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Assessment of hydrodynamic impacts on a vessel when encountering an abnormal wave

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Abstract. Current data indicate that abnormal waves of great steepness and height are quite common in the World Ocean. The assessment showed that the probability of a vessel encountering such waves can be quite high. The impact of abnormal waves on sea vessels poses a significant danger to them, since the possibility of a vessel encountering them is not taken into account during design. The two scenarios of a vessel's interaction with an abnormal wave are considered. In the first case, the vessel first hits its trough and then buries itself in the crest (the vessel passes through a "hole" in the sea). In the second case, the vessel is first exposed to the crest of the abnormal wave, after which it finds itself on its trough. The vessel dynamics are modeled using the mathematical apparatus developed by the author, including a modified system of equations for the vessel's longitudinal roll, which allows taking into account the vessel's behavior in burrowing conditions. The case of the appearance of one wave of abnormal height, sharply standing out against the background of the surrounding waves, is considered, while the height of the abnormal wave varied. An assessment of the magnitude of hydrodynamic effects on the bow end during interaction with the abnormal wave is made. The study showed that the first of the considered scenarios represents the greatest danger to the vessel. An analysis of the efficiency of the new design of the bow end developed by the author, which has a cylindrical shape and is equipped with a cylindrical bulb attachment, is carried out. It is shown that during interaction with an abnormal wave, this technical solution allows to significantly reduce the magnitude of the hydrodynamic load and increase the safety of the vessel.

Keywords: abnormal waves, hydrodynamic load, burying in a wave, loss of stability, loss of strength, new shape of the bow

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Научная статья

Оценка гидродинамических воздействий на судно при встрече с аномальной волной

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Аннотация. Современные данные свидетельствуют о том, что в Мировом океане достаточно часто встречаются аномальные волны, отличающиеся большой крутизной и высотой. Выполненная оценка подтвердила, что вероятность встречи судна с такими волнами может быть весьма высокой. Воздействие аномальных волн на морские суда представляет для них существенную опасность, т. к. возможность встречи судна с ними не учитывается при проектировании. Рассматривается два сценария взаимодействия судна с аномальной волной. В первом случае судно сначала попадает на ее подошву, а затем зарывается в вершину (проход судна через «дыру» в море). Во втором случае судно на первом этапе подвергается воздействию гребня аномальной волны, после чего оказывается на ее подошве. Моделирование динамики судна осуществляется с использованием разработанного автором математического аппарата, включающего модифицированную систему уравнений продольной качки судна, позволяющую учесть особенности поведения судна в условиях зарываемости. Рассмотрен случай появления одной волны аномальной высоты, резко выделяющейся на фоне окружающего волнения, при этом высота аномальной волны варьировалась. Выполнена оценка величины гидродинамических воздействий на носовую оконечность при взаимодействии с аномальной волной. Результаты исследования определили, что наибольшую опасность для судна представляет первый из рассмотренных сценариев. Проведен анализ эффективности разработанной автором новой конструкции носовой оконечности, имеющей цилиндрическую форму и оснащенной цилиндрической бульбовой наделкой. Доказано, что при взаимодействии с аномальной волной данное техническое решение позволяет существенно уменьшить величину гидродинамической нагрузки и повысить безопасность судна.

Ключевые слова: аномальные волны, гидродинамическая нагрузка, зарываемость в волну, потеря остойчивости, потеря прочности, новая форма носовой оконечности

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Introduction

One of the most common causes of shipwrecks is exposure to adverse environmental factors. The impact of anomalous waves reaching several tens of meters in height can pose a particular danger. As noted in [1], the crest of an anomalous wave is often preceded by a deep trough, known as a “hole” in the sea.

Remote sensing of the World Ocean's surface using satellites [1] has shown that the occurrence of high-altitude anomalous waves is not uncommon. The author assessed the probability $\overline{P}$ of ship encounters with anomalous waves [2] based on their characteristics (M_ρ, M_υ – mathematical expectations of the half-width and velocity of anomalies) for actual values of the anomaly flow intensity density obtained by scanning the ocean surface [1].

Research materials

The results presented in Fig. 1 indicate that this probability can be quite high, that is why investigation of the interaction of an anomalous wave with a ship's hull as it passes through such a wave is of particular interest.

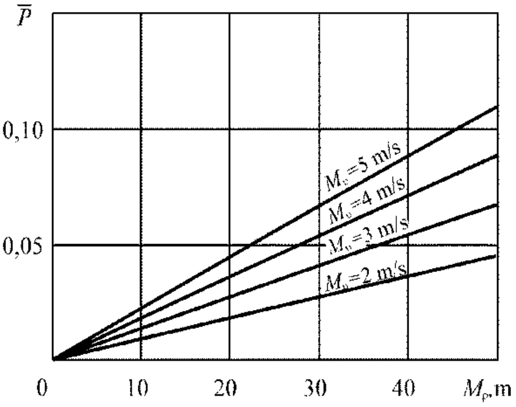


Fig. 1. The probability dependence of a vessel encountering an anomalous wave as a function of its characteristics [2]

Researchers emphasize that between 1969 and 1994, 22 supertankers were lost due to the impact of anomalous waves [1, 3]. Thus, we can draw a conclusion that the impact of anomalous waves on vessels is one of the causes of their disappearance and destruction. Encounters with such waves can lead not only to the loss of ships due to loss of strength or stability, but also to serious damage, resulting in their decommissioning and unscheduled repairs.

For example, the Queen Elizabeth 2 encountered a 29-meter wave during Hurricane Luis in the North Atlantic in September 1995. According to the master, the wave “came out of the darkness” and “looked like the White Cliffs of Dover” [4]. The ocean liner was reported to have attempted to “ride” the near-vertical wave to avoid sinking.

Figure 2 shows the effects of anomalous waves on the Norwegian tanker Wilstar in the Agulhas Current [1, 5].

Fig. 2. Damage to the bow of a large vessel caused by rogue waves

The cruise ships MS Bremen and MS Caledonian Star, both registered in the Bahamas, encountered 30-meter anomalous waves in the South Atlantic in 2001 [4]. The bridge glazing on both vessels was broken, and all electrical power and instruments were disabled.

To prevent the catastrophic impact of anomalous waves on seagoing vessels, it is advisable, whenever possible, to avoid areas with a high risk of anomalous wave generation. Such areas include, for example, the Agulhas Current zone off the coast of Africa. However the difficulty to implement this approach consists in the fact that the fundamental possibility of such waves occurring exists practically in all seas and oceans [1].

Anomalous waves have been recorded not only in the Pacific, Indian, and Atlantic Oceans, but also in relatively limited waters such as the Black and North Seas. Therefore, it is necessary to forecast the occurrence of anomalous waves using specialized methods, which, however, are not yet fully ready for practical application. One method is based on the modulation instability index (BFI), which characterizes favorable conditions for the occurrence of anomalous waves. Data on this index is currently being provided by weather forecasting centers [6] but its use is connected with difficulties and intensive research is currently underway in this area.

A method [2] can also be used to assess the likelihood of ships encountering anomalous waves. This method allows to assess the risk of this extreme situation using satellite-based ocean surface scanning data.

Figure 3 shows the results of wave height measurements taken from the Draupner platform. It can be seen that two troughs are located near the highest wave crest. However there are some cases when the depth of the trough is significantly greater than in the case presented.

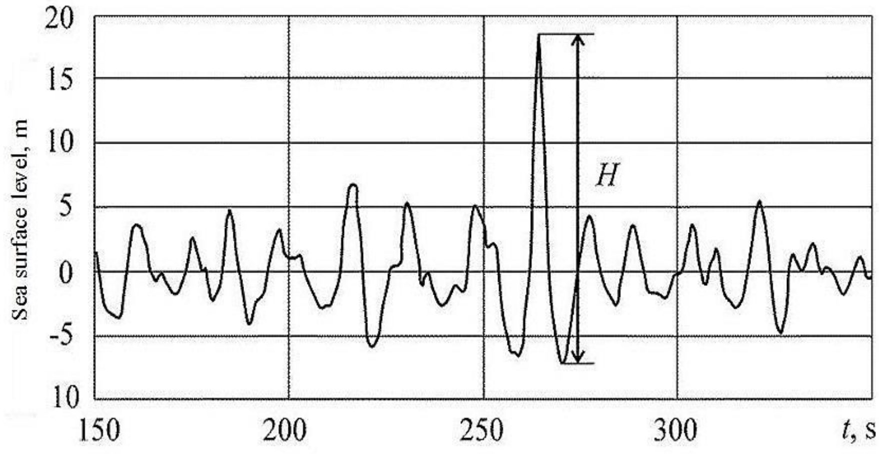


Fig. 3. Results of "New year wave" measurements from the Draupner platform [1]

In view of the above, the development of a computational methodology for modeling vessel interaction with an anomalous wave is of significant practical interest, as presented in this article. Two scenarios of vessel-wave interaction are considered: in the first case, the vessel initially encounters the trough of the anomalous wave (the vessel's passage through a "hole" in the sea), while in the second, it encounters the crest. This issue is discussed in more detail in the next section of the article.

A series of studies conducted by the author, aimed at studying the hydrodynamic forces acting on the bows of traditionally designed vessels, has shown that as the bow digs in a wave, normal hydrodynamic pressure develops on the deck, which results in a reset of the metacentric height, a hydrodynamic heeling moment leading to vessel capsizing, and a transverse force leading to vessel rotation. When interacting with abnormal waves, these forces increase significantly, ultimately leading to the vessel's demise due to loss of stability or strength. In the latter case, the bow may be torn off due to the additional bending moment generated by the hydrodynamic force, or the stern may break free from the water when the vessel pitches forward in the wave, or the hull may break into three pieces.

To eliminate the negative effects associated with traditional bow designs, the author has developed a new bow design [7] that is free of these disadvantages (Fig. 4). The following notations are used in the figure: *1* – main section of the bow; *2* – bulb attachment; *3* – transition section of the bow. In the proposed design, both the main section of the bow and the bow bulb are formed as straight circular cylinders with parallel axes.

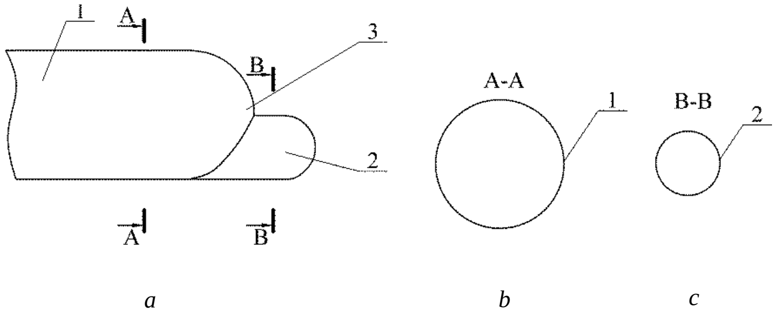


Fig. 4. Bow design reducing hydrodynamic loads:
a – general view of the bow; *b* – cross-section of the main hull; *c* – cross-section of the bow bulb

When the bow of this design digs in a wave, a restoring hydrodynamic moment develops on it (rather than a heeling moment, as with a traditional design). Furthermore, the magnitude of the lateral hydrodynamic force tending to turn the vessel is significantly reduced, as is the normal pressure that zeroes the metacentric height.

Research methods

We will model the dynamics of a vessel exposed to an anomalous wave using the computational methodology presented in [8]. This methodology is based on a system of longitudinal motion equations [9], modified to account for the specific interactions of a vessel with a wave when its bow is digged into the water [8]. We will limit our consideration to the case where the vessel is moving against a head-on wave that we will assume to be two-dimensional. Figure 5 shows the profile of the anomalous wave against the background of surrounding waves, obtained from satellite scanning of the ocean surface [1]. As the figure shows, the waves are irregular, which somewhat complicates the modeling of the vessel's dynamics.

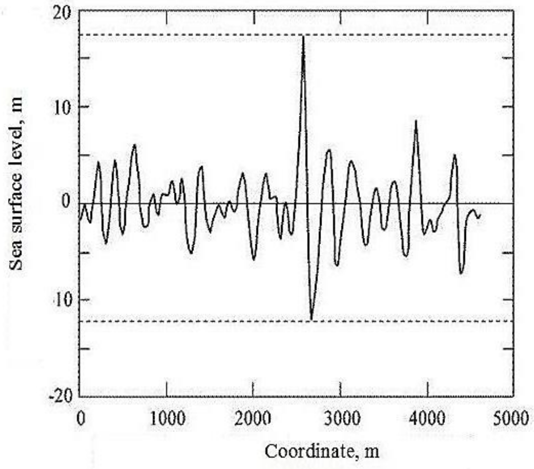
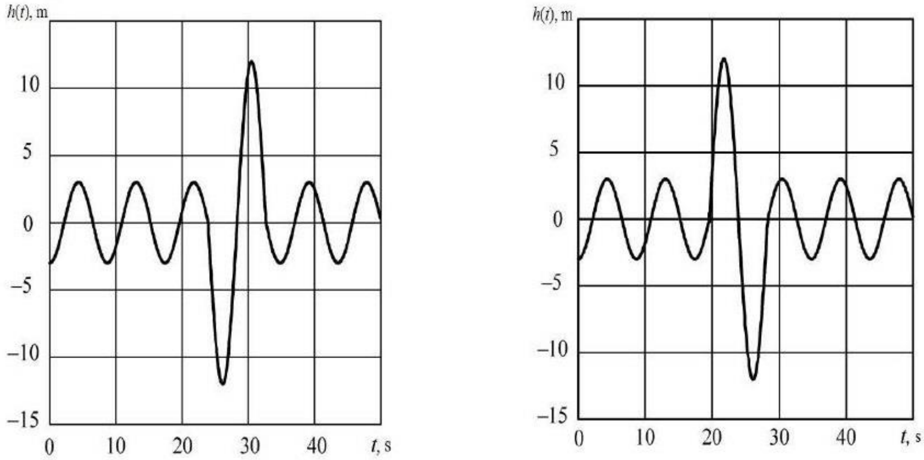


Fig. 5. Results of anomalous wave measurements [1]

To simplify the analysis in this article, we will study the vessel's dynamics under regular wave conditions, against which a single wave of anomalous height appears (Fig. 6).



a *b*

Fig. 6. Calculated wave profiles: *a* – the vessel initially encounters the trough of the anomalous wave; *b* – the vessel initially encounters the crest of the anomalous wave

It can be seen that the calculated wave used to model the vessel's dynamics (Fig. 6) generally reflects the nature of the water level change during the formation of an anomalous wave, while ignoring the irregular nature of the surrounding waves. The influence of wave irregularity on the dynamics of the vessel's interaction with the external environment during the occurrence of anomalous waves can be considered using the same approaches, taking into account professor S. N. Blagoveshchensky's recommendations for modeling vessel dynamics in irregular waves [10].

In accordance with the above, we will consider the behavior of a tanker with a length of L = 168 m under regular oncoming waves, initially assuming a wavelength λ equal to the vessel's length. Let's denote the wave height for a regular wave as h. We will model a situation where, among waves of the same height h, a single anomalous wave of height H appears. The corresponding wave profile is shown in Fig. 6 for the case of H / h = 4 and h = 6 m. As noted above, we will consider two scenarios of vessel interaction with the anomalous wave. In the first case, the vessel first encounters the trough of the anomalous wave and then the crest; in the second case, the vessel is initially impacted by the crest of the anomalous wave. To evaluate the effectiveness of the proposed design [7], we will conduct a comparative analysis of the behavior of vessels with a traditional and new bow shape.

It should be noted that other scenarios of vessel interaction with an anomalous wave are also of significant practical interest, in particular, the impact of such a wave on the side of the vessel [11]. However this issue should be the subject of a separate independent study and is not further considered in this paper.

Results of modeling the interaction of a vessel with a traditional bow with an anomalous wave approaching from the wave trough (passing through a "hole" in the sea)

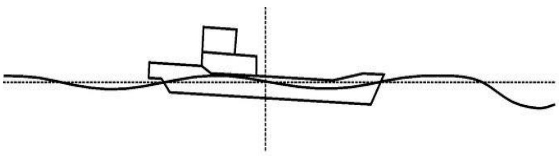
Let's first consider the case where the vessel's interaction with the anomalous wave begins with its impact with the trough (Fig. 6, *a*). The calculation results are presented in Fig. 7-9. Fig. 7 shows the change in the vessel's position relative to the rough sea surface. It can be seen that as a result of the bow of the vessel digging itself in the water under the influence of the anomalous wave, the stern of the vessel practically emerges from the water (Fig. 7, *h*–*k*). This leads to a sharp reduction in the supporting forces in the area of the stern end, which can lead to its separation, since the loss of two or three theoretical frame spacings leads to the occurrence of a significant bending moment in the vessel's hull [12]. In this case, the method presented in [12] can be used to calculate the overall strength.

Figure 8 presents the calculated results of the hydrodynamic force P_N acting on the bow end during the interaction of the vessel with an anomalous wave. The results are reduced to dimensionless form by dividing the above force by the vessel's displacement *D*. The figure presents a series of graphical dependencies for a range of *H* / *h* values, i.e., for various values of the ratio of the anomalous wave height to the height of other waves.

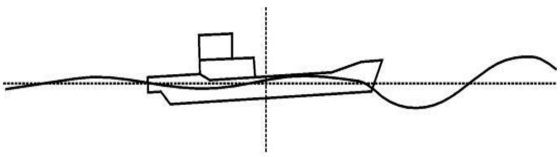
It is evident that the abnormal wave height has a significant impact on the magnitude of the hydrodynamic force. Thus, the maximum hydrodynamic force at *h* = 4 m is approximately $\overline{P}_N = 0.11$ (Fig. 9), and when the wave height doubles (Fig. 8), the hydrodynamic force reaches a value of $\overline{P}_N = 0.43$, i.e., increases almost fourfold. It should be noted that with such a load acting on the vessel's deck at the bow, a drop in the transverse metacentric height and a sharp transformation of the vessel's static stability diagram are observed [13, 14]. As shown in [13, 14], the vessel is unable to withstand the effect of such loads, even if its stability complies with regulatory requirements [15]. Therefore, if a vessel encounters the extreme situation described above, involving the impact of an abnormal wave, it will be destroyed either by loss of strength or by capsizing.

Summary graphs are presented in Fig. 9, which shows the maximum values of the hydrodynamic force generated by the impact of an abnormal wave on a vessel.

As shown in Fig. 9, doubling the wave height *h* from 4 to 8 m leads to a fourfold increase in hydrodynamic pressure $\overline{P}_N$ from 0.11 to 0.43 at *h* / *H* = 5. For *h* / *H* = 4, the hydrodynamic force $\overline{P}_N$ also increases almost fourfold, i.e. from 0.074 to 0.28. For other values of *h* / *H*, a more significant increase is observed, and for *h* / *H* = 1, no hydrodynamic force is generated at the bow due to the lack of burying.



a



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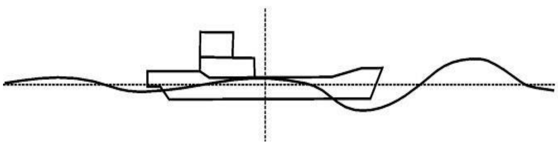

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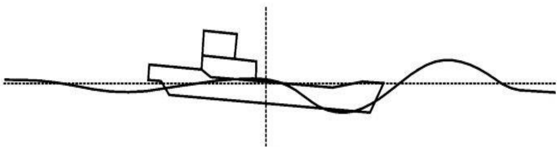

d

Fig. 7. The change in the position of the vessel when interacting with an anomalous wave over time *t* at *h* = 8 m and *H* / *h* = 4: *a* – 15 s; *b* – 20 s; *c* – 22 s; *d* – 23 s

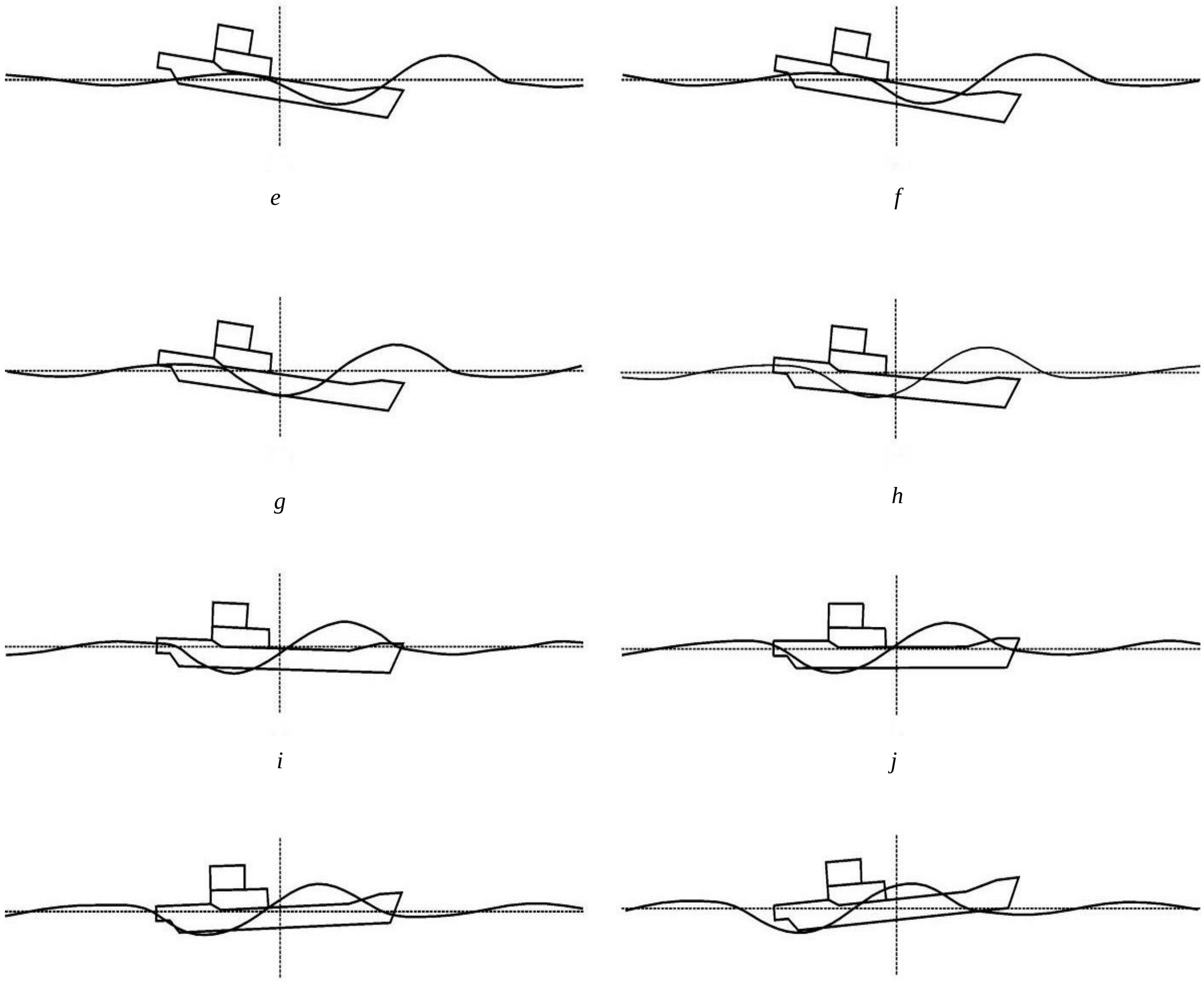

Fig. 7 (ending). The change in the position of the vessel when interacting with an anomalous wave over time *t* at *h* = 8 m and *H* / *h* = 4: *e* – 24 s; *f* – 25 s; *g* – 26 s; *h* – 27 s; *i* – 28 s; *j* – 28.5 s; *k* – 29 s; *l* – 30 s

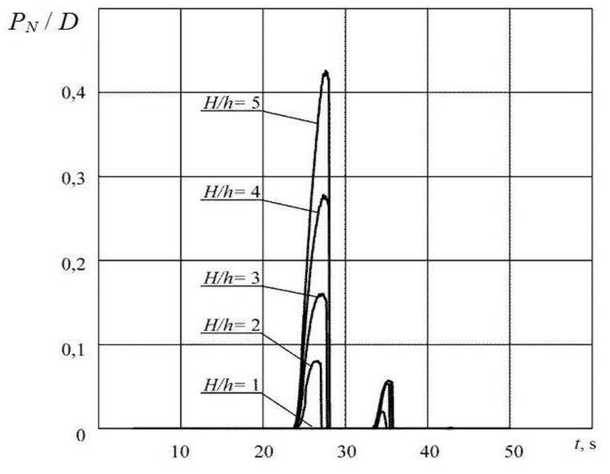

Fig. 8. Hydrodynamic force acting on the vessel's deck at the bow of a traditional design when interacting with an anomalous wave at *h* = 8 m passing through a “hole” in the sea

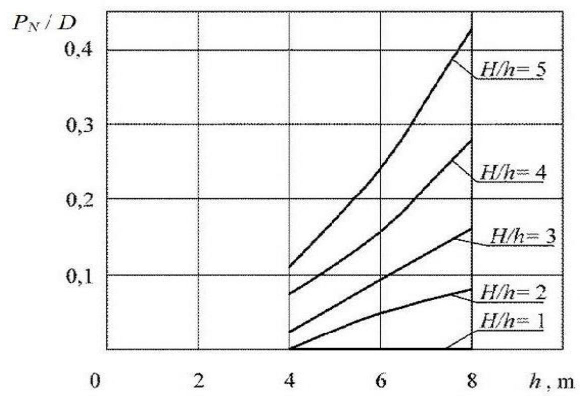

Fig. 9. Dependence of maximum hydrodynamic force values on wave height for a vessel with a traditional bow passing through a “hole” in the sea

Results of modeling the interaction of a vessel with a traditional bow design with an anomalous wave when the vessel approaches from the wave crest

Now let us consider the case where the vessel primarily interacts with the crest of the anomalous wave (Fig. 6, *b*). The vessel's positions in the wave are shown in Fig. 10.

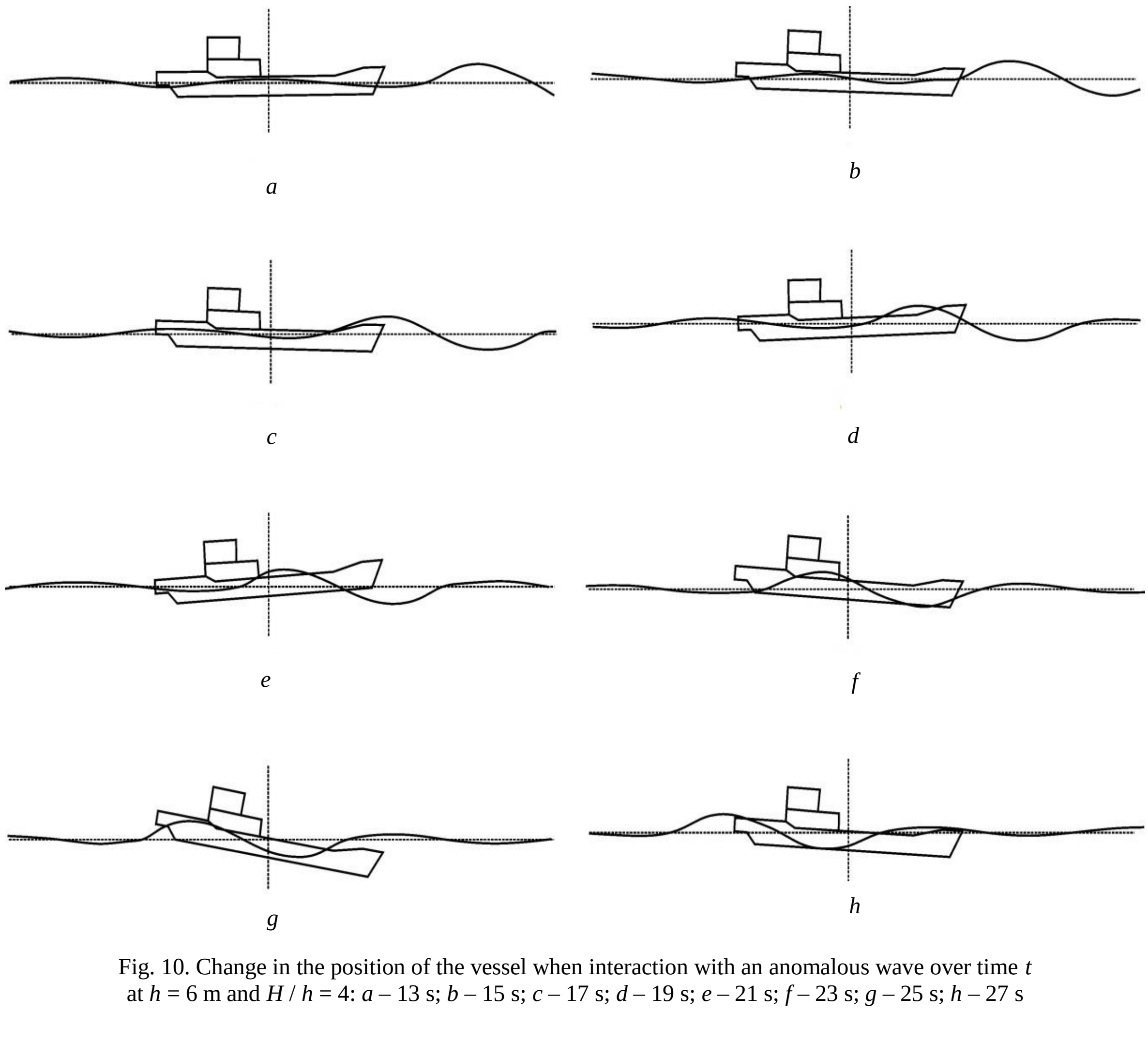

Fig. 10. Change in the position of the vessel when interaction with an anomalous wave over time t at h = 6 m and H / h = 4: *a* – 13 s; *b* – 15 s; *c* – 17 s; *d* – 19 s; *e* – 21 s; *f* – 23 s; *g* – 25 s; *h* – 27 s

Fig. 11, 12 present the calculated hydrodynamic forces for the vessel's interaction with an anomalous wave. It is evident that this scenario of interaction with an abnormal wave, in which the vessel first hits its crest, results in the maximum hydrodynamic force acting on the bow being somewhat lower than for the case considered in the previous section of the article. Thus, at H / h = 5, the maximum hydrodynamic deck pressure $\overline{P}_N$ decreases from 0.43 to 0.23, i.e., by almost half. For H / h = 4, the maximum hydrodynamic deck pressure $\overline{P}_N$ decreases from 0.28 to 0.16, and for H / h = 3, from 0.16 to 0.11.

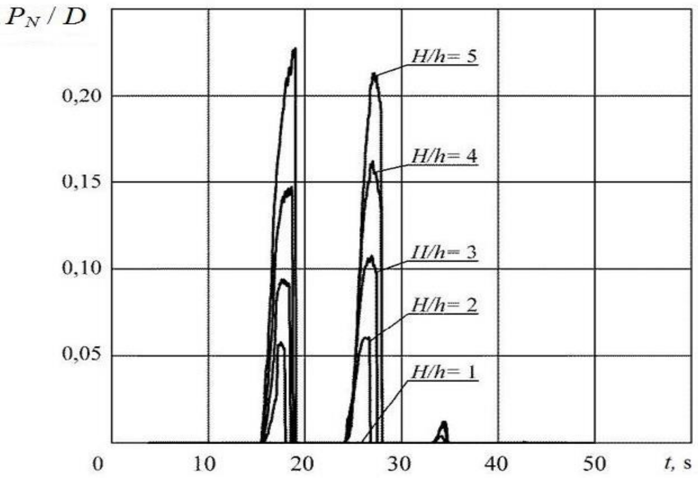

Fig. 11. Hydrodynamic force acting on the vessel's bow of a traditional design deck during interaction with an anomalous wave at h = 8 m when the vessel approaches from the wave crest

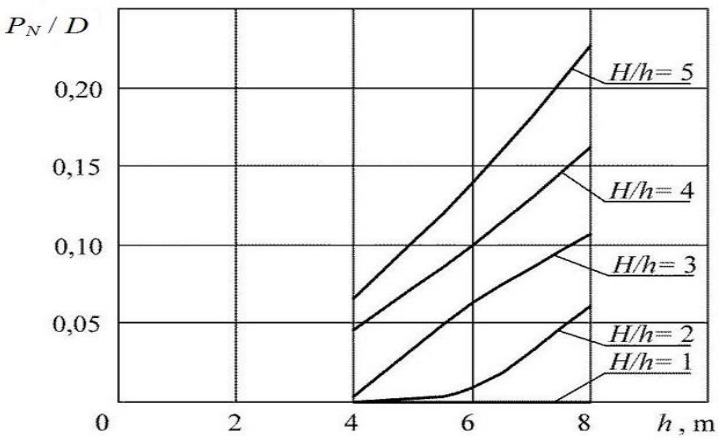

Fig. 12. Dependence of maximum hydrodynamic force values on wave height for a vessel with a traditional bow when the vessel approaches from the wave crest

As can be seen from Fig. 11, when the vessel enters an abnormal wave from the crest, two peak values of hydrodynamic force are observed, approximately equal in magnitude. This is explained by the fact that after passing the crest and trough of the anomalous wave, the bow buries itself in the crest of the next wave (Fig. 10, *g*). In this case, the maximum trim angle of the vessel increases slightly, compared to what occurs when the vessel passes an anomalous wave from its trough.

Nevertheless, despite the presence of two peaks and a slight increase in the vessel's maximum trim angle, a significant decrease in the hydrodynamic force is observed. This suggests that this scenario of vessel interaction with an anomalous wave poses less of a hazard than the passage of an anomalous wave from the side of a “hole” in the sea; however, even in this case, the vessel may be destroyed due to loss of strength or stability.

To assess the overall strength of a vessel's hull under the influence of an anomalous wave, one can use the methodology [12, 16], according to which, in the case of the stern end emerging from the water, the bending moment at the midships is calculated as for a rigidly clamped console loaded with a weight load. For theoretical frames that are not completely out of the water, residual support forces must be taken into account.

The analysis has shown that when the bow is entangled in an anomalous wave, bending moments arise in the vessel's hull that significantly exceed those determined using traditional approaches [17, 18]. This makes it impossible to assess the overall strength of the vessel's hull in such a situation using approaches based on the vessel's positioning in the design wave. It should be noted that the bending moment peak is located approximately one-third of the vessel's length from the bow perpendicular. Moreover, according to [17], the hull cross-sectional characteristics in this region begin to decrease compared to the midship section. This circumstance indicates the possibility of the vessel's bow being torn off during its interaction with the anomalous wave.

Improving navigation safety in conditions impacted by abnormal waves

As noted above, one way to improve vessel safety when exposed to abnormal waves is to use design solutions aimed at reducing the hydrodynamic forces and moments acting on the vessel during wave interacttion [7, 13], and, in particular, the new bow design shown in Fig. 4. It should be noted that these design solutions were developed to improve vessel safety in storm conditions without taking into account the impact of abnormal waves, so it is of interest to conduct a comparative analysis of their effectiveness in similar conditions.

Let us consider the effectiveness of the new streamlined bow design (Fig. 4) when a vessel interacts with abnormal waves. A previous study [19] showed that, in conditions of developed head seas, this design allows for a significant reduction in the hydrodynamic forces and moments acting on the bow when it burrows into the wave. The modeling results are presented in Fig. 13, 14.

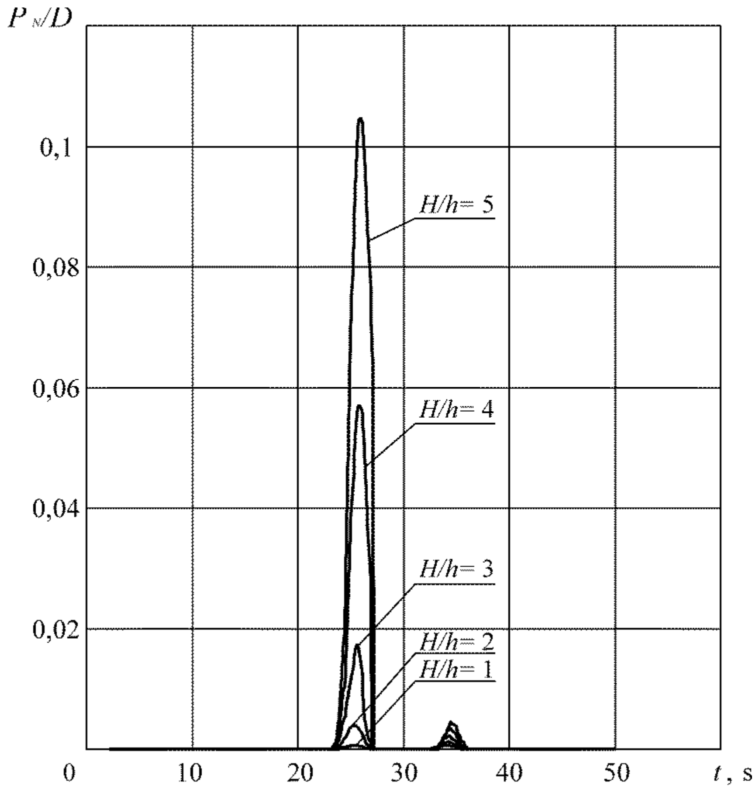

Fig. 13. Hydrodynamic force acting on the deck of a vessel at the bow of a new design [7] when interacting with an anomalous wave at h = 8 m

It is evident that the use of the new bow design [7] allows for a significant reduction in the magnitude of hydrodynamic effects. Thus, for the highest wave height studied, a nearly fourfold reduction in hydrodynamic force $\overline{P}_N$ is observed, from 0.43 to 0.105. At lower wave heights, the reduction in hydrodynamic load is even more significant. Thus, at h = 8 m and H / h = 3, the indicated force $\overline{P}_N$ decreases from 0.16 to 0.017, i.e. by almost an order of magnitude.

It should also be noted that when the water flow past the bow [7] when it is digged into a wave, the hydrodynamic moments developing on it are righting at virtually all heel angles and heading angles. This means that with this design, the hydrodynamic moment will tend to return the vessel to an upright position, which is a significant advantage compared to a traditional design.

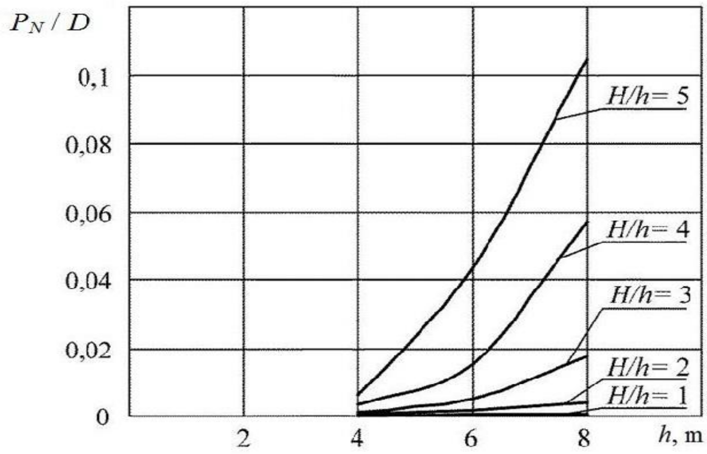

Fig. 14. Dependence of maximum hydrodynamic force values on wave height for the new bow design

Thus, the effect of using the new design is quite significant; however, with a large anomalous wave height, the hydrodynamic effects on the bow remain quite significant. Furthermore, only the scenario of an anomalous wave impacting the bow while sailing in headwater waves was considered above.

At the same time, the impact of an abnormal wave on the side of a vessel also poses a significant risk, potentially causing it to capsize. Therefore, even if ship designs are improved to increase their ability to withstand abnormal waves, wave forecasting capabilities will play a crucial role in minimizing the likelihood of ships encountering them.

Conclusion

1. To improve navigation safety, it is necessary to improve wave forecasting capabilities.

2. The likelihood of abnormal waves and ship encounters with them is quite high, and ignoring their existence when designing ships and other marine equipment, as well as when assessing navigation safety, can lead to serious consequences. However, the possibility of interaction with abnormal waves is currently not considered when designing ships. The issue of taking into account the impact of such waves when assessing the strength and stability of vessels is being considered by specialists in a number of countries; however, it is still far from being fully resolved. Accordingly, the current strength and stability requirements of classification societies do not include procedures for verifying the safety of vessels when exposed to such waves.

3. A methodology is proposed for simulating the impact of an abnormal wave on a vessel when the vessel is moving against the waves. It is noted that for a vessel with a traditional bow design, the magnitude of the hydrodynamic forces is sufficient to capsize the vessel or destroy its hull.

4. It is shown that the greatest danger is posed by the interaction of a vessel with an abnormal wave when it first hits its trough and then burrows into the wave crest (the vessel's passage through a “hole” in the sea).

5. The dynamics of the interaction of a vessel with a new bow design [7] with an abnormal wave are examined, and the effectiveness of this design is demonstrated. In the considered range of wave heights, a load reduction of four times or more is observed compared to a traditional design.

6. The developed model allows one to describe the vessel's dynamics when encountering an abnormal wave, which, together with the apparatus for predicting a vessel's encounter with such a wave [2], can be used in the overall strength and stability control units of the onboard intelligent system [20] to develop optimal vessel control solutions for improving its safety.

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