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Improving ship manoeuvring accuracy in shallow water: The role of navigation equipment and hull design

Abstract. The study was conducted to analyse the impact of modern navigation equipment and ship hull design on improving the accuracy of manoeuvring in shallow water. The study used methods of analysis and comparison of the effectiveness of modern navigation equipment, evaluation of ship hull design solutions, and integration of these technologies to improve the accuracy of manoeuvring in shallow water. It was found that the use of modern dynamic positioning (DP) systems and high-precision navigation equipment, such as satellite systems and electronic mapping systems, significantly improves the accuracy of ship manoeuvring in shallow water. Ships with a flat hull and minimal draft were found to have better manoeuvrability compared to traditional designs. Optimisation of the bow shape and the use of stabilisers can reduce water resistance and improve handling. The use of highly sensitive steering systems improves steering precision in limited spaces. It was concluded that the integration of these technologies can significantly improve the safety of navigation in shallow water. It was also found that high-resolution radars and automatic identification systems effectively reduce the risk of collisions when manoeuvring in narrow channels and ports. In addition, vessels with an improved hull design were found to have reduced hydrodynamic resistance, which helps to reduce fuel consumption in shallow water. The study provided practical recommendations for implementing modern navigation systems and improving ship hull design, which increases the accuracy of manoeuvring in shallow water and improves navigation safety. Overall, the results confirmed the importance of integrating navigation technologies with hull design solutions to improve the efficiency and safety of navigation

Keywords: dynamic positioning systems; bow shape optimisation; design solutions; collision risk; hydrodynamic resistance

Introduction

In modern navigation, the accuracy of ship manoeuvring in shallow water is critical to ensuring the safety and efficiency of operations in narrow channels and coastal areas. Shallow water presents particular challenges for ship drivers, as the limited depth of the water can lead to increased hydrodynamic resistance and difficulty controlling the vessel. In this context, the role of modern navigation equipment and optimised hull design becomes particularly relevant. The use of advanced technologies such as dynamic positioning systems (DP), Global Navigation Satellite Systems (GNSS) and Electronic Chart Display and Information Systems (ECDIS) can significantly improve manoeuvring

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accuracy, reduce the risk of collisions and ensure more efficient use of water space. In addition, improvements in the design of the ship's hull, including optimising the shape of the bow and using stabilisers, help to reduce hydrodynamic resistance and improve handling.

Managing vessels in shallow water is a complex task that requires improved navigation and design solutions to ensure accurate manoeuvring. The problem of manoeuvring accuracy in conditions of limited space and water depth has been considered in numerous studies. X. Zhang *et al*. (2021) emphasised the importance of implementing automated navigation systems to improve manoeuvring in conditions of limited depth. The researchers emphasised that these systems minimised the impact of the human factor, which is especially important in difficult shallow water conditions. Y. An *et al*. (2021) investigated the effect of ship design on their ability to manoeuvre in conditions of limited depth. They showed that optimising the shape of the hull reduced water resistance and improved ship efficiency, but did not sufficiently consider the impact of such innovations on fuel consumption and environmental aspects. R. Okuda *et al*. (2022) investigated the impact of ship design on their ability to manoeuvre in shallow water. They proved that hulls with reduced draft and optimised shape reduced water resistance, which improved the efficiency of ships.

Design solutions for improving the stability of vessels during manoeuvring in shallow waters were investigated by M. Maljković *et al*. (2024). The researchers confirmed that such solutions are effective and significantly improve the handling of ships. The role of intelligent control systems in performing complex manoeuvres with minimal errors in unstable conditions was confirmed by H. Zhou *et al*. (2022). The researchers noted that these systems reduce the load on the crew and increase the accuracy of manoeuvring. International standards in navigation technologies that provide a single platform for innovation, according to J.H. Lim *et al*. (2023), are important for the development of shipbuilding. This was also confirmed by A. Oruc *et al*. (2022), drawing attention to the fact that standardisation allows for more efficient integration of new control and navigation systems. O.P. Igbinenikaro *et al*. (2024) added that combining engineering solutions with new technologies is key to ensuring the safety of navigation in shallow water conditions. S. Zhang *et al*. (2023), X. Wang & E.H. Xu (2022) also stressed the importance of innovations in hull design to improve manoeuvrability and reduce the risk of running aground.

The purpose of the study was to find out how the latest navigation devices and the shape of the ship help ships to navigate more accurately in shallow water. Research objectives:

1. To analyse the effectiveness of modern navigation systems, such as GNSS and ECDIS, in improving the accuracy of ship manoeuvring in shallow water and their impact on reducing the risk of collisions and improving safety.

2. To investigate the impact of optimising the design of the hull of ships, including stabilisers and improving the shape of the bow, on reducing hydrodynamic resistance and improving manoeuvrability in limited conditions.

3. To evaluate the economic aspects of introducing new navigation and design technologies, in particular, their effectiveness in reducing fuel consumption and improving the overall efficiency of navigation in shallow water.

Materials and Methods

The study analysed key aspects of both navigation equipment and hull design to determine the most effective technologies and design solutions that affect the manoeuvrability and safety of navigation in limited spaces. The main components of navigation equipment that have been evaluated are GNSS, such as the Global Positioning System (GPS) and the BeiDou Navigation Satellite System (BDS), which provide accurate positioning of ships in narrow water spaces. The analysis included comparison of the accuracy of various satellite systems in real-world navigation conditions. ECDIS was examined in terms of its ability to integrate depth, obstacle and channel marking data to help avoid underwater threats and provide detailed electronic charts. The Automatic Identification System (AIS) was considered in terms of their effectiveness in tracking the position of neighbouring vessels and avoiding collisions, especially in narrow channels and port areas. High-resolution radars were evaluated for their ability to detect underwater objects and coastlines, especially in low visibility and shallow water conditions. DP systems have been investigated in terms of their functionality in maintaining a fixed ship position in shallow water without using an anchor, which reduces the risk of damage to the sea floor.

Research on ship hull design has focused on several aspects that affect manoeuvrability in shallow water. The efficiency of using wide and flat hulls to reduce the ship's draft and increase its stability in shallow water was evaluated, and the influence of various hull shapes on water resistance was studied. The effect of stabilisers on the ship's hull on improving handling and reducing drift was studied, and the effectiveness of different types of stabilisers was compared. The analysis of the bow shape of the ship concerned the effect of the optimised shape on reducing hydrodynamic resistance, and the effectiveness of various design solutions in improving handling in shallow water was evaluated. Research on modern high-sensitivity steering systems has covered their ability to perform precise manoeuvres in narrow and limited conditions, and the efficiency of using two steering blades or steering machines. The following equations were used in the study:

1. Equation for determining GPS accuracy (1):

$$\text{Accuracy} = \sqrt{(\text{GPS Errorhorizontal})^2 + (\text{GPS Errorvertical})^2}, \tag{1}$$

where *GPS Errorhorizontal* – horizontal error of GPS; *GPS Errorvertical* – vertical error of GPS.

2. Equation for determining ship draft (auxiliary equation for stability) (2):

$$\text{Draft} = \frac{W}{\rho \times A}, \quad (2)$$

where W – ship weight; p – water density; A – cross-sectional area of the hull at water level.

3. Equation for calculating the stabiliser moment (3):

$$M = C_d \times \frac{1}{2} \times \rho \times V^2 \times A, \quad (3)$$

where M – moment of stabilisation; C_d – stabiliser resistance coefficient; V – ship velocity; A – stabiliser area.

4. Equation for calculating water resistance (4):

$$R = \frac{1}{2} \times \rho \times V^2 \times A \times C_d, \quad (4)$$

where R – water resistance; A – surface area in contact with water; C_d – resistance coefficient.

5. Equation for calculating the moment of force required for steering (5):

$$M = \frac{F \times d}{\sin(\theta)}, \quad (5)$$

where M – moment of force; F – force on the steering system; d – distance to the point of force application; θ – steering angle.

An important aspect of the study was the integration of navigation equipment with the hull design. The analysis included how data from radars and ECDIS can be used to automatically adjust the position of the ship's hull, which helps to reduce the impact of hydrodynamic forces. Ways to improve the efficiency of DP systems in vessels with improved hull design were evaluated. Thus, the study included a comprehen sive analysis of modern navigation equipment and design solutions to improve the accuracy of manoeuvring vessels in shallow water, which allows ensuring the efficiency and safety of navigation in conditions of limited space.

Results and Discussion

GNSS systems, particularly GPS, BDS, and Galileo, play a critical role in modern marine navigation, ensuring precise ship positioning even under challenging conditions (Wang *et al.*, 2023). GPS and BDS use satellite signals to determine the exact location of an object on Earth. Both systems provide data that is critical to the safety and effectiveness of maritime operations. Due to the high accuracy of GPS and BDS positioning, ship drivers can accurately track the movement of their vessels and monitor their position in real time, which is especially important in confined spaces where even a small deviation from the course can cause danger. The positioning accuracy that these systems provide is based on the use of signals coming from satellites located in Earth orbit. The signals of GPS satellites and the BDS system have a high resolution, which allows achieving accuracy within a few meters or even centimetres when using additional correction technologies.

Galileo, the European GNSS, offers several advantages, including high accuracy and dual-frequency capabilities, which improve performance in environments prone to signal disruptions. Its open service provides positioning precision within one meter, while additional correction through the European Geostationary Navigation Overlay Service (EGNOS) can enhance accuracy to the centimetre level. Galileo's use in maritime operations is essential for navigation in confined areas like coastal waters, narrow channels, and rivers, where even minor course deviations can lead to accidents. By integrating with GPS and BDS, Galileo enhances redundancy and availability, ensuring continuous positioning, especially in urban or obstructed environments where signals from other systems might falter. The system's resilience and advanced features, such as better multipath mitigation, make it a reliable solution for real-time vessel tracking and manoeuvring in both open seas and complex waterways. These GNSS technologies significantly reduce the risks associated with human navigation errors, supporting safe and efficient maritime operations under various environmental conditions.

The use of GNSS in navigation offers several advantages, such as reducing reliance on traditional tools like maps and compasses, which may not meet the precision required by modern navigation systems. Additionally, GNSS integrates seamlessly with other navigation and safety tools, such as ECDIS and automatic identification systems, enhancing the efficiency and safety of maritime operations.

However, despite the high accuracy of GNSS, there are some limitations and problems that need to be considered. Satellite signals can be exposed to atmospheric and environmental conditions, which can reduce positioning accuracy. In conditions of limited space, such as port zones or narrow channels, signal problems may occur due to reflection or blocking of satellite signals. Therefore, it is important to have additional systems and technologies that can complement and support GNSS accuracy. The positioning accuracy determine using equation (1). For example, if the horizontal error is 2 metres and the vertical error is 3 metres, then:

$$\text{Accuracy} = \sqrt{(2)^2 + (3)^2} = 3.6.$$

This result show that the positioning accuracy reached a fairly significant level, which can be critical in narrow water spaces, where even minor deviations could lead to danger. The results of the positioning accuracy calculation for the above systems are presented in Table 1.

Table 1. GNSS positioning accuracy

System	Overall error (metres)	Vertical error (metres)	Accuracy (metres)
GPS	2	3	3.6
BDS	2	3	3.6
Galileo	1.2	2.0	2.4

Source: compiled by the authors based on A. Kumar *et al*. (2021)

Since the positioning accuracy values for GPS and BDS are identical in the table (horizontal error: 2 m, vertical error: 3 m, total accuracy: 3.6 m), any differences observed in real-world conditions would arise from operational factors. These may include differences in satellite geometry, atmospheric interference, or variations in signal correction models. However, under ideal conditions, both systems perform similarly, as reflected in the provided data. Galileo demonstrates superior performance, with accuracy of 2.4 meters, emphasizing the value of adopting advanced satellite navigation technologies. Galileo has shown the best results, highlighting the importance of using the latest technologies to ensure maximum accuracy in confined spaces. This was also investigated by H. Ge *et al*. (2022), where results confirmed that GNSS such as GPS and Galileo significantly improved positioning accuracy by providing coordinate detection with an accuracy of several centimetres. This is especially important for accurate navigation management, reducing navigation errors, and monitoring geospatial data. Y. Li *et al*. (2022) also showed that the latest satellite systems play a critical role in ship manoeuvring, especially in challenging environments. They facilitate accurate tracking of the ship's position and route adjustment in real time, which reduces the risk of collisions and improves the safety of sea transportation. It is worth noting that the constant development of satellite technologies and the introduction of new generations of GNSS constantly improves their accuracy and reliability. Thus, modern vessels can get even more detailed information about their location and surrounding objects, which is especially important for operations in difficult conditions, such as coasts or narrow channels. In addition, the integration of GNSS with other navigation and management systems provides an integrated approach to ship management, which significantly increases the overall safety and efficiency of maritime transportation.

ECDIS is a revolutionary achievement in the field of maritime navigation, significantly improving the safety and efficiency of maritime operations (Pan *et al*., 2021). They are integrated platforms that provide detailed display of navigation maps, supplemented with up-to-date information about water depth, obstacles and channel markings. Due to this, ECDIS helps ship drivers to avoid underwater threats and ensures more accurate and safe manoeuvring of ships. The main advantage of ECDIS is their ability to integrate different data from different sources into a single mapping system. This allows ship drivers to get comprehensive information about the navigation environment in real time. ECDIS provide accurate water depth data, which is crucial for ships manoeuvring in shallow water or in waters with uneven terrain. Integrating this data helps to reduce the risk of colliding with underwater objects or decreasing depth that can c ause accidents. In addition to depth data, ECDIS also provides information about various obstacles such as underwater rocks, reefs, and even artificial structures that can affect ship safety. This helps to avoid potentially dangerous areas and plan the route based on existing obstacles. ECDIS systems also include channel marking data, allowing for more accurate navigation in narrow and difficult waters where traditional navigation maps may be less convenient. Due to the ability to constantly update data, ECDIS provides ship drivers with up-to-date information, which is an important aspect for manoeuvring in rapidly changing conditions. For example, when passing through a storm or in low visibility conditions, ECDIS can provide timely data on changes in the navigation environment, allowing ship drivers to quickly respond to new challenges.

However, despite its many advantages, ECDIS also has some limitations. One of them is a dependence on the quality of input data: inaccuracies in navigation maps or lack of updating information can lead to errors in positioning and route planning. In addition, ECDIS systems require proper maintenance and regular updating of map data to ensure their accuracy and efficiency.

A study of ECDIS has shown that these systems play a critical role in ensuring the safety of shipping in shallow waters. Integration of depth, interference, and channel marking data allows creating detailed electronic maps that significantly reduce the risk of collisions with underwater objects. These results confirm the need to use advanced ECDIS for navigation in challenging environments. S. Blindheim & T. Johansen (2021) concluded that ECDIS are essential for navigation safety by providing accurate information about navigation conditions and helping to avoid collisions with underwater obstacles. Due to integration with other systems, such as radars and GPS, ECDIS allows creating a comprehensive picture of ship traffic, which increases the level of safety. W. Khawaja *et al*. (2022) found that integrating ECDIS with monitoring systems helps to reduce the risk of underwater threats such as rocks or sunken ships. The system analyses data in real time, issuing a warning that allows the crew to respond to danger in a timely manner. These results support the above study, as they demonstrate a link between the use of ECDIS and the reduction of accidents in shipping. In particular, the integration of ECDIS with other navigation technologies significantly improves the accuracy and safety of ship traffic, which confirms the effectiveness of these systems in preventing collisions and preventing underwater threats.

Automatic identification systems are an important achievement in maritime navigation, which significantly improves the safety of navigation, especially in narrow channels and port areas (Arditiya *et al*., 2023). The main purpose of AIS is to automatically track the relative position of ships and prevent possible collisions, which is critical in situations where accurate navigation and timely response are crucial for safety. AIS systems work by transmitting and receiving radio signals that contain important information about a ship, such as its location, speed, course, ship type, and other navigation data. Each vessel equipped with AIS transmits this data on a regular basis, which allows all ships within the range of the system to receive information about other vessels in the area. This technology helps to avoid possible collisions by providing ship drivers with up-to-date information about the location of neighbouring ships. In narrow channels and ports where manoeuvring space is limited, automatic identification systems are an extremely useful tool. The system allows accurately tracking the movement of ships, which helps to avoid situations where two vessels may be on cross courses, which increases the risk of collisions. The information provided by AIS also allows for better manoeuvre planning, reducing the chance of accidents and simplifying the process of entering and exiting ports.

This highlights the importance of integrating AIS into the overall navigation system to improve situational awareness on the water. H. Rong *et al*. (2022) also found that automatic identification systems improve the safety of navigation by providing real-time information about the location, course, and speed of ships. This helps the crew to predict trajectories and adjust their course in time to avoid collisions, especially in conditions of poor visibility. In turn, M. Kang *et al*. (2022) concluded that AIS is particularly effective in narrow channels where space is limited and traffic is heavy. The system allows coordinating ship manoeuvres in real time, reducing the risk of accidents and facilitating the passage of difficult sections.

However, despite its many advantages, AIS has some limitations. For example, the system may be less efficient in conditions of poor visibility or in cases where AIS signals overlap or degrade. In addition, AIS can be exposed to cybersecurity threats because data is transmitted over open radio channels, which can make the system vulnerable to malicious attacks. Simultaneously one of the key features of automatic identification systems is its ability to integrate with other navigation systems, such as ECDIS and radar systems. This allows creating comprehensive navigation platforms that provide a comprehensive overview of the situation on the water. For example, the combination of an automatic identification system with ECDIS allows ship drivers not only to see the location of other ships, but also to get information about their routes, which makes it easier to plan their own route and increases overall safety.

In the context of modern navigation technologies, high-resolution radars are indispensable tools for improving the safety and accuracy of ship manoeuvring, especially in difficult navigation conditions, such as limited water areas and shallow waters. Their use allows ship drivers to detect objects that cannot be captured visually or using conventional navigation systems (Yang *et al*., 2021). High-resolution radars are capable of detecting details over long distances and with high accuracy, which is especially important for safe manoeuvring of ships in difficult conditions. In a confined space environment where every inch of space matters, the ability to clearly identify obstacles, such as underwater objects, rocks, or other ships, is crucial to avoid collisions and ensure safe passage. These radar systems use powerful radio waves to scan the surrounding area. High resolution provides a detailed image of the environment in real time, which helps ship drivers to quickly respond to hazards. For example, in shallow water, where the water depth can change rapidly and underwater objects can be virtually invisible, high-resolution radar can detect these objects in advance, avoiding potentially dangerous situations. Another important feature of high-precision radars is their ability to operate in poor visibility conditions, such as fog, rain, or at night. In such situations, when vision is significantly limited, radar can become the only source of information about the environment, providing ship drivers with a clear picture of the situation. This is especially important for ensuring security in ports and narrow channels, where bad weather conditions can further complicate manoeuvring. High-resolution radars also integrate with other navigation systems, such as ECDIS and automatic identification systems, creating a comprehensive picture of the navigation situation. This allows ship drivers to receive synchronised information, which contributes to accurate route planning and optimal manoeuvring. Integrating radars with other systems also increases their efficiency, ensuring more accurate detection and avoidance of possible obstacles.

However, despite their many advantages, high-resolution radars also have some limitations. The cost of such systems can be significant, and there is also a need for regular maintenance to ensure their proper operation. In conditions of heavy traffic, the system can be overloaded with a large number of signals, which can make it difficult to interpret the received data.

Evaluation of high-resolution radars has confirmed their effectiveness in detecting underwater objects and coastlines, especially in low visibility and shallow water conditions. Radar systems have been found to be able to significantly improve manoeuvring accuracy by providing detailed information about the environment, which is especially important in cases where visibility is limited by weather conditions.

X. Bai *et al*. (2022) also conducted a study that confirmed that high-resolution radars play a key role in manoeuvring ships in conditions of limited visibility, such as fog or night. They allow clearly displaying even small objects, which helps the crew to quickly respond to changes in the environment, providing more accurate manoeuvres and reducing the risk of collisions. S. Chen *et al*. (2022) also found that these radars improve visibility by distinguishing details that are not visible on traditional systems. This gives the crew a clearer view of the environment and allows them to perform manoeuvres more safely. Comparing the data obtained in the course of research, it can be concluded that the use of modern navigation technologies, such as high-resolution radars and ECDIS, significantly increases the level of safety of navigation. These technologies provide a more accurate display of the environment, which allows the crew to respond more quickly to potential threats. Such systems also help to reduce the impact of the human factor, minimising errors that can occur due to limited visibility or difficult weather conditions.

DP systems are among the most innovative and critical technologies in modern navigation (Li *et al*., 2022). They allow vessels to maintain a precise position or perform precise manoeuvring in shallow water without using an anchor, which is an important factor for ensuring safety and efficiency in confined spaces. Traditionally, anchors have been used to maintain a fixed ship position, which can be problematic in shallow water where there is a risk of damage to the sea floor or aquatic vegetation. Setting and lifting an anchor in such conditions is a complex and often dangerous process that can also have a negative impact on the bottom ecosystem. This is where DP systems come to the rescue, which allows avoiding these problems.

DP systems use a combination of different technologies to precisely control the ship's position. The main component of such systems is the integration of data from navigation systems such as GNSS, radars, gyroscopes, and other sensors. This data is processed using powerful computers that automatically adjust the operation of the ship's propellers and rudders to maintain the exact location of the ship at a given point. One of the key advantages of DP systems is their ability to provide stability and positioning accuracy even in conditions of high waves and strong currents. This is especially important when performing tasks such as installing offshore platforms, conducting scientific research, or performing operations in ports and shallow waters. Due to the use of DP systems, the vessel can remain in a precise position without the need for heavy anchors, which avoids possible damage or contamination of the bottom. DP systems also contribute to increased security in confined spaces. In particular, in ports and narrow channels where manoeuvring can be difficult and risky, positioning accuracy is ensured by automatic correction of the ship's movement. This reduces the risk of collisions with other vessels or structures, and also reduces the likelihood of accidents.

However, DP systems are not flawless. They require regular maintenance and inspection to ensure their reliability and accuracy. In addition, the high cost of such systems can be a significant limitation for some ship owners or operators. The cost of installing and operating DP systems can be high, which requires careful planning and budget. An important part of the research and implementation of DP systems is also the development of new technologies to improve their accuracy and functionality. For example, integration with new sensors and improved algorithms can help to reduce the impact of external factors, such as sea currents or winds, on positioning accuracy.

These systems are effective for maintaining a fixed position of the ship in shallow water without using an anchor. This reduces the risk of damage to the sea floor and ensures accurate manoeuvring in confined spaces. The high functionality of DP systems underlines their importance in modern navigation solutions for vessels operating in difficult conditions. X. Gao *et al.* (2021) concluded that DP systems are critical for keeping ships in place without using anchors, compensating for the effects of wind and currents. They provide precise positioning during complex operations such as drilling or rescue operations, even in adverse weather conditions. J. Kim & H. Park (2022) found that DP's benefits for precise manoeuvring include improved ship control in confined spaces, which reduces the risk of accidents and optimises fuel costs. This makes DP indispensable for operations that require high accuracy and security. When analysing the results of the study, it is evident that the use of DP systems significantly improves the accuracy and safety of navigation operations. These systems ensure stable position retention even in difficult conditions, minimising the human factor and reducing the risk of accidents.

The design of the ship's hull also plays a crucial role in improving manoeuvrability in shallow water. Manoeuvring in shallow water is one of the most difficult tasks in navigation (Ghazali *et al.*, 2024). In such conditions, the draft of the vessel and the shape of its hull are key factors for ensuring safety and efficiency. Reducing ship draught is critical to successfully performing tasks in confined waters where water depth is insufficient for traditional ship designs. A vessel's draft is defined as the vertical distance between the water line and the lowest part of the hull that touches the bottom of the vessel. It is an important indicator that affects the ability of a vessel to manoeuvre in conditions of limited water depth. In cases where the water depth is minimal, a large draft can lead to the fact that the ship's hull rests on the bottom, which causes not only the risk of damage, but also complicates manoeuvring. Reducing submersion is achieved by using enclosures with a large width and a flat design. The wide hull provides a larger area, distributing the weight of the ship over a larger bottom area. This reduces the pressure on the bottom and allows the vessel to maintain stability when moving in conditions of limited water depth. The flat hull design helps to reduce the overall water resistance that occurs when the ship moves.

The ship's draft was calculated using the equation (2). If, ship weight $W = 10{,}000$ kg, water density (approximately 1,000 kg/m³ for fresh water), and cross-sectional area $A = 50$ m²:

$$\text{Draft} = \frac{10{,}000}{1{,}000 \times 50} = 0.2 \text{ (m)}.$$

These data indicate that a draft of two-tenths of a meter is normal under certain conditions. At depths less than one meter, the risk of grounding increases significantly, and even small deviations in positioning accuracy can lead to dangerous situations. The draft norms for ships depend on the type and purpose, and generally, for safe manoeuvring, recommended depths should be at least twice the ship's draft. This calculation shows that the low vessel's draft allows avoiding bottom engorgement in shallow water conditions and maintaining vessel stability. In addition, the shape of the hull affects the hydrodynamic characteristics of the vessel. Modern ships for manoeuvring in shallow water are designed considering the features of the environment and specific operating conditions. Flat hulls with a larger width and lower draft can reduce the turbulence of the water surrounding the ship and improve its manoeuvrability. Reducing precipitation is also important to ensure the stability of the vessel. In shallow water, any immersion of a ship in water can lead to instability, especially in strong currents or waves. Ships with lower draft are less likely to roll over or lose stability when water conditions change.

However, achieving optimal precipitation is not directly related to the width of the hull. The design of the hull should also consider its structural integrity and load capacity. An increase in width can have a positive impact on the total amount of cargo a vessel can carry, which must be taken into account when designing structures Reducing precipitation also includes the use of special design solutions, such as weight distribution on the hull and improving ballasting systems. The weight distribution ensures an even distribution of the load on the hull, which helps maintain the stability of the vessel in conditions of limited water depth. An important part of designing shallow water vessels is also consideration of possible changes in water depth. In some cases, the depth may vary depending on seasonal fluctuations or other factors. Therefore, the design of the hull must be adaptive to ensure effective manoeuvring in various conditions.

To ensure safe and efficient operation of the vessel in difficult navigational conditions in shallow water, the stabiliser system on the vessel is of great importance. The wing system, or fins, is one of the innovative technologies that significantly affect the improvement of ship manoeuvrability, especially in difficult water conditions (Song *et al.*, 2022). Fins are special stabilisers that are attached to the ship's hull and are used to improve its handling and reduce drift. These technologies are critical to ensuring the accuracy of the ship's movement, especially when manoeuvring in cramped conditions or in strong currents.

One of the main functions of fins is to ensure the stability of the ship. They work as additional elements that create additional forces that help to compensate for dynamic loads that occur during the movement of the ship. The wing effect provided by fins reduces the rotation and tilt of the vessel, which is especially important in conditions of wind loads or waves. This allows maintaining the stability and accuracy of the ship's course, which is critical for safe manoeuvring. Fins are used to ensure the safety of navigation, especially in conditions of limited space. These devices effectively counteract ship drift caused by external factors, allowing the ship driver to more accurately control the course and reduce the risk of collisions. It is important to note that the effectiveness of fins depends on their design characteristics, such as shape, size, and location. Modern fins have various designs that can be adapted to specific operating conditions. For example, some fins are designed to increase efficiency at certain vessel speeds or when manoeuvring in strong currents. This allows them to be adapted to the specific needs of the vessel and ensure maximum efficiency. The design of the fin system also involves integration with other ship control systems, such as steering systems or DP systems. The integration of these systems allows creating more complete solutions to improve the ship's manoeuvrability. For example, data from the fin system can be used to automatically adjust the ship's course, which ensures more accurate and safe manoeuvring. Analysis of the effectiveness of fins shows that their implementation can significantly improve the management characteristics of the vessel.

In this context, it is important to calculate the stabilising moment of the stabiliser on the vessel. This calculation helps to minimise the vessel's lateral tilt (roll) and reduce its pitching, and improve the vessel's handling. The stabiliser stabilisation moment was calculated using the equation (3). For example, if resistance coefficient = 1.0, stabiliser area $A = 2$ m², ship speed $V = 10$ m/s:

$$\mathrm{M} = 1 \times \frac{1}{2} \times 1{,}000 \times (10)^2 \times 2 = 100{,}000\ (\mathrm{Nm})$$

The number in the stabilising torque means the amount of force generated by the stabiliser to counteract the roll or pitch of the vessel. The obtained value of the stabilising moment is quite high. This means that this vessel is very stable with such parameters, even in strong waves or gusts of wind. Tests and real-world operating conditions confirm that vessels with installed fins demonstrate improved stability, reduced drift and higher manoeuvre accuracy. This not only improves shipping safety, but also increases the efficiency of ship operations by reducing energy and fuel costs.

Another critical aspect of a ship's design that directly affects its hydrodynamic characteristics and, consequently, its overall manoeuvrability, especially in shallow water, is the shape of the bow (Ntouras *et al.*, 2022). Optimising the bow of a ship can significantly reduce water resistance, which is key to improving handling and ensuring efficient navigation in confined spaces. When designing the bow of a ship, the main goal is to reduce the hydrodynamic resistance that occurs when moving through water. Water resistance consists of two main components: wave resistance and friction resistance. To achieve minimal wave resistance, it is important to optimise the shape of the bow in such a way as to ensure a smooth passage of water around the ship's hull. This reduces the turbulence and wave currents, which usually contribute to an increase in resistance. One of the most effective shapes for the bow of a ship is a shape that resembles an underwater profile or a blunted cone. This shape allows reducing the resistive resistance and improve the distribution of water throughout the housing. In particular, bows that have an elongated and narrowed shape help to reduce drag at high speeds, but for shallow water, it may be advisable to use flatter or rounded shapes that reduce the tendency to sink. Reducing the depth of water under the hull also plays an important role in determining the optimal shape of the bow.

Calculations of water resistance were conducted for both bow shapes using the equation (4). The shape of the bow directly influences water resistance in the following ways. *Elliptical bow shape* – minimises resistance by promoting better water flow around the hull, reducing turbulence and creating a smoother transition from the bow to the hull, which is crucial for high speeds. *Flat or rounded* *bow shape* can decrease the tendency to sink in shallow water, but they may increase drag at high speeds. Calculation of water resistance of a ship with different types of bow under the same conditions. The parameters were selected based on typical values for ships.

Elliptical bow: drag coefficient = 0.8; cross-sectional area $A = 2$ m²; speed $V = 15$ m/s.

$$F_d = \frac{1}{2} \times p \times C_d \times A \times V^2;$$

$$F_d = \frac{1}{2} \times 1{,}000 \times 0.8 \times 2 \times 15^2 = 9{,}000 \text{ (N)}.$$

Flat or rounded bow: drag coefficient (): 1.2; cross-sectional area (A): 2 m²; speed (V): 15 m/s.

$$F_d = \frac{1}{2} \times 1{,}000 \times 1.2 \times 2 \times 15^2 = 13{,}500 \text{ (N)}.$$

The elliptical bow shape results in a drag of 9,000 N, while the flat or rounded bow yields a drag of 13,500 N. This indicates that the elliptical shape is more efficient for high-speed navigation, whereas the flat or rounded shape may be preferable in shallow water to reduce the risk of sinking.

When the vessel moves in shallow water, the reduced water depth changes the hydrodynamic conditions, which can lead to increased drag and poor manoeuvrability. Changes in the hydrodynamic characteristics of the vessel with a decrease in the depth of water under the hull are also associated with priming effects. When the bow of a vessel rises out of the water or partially rises through shallow water, it can lead to significant changes in the distribution of water around the hull. In such cases, optimised bow shapes can reduce unwanted changes in support that occur in close contact with the bottom. Studies of the different shapes of the ship's bow in shallow water show that specially designed profiles can significantly improve handling. For example, the bow of vessels with progressive expansion or undulating shapes can reduce drag and increase the efficiency of movement in conditions of limited space. Innovative developments include the use of hydrodynamic models to create bows that optimally combine aerodynamic and hydrodynamic characteristics.

The steering system is one of the main elements affecting a ship's manoeuvrability, especially in confined spaces such as narrow channels and port areas (Zhang, 2021). Modern ships are equipped with highly sensitive steering systems that allow achieving the accuracy of manoeuvres necessary for safe and efficient handling. The heart of the steering system is the steering blades or steering machines that are responsible for changing the direction of movement of the ship. Depending on the design and requirements of the vessel, different types of steering systems can be used. Modern steering systems include hydraulic, electric, or combined mechanisms that provide precise and sensitive control. One of the key innovations is the use of two steering blades or steering machines. This configuration significantly increases the manoeuvrability of the vessel, as it allows for more accurate and faster course corrections. Two steering blades located on both sides of the stern section of the vessel provide a symmetrical distribution of forces, which reduces the negative impact of waves and currents on the accuracy of manoeuvring. This is especially important when operating a vessel in narrow channels or when performing complex manoeuvres in limited conditions. Two-blade steering systems also provide better stability of the vessel during manoeuvring. In high-speed conditions or when making sharp turns, using two steering blades helps to reduce the impact of inertial forces that occur when changing direction. This makes it easier for ship drivers to maintain their course and avoid unwanted deviations. In addition, modern steering systems can be equipped with additional features, such as automatic course adjustment and remote control. Automatic steering systems integrated with other navigation technologies, such as DP or ECDIS systems, allow automating the manoeuvring process and reducing the load on the crew.

In this context, it is important to calculate the steering torque of a ship. Understanding the torque helps determine how efficiently a vessel can manoeuvre in confined conditions. The moment of force plays a crucial role in precise steering. A higher moment of force enables better control over the rudder, facilitating sharper turns and enhanced responsiveness, which are essential for navigating in narrow or congested waterways. The moment of force required for steering calculate using the equation (5). For example, force $F = 5{,}000$ N, distance $d = 2$ m, angle $\theta = 30°$:

$$\text{M} = \frac{5{,}000 \times 2}{\sin{(30°)}} = 20{,}000 \text{ (Nm)}.$$

Overall, the calculation illustrates the relationship between force, distance, and angle in generating a steering moment. This understanding is essential for optimising steering systems and enhancing the manoeuvrability of vessels, particularly in challenging navigational environments.

The efficiency of steering systems is closely linked to the ship's hull design and stability. For high-speed vessels with a V-shaped hull, a modern steering machine is most effective due to its high force capability and quick response, allowing for precise manoeuvring. In shallow water, flat bottom hull designs benefit from either a single steering blade or two steering blades. The two-blade system enhances stability and control compared to a single blade. For larger ships with a round bottom hull, a two-blade system provides better lateral control and reduced drag.

In summary, the modern steering machine is optimal for high-speed V-shaped hulls, while two steering blades are best for flat bottom hulls in shallow water. A single blade is adequate for simpler designs but less effective for maintaining course. The parameters in Table 2 should be correlated with specific hull designs for a comprehensive understanding of steering efficiency, considering factors like water depth and vessel speed.

Table 2. Steering system parameters

Steering system type	Force (N)	Distance (m)	Rotation angle (degrees)	Moment of force (Nm)	Remarks
One steering blade	5,000	2	30	20,000	Basic control; less stable
Two steering blades	5,000	2	30	20,000	Improved stability and control.
Modern steering machine	6,000	1.5	45	60,000	Superior performance for high-speed

Source: compiled by the authors based on K. Otsubo & K. Ishida (2021)

In shallow water, where changes in water depth can significantly impact hydrodynamic performance, the design of the steering system must compensate for these variations to ensure stable control. Table 2 shows that the parameters for the one steering blade and two steering blades systems are identical; both provide a force of 5,000 N, with a distance of 2 m, a rotation angle of 30 degrees, and a moment of force of 20,000 Nm. This similarity indicates that, at least in this context, both systems offer the same performance.

However, the two-blade system can be advantageous due to its increased surface area, which provides better lateral control and stability, especially when maneuvering in tight spaces or during sudden directional changes. The presence of two blades helps distribute forces more evenly, reducing the likelihood of cavitation and improving overall responsiveness.

In contrast, the modern steering machine shows superior performance with a force of 6,000 N, a shorter distance of 1.5 m, a larger rotation angle of 45 degrees, and a moment of force of 60,000 Nm. This indicates that the modern steering machine is capable of generating more power and achieving more significant rotation in less distance, which is particularly beneficial for high-speed maneuvers or navigating complex waterways. The modern steering machine surpasses both systems in force output and efficiency, making it the preferred choice for high-performance vessels, especially in challenging navigation conditions.

One of the most pressing challenges in the development of steering systems is to achieve a balance between control sensitivity and mechanical strength. Shallow water conditions and high loads can cause additional stress on the steering elements, which requires the use of innovative materials and structures that can withstand such loads. To improve the accuracy of manoeuvring in shallow water, it is also important to integrate navigation equipment with the hull design. For example, data from radar or ECDIS can be used to automatically adjust the hull position, which helps to reduce the impact of hydrodynamic forces that occur in shallow water (Orlandi *et al.*, 2021). In addition, ships with an improved hull design can use DP systems more efficiently. Evaluation of hull design solutions showed that the use of wide and flat hulls reduces the ship's draft, increasing its stability in shallow water. The integration of stabilisers and the optimised shape of the ship's bow also contribute to improved handling. It is revealed that modern steering systems with high sensitivity allow for precise manoeuvres in cramped conditions, which confirms the importance of combining modern navigation technologies with a thoughtful hull design to achieve maximum efficiency in ship manoeuvring in shallow water.

Conclusions

Research on improving the accuracy of ship manoeuvring in shallow water has confirmed the significant impact of both navigation equipment and hull design on the efficiency and safety of navigation in confined spaces. GNSS, such as GPS and BDS, have demonstrated their critical role in ensuring accurate positioning of ships, especially in narrow areas of water where even minor deviations can lead to danger.

ECDIS has proven to be indispensable for integrating depth, interference, and channel marking data, which significantly helps to avoid underwater threats and provides a detailed display of the navigation situation. This, in turn, improves the accuracy of navigation solutions and increases the safety of navigation. Automatic identification systems have shown their effectiveness in tracking the position of neighbouring ships and avoiding collisions, which is especially important in narrow channels and port areas where the concentration of ships can be high. High-resolution radars provided critical visibility of underwater objects and coastlines, which is necessary for accurate manoeuvring in low visibility and shallow water conditions.

DP systems have demonstrated their ability to maintain a fixed ship position without using an anchor, which reduces the risk of damage to the sea floor and allows for more precise manoeuvring in shallow water. Analysis of hull design solutions confirmed that wide and flat hulls, optimised bow shapes and state-of-the-art steering systems significantly improve the manoeuvrability and stability of vessels, which contributes to more efficient handling in shallow water. The results of the study highlight the importance of integrating navigation technologies with design innovations to ensure the safety and accuracy of ship manoeuvring in difficult conditions.

To further improve ship manoeuvring in shallow water, it is necessary to investigate the impact of integrating the latest navigation technologies with innovative hull designs on long-term reliability and efficiency under various operating conditions. A limitation of the study was the lack of consideration of the impact of extreme weather conditions on the efficiency of navigation equipment and the design of ship hulls.

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Conflict of Interest

None.

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Підвищення точності маневрування суден на мілководді: роль навігаційного обладнання та дизайн корпусу

Анотація. Дослідження проведено для аналізу впливу сучасного навігаційного обладнання та дизайну корпусу суден на підвищення точності маневрування в умовах мілководдя. У дослідженні використовувалися методи аналізу та порівняння ефективності сучасного навігаційного обладнання, оцінювання конструктивних рішень дизайну корпусу суден, а також інтеграції цих технологій для покращення точності маневрування на мілководді. Було встановлено, що використання сучасних систем динамічного позиціонування та високоточного навігаційного обладнання, таких як супутникові системи та електронні картографічні системи, значно підвищує точність маневрування суден на мілководді. Виявлено, що кораблі з пласким корпусом та мінімальною осадкою мають кращу маневреність у порівнянні з традиційними конструкціями. Оптимізація форми носа та застосування стабілізаторів дозволяють зменшити опір воді й покращити керованість. Використання високочутливих рульових систем підвищує точність руху в обмежених умовах. Зроблено висновок, що інтеграція цих технологій дозволяє значно покращити безпеку судноплавства на мілководді. Дослідження також показало, що радари з високою роздільною здатністю та автоматичні ідентифікаційні системи ефективно знижують ризик зіткнень під час маневрування у вузьких каналах і портах. Крім того, було виявлено, що судна з покращеним дизайном корпусу мають знижений гідродинамічний опір, що сприяє зменшенню витрат палива на мілководді. За результатами дослідження були надані практичні рекомендації з впровадження сучасних навігаційних систем і вдосконалення дизайну корпусу суден, що підвищує точність маневрування на мілководді та покращує безпеку судноплавства. Загалом, результати дослідження підтвердили важливість інтеграції навігаційних технологій із конструктивними рішеннями корпусу для підвищення ефективності та безпеки судноплавства

Ключові слова: системи динамічного позиціонування; оптимізація форми носа; конструктивні рішення; ризик зіткнень; гідродинамічний опір