommendations by Bureau Veritas (BV). Similar values are proposed in the rules of Germanischer Lloyd (GL), for relative speed $Fr_V = 2$, midpoint of the transitional mode. The value of the coefficient n changes depending on the relative speed, GL.

After a joint graphical solution of two equations (3) and (4), in Figure 5, it is possible to determine a value $\frac{W}{\Delta}$ = 0.0003 m^3/t, for steel hull, satisfying the requirements of general strength and taking into account the geometry of the hull.

It is interesting to note that some Rules are created specifically for vessels less than 65 m length (Bureu Veritas, 1990).

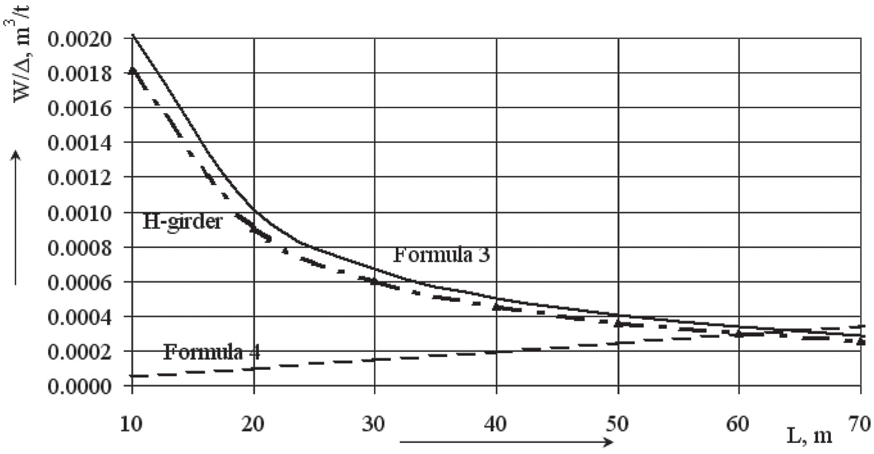

Fig. 5. The value of the relative section modulus.
Source: Own elaboration

The solution obtained by the graphical method does not take into account the case deadrise. Next, an analysis will be made of how much the section modulus of hulls with different deadrise differs from the section modulus of the hull without deadrise. Based on the analysis of the coefficient of the profile u, in the formula $W = \frac{u}{2} D\Omega$, that includes the depth D and the area of cross section of ship Ω, it can be assumed that the difference in value of the section modulus for deadrise hull and for non-deadrise hull is on average about 10% (Kanifolskyi, 2010), Figure 3. Taking into account this fact, the value of the relative section modulus of the deadrise steel hull taken for further calculations can be considered about $\frac{W}{\Delta} = 0.00027$ m^3/t. To check the obtained values $\frac{W}{\Delta}$, it is possible to conduct an additional calculation. As noted above, the type of the balk, which corresponds to the equivalent girder of the hull of the vessel, in approximate calculations is the H– girder. Using the data (Barabanov, 1969) on the dependence of the weight of one meter of an H– girder on its section modulus and adopting various lengths of the beam, it is possible to get a value close to 0.0003 m^3/t, for a balk with length 64 m, Figure 5.

Using the obtained information about the value $\frac{W}{\Delta}$, it is possible to determine the relative length $\frac{L}{\sqrt[3]{V}}$ of the steel vessel from the conditions of general strength

$$\sigma_a W \geq \frac{\Delta L}{k} n .$$

The values of the overload n, depending on the Froude numbers, in the speed range $2 \leq Fr_V \leq 3$, were analyzed in the article (Kanifolskyi, 2010) and the formula was proposed there

$$n = 0,3 Fr_V^2 = 0,3 \frac{v^2}{g\sqrt[3]{V}} .$$

After substituting the formula for overload n into the general strength condition $\sigma_a W \geq \frac{\Delta L}{k} n$, the inequality for relative length is

$$\sigma_a \frac{kgW}{0,3v^2\Delta} \geq \frac{L}{\sqrt[3]{V}} \quad (5)$$

The relative length $\frac{L}{\sqrt[3]{V}}$ depends on the relative residual resistance $\frac{R_o}{\Delta}$. The relative total resistance of water $\frac{R}{\Delta}$ is included in the simplified equation for the calculation of the energy efficiency design index $EEDI = \frac{443.8R}{k_1 k_2 \eta \Delta}$ (Kanifolskyi, 2014). The way of obtaining this equation and the formula, showing the dependence of the relative residual resistance on the change in the relative length $d(\frac{R_o}{\Delta})_2 = -5.03(\frac{L}{\sqrt[3]{V}})^{-2.99} d(\frac{L}{\sqrt[3]{V}})$, at the Froude numbers $Fr_V = 2$, are described in (Kanifolskyi, 2014).

So, the opportunity to apply the presented formulas in practice, on the example of a real ship appeared.

For the calculation, the high-speed small vessel "Mangusta 110" was chosen, with length 30 m, width 7.2 m., speed 30 knots, weight displacement 135 tons, $Fr_V = 2.2$, the material of the hull is fiberglass. The overload of the vessel, in the example, (one of the cases of the used method) has a smaller value $n = 0,3Fr_V^2 = 0,3\frac{v^2}{g\sqrt[3]{V}}$ = 1.45, than n in the graphic solution, therefore, the assumption is made to the safe side.

The researcher can apply the materials, value n and the requirements of any rules chosen by him to solve the task in the proposed method.

The real value of the relative length of this vessel is $\frac{L}{\sqrt[3]{V}} = 6$. The maximum allowable value calculated by the formula (5) is $\frac{L}{\sqrt[3]{V}} = 9$ (hull material and thickness were taken into account when calculating). If we assume that this value will be increased by one unit, will take the value $\frac{L}{\sqrt[3]{V}} = 7$, then the relative residual resistance will receive a decrease $d(\frac{R_o}{\Delta})_2 = -5.03(\frac{L}{\sqrt[3]{V}})^{-2.99} d(\frac{L}{\sqrt[3]{V}}) = -0.025$. The total resistance "Mangusta 110" is about R = 15.3 tons.

Considering the fact that the residual resistance, at $Fr_V = 2$, is about 70% of the total resistance of bare hull, the overall decrease in relative total resistance $\frac{dR}{\Delta}$ can be significantly reduced.

The influence of the relative length of the vessel on the residual resistance was considered in the article. This component of resistance has a dominant part in the total resistance in the transitional mode. According to the data (Basin & Anfimov, 1961) the residual resistance is about 70% of the total resistance, in this mode. Test data of a systematic series of models of boats are given in (Voitkunsky & Anfimov, 1985). From these data it follows that the average value of the residual resistance is about 65% of the total and depends on the load coefficient $C_\Delta = \frac{\Delta}{\gamma B^3}$ in the transitional mode. The friction resistance will also change after changing the relative length, but will have less impact on the total resistance, since the residual resistance is dominant.

To verify the assumptions made, the calculation of the components of the resistance for the vessel "Mangusta 110" and "Variant of the ship" was carried out, in Figure 6.

An increase in the relative length for "Variant of the ship" was achieved by increasing its length by 14% and reducing its block coefficient by the same value, displacement are unchanged. Light weight can be also reduced by the use of other materials, such as aluminium alloys. This approach involves the choice of the relative length of the vessel at an early stage of the project.

The values of relative residual resistance were taken from (Kanifolskyi, 2014), in Figure 7. To create this graph, data from a many of towing tanks were used.

Vessel characteristics	"Mangusta 110"	"Variant of the ship"	Difference, %
The relative length	6	7	14
The relative residual resistance $\frac{R_o}{\Delta}$ (Figure)	0.071	0.05	30
The change $d(\frac{R_o}{\Delta})$	-	-0.021	-
The residual resistance R_o	9.59	6.75	30
The friction resistance R_f, t	4.65	4.57	2
The appendage resistance, t	1.0	0.79	20
The air resistance, t	0.04	0.04	0
The total resistance, t	15.3	12.2	20
The change $d(\frac{R_o}{\Delta})_2 = -5.03(\frac{L}{\sqrt[3]{V}})^{-2.99} d(\frac{L}{\sqrt[3]{V}})$	-	-0.025	-
The residual resistance in total resistance of bare hull, %	67	-	-

Fig. 6. The components of the resistance for the vessels.
Source: Own elaboration

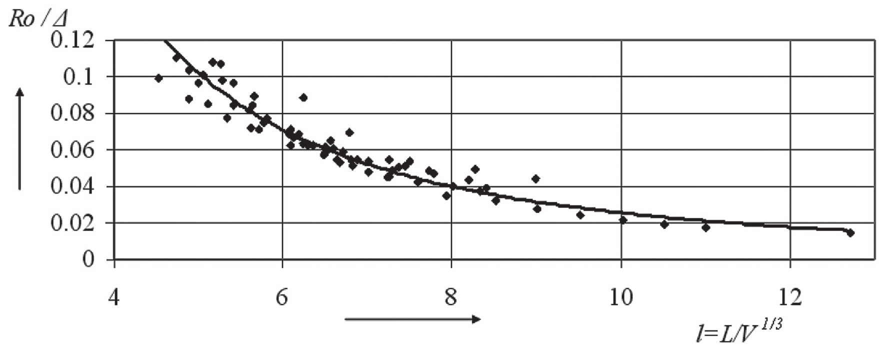

Fig. 7. The dependency of the relative residual resistance on relative length, at Fr_V =2.
Source: Own elaboration

An approximate formula for estimating the energy efficiency factor is $EEDI = \frac{443.8R}{k_1 k_2 \eta \Delta}$. Consequently, as a result of the performed operations, a significant, about 20%, reduction of carbon dioxide emissions into the atmosphere is possible.

Conclusions

To solve the problem of determining the relative section modulus of an equivalent girder for a small vessel, the methods of structural mechanics and the theory ship design were applied: the equation of general strength, taking into account the overloads, and the method of preliminary calculation of the section modulus.

The joint solution of the above-mentioned equations gives the value of relative section modulus of a transitional mode small vessel equal 0.0003 m^3/t. Taking into account the deadrise of the hull, a value of $\frac{W}{\Delta}$ =0.00027 m^3/t can be adopted. The data of the verification calculation of the relative section modulus, for the H-girder, confirmed the obtained results.

The maximum value of the relative length of a small high-speed vessel $\frac{L}{\sqrt[3]{V}}$, taking into account overloads and $\frac{W}{\Delta}$, can be found from inequality $\sigma_{доп}\frac{kgW}{0,3v^2\Delta} \geq \frac{L}{\sqrt[3]{V}}$.

Increasing the value of the relative length of the vessel leads to a decrease in water resistance, which in turn positively reduces the value of the factor $EEDI$ and therefore reduces carbon dioxide emissions into the atmosphere.

Combining the three qualities of a ship: the general strength, propulsion and energy efficiency presented in this article will help create safer and more energy efficient ships.

Indeed, IMO does not propose to apply the coefficient $EEDI$ for high speed small vessels, but the attempt made in this article is a step in a new direction. Moreover, studies in this direction have been made by other authors (Chris van Hooren, 2014).

Improvement of existing technologies may lead to the appearance of new technologies. The software is based on algorithms. The creation of such algorithms is necessary for new programs or for "one digital" assessment of the project, at the beginning of making design decisions. The algorithm proposed in this article can be used to achieve such goals.

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