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Technical and Ecological Aspects of Water-lubricated Stern Tube Bearings

Abstract

A ship's propulsion system has a significant impact on the ship's energy efficiency, environmental friendliness, reliability and safety. An indispensable part of a propulsion system with mechanical power transmission is a stern tube with bearings. During operation, the sliding bearings material is subjected to stresses caused by a force proportional to the total mass of the shaft and propeller. The reliability of stern tube bearings is particulary important for safety, and their durability has a significant impact on maintenance costs. Depending on the lubricant, there are bearings that are lubricated with oil or water. The permissible bearing load with hydrodynamic lubrication depends primarily on the material, the viscosity of the lubricant used and the shaft speed. Metals and their alloys with a low coefficient of friction are used for oil-lubricated bearings. Bearings lubricated with water are made of a special type of hardwood ("tree of life", lat. *lignum vitae*), rubber or various synthetic materials. The main advantages of oil-lubricated bearings are higher allowable load and durability than water-lubricated bearings. This paper analyses the technical and environmental aspects of the application of water-lubricated bearings whose main advantages are simplicity, better cooling and environmental protection.

Keywords: stern tube bearing, water-lubrication, environmental protection

1. Introduction

The reliability, competitiveness and safety of a ship depend largely on the propulsion system and the individual parts of that system. The main component of the propulsion system of most modern ships is the internal combustion engine, while the propeller is used as the propulsor. In cargo ships, slow-speed diesel engines with mechanical power transmission to the propeller are mainly used for reasons of reliability and economy in operation. A much smaller share refers to medium-speed diesel engines, steam and gas turbines with mechanical or electrical power transmission. The low rotation speed of diesel engines allows easy mechanical transmission of torque from the crankshaft to the propeller shaft. When higher speed prime movers are used, the speed must be reduced to that required for the propeller using a suitable mechanical or electrical transmission. When selecting a propulsion system, consideration is given to the energy, economic and environmental acceptability of the system as a whole and of each individual part of the system.

The prime mover largely determines the characteristics of the propulsion system, and a significant impact on safety, reliability, cost, and the environment is also exerted by the part of the propulsion system called the stern tube. The stern tube with its associated radial bearings, transmits the load caused by the mass of the shaft and propeller to the structure of the ship. In addition, depending on the design, the stern tube is equipped with appropriate seals and other elements necessary for lubrication and cooling of the bearings. Depending on the lubricant used, there are different versions that use water (freshwater or seawater) or oil to lubricate the stern tube bearings. Non-metals such as special types of hardwood and various synthetic (*polymeric*) materials are mainly used for water-lubricated bearings, while the material for oil-lubricated bearings are metals or their alloys (*bronze, lead and tin alloys*). The main advantages of water-lubricated bearings compared to oil-lubricated bearings are simple construction and maintenance, as well as environmental friendliness. Oil-lubricated bearings are durable and can withstand higher loads, but in the event of seal damage, oil leakage and marine pollution occurs.

In maritime transport, as in all other activities, we strive to achieve the highest possible efficiency, and at the same time reduce the negative impact on the environment to a minimum. MARPOL 73/78 does not allow the release of oil into the sea from ships (engine room and cargo space), except in exceptional circumstances. The IMO Polar Code, in force since January 2017, also prohibits the discharge of even the smallest quantities of oil in the Arctic and Antarctic region [1]. Recently, there has been an increase in the interest and number of commercial voyages in the North Sea, so there is a need for technical solutions that ensure the environmental friendliness of maritime transport. According to IMO requirements, in particularly sensitive sea areas and marine ecosystems, no tolerance is required for any type of pollution that might be caused by oil spills from ships. To avoid pollution when mineral lubricating oil is used in USA territorial waters, the use of biodegradable lubricating oil for the stern tube bearings is required. Since the oil used to lubricate the stern tube bearings is a potential source of pollution and biodegradable oils are expensive, the use of water-lubricated bearings is recommended.

2. Stern tube design

In this paper, the stern tubes are distinguished according to the medium used to lubricate and cool the bearings. The stern tube bearings can be lubricated and cooled with water or oil, depending on the design and material. Until the middle of the last century, stern tube bearings made of a special type of hardwood *lignum vitae* (from Latin „wood of life) from South America were predominant. The lignum vitae contains natural oil that contributes to the self lubricating effect of the bearing.

The main reason for switching to versions with oil-lubricated bearings is the relatively short service life of water-lubricated bearings. As a rule, a bearing made of *lignum vitae* had to be replaced after five years of use. Depending on the operating conditions of the ship, bearing problems would occur much earlier, which caused additional costs and could endanger the safety of the ship. These reasons led to the use of oil-lubricated bearing systems that prevailed in the second half of the 20^{th} century marginalizing the use of water-lubricated bearings. All stern tube bearing lubrication systems, regardless of the lubricant used, must reduce friction and provide hydrodynamic lubrication of the bearings to prevent excessive bearing wear and heating. However, the requirements for zero tolerance to pollution and the development of new technologies and materials offer water-lubricated bearings a new opportunity.

According to [2], a total of 130 to 244 million liters of oil escape from the sterntube bearing lubrication system into the sea each year. As well as [3] estimates that even under ideal conditions, at least 10 million liters of oil would leak from the stern tube into the sea each year. According to an analysis by EMSA (*European Maritime Safety Agency*) of data collected by satellites during 18 months in 2007 and 2008, 4027 possible cases of oil spills from ships were detected. Subsequent inspections from the air or from the ship confirmed that in almost 80% of the cases there was a mineral oil spill [4]. In [5], it was pointed out that due to difficult working conditions (bad weather conditions and vibrations), it is not possible to completely avoid oil leakage from the stern tube into the sea. The analysis of propeller shaft-related failures conducted in [6] showed that in the observed period of 20 years, 10% of the failures affected the aft bushing of the shaft and 4% to the forward bushing. It is also interesting to note that damage to the sealing rings accounted for 43% and 24% of the total number of failures, respectively.

It follows that achieving the goal of zero tolerance to oil pollution from the operation of ship systems depends on the application of environmentally friendly solutions. In doing so, special importance is given to materials that allow the efficient use of seawater as a lubricant for the stern tube bearings. According to [7], more than 2000 ships in operation are equipped with THORDON bearings lubricated with seawater.

Below is a brief overview of the stern tube bearing lubrication systems using oil and water with a comparison of their characteristics.

2.1. Closed stern tube lubrication systems

Modern systems that use oil to lubricate the stern tube bearings are also called “closed” stern tube systems. In closed systems, there are two radial slide bearings in the stern tube. Oil leakage and sea penetration into the stern tube is prevented by several sealing rings (lip seals). The most common designs are with three or four lip seals on the propeller side (aft seal) and two lip seals on the engine room side (forward seal). The beginning of the use of the closed stern tube system dates back to 1948 when the Blohm & Voss company introduced the Simplex seal lubrication system for white metal bearings [8], [9].

In most versions, cooling of the bearing or lubricating oil is achieved by transferring heat from the stern tube to the sea into the aft peak tank. For this reason, the aft peak tank is always partially filled with water. The heat from the water in the tank is transferred by convection through the hull to the surrounding sea, faciliating the movement of the ship. Stern tube lubrication systems with a pump and oil cooler are less commonly used. An important part of the system is the gravity tank, which provides a higher oil pressure in the stern tube than in the surrounding sea, preventing seawater from entering the stern tube in the case of damage to the lip seals. Systems with “low” and “high” gravity oil tanks are mainly used to achieve the appropriate pressure difference when the ship is empty or loaded with cargo. With one or two gravity tanks, it is not possible to achieve an optimal pressure difference under all operating conditions. A deviation from the optimum pressure difference, especially with simultaneous damage to the seals, can lead to oil leakage or seawater penetration into the stern tube.

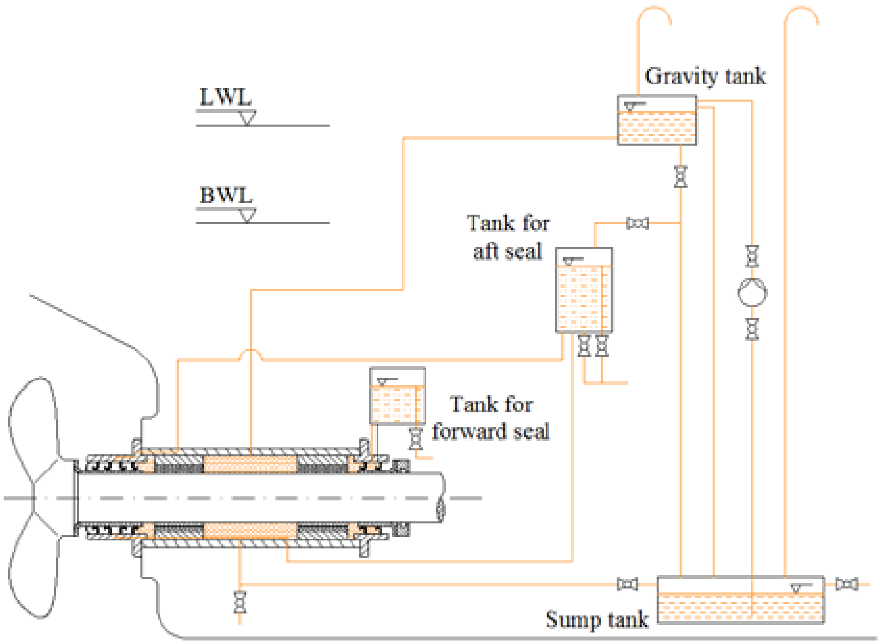


Fig. 1. Closed stern tube system with one gravity tank (source: Authors)

The closed stern tube system with one gravity tank is shown in Fig. 1. The use of only one gravity tank allows the pressure difference to be adjusted only in a limited range depending on the draft of the ship. This disadvantage is particularly pronounced in case of damage to the seals on the propeller side when the ship is immersed to the ballast water line (BWL). In this case, there is higher probability of the oil leakage from the stern tube due to the greater pressure difference.

The described disadvantage can be partially compensated by the application of the lubrication system in Figure 2 with two gravity tanks. However, even with the version with two gravity tanks, despite the greater possibility of regulating the pressure difference, increased oil leakage can occur if the seals on the propeller side are damaged.

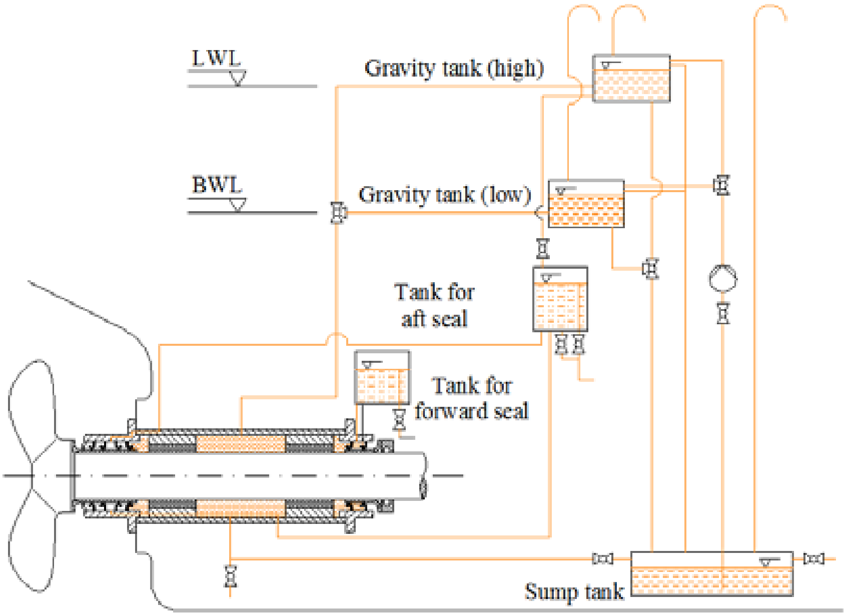


Fig. 2. Closed stern tube system with two gravity tanks (source: Authors)

Figure 3 shows the aft seal system with water, air and oil chamber. The air chamber has the function of preventing oil leakage or sea penetration into the stern tube under all operating conditions as well as in case of damage to the seal on the propeller side.

The detail of the aft seal used in the previous example is shown in Figure 4. The drawing shows a sealing system with four seals bounding the chambers filled with water, air and oil. The special part of the system shown in Figure 3 maintains the appropriate pressure in the air chamber under all operating conditions of the ship, even in case of minor damage to the outer seal. With this type of aft seal, oil leakage is not completely prevented, but is significantly reduced in the case of minor damage to the aft lip seal.

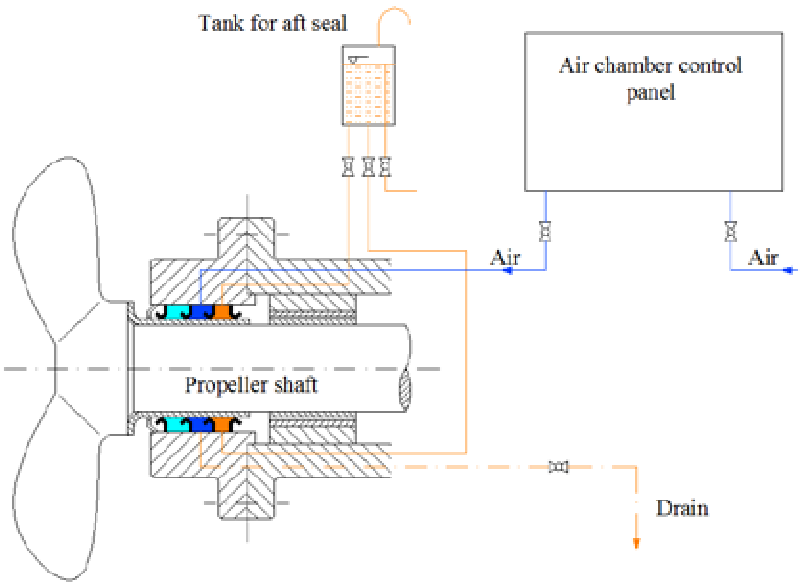


Fig. 3. Aft seal system with air chamber (source: Authors)

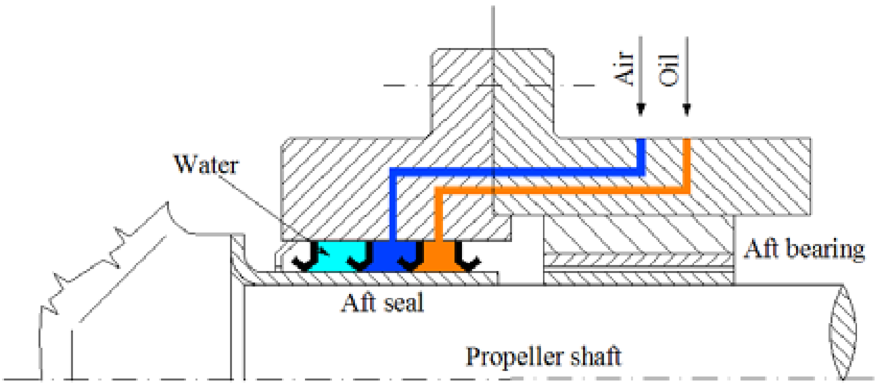


Fig. 4. Design of the aft seal with an air chamber (source: Authors)

The pressure in the air chamber adjusts to the draft of the ship. The adjustment can be manual or automatic. Automatic adjustments are especially important for vessels that have large differences in draft between load and ballast conditions. An additional input signal from a draft meter or pressure sensor is required to automatically adjust the air pressure to the ships draft.

2.2. Open stern tube lubrication systems

Open stern tube systems made of natural material, a special type of hardwood from South America, *lignum vitae*, were used intensively in the first half of the 20th century. They are characterized by their simplicity, but since the natural material is used, its mechanical properties are not uniform. Non-uniform mechanical properties, as well as the inability to adapt the material to specific requirements in some cases, lead to damage occurring much earlier, which cannot be predicted or detected by regular inspections. An example of an open stern tube with aft bearing made of *lignum vitae* is shown in Figure 5.

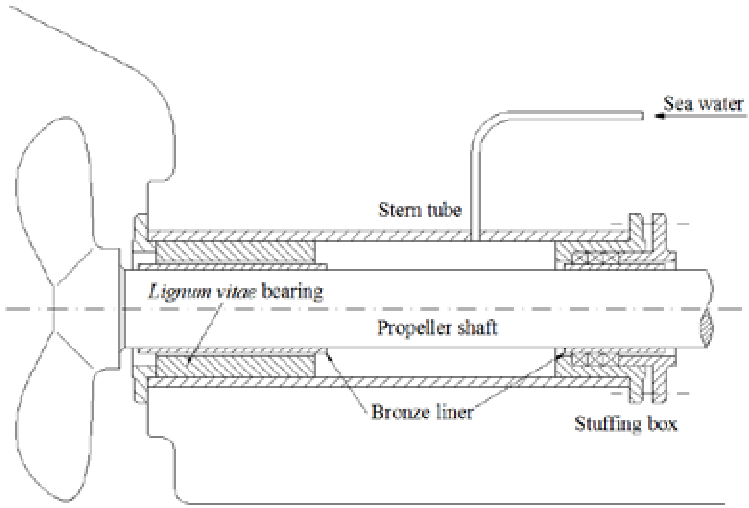
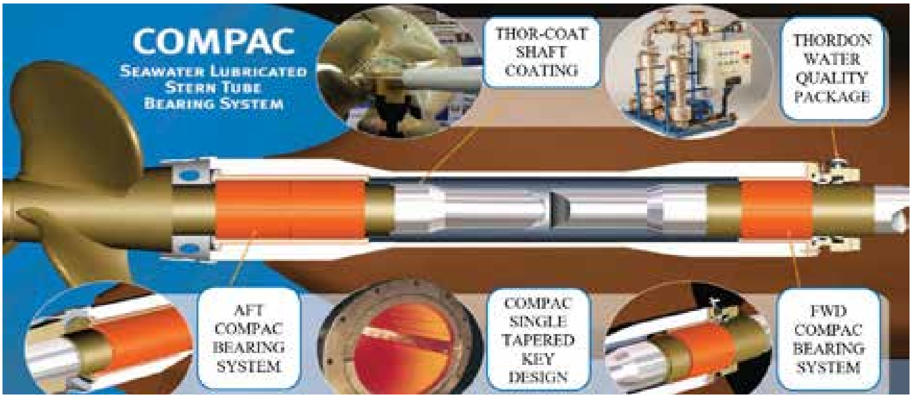


Fig. 5. Open stern tube system with bearing made of wood (source: Authors)

In the second half of the 20th century, open stern tube systems began to be pushed out of use by closed systems that use lubricating oil and relatively complex sealing systems. Closed oil systems are prone to damage on the propeller side and increase oil leakage, which cannot be completely avoided even by using complex seals. At the turn of the century, ships primarily used closed sterntube systems. However, in the 21st century, there is another opportunity to open stern tube systems in which the water-lubricated bearings are made of synthetic polymer and composite materials. In modern open stern tube lubrication systems, water or sea treatment (purification) devices are used in some cases to avoid the abrasive effect of seawater. Such a system is shown in Figure 6.



Open stern tube system with a bearing made of polymeric material (source: [7], adapted by the authors)

3. The principle of operation of fluid-lubricated bearings

The bearing must be designed to separate shaft from the bearing during rotation to minimize the operation under conditions of “dry” friction. According to the hydrodynamic principles of the sliding bearing operation, the formation of a thin lubricant layer is affected by the bearing load, the shaft speed, the lubricant used and the profile of the bearing surface. For each bearing design, there is a minimum speed at which the shaft must rotate to achieve hydrodynamic lubrication.

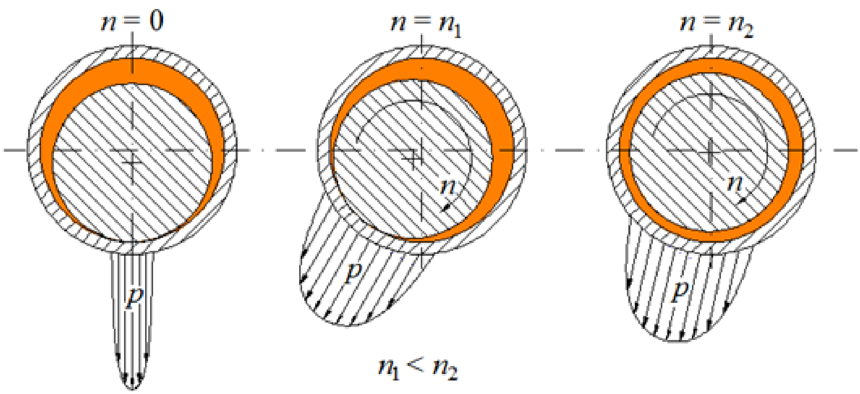


Fig. 7. Hydrodynamic lubrication principle (source: Authors)

Figure 7 shows the formation of the oil layer required for hydrodynamic lubrication of the slide bearing. At the moment when the shaft starts to rotate, a thin layer of lubricant is formed, and when the conditions are met, the shaft journal separate from the bearing. In this way, a significant reduction in friction is achieved, resulting in lower heating and lower bearing wear. In bearings that operate according to hydrodynamic principles in normal operation, significant bearing wear occurs when the shaft rotation is started and stopped. This occurs because the bearing runs "dry" during these periods and the pressure in the oil layer is not high enough to separate the shaft from the bearing. Metal bearings use special metal alloys (bronze, white metal and others) that can withstand short-term operation under conditions of "dry" friction. Synthetic polymers and composites used for bearings have high resistance to surface pressure and wear under dry friction conditions. To protect the propeller shaft from damage coused by the corrosive and abrasive action of seawater, a replaceable bronze liner made of metal or other corrosion-resistant material is placed on the part of the shaft that comes into contact with the bearing.

Considering only the technical aspects, the application of lubricating oil generally provides better lubrication than freshwater or seawater. With oil lubrication, the conditions for hydrodynamic lubrication occur due to the higher viscosity of the oil at lower speeds. However, water has an advantage in cooling efficiency, due to its higher specific heat compared to oil. Water (freshwater or seawater) is an environmentally friendly solution and is also fully compatible with open stern tube systems.

3.1. Metal bearings

Fig. 8. Oil-lubricated stern tube bearing made of metal (source: [10])

Oil-lubricated stern tube bearings are manufactured as one-piece bearings in which a layer of white metal alloy is applied or cast onto a metal (steel) bearing bracket. An example of such a white metal alloy bearing is shown in Figure 8.

3.2. Bearings made of polymeric material

Bearings made of polymeric material are mainly made of a type of material whose characteristics correspond to the requirements of the application. The bearing bracket is usually made of steel, and its shape and dimensions are designed for quick and easy installation in the stern tube. Figure 9 shows a Thordon COMPAC type bearing designed to operate in seawater. Material properties have been selected to minimize the coefficient of friction to minimize wear under dry friction conditions. The lower half of the bearing is smooth and the upper half has longitudinal grooves for better lubrication and cooling.

Fig. 9. Stern tube bearing lubricated with seawater (source: [11])

Figure 10 shows the design of a composite polymer bearing in which the inner layer is made of a material with high resistance to the abrasive action of the water mud to which tugs are exposed on rivers. The outer layer of the Thordon RIVER TOUGH type is designed to compensate for shock and vibration and has longitudinal grooves that allow better cooling of the bearing.

Fig. 10. Stern tube bearing lubricated with water (source: [11])

Reinforced composite plastic material that has a very low coefficient of volume expansion is suitable for use in extremely cold (North Sea) or warm (tropical) conditions. The bearing was developed by Durmax Marine. An example of the installation is shown in Figure 11.

Fig. 11. Bearing made of composite material lubricated with seawater (source: [12])

4. Technical and environmental aspects of the application of water-lubricated bearings

When analyzing the technical and environmental aspects of the application of water-lubricated bearings, attention should be paid to features such as durability, reliability, safety, investment cost, installation, maintenance, compliance with regulations and environmental friendliness. A comparison of the characteristics of the stern tube system mentioned in this paper shows that open systems using water or seawater lubricated bearings are absolutely environmentally friendly. It is undisputed that the environmental friendliness of the lubricant deserves special attention. The graph in Figure 12 shows that the leakage of lubricating oil accounts for more than 10% of the total marine pollution caused by oils [13].

The design and number of parts of the stern tube with water-lubricated bearings is much easier to manufacture and maintain, and there is no costs to purchase lubricants. Therefore, it is realistic to expect that the total cost of using water-lubricated bearings will be lower.

The significant reduction in costs when using water-lubricated bearings is supported by the fact that systems using oil-lubricated bearings to reduce the negative impact on the environment are much more complex not only in production but also in maintenance. One disadvantage of water-lubricated bearings is the inability to achieve hydrodynamic lubrication at high loads and low propeller shaft speeds. This disadvantage can be compensated by the development of new composite materials, suitable design and design of the bearing surface.

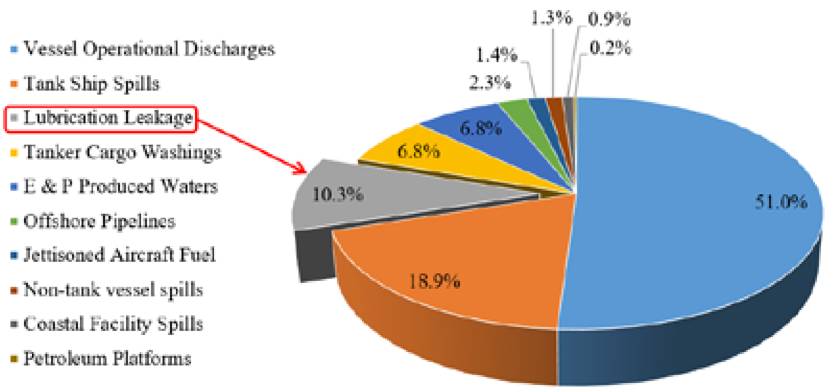


Fig. 12. Marine environment pollution by oils (source: [13], adapted by the authors)

Table 1.: Ecological acceptability of various technical solutions for lubrication of stern tube bearings (source: [13], adapted by the authors)

Enviro Solution Level	Aft Seal Configuration	Lubrication	Uses of EAL* in seawater interfaces	Risk of disscharge above limit during normal operation	Risk of discharge above limit following severe damage	
Enviro 1	No Aft Seal	Sea or Water	Compliant	Zero	Zero	Increasing Environmental Acceptance
Enviro 2	Conventional Seal	Fresh Water	Compliant	Zero	Zero	
Enviro 3	Anti Pollution – No Oil Water interference seal	EAL*	Compliant	Zero	High	
Enviro 4	Anti Pollution – No Oil Water interference seal	Mineral Oil	Compliant	Zero	High	
Enviro 5	Conventional Seal Oil Water interference seal	EAL	Compliant	Low	High	
Oil water interface seal (90% of vessels)		Mineral oil	Not compliant	NA	Very High	

** EAL – Environmentaly acceptable lubricants*

Table 1 shows the level of environmental acceptability of technical solutions that use oil or water to lubricate the stern tube bearings.

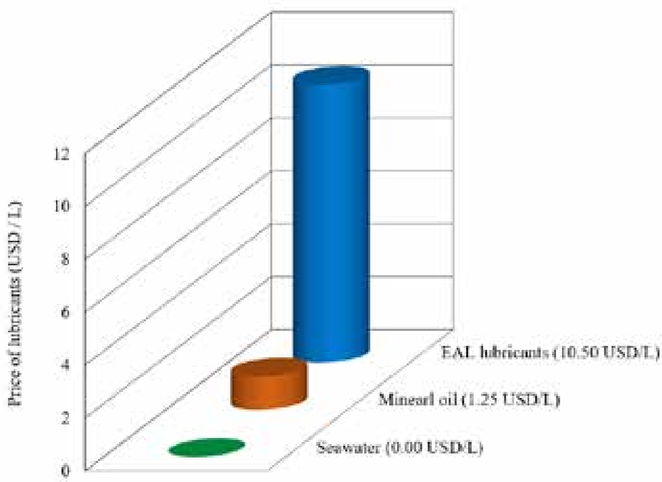


Fig. 13. Comparison of lubricant costs for stern tube bearings (source: [14] [15], adapted by the authors)

According to the data in Figure 13, a comparison of the costs associated with the use of a particular lubricant shows that the use of environmentally friendly lubricants has about eight times higher costs compared to mineral oils.

The results of the research conducted by Thordon show that stern tube bearings made of high-quality materials and lubricated with water can fully satisfy in terms of durability, reliability, safety and low maintenance costs. The research confirms the usability of water-lubricated bearings with a large (615 mm) propeller shaft diameter. Figure 14 shows the increase in the clearance of the water-lubricated bearing on a passenger ship. The measurements were performed on a ship with two propellers, and average clearance values were given for the aft bearings of the left and right propeller shafts. The results obtained show that the increase in bearing clearance is less than allowed even after 18 years of operation, and the total bearing life is estimated at 25 years.

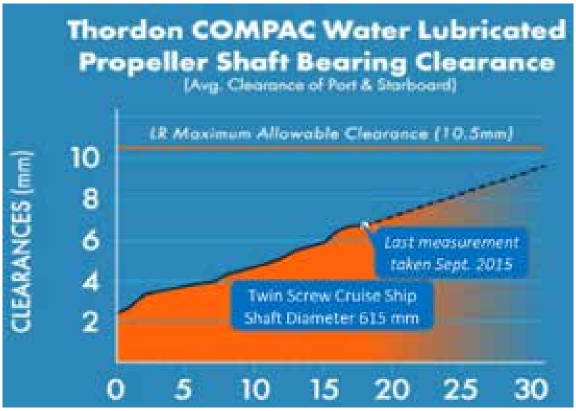


Fig. 14. Increasing the clearance of the stern tube bearing in operation (source: [14])

5. Conclusion

When choosing the optimal technical solution for stern tube bearing lubrication, one can choose between open and closed lubrication systems. All closed systems presented in this paper use lubricating oil, while the open systems use freshwater or seawater. The lubricant used has a significant impact on the complexity, durability, reliability, investment and maintenance costs of the stern tube system, and also on the environmental impact of the chosen technology.

According to the current state of development of materials and technical solutions entrusted and accepted by the shipbuilding industry, the application of oil-lubricated bearings predominates in the world maritime fleet. Their main advantage is the ability to create conditions for hydrodynamic lubrication at lower shaft speeds and higher bearing loads than water-lubricated bearings. Due to its higher viscosity, oil is technically a much more favorable lubricant than water. However, the advantages of water as a lubricant are significantly better bearing cooling and complete environmental friendliness. Even with closed oil stern tube systems that use oil in operation, it is not possible to completely avoid the leakage of oil into the environment.

The progress made in improving the characteristics of water-lubricated bearings, as well as the contribution to environmental protection, show that their use is justified. It is expected that in the near future there will be a transition from a system using lubricating oil to systems that use freshwater or seawater for lubrication.

Acknowledgement

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