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Classification of Ship Propeller Types and Energy-Saving Devices Under Technology Developments

Teknolojik Gelişmeler Kapsamında Gemi Pervane Tipleri ve Enerji Tasarruf Cihazlarının Sınıflandırılması

Türk Denizcilik ve Deniz Bilimleri Dergisi

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Murat BAYRAKTAR [1,*], Onur YÜKSEL[1], Burak GÖKSU[1]
[1]*Zonguldak Bülent Ecevit University, Maritime Faculty, Zonguldak, Turkey*

ABSTRACT

The propulsion system and its components need to be thoroughly analyzed and optimized for marine vessels to operate as efficiently as possible in applications where new builds or retrofitting are performed. Gearboxes, bearings, and other transmission equipment in the component of the power transmission from ship engine, which is the primary source of propulsion for most marine vessels, to propeller cause a variety of losses. To maximize propulsive efficiency, propeller selection should be performed precisely on the basis of ship type, operation mode, and area. Propulsion efficiency, fuel consumption, robustness, reliability, emissions, vibration, cavitation, complexity and cost are investigated in both conventional propellers and cutting-edge technology in propeller systems. This study will guide academicians, experts, and sector stakeholders in determining which propeller type will be more efficient for marine vessels since propulsion efficiency is critical for the sustainability of maritime transportation.

Keywords: Energy efficiency, Propeller types, Marine vessels, Propulsion system

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*(corresponding author)
e-mail: bayraktarmurat@beun.edu.tr

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ÖZET

Sevk sistemi ve bileşenlerinin, yeni inşaların veya güçlendirmenin gerçekleştirildiği uygulamalarda deniz taşıtlarının mümkün olduğunca verimli çalışması için kapsamlı bir şekilde analiz edilmesi ve optimize edilmesi gerekir. Çoğu deniz taşıtının ana itme kaynağı olan gemi makinelerinden pervaneye güç aktarımı bileşenindeki dişli kutuları, yataklar ve diğer aktarma ekipmanları çeşitli kayıplara neden olmaktadır. Sevk verimini en üst düzeye çıkarmak için pervane seçimi tam olarak gemi tipine, operasyon moduna ve alana göre yapılmalıdır. Pervane verimliliği, yakıt tüketimi, sağlamlık, güvenilirlik, emisyonlar, titreşim, kavitasyon, karmaşıklık ve maliyetler hem geleneksel pervanelerde hem de en son teknoloji pervane sistemlerinde incelenmektedir. Bu çalışma, deniz taşımacılığının sürdürülebilirliği için itme verimliliği kritik öneme sahip olduğundan, akademisyenlere, uzmanlara ve sektör paydaşlarına deniz taşıtları için hangi pervane tipinin daha verimli olacağını belirlemede yol gösterici olacaktır.

Anahtar sözcükler: Enerji verimliliği, Pervane çeşitleri, Deniz taşıtları, Sevk sistemi

1. INTRODUCTION

The team in the design department conducts ship resistance evaluations that primarily impact ship service speed, propeller selection, installed engine power, and propeller RPM (Abramowskiet *et al.*, 2010). The right propeller selection is a crucial factor to come over the total resistance at the specified service speed considering the installed ship engine power output in order to guarantee that the analysis is as effective as possible (Gharbi *et al.*, 2018). Distinct or comparable propeller types are deployed for each ship type, with the greatest diversity in propeller size occurring when both ship and propeller types are included. How much of the ship's main engine's power is transmitted to the propeller is a crucial factor when selecting a propeller. Figure 1 describes the power transmission process of a ship, including indicated to thrust horsepower phase.

The downward force exerted on the piston as a result of the combustion of the delivered fuel is referred to as the indicated horsepower. The bore of the cylinder, the cylinder stroke length, indicated pressure, and engine revolution are the primary factors used to calculate indicated power (IHP). The rate between the engine's indicated power to the maximum power (MP) that can be obtained from the amount of fuel injected to combustion chamber per second ($\dot{m}_f$) based on low calorific value (LCV) in which there is not any loss of power expressed as indicated thermal efficiency (η_{ite}).

$$\eta_{ite} = \frac{\text{IHP}}{\dot{m}_f \cdot \text{LCV}} \tag{1}$$

Calculated by measuring the amount of torque at the engine coupling output, brake horsepower (BHP) represents the useful work performed by the engine. The ratio between MP and BHP is describes as brake thermal efficiency (η_{bth}).

$$\eta_{bth} = \frac{\text{BHP}}{\text{MP}} \tag{2}$$

The power measured over the shaft is shaft horsepower (SHP), and the losses between brake horsepower and shaft horsepower are caused by transmissions and bearings. After all shaft-line losses, the power supplied to the propeller is referred to as delivered horsepower (DHP). The ratio between DHP and BHP defines shaft transmission efficiency (η_s).

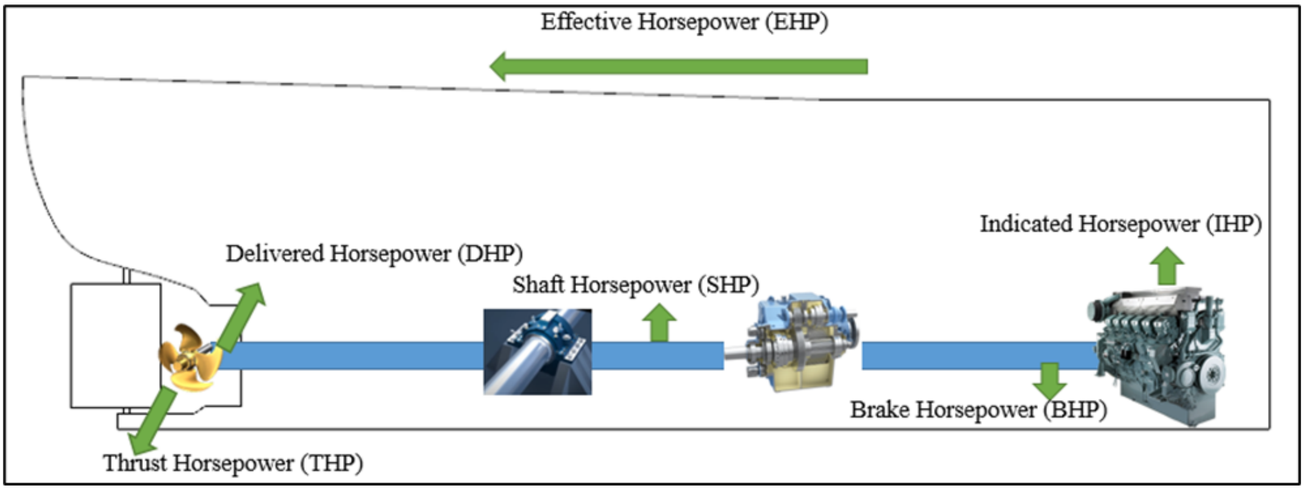


Figure 1. Ship Powertrain Systems

$$\eta_s = \frac{\text{DHP}}{\text{BHP}} \tag{3}$$

The power derived from the propeller is referred to as thrust horsepower, and the majority of efficiency losses between DHP and THP are attributable to propeller efficiency which is the ratio between DHP and THP defines propeller efficiency (η_p). Propeller type, number of blades and dimensions are fundamental factors on propeller efficiency throughout the operations.

$$\eta_p = \frac{\text{THP}}{\text{DHP}} \tag{4}$$

Effective horsepower (EHP) is based on the resistance components that occur at a given speed and the ratio of EHP to THP is described as hull efficiency (η_h).

$$\eta_h = \frac{\text{THP}}{\text{EHP}} \tag{5}$$

In current diesel engines, the transmission of power from the connection to the propeller results in a power loss of between 8 and 10 percent (Ganesan, 2012; Kuiken, 2017). Figure 2 provides a full description of the propeller's terminology and geometry.

Propeller geometry is based on the propeller root and tip, propeller blade surfaces, and propeller hub. The connection points of the propellers to the hub are referred to as the propeller root, while the outermost portions are referred to as the propeller tips. The high-pressure side is the propeller's face and is responsible for propelling the flow ahead. The low-pressure side, on the other hand, is the back of the propeller and generates suction power.

The leading edge of the propeller is the first region to cut off the water flow, and the trailing edge is where the water flow leaves the propeller blade. Pitch refers to the amount of forward movement gained each completed propeller rotation. In addition, the discrepancy between the actual pitch and the predicted pitch is known as a slip. Figure 3 defines the propeller-critical parameters rake and skew (Michigan Wheel, 2000; Çelik, 2010).

The blade's fore or aft slant with respect to a line perpendicular to the propeller's rotational axis is described as the rake. Blade slants towards the aft and the forward end of the hub are described as positive and negative rakes respectively. Skew is the transverse sweeping of a blade such that looking at the blades from the front or back is described as an asymmetrical shape in Figure 3 (Michigan Wheel, 2000). Disc area, propeller sections, expanded outlines, blades outlines and areas are described in Figure 4.

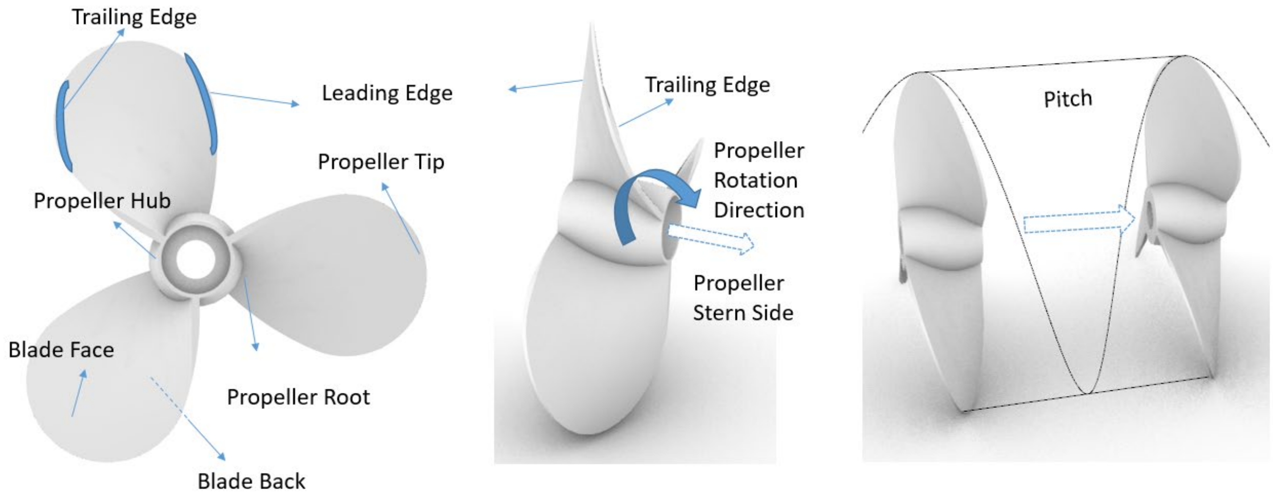


Figure 2. Propeller geometry and terms

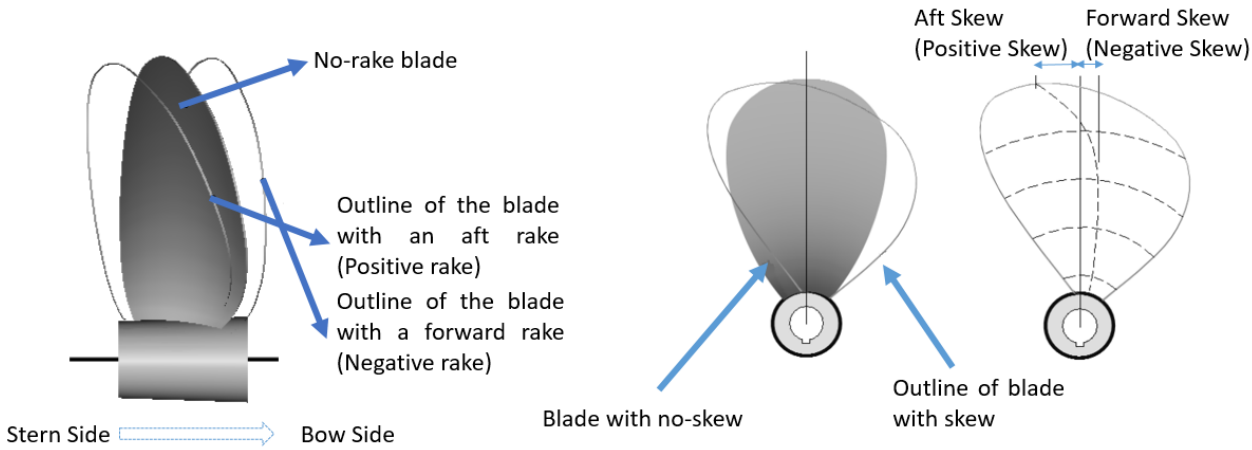


Figure 3. Rake and skew of the propeller

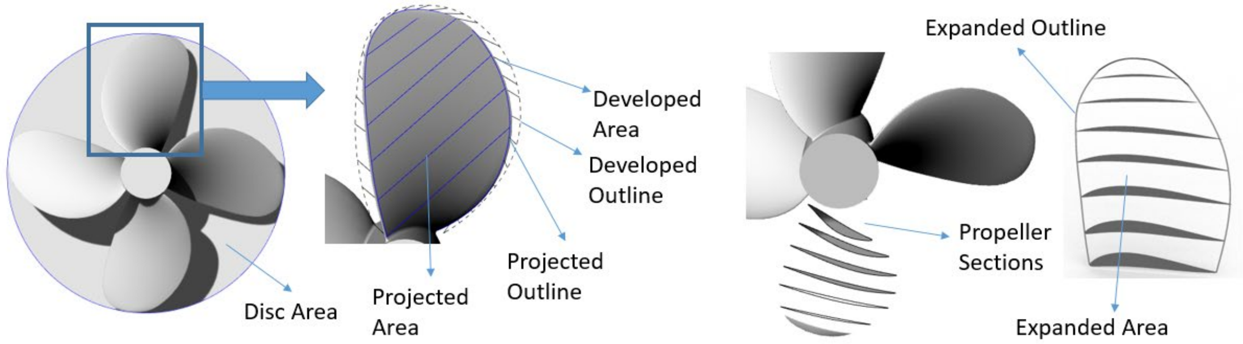


Figure 4. Disc area, propeller sections, expanded outlines, blades outlines and areas

The area of the circle which is drawn based on propeller tips refer to disc area and it is calculated using the propeller diameter (D).

$$\text{Disc Area} = \frac{\pi D^2}{4} \tag{6}$$

The ratio of blade areas to disc area is expressed as the blade area ratio (BAR). Projected outline is the viewed plotting from the face or the back of the propeller blade in which the shaft centerline and the view are on the same axis and also in which plotting area is described as Projected area. Developed outline in which the propeller blades are separated from the propeller hub and their pitch value is reduced to zero so that helically based views are acquired. The area remaining inside developed outline is developed area. Expanded outline in which the chord lengths are plotted around the directrix at the appropriate radial stations. The outline is created by laying off the chord length along a straight line at each radius r. The propeller is changed from a helix to a flat plane in the expanded view. Expanded area is the area covering along the outline drawing. In addition, projected area, developed area and expanded area to total disc area are expressed as Projected Area Ratio (PAR), Developed Area Ratio (DAR) and Expanded Area Ratio (EAR) respectively (Roh, 2006; Hydrocomp, 2007). Each ratio differs according to the propeller type and the applied vessel types. Propeller types and features have been explained in detail in the second part.

2. PROPELLER TYPES AND FEATURES

Cavitation, vibration, underwater noise level, propulsion efficiency, and maneuverability are crucial aspects to consider while selecting a ship's propeller (Carlton, 2018). In this paper, the diversified propeller types and their efficiency improvement applications have been investigated in terms of specified criteria. Fixed pitch propeller (FPP), controllable pitch propeller (CPP), ducted propellers, contra-rotating propellers (CRP), Z-drive units, podded azimuthing propellers, waterjet propulsion, tandem propellers, super cavitating or surface-piercing propellers, cycloidal propeller, overlapping propeller, grim vane wheel propeller, tip vortex free, contracted loaded tip (CLT), Mewis ducted propeller, Kappel propeller, paddle wheels have been evaluated as propeller types. In addition, propeller boss cap fins (PBCF), Grothues spoilers, and an asymmetric stern are considered auxiliary applications that improve the propeller's effectiveness. Figure 4 describes each propeller and efficiency-enhancing technique.

FPPs as implied by the name provide constant thrust with each turn of its fixed pitch (Kongsberg, 2009; Carlton, 2018; Wärtsilä, 2018). In ship operations where maximum efficiency is needed, the FPP is favored due to its robustness, dependability, ease of troubleshooting, short maintenance interval, and simple construction (MAN-ES, 2022; Wärtsilä, 2018). Throughout maintenance and repair operations, FPP may be disassembled and reassembled rapidly and without difficulty (Kongsberg, 2009). The number of blades on this type of propeller ranges between two and seven, with additional blades being utilized for military applications. Three-blade FPP propellers are commonly used on tugboats and fishing boats, but four-, five-, and six-blade propellers are utilized on ocean-going merchant vessels such as container ships, tankers, dry cargo ships, passenger ships, and bulk carriers (Kongsberg, 2009; Carlton, 2018; Wärtsilä, 2018). Similar to tugboats and fishing boats, 2 or 3-blade FPPs are preferred in small-scale special-purpose ships (Carlton, 2018). In addition to these vessels, FPPs are also deployed on polar ships and drilling ships. This circumstance demonstrates that FPP propellers can be fitted on a variety of ship types (Kongsberg, 2009). The FPP hub diameters range from 0.16 to 0.25 times the diameter of the entire propeller, based on the values of the dimensions obtained thus far from FPP applications (Carlton, 2018). Fins fitted to propeller end caps reduce fuel usage by 2%. FPP propellers have the potential to boost thrust efficiency in a variety of applications, and their installation may be accomplished at minimal expense. Due to its low installation costs, this equipment can recoup its initial investment expenditures in as little as one year, and it contributes significantly to fuel savings and emissions reduction (Wärtsilä, 2018).

CPP system permits the modification of propeller pitch by means of a hydraulic mechanism that gives interference to the blade angles to accommodate different loading situations throughout the operation of marine vessels. This enables CPP to fulfill varied power requirements without a transmission and to deliver improved mobility. In addition, the primary engine speed and cylinder pressures remain constant throughout operation. This not only contributes significantly to performance and efficiency, but also greatly reduces noise and vibration levels. In addition, the CPP system is capable of providing ships with reverse thrust (Carlton, 2018; Falzarano, 2018). CPP is commonly utilized by ships with medium- and low-speed ship engines in the maritime industry, where about 20,000 vessels are equipped with CPP systems (Tupper and Rawson, 2001; Molland, 2008; Carlton, 2018; Wärtsilä, 2018b). CPP is ideal for ferries, passenger ships, ice-class vessels, general cargo ships, tugboats, and navy vessels whose engine loads fluctuate significantly during operation (Carlton, 2018; Falzarano, 2018) as well as being appropriate for marine vessels that conduct dynamic positioning operations (Wärtsilä, 2018b; Ren *et al.*, 2019). CPP has a big market share since there is a constant relationship between revolutions per minute and torque in FPP, whereas this coefficient fluctuates with the amount of pitch in CPP (Molland, 2011). CPP is performed with very low efficiency losses of up to two to three percent, which provide fuel consumption and remove fuel-based harmful emissions. CPP is appropriate for retrofitting applications that emphasize this propeller type. Additionally, it has a lighter weight than conventional propellers and a structure that is exceptionally reliable (Falzarano, 2018; Wärtsilä, 2018b). CPP systems are highly beneficial on ships that already have shaft generators or have the possibility to install them in order to serve accommodation loads or other electrical requirements (Wärtsilä, 2018b; Ren *et al.*, 2019). As in FPP, fins and nozzles are integrated into CPP, and efficiency increase is acquired (Wärtsilä, 2018b; Ren *et al.*, 2019). In contrast to traditional propeller types, CPP propellers have a more complex structure, which raises initial investment and maintenance costs (ATZ Martec, 2021). When the Blade Area Ratio (BAR) is close to 0.8, CPP transfer of greater powers in large-scale maritime boats is problematic, and excessive cavitation occurs (Tupper and Rawson, 2001).

Ducted Propellers have a circular, fixed channel that can be redirected based on the flow around the propeller. This channel, which features a hydrofoil part, must be designed so that its inner surface and the propeller tips are in close proximity. An increase in the distance between them causes efficiency losses (Wartsila, 2022). There are ducted propeller types that slow down or accelerate the flow on the propeller according to their nozzle structure (Villa *et al.*, 2020; Falzarano, 2018). The enhanced thrust efficiency of the propeller is a result of the accelerated flow through the ducted area, and vice versa. Ducted Propellers are deployed on tugboats, anchor handling tug supply (AHTS), trawlers, general cargo ships, fishing vessels, research vessels, and marine vessels operating in inland waters (Falzarano, 2018; Becker Marine Systems, 2022; Kortpropulsion, 2022). Ducted propellers are also referred to as Kort nozzles since the company Kort Propulsion got the first patents in this field that are regarded as a benchmark (Carlton, 2018). FPP or CPP type of propellers are utilized in ducted propeller systems (Carlton, 2018). Three distinct nozzles have been integrated into the CPP based on B and Kaplan series model propeller and thrust efficiency has been boosted to the upper levels by increasing the flow velocity rate on the propeller (Bhattacharyya *et al.*, 2016; Bahatmaka *et al.*, 2017). In contrast, cavitation and noise are minimized when the flow velocity on the propeller is slowed in a ducted propeller system. This is particularly beneficial for military applications involving huge cargo ships and tankers (Falzarano, 2018). The construction and structure of the nozzle are vital to its performance, as it improves maneuverability, reduces propeller degradation, and facilitates DP operations (Becker Marine Systems, 2022). CPPs have the ability to be utilized by maritime vessel nozzles with a diameter of up to 5,300 millimeters. This system generates around fifty percent of the total thrust at relatively moderate speeds, but at high speeds it can cause additional resistance (Carlton, 2018). With the enhancements made to nozzle propellers, the bollard force of tugboats operating at zero knots is raised by 5 percent. In addition, a 3% to 4% increase in efficiency can be achieved in towing operations when the tugboat is operated between 2 and 8 knots. With the exception of all other low-speed procedures, improvements in excess of 2% are offered (Bhattacharyya *et al.*, 2016; Bahatmaka *et al.*, 2017).

Counter-rotating propellers (CRP) are comprised of two propellers that rotate in opposite directions on the same axis. Typically, the outer propeller is smaller in size and has a different number of blades than the inner propeller. CRP propellers are 5–7% more efficient than standard propellers. Due to the existence of a second propeller, CRP application in marine boats is hampered by added weight, increased maintenance expenses, a high initial investment, and a complicated structure (Tupper and Rawson, 2001; Falzarano, 2018). While CRPs are highly efficient in high-speed outboard engines, their use in long shaft applications on large ships presents numerous mechanical challenges. The lower stresses on CRP propellers provide advantages in terms of cavitation and noise compared to traditional propellers. CRPs employ both conventional and pod propellers, enabling their employment on large ships (Carlton, 2018).

In contrast to traditional propellers, Z-Drive Units that transfer power to the propeller via bevel gears and shaft brackets are not required. Z-Drive Units are highly maneuverable without a rudder, which minimizes rudder maintenance expenses, and have the potential to be utilized with a nozzle. Vibration, cavitation, and noise emission reduction are the primary features of this system (Falzarano, 2018). Podded Azimuthing Propellers (Azipod) allow 360^0 maneuverability without the use of a steerable gear propulsion system thanks to the podded AC electric motor. In addition to their exceptional maneuverability, Azipod offer up to 20% lower fuel consumption than conventional propulsion systems. As pod propellers, Azimuth Stern Drive (ASD) is the most common propulsion technology for tugboats. Specified pod propeller systems feature two propellers that function as tandem or counterrotating propellers (Falzarano, 2018; ABB, 2022). CRP Azipod applications deliver greater than 10% efficiency on fast ferries and ultra-large container ships, and CRP Azipod hybrid systems enhance the level of comfort on cruise ships (ABB, 2022; Wartsila, 2022)

Particularly prevalent in high-speed maritime boats with high-speed engines is the incidence of cavitation (Carlton, 2018). In some instances where the Azipod technology is integrated into a ducted system, large power outputs of up to 7.5 MW are achieved. In many applications, the use of flaps and fins has also improved maneuverability and cruising performance (Falzarano, 2018; ABB, 2022). Although Azipod devices are inapplicable to very big vessels, they are commonly utilized on icebreakers and passenger vessels. They have the ability to install up to 17 Megawatts aboard icebreaker ships whose Azipod towing systems are highly effective (ABB, 2022). “Harmony of the Seas” is one of the largest cruise ships in the world and is operated with a 20000 kW Azipod propulsion unit (Carlton, 2018; Wartsila, 2022). Azipod provides the easy loading and unloading of vehicles, particularly on Ro-Pax ships that permit the utilization of maximum loading area onboard (ABB, 2022). The distinction between azimuth and pod propellers is the installation location of the motor drive and the Z and L types of the most common drive units (Carlton, 2018). Z-Drives thrusters provide fuel consumption reduction, prolonged maintenance interval, increased hydrodynamic efficiency, high customer satisfaction and improved maneuverability without rudders (Thrustmaster, 2013; Hanninen, 2023). L-drive thrusters consist of motor, flexible coupling, gear coupling and propeller. Thanks to its simplified system, they provide lower fuel consumption, and high efficiency in a wide speed range with minimum energy losses. They are especially suitable for tugboat operations (Konsberg, 2021; Manngard, 2022). The installation of the Azipod propulsion unit gives advantages over conventional propulsion systems in which the existence of a stern tube, liner, and shaft bearing are the primary obstacles (Wartsila, 2022). In hybrid applications for this type of technology, vibrations occur when optimization studies are not conducted correctly (Carlton, 2018). Azipod systems compensate for the weight and moment problems associated with tandem propellers, allowing for more efficient operations (Carlton, 2018). From 1 MW to 7 MW, compact Azipod systems can be placed on ships for operation in coastal and open waters. The use of permanent magnet synchronous motors in these systems eliminates the need for additional rotor cooling, making the system more suitable for marine vessels (Wartsila, 2022).

Waterjet propulsion systems in which high-velocity jet units displace water to produce thrust for ship operation. They are chosen over conventional systems due to their excellent manoeuvrability, ability to direct water flow without a rudder system, ease of operation in shallow seas, and low noise emission and vibration. In contrast to traditional propulsion systems, they have a significantly lower propulsion efficiency output at low speeds (Falzarano, 2018; Wartsila, 2022). Waterjet Propulsion systems can be utilized on a variety of ship types, including marine sports vehicles, jet skis, rescue boats, and diving support vessels (Falzarano, 2018). In Tandem propellers, multiple propellers are attached to the same shaft axis so that the required thrust is produced by multiple propellers and the weight is distributed at multiple points. The presence of numerous propellers decreases the risk of cavitation and spreads it throughout the propellers (Carlton, 2018; Falzarano, 2018). Multiple propellers generate significant bending moments and varying weight distributions, resulting in damage to the shaft bearings and shaft liner on the same axis (Carlton, 2018).

Supercavitation or Surface-Piercing High-revolution-rate propellers reduce the impact of cavitation in shallow water, therefore propellers are particularly beneficial under these conditions. Compared to traditional propellers, they are 20 to 25 percent more efficient. In low-speed applications where cavitation is low, however, they incur a 15% efficiency loss (Çelik, 2010). This type of propeller delivers exceptional operational efficiency on yachts and navy vessels that reach 40-45 knots in speed. High-speed yachts demand Surface-Piercing propellers with more than four blades. Typically, the propeller is completely submerged as the ship begins to cruise. At high speeds, the ship creates a planar movement in which half of the propeller diameter remains submerged in the water (Carlton, 2018; Falzarano, 2018). The Cycloidal Propeller possesses six or eight propeller blades with a vertical axis airfoil shape, is positioned at the bottom of the ship, and provides thrust in all directions. Two servo motors collaborate to generate the necessary thrust, with one providing forward and reverse motion and the other creating thrust in the transverse direction to conduct port and starboard movements. The Cycloidal Propeller is also known as the Voith-Schneider propeller, which is manufactured by one of the most well-known companies in this industry. The Voith-Schneider propeller has a high degree of maneuverability, allowing it to respond quickly to sudden congestions. The Voith Schneider propeller systems offer high dependability, low vibration and fuel consumption, as well as a reduction in noise emissions, particularly in places where currents, waves, and ice effects are significant and operations are challenging (Voith, 2022).

Overlapping propeller systems with propulsion generated by the rotation of overlapping or side-by-side propellers on different shafts, resulting in a complicated wake flow. They offer significant benefits in terms of field energy at low speeds, resulting in greater efficiency. When compared to single conventional propellers, there are fluctuations in torque and thrust. The optimal distance between shafts is equivalent to 0.8 times the required propeller diameter, and vertical distance has a considerable impact on vibration. Additionally, more cavitation occurs than with ordinary propellers, necessitating additional measures to reduce this development. Installation of this sort of propeller must therefore be performed with extra attention (Çelik, 2010; Anda *et al.*, 2011; Carlton, 2018). Grim Vane Wheel Propeller provides up to 10% energy savings and a 20% reduction in fuel consumption as a result of the grim wheels that are 20% larger in diameter than the propeller. Grim wheels also boost thrust, decrease drag on the rudder, and improve stopping power. Wheels typically utilized on cargo ships. Siem Curie, which carries vehicles, is one example of a cargo ship in this area (Çelik, 2010; Siem, 2020).

Tip Vortex Free TVF, in which circulation distribution is appropriately provided by the end plates of the propeller, gives up to 5 percent efficiency. Contracted Loaded Tip (CLT), which is based on TVF propellers, is deployed on more than 280 ships, including chemical tankers, Ro-Pax, and other ship types. CLT propellers are superior to conventional propellers in terms of maneuverability, vibration, and noise emissions, and they offer between 5 and 8 percent greater energy efficiency. In addition, initial investment costs are recouped within three to six months (Çelik, 2010; Gennaro and Gonzalez-Adalid, 2012). Compared to conventional propellers of the same power, Mewis Duct Propellers deliver faster cruising and greater energy savings at low speeds. This nozzle, which is located on the propeller's bow, is deployed in combination with fin systems. This method enhances net thrust by accelerating and smoothing the wake region, while reducing cavitation and vibration production. It is appropriate for tankers, bulk carriers, and multipurpose vessels (MPV). The bulk carriers had the greatest increase in efficiency at 6%-8%, followed by tankers at 5%-7% and MPVs at 3%-5%, respectively (Becker Marine Systems, 2022).

KAPPEL Propellers have a curved structure with their blade tips relative to the suction side and are up to 5 percent more efficient than standard propellers. There are uses for KAPPEL propellers with 3, 4, 5, and 6 blades on many types of ships. In the process of gaining a curved structure, a great deal of effort is required, and incorrect designs and outputs enhance the formation of vibration and loss of efficiency. Its first use is aboard MT NORDAMERIKA, a 35,000 DWT chemical tanker, and the resulting energy efficiency is close to 4%. The Kappel application executed on the 30,000 kW Ro-Ro saves 774,000 dollars. However, based on an endurance test, the pressure resistance levels of the latest generation of propellers are lower (DTU Mechanical Engineering, 2017; MAN Diesel Turbo, 2022; Wartsila, 2022). In addition to these technologies, paddle wheels were used in the 19th and early 20th centuries, and each wheel's thrust is proportional to the volume of water it moves as it turns. Paddle wheel installation is typically performed on the ship's port and side. It is uncommonly mounted near the ship's stern, except for this particular version (Falzarano, 2018).

Various applications are implemented to regulate the flow on the propeller, hence enhancing the propeller's efficiency. One of them is the Propeller Boss Cap Fins (PBCF), which reduce hub vortex and energy loss. PBCF reduces fuel consumption by about 3% to 5% and reduces CO_2 emissions by more than 9,000 tons, based on the results of its implementation on large container ships. PBCF may be effortlessly placed on ordinary propellers to reduce vibration and underwater noise. Alternatively, it reduces wearing on the rudder (MOL, 2015). Grothues spoilers are small, curved, triangular plates that are welded on both sides to the stern of the ship. The Grothues spoilers regulate the flow and boost the propeller's efficiency. As a result of an erroneous mounting location, the resistance of the ship's appendages increases, and full regularity of flow to the propeller is not obtained (Howden, 2019). In addition to offering up to 9 percent energy savings in model test studies, it reduces vibrations in ship applications with vibration issues (Bertram, 2012).

In a ship with an asymmetric stern, the port and starboard stern sides do not have the same hull shape. Asymmetric stern increases fuel economy by roughly 5% without any alterations to the propeller and without the use of fins or nozzles. Ships with high block coefficients yield the most efficient applications. Recently, RANS-based simulations have been done on various asymmetric sterns to determine the optimal design. According to towing tests conducted on a 3000 TEU container ship, 3% less energy is required to obtain comparable speeds compared to a symmetric stern (Çelik, 2010; DNV, 2022).

3. GENERAL ASSESSMENTS ON PROPELLER TYPES

Propeller types, their cost, complexity, resilience, manoeuvrability, noise and vibration levels, thrust efficiency, emission rates, maintenance intervals, fuel consumption reduction, and applicability have been described Table 1 according to ship type, based on academic research and industry data. For each type of propeller, critical spots are highlighted.

Table 1. Propeller types and characteristics

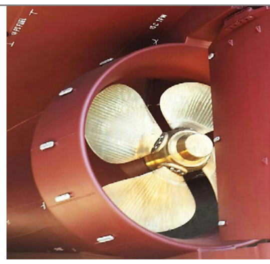
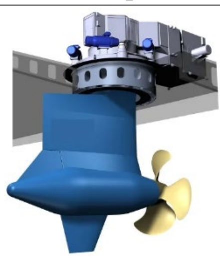
Fixed Pitch Propeller (FPP)	**Controllable Pitch Propeller (CPP)**	**Ducted Propellers**
		
• Simple Structure, Robustness, Reliability, Shorter Maintenance Intervals • Naval Ships, Container Ships, Tankers, Dry Cargo Ships, Passenger Ships, and Bulk Carriers	• Low Noise and Vibration Level, High Manoeuvrability • Passenger Ships, General Cargo Ships, Tugs, and Naval Ships	• Nozzle types that speed up or slow down the flow on the propeller • Cavitation and noise reduction • Up to 5% increased efficiency • Tugboats, Supply Vessels, Fishing Ships, General Cargo Ships
Contra-Rotating Propellers (CRP)	**Podded Azimuthing Propellers Azipod**	**Waterjet Propulsion**
		
• Complex structure • Added weight and extra maintenance efforts due to the secondary propeller. 5% to 7% energy efficiency gain	• 360° maneuverability • Fuel consumption saving up to 20% Tugboats, Supply Vessels, Fast Ferries, and Ultra-Large Container Vessels	• Highly efficient at high speeds • High cost and difficulty of implementation for Large-scale vessels Marine Sports Boats, Jet Skis, Rescue Boats, and Diving Support Vessels

Table 1. Continued

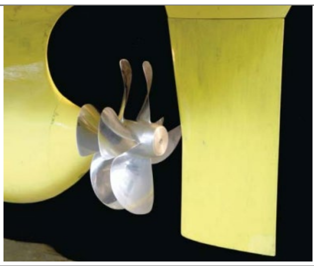
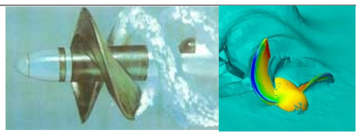
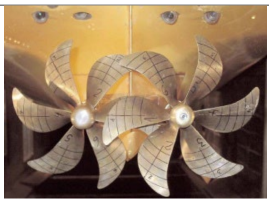
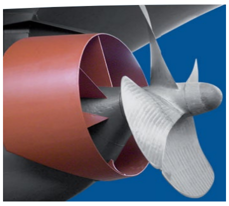
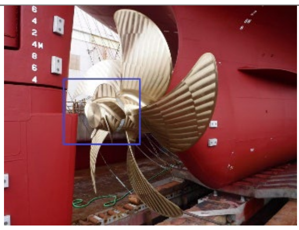
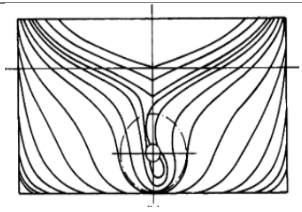
Tandem Propellers	**Supercavitating and Surface-Piercing Propellers**	**Cycloidal Propeller**
		
• Cavitation Reduction • Providing load distribution on propeller • Occurrence of excessive bending moment • Different weight distributions damage the shaft bearings and liner	• Providing 20%-25% efficiency when rotational speed and cavitation are high. On the contrary, 15% less efficient • Preferred in high speed boats. • Optimal design requires a lot of effort	• Providing 360o thrust • No need for rudder • Tugboats, Ferries and Support Vessels • Proven high reliability • Low vibration and reduced noise emissions
Overlapping propeller	**Grim Vane Wheel Propeller**	**Tip Vortex Free (TVF) and Contracted Loaded Tip (CLT)**
		
• Provides wake energy recovery • Torque and thrust fluctuations are generally occurred	• Energy saving up to between 5% and 10% • Providing extra thrust and reducing drag on the rudder	• Energy saving up to between 5% and 8% • Increasing maneuverability, reducing vibration and noise emissions
Mewis Duct	**KAPPEL Propeller**	**Paddle Wheels**
		
• Up to 8% fuel efficiency depending on the ship type • Cavitation and vibration reduction • Suitable for Tankers, bulk carriers	• Up to 5% efficiency increase • Fuel consumption and emission reduction • Low impact strength	• Propulsion from both port and side also aft side • More popular in the 19th and early 20th centuries

Table 1. Continued

Propeller Boss Cap Fins (PBCF)	Grothues spoilers	Asymmetric stern
		
• Fuel consumption reduction between 3% and 5% • Vibration and underwater noise reduction	• Up to 9% energy saving • Vibration reduction	• Up to 5% fuel efficiency • More efficient in ships with large block coefficient (C_b)

EEDI and EEXI were developed by IMO to minimize global carbon dioxide emissions from maritime vessels. Propeller selection is particularly important for these initiatives (Ren *et al.*, 2019). Numerous academic and maritime industry research have examined propellers in an effort to adapt global decarbonization plans. Kolakoti *et al.* (2013) and Gharbi *et al.* (2018) have performed experimental results based on the resistance calculation formulas and Wageningen B-series in which an interface is created in the MATLAB program that provides the selection of the propeller with minimum cavitation. The results are quite similar to the towing test data, which demonstrates the applicability of the interface. As a result, analysis may be performed with fewer resources and in less time. Kolakoti *et al.* (2013) prove that the difference between CFD and experimental results varies between approximately 4% and 6%.

In recent years, existing propeller improvements have garnered more attention than new propeller designs, and numerous computational fluid dynamics-based studies have been conducted. Xiong *et al.* (2013) described that the utilization of fins on the propeller hub cap provides an approximate 1% to 5% efficiency increase on the open water efficiency of CPP propeller. The simulations with the NACA 66 airfoil profiles installed at an angle of zero degrees and with a diameter of roughly 0.42 D of the propeller produce the most efficient results. Additionally, the fins have altered the flow pattern, preventing the creation of core vortices (Xiong *et al.*, 2013). Nouri *et al.* (2018) have performed RANS-based CFD analysis to investigate the hydrodynamic performance obtained from contra-rotating propellers (CRP). Bahatmaka *et al.* (2017) has analyzed the efficiency of 3 different nozzles that integrated into B series and Kaplan Series via CFD. At each nozzle, gains are realized in terms of force and torque, and throughout the studies, the greatest efficiency has been attained with 3.5% force and 4.4% torque, respectively. Mizzi *et al.* (2017) have performed an optimization study on 120 different PBCFs with CFD which based on RANS validated by experimental tests. Net energy efficiency gain of 1.3% is achieved with the most optimized PBCF. In order to improve the propulsion system efficiency of the 6000 TEU container ship, Lim *et al.* (2014) have utilized PBCF and hub cap together based on experimental test data and CFD analyses. Both are employed for the purpose of comparing and validating outcomes. Diversified hubcaps offer roughly 2% greater propulsion efficiency than conventional hubcaps. However, the usage of varied hub caps in conjunction with PBCF results in efficiency losses ranging from 2.7% to 7.5%. Diversified hub caps decrease hub vortex and raise torque coefficient, whereas combination diversified hub caps with PBCF enhance hub vortex, resulting in a decrease in torque coefficient.

Propeller selection according to ship type and added equipment to increase propulsion efficiency provide a certain amount of energy gain. That's why, Falzarano (2018) described that the utilization of renewable energy sources on ship propulsion systems such as wind, wave and solar energy are the main strategies in order to meet decarbonization targets (Falzarano, 2018). Prior to the maritime industry's full adaptation to renewable energy sources, the efforts performed to reduce carbon emissions and the attempt of existing systems with high efficiency are quite critical for the sustainability of maritime transportation.

4. RESULTS AND DISCUSSIONS

Selecting the optimal propeller will result in significant energy savings throughout ship operations, facilitating the ability for ship operators and owners to comply with International Maritime Organization (IMO) energy efficiency requirements. This paper outlines the types of propellers, their energy-saving rates, their applicability according to ship type, as well as technological advancements and other equipment that work in conjunction with the propeller to increase propeller efficiency in order to make the propeller selection process easier and faster. Although there are several propeller types, certain propellers, such as the FPP, CRP, CPP, Azipod, Ducted, and Cycloidal Propeller, are deployed more frequently than others in the marine industry. The most notable auxiliary equipment to boost propeller efficiency is PBCF, which has been the subject of current academic and commercial research since it can be simply and affordably integrated into existing propeller systems.

5. CONCLUSION

This study will serve as a valuable resource for academia, ship owners, operators, and industry stakeholders by outlining recent propeller system developments. In light of this study's findings, the design of the propellers to be integrated with PBCF will be based on computational fluid dynamics in a future study.

AUTHORSHIP CONTRIBUTION STATEMENT

Murat BAYRAKTAR: Conceptualization, Investigation, Data curation, Formal analysis, Methodology, Validation, Writing – original draft, Writing – review & editing.
Onur YÜKSEL: Conceptualization, Investigation, Visualization, Methodology, Validation, Writing – original draft, Writing – review & editing.
Burak GÖKSU: Conceptualization, Investigation, Visualization, Methodology, Validation, Writing – original draft, Writing – review & editing.

CONFLICT OF INTERESTS

The author(s) declare that for this article they have no actual, potential or perceived conflict of interests.

ETHICS COMMITTEE PERMISSION

No ethics committee permissions is required for this study

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ORCID IDs

Murat BAYRAKTAR:
https://orcid.org/0000-0001-7252-4776
Onur YÜKSEL
https://orcid.org/0000-0002-5728-5866
Burak GÖKSU
https://orcid.org/0000-0002-6152-0208

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