

# **Ships-To-Ship Magnetic Mooring Systems – The New Perspectives**

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**ABSTRACT:** Each type of ship must have appropriate mooring systems adapted to the fact that after the end of the voyage and shutdown of its propulsion, it is moored and is not exposed to the dangers related to the negative influence of external factors. Moreover, the mooring of two ships of different and/or similar sizes at sea for transshipment or service always requires special techniques and special care to ultimately avoid damage to the vessel throughout the approach or breakage of the lines due to excessive loads. As reported by the UK P&I Club, mooring incidents are among the top seven types of insurance claims. Most of the vessels still use traditional mooring systems, known for centuries. Despite changes in regulations to reduce the number of incidents, also new technologies related to the mooring of ships began to develop. This article provides a review of the latest research focuses, applications, and future perspectives regarding mooring systems mainly related to ship-to-ship interaction. Moreover, a new device called Mobile Electromagnetic Mooring System (MEMS) has been introduced and described. Finally, modern mooring systems' challenges and future perspectives have been discussed.

## 1 INTRODUCTION

Safe and efficient mooring is essential for ensuring the safety of the ship, terminal, and environment. Therefore, it is important to continue developing and improving mooring systems. Traditionally, ship mooring systems have relied on an arrangement of mooring lines that attach the vessel to the shore, or to the other vessels and onboard fittings such as chocks-fairlead, pedestal rollers, and bitt-bollards [1]. However, novel systems of mooring have come into play by applying alternative physical principles to join the ship to the quay or the other vessel ([2],[3]). The components of the mooring system are determined by vessel type and size, regulations, and rules from the classification society chosen by the ship owner.

A mooring system for a ship must withstand various forces including wind, currents, surges, waves, and swells. It is also necessary to consider factors such as vessel type and size, mooring system characteristics, terminal disposition, and physical port or sea conditions [1]. The influence of disturbing hydrodynamic forces generated by the propellers of other ships passing in close proximity to the vessel, the ship's trim, its draft and freeboard height, and thus also different angles of the so-called "looking" and "bending" of traditional mooring lines used in the STS mooring system [4]. In practice, however, due to variable loads, it is recommended to avoid mixed mooring techniques that use different types and categories of ropes, as this may cause uneven and/or excessive load on individual ropes, leading to their breakage and uncontrolled disconnection of previously moored vessels, exposing these vessels

and their crews to danger [5]. In the past, accurate estimates of ship movement and loads on mooring ropes were only possible through costly tests with scale models. However, with increased computational power, numerical methods based on simplifications have become available, allowing for the development of mathematical models for calculating moored ship motions [6].

Nevertheless, the design requisites for mooring systems must consider the elasticity of mooring lines and how ships are subject to wind, currents, and wave forces. The designer can then choose and position mooring equipment and fittings on board. Wind action is an important factor, considering changes in intensity and the longitudinal or transverse angle of incidence. Maximum current also plays a crucial role in the ship's draught's interaction with under-keel water clearance.

The transportation industry has seen a significant increase in the number of ships and ports due to the growing demand for shipping operations [7]. For thousands of years, ships were moored by human hands using ropes, which have become increasingly difficult and time-consuming to handle. The traditional rope mooring method has resulted in hundreds of accidents and injuries each year, causing losses of millions of dollars [8]. The statistics on rope and wire mooring accidents are presented from various sources such as the European Harbour Master's Committee (EHMC) [9], the UK P&I Club [10], the Australian Maritime Safety Authority [11] and the International Maritime Organization (IMO). As per the UK P&I Club report, approximately 300 people have died every year in accidents related to ship mooring, 95% are caused by ropes and wires, and 60% of these injuries happen during mooring operations [10].

There is a plan to update and modify the central rules and regulations to decrease the numbers related to the unsafe mooring. These updates include changes to SOLAS regulation II-1/3-8 and the introduction of fresh guidelines for the secure mooring of ships. They were sanctioned in 2019 and are anticipated to come into effect on 1 January 2024 [12]. According to the updated rules, all new ships must follow the revised regulations for mooring designs that are safe to use. On the other hand, existing ships need to comply with new regulations concerning the inspection and maintenance of mooring equipment and lines while also providing appropriate documentation [13],[14]. Therefore, it is up to flag states, governing states of the ports, ship-owners and loaders to create the regulatory framework that makes it possible for the ship to operate safely. The International Association of Classification Societies (IACS) [15] has produced a document to harmonize requirements for mooring, anchoring, and towing ships but has not specified the design requirements for mooring winches. The Oil Companies International Marine Forum (OCIMF) [1] has also established guidelines for safe mooring systems. Recent influential guidelines such as MEG4, Section 2, have incorporated principles of human-centric design that take a comprehensive approach to mooring equipment and procedures to ensure safer operations. These guidelines emphasize managing mooring lines in a way that considers the well-being and safety of humans.

Therefore, mooring two ships of different and/or similar dimensions for transshipment and/or service always requires special techniques and extreme caution to ultimately avoid damage to the units throughout the approach or breakage of the lines due to excessive loads during their securing. Such mooring can be done in three ways: (a) in port, using the so-called double berth, where one of the ships is already berthed to the quay and the other is moored to its outer side on the side opposite from the quay, (b) at anchorage, when one of the ships is at anchor and the other is approaching and mooring to the ship already anchored, (c) when mooring operations are being carried out when both ships are in motion in the water and/or over the ground (drifting).

In this respect, the issue of mooring a small service unit to the side of another ship with a very high freeboard becomes particularly dangerous. In such a situation the lines are usually directed at a very large vertical angle upwards from the service watercraft to the mooring bollards situated on the main deck of the serviced vessel, usually, a larger, longer vessel with a high freeboard, to which other vessels need to moor. Such a situation limits the correct distribution of the forces keeping the service watercraft at a stable mooring position at the side of the serviced vessel, exposing it, especially in the event of unfavorable hydrometeorological conditions in the area of work, to uncontrolled longitudinal and transverse displacements with dynamic oscillations of the ship on the wave and dynamic impacts of its hull against the larger serviced vessel.

An additional problem that arises in the case of a small vessel performing underwater works due to damage to the serviced ship is the propulsion, which must always remain turned off for both the intervention boat and the serviced vessel. The propulsion on both units must be secured against any unwanted activation at least for the duration of time when divers are underwater and could be exposed to the associated dangers of injury or death. Therefore, such ships cannot support their mooring position by dynamic positioning (at a given position and/or course) using ship propellers. Such practices are necessary to maintain the required safety procedures when performing underwater work. The correct mooring of two ships side to side with the propulsors and water-jet propellers turned off is in this case crucial for the safety of divers below the water's surface.

The type of mooring system used depends on the size of the ships involved in the operation [16]. To begin, the maneuvering vessel must approach the anchored or drifting vessel at a steady course, minimizing the approach angle. The preferred approach area is located behind the traverse of the vessel being approached. The maneuvering vessel should steer parallel to the other vessel's course and decrease the distance between them gradually and slowly, using the engine and rudder movements. Once the appropriate distance has been reached, the fenders located on the sides of the vessels make contact, allowing the two ships to connect in parallel and the ropes to be secured according to the mooring plan. This process is challenging for both the operator of the maneuvering vessel and the crews responsible for the safe and efficient mooring of the ships.

The currently proposed mooring systems, in particular with regard to small intervention, diving, service and cargo or people transfer units where it is also crucial to perform underwater repair works, pose many problems, including: (a) they increase the risk of the mooring breaking or sliding off, which may result in serious injury or death to crew members; (b) they cause a high angle of the mooring lines directed upwards to the main deck of the serviced mothership with high freeboard, which has a significant impact on the level of stresses and breaking forces (loads) generated there, and in combination with unfavorable hydrometeorological conditions (e.g. strong wind, current and sea wave) may cause significant mutual vertical and horizontal oscillations of both units with dynamic impacts of the intervention/service unit against the serviced hull with the possibility of breaking the mooring lines and drifting of the previously moored unit; (c) the prolonged time of the required emergency response usually increases the risk of more serious consequences of an accident, e.g., in the event of a dangerous cargo leak from damaged bottom tanks. The fast mooring and movement of an intervention/service vessel along the side of a ship in need (e.g., to locate damage) is usually time-consuming, and in emergencies, every minute counts, especially in the case of ships with damaged hull plating. There is also the necessity to engage many people from the crews of both involved vessels in the mooring, unmooring, and moving of the service watercraft along the side of the serviced ship. During an accident, the crew of a damaged ship is usually involved in performing other tasks related to the breakdown, performing other official duties, including saving lives and property. On the other hand, the process of mooring and moving the intervention/service unit alongside the serviced ship is very time-consuming and requires the involvement of a few additional people on the serviced ship and the intervention unit. This issue has not been fully resolved to date.

Traditional mooring systems have been known to present numerous challenges, including the risk of mooring line breakage, the involvement of personnel in hazardous operations, and the time-consuming nature of these processes. Therefore, there is an urgent need for a safer and more efficient mooring system to solve the above problems. In recent years, automated vacuum and magnetic mooring systems have gained attention as an alternative to traditional mooring systems for ships [17]. These systems offer numerous advantages over traditional mooring systems, such as reduced crew workload and improved safety, which can have made them increasingly popular. This paper aims to provide an overview of the current state of the art in ships-to-ship mooring systems, in particular with regard to small service vessels.

Introduced by the authors, the Mobile Electromagnetic Mooring System (MEMS) signifies a considerable breakthrough in the field of mooring operations, specifically tailored to tackle the primary challenges faced by small service vessels. By offering a safer and more efficient alternative, the MEMS holds the potential to transform the industry, enhancing the overall safety and expediency of mooring operations. This inventive system utilizes electromagnetic technology to mitigate the risks associated with

conventional mooring methods, ultimately boosting the operational capabilities of small service vessels. As the project advances, a MEMS prototype is presently being installed on the fast motorboat Merlin 6.15, which will be employed for conducting sea trials. These trials will yield valuable insights into the system's performance and functionality under real-world maritime conditions, laying the groundwork for potential implementation and widespread adoption of the technology.

This article aims to present a thorough overview of MEMS technology, its design, and its potential advantages and applications within the maritime sector. By examining the difficulties encountered with traditional mooring systems and the benefits of this innovative approach, the article strives to underscore the significance of ongoing innovation in the realm of mooring operations for small intervention, diving, service, and other vessels. This article will explore the distinctive features of the MEMS system, its fundamental principles, and how it addresses the challenges inherent in mooring operations. Additionally, the article will discuss the potential applications and advantages of MEMS technology across various maritime settings, emphasizing its transformative influence on the industry.

While detailed research results will be published upon obtaining full intellectual property rights, this article offers a comprehensive introduction to the MEMS technology, highlighting its significance and potential for revolutionizing the maritime industry. The remainder of this paper is as follows: the evolution of the modern mooring systems is elaborated in Section 2. The currently proposed Mobile Electromagnetic Mooring System (MEMS) for small service watercraft, is presented and analyzed in Section 3. Section 4 presents the results and discussions. Section 5 concludes the paper.

## 2 EVOLUTION OF MODERN MOORING SYSTEMS

To address issues with excessive ship motions during berthing or mooring operations, there are two main methods: reducing wave action or modifying the mooring system's response. One solution involves changes to port infrastructures, such as reducing wave reflection or extending breakwaters. Whereas the other one modifies the mooring system itself and can be cost-effective. There is no one-size-fits-all solution, and each case requires a dynamic analysis of the berthed ship and its mooring system. However, some studies have proposed solutions to improve operational safety and reduce downtime [18]. For instance: Yoneyama et al. (2009) presented a method of reducing low-frequency surge ship motions using computer-controlled hybrid mooring winches to change the mooring system's natural period [19]. In a study by Rosa Santos et al. (2014), different mooring arrangements were analyzed to improve safety and operational conditions at the Leixões oil terminal in Portugal [20]. The results of wave tank experiments indicated that high friction fenders could increase tension mooring efficiency and reduce ship motions, particularly when close to the system's natural oscillation periods.

De Bont et al. (2010) conducted field measurements and numerical simulations at the Port of Shalah in Oman to investigate the effect of the MoorMaster™ system on reducing surge motions of moored containerships [21]. The MoorMaster™ system, developed by Cavotec [22], uses vacuum pads and hydraulics to secure and control moored ships. While the researchers found that the system reduced surge motions, some parameters were not measured and the results were inconclusive. Van der Molen et al. (2015) later investigated alternatives to mooring configurations in Geraldton Harbour in Australia and found that a combination of pneumatic fenders and constant tension winches or nylon breast lines resulted in the highest reduction of vessel motions [23]. In addition, a new hydraulic mooring system called ShoreTension has been developed by the KRVE mooring company at the Port of Rotterdam [24]. The system automatically keeps mooring cables tense in severe conditions and was shown in simulations to significantly decrease vessel motions and loads on mooring lines.

Moreover, there are currently various systems and technical devices in use for mooring vessels, including single-point mooring systems implemented with a single mooring, tandem systems, mooring and transfer installations based on telescopic gangways with a single mooring point, bottom mooring and loading systems, and traditional multi-point mooring systems. There are also different systems used for mooring one ship to the stern and/or the side of another ship in the ship-to-ship (STS) system, implemented based on flexible connections with mooring lines (natural, synthetic, steel, and/or a combination) or based on rigid connections (e.g., mechanical connections of a barge with a pusher-type tug, connection of a Hiloat DP1 unit with a tanker using the so-called Remora-type hydrostatic bottom suction, or connection of two ships with the use of electromagnetic mooring systems) [25].

Basically, the alternative mooring methods can be divided into 3 groups. Shore Tension System, Vacuum Mooring System, and Magnetic Mooring System.

### 2.1 Shore Tension System

The Shore Tension (see Figure 1) is a cylindrical device that exerts constant pressure on mooring lines fixed to bollards on the quay. It uses a hydraulic system for proper tension and can move along with the forces working on the mooring line, reducing ship movement and absorbing energy produced by the ship. The system is CO<sub>2</sub> neutral and can function without external energy after initial activation. High-quality mooring lines can be used in conjunction with the Shore Tension for better security. With the increasing demands of marine terminals and challenges posed by climate change, the Shore Tension can enhance the mooring capabilities of large vessels and reduce vessel movement and downtime. While conventional tension winches on the deck can prevent mooring lines from snapping, they require a lot of energy and cannot provide the same benefits as the Shore Tension.



Figure 1. Automated Mooring System – Shore Tension. SOURCE: Shore Tension:[ <https://shoretension.com>], [24]. Accessed on 20.03.2023

The Shore Tension System offers several benefits such as reducing the likelihood of lines breaking and therefore minimizing personal injuries. This could potentially lead to lower insurance premiums due to fewer mooring accidents. Additionally, the system enhances the stability of the ship while being moored and improves the safety and speed of loading and unloading. It is adaptable and can be installed on almost every quay or jetty, providing a steady tension of up to 60 metric tons (600kN) and a safe working load of up to 150 metric tons (1,500kN). The system includes sensors that monitor rope loads, which can be accessed by the ship's master, port, and terminal operators. The data is logged for review of the berth, and a warning system can be set up to alert when force or displacement limits are exceeded. However, one drawback of the system is that it requires a considerable amount of space on the quay [24] and cannot be used on small service vessel.

### 2.2 Vacuum Mooring System

The vacuum-based mooring system is an innovative method used for berthing sea vessels. The system uses vacuum technology, robot arms, cables, automated winches, and fenders to dock the vessel safely and quickly [26]. The vacuum pump starts when the ship is a few meters away from the quay, which gently sucks the vessel to the quay using vacuum pads that apply a constant force on the ship during mooring. The safety system ensures that the vessel remains connected to the quay even during a power outage, as the vacuum is maintained for up to two hours, allowing enough time to address any leaks or restore power. The system includes a vacuum pump, hydraulic system, steel, monitors, and power supply for controlling the whole operation. The vacuum pads are connected to hydraulic arms that can move horizontally up to 0.5 meters but cannot move vertically, requiring them to walk on the ship to adjust to changes in tides or displacement. The system has sensors and monitors to detect any issues, triggering an alarm on the bridge of the vessel, and the shoring system if the vacuum drops to 60%. The vacuum pad sensors measure the vacuum level continuously and convert it into forces acting on the ship's hull, while sensors in the hydraulic components monitor the ship's movements, which are displayed on screens. A small emergency generator is also included in the system as a backup power source. The vacuum system remains stationary on the quay and is configured with a varying number of pads to accommodate different ships.

The main companies in possession of automated vacuum moorings at present are Cavotec [22] and Trelleborg [27]. The MoorMaster (Figure 2) range

applications and the AutoMoor device are introduced as effective solutions to the traditional rope mooring method. The mainframe of MoorMaster is a linkage mechanism that generates a suction force per mooring unit during the operation, with small movements and rotations at the end [21]. Trelleborg developed the AutoMoor device using the environment detection technology SmartPort and passive damping technology, which uses vacuum technology to fix the vessel to its berth securely, inhibits vessel movement, and continuously monitors the mooring load of the moored vessel.

The first automated ship-to-ship docking system was developed by Cavotec in 2014, where two ships could exchange deck cargo in the ocean. The system mainly consists of vacuum pads, robot arms, cables, automated winches, and fenders [22]. However, they were two large ships of similar dimensions.



Figure 2. Automated Mooring System – Moor Master - Cavotec. SOURCE: MoorMaster:[<https://www.moormaster.com>], [28]. Accessed on 20.03.2023

The vacuum mooring system is a safe alternative to traditional mooring methods that do not require a crew on the shore or on the vessel's deck. Securing the vessel to the quay with ropes is also made easier by this system. Additionally, the vacuum mooring system is time-efficient, as it can moor a vessel in as up to two minutes [28]. The forces exerted on the vessel can be easily calculated using sensors and software on the monitor. This system also results in lower fuel consumption as it is quicker to connect the vessel to the berth. Compared to the magnetic system, the vacuum pads of the vacuum mooring system can apply and release pressure gently.

The biggest disadvantage of that system is the inability to move arm laterally, and therefore cannot be utilized in ports with significant ebb and flood currents unless some improvements are made. The cost of investment varies depending on the size of the vessels being serviced. The hydraulic arms cannot move vertically and the pads can only attach to a flat surface, making it impossible to attach to the bow or stern of a vessel at an angle. The system is specific to each ship, and if the system is designed for a smaller ship, it may not be able to handle the forces of larger ships due to significant differences between vessels.

### 2.3 Magnetic Mooring System

Currently, electromagnetic technology has reached a high level of development and is extensively utilized in various industries such as metal production, machining, and automobile manufacturing. The implementation of magnetic mooring systems is a significant step towards automating shipping

operations. Such systems utilize piers, wharves, and mooring buoys to secure ships, alongside several components such as electrical cables, fenders, magnetic pads, hydraulic arms, and a power supply that generates magnetism. By using electrical power to create electromagnetic fields, magnets are activated, and these fields are utilized for mooring ships. The temporary magnets act as electromagnets by using an electric current, with the solenoid functioning as a magnet as long as the current is flowing. However, when the current is turned off, the solenoid loses its magnetism.

The magnetic system offers advantages over traditional rope mooring systems in terms of ease, safety, and efficiency. It reduces the time for mooring and unloading, eliminates the risk of snapping and slipping ropes, and requires fewer workers to operate [29]. The system is also cost-effective as it eliminates the need for expensive mooring ropes, reduces mooring costs, and generates savings for ship owners by eliminating the need for rowers. The magnetic system can be released in only 20 seconds and reduces average calling time by 40 minutes, which enables faster and more efficient working.

According to Mampaey - the main company related to magnetic mooring systems, there are few limits to the magnetic mooring system, and it is possible to increase the force by adding hydraulic arms and pads [30]. This would decrease the risk and provide more stability. The system involves two pads that work together and "walk" along the ship's hull automatically, disconnecting and reconnecting as needed due to changes in the ship's draft or tide. The system is flexible and can be adjusted by changing the number or size of the pads. Currently, the system can only be used in ports with slack water, but it can be made more flexible with the addition of a ball joint. While the system is suitable for most vessels, it can be challenging to moor tanker vessels due to the risk of electrical sparks. However, this risk is minimal because there are usually no dangerous gases present around the tanker during the mooring process. Moreover, the thickness of a ship's hull is a potential issue for the magnetic mooring system. If the hull is less than eight millimeters thick, the magnetic force could cause it to bend during mooring or unmooring. However, this is not a significant limitation as modern ships typically have hulls thicker than eight millimeters. Fenders are placed between the moored vessel and the quay to protect them from damage, and the maximum force of the magnetic mooring system must be less than the maximum force that the fenders can withstand. The system's fixed pads and hydraulic arms can be a limitation if the quay is used for different types of vessels with varying lengths and drafts, but this can be overcome by using a portion of the pads. The system can be affected by electrical blackouts, so emergency generators, connecting the system to the vessel's diesel generators, and backup ropes and springs are recommended

Three known solutions use the electromagnetic mooring arms disclosed in patent descriptions: EP2844542 [31], CN108674582 [32], and WO2012060511 [33] have been shown on Fig. 3. The solution enables quick and reliable fixing of the mooring vessel relative to the quay. However, the



main disadvantages of the above-mentioned systems are, on the one hand, their extensive dimensions, which prevent them from being used on smaller vessels not exceeding 24 m in length, and, on the other hand, the inability to move fast the moored vessel horizontally along the mooring system. These are large-size port facilities and cannot be used in service watercraft operations. The proposal to use one of these systems has been suggested in the Port of Rotterdam on fuel bunkering barges - it is currently at the conceptual research stage [34].

The Mobile Electromagnetic Mooring System solution, tackles the problems and requirements of small intervention or service watercraft, including work dive boats, during mooring to a larger serviced unit.

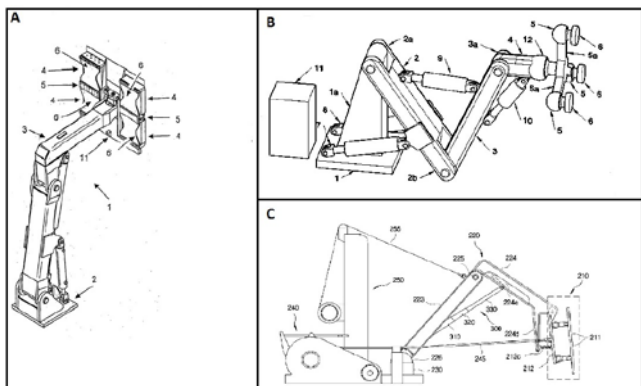


Figure 3. Diagrams of devices using electromagnetic mooring arms, SOURCE:: A - EP2844542[31], B- CN108674582[32], C - WO2012060511[33].

### 3 MOBILE ELECTROMAGNETIC MOORING SYSTEM

The main problems encountered by small intervention, diving, service, and other vessels during mooring operations necessary for underwater repair work can be defined. These problems include:

- The risk of the mooring line breaking or slipping, which can cause serious injury or death.
- The high angle of mooring lines directed towards the main deck of the serviced high-freeboard mother vessel has a significant impact on the level of generated stresses and braking forces, which, when combined with unfavorable hydrometeorological conditions in the area (e.g., strong winds, currents, and waves), can cause significant vertical and horizontal oscillations of both vessels with dynamic impacts of the intervention vessel against the hull of the mother vessel, with the possibility of the mooring lines breaking and the previously moored vessel drifting away.
- The prolonged reaction time required for intervention usually increases the risk of more serious accident consequences, e.g., during emergencies with hazardous cargo leaks from damaged bottom tanks. The mooring and movement of the intervention vessel along the side of the vessel in need (e.g., to locate its malfunctions) is usually very time-consuming, and

in emergency situations, such as on ships with damaged hull plating, every minute counts.

- The need to involve many crew members from both involved vessels in mooring, unmooring, and moving the intervention vessel along the side of the mother vessel. During emergencies, the crew of the damaged vessel is usually engaged in performing other tasks related to the emergency, performing other official duties, including saving lives and property. The process of mooring and moving the intervention vessel along the mother vessel is very time-consuming and requires the involvement of several additional personnel needed on the service vessel and the intervention vessel.

In response to the problems and requirements faced by small intervention units, including diving work boats, when mooring to a larger vessel (mother ship) (see Figure 4), the concept of designing an innovative mooring and movement system for the servicing boat along the serviced unit has been developed, which eliminates and/or minimizes the risks associated with the possibility of mooring lines breaking. Moreover minimizes the involvement of personnel in the mooring and/or mutual movement of these vessels, which ultimately has a very positive impact on the overall safety and speed of mooring operations, as well as on the safety and speed of intervention activities carried out there.



Figure 4. Visualization of service watercraft equipped with Mobile Electromagnetic Mooring System during mooring operations. Source: Authors' own study carried out on manoeuvring simulators of the Gdynia Maritime University in December 2022.

The Mobile Electromagnetic Mooring System (MEMS) is intended to equip a small surface intervention unit mooring to the side of larger vessels to carry out servicing, repairs, or the transfer of cargo or people. The main idea of MEMS is that is placed on the overwater zone above the waterline of a small service vessel. This system has at least two mooring winches located at each end of the intervention vessel. The mooring ropes have constant tension and can be attached to floating power supply buoys with insulated power cables. The ropes are held horizontally in electromagnetic grippers that are controlled from the central control panel of the service watercraft. Each group of electromagnetic grippers with an electromagnet that is powered by a floating power supply buoys. The power supply can be also provided from the integrated battery or a power source supplied by a service or serviced unit. Additionally, each electromagnetic gripper should have an emergency electromagnetic release, which can be activated from the central control panel of the service vessel. Moreover, each mooring winch is equipped with an integrated system to measure and maintain constant tension on each mooring line

connected to the floating power supply buoy through a common control panel.

The MEMS allows the small intervention or service watercraft to move freely along the serviced unit, which eliminates the risks associated with the possibility of breaking the mooring lines and minimizes crew interference involved in the mooring process and/or mutual movement of these ships, which in turn has a very positive effect on the general safety and speed of mooring operations carried out on the side (mooring and unberthing).

The main advantages of the presented solution are the reduction of the probability of an accident related to operations on the mooring lines by reducing the "high viewing angles" and the breakage of the mooring lines. In classic systems, the mooring lines look up to the ship's main deck, usually with a very high freeboard. In MEMS, the mooring lines look horizontal and are attached to the mobile electromagnetic grippers attached to the hull of the intervention vessel. Through the reduction of the level of stresses and loads generated on the mooring ropes located in the horizontal position of the MEMS and the limitation of inertial movement of the unit, the risk of accidents related to operations on mooring ropes is reduced to a minimum. An additional advantage of the system according to the invention is the short time of mooring and unberthing operations, as well as the unnecessary of the crew of a damaged/serviced ship interfering with mooring operations. The valuable importance is the movement of the intervention unit along the side of a larger vessel to carry out the necessary work without the interference of the crew of the serviced vessel and to improve the safety of the diver in case of underwater works. The central control panel of the Mobile Electromagnetic Mooring System guarantees quick disconnection of the electromagnetic grippers with floating power supply buoys. The use of conventional mooring winches ensures the system's mobility. The solution allows the intervention unit to be attached to a larger ship with a steel hull, even if it is contaminated, which in standard conditions makes such operations difficult.

Figure 5 presents visualization of: a) traditional way of mooring small service craft, and b) service watercraft equipped with MEMS.

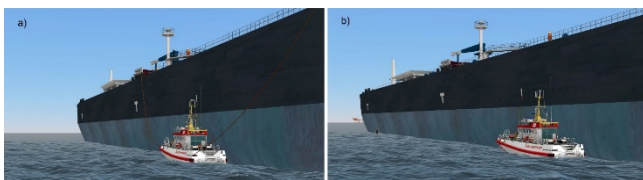


Figure 5. visualization of: a) traditional way of mooring small service craft, and b) service watercraft equipped with MEMS. Source: Authors' own study carried out on manoeuvring simulators of the Gdynia Maritime University in December 2022.

The principle of operation is described as follows: the service vessel approaches the side of the serviced unit by its stern at the point closest to the bow of that vessel. The electromagnetic gripper is attached to the hull of the serviced unit above sea level. The intervention boat, flowing perpendicularly from the

serviced unit, releases the mooring ropes using mooring winches and places floating power supply buoys in the water. Next service vessel with the use of its propulsion system, loosening and keeping the mooring ropes under constant, safe tension through the mooring winches located at the stern of this unit, approaches the side of the serviced unit in the place closest to the stern of this unit. The electromagnetic grippers are attached to the hull of the serviced unit. The service boat, while departing from the serviced vessel, releases the mooring ropes on the bow and, by using the integrated mooring winches and the control panel, maintains constant tension on the winches. Floating power supply buoys are placed in the water and both units are brought into contact with their sides by pneumatic spacer fenders. When all electromagnetic grippers are connected to the hull of the serviced unit the mooring winches start maintaining constant tension on these lines. The system is activated by the control panel, and the service unit can move to its final position relative to the serviced vessel at any moment and at any time without the assistance of the serviced unit's crew. The unberthing is the reverse process of the mooring process. Moreover, for safety reasons, in the event of any failure or the need for immediate unberthing, each of the electromagnetic grippers is equipped with an emergency electromagnetic release, which is activated by the control panel of the service watercraft.

The subject of the invention is shown as an example in the drawing Fig. 6 shows a Mobile Electromagnetic Mooring System (variant with two mooring points): a) top view in the side-to-side system; b) vertical view from the bow and/or stern and c) a view in the vertical plane from the ship's side.

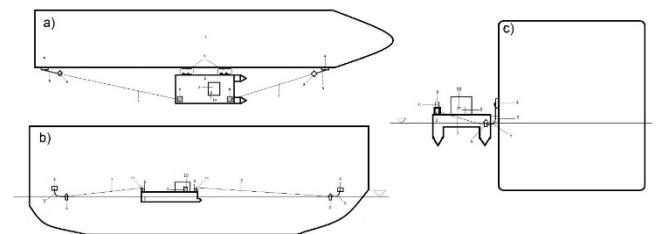


Figure 6. Mobile Electromagnetic Mooring System a) top view in the side-to-side system; b) vertical view from the bow and/or stern; c) a view in the vertical plane from the ship's side.

Based on the defined problems above, and their solutions in the form of the concept of a MEMS, an analysis of the current state-of-the-art and scientific databases was conducted. The aim of the study was to examine the available scientific information related to the MEMS system. This goal was achieved by searching selected Polish and international scientific databases, which include review publications, informational articles, and reports from journals and monographs published in both print and electronic form. The different scientific databases, that corresponded to the scientific discipline related to the analyzed topic were filtered out. The chosen databases were searched according to the established criteria using keywords in various configurations. The advantage of the adopted search method is narrowing the scope of the search only to the sought-after terms

and obtaining results that strictly describe the issue. In case of gaps in the search, related topics were sought. During the study, both scientific publications and national and international patent databases were analyzed. From the analysis of the state of the art, it can be concluded that the consideration of the MEMS system is a niche issue, at the same time requiring specialist knowledge and experience in the industry.

Currently, the MEMS project is at an advanced stage of research. A series of simulations and laboratory studies have been conducted on individual components of the system. Starting from the investigation of material strains and loads, through the examination of the magnetic field of electromagnets, to the studies of breaking forces. Prototypes of various electromagnetic gripper variants have been built, allowing for adaptation to different ship hull shapes. In addition, a control system for winches has been designed and tested. Currently, the prototype of the system is being mounted on the fast motorboat Merlin 6.15, on which sea trials will be conducted. The invention has been filed with both the Polish and European Patent Offices (IP: EP4082888A1). Nevertheless once full intellectual property rights are secured, detailed research findings will be published. In the meantime, this article presents an extensive introduction to the MEMS

technology, emphasizing its importance and capacity to transform the maritime industry.

#### 4 DISCUSSION

This study highlights the critical need for safer and more efficient mooring systems in the maritime industry, particularly in light of the increasing number of accidents and injuries associated with traditional rope mooring methods. In response to these concerns, various alternative mooring systems have been developed, such as the Shore Tension System, Vacuum Mooring System, and Magnetic Mooring System. Each of these systems demonstrates unique advantages and limitations, emphasizing the need for continued innovation in the field.

The Shore Tension System demonstrates its effectiveness in reducing the likelihood of line breaks and minimizing personal injuries, enhancing ship stability, and improving the safety and speed of loading and unloading operations. However, it requires a considerable amount of space on the quay, which may limit its applicability in some scenarios, like usage on small service watercraft. Table 1 presents the advantages and disadvantages of the MEMS system compared to traditional solutions.

Table 1. Feature, benefits, and advantages of MEMS compared to traditional solutions

Feature	Benefit	Advantage
Mitigation of swaying - the ability to maintain an unlimited position of a mooring vessel to a larger unit while allowing for safe repair/ service work to be carried out until the occurrence of the boundary conditions specified in international regulations, such as the Marine Guidance Note MGN 280 "Small vessels in commercial use for sport or pleasure, workboats and pilot boats – alternative construction standards," i.e., maximum wind force no greater than 4° on the Beaufort scale (5.5-7.9 m/s), corresponding to a sea state of 3/4 and wave height up to 1.5 meters. Reducing the adverse impact of hydrometeorological conditions on the degrees of freedom of the vessel.	This feature will be achieved through the use of an integrated mooring system. Electromagnetic grippers attached to the hull of the serviced vessel along the waterline will be connected through mooring lines to constant-tension mooring winches located on the service unit.	The service unit mooring to a larger vessel will not be restricted in any way by fixed elements connecting the two units. The system is flexible, and breaking forces are reduced. A unit equipped with MEMS can freely operate in sea conditions with a 4° Beaufort scale. A solution used by another mooring system based on electromagnets has its limitations due to the use of arms on extensions, which allow for operations up to a maximum wave height of 0.5 meters.
Mooring time - minimizing the time required for the mooring and unmooring process, as well as the movement of the auxiliary unit along the side of the base ship.	This feature will be achieved by making the docking vessel's crew independent from the base ship's operations. Financial benefits are gained by the shipowners who pay for every hour of the crew, machinery work, and laytime at anchorage.	The process of traditionally mooring a service ship to a base ship takes several to tens of minutes longer than mooring using an automated mooring system. Reduction of the processing time - comparison of standard mooring and using the MEMS system.
Safety - In relation to the number of accidents on the service ship and the serviced ship, it has been measured through a Job Hazard Analysis (JHA) assessment, also known as occupational risk.	The main benefits achieved through the use of the MEMS system will include: - elimination of the high angle of lines directed upward towards the high side of the serviced ship. - elimination of the involvement of the serviced ship's crew in the entire mooring, shifting, and unmooring process. - reduction of stress and loads on the lines and limitation of the vessel's inertial movement, which minimizes the risk of accidents related to mooring line operations. - elimination of the risk associated with accidents on the serviced vessel during the mooring, shifting, and unmooring process.	The use of the integrated Mobile Electromagnetic Mooring System (MEMS) in ship-to-ship (STS) mooring operations during the third stage (approach of the service vessel to the serviced vessel), fourth stage (mooring), fifth stage (repositioning the service vessel along the side of the serviced vessel to any chosen work point, changing mooring location), and sixth stage (unmooring) results in a 50% reduction in the risk of accidents at each stage compared to the traditional mooring system.
Elimination of the serviced vessel's crew involvement in the mooring process.	When using the mooring system, a crew is required only on the service vessel. There is no need for paid man-hours and human	A reduction in the number of people involved in mooring by (2-4) individuals.



<p>The mobility of the system allows for remote control of the system. Remote control of the gripper attachment provides greater freedom for the operator in detaching and reattaching the grippers. The service vessel can move along the serviced vessel without the involvement of both crews (2-4 people), with only one system operator being sufficient. In case of an emergency unmooring, the electromagnetic gripper detaches remotely by pressing the emergency button - the operation time is reduced to the time needed to wind the mooring line onto the winch (30m/min). This also results in a reduction of the negative impact on the environment.</p> <p>Avoided cost.</p>	<p>errors are eliminated.</p> <p>The continuous operation of the engine under load from the working propeller is eliminated:</p> <ul style="list-style-type: none"> <li>- reduction of mooring and unmooring time, meaning the engine operates for a shorter duration.</li> <li>- the engine does not operate while the service vessel moves along the serviced vessel.</li> </ul>	<p>Reduction of fuel consumption as a function of the time needed to move the vessel and a decrease in greenhouse gas emissions to the atmosphere during the service vessel's movement along the serviced vessel.</p>
<p>Mooring time - minimizing the time required for the mooring, unmooring, and moving of the support vessel along the side of the serviced vessel.</p>	<p>The reduction in the time it takes to perform mooring operations and moving the service vessel along the side of the serviced vessel can enable quicker detection of potential oil leaks or other damages.</p> <p>This feature will be achieved by making the docking vessel's crew independent from the base ship's operations. Financial benefits are gained by the shipowners who pay for every hour of the crew, machinery work, and laytime at anchorage.</p>	<p>Shortening the time it takes to detect a hull leak allows for quicker containment of the leak. This results in lower costs associated with compensation for the amount of pollution introduced into the marine environment. More cargo can be retained in the vessel's tanks. Faster detection and repair of the malfunction enables the vessel to return to normal operation more quickly (cost of chartering the vessel per day).</p> <p>The process of traditional mooring of an intervention vessel to a serviced vessel takes several to several dozen minutes longer compared to mooring using the automated mooring system. The reduction in process time can be observed by comparing the standard mooring procedure with the utilization of the MEMS system.</p>

The Vacuum Mooring System, on the other hand, offers a safe, quick, and efficient alternative to traditional mooring methods that do not require a crew on the shore or the vessel's deck. This system also results in lower fuel consumption and allows for the gentle application and release of pressure. Nevertheless, its hydraulic arms' inability to move laterally and vertically, as well as its specificity to particular ship types, may limit its application in certain situations.

The Magnetic Mooring System presents a significant step towards automating shipping operations, providing ease, safety, and efficiency compared to traditional rope mooring systems. However, the system faces limitations in certain scenarios, such as mooring tanker vessels due to the risk of electrical sparks or when the ship's hull is less than eight millimeters thick. Moreover, the system may be affected by electrical blackouts, necessitating backup power sources, and contingency measures.

The primary drawbacks of the previously mentioned systems include their large size, making them unsuitable for smaller vessels under 24 meters in length, and their inability to quickly move the moored vessel horizontally along the mooring system. These systems are designed for large port facilities and are not suitable for use in service watercraft operations.

The Mobile Electromagnetic Mooring System (MEMS) presented in this research article is a novel approach to address the challenges faced by small intervention, diving, service, and other vessels during mooring operations necessary for underwater repair work. By reducing the probability of accidents related to mooring line operations and improving the

efficiency of mooring and unberthing processes. The MEMS has the potential to significantly enhance the safety and effectiveness of these operations. One of the key benefits of the MEMS is its human-centric design, aligning with the recent MEG4 guidelines, which prioritize the safety of crew members during mooring operations. By reducing the involvement of personnel in the mooring process and ensuring a safer mooring arrangement, the MEMS can contribute to a more secure working environment for divers and other crew members involved in underwater work.

The state-of-the-art analysis conducted by the authors indicates that the MEMS system is a niche subject, underscoring the importance of specialized knowledge and experience in the industry. As the MEMS project advances through its research and development stages, including sea trials using a prototype mounted on the fast motorboat Merlin 6.15, the potential impact of this technology on the safety and efficiency of mooring operations for small intervention units and their serviced vessels becomes more apparent.

While the MEMS shows great promise in addressing many of the challenges associated with traditional mooring systems, it is essential to continue exploring alternative mooring technologies and strategies to further enhance safety and efficiency in the maritime industry. Future research should focus on addressing the limitations of existing mooring systems and exploring the applicability of innovative technologies like the MEMS in various maritime scenarios. In doing so, the industry can continue to evolve and adapt to the ever-changing demands of global

shipping operations while prioritizing the safety of all personnel involved.

## 5 CONCLUSION

This study highlights the evolution of modern mooring systems and their impact on addressing excessive ship motions during mooring operations. The analysis focuses on three alternative mooring methods: Shore Tension System, Vacuum Mooring System, and Magnetic Mooring System, each offering different benefits and drawbacks.

The current problems associated with traditional mooring systems, such as the increased risk of mooring breaking or sliding off, high angles of mooring lines, and the prolonged time required for emergency responses, necessitate the development of safer and more efficient mooring systems. Automated vacuum and magnetic mooring systems have emerged as promising alternatives to traditional mooring systems, offering benefits such as reduced crew workload and improved safety.

In conclusion, this study underscores the importance of continued development and improvement of mooring systems to ensure the safety of ships, terminals, and the environment. It is crucial to address the current challenges and limitations of traditional mooring systems through the development of novel systems that prioritize safety, efficiency, and human-centric design. Collaboration between regulatory bodies, industry stakeholders, and researchers will be essential in driving innovation and creating mooring systems that meet the ever-evolving needs of the shipping industry.

The Mobile Electromagnetic Mooring System represents a significant advancement in the field of mooring systems for small intervention, diving, service, and other vessels. By addressing the main problems encountered during mooring operations and providing a safer and more efficient solution, the MEMS has the potential to revolutionize the industry and improve the overall safety and speed of underwater hull inspection, cleaning or repair work, and other related operations. Further research and development, as well as real-world testing, will help refine the system and ultimately contribute to its successful implementation in the field.

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