30TH INTERNATIONAL TOWING TANK CONFERENCE
22–27 SEPTEMBER 2024 | HOBART TASMANIA AUSTRALIA

Report of the Wind Powered and Wind Assisted Ships Committee

1. INTRODUCTION

Wind assistance as a means to reduce fuel consumption of ships has gained an increased interest in the last few years. The number of companies providing wind propulsion technologies is increasing rapidly. In the coming decades the number of wind-powered ships is predicted to increase to 10 000+ ships according to UK Clean Maritime, Plan (2019) and Nelissen (2016). ITTC can play an important role in this development, especially regarding performance indicators, performance assessments and sea trials. Before this background, the 29th ITTC established the first Specialist Committee for Wind Powered and Wind Assisted Ships.

2. MEMBERSHIP AND MEETINGS

The members of the Specialist Committee on Wind Powered and Wind Assisted Ships Committee of the 30th ITTC are:

- Dr. Sofia Werner (Chair)
  RISE SSPA Maritime Centre,
  Sweden.
- Dr. David Trodden (Secretary)
  Newcastle University,
  United Kingdom.
- Dr. Anders Alterskjær
  SINTEF Ocean,
  Norway.
- Ir.Rogier Eggers,
  Maritime Research Institute Netherlands (MARIN),
  Netherlands.
- Dr. Yeongyu Kim,
  Korea Research Institute of Ships and Ocean Engineering (KRISO),
  South Korea.
- Dr. Yuling Gao,
  Shanghai Ship and Shipping Research Institute (SSSRI),
  China.
- Dr. Xinshu Zhang,
  Shanghai Jiao Tong University (SJTU),
  China
- Dr. Kenichi Kume
  National Maritime Research Institute (NMRI), Japan

5th committee meeting in Shanghai. From left: Rogier Eggers, Anders Alterskjær, Sofia Werner, Yuling Gao, Kenichi Kume and Xinshu Zhang

Five committee meetings have been held during the work period:

- The first meeting was held online on the 13th September 2021
- The second meeting was held online on the 18th & 19th January 2022
- The third meeting was hybrid held online and Trondheim, Norway on the 24th to 25th August 2022
- The fourth meeting was online on the 21st and 28th February 2023
- An intermediate meeting was online on the 17th November 2023
- The fifth meeting was hybrid held online and Shanghai, China from the 16th to 19th January 2024

3. TASKS

The recommendations for the work of the Wind Powered and Wind Assisted Ships Committee as given by the 29th ITTC were as the following Terms of Reference (ToR):

1. Review technologies for wind propulsion and wind assistance. Clarify the distinction between wind powered and wind assisted ships.

2. Review methods of ship model hydrodynamic tests, wind tunnel tests, CFD, ship dynamics simulations and routing relevant for predicting the performance and safety of wind powered and wind assisted ships at design stage with particular attention paid to higher side forces and drifting of the ship due to wind powering.

3. Review long-term statistics of winds and waves from the point of view of applicability for the evaluation of wind assisted ships at design stage.

4. Derive a guideline for predicting the fuel consumption of a wind propulsion ship on a route at design stage with the consideration of weather-routing effects.

5. Review safety and regulatory issues related to hydro/aero dynamic testing and evaluation and recommend measures to take at design stage.

6. Derive performance indicators for comparing the performance of wind propulsion at design stage.

7. Investigate the effect on propulsive factors due to reduced propeller load arising from the use of wind power. Identify the effects of wind propulsion on the propulsion system, e.g. pressure side cavitation occurrence. Liaise with Resistance and Propulsion Committee and SC on Cavitation and Noise.

8. Derive a modified procedure for full scale trial of wind propulsion ships. Liaise with Full Scale Performance Committee.

9. Cooperate with MEPC on the continuous development of the EEDI for wind propulsion ships. Liaise with Full Scale Ship Performance Committee.

10. Liaise with the Ocean Engineering Committee regarding their work on SiL and controllable fans to model wind loads.

4. STATE OF THE ART

This section describes the work done by the committee on tasks 1, 2, 3, 5, 7, 9 and 10 described in the previous "Tasks" Section 3.

The work done in the other tasks (4, 6, 8) can be found in the "Procedures" Section 5.

4.1 Review technologies for wind propulsion and wind assistance

The scope of this section is to briefly review the main technologies currently used in the production of power from wind for the use onboard ship. It serves as a reference for the ITTC Specialist Committee on Wind Powered and Wind Assisted Ships and defines a distinction between wind powered and wind assisted ships, which can be used to maintain consistency throughout other ToRs.

The technologies focus mainly on propulsion power, rather than power required for hotel loads etc.

There are seven predominant categories of wind propulsions systems (WPS), (International Windship Association, 2021):

1. Rotor Sails: Based on the "Magnus" effect. Commonly referred to as a Flettner rotor.

2. Kite Sails: Flown off the bow to assist propulsion, can be dynamic or passive.

3. Soft Sails: Traditional cloth and modern adaptations.

4. Hard Sails: Also referred to as wingsails. Have flaps to vary the camber for tacking.

5. Suction Sails: Non-rotating wing with boundary layer suction to increase maximum lift values

6. Turbines: Wind turbines used to generate electrical energy

7. Hull Form: Redesign of a ship's hull-form to capture the wind force and generate thrust

The main disadvantages of all these technologies are that they cannot produce as much power as conventional prime movers, and that power levels cannot be guaranteed.

Table 1 summarises the maturity, costs, technical and operational aspects of sails, kites and rotor sails-

Table 1: Some aspects to consider when selecting a WPS (Gerhardt, Werner et al. 2021)

	Aspect	**Flettner Rotors**	**Kite**	**Wingsails**	**Soft Sails**	**Suction Wing**
Maturity	Proven Technology.	First tested in the 1920s. Most accepted + proven solution on the modern market.	Tested in a few commercial vessels.	Some experience from applications in the 1980s Yacht racing.	Long history of traditional sails.	Some experience of Turbosails. New technology being tested.
Commercial	System/Equipment Availability	Commercially available.	Commercially available.	Several concepts. Only a few off the shelf.	Available in large scale super yacht segment.	Available in small scale.
	CAPEX	High	Low	High	Medium	High
	OPEX	Low	High (wear and tear)	Low, medium if reefable	High (wear and tear)	Low
Technical	Retrofit off hire impact	Weeks	Days – Weeks	Weeks – Months	Weeks – Months	Hours (Containerised small-scale units)

	Deck space requirements	Open deck for optimal performance.	Deployed form a small mast near the bow.	Open deck for optimal performance.	Open deck for optimal performance. Removable container can be placed on cargo holds.	
	Operational wind directions	Optimal operation in $90° - 150°$.	Broad reach to downwind. Risk that kite falls into the water in low wind speeds.	Efficient upwind, less efficient downwind.	Similar to wingsail but less efficient.	Similar to wingsail but less efficient.
	Sail Trimming	Only rpm can be adjusted.	Figure-eight pattern can be adjusted with windspeed.	Not many options to trim rigid wings. Twist impossible.	Can be trimmed in many ways.	Not many options to trim rigid wings. Twist impossible.
Operational	Cargo handling constraints	Foldable and movable solutions available on the market.	None.	Some concepts are foldable or collapsible to avoid constraints.	The rig implies constraints even with furlable and reefable sails.	Removable container available.
	Air draft	Largest available systems today 35m and tiltable.	No constraints when not sailing.	Often taller than rotor sails.	Often taller than rotor sails.	Containerised system 10.5 m.
	Risks imposed by adverse weather	Slender profile and robust design	Can be retrieved in storm	Required fast vaning response.	Reefable sails.	Small systems collapsible.
	Operational effects	Risk of reduced visibility. Gyroscopic roll stabilisation effect. Reverse rotation possible for improved manoeuvrability.	No contribution to heel. Cannot be used in areas with dense traffic.	Risk of reduced visibility.	Risk of reduced visibility.	Risk of reduced visibility.

4.1.1 Working Principles of Operation

To determine how a WPS generates a force, consider a fluid particle travelling at constant velocity along a curved streamline. The streamline is curved as it flows over the surface of the WPS. Because the particle is changing direction, there must exist a centripetal force acting normal to the direction of motion. Ignoring all other forces, this centripetal force can only be generated from pressure forces, i.e. the pressure on one side of the particle is greater than on the other. So, if a streamline is curved, there must be a pressure gradient across the streamline, with the pressure increasing in the direction away from the centre of curvature (Babinsky, 2003).

This analogy can be used to describe how a lift force is generated from a WPS.

To calculate the force produced from sails, provided the flow largely remains attached, inviscid codes have successfully been implemented since the 1960s (Milgram 1968). If the sails experience large regions of flow separation, then viscous flow solvers become necessary, increasing the time and resources necessary to complete the analysis.

All of these technologies work on the apparent wind velocity flowing over a WPS which produces lift. If the wind direction is not favourable, then the mechanism will produce more drag than lift, usually resulting in either a change in course or the cessation in use of the WPS.

4.1.2 Sails

This section will summarise the three main sail types, namely soft sails, wing sails (or rigid sails) and suction sails.

Generally, due to the nature of the structure being relatively tall, sails are more suited to vessels with low air draught.

4.1.3 Soft Sails

4.1.3.1 Background

Soft sails are usually manufactured from a flexible fabric, such as canvas or polyester. They are supported through various rigging configurations. The use of soft sails is a well-established and proven method of propelling water-borne vehicles, with evidence of their use dating back to 6000 B.C. (Carter 2012).

The sails generate thrust through different mechanisms depending on the apparent wind angle. When the vessel is on a broad reach or running before the wind, the sails no longer generate force from lift, but from drag, which is somewhat less efficient.

Greater lift coefficients can be obtained from using higher aspect ratio sails; however, this results in a relatively higher vertical centre of effort and consequently a greater heeling arm. To circumvent the higher heeling arm whilst retaining a high lift coefficient, many sails can be used. It is common to see three or perhaps four masts on commercial vessels, however little research has been conducted on sail interaction for many-masted vessels, as well as sails configured in rows, athwart ships.

Specialist rigs for large craft have been developed using modern materials and design methods (Thomas 2015), where the hullform and rig are designed together. One such rig is the DynaRig and resembles a traditional square rig. The masts are free-standing and able to rotate so as to adjust the sails' angle. The rig is able to be controlled by a single person. When fully deployed, there are no gaps between the sails, contributing to high efficiency, which is estimated to be twice that of a traditional square rig (Perkins, Dikstra et al. 2004).

Fore and aft rigs tend to have better upwind performance, whereas square rigged vessels generally have better downwind performance (Marchaj 1988).

4.1.3.2 Advantages and Disadvantages

Soft sails require no external power source to operate and can be easily reefed or furled and stowed due to their flexible nature. If designed correctly, spars and booms which support the sails can also be used as derricks for cargo handling.

Soft sails take up a large amount of deck space, meaning that consideration needs to be given in the design of the rigging to allow access to cargo hatches and docking.

4.1.3.3 Potential Energy Savings

The reduction potential is dependent on vessel size, segment, operation profile and trading areas. The likely reduction potential is estimated to be in the range of 1% to 10% on main engine fuel consumption (Glomeep 2019). However, given enough sail area, it is possible to propel the vessel using nothing other than the power from the sails.

4.1.3.4 Cost

Soft sails are relatively cheap to produce and can be manufactured in existing facilities. Operational costs of soft sails can be quite high, as extra, specialist crew is required to operate them and the rigging.

The price per mast (including installation) is expected to decrease dependent on how many masts are installed on board. Thus, the capital cost involved will range from $170,000 to $300,000 (USD) per mast installed (Glomeep 2019).

4.1.3.5 Commercial Adoption

The *Tres Hombres* is a successful example of a commercial cargo vessel, solely propelled by soft sails. It has been trading since 2007. Numerous commercial fishing vessels are operated solely by soft sails, especially in the middle and far East.

4.1.4 Wing Sails

4.1.4.1 Background

Wing sails, also known as hard sails, are rigid sails which operate in a similar way to their soft-sail counterparts. The main advantage of wing sail over traditional soft sails is that their camber can be varied, confer to Figure 1. This results in a sail that can be tuned more effectively to provide a greater lift to drag ratio than soft sails, greater efficiency, and more precise control. Wing sails can be constructed of metals, plastics with elements of fabric to reduce weight.

Figure 1: Top view of a rigid wing-sail from the Oceanbird concept (Oceanbird 2023).

4.1.4.2 Advantages and Disadvantages

Wing sails are usually operated on a rotating mast. This results in an optimum angle of attack over any apparent wind angle, and thus a greater efficiency compared to soft-sails is achieved.

Because of the rotating mast and variable camber, more precise control is available, making this technology more amenable to autonomous control. This in turn means that no extra crew are required for its operation.

Due to the rotating mast and sail, careful consideration needs to be given with regards to deck space and sail dimensions to ensure adequate clearance.

4.1.4.3 Potential Energy Savings

The Shin Aitoku Maru was fitted with a wing sail from NKK, an increase in power from the wing sails was measured between 5% and 10% when operated in the East China Sea.

The reduction potential is dependent on vessel size, segment, operation profile and trading areas. The likely reduction potential is estimated to be in the range of 1% to 10% on main engine fuel consumption (Glomeep 2019). However, given enough sail area, it is possible to propel the vessel using nothing other than the power from the sails.

4.1.4.4 Cost

Capital costs are larger for wingsails compared to soft sails.

The price per mast (including installation) is expected to decrease dependent on how many masts are installed on board. Thus, the capital cost involved will range from $170,000 to $300,000 (USD) per mast installed (Glomeep 2019).

4.1.4.5 Commercial Adoption

Commercial adoption of Wing Sails started to gain popularity in the late 1970s and early 1980s, where Japanese company NKK fitted a folding wingsail to the Shin Aitoku Maru and about 10 other vessels. The system successfully demonstrated fuel saving potential.

In 1986 Walker Wingsail Systems (WWS) plc built and sold an 8 tonne wingsail for use on MV Ashington. The WWS used a unique tandem arrangement of wingsails to allow for automatic feathering. In the Ashington's trading area, "usable wind" was restricted during the trial to approximately 30% of the total passage time. Average wind speeds were relatively low. There was also significant downtime due to necessary wingsail maintenance, and the vessel's fuel consumption results were not consistent. In summary, the wingsail produced thrust equivalent to 8% of normal engine load. At this time, there was a collapse of the world's oil prices which destroyed the economic use case, this and lack of investors ultimately lead to the demise of WWS plc (Cooke Associates 2023).

More recently the use of wing sails are becoming more popular, with the likes of Becker Marine Systems (Becker Marine Systems 2023) and OceanBird (Oceanbird 2023) investing in the wing sail concept.

4.1.5 Suction Sails

Suction Sails are a relatively new method for creating lift from wind, with the original Turbosail developed by Jacques Cousteau (Charrier, Constans et al. 2985). More recently the Ventifoil, which is based on the same principle, is currently being developed by (Econowind 2022).

Suction Sails operate on the same principle as conventional sails or aerofoils, generating lift from flow over the surface. However, Suction Sails have a relatively thick cross section with a moveable fin or flap (confer to Figure 2).

Such a thick profile would usually result in flow separation due to the adverse pressure gradient near the trailing edge and consequently a loss of lift. However, a fan provides suction to the leeward edge of the sail (through a mesh) which removes the retarded flow, leaving a thin, fast moving boundary layer which remains attached much further downstream and thereby producing relatively high lift coefficients.

Depending on which side of the ship the apparent wind is coming from, the flap can switch sides to cover the mesh on the windward side, thus enabling the Suction Sail to tack like a conventional sail.

Automatic control systems allow trimming and reefing of the Suction Sail through rotation of the 'mast' and variation of the suction strength respectively. This minimises additional training of crew. The Suction Sail can relatively easily be retrofitted, either by directly mounting on a reinforced deck, or deployed from a secured 40 foot shipping container, as on the Ventifoil system (Econowind 2022).

The lift of Suction Sails is comparatively very high but drag is also high and so the lift/drag ratio is limited. This leasd to restricted upwind performance, but high performance across and downwind on reaching courses.

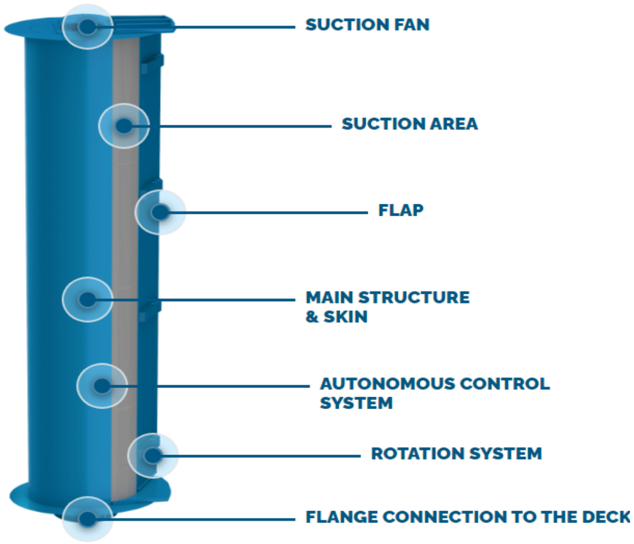


Figure 2: Main components of a suction sail (Bound4Blue 2022)

4.1.5.1 Advantages and Disadvantages

Some energy must be used to control the boundary layer separation; however this must be balanced with the extra lift that these WAP devices produce. Suction sails can be relatively easy to retrofit and can be versatile in their placement.

4.1.5.2 Potential Energy Savings

Boomsma Shipping retrofitted two Flatrack 11m suction wings from Econowind on the 6,446 DWT Frisian Sea and estimate a power saving of 10%.

4.1.5.3 Cost

There is insufficient data to make a meaningful analysis, however it is expected that both CAPEX and OPEX would be comparable to Rotor Sails, or perhaps a little more expensive from added complexity.

4.1.5.4 Commercial Adoption

As part of the EU Interrg WASP project, the 3,600 DWT general cargo vessel MV Ankie, made its first voyage with the two wings installed, sailing for Wagenborg from Delfzijl to Hamburg, onwards to Norway and back to Rotterdam. With this auxiliary propulsion, a proposed fuel saving of 1000 litres per day can be achieved. This installation is part of EU Interreg WASP project (Interreg North Sea Region 2021).

The 2300 DWT Tharis has also been retrofitted with two 9m x 3m TwinFoil retractable wingsails from Econowind in a similar Interreg WASP project.

4.1.6 Kites

A variety of WASP technologies are available on the market with each having its distinct characteristics. Kite propulsion has emerged as an attractive means to harness wind power in a way that yields environmental and financial benefits, which has been studied and installed on commercial ships. Kites offer significant advantages compared other WASP technologies and subject to some limitations at the same time. Some aspects such as maturity, operational potential of power saving etc. of this technology are reviewed.

4.1.6.1 Background

Although kites are believed to have existed since circa 500 BC, record of their use for propulsion only dates back to the 1820s. The concept of kite powered ships did not actually appear attractive at the time and was only brought back a few decades ago.

Kite is applied in naval transportation usually by two ways.

The kite is used to directly tow a ship, like a classical sail does. They provide thrust to ships with the lift generated by high altitude winds.

Another way is using a kite energy system, able to convert wind energy into electricity onboard, so that the ship propulsion can be obtained from the wind not only directly, through the towing forces exerted by the kite's lines, but also indirectly, through electric propellers. Electricity is supplied to the propellers, onboard auxiliaries like lights, pumps, etc. by a battery pack, and the batteries are recharged with the electric energy generated by the kite energy generator itself. This may not in the scope of wind-assisted propulsion options.

Kite propulsion has emerged as an attractive means to harness wind power in a way that yields environmental and financial benefits. Kite Systems (Figure 3) provide thrust to ships with the lift generated by high altitude winds. It can be seen in Figure 3 that the kite systems consist of three main components. These are a towing kite, a control system for automatic operation and a launch and recovery system. From 2006 to 2021, some commercial applications of towing kites were developed.

Figure 3: Towing kite - Airseaks L Line
https://airseas.com/

A distinction is made between static and dynamic flight for kites (Cadalen, Griffon et al. 2018). A static flight would be a much more passive system, where the kite acts primarily as a drag generating device, and thus only contributing to the ship's propulsion when sailing close to dead-downwind. Roughly speaking, the kite is able to pull the boat if the angle between the wind and the boat speed vector ranges from 0° (i.e. the boat moves downwind) to approximately 135° (i.e. 45° against the wind). Conversely, a dynamic flight would operate in an eight-shape pattern, with a very different kite design allowing lift. As such, a wider range of sailing angles can be achieved, and far greater performance attained. Typically, the dynamic mode can provide 13 to 30 times more force than the static flight (Paulig, Bungart and Specht 2013).

4.1.6.2 Advantages and disadvantages

The kite has significant practical advantages which make its commercial application attractive (Dadd 2013). Firstly, the ease of installation and ability to be fitted, or retrofitted, to virtually all ships. Secondly, Since the line tension acts through its tether at deck level, the heeling moment arm (between the centre of hydrodynamic and aerodynamic centres of effort) is reduced greatly compared to other conventional sailing rigs such as sails and rotors, thereby alleviating the significant stability concerns of the other methods. Thirdly, the towing kite may be mounted at the bow and does not require a large support structure such as a mast, so can be retrofitted without affecting the existing deck layout or operation. Kites can be retrieved in storm and there were no constrains when not sailing. Furthermore, additional performance benefit can be realised by raising the propulsive kites higher in the atmospheric boundary layer enabling exploitation of stronger winds at altitude. Lastly, kites have their own velocity in dynamic flight, which increases the apparent wind, and then the towing forces. The inflatable leading edge is another advantage, it shapes the kite and makes the launch easier.

There are practical disadvantages to the use of kites that must be avoided if they

are to continue successful use on shipping fleets. These difficulties arise primarily with launch and recovery reliability. In particular, excessive bow motions on many ships induce an undesirable vertical wind component that makes it very difficult to maintain steady line tension and this impairs the stability of the kite. Risk that kite falls into the water exists in low wind speeds. The consequences of a crash are uncertain; at the least it would cost the ship operators time to recover the fallen kite, and worse the kite would sustain significant damage and render the system unusable if there is no replacement kite.

For safety reasons the kite must fly sufficiently far from the sea and the line forces have to be contained, so to avoid line breaking and excessive roll moments on the boat speed. Kites cannot be used in areas with dense traffic.

4.1.6.3 Potential Energy Savings

Fuel saving predictions have been carried out in the literature by (Naaijen, Koster and Dallinga 2006), (Leloup, Roncin et al. 2016), and (Podeur, Merdrignac et al. 2016). The cost saving of the ship can be reduced from 10% to 35% considering the wind conditions by the virtue of the kite systems. At the optimal conditions, the amount of the cost saving reaches instantaneously about 50%. Actually, all cargo ships and newly built ships can be equipped by the kite systems.

Naaijen, Koster and Dallinga (2006) estimated the fuel saving potential of kite towing ships. As the estimation depends on the wind velocity, he showed the necessity to optimize the shipping route. His estimation of fuel saving can go up to 50% at Beaufort 7 using a kite of $500m^2$ attached to a $350m$ towing line for a 50,000 dwt (dead weight tonnage) tanker.

Leloup, Roncin et al. (2016), also implemented a procedure to predict the fuel saving potential by optimizing the elevation of the kite and the trajectory orientation and position (azimuth and elevation). The prediction are higher than Naaijen’s because Leloup introduced additionally the modeling of static flight in the optimization process, when Naaijen only took into account the dynamic flight. The kite can also switch between horizontal and vertical flight paths, which is useful for upwind conditions. Leloup predicted a fuel saving of about 10% for a 50,000 dwt tanker using a kite of $320m^2$ with a wind velocity of $10ms^{-1}$.

Kukner, Bulut and Halibese (2016) investigated wind-based propulsion for small craft and highlighted some further benefits of the towing kite approach.

Glomeep (2019) conclude that the reduction potential is dependent on vessel size, segment, operation profile and trading areas. The expected reduction potential is in the range of 1% to 5% on main engine fuel consumption.

Podeur, Merdrignac et al. (2016) performed fuel predictions on a 2200 TEU container ship towed by a kite of $800m^2$, over a 5-year period, a potential fuel economy of around 12% and 6.5% can be reached respectively at 16 and 19 knots on a North Atlantic crossing. Table 2 gives a review of fuel-saving performance of kites.

Table 2: Review of fuel-saving performance of kites

Study	Dimensions Area = a, Rope Length = l	Ship Type	Route	Fuel Saving Found
Naaijen, Koster and Dallinga (2006)	1 kite: $a = 500m^2, l = 150m$	50k dwt Tanker	N.A.	Up To 35%
	1 kite: $a = 500m^2, l = 350m$	50k dwt Tanker		Up To 50%
Naaijen, Koster and Dallinga (2006)	1 kite: $a = 500m^2, l = 350m$	50k dwt Tanker	N.A.	Up To 50%
Ran, Janson and Allenström (2013)	1 kite: $a = 640m^2, l = 600m$	73k dwt Tanker	N.A.	40%
Traut, Gilbert et al. (2014)	1kite: $a = 500m^2, l = 350m$	7k Dwt Roro	Dunkirk-Dover	3%
		8k dwt Product Tanker	London-Milford Haven	24%
		6k dwt Product Tanker	Varber-Gillingham	32%
		50k Dwt Bulk Carrier	Tubarao-Grimsby	6%
		30k dwt Container Ship	Yantian-Felixstowe	1%
Naaijen, Koster and Dallinga (2006)	1 kite: $a = 400m^2, l = 350m$	5k dwt Tanker	Worldwide Trades Of Each Ship Type According To AIS Data	9%–15%
		90k dwt Tanker		3%–4%
		7k dwt Bulk Carrier		9%–14%
		90k dwt Bulk Carrier		5%–9%
		1k TEU Container Ship		2%–4%
		5k TEU Container Ship		1%–2%
Leloup, Roncin et al. (2016)	1 kite: $a = 320m^2, l = 300m$	50k dwt Tanker	N.A.	10%–50%
Podeur, Merdrignac et al. (2016)	1kite: $a = 800m^2, l = 300m$	2200 TEU Container Ship	Le Havre - Halifax	12% at 16kn, 6.5% at 19kn

4.1.6.4 Cost

The main cost elements for the kite will be purchase, installation and operational expenses, and these are expected to increase with the size of the kite as shown in Table 3.

Table 3: Overview of size of kite and installation cost (Glomeep 2019)

Size of kite $[m^2]$	Power generated [kW]	Purchase cost [USD]
160	600	280 000
320	1 200	480 000
640	2 500	920 000
1 280	4 900	1 755 000
2 500	9 600	2 590 000
5 000	19 200	3 420 000

4.1.6.5 Commercial applications

Kite sails have been installed and tested in numerous commercial vessels. Ships can be retrofitted with kites in a few days or weeks. The CAPEX is relatively low, but the OPEX is high due to wear and tear (Gerhardt, Werner et al. 2021).

The French company Airseas has installed its first half-size automated Seawing kite to a cargo ship chartered by Airbus, and commence six months of trials from January, 2022. The full-size kite is estimated to save up to 20% of fuel burn and emissions.

The German company *SkySails* was one of the first to equip a cargo ship with a kite as an auxiliary propulsion device. In 2008, the company set up a prototype of kite propulsion system of $320m^2$ on a $132m$ ship (Erhard and Strauch 2012), (Fritz 2013).

In 2017, *SkySails* equipped the $35m$ catamaran Race For Water with a $40m^2$ ram air kite. The *Energy Observer* was launched in 2017, equipped with a Leading Edge Inflatable (LEI) kite from *Beyond the Sea*. Both types of kite have been deemed a success.

The *Airbus Group* has installed one $500m^2$ kite from *Airseas* on the Ro-Ro vessel *Ville de Bordeaux* in November 2020. Japanese ship owner *Kawasaki Kisen Kaisha (K Line))* installed one $1{,}000m^2$ kite on one capsize bulk carrier in 2021, and *Airseas* indicated that *K Line* would consider 50 possible installations conditional on a successful first delivery (Lloyd’s List 2020), (Maritime Global News 2022).

The 210,000 dwt vessel will be built at Nihon Shipyard with delivery scheduled for the first half of 2024. In addition to LNG power to reduce emissions K Line will be installing an Airseas “Seawing” automated kite for wind propulsion (Hand 2021).

Table 4 provides further examples of commercial uptakes of kite technology.

Table 4: Some examples of the adoption of kite systems installed on merchant ships (Chou, Kosmas et al 2021)

Ship Name	Ship Type	DWT	Dimension of kite $[m^2]$	Ship Built Year	Installation Year
Michael A.	General Cargo	4884	160	1994	2008
BBC Skysails	General Cargo	9832	320	2008	2008

Theseus	General Cargo	3667	160	2009	2009
Aghia Marina	Bulk carrier	28522	320	1994	2012
Ville de Bordeaux	RoRo	5200	500	2004	2020

4.1.7 Rotor Sails

The Rotor Sail, commonly referred to as a Flettner rotor after its inventor Anton Flettner, is an electrically powered rotating cylindrical structure, with one end vertically installed on the deck.

4.1.7.1 Background

Referring to Figure 4, thrust is generated using the principle of the Magnus effect. This is caused by the wind encountering the spinning cylinder which, due to skin friction, pulls the air around to one side of the cylinder, creating a pressure difference across it. This results in a net force towards the low pressure side which, if the apparent wind is favourable, can be resolved into a thrust in the direction of the ship's travel.

If the ship changes tack, that is the apparent wind is now coming across the rotor on the other side, the direction of the rotation must be reversed to produce a thrust in the direction of travel, otherwise the force would be opposing the direction of travel.

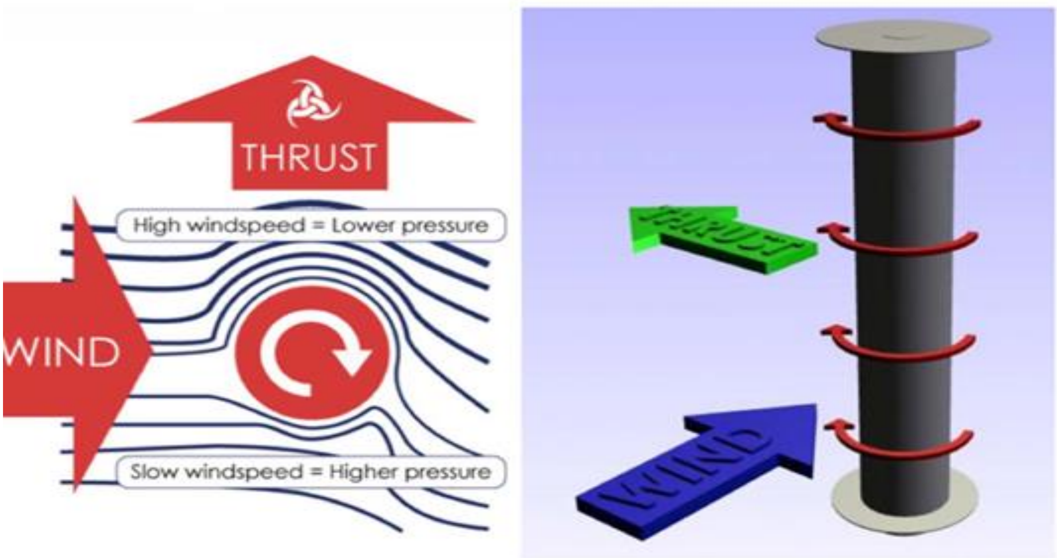


Figure 4: Magnus effect on rotating cylinder. (Source: *http://www.norsepower.com/rotor-sail-solution/technology*)

(Lu and Ringsberg 2020) studied the fuel saving performance of three wind-assisted ship propulsion technologies–the Flettner rotor, the DynaRig and a wingsail – for an Aframax Oil Tanker was simulated and compared on two actual voyages on two different routes. The results show that all three sail technologies contribute to fuel savings between 5.6% and 8.9%. The Flettner rotor contributed the most to fuel savings with the least sail area on the studied routes. Their parametric study of the Flettner rotor sail technology was presented to analyse the sensitivity in Flettner rotor dimensions, operations, and positioning of the rotor. The study was carried out on two ships on two routes. The results show that the Flettner rotor has a better performance for the smaller Handysize Bulk Carrier in comparison with the Aframax Oil Tanker, especially when the rotor is installed in the fore part of these two ships. Ship speed has a stronger effect on fuel savings compared to that of the rotor. However, the higher spinning speed and bigger sizes (keeping the same aspect ratio) of the rotor is not always positive to fuel savings. Therefore, it is necessary to select and operate the Flettner rotor according to its ship type, speed, voyage routes and corresponding weather conditions.

Seddiek and Ammar (2021) performed a case study, where one of the bulk carrier ships operating between Damietta port in Egypt and Dunkirk port in France has been investigated. The results showed the high influence of the interaction between ship course and wind speed and direction on the net output power of Flettner rotors.

4.1.7.2 Advantages and Disadvantages

Due to the vector of forces being generated, a rotor ship is able to sail closer to the wind than a conventional ship and the deck space required is relatively less than that of soft sails and wing sails.

4.1.7.3 Potential Energy Savings

Mittal and Kumar (2003), Craft, Iacovides et al. (2012) and Karabelas, Koumroglou et al. (2012) studied the aerodynamic performance of the Flettner rotor using computational fluid dynamics (CFD) simulations. Based on the CFD simulation results, Traut, Gilbert et al. (2014) proposed a performance model to simulate the power savings contributed by Flettner rotors. In their case study, a 5500 DWT cargo ship with three Flettner rotors (27 m in height and 4 m in diameter) installed onboard could save up to 50% of the power required by the main engine.

In 2015, two Norsepower rotors 18 m in height and 3 m in diameter were retrofitted on the 9700 DWT Ro-Ro Carrier M/V Estraden. It was confirmed by the company Norsepower and the ship owner that 5% fuel savings on yearly basis have been saved (confer to http://www.norsepower.com).

In another study, the classification society Lloyd's Register followed up the performance and handling test of the Integrated Greenwave MK1 Rotor assembly on a Panamax Bulk Carrier (Hirdaris and Cheng 2012). For a 1/85th scale model for a 182m waterline bulk carrier fitted with the Greenwave Flettner rotor, the performance and handling tests indicated that the Flettner rotor was capable to provide 50% of the required thrust in light winds and 100% of the required thrust in moderate winds.

Glomeep (2019) estimate the reduction potential of a Flettner motor as 3% to 15% on main engine fuel consumption depending on vessel size, segment, operation profile and trading areas. Some have reported reductions as high as 35%, but for a reduction potential in general, this is seen as high.

4.1.7.4 Cost

The range of cost for a Flettner rotor is \$400,000 to \$950,000 (USD) depending on the model (size) of the rotor. Size of a typical delivery with multiple rotor sails starts from \$1,000,000 to \$3,000,000 (USD) (Glomeep 2019).

4.1.7.5 Commercial Adoption

Flettner, with the aid of Betz, Ackeret and Prandtl, applied this concept to a marine vessel and created the first wind-powered ship called "Buckau" (Figure 5), which utilised the Flettner towers as the primary source of propulsive power. Flettner's attempts were considered not successful, because of inadequacies in overall operational performance and economics of the ship. One of the main reasons is that fossil fuels at the time were relatively cheaper. However, fossil fuels as a resource are limited and expensive. Recently, environmentally optimised solutions are being pursued and a renewed interest in this technology has been emerged recently.

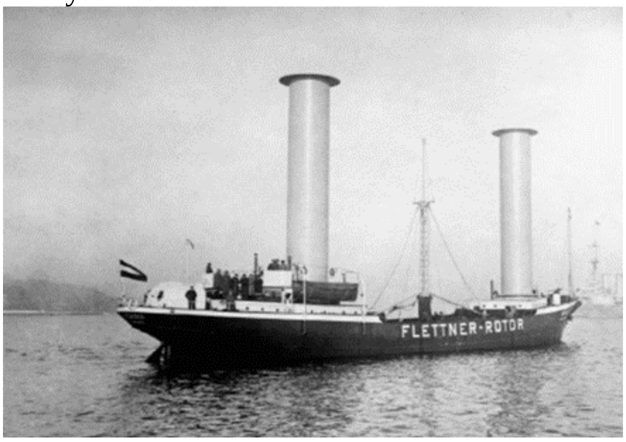


Figure 5: The Bukau, the first vehicle to be propelled by a Flettner rotor, photographed in 1924.

In 2008, the company ENERCON launched the first prototype vessel using this technology. The vessel 'E-Ship 1' is equipped with 4 Flettner towers, which are $27m$ in height and have a diameter of $4m$ each. The performance of the towers is controlled through the rotational speed of each individual tower and the study reports a maximum fuel consumption reduction of almost 25% (Morsy El Gohary 2013), (Schmidt, 2013).

4.1.8 Turbines

4.1.8.1 Background

Wind turbines can potentially be used in a number of ways. They can be coupled directly to a generator to produce electricity, or, on smaller vessels, they can be operated in autogyro mode or windmill mode, depending upon apparent wind direction. In the latter two cases, the turbine is attached to a propeller through some mechanism (mechanically, electrically or hydraulically) (Twidell 2021).

With the wind over the beam (i.e. on a reach), the turbine is used in autogyro mode, where no power is transmitted to the propeller and the turbine acts in the same manner as a conventional sail. When the vessel is sailing downwind, the apparent wind speed decreases with increasing ship speed. When the ship speed is greater than or equal to the wind speed, the apparent wind speed is zero (or negative), so the wind turbine cannot generate power or thrust in the autogyro mode. Windmill ships are thus limited to less than the wind speed when running before the wind, just as conventional sail driven vessels.

Generally, the force generated by the turbines alone is not sufficient to propel the vessel, unless the hullform has been specifically designed for reduced friction, such as multihulls or hydrofoils.

Research is still ongoing as to the most suitable design of rotor system. There are two main types, the Horizontal Axis Wind Turbine (HAWT), which tends to have a relatively higher centre of effort, and the Vertical Axis Wind Turbine (VAWT), such as the Savonius. The HAWT needs to yaw to find the correct position of the apparent wind direction, while the VAWT operates in all wind directions. The VAWT tends to be quieter than its HAWT counterpart as the blade tip-speed is lower.

4.1.8.2 Advantages and Disadvantages

Wind turbine propulsion systems are unique in that the device can provide propulsion in at all apparent wind angles, including directly into the wind. Performance is restricted, especially upwind, by the efficiency of transferring energy from wind to the water, wind turbine propulsion generally provides higher propulsive force than wingsails per turbine/sail area only when the ship speed is less than about half the wind speed (Blackford 1985). This implies that ship speeds should be slow, or the area of operation should have strong winds.

The engineering design of wind turbine systems is more complex compared to other WAP devices. Careful consideration needs to be given to the stability of the vessel, due to the large mas of rotating equipment required at height above deck, as well as dangers that this may impose to crew.

In order to operate efficiently in the typically slow speed through the water, the propeller must be large enough to generate more upwind thrust than the combined downwind force of the wind turbine and the air and water resistances of the ship structure itself. The design for this propeller may be different to the design of a propeller driven by the main engine, and thus may be an inefficient compromise.

Automatic control can easily be incorporated into the design of a wind turbine system.

4.1.8.3 Potential Energy Savings

Bøckmann and Steen (2011) conducted a fuel estimation analysis for a notional HAWT used as auxiliary propulsion for a $150\ m\ L_{WL}$ tanker, operated between Peterhead, UK and Bremerhaven, Germany. They concluded that using a pre-designed HWAT resulted in an energy saving of 24.4% and for an optimised wind turbine design, the energy saving was 33.1%.

Bøckmann and Steen (2011) also compared the energy savings from using an optimised HAWT to wingsails. In this comparison, the area of the wingsail was set equal to the wind turbine's rotor disc area and analysed on the same notional hullform. Using this method, this resulted in a fuel saving of 31.8%.

4.1.8.4 Cost

As there are no practical applications of the use of wind turbines being used for propulsive power generation, there is insufficient data to make an analysis.

4.1.8.5 Commercial Adoption

There are very few wind turbine driven vessels that have been built, and while some small craft and research vessels exist, there are no full-scale commercial ships existing using wind turbines for propulsive power generation. This is due to the disadvantages outlined above.

An early example of a wind turbine-powered vessel is the City of Ragusa, which was a converted lifeboat crewed by two men and a dog. They had the idea that the boat would be able to sail directly upwind without tacking by using the wind turbine to drive a propeller. The crossing was done East to West, into the wind and it took them 96 days to go from Liverpool, UK to Boston, USA (Anonymous 1870). There is some debate as to whether the turbine was actually utilised (Longyard 2005).

The Bois Rosé, produced by a French engineer Constantin was built in 1924 (Bose 2008). More recent examples include the Falcon, which was aimed at researching potential fuel savings for larger ships (Bose 2008).

Applications are most suited to slower speed vessels, or if used for electrical power generation, on vessels with a high electrical load.

4.1.9 Hull Form

Another interesting technology is that of the design of the hullform that can itself generate lift from the prevailing wind. Lade AS in Norway was established in 2010 and have been developing the project Vindskip (Lades AS 2023). Project Vindskip is a hybrid merchant vessel for sustainable sea transport.

The hull is shaped similar to a giant sail (Figure 6) and thus generates a forward thrust towards the apparent wind. This is Vindskip's Wind Power System. The ship is fitted with an LNG-electric propulsion system as well, the combination of the two forming a dynamic system that maintains a constant ship speed. Using computerized weighting of meteorological data, a computer program will calculate the best sailing route to exploit the available wind energy potential.

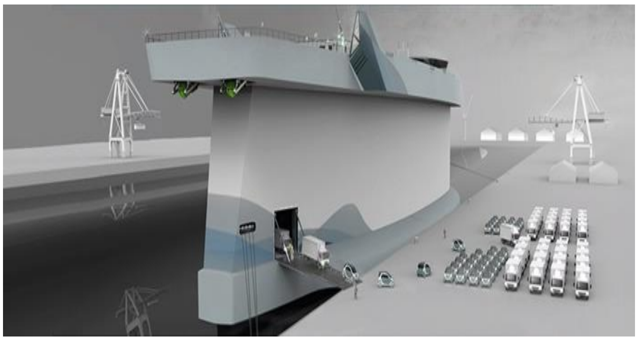


Figure 6: The Vindskip hybrid propulsion concept, *https://ladeas.no/*

Ship types that are particularly relevant to the Vindskip design are

- RoRo
- RoPax
- PCTC
- Passenger ships
- Container Ships

4.1.9.1 Advantages and Disadvantages

Because the hullform is shaped like a wing, air-draught may need to be increased in order to maintain cargo carrying capacity.

4.1.9.2 Potential Energy Savings

According to Lade AS the ship's design is estimated to cut fuel use by 60% and carbon emissions by up to 80% (Lades AS 2023).

4.1.9.3 Cost

There is no cost information available due to the concept not having been built yet. The more complex hullform shape may increase capital costs.

4.1.9.4 Commercial Adoption

The Vindskip is presently a concept design.

4.1.10 Conclusions

Section 4.1 has briefly reviewed the main technologies currently considered as the main source of power from wind for use onboard ship. This ToR can be used further in the ITTC Specialist Committee on Wind Powered and Wind Assisted Ships to maintain consistency.

4.2 Clarify the distinction between wind powered and wind assisted ships.

4.2.1 Introduction

The Committee was tasked to provide a distinction between wind powered and wind assisted ships. Possible usage scenarios for the distinction between wind powered and wind assisted ships could be general or specific. Specific use cases are normally associated with their own definitions. Indeed, the ToR calls for a distinction, rather than a definition.

The scope of the following commentary should therefore be for general use in initial design and vessel classification.

4.2.2 Rationale for the distinction

It is assumed that distinct definitions will be required for specific purposed, such as the application of rules and regulations of various kinds. However, since the scope of those applications differs, it is not wise to formulate one explicit definition that is valid for all purposes. Instead, each rule and regulation should include its own definition.

The distinction that the Committee propose is intended to be used when describing a type of ship in *general terms*. It is not an explicit definition that can be calculated for each ship. For example, if it is stipulated that a "Primary Wind Powered ship is powered by the wind for at least 90% of the time when full away on passage", then this becomes route and speed dependent, and requires definitions of calculation method to derive the percentage time. It would then chance its "status" if the route or speed is changed, which would be confusing.

The Committee propose the distinction given in Table 5.

Table 5: The SC proposal for distinction

Primary Wind Power	A Primary Wind Powered Ship is one which is designed to maintain service speed the majority of time using wind propulsion only.
Wind Assisted Ships	A Wind Assisted Ship is a motor ship which is adapted such that in favourable wind conditions, the propulsive power to maintain service speed is reduced from using wind powered technology.

During the work, the Committee has been in contact with the International Wind Ship Association (IWSA) regarding the distinction, since it would be favourable to have the same distinction throughout the industry. IWSA use currently the wording given in Table 6. It is noted by the Committee that IWSA's distinction describes the actual state of a ship in operation, where its status can change if it is operated on a different route or speed. ITTC's distinction seeks to categorise a vessel from its design and purpose.

Table 6: IWSA distinction (International Windship Association, 2024)

Primary Wind Power	Wind propulsion is the primary propulsion energy for that ship
Wind Assisted Ships	Wind propulsion system delivers on average less than 50% of the propulsive power to the ship at a given commercial speed

4.3 Review of methods for prediction of performance and safety of wind powered ships

Performance of ships with wind and wind-assisted propulsion in wind and waves is more complicated than ships with traditional propulsion. A lot of effort has been dedicated in the last few years to the study of predicting the performance of wind powered ships.

The following are the methods of ship model hydrodynamic tests, wind tunnel tests, CFD, ship dynamics simulations and routing relevant for predicting the performance and safety of wind powered and wind assisted ships at the design stage with particular attention paid to higher side forces and drifting of the ship due to wind powering.

4.3.1 Ship Performance prediction

Performance Prediction Programme (PPP) for WASP concepts couple the aerodynamic and hydrodynamic forces to obtain a solution for velocity under sail and ultimately power saving. The performance prediction fundamentally relies on achieving equilibrium for the degrees of freedom (DoFs) considered. Velocity prediction programs (VPPs) or Energy Prediction Programs (EPPs) or performance prediction programs (PPPs) for wind-assisted ships typically consider either: 3-DoF (surge, sway, roll), 4-DoF (surge, sway, roll, yaw), 6-DoF (surge, sway, roll, yaw, pitch , heave).

4.3.2 Performance Prediction Program

VPP was presented in (Tillig and Ringsberg, 2018; van der Kolk et al., 2019a; Viola et al., 2015). In (Viola et al., 2015; Lee et al., 2016), the aerodynamic interaction effects were evaluated using CFD computations, while the model in (van der Kolk et al., 2019a) was based on model tests. Typically, the hydrodynamics of a hull are based on empirical methods from maneuvering research, as in (Tillig and Ringsberg, 2018; Viola et al., 2015), or on CFD or model test results using standard series hulls (van der Kolk et al., 2019b; van der Kolk, 2016).

A 4-DoF ship performance prediction model called "ShipCLEAN" has been developed by Tillig and Ringsberg (2020), which includes aero-hydro coupling and a method for rpm control of Flettner rotors on a ship to maximize fuel savings. This ship performance prediction model based on analytical and empirical methods as well as on propeller and hull standard series. Thies et al. (2021) used the model ShipCLEAN in the example with a ferry operating on a short route in the Baltic Sea. Focus is put on evaluating the difference between 1-DoF and 4-DoF methods as well as the impact of aerodynamic interaction effects in between multiple sails.

Based on a generic energy systems model proposed by Tillig et al. (2017) and Tillig and Ringsberg (2019), the performance prediction model for ships at sea (ShipJOURNEY) is further developed by Ruihua Lu & Ringsberg (2019) which is a 4-DoF balance model. Ship profiles, voyage routes, operational conditions and sail technologies are the essential inputs and the voyage time and main engine fuel consumption are the major outputs (Figure 7).

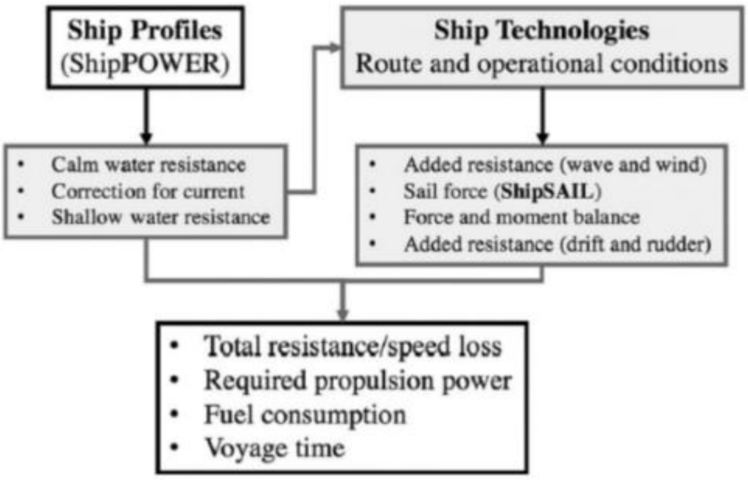


Figure 7. Schematic flowchart of Ship JOURNEY(Ruihua Lu & Ringsberg , 2019)

Reche-Vilanova et al. (2021) presented a 6-DoF PPP based on semi-empirical methods and a WAPS aerodynamic database created from published data on lift and drag coefficients which can predict the performance of any commercial ship with three possible different WAPS installed: rotor sails, rigid wing sails and DynaRigs. The tool was with only the ship main particulars and general dimensions as input data (Figure 8). The model did not take the sail-sail and sail-hull interaction effects on the aerodynamic performance.

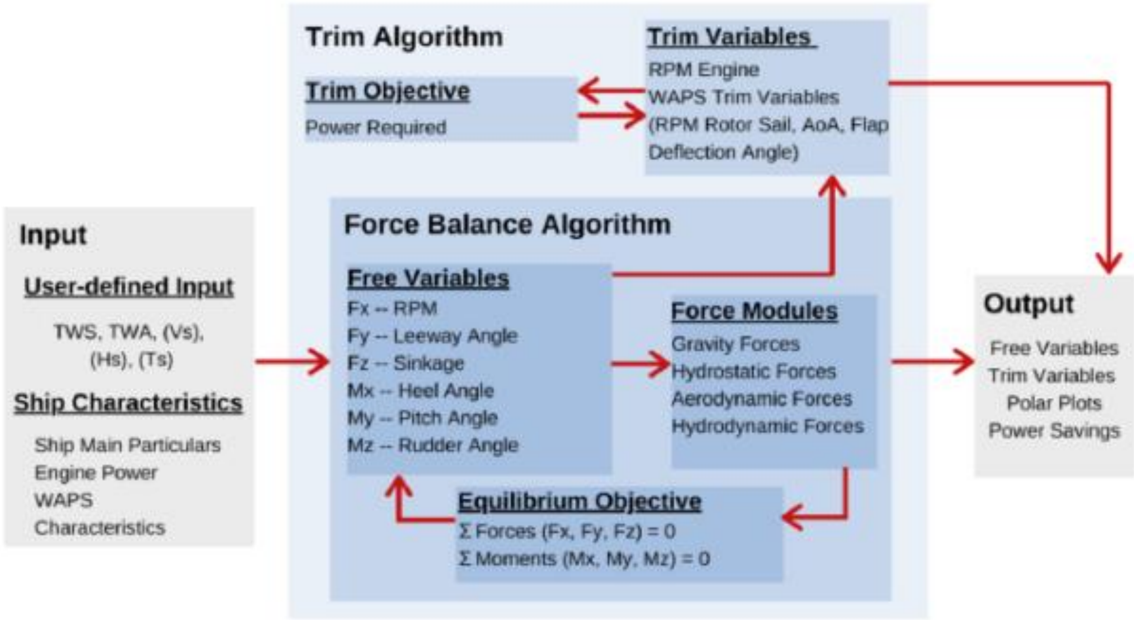


Figure 8. Outline of Performance Prediction Program (Reche-Vilanova et al., 2021)

Bataille et al. (2023) took the vessel ONRT as a reference study case to assess the wind-assisted vessel's performance on its operating route, based on the PERFO methodology (Figure 9) which contains two existing PPP tools: xWASP as an open-source solver is a 6 DoFs Dynamic VPP/PPP using semi-empirical formulations dedicated to WASP and SEECAT (Ship Energy Efficiency Calculation and Analysis Tool) with loads from CFD modelling is aiming at assessing the global efficiency of ships for realistic operational profiles and weather conditions and capable of modelling any kind of marine propulsion architecture.

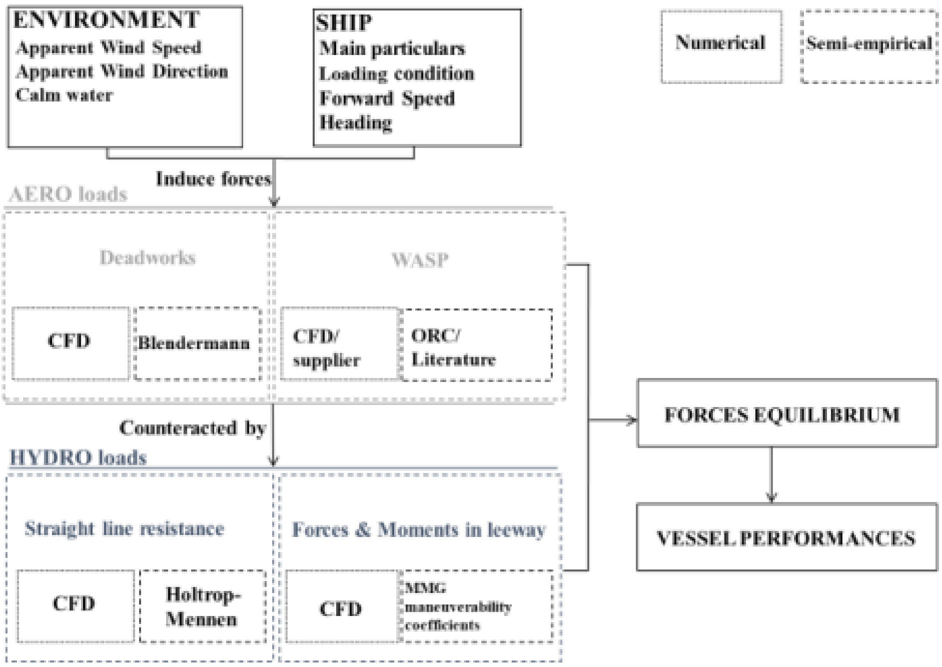


Figure 9. PERFO methodology (J Bataille et al. 2023)

Mason et al. (2021) described a performance prediction model developed by Bordogna et al. (2019, 2020) and van der Kolk et al. (2019, 2020, 2021). Specified lift and drag coefficients, scale effects, interaction effects between multiple Flettner rotors, as well as interaction effects between the Flettner rotors and the ship's deck are accounted for and the results were derived from the performance of dedicated wind tunnel experiments (Bordogna et al. 2019, 2020). The hydrodynamic and aerodynamic models combine to calculate the resulting force in the direction of motion of the ship that is required to achieve a given speed. For a range of wind speeds and wind angles, the forces are combined to calculate the main engine power, or brake power.

4.3.3 Route optimization method

Mason (2021), Paakkari (2022) and Dupuy et al. (2023) have highlighted the importance of weather routing for the performance of wind propulsion as it has been shown that the performance of wind propulsion can be as much as doubled when weather routing is utilized. On the other hand, different wind propulsion technologies have significantly different characteristics in terms of propulsion performance. Comparisons between different wind propulsion systems have been made by Sarsila (2022) and Maxime Dupuy et al. (2023) .

Mason et al. (2021) investigated the combined abatement fuel consumption potential of wind propulsion and voyage optimisation, alongside their subsequent interaction with speed reduction. The development and analysis of the ship routing model used the Voyage Optimisation for the International Decarbonisation of Ships routing model to calculate carbon savings from a Flettner rotor-assisted ship on the great circle route and optimised voyage route.

4.3.3.1 Safety prediction

There are several criteria and methods to evaluate the stability of sail-assisted ship as proposed by Classification Societies. Hussian (2021) used the recommended stability criteria on a sail assisted ship to do stability and structural analysis.

Van der kolk et al. (2019) presented the experimental results for the sailing performance of ships fitted with bilge keel appendages. Systematic variations in appendage height, length and position were tested, including several special cases (multiple bilge keels). The appendage typology has been shown to mitigate the strong "destabilizing" yaw moment that is characteristic of wind-assisted commercial vessels and to promote the non-linear sideforce component.

Wang et.al（2022）studied the dynamic stability under the combined wind and wave loads by using the spectral analysis method and the time domain analysis method with consideration of multiple wind spectrum, wave spectrum, and wave direction. The spectral analysis method did not consider the system nonlinearity, while the time domain analysis method considered the nonlinearity of the roll restoring stiffness.

Kite operation may enter resonance with ship roll or pitch natural period and dramatically impact the ship stability. Richard (2014) calculated the roll, pitch natural periods and kite structure behaviour with three different approaches. The results showed that for shorter tethers length, the risk of kite flight period entering resonance with the ship roll or heave period may appear and the kite flight trajectory may be adapted in order to prevent any risk of such phenomenon.

4.3.4 Hydrodynamic characteristics

4.3.4.1 Hybrid testing approach

In hybrid testing approach (cyber-physical approach), one part of the system is modeled physically, while the other part, whose behavior is assumed to be well described theoretically, is modeled numerically.

For sailing ships, generally, experimental methods of prediction seakeeping and manoeuvring can be grouped as captive tests and free sailing tests. With the various sub-categories shown in Figure 10.

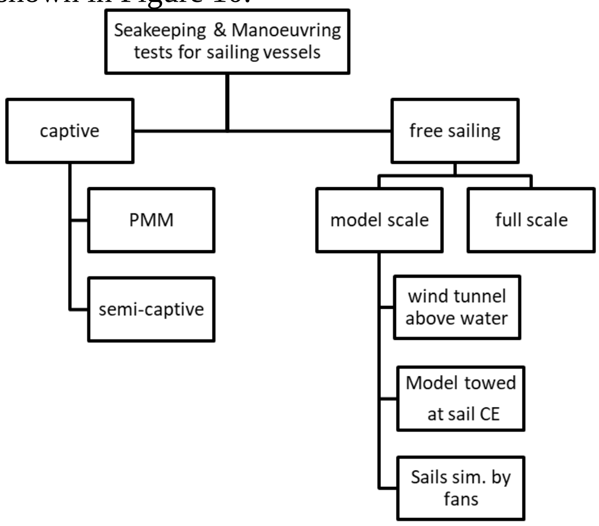


Figure 10. Alternatives for seakeeping and manoeuvring tests with sailing ships (F C Gerhardt et al. ， 2021)

The hybrid testing approach was used by F C Gerhardt et al. (2021) to investigate the seakeeping and manoeuvring properties of "Wind Powered Car Carrier" called Oceanbird , which is the "mirror image" of Hansen's RT-VPP: the sail forces are simulated (by fans) while the hull is tested in waves (Figure 11). The setup consists of the physical subsystem "hull" that is tested in the seakeeping basin and the numerical subsystem "sails" that is simulated by the two azimuth and rpm-controlled fans. As illustrated, strain gauges are used to measure the axial force of each fan. This allows determining the actual "sail" forces and moments.

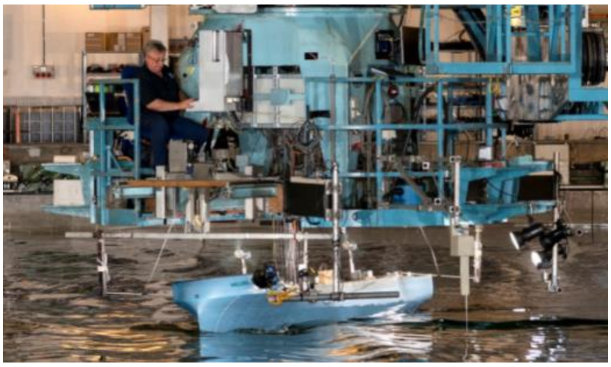


Figure 11. Wave tests with a model of Oceanbird (the wing sails have been replaced by fans/airscrews) (F C Gerhardt et al. , 2021)

Sauder and Alterskjær (2022) used the cyber-physical approach to study a bulk carrier model (SOBC-1) retrofitted with four (virtual) Flettner rotor sails. The ship model was placed in the seakeeping carriage and the loads were applied on the frame through six thin wires visible as depicted in Figure 12. In the experiments, the ship model was running at self-propulsion, where propulsion was delivered from four numerically modelled Flettner rotors based on published CFD simulations results (De Marco et al. 2016), in addition to a single screw conventional propeller. The forces generated by the wind propulsors were applied to the model using a system of wires, connecting the model to actuators, providing forces in 5 degrees of freedom (except the heave force) according to prescribed wind conditions. Aerodynamic loads on the sails were computed in real-time based on the ship motions and on computational fluid dynamics results.

Figure 12. Model of SOBC-1 in the towing tank (left). Two of the six actuators mounted on the car-riage (right).(Sauder and Alterskjær , 2022)

4.3.4.2 Numerical methods

Bigi et al. (2018, 2020) proposed a numerical modelling associating the strip theory for the ship motion simulation and the zero-mass modelling for the kite force and motion simulation.

An extensive test matrix, adapted to assess the hull and appendages behaviour in a range of flow speeds and directions, was simulated in CFD to obtain the hydrodynamic forces and moments acting on the underwater part of the ship in Marimon et al (2020). Being a wind-assisted vessel, three different conditions were tested where the ship is propelled using only the propulsive power from the sails/wings, using only the propulsive power from the engine and a combination of the former two (50% sail, 50% power).

Kjellberg et al. (2022) developed a numerical method for predicting a ship's motions and loads in its rigid wing sails. The numerical method is based on an unsteady 3D fully nonlinear potential flow hydrodynamic model coupled with a hybrid 2D RANS/3D lifting-line aerodynamic model. Simulations in a seaway with short-crested irregular waves and corresponding wind conditions are conducted, resulting in time histories of the aerodynamic and inertial forces acting on the rig.

Fabio Pili et al. (2023) investigated the effect of Flettner rotors on the seakeeping of a catamaran, predicting the motions of the ship in the 6-DoFs. The rotors were modelled using a quasi-static approach and a linearized approach to analyze the effect of the rotor in pure roll motion in beam seas. The seakeeping model is based on regular waves. The aerodynamic interactions between the four rotors and variation of the hull wetted surface were neglected in this study.

4.3.5 Aerodynamic characteristics

4.3.5.1 Wind tunnel tests

Bordogna (2020) and Chen et al. (2023) experimentally investigated the aerodynamic performance of large-scale Flettner rotors for marine applications.Wind-tunnel experimental campaign on a single Flettner rotor and two analogous Flettner rotors for a range of different relative positions and velocity ratios (Figure 13 and Figure 14). In this series of tests, their lift and drag coefficients were measured and then compared to those of the single Flettner rotor to investigate the effects of the aerodynamic interaction.

Figure 13. The Delft Rotor and two Flettner rotors in Pol-ytechnic University of Milan wind tunnel (Bor-dogna, 2020)

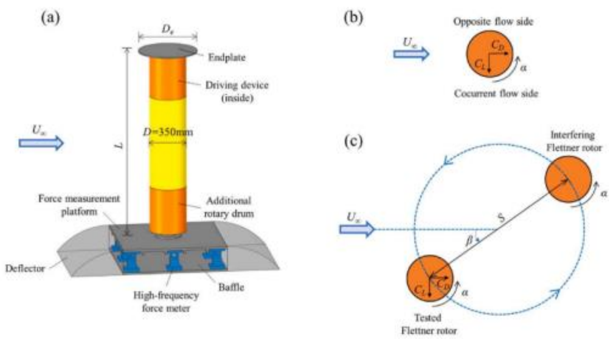


Figure 14. Experimental setup (a) tested model and meas-urement system, (b) single Flettner rotor, and (c) two Flettner rotors (Chen et al., 2023)

Aerodynamic interaction of two similar rigid sails exposed at apparent wind angles, the lift and drag forces, as well as the pressure measured on each sail, were compared with the results of measurements carried out on an analogous single sail in Bordogna (2020), shown in Figure 15. These results are eventually used to compare the performance, expressed in terms of driving and heeling force coefficients, of a "ship" equipped with one or two rigid sails. The number of sails employed and their gap distance are key parameters in the determination of the effects of the aerodynamic interaction on the performance of multiple sails.

Figure 15. Single sail model and two-sail arrangement mounted on the wind-tunnel turntable during the experiments (Bordogna 2020)

James et al. (2019) carried out Wind tunnel tests on a model of Actively Controlled Wing Sail. The data exhibits clear trends of increasing lift as injection momentum increases, with critical flow attachment points being identified at specific combinations of jet momentum coefficient and angle of attack.

A wind tunnel testing campaign was conducted to confirm the findings of the CFD optimisation study of the suction sail by A. Llopis Pascual, et al. (2023). The model consists of a main body and a span with interchangeable components: flap, porous plate, and winglets. The model was attached to a turntable, used to vary the angle of attack of the model.

4.3.6 Kite performances experiments

Wind tunnel testing of large deformable soft kites is in many cases practically not feasible. Johannes Oehler et al. (2019) reviewed experiments described in the literature to determine the lift-to-drag ratio of kites, and presented an experimental method for aerodynamic characterization of flexible membrane kites by in situ measurement of the relative flow, while performing complex flight maneuvers.

Experimental campaigns onshore by M. Behrel et al. (2018) and at sea by Kostia Roncin et al. (2020) were achieved to control and measure performances of small leading edge inflatable kite shown in Figure 16. Experiments set-up in M. Behrel et al. (2018) are a three-dimensional load cells to get kite force and kite position into the wind window. Kite is controlled using winches, and an autopilot performs repeatable 8-pattern trajectories. Experimental boat Kitelab (Kostia Roncin et al. 2020) experienced ten full days of measurements, keeping all parameters as fixed as possible. Various configurations of sailing were tested, using different kites, different lengths of tethers, different dagger boards, different points of sail and so various true wind angles. All these data were analysed using only average values for each run to get to an overview of the kiteboat performance.

Figure 16. Kite control and measurement device deployed on shore and picture of the Kitelab . (Kostia Roncin et al. 2020)

Cadalen et al. (2018) described experiments recorded by "Beyond The Sea" on the ground. The anchor point consists of a fixed manual steering device that allows for asymmetrical and symmetrical steering by acting on two handles at the end of the two steering lines. The traction line is connected to the ground as well, but is not used for control. On the wing, the measurements are made with an inertial measurement unit (IMU). On the steering device, each tether is connected to a load cell to measure the sustained force. Shaft encoders measure each line displacement. Additionally, an anemometer measures the wind speed and direction. The kite is then steered manually, via the two steering lines. The sensors measure the kite attitude, the tethers’ force and their steering.

4.3.7 Kite force and motion simulation

In most wind conditions, compared to a static flight, a dynamic motion of a tethered wing with an eight-shaped pattern can provide sufficient force through traction to tow a ship.

4.3.7.1 Zero-mass model

The zero-mass kite modelling neglects the weights of the kite, the inertial forces and deformation of the tethers. The zero-mass model was established by Wellicome (1984) and is often used to estimate the kite performances. Under the assumptions of the zero mass model, Dadd et al. (2010, 2011, 2013) and Naaijen et al. (2006) calculated the kite velocity with an iterative algorithm. Dadd et al. (2010) used the zero-mass kite manoeuvring theory to predict kite line tension and other performance parameters. These results were compared with real kite trajectories that had been recorded using a purpose-specific kite dynamometer. Traut (2014) introduced a numerical performance model applying zero-mass model on a kite to predict wind-generated thrust and propulsive power which were computed as a function of local wind and ship velocity and linked with wind data along a set of five trade routes.

A kite flight modelling based on the zero-mass assumptions was rewritten by Leloup et al. (2014) in order to speed up the velocity and tether tension calculations along a flight path. The wind gradient and the ship velocity were integrated to the kite flight modelling.

C. Duport et Al. (2016) developed a 3D non-linear model based on the lifting line of Prandtl to be able to quickly estimate the traction that can provide a kite according to its trajectory. An iterative equilibrium procedure has been developed, based on zero-mass model assumptions. It allows the rapid calculation of aerodynamic forces for a wing with any laws for the dihedral angle, the twist, and the sweep angle, along the span; and for a general flight kinematic taking into account translation velocities and rotation rates.

4.3.7.2 Point mass model

A point mass model assumes that the kite mass is concentrated at a point and this entails the apparition of inertial forces and weight. It has been proposed in Fagiano (2009), Williams et al. (2008), Jehle and Schmehl (2014). Williams et al. (2008) used the point mass model of the kite to determine the optimal trajectory to maximize power generation while keeping low the efforts needed to control the kite. In order to obtain a sufficiently realistic model which can also be easily implemented in a controller, a point mass model was chosen by Baptiste (2018) and a transverse aerodynamic force nullifying the drift angle, as well as a slacking and hauling command have been taken into account. The steering lines are considered constant in length and non-deformable. Their effects on the wing dynamical behaviour are neglected .

Dadd et al. (2010) compared the results of the zero mass model with the point mass model , which showed that the mass of the kite and the tether can be neglected if the weight is small enough in comparison with aerodynamic forces.

Behrel et al. (2018) presented experimental results comparing zero mass and point mass modeling. Differences are about few percent. Actually, both modelings give the same results when their coefficients identification is consistent. If taking into account the mass can be important for control issue, this is clearly not the case for performance assessment.

4.3.8 CFD computations on other WPS

Karman D.（2016） investigated the flow around a Flettner-rotor without its end plate in 2D and 3D by CFD package. Several unsteady (LES and URANS) and steady (RANS) simulations were carried out and compared among several turbulence models. Two LES subgrid models: the Smagorinsky-Lilly and the Wall-

Adapting Local Eddy-Viscosity (WALE) were compared, also the analysis several RANS runs were carried out with the $\kappa - \varepsilon$, the $SST\ \kappa - \omega$ and the RSM stress$-\omega$.

De Marco et al. (2016) performed a parametric study with CFD aimed at establishing the drag and lift coefficients on various rotor sails geometries operating at various rotational speeds. Unsteady RANSE was solved using $SST\ \kappa - \omega$ turbulence model. Hybrid mesh approach, coupling unstructured and structured mesh, has been used for all the simulations.

A. Persson et al. (2019) presented CFD simulations on rotor sails and wing sails. The 3D lift and drag coefficients of the wing sail predicted by the different methods of Quasi-3D methods including Sectional Integration with 3D-correction (SILL), Non-linear Lifting Line algorithm (NL-LL) and 3D Sectional Integration Method (3D-SIM). They were compared with the 3D CFD simulations.

L. Jones et al. (2019) carried out a series of CFD simulations to evaluate the impact of parametric changes in Flettner rotor design, including the impact of multiple rotors operating in combination, and the influence of the ship induced flow field. Simulations were conducted using an unsteady Reynolds averaged Navier-Stokes based transient solver. Turbulence effects were accounted for using a $SST\ \kappa - \omega$ turbulence model, with the viscous sublayer modelled using wall functions.

James Cairns at.al (2019) carried out 2D CFD simulations on Actively Controlled Wing Sail using the Spalart-Allmaras model with rotation correction (SARC) and the $SST\ \kappa - \omega$ model with curvature correction (*SST-CC*). Good agreement was found when comparing simulation and experiment for low jet momentum coefficient, detached flow cases. However, certain simulation conditions exhibited a well-documented shortcoming of RANS-based turbulence models for circulation control flows and over-predicted surface pressures and lift coefficient for fully attached flow cases.

Will Hopes et al.(2021) carried out a CFD study on the performance of Suction Aerofoils choosing the RANS-based Shear Stress Transport (SST) turbulence model to determine values for the lift and drag coefficients over a range of angles of attack and suction levels. Supplementary studies also investigated the effects of introducing an endplate to reduce end vortices, and the effect of a ship side on the wind speed incident on the Suction Aerofoil.

4.3.8.1 Interaction effects

To improve the methods of performance prediction for wind-assisted propulsion, the importance of interaction effects in between the sails and between the sails and the hull, i.e., rudder angle and drift, was discussed in (Viola et al., 2015; van der Kolk et al., 2019b).

4.3.8.2 Aerodynamic interactions

Complex aerodynamic interaction effects of various wind-propulsion systems occur and that eventually have an impact on the amount of wind-generated thrust. Aerodynamical interactions are crucial to model to accurately predict the jaw moments and thus the necessary rudder angle and for reliable sail control. The results of studies from Bordogna (2020), Tillig and Ringsberg (2020) showed that in-between sails, potential flow interaction effects are predominant (Figure 17).

Wind tunnel tests interaction between two rotating cylinders were carried out by B Charrier (2021) to demonstrate the effect of the aspect ratio, the rotating endplates and the Reynolds number.

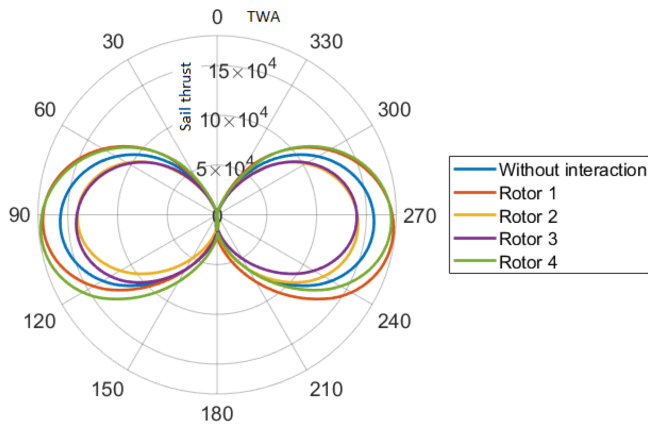


Figure 17. Effects of sail interaction (Tillig and Ringsberg, 2020)

An investigation into combination of the various aerodynamic interaction effects on the lift and drag was performed by Jones et al. (2019) on the interaction between multiple rotor sails, a block located at various positions relative to the rotor and the ship and superstructure. Garenaux et al. (2021) developed a numerical approach using steady full scale RANS simulations to estimate the effects of the interaction between the ship and its three Flettner rotors. Large interaction effects are found to depend on the apparent wind angle.

The Non-linear lifting line method described by Phillips (2000) was adapted for use for wind propulsors and implemented in the module of Wind Propulsor Interaction(wpi) by Schot and Garenaux(2023). The method can use a non-uniform wind profile which consists of an atmospheric boundary layer profile, ship speed and the disturbed wind from the ship and superstructure.

A. Llopis Pascual, et al. (2023) conducted CFD study to analyse the sail-to-sail interaction of two model eSAILS (suction sails) fitted at the stern of a ship. The images are aligned with the ship, where the bow is to the left and the wind is simulated at different apparent wind angle. A detailed analysis of these results allows to understand the influence each eSAIL has on the other and use that information to customise the control algorithm to maximise the performance of the systems for this specific installation.

4.3.8.3 Aero-hydrodynamic interactions

Integrated aero-hydrodynamic models in VPPs or PPPs for the prediction of performance of WPS usually include static VPPs and dynamic VPPs. Bigi et al. (2016) investigated the influence of the kite attachment point on the deck of a fishing vessel. A manoeuvring modelling limited to horizontal ship motions is implemented with a monolithic coupling approach between the ship and the kite. The water is supposed to be calm and the effect of the radiated waves on the ship motions was not taken into account. To consider drift and yaw effect on propulsion system, a MMG mathematical model-based simulation was carried out for different drift angles of motion of the ship considering hard sail-based wind loads in Hussain et al. (2021).

Steady-state VPPs are very efficient and fast , but it is not able to consider dynamic effects such as unsteady wave forces on the hull and the ship's motions in a seaway that the angles of attack of the sails fluctuate. Martin Kjellberg et al. (2023) used an unsteady 3D fully non-linear potential flow hydrodynamic model coupled with an efficient lifting-line aerodynamic model to investigate the differences in sailing performance of a vessel sailing in steady conditions to the performance when sailing in a seaway and gusty wind based on a spatio-temporal wind model. The analysis showed clearly that the unsteady wind model affected the predicted performance.

The motions of a ship towed by a kite are highly dynamic since a kite experiences a periodic dynamic flight. To perform a strong coupling between the kite and the ship, Bigi et al. (2020) applied a time domain method to assess the importance of taking into account the coupling between the kite and the ship motions. Seakeeping modelling is coupled with a zero-mass kite modelling assuming linear dependence of aerodynamic characteristics with respect to turning rate.

4.3.8.4 Fluid-structure interactions (FSI)

Fluid-Structure Interactions (FSI) is the interaction of the deformable structure with a surrounding flow. Such interactions are generally investigated numerically using the coupling of fluid simulation and structural simulation.

4.3.8.5 Numerical method

Breukels et al. (2011, 2013) carried out CFD simulation on a 2D aerofoil to compute its lift, drag and moment coefficients as a function of the angle of incidence, thickness and camber of the aerofoil. A model simulation was also compared with experimental data, tension in the four lines of various kites during a loop. Bosch et al. (2012, 2014) chose a complete finite element modelling of the wing. The canopy is modeled by triangular shell elements and the battens by beam elements. The fluid model is the same as the one used by Breukels (2011) and gives the forces distribution on the canopy as a function of the angle of incidence, thickness and camber of the section. .

Monolithic coupling to FSI problems where fluid and structure are solved simultaneously was used in Le Tallec & Mouro (2001). Monolithic coupling is more stable and more accurate than partitioned coupling (Michler et al. (2004)) but also more computationally expensive.

A fast and robust approach to model FSI for yacht sails is presented in Morvan et al. (2021). Specifically, interaction effects between the jib and the mainsail are taken into account in the flow model presented. The flow model is coupled with a structural finite element software, using shell elements for the modelling of sail membranes, beam stringers for battens modelling and a quasi-static resolution based on a dynamic backward Euler scheme.

4.3.8.6 Experimental method

The possibility of measuring a structural deflection under fluid load and the flow behaviour around the structure is particularly interesting with the rise of composite materials. A robust and repeatable experimental methodology will also provide researchers with a validation case for numerical FSI simulations.

A fully coupled FSI methodology was developed in a wind tunnel to assess the response of a PAC aerofoil in L. Marimon et al. (2017, 2018, 2020). Digital Image Correlation (DIC) and Particle Image Velocimetry (PIV) were used in-air to obtain high-speed full-field wing deformation and flow field velocity data in synchronous with forces and moments. Laura and Ivan (2021) carried out a detailed review of the experimental methods able to describe FSI events in an underwater dynamic environment. A feasibility study is carried out to understand the implications, limitations and advantages of being able to measure with full-field techniques in a towing tank.

4.3.9 Validation and Verification of CFD

Numerical methods are typically validated towards experimental results. In the case of performance predictions for wind assisted vessels, sail models can be validated by (or generated from) e.g. wind tunnel tests, hydrodynamic force models towards for instance PMM (Planar Motion Mechanism) tests, propeller and rudder models towards dedicated propulsor tests, and so on.

A modified version of the horseshoe vortex method to compute the velocity field behind a given wind-propulsion system were compared with numerical tools (CFD body force method and a standard RANS solver) as well as with experimental data obtained by means of dedicated wind tunnel tests in Bordogna (2016). Duport et al. (2016, 2019) developed a 3D non-linear model based on the lifting line of Prandtl for calculation of aerodynamic forces and this model has been verified by comparison with 3D RANSE simulations and produces satisfactory results in incidence and sideslip.

Duport et al. (2016) did estimation of the numerical accuracy of the RANSE simulations including the deviations, coming from the variations of the domain size, of the mesh and of the turbulence model. The numerical results were compared with experimental ones obtained in wind tunnel at the same Reynolds number.

ITTC procedure and guidelines and American Society of Mechanical Engineers (ASME) standard procedures are applied to verification and validation of RANS CFD simulations on hydrodynamics of wind-assisted ship propulsion in van der Kolk et al. (2016, 2017, 2019, 2020). The verification has been conducted with particular focus on the hydrodynamic sideforce, as a leading component of the hydromechanics of wind-assisted ships. Based on the results, the uncertainty procedure developed by Eça (2010), based on the Grid Convergence Index (GCI) of Roach (1997), was the most robust approach.

The RANS numerical set up has been extensively verified and validated using different experimental data including a twin rotor configuration by M Garenaux and J J A Schot (2021). A good correlation is found with experiments for both standalone rotor and twin-rotor configuration.

Kume et al. (2022) compared the results of RANS-based CFD calculations and wind tunnel tests of aerodynamic forces on a VLCC equipped with 4-Flettner rotors using model scale, indicating that CFD can be ued as a substitute for wind tunnel test. Eide et al. (2023) performed cyber-physical empirical model test of a wind-assisted cargo ship to validate a steady numerical simulation method which is a prediction program solving the motion of the vessel in three degrees of freedom (surge, sway and yaw).

N Abiven et al. (2023) demonstrated wind-powered cruise ship aerodynamic simulations, hydrodynamic simulations and correlations. Series of drift hydrodynamic numerical / experimental simulations and correlations to assess induced lateral drag and impact on ship hydrodynamic behaviour, in particular course stability and manoeuvrability have been developed and conducted.

R Azcueta and H Ward（2023） presented CFD simulation results of open water propeller, towing resistance at model and full scale and propulsion with the virtual disk and with rotating propeller approaches of a bulk carrier and the 6-DoF simulations of the full-scale vessel in motor-sailing conditions including the WASP devices which were validated by comparison to the test results. Numerical uncertainty analysis following the ITTC and IACS recommendations are described to verify the qualification of the CFD solution.

4.3.10 Conclusions

A review of the literature on the methods of ship model hydrodynamic tests, wind tunnel tests, CFD, ship dynamics simulations and routing relevant for predicting the performance and safety of wind powered and wind assisted ships has been undertaken. Verification and validation of numerical method including uncertainty analysis are commonly performed on hydrodynamics and aerodynamics.

The performance prediction methods show great promise in becoming a tool for designers and researchers for analysis and optimisation of wind propulsion device layout and operational parameters. To generate more accurate results for a specific ship with WPS, further investigation into the effects of drift angle on propulsion performance and resistance, routing simulations are needed for ship performance prediction of ship with wind and wind-assisted propulsion in wind and waves.

Detail developments of hybrid wind-propulsion ship for different ship applications with specific new features to address heel and drift during navigation and manoeuvring (e.g. development of anti-drift equipment and potential additional appendages), and corresponding ship design assessments and validations: stability, power management strategy, coupled aerodynamic / hydrodynamic CFD simulation and experimental tests at large scales on standard ship operation conditions (sailing, manoeuvring) as well as extreme cases (safety issues and rules) need to be investigated.

Sailing performance with an improved manoeuvring model and CFD simulations, simulations and hybrid model tests performed in waves, zig-zag manoeuvring model tests and time domain simulations, investigation into the effects of dynamic heel, trim and drift angle on the propeller wake are to be further studied.

4.4 Review long-term statistics of winds and waves from the point of view of applicability for the evaluation of wind assisted ships at design stage.

4.4.1 Introduction

Long-term statistics of winds are essential for the evaluation of wind assisted ships at the design stage. The Global Wind Probability Matrix is used to calculate the EEDI and EEXI for Wind Assisted Propulsion Systems, however the area of applicability is limited to the main global shipping routes as shown in Figure 18

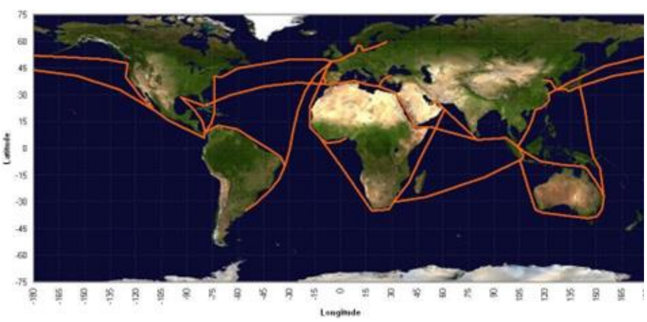


Figure 18. The main global shipping network used for the wind chart (MEPC 62, 2011)

Inadequacies with this method may potentially arise when used outside of these routes. Werner et al. (2021) describes a methodology to analyse full scale speed trials on a wind-assisted hybrid ferry. The trial area is off Gedser, Falster, Denmark, outside of the main shipping routes depicted in the Global Weather Matrix. Wind statistics were obtained from the Global Wind Atlas (2022) and results are complimented with the wind statistics from the EEDI Global Weather matrix. As can be seen from Figure 19, the Global Wind Atlas predicts higher wind speeds for the actual sea area the ferry operates in, compared to the EEDI global weather matrix.

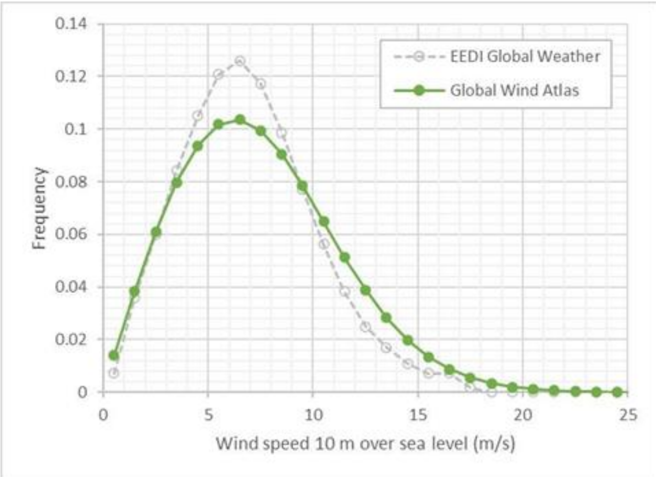


Figure 19. Wind speed distribution from Global Wind Atlas for ferry route, and the EEDI Glob-al Weather matrix (Werner et al., 2021)

Since global wind speed datasets are assembled from various sources of satellite and reanalysis data, the most-suitable dataset for a particular purpose is often unclear. The accuracy of global datasets differs depending on the ocean area. Due to their coarse resolution, reanalyses are known to fail to represent local climatic conditions adequately (Werner et al., 2021).

While global reanalysis data sets offer the advantage of conducting multi-country or global analyses without the need for country or region-specific climate data sources, their use for wind power simulation would benefit from a more granular spatial resolution (Staffell et al., 2016), as offered by regional reanalyses such as COSMO-REA (2019) which in more detail represents the local climatic conditions.

The great advantage of numerical models is their wide coverage on a high time and space resolution in a global scale, making it possible to produce long-term wind (and wave) climatologies without gaps.

4.4.2 Wind Models

To assess potential savings in power for wind assisted ships at the design stage, various data-sets incorporating different data assimilation models were selected for evaluation. Some data-sets are superseded by others but are included as many present-day methodologies still use them (Li et al., 2022). These climate models are summarised in the following sections, and in Table 7.

4.4.2.1 ERA-Interim

ERA-Interim dataset is provided by the European Centre for Medium-Range Weather Forecasts (ECMWF). It is a global atmospheric reanalysis from 1979, continuously updated in real time and replaces the previous ERA-40 reanalysis dataset. ERA-Interim is now obsolete and has been replaced by ERA-5.

4.4.2.2 ERA-5

ERA-5 dataset is provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) and produced by the Copernicus Climate Change Service (C3S). It is a fifth-generation atmospheric reanalysis of the global climate covering the period from January 1940 to present, providing hourly estimates of a large number of atmospheric, land and oceanic climate variables. It is the most recent model out of the ones listed here.

4.4.2.3 NCEP – National Centre for Atmospheric Research (NCAR)

The National Centre for Atmospheric Research (NCAR), also known as R-1, is an atmospheric reanalysis produced by the National Centres for Environmental Prediction (NCEP). The time period spans from 1948 to the present.

4.4.2.4 NCEP – Department of Energy (DOE)

The Department of Energy (DOE), also known as R-2, is a climate model from the National Centers for Environmental Prediction (NCEP). It is based on the NCAR reanalysis but fixes some errors and uses updated parameterisations of physical processes.

4.4.2.5 NCEP – Climate Forecast System Reanalysis (CFSR)

The Climate Forecast System Reanalysis (CFSR) was developed by the National Centre for Environmental Prediction (NCEP) and spans the period from 1979 to 2017. It is a third-generation reanalysis product, superseding R-1 and R-2.

It is superior to previous NCEP reanalyses, having an improved model, including atmosphere-land-ocean-sea ice coupling, finer resolution and more advanced assimilation schemes.

There have been relatively few evaluations of CFSR so the performance is not well-known. Ocean-atmosphere interactions are not used directly. Rather the information is used for background information, meaning the actual reanalysis is uncoupled.

4.4.2.6 The Modern-Era Retrospective analysis for Research and Applications (MERRA)

The Modern-Era Retrospective analysis for Research and Applications (MERRA) is produced from the National Aeronautics and Space Administration (NASA). MERRA data span the period 1979 through February 2016. It is based on a version of the GEOS-5 atmospheric data assimilation system that was frozen in 2008. The MERRA dataset is superseded by MERRA-2.

4.4.2.7 The Modern-Era Retrospective analysis for Research and Applications Version 2 (MERRA-2)

The Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) is produced from the National Aeronautics and Space Administration (NASA). provides data beginning in 1980 to the present. It replaces the original MERRA dataset because of the advances made in the assimilation system.

4.4.2.8 The Cross-Calibrated Multi-Platform wind vector analysis (CCMP)

The Cross-Calibrated Multi-Platform (CCMP) is a gridded Level 4 (L4) product that provides vector wind over the world's oceans. It is produced by Remote Sensing Systems (RSS), (https://www.remss.com/). CCMP is a combination of ocean surface (10m) wind retrievals from multiple types of satellite microwave sensors and a background field from reanalysis. Data spans from 1987 to the present.

The reanalysis used in the latest version of CCMP (v3) is ERA-5.

The CCMP model generally performs poorly in rain and under high wind conditions (> 15m/s) and is not well suited for studies of global wind trends (CCMP, 2023).

4.4.2.9 JRA-55

The Japanese 55-year Reanalysis (JKA-55) dataset is provided by the Japan Meteorological Agency (JMA). The JMA carried out this second reanalysis project to address some of the shortcomings of the previous JRA-25 model, including the use of a much-improved data assimilation system. The analysis period covers the 55 years from 1958, when regular radiosonde observation began on a global basis.

The result of the JRA-55 project is the production of a high-quality homogeneous climate dataset covering the last half century.

4.4.3 Summary of Wind Models

A summary of the different wind models can be found in Table 7

Table 7. Summary of data sets used in analysis.

Data-set Name	Institution	Time Resolution (hours)	Spatial Resolution	Assimilation Method	Refs
CFSR	NCEP	1	0.3° × 0.3° (v1) 0.2° × 0.2° (v2)	3D-VAR	Saha et al. (2010)
NCAR	NCEP	6	1.875° × 1.875°	3D-VAR	Kalnay et al. (1996)
DOE	NCEP	6	1.875° × 1.904°	3D-VAR	Kanamitsu et al. (2002)
ERA-Interim	ECMWF	6	0.75° × 0.75°	4D-VAR	Dee et al. (2011)
ERA-5	ECMWF	1	0.1° × 0.1°	4D-VAR	Hersbach et al. (2020)
JRA-55	JMA	3	0.5625° × 0.5625°	4D-VAR	Kobayashi et al. (2015); Harada et al. (2016)
CCMP	RSS	6	0.25° × 0.25°	Scat/Rad	Atlas et al. (2023)
MERRA	NASA	6	0.5° × 0.66°	GEOS-5	Rienecker et al. (2011)
MERRA-2	NASA	1	0.5° × 0.625°	GEOS-5.12.4	Koster (2015)

4.4.4 Comparison of Wind Models for Reliability and Accuracy

The datasets outlined in the previous section are compared with a view to determining if there is an overall model which is most suitable for use in the applicability for the evaluation of wind assisted ships at design stage.

Suzuki et al. (2018) analysed the CCMP, NCEP/CFSR, NCEP-R1, NCEP-R2, ERA-Interim and JRA-55 global wind datasets and compared them to the measured wind speed from buoys. The data were analysed for the year, 2001 in which neither El Niño nor La Niña events occurred. The wind speed at 10m above sea surface was used. The wind speeds in the global dataset were converted to the smallest grids with 0.25°×0.25° through interpolation. To examine the validation, the wind speeds on a grid closest to the buoy location were used. 57 buoys were used, located in the Indian Ocean, Tropical Pacific, Tropical Pacific, Tropical Atlantic, North Pacific and Atlantic. The data from the buoys were converted to a value corresponding to 10m above sea level so as to correlate with the global wind speed datasets.

The Root Mean Square Errors (RMSE) for all datasets were calculated to investigate random errors of wind speed. Lower values indicate higher reliability. Results are shown in Table 8. The CCMP dataset is shown to be consistently the most reliable.

Table 8: RMSE of the wind speed of each datasets against the all buoy wind speed measurements

Data set	RMSE [m/s]	Data set	RMSE [m/s]
CCMP	1.05	NCEP/CFSR	1.53
NCEP-R1	2.16	ERA-Interim	1.42
NCEP-R2	2.46	JRA-55	1.64

The reliability of the datasets was also compared against buoy wind speed measurements for localised regions, as shown in Table 9

In all regions, the CCMP dataset is shown to be the most reliable. It can also be seen from the table that the lowest RMSE in Indian Ocean followed by Tropical Pacific, Tropical Atlantic, North Pacific, and North Atlantic.

Table 9: Reliability of datasets in localised regions.

Area	Data Set	RMSE [m/s]	Data Set	RMSE [m/s]
Indian Ocean	CCMP	0.89	NCEP/CFSR	1.32
	NCEP-R1	1.65	ERA-Interim	0.92
	NCEP-R2	2.08	JRA-55	1.29
Tropical Pacific	CCMP	0.99	NCEP/CFSR	1.54
	NCEP-R1	2.07	ERA-Interim	1.28
	NCEP-R2	2.20	JRA-55	1.57
Tropical Atlantic	CCMP	1.04	NCEP/CFSR	1.49
	NCEP-R1	1.86	ERA-Interim	1.22
	NCEP-R2	2.32	JRA-55	1.51
North Pacific	CCMP	1.23	NCEP/CFSR	1.45
	NCEP-R1	2.73	ERA-Interim	2.07
	NCEP-R2	3.41	JRA-55	2.07
North Atlantic	CCMP	1.52	NCEP/CFSR	1.73
	NCEP-R1	2.88	ERA-Interim	2.10
	NCEP-R2	3.73	JRA-55	2.07

Suzuki et al. (2018) concluded that the wind speed dataset in CCMP is the most accurate for any local ocean area. In the North Pacific and North Atlantic, all the tested datasets were inaccurate. All global wind speed values differ from the buoy wind speed measurements in low wind speed range. Distribution trends of all the global datasets are similar to that of the buoy's wind speed measurement. Compared to the buoy wind speed measurements, the NCEP-R1 and NCEP-R2 datasets show especially large dispersion and the CCMP dataset shows the smallest variation.

Gruber et al. (2022) conducted a study on the assessment of wind power simulation from bias-corrected MERRA-2 and ERA-5 reanalysis. They concluded that ERA-5 on average performs better than MERRA-2 in all regions, with ERA-5 showing approximately 0.05 higher correlations than MERRA-2 and 0.05 lower RMSEs in most regions. Only in New Zealand, MERRA-2 performs better on average than ERA-5.

Stefanakos (2021) studied several statistical features of the datasets are assessed, such as seasonal variability, quantiles of the probability distribution, monthly, annual and inter-annual variability, and several error metrics on two reanalysis products, ERA-5 and CFSR. The analysis was per-formed at both a global and regional scale. They conclude that the two datasets are in a very good agreement, with CFSR having little greater variability than ERA5.

Carvalho (2019) have made comparisons between NCEP-CFSR, ETA-Interim and JRA-55 and were analysed to evaluate the MERRA-2 model. Results showed that MERRA-2, CFSR, ERA-Interim and JRA-55 showed similar error metrics. All reanalyses showed a tendency to underestimate ocean surface winds, particularly in the tropics. MERRA-2 showed lower wind errors in the poles when compared to the other reanalyses.

4.4.5 Wave statistics

There are a number of approaches to obtain wave data. For instance, Fang and Lin (2013) used WAVEWATCH III to obtain the precise forecast of environmental factors along routes for ship route optimization. Eggers (2018) used wave scatter diagram to perform the route optimizations.

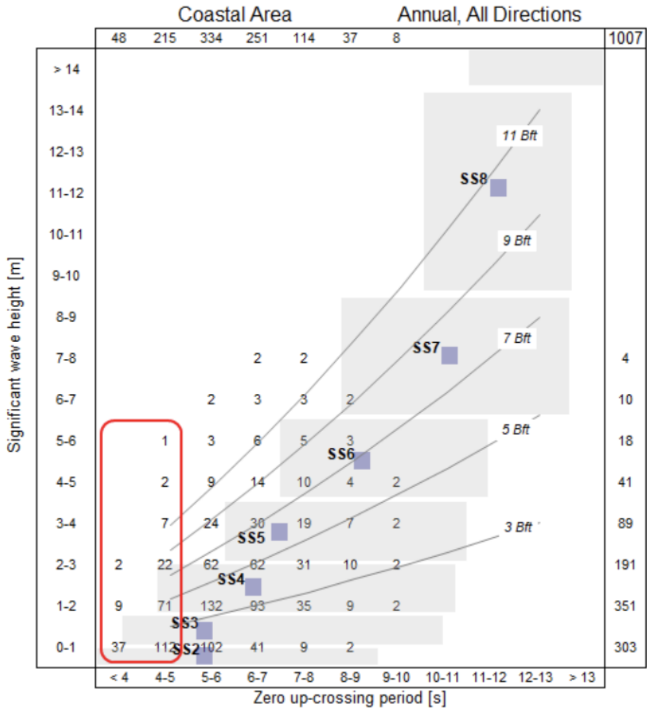


Figure 20. Typical wave scatter diagram (Egger, 2018), IACS wave scatter diagram.

Figure 20 Typical wave scatter diagram (Egger, 2018), IACS wave scatter diagram.

The IACS wave scatter diagram describes the wave data of the North Atlantic, covering the area as defined in the Global Wave Statistics (GWS) with more realistic considerations of the wave steepness. Short-term sea states are assumed to be statistically independent and hence uncorrelated in the standard procedure for the long-term response analysis (IACS, 2000). It should be noted that Bretschneider or two parameter Pierson-Moskowitz spectrum is recommended for the North Atlantic.

Global Wave Statistics (Figure 21) provides nearly worldwide coverage of wave climate in 104 sea areas, and an additional database providing smaller sea areas for the North European Continental Shelf. Based on 130 years of ship visual observations to provide a stable climatic average, the data has been quality enhanced by the well-established NMIMET process.

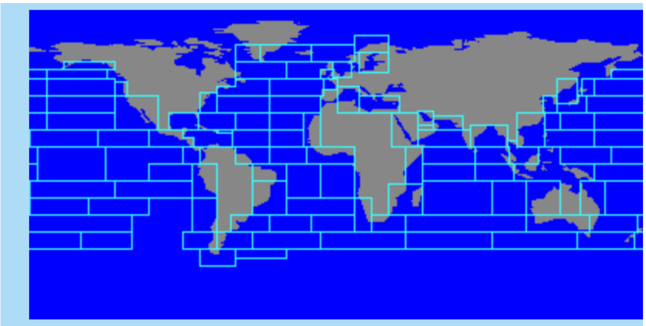


Figure 21. GWS plot

Bitner-Gregersen et al. (2013) investigated uncertainties in the Global Wave Statistics data and their effects on ship loads and responses, as well as on fatigue damage. They have concluded that the GWS should be used with care.

NMRI in Japan developed a system called Globus which can offer statistical results of global winds and waves, which are analysed by NMRI. The statistical data are based on the numerical weather prediction of 10 years, from 2006, calculated by Japan Meteorological Agency and these are composed of significant height, peak period and primary direction of waves, and mean speed and direction of winds in 2.5 degrees interval in space and 6 hours interval in time.

In terms of the wave forecast system, ECMWF was developed in Europe and Global Real Time Ocean Forecasting System (RTOFS) was developed by NOAA, US.

For the fatigue life prediction of ship structures, it is important to obtain both the long-term distribution and the time history of wave-induced loads. Gracia et al. (2019) compared two statistical wave models and validated them by a ship's actual encountered wave conditions. They found that Statistics of wave height and stresses generated from the two models agree well with that from hindcast and onboard measurements. They also concluded that the actual wave environments encountered by the ship differ significantly from the wave scatter diagram provided by class guidelines for ship fatigue design. Today's onboard wave radar sensor can provide rough approximation of a ship's encountered sea conditions, but the measured significant wave height may contain large errors in comparison with the hindcast wave data in particular at harsh sea environments.

Mikulić et al. (2021) studied the effect of spatial correlation of sea states on extreme wave loads of ships. By comparing the results using "uncorrelated scatter diagram" and "scatter diagram", they concluded that spatial correlation may considerably reduce extreme vertical wave bending moments.

4.4.5.1 Correlation between Wind and Wave Statistics

Sea surface wind speed and significant wave height follow a monotonical relationship under a growing sea up to the fully developed stage. This final stage is usually reached when the phase velocity corresponding to the dominant peak wave slightly exceeds the wind speed (Chen et al., 2002).

Wave forecasting models always employ the concept of a fully developed sea. For a given constant wind speed, if the upwind distance to the point of observation over which the wind has blown is larger than a certain distance and if the duration of the wind is longer that a certain time, then the wave height will be solely a function of wind speed (Sverdrup and Munk, 1947). Based on the statistics of wind speed and significant wave height of developed seas for a large enough fetch and a long enough duration, Pierson and Moskowitz (1964) found the significant wave height is positively related to the square of wind speed, i.e. $H_s = \alpha U^2$ (H_s is the significant wave height, U is the wind speed, α is a coefficient obtained by linear fitting). They reconciled the differences in wind speed at different heights and found $\alpha = 2.45 \times 10^{-2}$. Ewing and Laing (1987) found 33 examples of spectra for "nearly" fully developed seas by means of a study of the past winds at the measurement site and the wind pattern upwind of the measurement, and they proposed a third-order polynomial to describe the relation between the significant wave height and wind speed, i.e. $H_s = 10^{-3}(8.7U^2 + 0.728U^3)$. However, the Wave Model (WAM) found the relation $H_s = \alpha U^2$ applies to the lower wind speed, i.e. $0 < U < 7.5\ m/s$. To improve the accuracy of wave forecast in condition of larger wind speed, they adopted a third-order polynomial, i.e. $H_s = 10^{-3}(10U^2 + 0.81U^3)$ (Hasselmann et al., 1988).

Based on collocated wind speed and significant wave height measurements from simultaneous satellite scatterometer and altimeter sources, Chen et al. (2002) analyzed the global statistics of wind wave and swell, and plotted a scatter diagram of sea surface wind speed and significant wave height, which is shown in Figure 22. The three different lines are theoretical relations between wind speed and significant wave height for fully developed seas according to Hasselmann et al. (1988), Ewing and Laing (1987) and Pierson and Moskowitz (1964), respectively. Measurements lying below the curves are mostly from a growing sea, while those above the curves are probably swell dominated.

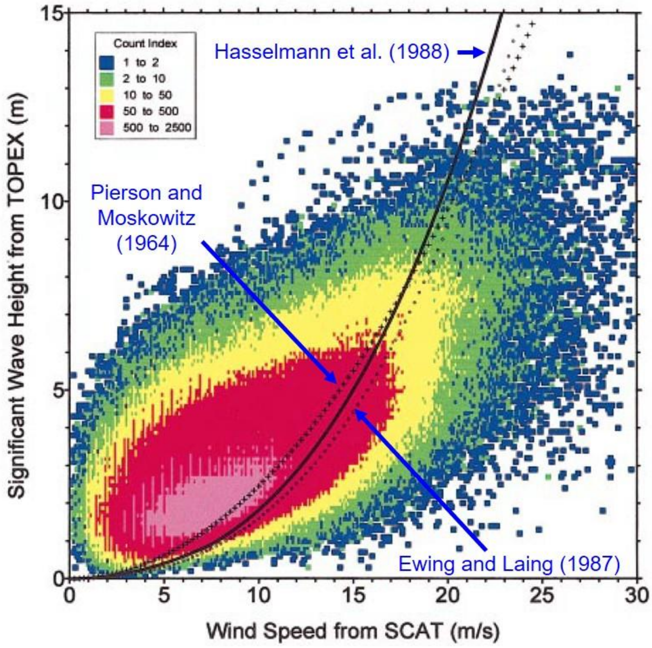


Figure 22. Scatter diagram of sea surface wind speed and significant wave height based on global wave data and wind data (Chen et al, 2002)

The wind speeds are extracted from QuikSCAT, and the significant wave heights are extracted from the TOPEX altimeter (Chen et al, 2002).

Because of the complexity of the wind wave-swell coupling, the assumption that the wave height is solely a function of wind speed in a fully developed sea is not suitable to the real sea state. Waves depend on both local and global wind conditions. It is not only the local wind that defines local waves, and wind from distant regions generates swells that may reach the target point (Ardhuin and Orfila, 2018).

Considering the complexity of the wind wave-swell coupling, Obakrim et al. (2023) developed a method to predict the significant wave height in wind seas and swells by including local and global predictors. Wind speed, duration, and the fetch are used as local predictors, while the zonal and meridional components of the wind data are used as global predictors. A regression-guided clustering method is used to constructed weather types, and the resulting clusters correspond to different wave systems (wind seas and swells). Then, in each weather type, a penalized linear regression model is fitted between the predictor and the significant wave height.

The extreme wind and wave storms can pose a threat to the safety of both marine structures. Based on the data from four meteorological (buoys and anemometers) stations of the National Data Buoy Center moored off the East Coast of the United States, Laface and Arena (2021) proposed a criterion to identify and associate wind and wave storm. An optimal threshold combination is achieved assuming both wind speed and significant wave height threshold as 1.5 time their respective averages. The wind speed is characterized by a higher variability with respect to the significant wave height. The significant wave height increases with the wind speed. However, the peak of the significant wave height does not always occur after that of the wind speed.

4.4.6 Conclusions and Recommendations

For the general purpose of the evaluation of wind assisted ships at design stage, it is recommended that the ERA-5 Reanalysis or CCMP product is used. However, if a shipping route is particularly localised, it may be beneficial to use a regional high-resolution reanalysis system such as COSMO-REA6 for Continental Europe, for increased accuracy and reliability. Regarding the wave scatter diagram, there is no special requirements for wind-assisted ships.

4.5 Review safety and regulatory issues related to hydro/aero dynamic testing and evaluation and recommend measures to take at design stage

4.5.1 Introduction

After discussion with the Advisory Council, it was understood that the main aim of this term of reference is to specify testing and evaluation methods. However, these methods of course need to address specific safety and regulatory issues as relevant for wind powered and wind assisted ships. Therefore, the present section begins with a review of safety (and operability) issues. Following that is a discussion of existing rules and regulations. Both of these sections describe scenarios and criteria that are to be satisfied. The final main section then discusses testing methods that may be used to simulate the scenarios and to evaluate compliance.

The scope of behaviour that is covered in the present section are those activities generally conducted by ITTC members, extended with aerodynamics. This means that the following topics are covered:

- Motions and accelerations
- Forces
- Energy and power as relevant to safety and rules & regulations.

Considering the focus is on safety, any rules & regulations on performance in steady conditions are not handled here. These are part of other Terms of Reference.

As will be seen in the following sections, rules and regulations on safety are at present not tailored for wind powered and wind assisted ships. Ships with modest assistance may operate with only small changes to their behaviour as a conventionally propelled ship. However, with more powering provided by the wind, ships start to behave differently. As of yet there are not much research results that give a general overview of the impact. Perhaps matching that, class societies have only provided guidelines, that also vary quite a lot from society to society. As a result, some assumptions are unavoidable to anticipate what kind of testing will be required going forward.

4.5.2 Potential safety and operability issues for wind powered and assisted ships

Potential safety and operability issues are discussed based on available literature. This is partially the same literature discussing testing and simulation methods as addressed in section 4. There is much to be said on the accuracy and practicality of these methods. However, that is discussed in section 4.5.6. For the purpose of the discussion here, the methods are deemed sufficiently accurate.

4.5.2.1 Course keeping

In principle one can think of two mechanisms for wind propulsion to affect course keeping ability:

1. Dynamic aerodynamic forces (wind gusts, changes in wind direction) that push the ship of course directly
2. Loss of steering capability from conventional actuators (rudders, thrusters, pod) due to a lower propeller thrust that reduces the flow along these actuators. This, combined with other external forces, specifically waves from the stern quarter, can lead to a decrease in course keeping performance. Part of the available rudder action is already committed to counter the (quasi-)steady sway forces and yaw moment from the wind propulsion system, thus, less margin may be available for countering unsteady forces from wind, waves and current.

Course changes directly through variable aerodynamic forces (mechanism 1) were tested and reported by Sauder and Alterskjær (2002). In a model test, a ship with three four Flettner rotors was exposed to wind gusts and variable wind directions. The model showed only marginal course changes and some modest rolling. The mentioned reason for the small course variation is the ship, which its large mass, that acts as a filter. The frequency of the excitation through the wind is much higher than the ship response. Inertia in heel is relatively less, which means that some rolling could still occur.

Eggers and Kisjes (2019) have illustrated mechanism 2. In substantial wind conditions (roughly 7 Beaufort) and a matching sea state from the stern quarter, four times increase of the yaw angle variation was observed for the coaster design that was tested with three Flettner rotors. The reference was the same ship in a very mild wind condition. Differently to mechanism 1, the excitation comes from the waves, and this excitation can have a substantial amplitude and relevant frequency in stern quartering seas, with a lower encounter frequency. In contrast, Gerhardt et al (2021) found in experiments that yaw oscillations were not substantially affected when testing a Car Carrier with three wing sails. The difference in conclusions may be attributed to the designs and test conditions. In the experiments by Eggers and Kisjes an existing ship model was taken without substantially changing it for wind propulsion, whereas the car carrier in the experiments by Gerhardt et al (Gerhardt et al. 2021) was a dedicated design. Also, wave heading was arguably more demanding in the coaster case. Based on this scarce data it can be concluded that wind propulsion could present a challenge for course keeping, but not necessarily always.

The discussed papers showed only a few ship designs and wind and sea conditions. Thus, the general applicability of the conclusions on more ship types and environmental conditions is not yet known.

4.5.2.2 Ability to keep speed in adverse bow (quartering) wind and waves

Keeping control in adverse bow (quartering) wind and waves is an important ability.

Whereas the main purpose of wind propulsion is to aid in the propulsion of the ships, there are two mechanisms in which wind propulsion may also lead to a decrease in performance in the conditions discussed here:

1. When wind propulsion systems cannot be fully reefed/lowered, then the windage of a ship can increase when sailing in unfavourable bow (quartering) wind. This adds to the overall resistance. Especially combined with a low/reduced capacity propeller and engine, ships could have trouble to remain under control. The speed of the ship could be reduced by too much.
2. Wind propulsion changes the equilibrium condition of the ship, in general affecting heel, leeway and rudder angle. These aspects could potentially impact the second order mean wave drift forces (which includes added resistance in waves). The hydrodynamic shape and inflow under water changes, which means that the general knowledge on added resistance in waves may need extension.

Heel, leeway and rudder angle may also directly by themselves lead to an increase in drag. However, it is considered that any smart design and control will make sure that this drag component is modest in relation to the thrust of the wind propulsion system. And if it is not, then the wind propulsion system may be depowered or disabled.

In most cases, wind, wind sea, and swell are assumed to be aligned in direction, i.e. they are "co-linear". However, they don't always need to be in equilibrium. Particularly swell does not full correlate with wind. If the sea or swell direction that provides the largest contribution to the second order mean drift forces has a considerable offset in direction compared to the wind direction, then there may be possibility for the wind propulsion to assist in the propulsion of the ship, thereby helping to maintain control in head waves. Although such a scenario may occur, it will likely be something that one can depend on. Nevertheless, it would be interesting to see this scenario elaborated in future research.

4.5.2.3 Heel, roll and stability

Heel (steady average value) and roll (dynamics) can affect the safety and comfort and result in loads on ship parts and cargo. This is already relevant for modest angles. However, ultimately too large roll may even lead to capsize. This is valid for all but one wind propulsion technology. Kites are an exception here: if the connection point on deck is relatively low, then the introduced roll moment is very low compared to other technologies and heel and roll effects are likely minimal.

Very generally it is found that wind propulsion:

1. Leads to an increased heel angle through the heeling moment directly introduced by the wind propulsion system
2. Can lead to increased roll motions due to dynamics in the wind propulsion systems, introduced e.g. through wind gusts
3. Can lead to decreased roll motions because of an increase in roll damping

Mechanism 1 is shown already in static VPP / PPP calculations for which there is a relatively large amount of data available in literature. The extent of heel depends on the vessel stability and the relative size and height of wind propulsion. Some new designs directly implement methods to limit heel. For instance, some projects are already using dedicated water ballast on board that can be pumped from side to side, so called "anti-heel tanks". On few conditions, fin stabilisers are also used to provide a heel restoring moment.

Sauder and Alterskjaer (2022) show some test data where a wind spectrum leads to variable roll angles. In their tests the wind speed was variable. A variation in "quasi-static" roll due to variable wind is to be expected for any system (except kites if mounted low). However, on this aspect there is little literature.

Eggers and Kisjes (2019) showed the increased aerodynamic roll damping for Dynarigs and Flettner rotors. Especially with apparent wind from the bow quarter, roll motions lead to a strong variation of angle of attack, resulting in roll damping. When using relatively large devices compared to the ship, the aerodynamic roll damping may be similar in magnitude to the hydrodynamic damping and therefore its impact on roll motion is substantial. Devices that are not dependent on an angle of attack for their force magnitude, such as Flettner rotors still show increased roll damping due to the changing apparent wind speed, however with a smaller impact. If dynamic roll is much reduced then the acceptability of a non-zero (quasi) steady heel angle may be increased, though no research has been identified on this topic.

4.5.2.4 Manoeuvring in transit

Manoeuvring in transit has been studied by Vahs (2019), Gerhardt et al. (2021) and Eggers and Kisjes (2019), (2023) and Kisjes at al (2023). The general test case here are the manoeuvring criteria specified by IMO in resolution MSC 137(76) with the criteria further discussed in section 4.5.3.3.

The results for a coaster with a single Flettner rotor in 4 Beaufort wind presented by Vahs for the turning circle and crash stop easily comply with IMO criteria. Although the results for a ship without wind propulsion are not shown, the conclusion that wind propulsion had very small effect seems plausible.

The other publications, with a relatively larger contribution from wind propulsion, show an appreciable influence of sail propulsion on zig-zag overshoot angles. In Gerhardt et al. (2021) these are all increasing for the ship with wind propulsion, while the trend in Eggers and Kisjes varies. This may very well be case and wind condition specific. In the MHTC case presented by Eggers and Kisjes it was expected that the yaw moment that is introduced by increased or decreased heeling close to the wind may in fact stabilise the manoeuvre. When bearing away from the wind, the angle of attack and heeling moment increases. Heeling puts the thrust from the sails further outboard on the leeward side, generating a luffing moment, thus returning to the original course. The reverse happens when luffing to the wind. Such an affect may be irrelevant with little heel, other device types and other wind conditions. Eggers and Kisjes also show that there are also changes in the other derived characteristics from the zig-zag manoeuvre. The MHTC tested by Eggers and Kisjes already had trouble to comply with the manoeuvring standards in IMO Resolution MSC 137(76) without wind propulsion. With some parameters deteriorating with wind propulsion, compliance could not be achieved. The MARIN Ferry case (Eggers and Kisjes, 2023) shows how manoeuvring is affected for ship that has a better “base” manoeuvring performance. Compliance is not exceeded. However, what is shown is the heel angle can increase substantially for a ship with a relatively low stability.

In the publications referred to, the control of the wind propulsion is not used to aid the manoeuvre. Some work underway suggests that controlling the wind propulsion to aid manoeuvring could help. The results likely vary per type of wind propulsion. E.g. it is known that some Flettner rotors have a slow response time to substantially change their rotation rate (or to stop), whereas other devices, that need to only slightly change their angle of attack, can respond rather fast. However, it is expected, that these specifications will prove to be important, the specifications of all devices can likely be changed in order to aid manoeuvring. Thus, this field of research is highly relevant. The possibilities to use wind propulsion to steer the ship should also be clearly identified in regulations, as discussed in section 4.5.3.

4.5.2.5 Manoeuvring in port or laying at anchor

It is assumed that wind propulsion is disabled when in port as far as possible. Wind propulsion devices that can be fully folded down or retracted should not lead to any change in manoeuvrability in port. However, devices that are still (partially) erect will lead to increased windage that will need to be dealt with. Likely, the capacity of on board thrusters or tugs needs to be increased if the (un)berthing still needs to happen at the same wind speeds.

Aside from a change in side force, the centre of effort of windage force may also be moved far forward in case of a wind propulsion system that is only fitted on the bow. This could introduce instabilities at anchor, potentially triggering fishtailing behaviour.

4.5.2.6 Structural loads

Wind propulsion devices and also their foundation on ships must be able to cope with the loads that they are subjected to. Loads originate from the aerodynamics. However, also ship motions, both as a rigid body and with deformations can yield loads due to structural inertia and added mass. In the specific case of Flettner rotors the loads are further increased due to precession load related to the rotation speed of the device. Devices could stop to work properly in case of excessive (elastic) deformation, It could fail on ultimate strength or fatigue. If a device fails then for modest assistance it is not likely to endanger the entire ship. However, in case of a ship where the majority of propulsion is from wind, the loss of one or more devices may be critical.

Limited literature gives few indications on the relevance of the topic. Eggers and Kisjes (2019) in their preparations identified that motion related loads on Flettner rotors may be in the same order of magnitude as the average aerodynamic loads, such that these should always be accounted for. However the loads are of course highly dependent on the encountered waves and motion response of the ship. Kjellberg (2022) performed an extensive analysis to estimate fatigue loads for wing sails.

4.5.2.7 Dead ship condition

In case a ship is sailing with wind propulsion, and loses all power due to a system malfunction (“dead ship” condition) , it may be more vulnerable than other ships. Unless there is a method onboard that readily disables the wind propulsion system, it will generally continue to exert forces on the ship. For small systems, this may not be problematic. However, for larger installations, the wind propulsion system may push the ship of course and potentially increase heeling moment when the angle of attack on sails or wings increases. Particularly combined with a demanding sea condition from the stern quarter, controllability of the vessel may be challenging. Nevertheless, no literature is published on this topic.

4.5.2.8 Loss of kites

A topic that is regularly raised is the potential loss of kites. If such a thing would happen, retrieving the kite from the sea or abandoning it would present an operational challenge and/or large cost in damage. One could also imagine the kite cable falling over the ship, damaging structures on deck. Such concern are sometimes raised in discussions within the wind propulsion community and stake holders, however no literature is available to illustrate whether this risk is real or can be practically avoided with autonomous control and proper safeguards in operations. Hence, the topic is not discussed further here.

4.5.3 Existing rules and regulations

This section is split in several sections. Statutory regulations are those that are established at IMO and should be enforced by flag and harbour states. Class rules are dealt with separately. IMO and class rules are effectively mandatory to be complied with. However, as already concluded in the previous sections there also aspects of ship behaviour with wind propulsion that are presently not associated with mandatory requirements. Nevertheless, owners may come up with criteria by themselves and later on new criteria may be considered for adoption at class or IMO. These are together discussed in the last section.

The rules and regulations discussed in this report is a selection that are relevant for hydrodynamic and aerodynamic testing and calculations at ITTC members. A larger number of rules and regulations are relevant for wind propulsion in shipping though these are not discussed here.

4.5.3.1 Statutory regulations (IMO)

4.5.3.2 Stability

IMO sets requirements on the GZ curve, down flooding angles and subdivision in the following documents:

- International Code on Intact Stability
- SOLAS II-1, Consolidated text of the International Convention for the Safety of Life at Sea
- MSC.429(98), Revised Explanatory Notes to the SOLAS Chapter II-1 Subdivision and Damage Stability Regulations
- SDC 7/WP.6 Finalization of Second Generation Intact Stability Criteria

Compliance to these criteria is checked generally by design offices using calculations. No tests or simulations are generally required. An exception is the severe wind and rolling criterion (weather criterion) as defined in the intact stability code, where this is often also tested in a basin.

4.5.3.3 Manoeuvring in transit

IMO MSC Resolution 137(76) (2002) specifies criteria that are to be verified with zig-zag, turning circle and crash stop tests. The purpose of these tests is to ascertain that ships have a satisfactory manoeuvring performance when sailing at speed. When following the rules to the letter, it is not relevant to ships with wind propulsion, because compliance needs to be demonstrated in a calm environment (with as little wind as possible). However, class societies are generally interpreting the rules such that all ships should be able to do evasive manoeuvres when in transit, including when sailing with wind propulsion. Though, interpretation amongst class societies varies on how to apply IMO Resolution 137(76) with wind propulsion.

4.5.3.4 Controllability in adverse conditions

4.5.3.5 Minimum Power Requirement

Ships equipped with a single diesel-direct propulsion line need to have a certain minimum power level on board to ascertain that they remain controllable in demanding wind and sea from the bow (quarter) as specified by IMO (2001). The requirement is evaluated in a tiered approach. In the simplest but most conservative method (assessment level 1), the required power is only dependent on deadweight and ship type, which does not consider whether a wind propulsion system is fitted. On the one hand this means that it does not require much effort at all to demonstrate compliance. However, It can be questioned whether the empirical relationships account properly for ships with wind propulsion. Assessment levels 2 and 3, require consideration of aerodynamic resistance. If potential increased windage with wind propulsion is properly accounted for, then the required engine power is automatically adjusted and any safety implications of fitting a wind propulsion system is properly accounted for in head wind and sea.

It is noted however, that the requirement is specified only for head wind. The requirement effectively assumes that being able to keep a head wind and sea heading is a requirement for safety. It may be argued that ships could be safe as well when adopting other headings in which conditions a wind propulsion could actually provide (part of) the ship propulsion. If this is indeed the case then the Minimum Power Requirement could be seen as conservative. However, that ships can generally be safe in a wind and wave heading where the wind propulsion can be used effectively is something that has not been demonstrated by research.

4.5.3.6 Safe Return to Port

The safe return to port requirement is defined in SOLAS [19] II-2 regulation 21 (Regulation 21 - Casualty threshold, safe return to port and safe areas), article 4, however specific guidance is given in explanatory notes MSC.1/Circ.1369 (2010). The requirement applies to passenger vessels of 120m in length or above. Such ships should have double engine rooms and/or propulsion rooms. In case one engine room or propulsion room is disabled and one of the propeller shafts or propulsion units becomes blocked, the ship should still be able to reach the nearest port while sailing through demanding wind and sea conditions. A minimum speed of 6 knots while heading into Beaufort 8 weather and corresponding sea conditions is recommended to show compliance. As this regulation accounts for windage in head wind, similarly like for the minimum propulsion requirement, any additional windage due to wind propulsion systems that cannot be completely retracted is to be accounted for. Therefore it is judged that the regulation does properly account for the impact of a wind propulsion system on performance in head wind.

A similar comment can be made as for the Minimum Power Requirement. If in the future it could be demonstrated that ships can be safe and reach port without needing to keep a minimum ship speed only in head wind and sea then, potentially, the wind propulsion system could help rather than only increase windage when it cannot fully be retracted.

4.5.4 Class rules

Class societies also commonly set requirements on the topics described above or they provide their own interpretations. However, in the overview here, focus is given on topics that are only addressed by class societies and not by IMO. Documents from the following class societies were considered to prepare the summary below: American Bureau of Shipping (2022) ,Bureau Veritas (2021), ClassNK (2023), Det Norske Veritas (2023), Lloyd’s Register (2023a), (2023b). Except for DNV, the referenced documents concern dedicated rules for wind propulsion. Though the general rules from these organisations may also impact wind propulsion. In the cases of Class NK and Lloyd’s Register the wind propulsion specific documents include only guidelines, e.g. they are not mandatory. The other referenced class societies have mandatory rules and regulations. In either case, guidelines or rules may not still cover all eventualities. Thus, custom processes may be required, such as Failure Mode and Effects Analysis (FMEA), Hazard Identification (HAZID) or Hazard and Operability Study (HAZOP). Using such procedures class may ascertain that a ship is safe, without having dedicated firm rules & regulations for a specific design feature.

4.5.4.1 Loads

Loads (and structural response) is a topic generally addressed by class. Although the elaboration is different per class, generally load cases are defined for:

- Wind load, by deriving the maximum wind load with the wind propulsion in operation and also when it’s inactive
- Inertia loads (heel and ship motions)
- Green water loads

Subsequently it must be checked that the structure can cope with it considering various failure modes, including also fatigue. The rules & guidance generally includes methods to estimate the loads. However, it may be interesting to get this information from testing. Obtaining inertia loads for instance may be done using model tests. Testing methods have not been specified.

4.5.4.2 Machinery systems and control

So far in classification rules, wind propulsion has been purely treated as assistance in propulsion. The propeller propulsion is still there. Therefore the operability of wind propulsion is not a safety requirement. Redundancy to always have wind propulsion is not required. Nevertheless, the instrumentation of wind propulsion systems is subject to specific requirements. Nevertheless, the hydro- and aero dynamic testing doesn't seem to be directly relevant for these requirements.

4.5.5 Potential owner criteria or new formal regulations

It is identified that wind propulsion may trigger some behaviour that is undesirable but for which there are no accepted criteria. They have been identified already in section 4.5.3.2. In the feature we may see that either owners can up with their own criteria or that formalised criteria are developed.

4.5.5.1 Heel

Heel has an impact on stability. Although interpretation may be required, this is handled in the rules discussed in section 4.5.3.2. Heel may also have an effect on loads on the ship and cargo and this should also be accounted for, principally in class rules as discussed in 4.5.4.1.

But heel can have other impacts that are not covered by existing criteria. For instance, crew and passenger comfort may be decreased. Further specific systems on board may not function with large heel angles. We are considering here the (quasi-) steady heel. However, the impact is realised generally in combination with oscillatory heel due to waves.

We see in some publications that heel thresholds are used. Though, a clear rule or converged value, even for specific ship types, could not be identified. Though there are some (proposed) criteria for other applications that could give some reference:

- RINA (2012) proposed a maximum heel angle of 10 degrees for the steady part of a turning circle
- Dallinga and Bos (2010) derive a maximum "Effective Gravity Angle" (equivalent to heel in steady conditions) of 9 deg for naval staff and they suggest it should be about half for passengers that are not trained
- As identified also by Dallinga and Bos the ITTC (1999) suggested a maximum lateral acceleration of 0.8 m/s2 onboard high speed craft. This corresponds to about 4.6 deg of heel.

These references suggest a threshold in the range of about 5 to 10 deg. However, the higher side of that is really intended for trained crew and a temporary situation in a turning circle. They may therefore be judged as high. Although this report does not claim that it is well verified for the specific application of wind propulsion, a threshold maximum heel angle of 5 deg may be reasonable as a first reference. It is however expected that actual thresholds considered in projects will be adjusted to the specific ship type and operations. For instance, on a cruise ship, where untrained individuals are on board and comfort is paramount, a much lower threshold is expected.

4.5.5.2 Yaw and/or rudder angles

As discussed in section 4.5.2, wind propulsion may lead to larger yaw oscillations. At some point, controllability may be decreased as a result. Depending on control settings, the rudder gear needs to work harder, leading to more wear. It is not yet understood if and how problematic these changes in behaviour are, but it can be imagined that in the future owners will set criteria on the maximum variability of yaw and/or rudder angle.

4.5.5.3 Manoeuvring in port or laying at anchor

As discussed in section 4.5.2.5, due to increased windage, the maximum forces delivered by tug(s), tunnel thrusters and/or mooring equipment may need to be increased. How an owner will deal with this likely varies. In some cases the impact of increased windage may be well within the capabilities of the ship and port. Nevertheless, in other cases some increase cost may need to be anticipated. Operational cost for tugs of higher capacity or numbers or a larger investment in transverse tunnel thrusters.

A common indicator to describe how well ships can berth is the crabbing capability as for instance described by Ferrari et al (2018). The indicator is effectively the maximum wind speed that can be sustained at all wind angles when berthing. An example from Ferrari et al is shown in Figure 23. When an owner specifies that the same wind speed must be sustained for a ship with wind propulsion, then an increase in windage will be compensated for by specifying larger capacity tunnel thrusters (and/or tugs).

It is unknown to the owners how owners may specify criteria for increased anchor loads and yaw instability that could occur at anchor.

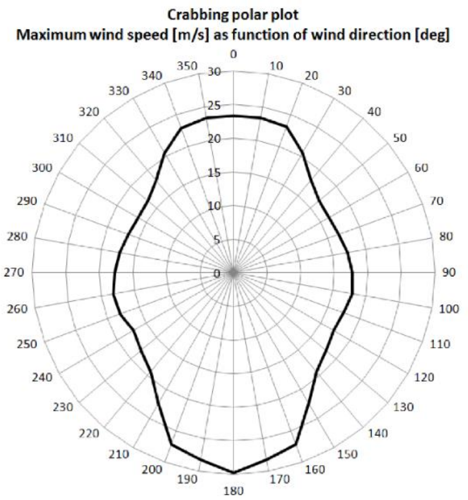


Figure 23: Crabbing capability plot from Ferrari et al (2018)

4.5.6 Testing and simulation methods

4.5.6.1 Simulations

4.5.6.2 Calculations on desktop and HPC

Whereas high fidelity simulations, at the level of CFD, have been shown for sailing yachts in waves, e.g. Mazas et al (2017) and Azcueta (2002), it is judged that this technology is not yet ready for a comprehensive analysis of safety and operability on its own. Assessing safety and operability requires a large amount of simulations with many degrees of freedom involved. The degrees of freedom do not only relate to motions of the vessel, but also the environment conditions, including several parameters for wind, wind sea, swell and potentially current. Long time traces are also required to derive statistics with sufficient certainty for seakeeping. The time (and cost) involved to resolving a full assessment is generally too high for running CFD. Nevertheless, these methods can be highly valuable for assessment of specific conditions. The simplified methods as discussed below are generally constrained to first order forces and motions strictly following a linear relation to wave height and second order forces a quadratic relationship, which are both simplifications. CFD does away with such assumptions.

For good reason, research on simulations has so far also focussed on simplified methods.

Kjellberg (2022) provides an extensive description of time domain simulations. In summary, the hydrodynamics is simulated in potential flow, with viscous corrections. The aerodynamics is simulated using a stripwise approach akin to lifting line. Whereas the principal objective was to verify fatigue loads in the rigs, the same calculation approach can deal with all kinds of manoeuvring and seakeeping scenarios. Hydrodynamic “manoeuvring” coefficients need to be prepared in advance as well as the stripwise aerodynamic forces.

Eggers and Kisjes (2023) and Kisjes and Eggers (2023) also documented manoeuvring simulations. For manoeuvring their approach is similar. It is based on pre-processed manoeuvring coefficients. The aerodynamics are implemented using coefficients just using the wind conditions at the centre of effort height of the rig(s). Although not documented in the publication, when modelling seakeeping, the MARIN methods rely on pre-processing to model wave excitation, radiation and damping using calculations in the frequency domain with a Boundary Element Method.

4.5.6.3 Bridge simulations

Vahs (2019) published on bridge simulations with wind propulsion. The Flettner rotor forces were accounted for in the simulations, although no detailed description is given on the methods. Manoeuvring simulations were conducted.

4.5.6.4 Model tests in wind tunnels

Quite some publications are available on wind tunnel tests with individual wind propulsion units up till complete ships with wind propulsion. However, no publications are known where the emphasis was on safety issues. The general focus is on steady forces as input to performance predictions. The data generally does allow to assess the loads against structural limits. However, as these are only the steady loads, it is likely not the full answer. It is known that tests have been conducted with dynamics, such as wind gusts, however these are not yet published.

For sailing yachts, experiments are known with some dynamics, such as by Fossati and Muggiasca (2011). They put a sailing yacht model with rigid sails on a set-up that culd make pitching motions. The methods used there could be used also for ships and systems deployed in merchant shipping.

4.5.6.5 Model tests in basins

Various approaches have been used to model wind propulsion in a model test basin with waves. It appears that modelling wind in the experiment itself is very challenging as described below. An approach where a simulation is running the loop (SiL) to calculate aerodynamic forces in real time seems to be preferred amongst several tests institutes. However, there are differences in the tools used to apply aerodynamic loads, e.g. winches versus wind fans. Relative advantages of one method over another are not yet clear. Details are described in the sections below.

4.5.6.6 A wind tunnel in the basin

Eggers and Kisjes (2019) fitted a (simplified) wind tunnel in a wave basin, to model both the aerodynamics and hydrodynamics experimentally. As also discussed by Gerhadt et al (2021), in such an approach it is impossible to satisfy similarity on Froude number and Reynolds number simultaneously. It has not yet been ascertained how important it is for the end result. In wind tunnels it is accepted practice to run wind tunnel experiments not at the Reynolds number of the actual application. However, assuming that some corrections are necessary, these are not trivial to apply. Moreover, the experiments by Eggers and Kisjes showed that on average the target wind conditions could be achieved in the centre of test section. However, there were deviations outside that centre. These could not be avoided with disturbances from the openings in the test section that were still required to run the tests. In order to create a better wind field throughout the test section, the section would need to be closed of further and likely more wind fans would need to be used. This would drive up the time (and cost) required for such experiments substantially. The method may have value in case the aerodynamic properties are not known and they are to be determined in the combined experiment itself. However, in general it appears to be more practical to apply aerodynamic forces using a numerical model using the methods described in sections 4.5.6.8 or 4.5.6.8. Nevertheless, experiments were done using the simplified wind tunnel, as shown in Figure 24. Results are discussed in section 4.5.2.1.

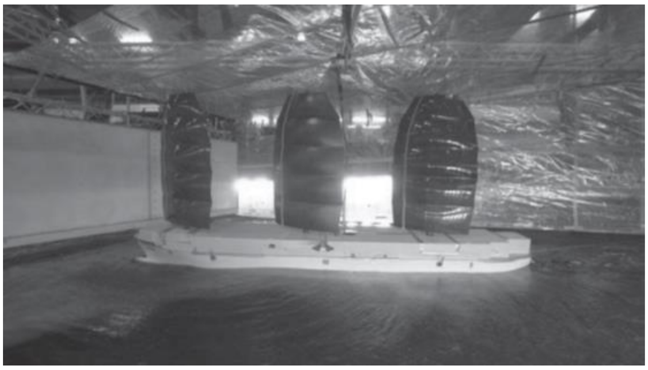


Figure 24: Coaster with Dynarigs in simplified wind tunnel in wave basin (Eggers and Kisjes, 2019)

4.5.6.7 Numerical aerodynamic loads applied using winches

Eggers (2018) demonstrated free running tests with winches on a sailing yacht. The same test set-up is in use for merchant ships with wind propulsion at MARIN. The aerodynamic loads are modelled dynamically in the (ship fixed) sway and surge directions using two winches. This is done using an adjustment in height of the winches on the carriage to an expected average heel angle per test. The connection point on the model is in the aerodynamic centre of effort. Assuming that this aerodynamic centre of effort remains constant throughout a test, the pitch moment and heeling moment are also modelled correctly. A third winch is used to correct for viscous scale effects, pulling strictly from the bow. The set-up is extendable with more winches, allowing more degrees of freedom to be modelled dynamically.

Sauder and Alterskjær (2022) have conducted experiments with a free running model using an advanced winch system named Cable-Driven Parallel Robots, essentially also a combination of multiple winches. Using 6 winches allows to dynamically apply forces in 5 degrees of freedom (only heave excluded). Assumptions on centre of effort are not necessary. Tests were run in calm water, but using a variation of wind conditions, including a spectrum. The tests showed that the target forces could be applied accurately.

4.5.6.8 Numerical aerodynamic loads applied using wind fans

Gauvain (2019) published on an unrestrained test set-up to apply aerodynamic loads for a yacht sailing in waves or manoeuvring. Although results are shown for a yacht as illustrated in, the set-up should also be suitable for merchant vessels. The set-up includes a mast with a single fan. With a possibility to rotate the fan on the mast manually, the proportion of surge and side force can be adjusted in between tests. It is not mentioned whether yaw moment can be varied, but this is assumed to be the case by moving the position of the mast in the model. A particular point of attention in the test set-up was to eliminate any connection to the carriage, thereby eliminating and unwanted influence from such connections.

Gerhardt et al (2021) published on manoeuvring and seakeeping tests with a wind powered car carrier. As opposed to using winches, air screws (fans) were used to impose aerodynamic loads. The set-up allowed to dynamically model forces in surge, sway and yaw moments. The publication discusses various options to apply aerodynamic loads and reflects on the impossibility to adhere to all scaling/similitude laws when real wind is used in the basin test. Viscous scale corrections are described in an accompanying paper by Giovanetti et al (2022).

4.5.6.9 Onboard trials and monitoring

A modest amount of publications is available on onboard trials an monitoring. However, also, on this topic, the emphasis is on (quasi-steady) performance measurements. No publications are known with an assessment concerning operability or safety.

4.5.7 Summary

The emphasis in research and projects directly for industry has mostly been on steady equilibrium conditions, which are directly relevant for performance, but are less relevant for operability and safety. This is evident both in regulations as well as methods to verify safety, operability and compliance.

There is a gap in regulations. These are presently dealt with for a large part within custom HAZID and HAZOP studies. As experience is gained with operation of ships with wind propulsion, it is expected that more rule or risk-based guidance will be specified.

New or existing assessment methods are trialled mainly in (subsidised) research studies. Some methods show good potential and it is expected that with their continued use, a convergence and refinement will be seen in the methods that are used.

4.6 Investigate the effect on propulsive factors due to reduced propeller load arising from the use of wind power.

The goal of this ToR is to investigate the effect on propulsive factors due to reduced propeller load arising from the use of wind power, identify the effects of wind propulsion on the propulsion system, e.g. pressure side cavitation occurrence and liaise with Resistance and Propulsion Committee and SC on Cavitation and Noise.

4.6.1 State of the art of effect on propulsive factors for wind propulsion ships

The research about effect on propulsive factors due to reduced propeller loading for wind propulsion ships has been few. Many researches have focused on propeller overloading due to added resistance by waves because of IMO regulations on EEDI (Energy Efficiency Design Index) and minimum propulsion power in adverse weather.

Propulsive factors like as wake fraction (w), thrust deduction factor (t) and propulsion efficiency (η_D) should be investigated for wind propulsion ships. Wind propulsion ship in steady state navigation has been in reduced propeller loading, drift angle, heel angle, wind and wave conditions.

Sauder & Alterskjaer(2022) carried out free running tests where real-time sail loads interact by Cable-Driven Parallel Robots. The target ship was SOBC-1(SINTEF Ocean Bulk Carrier-1, Lpp=190m), 4 rotor sails (height=35m, diameter=5m, top end plate diameter=6m), and all rotor sails are located on the ship's centreline. Figure 25 shows propulsive factors as a function of the true wind direction(TWD) and true wind speed(TWS). Vessel sails towards North. TWS = 10, 15, 20 m/s are represented in black, blue and red, respectively. The dashed black reference line represents values for the case without rotor sails at vessel speed 12.25 knots.

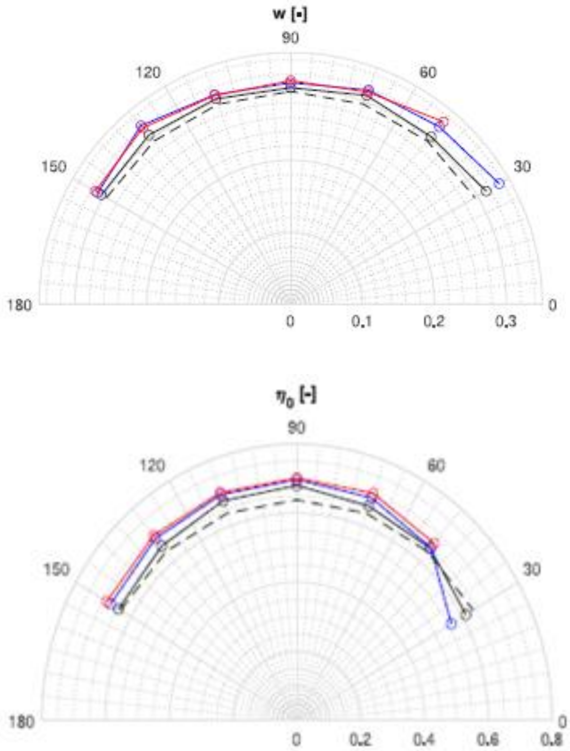


Figure 25. Propulsion parameters of model tests

Schot & Eggers(2019) studied on the effect of leeway(drift) angle on the propulsive factors by viscous flow calculation and captive model test. The predicted Taylor wake feaction(w_T) is compared with measured data for KVLCC2 in Figure 26.

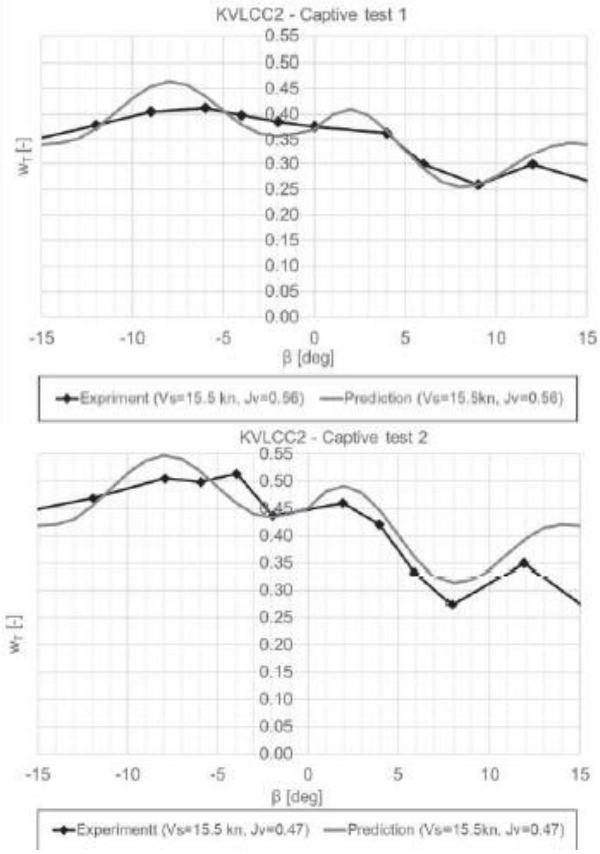
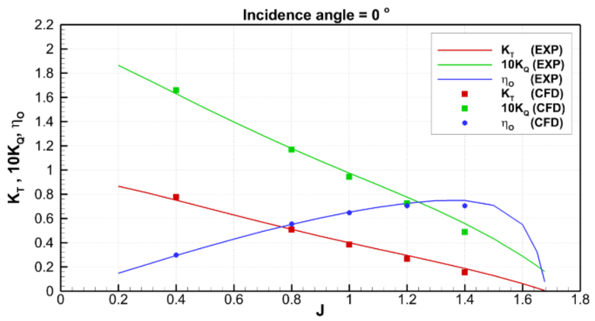


Figure 26. Comparison of the predicted wT and measured values for the two model tests campaigns on the KVLCC2

Yang et. al(2019) carried out CFD calculation for POW characteristics in oblique flows. Figure 27 shows the comparison results for Potsdam Propeller Test Case(PPTC).



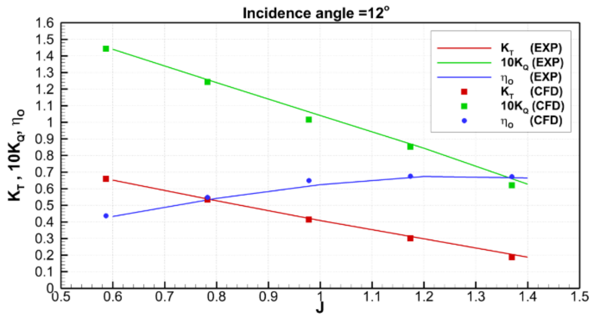


Figure 27. Comparison of POW curves for PPTC(Upper: incidence angle 0o, Lower: incidence angle 12º)

China(2018) proposed the thrust deduction factor and wake fraction at low speeds as t = 0.1 and w = 0.15 on IMO MEPC. (Figure 28)

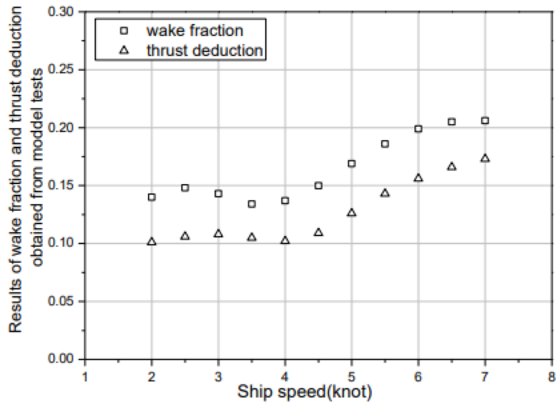


Figure 28. Model test results of wake fraction and thrust deduction at low speeds.

4.6.2 Modelling of propulsive factors for wind propulsion ships

With the steady state assumption the wind propulsion ship has drift (β) and heel angle. Manoeuvring mathematical model considers with drift angle for the modelling of wake fraction where POW test result is used to predict the wake fraction. POW test with drift angle can be carried out, but it is difficult to predict the inflow angle at the propeller position. However, the thrust deduction factor is kept constant value with the given speed for manoeuvring simulation. It is available to make a modelling of thrust deduction factor with drift angle.

Yasukawa & Yoshimura (2015) introduced the MMG mathematical model for manoeuvring simulation, and proposed several models for wake fraction with drift angle are as follows.

$$w_P / w_{P0} = \exp\left(-4\beta_P^2\right) \quad (1)$$

$$\frac{1-w_P}{1-w_{P0}} = 1 + C_1\left(\beta_P + C_2\beta_P|\beta_P|\right)^2 \quad (2)$$

$$\frac{1-w_P}{1-w_{P0}} = 1 + \left(1 - cos^2\beta_P\right)\left(1 - |\beta_P|\right) \quad (3)$$

$$\frac{1-w_P}{1-w_{P0}} = 1 + \{1 - \exp(-C_1|\beta_P|)\}(C_2 - 1) \quad (4)$$

$$\beta_P = \beta - x_P' r'$$

Where w_p is the wake fraction in manoeu-vring motion and wp_0 is the wake fraction in straight-line motion

In Figure 29 the analysis results of wake faction with drift angles using Eq. (4) are shown.

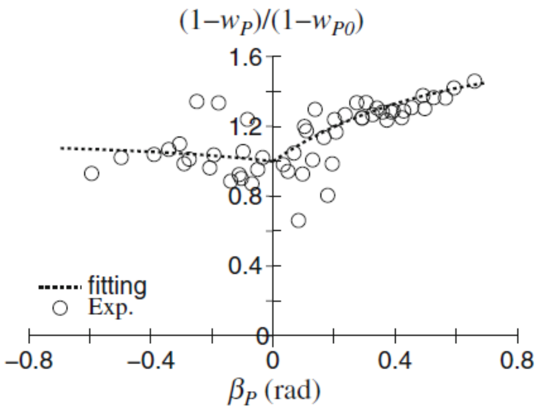


Figure 29. Analysis results of wake fraction in manoeu-vring motions for KVLCC2 model (Eq, (4))

4.6.3 Example of model test of effect on propulsive factors for wind propulsion ships

To investigate the propulsive factors in reduced propeller loading, model tests were carried out by Korea Research Institute of Ships and Ocean Engineering (KRISO). The Target ship is Ksupramax (KRISO Supramax class Bulk Carrier, Lpp=192m), and the test speed is 12 knots of real ship. The scale ratio of model ship is 26.087. Figure 30 shows the body plan and model ship of Ksupramax.

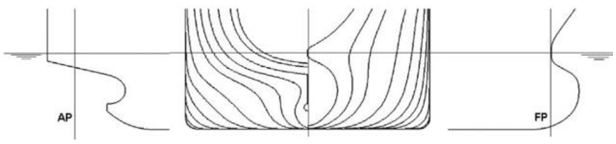


Figure 30: Body plan and model ship of Ksuparamx Bulk carrier

Two types of model test were carried out. One is load variation test, and the other is static drift test in reduced propeller loading condition. The wake fraction, thrust deduction factor and propulsive efficiency were analysed by ITTC Recommended Procedures and Guidelines 7.5-02-03-01.4. Wake fraction is obtained by thrust identity method and using POW data. Thrust deduction factor is obtained by using the measured thrust and resistance forces considering skin friction correction. Propulsive efficiency is obtained by using thrust deduction factor, measured propeller thrust force and torque.

4.6.3.1 Load variation test in reduced propeller loading

The loading conditions of load variation test on design draft condition is 50% ~ 130% of resistance force including skin friction correction, F_D. The photo of load variation test using self-propulsion test equipment is shown in Figure 31.

Figure 31: Photo of load variation test on design draft condition

The analysis results of propulsive factors are shown in Figure 32, Figure 33 and Figure 34.

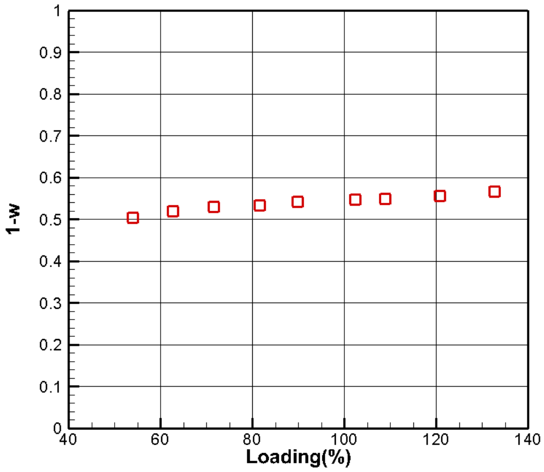


Figure 32: Analysis results of wake fraction with propeller loadings (design draft condition)

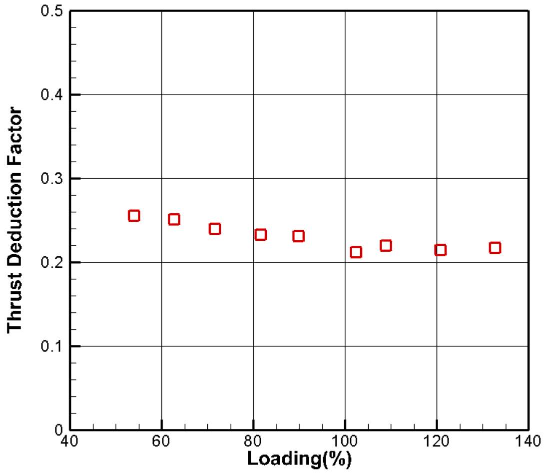


Figure 33: Analysis results of thrust deduction factor with propeller loadings (design draft condition)

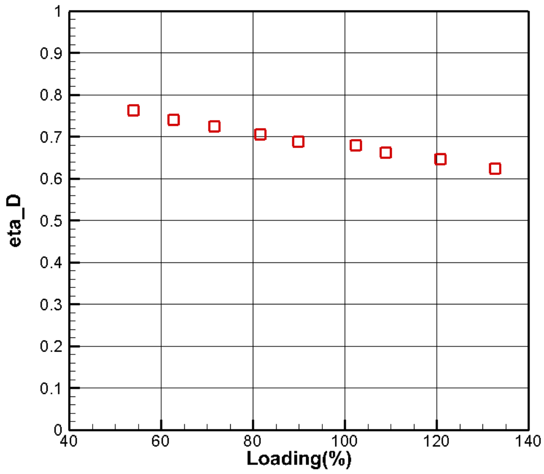


Figure 34: Analysis results of propulsive efficiency with propeller loadings (design draft condition)

4.6.3.2 Static drift test in reduced propeller loading

Static drift test in reduced propeller loading was carried out by planar motion mechanism (PMM) equipment of KRISO. Test speed of 12 knots of real ship on heavy ballast condition because of some problems of PMM system. The range of drift angles is -20° ~ + 20°, and propeller loading is at 60%, 80% and 100% of real ship's self propulsion point. Figure 35 shows the photo of static drift test.

Figure 35: Photo of static drift test on heavy ballast condition

Figure 36 to Figure 38 show the analysis results of wake fraction, thrust deduction factor and propulsive efficiency.

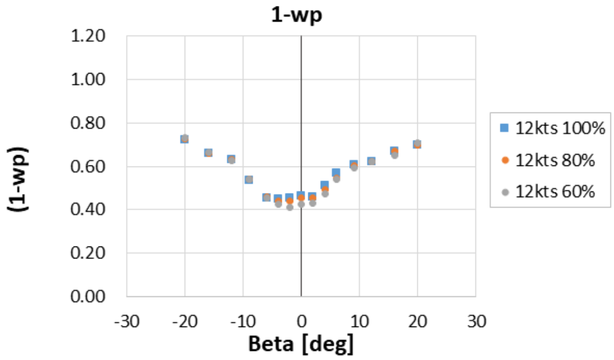


Figure 36: Analysis results of wake fraction with drift angles (heavy ballast condition)

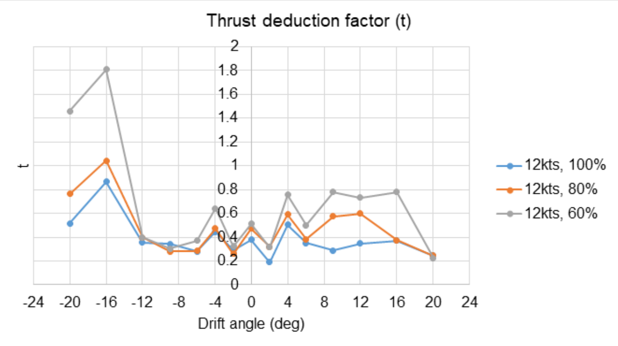


Figure 37: Analysis results of thrust deduction factor with drift angles (heavy ballast condition)

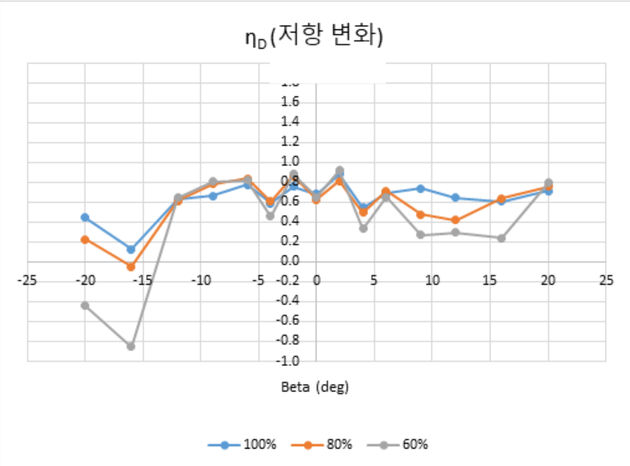


Figure 38: Analysis results of propulsive efficiency with drift angles (heavy ballast condition)

Wake fractions in several propeller loadings are fitted by Eq. (5), and the fitted result of 100% loading and manoeuvring coefficients are shown in Figure 39 and Table 10.

$$w_P/w_{P0} = \exp\left(-C_P v_P^2\right) \qquad (5)$$
$$v_P = v' + x_P' r'$$

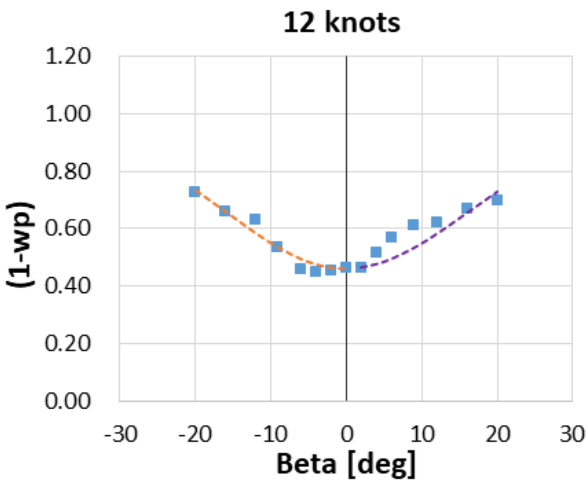


Figure 39: Fitted results of wake fraction by Eq. (5) (100% loading, 12 knots)

Table 10: Fitted results of wake fraction (Eq. (5))

	100% loading	80% loading	60% loading
C_P (for $+v_P$)	5.891	6.702	6.684
C_P (for $-v_P$)	6.019	6.236	6.989

The analysis of propulsive factors is proper, and the values of wake fraction are reasonable. But the values of thrust deduction factor and propulsive efficiency isn't acceptable. It is the reason that the measured propeller thrust and torque are appropriate values, but the X force measuring system of PMM of KRISO isn't appropriate to maintain the accuracy of X force. The X forces during static drift test in real ship's self-propulsion point are very small contrast to large capacity of X force gages because the X force measuring system of PMM should withstand the acceleration and deceleration forces during the tests. More accurate analysis of propulsive factors in manoeuvring motion, it is inevitable to use more accurate X force measuring system like as the clamp system for PMM.

Based on the experience reported above, the Committee recommends that for static drift test without accurate X force measurement system, the thrust deduction factor should be kept constant value obtained from self-propulsion test with given speed.

4.6.4 Liaise with other Committees

One of the goals of this ToR is to liaise with general committee on Resistance and Propulsion and specialist committee on Cavitation and Noise about the propulsive factors and reduced propeller loading.

The TOR 9 of the general committee on Resistance and Propulsion which is to update load variation test method in 7.5–02-03–01.4 "1978 ITTC Performance Prediction Method" taking into consideration a wider range of resistance and develop a new method if necessary, is related with this TOR. It is suggested that reduced propeller loading conditions (including 70%, 80% and 90% of resistance force) should be included in load variation test.

There is no related TOR of specialist committee on Cavitation and Noise. But it is necessary to investigate the pressure side cavitation occurrence, noise, vibration etc. in reduced propeller loading. The controllable pitch propeller (CPP) would be recommend to avoid the pressure side cavitation.

4.7 Cooperate with MEPC on the continuous development of the EEDI for wind propulsion ships. Liaise with Full Scale Ship Performance Committee

The Committee did not initiate action within this period to propose improvements to the Marine Environment Protection Committee (MEPC) in IMO. Until release of the ITTC guideline and procedure in September 2024, the only publicly available guideline for performance prediction for ships with wind propulsion is included in MEPC.1/Circ.896 as published in 2021. That guideline only serves to quantify the benefit of wind propulsion under EEDI and EEXI, which may justify that it does not necessarily need to achieve best accuracy. However, the Committee is of the opinion that there is substantial scope for improvement, even without increasing the effort for ship owners and their partners to follow the MEPC guideline. A submission for the 81th MEPC by IWSA and RINA (IMO, 2024, MEPC 81/INF.40), building on work by MARIN in the WiSP2 project illustrates how at present the specification of wind statistics does greatly influence the predicted savings. The submission illustrates that the benefit of the present specification can likely not be achieved in real operation. The submission also illustrates potential other methods to derive wind statics, which are more similar to what can be achieved in reality, without resorting the methods that were in place before 2021 (and that arguably disadvantaged wind propulsion). A follow-up specialist Committee, supported by R&D projects, may pick up this and other topics to deliver submissions to IMO’s MEPC for adopting better guidance in MEPC.1/Circ.896.

4.8 Liaise with the Ocean Engineering Committee regarding their work on SiL and controllable fans to model wind loads.

We have unfortunately not been able to achieve any fruitful outcome in this task. We recommend that the next committee should focus more on sea keeping model test of wind powered ships in general.

5. PROCEDURES

This section describes the work done by the committee on tasks 4, 6 and 8 described in Section 3.

The work done in the other tasks (1, 2, 3, 5, 7, 9 and 10) can be found in “State of the Art” Section 4.

5.1 Proposed guidelines for performance predictions of wind assisted ships

The Specialist Committee for Wind Assisted and Wind Powered Ships under the 30th ITTC has prepared guidelines for prediction of power saving of wind propulsion technology. This section gives an outline of how the guideline is structured and how it connects to performance indicators.

In the process to derive common KPI's, several focus group meetings were held with industry stakeholder in cooperation with the International Wind Ship Association (IWSA) and the Interreg North Sea region project WASP. The proposed process was also presented at several international conferences in Europe and Korea (Werner 2022a, Werner 2022b). Furthermore, the Committee run several workshops with industry representatives, with the purpose to get feedback on the proposed method. The last workshop was held in February 2024, and the participants had received draft versions of the procedure beforehand. 18 organisations submitted in total 174 comments.

Some of the key pieces of feedback received from industry on the provisional version of the procedure document are listed below.

- The air density should as default have the value of 1.225 kg/m^3, equivalent to standard value for 15 deg, sea level.
- A standard value for power law exponent should be provided, but the user should in the end seek relevant documentation of the appropriate value for route to be studied.
- Uncertainty analysis and sensitivity analysis of all assumptions and models should be performed.
- Guidelines for route optimization should be further developed in future revisions

The proposed guideline is the first attempt to create a common ground and common terminology for expressing performance expectations of wind powered ships at design stage. It focuses on methodologies for predicting the power saving of a wind powered ship on a route at design stage, compared to the corresponding ship without wind propulsion. The guidelines give an overview of the type of methods that are suitable for the different stages of the ship design process, considering the balance of confidence level and computational cost. It is not the intention to provide detailed procedures. It is assumed that the organization conducting the predictions has relevant background knowledge and tools.

The guidelines are intended to be used by organizations conducting performance predictions for wind powered ships (e.g. consultants, yards, technology providers). They are also intended to be used indirectly by all stakeholders who need to discuss the resulting performance indicators (e.g. ship owners, operators, investors). By providing standard indicators that are linked to prediction procedures of varying confidence levels, the guidelines aim to provide a common terminology for all stakeholders.

The guidelines are mainly applicable to cargo vessels with wind assistance technology (moderate size of wind propulsion), although they can to some extent be applied to vessels with primary wind propulsion. Sailing yachts, racing boats or traditional sailing vessels are not in the scope.

The focus of the guidelines is the relative performance of wind assisted ships, i.e. the power saving relative to the same ship with conventional motor propulsion. The industry today still sees the conventional motorship as the benchmark which the business case for novel technologies relate to. However, this perspective may change in future versions. It is expected that the guidelines will be updated frequently the coming years as the knowledge and tools in the industry develops.

Deriving the expected fuel saving from a wind propulsion solution involves four principal steps:

1. Generating background data. (Towing tank tests, wind tunnel experiments, CFD simulations).
2. Generating models from the background data, which describes the sub-systems response to a changed of state. For example, describing the aerodynamic force of a sails in different wind angles.
3. Deriving steady state force equilibrium with Velocity Prediction Programs (VPPs) or Performance Pre-diction Programs (PPPs).
- Route studies, where the variation of environmental conditions that the vessel will meet on a route is combined with the static performance model to derive the expected average power or energy saving due to the wind propulsion.

Predictions of the power savings from wind propulsion systems are used at various stages of the design process, from initial assessments to final performance expectation. The guidelines are arranged into various levels of accuracy to meet the specific needs, requirements, and availability of data of each stage. The fidelity and the required efforts increase with increasing level. An overview is given in Table 11, the complete table is found in the guideline.

Table 11: Overview of methods for prediction of power sav-ing of wind propulsion technologies

	Level 0	Level I	Level II	Level III	Level IV
Applicability ->	**WPS rated power**	**Early idea**	**Early business case assessment**	**Business case & Performance expectation**	**Advanced Business case & Performance expectation**
Force balance	1DOF	1DOF	3-4DOF	4DOF	4 DOF (at least)
Aerodynamics	Specific	Generic	Low/Mid fidelity*)	High fidelity**)	High fidelity
Hydrodynamics		Generic	Low/Mid fidelity	High fidelity	High fidelity
Machinery interaction			Generic SFOC + limitations	Specific SFOC + limitations	Specific SFOC + limitations
Weather on the route		EEDI or intended route	Intended route	Intended route	Intended route or weather routing
					Optional effects: e.g. ship motions and varying wind energy management optimisation

*) Low/Mid fidelity methods can be for example high fidelity data or regression models from similar cases, or case specific lifting line methods

**) High fidelity refers to case specific CFD, model test or full-scale test.

5.2 Derive performance indicators for comparing the performance of wind propulsion at design stage.

The maritime wind propulsion industry is evolving rapidly, and many new wind propulsion technologies have emerged on the market. All these technologies have their specific strengths and weaknesses, which need to be assessed and quantified when selecting a WPT for a particular application. The wind propulsion community has, however, up to now not agreed on common key performance indicators (KPI). Some technologies are described using aerodynamic coefficients, others by e.g. expected fuel savings. Percentage saving figures are commonly used, but it is often unclear what is included in the comparison. This complicates comparing technologies, puts the level playing field at risk, and delays investment decisions.

Before this background the 29th ITTC Specialist Committee for Wind Assisted Ships co-operated with the Interreg North Sea region project WASP and the International Wind Ship Association (IWSA) to develop and propose KPIs for wind-assisted ships. As part of this effort, several focus group meetings were held during the autumn of 2022. These online workshops were open to all stakeholders from the wind propulsion community and aimed at sharing ideas and discussing implications of various KPI alternatives. Figure 40 summarises and groups the participants.

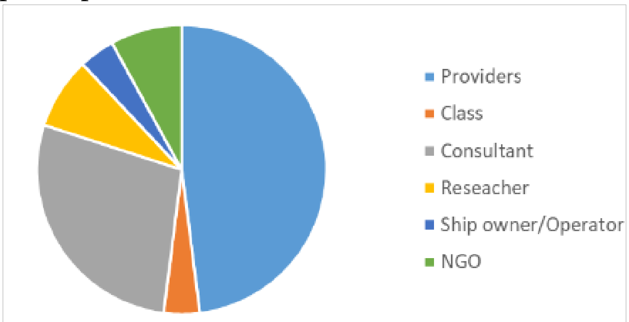


Figure 40: ITTC, IWSA and the WASP project hosted focus group meetings with the industry aiming for deriving harmonised KPIs. The participants affiliation business types are show the graph.

A summary of the considerations and recommendations from the Committee is given here. More details are given by Werner et.al (2023).

The industry focus groups indicated that the need from the industry can be summarised as:

- It would be helpful to have a set of agreed KPIs, especially for expressing ship specific fuel saving potential in the business case and procurement phase.
- KPIs that will be communicated to ship owners and operators should be tangible to their business.
- It would be useful if the KPIs reflect the prediction method used to derive the value.
- It would be useful to have a set of KPI definitions that is consistent and can accompany the ship design process from early concept stage to operation stage, gradually adding more and more complexity.

5.2.1 Recommended KPIs for Stand-alone wind propulsion units

Indicators in this category should describe the characteristics of wind propulsion units alone, without considering a ship. The Committee concluded the following recommendations:

- Nondimensional stand-alone coefficients are useful to understand the characteristics of a WPT but not directly the fuel saving potential. This is relevant for experts working with the design or assessment of wind powered ships. However, it should not be the first choice when communicating performance with community in general.
- There is no single nondimensional coefficient that describes all the important characteristics of a WPT. The best demonstration of the complete picture is a power coefficient curve over apparent wind angle.
- In the early concept phase, when scanning the market and shortlisting possible devices, it could be convenient to have easy, ship independent indicator of a unit size or its power. This could be achieved via a nominal or “rated” power derived in the same way as the “f_{eff}*P_{eff}” in MEPC.1/Circ.815 (2013)

$$Rated\ WPU\ Power_{10} = \sum_{i,j}^{n,m}\left[\frac{F_x \cdot V_s}{\eta_D} - PTI\right]_{i,j} \text{ x } [\mathrm{W}_{i,j}] \quad (6)$$

where

$\mathrm{W}_{i,j}$ is the EEDI weather matrix (pre-2021)
η_D=0.7
F_x is the force matrix at the corresponding wind
V_s=10 knots

PTI is the power required by the wind propulsion unit (eg spinning a rotor)

Rated power values for other standard ship speeds (e.g. 15 and 20 knots) can be worked out in a similar way

This KPI is one way to describe a device while including the size. It is a theoretical number and gives an indication of a unit's theoretical potential. It should be understood that it this ignores the effects of aerodynamic side forces and that the propulsive efficiency, η_D may be different for a specific ship.

It is important that Standard conditions for nondimensional KPIs are defined by for example ITTC. That could be:

- Uniform/rectangular wind profile
- Area A defined as projected/planform area of WPT
- Standard air density of 1.225 kg/m3

5.2.2 Recommended KPIs for Performance expectation and business case input

The purpose of this type of indicators is to communicate a realistic expectation of the saving potential from a WPT. They are typically used as decision support for business cases, or for agreements between commercial stakeholders.

<u>Power saving, fuel saving, energy saving or CO_2 saving?</u>

The saving due to a WPT in absolute terms can be expressed either as power, fuel, energy, or CO_2 saving. While this choice will not affect the ranking between the WPTs for the same ship it can make a difference in how far a KPI resonates with different stakeholders of the shipping industry. Owners and operators tend to think in tonnes of bunker per day, engineers are more familiar power or energy-based numbers, lawmakers will mostly focus on CO_2 savings.

If we consider ships with conventional diesel engines and power saving for constant operational speeds, then there is an almost linear relation between the predicted power, fuel, and energy savings. This allows for an easy conversion between the savings expressions by simply post-processing route simulation results. For hybrid propulsion systems, and if routing and speed optimisation are included, the relation is not that so straight forward and must be modelled within in the voyage simulations. Some of the advantages and disadvantages of the various units for savings are summarised below. These points were raised during discussions with industry stakeholders.

5.2.3 Fuel saving

Definition: difference in fuel consumption between ship with WPT and without WPT for same route and speed.

Comments from industry focus group:

- Ship owners can relate to fuel (tons/day and kg/h).
- Tons/miles makes it easier to scale to different routes.
- Can be used in a transition period when HFO is still the standard in shipping.
- Need modelling of machinery efficiency, or stipulate fixed specific fuel oil consumption (SFOC).
- Not easy for hybrid propulsion systems.

5.2.4 Energy saving

Definition: difference in energy (=propulsion power x time on route) between ship with WPT and without WPT for same route and speed.

Comments from industry focus group:

- Using propulsion energy instead of fuel allows to leave out engine efficiency.
- For specific cases ship owners can translate to fuel themselves.

- More future proof considering future fuels.

5.2.5 CO_2 savings/ CO_2s avoided

Definition: difference in CO2 (=fuel x conversion factor) between ship with WPT and without WPT for same route and speed.

Comments from industry focus group:

- Parameter assessed in EEDI, CII and emission trading schemes like EU-ETS.
- Of interest to the wider society.

5.2.6 Power saving

Definition: difference in propulsion power between ship with WPT and without WPT for same route and speed.

Comments from industry focus group:

- Propulsion power is a measure that both yards, designers, ship owners and operators are familiar with.
- It does not require any modelling of engine efficiency or assumptions of fuels and hybrid propulsion.
- WPT providers do not always have information on the details of the propulsion system or engine efficiency. In this case the power makes for safe option for the saving prediction.

Considering these pro and cons, it appears that "power savings" are the most feasible way of expressing WPT performance and are also a concept that is familiar to owners and operators. However, nothing prevents showing them all in a prediction report.

5.2.7 Percentage

The percentage fuel saving is the most common KPI in communications around wind propulsion today.

The ship's propulsion power when employing the WPT is compared to the propulsion power when there is no WPT, for the same sea leg and same speed:

$$\Delta P\% = \frac{P_{no\ WPT} - P_{with\ WPT}}{P_{no\ WPT}} \qquad (7)$$

One could think that a percentage saving is a clear KPI that can be used for comparison between different installations, since it is nondimensional. Very often, percentage saving claims are published without any further description of the specific cases. This is, however, a problematic approach.

The first issue is to *what* the savings have been related to, i.e. what number to have in the denominator. The calm water power, or power including sea margin, and should we use the fuel consumption for propulsion of the total fuel consumption including electric generation, harbour operation etc? That can change the KPI [%] by several %-units. Moreover, the percentage saving figure is very sensitive to ship speed. A higher ship speed gives much reduced %-saving. Thus, a percentage saving number, taken out if its context, may be misleading. A percentage number gives the false impression that it can be universally compared with other percentage saving predictions. For the reasons addressed here, many of the industry partners participating in the study are sceptical of using this KPI.

5.2.8 Power reduction

The performance of WPT could also be expressed as power reduction in kW, $\Delta P = P_{no\ WPT} - P_{with\ WPT}$. Several options for a standardised KPI related to ΔP were suggested by the industry partners involved in this study:

i. Max ΔP for TWS=10m/s (at the best wind direction)
ii. ΔP at a specified "design point" which could be for example TWS 10 m/s, TWA=60 deg
iii. ΔP at the most frequent weather

iv. ΔP on a given route, averaged over a year to include all season's weather
v. ΔP from the EEDI equation (pre or post 2021), but using weather statistics for an actual route

The advantage of option i) – iii) is that the prediction does not require any routing/voyage analysis tool. However, selecting one condition where ΔP is extracted can give large over or under predictions of the power reduction compared to the average saving on a route. The maximum ΔP gives also a misleading comparison between high lift versus high lift/drag devices. The same drawback is true for the option to derive ΔP at a specified "design point". Selecting the most frequent weather as the design point is completely misleading. The most frequent weather could well be head wind, where WPTs cannot even be employed. Figure 41 shows the comparison of three fictive wind propulsion technologies (WPT 1-3) fitted on the same ship, evaluated with the different suggested KPIs. The left most value is the Max ΔP for TWS=10m/s, which gives a very optimistic value compared to the result from the route analysis in the graph to the right. On the other hand, using the most frequent wind (third option in the left graph) gives over-pessimistic values (almost no saving). This shows that there is no way around using voyage simulations for deriving the power saving potential. The right graph shows the importance of conducting the analysis in the actual route, as the result is rather different for various routes.

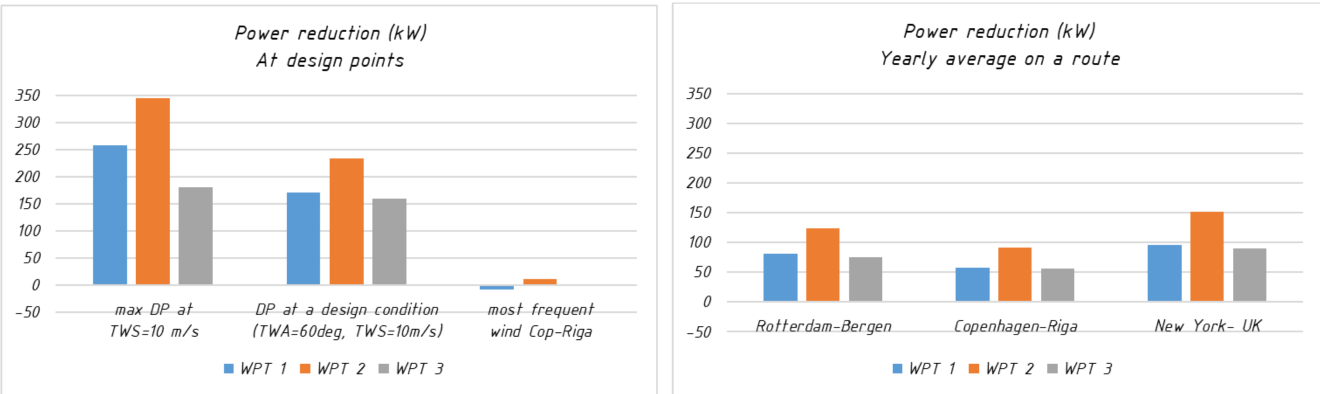


Figure 41: Example of how power saving can be computed in different ways, and different conditions, which results in different performance expectations. WPT 1, 2, 3 are fictive test cases.

5.2.9 Power Saving Potential (PSP)

No matter how accurate we try to model the power saving on a route, it is still a theoretical value. The real saving achieved in operation will depend on many practical aspects which cannot be foreseen in the predictions, such as maintenance time, changed route and speed, changed hull efficiency due to fouling, crew skill, function of the automated WPU control system, icing and wear. For this reason, it would be wise to denote the predicted ΔP the "Power Saving Potential". This will indicate that it is an ideal number derived under certain conditions. The PSP should be possible to verify during a short, controlled sea trial. After that, it is up to the owner, operator, and crew to use this potential in the best way.

5.2.9.1 Comparison of power saving

Some industry partners request that KPIs derived by different organisations should be truly comparable with each other also in terms of the derivation method. To ensure that all actors in the industry derive indicators that are truly comparable would require that some organisation could derive detailed procedures prescribing methods for CFD simulations and wind tunnel test. This is not a feasible solution. A true "apple to apple" comparison can only be achieved if the same simulation platform is used for the cases to be compared. However, we believe that it would be an improvement compared to today's situation if the industry agreed on a number of KPIs that are linked to certain levels of confidence. This is reflected in the proposed Guidelines for performance prediction, see section 5.1.

5.3 Derivation of a procedure for full scale trial of wind propulsion ships

5.3.1 Considerations before deriving a sea trial method for wind propulsion

Verifying the performance of wind propulsion solutions is essential for both shipowners and technology providers. Even without contractual obligations, such verification provides valuable confirmation for investments. Shipowners benefit from knowing the actual performance, while technology providers can use the data to enhance their designs and promote the technology. Additionally, accurate performance models are crucial for routing and performance monitoring software.

The Committee was tasked to suggest a method to verify the power saving from wind propulsion technology. After discussions with the industry, the current requirement for a verification method was identified:

- A method that verifies the saving from wind propulsion technology, not the absolute power. This is currently how WPT systems are sold, contracted, and also how it is treated in EEDI.
- A method that is commercially feasible for all yards and providers.
- A method that is transparent and possible to check by external verifiers.
- A method that does not require complex calculations or advanced equipment.

Various alternative strategies where discussed. Published full-scale campaigns for wind assisted ships have mainly been based on long-term monitoring data, such as for m/v Viking Grace Paakkari (2019) and for m/v Maersk Pelican Paakkari (2020). An advantage of this type of data is that it reflects the variety of weather conditions and operational profile that the ship encounters, as well as the real operability factors like idling time due to maintenance, weather routing, and crew skills. A challenge of using long-term monitoring data to detect even moderate power savings is the large scatter of such data, together with difficulties to find a comparable reference period with all other conditions except the wind propulsion installation unchanged. The main disadvantage is, however, the long period of time that such campaign requires. This is both costly and impractical in a commercial context and for EEDI verification.

Another alternative could be to measure the thrust forces from the wind propulsion devices directly. This requires, however, very complex measurement techniques that is now mature today. Moreover, with this method, the increased drift, increased rudder angle, and effect on the propeller are not taken into account.

The Committee suggests instead a process based on short sea trial runs, with the wind propulsion device turned on and off. The procedure is summarised in the next section.

5.3.2 Summary of recommended procedure

This section gives a summary of the new ITTC 7.5-04-01-02 Recommended Procedure Sea trials for assessing the power saving from wind assisted propulsion.

Like a conventional speed trial, the wind propulsion sea trial consists of a series of short runs. The main difference to a conventional sea trial is that the outcome is not the absolute value of the speed-power curve, but the power reduction due to the wind propulsion system. The effect of the wind propulsion system is extracted by comparing speed and power of single runs with and without wind propulsion for the same wind condition. The measured speed difference is converted to a power difference using the shape of the speed power curve and with some corrections for speed differences.

The minimum test program includes 5 wind conditions and can be conducted within one day. However, the scope can well be extended to include a larger number of conditions and can be conducted over a longer period during operation.

The signals to be measured are the same as for a normal speed-power sea trial: ship's speed, power, wind. In contrast to the normal procedures, the correction of current, which is usually done based on double runs, cannot be applied when wind propulsion is active. To overcome this, the speed is measured using the ship's log if the trial is conducted in a location which is known to be affected by tidal current. Since the purpose is to derive a speed difference, the relatively poor accuracy of the speed logs is acceptable.

The wind propulsion sea trial can be carried out at any wind conditions that gives sufficient driving force from the wind propulsion system, typically between Bf 4-7.

In the development of the procedures, the process was tested for five ships in the EU Interreg North Sea Region project WASP, and reported in Werner (2022).

Note that described procedure applies to ships with wind assisted propulsion, not primary wind powered ships.

The largest source of uncertainties probably originates from the measured wind. To minimise the uncertainty, it is recommended to use one, or even better, several, well calibrated, modern anemometers. However, it is unavoidable that the anemometers are disturbed by the superstructure, freeboard and WPS on the wind measurement. It is highly recommended if possible, to use a Lidar either to measure the wind at the trial, or to correct/calibrate the anemometer readings before the trial. CFD simulations can be used to find the most undisturbed position for the anemometer.

The uncertainty of wind propulsion sea trials is yet not fully investigated and document. It is recommended that the next Committee continue to improve the procedure and investigate the uncertainty.

5.3.3 How to apply the sea trial in contractual context

The wind propulsion sea trial verifies the power saving at one ship's speed, one wind speed, and a range of wind directions. It thus gives only spot check of the complete performance. To derive the total power saving potential for a given route or representative operational weather conditions, the sea trial needs to be combined with a performance prediction in the following manner:

1. The power saving is predicted according to ITTC 7.5-02-03-01.9 or for EEDI according to MEPC.1/Circ.896 sec 2.3 for all wind speeds, directions and relevant ship speeds.
2. The sea trial verifies the power saving for a limited number of wind conditions.
3. If the comparison between the predictions and the sea trial is satisfactory, the power saving for a given route or representative operational weather conditions can be calculated according to ITTC 7.5-02-03-01.9.
4. In case the comparison is not satisfactory, the provider of the prediction should give an updated prediction and a description of what has been modified. The changes should reflect all wind conditions in a reasonable way, not just the conditions tested in the sea trial.

The conventional motor-ship speed/power trial, which is conducted by shipyards before delivery of a new build ship, needs to be done in calm weather. It is very important to run the conventional speed/power trial as accurately as possible in calm weather. The introduction of wind propulsion systems should not be used as an excuse for performing the yard sea trial in heavier weather. Therefore, the wind propulsion sea trial needs to be done at a different occasion, when the wind conditions are suitable. If the wind condition is not suitable for wind propulsion sea trials at the time or location of delivery from a yard/retrofit site, it is suggested that the wind propulsion trial is conducted during service within an agreed period after delivery/installation.

The conventional speed/power trial procedure 7.5-04-01-01.1 do not need to be modified. In that trial, the ship is treated as a normal motor ship. This is the most useful and feasible way to treat wind assisted propulsion. If we in the future will build almost completely sailing vessels, there may be need for different approaches.

The proposed process was presented at several international conferences in Europe and Korea (Werner 2022a, Werner 2022b). The Committee also run several workshops with industry representatives, with the purpose to get feedback on the proposed method. The last workshop was held in February 2024, and the participants had received draft versions of the procedure beforehand. 18 organisations submitted in total 174 comments. Some of the key pieces of feedback received from industry on the provisional version of the procedure document are listed below.

- The instructions for the wind angle to be set during sea trial should be specific.
- The method of manoeuvring the ship during sea trial should be specified as either a constant heading or a constant course.
- It should be indicated how to determine whether a steady state is reached before measurement.
- The influence of errors in the electromagnetic logs for measuring ship speed on the results should be clarified.
- The acceptable difference in ship speed when a constant power condition is selected should be clarified.
- Clarify the rationale for the minimum wind speed conditions that are appropriate as sea trial conditions.
- Perform an uncertainty analysis and sensitivity analysis of all assumptions and models.

It is expected that the procedure will be updated ones more experience is gained. The uncertainty of the sea trial procedures, as well as the uncertainty of the performance predictions are still not well established. At current stage it is recommended to not yet use sea trials to confirm performance guarantees in a contractual context. However, it is strongly recommended to conduct sea trial of each wind propulsion installation to confirm the performance in a standardised manner.

6. CONCLUSIONS AND RECOMMENDATIONS TO THE 30TH ITTC

Wind propulsion for ships is a new area and it is developing quickly. Up to now, most wind installations are retro-fit ships with rather moderate wind assistance technology. A few ITTC members have been involved in research and commercial services related to wind propulsion, for example supporting ship owners with feasibility studies. The coming years, the interest in wind propulsion is expected to increase worldwide and there will likely be more new-built ships with very powerful wind installations. ITTC members can play an important role to support ship builders and ship designers in designing and assessing these new-built ships. Not only performance but also safety and regulation aspects will be important issues where ITTC members can contribute to the industry.

The 30th Specialist Committee on Wind Powered and Wind Assisted Ships has fulfilled all its TOR's except for one and produced two Procedures/Guidelines. Large efforts were spent on aligning these procedures and guidelines with the industry outside the ITTC. The development was presented at several public conferences and seminars. Several dedicated workshops were also held with technology providers, ship owners and designers.

The vast feed-back that the Committee received from the industry shows that there is a great interest in the coming procedures. Many stakeholders outside ITTC expressed their gratitude to our attempts. The young and developing industry seems to have lacked a common ground, and the new procedures fill a gap.

The Committee recommends to the full conference that the Specialist Committee is continued or even be turned into a permanent committee.

Producing two Procedures from scratch in a few years required large efforts. Although the procedures are complete, they can certainly be refined. More effort should be spent on scrutinizing every step and assumption. Thresholds and guides should be better motivated, and the uncertainty assessed.

The next committee should seek more closer cooperation with IMO, offering to assist with e.g. EEDI.

We also recommend wind tunnels to join ITTC and the SC.

The scope should be widened to include sea keeping and manoeuvring aspects. This is important when there will be very powerful wind powered ships being designed.

6.1 Future work

The Committee suggests the research community to study the following topics:

- Uncertainty analysis of sea trials for ships with wind assistance propulsion
- How to correct/calibrate anemometer with Lidar or CFD
- Sensitivity analysis of which wind statics is used in performance prediction on a route (source, year, duration)
- Effect of leeway and heel on propulsive efficiency determined with CFD. Validation and experience of different hull forms.
- Effect of leeway and heel on wave making and added resistance in waves
- Effect of reduced propeller flow on rudder
- The effect of wind propulsion on motions in waves, and conversely, the effects of motions on wind propulsion performance
- The effect of wind propulsion on manoeuvring
- The effect of control systems on performance, in relation to the actual wind experience by the WPU

7. REFERENCES

Abiven, N., Vautier, V., Cany, F., Fabre, J.B. and Rouxel-Duval, L. (2023). "Wind propulsion towards zero-emission cruise vessels". Wind Pro-pulsion ,16th – 17th February 2023, London, UK

American Bureau of Shipping, (2023). "Requirements for Wind Assisted Propulsion System Installation July 2022."

Anonymous. (1870). "The City of Ragusa, two tons burden, now crossing the Atlantic". The Illustrated London News.

Ardhuin, F., Orfila, A., (2018), "Wind waves", New Frontiers in Operational Oceanography, Vol. 14, pp. 393-422.

Atlas, R., Hoffman, R., Ardizzone, J., Leidner, S., Jusem, J., Smith, D. and Gombos, D., (2011), "A cross-calibrated, multiplatform ocean surface wind velocity product for meteorological and oceanographic applications", Bulletin of the American Meteorological Socie-ty, Vol. 92, pp. 157-174.

Azcueta, Rodrigo. (2002). "RANSE Simulations for Sailing Yachts Including Dynamic Sinkage & Trim and Unsteady Motions in Waves." In High Performance Yacht Design Conference. Auckland, New Zealand: High Performance Yacht Design Conference.

Azcueta, R. and Ward, H. (2023). "Performance prediction of wind propulsion technologies via CFD" . Wind Propulsion ,16th – 17th February 2023,London, UK.

Babinsky, H. (2003). "How do wings work?" Physics Education 38(6).

Bureau Veritas. (2021). "Wind Propulsion Systems.", NR 206 DT R01 E

Baptiste Cadalen, Fabien Griffon, Patrick Lanusse, Jocelyn Sabatier, Yves Parlier, (2018). "Modelling and control of a tethered kite in dynamic flight". Journal of Sailing Technology, Article 2018-03.© 2018, The Society of Naval Architects and Marine Engineers.

Bataille, J., Blayo, C. and Sergent, P. (2023). "Performance Methodology benchmark for wind assisted propulsion ship Performance estimation". International Conference on Wind Propulsion, 16-17 February 2023, London, UK.

Becker Marine Systems (2023). "Becker Marine Systems Joins Growing Wind Propulsion Family Of Technologies With Wingsail Project." from https://www.becker-marine-systems.com/news-media/beckers-wingsail-joins-growing-wind-propulsion-family.html.

Behrel, M.,Roncin, K., Leroux, J. Montel, F., Hascoët, R. (2018). "Application of phase averaging method for measuring kites performance: onshore results". Journal of Sailing Technology, The Society of Naval Architects and Marine Engineers, 2018, pp.2018-05. hal-01889988.

Blackford, B. (1985). "Optimal blade design for windmill boats and vehicles." Journal of ship research 29(02): 139-149.

Bigi, Nedeleg, Kostia Roncin, Jean-Baptiste Leroux, and Yves Parlier, (2020). "Ship Towed by Kite: Investigation of the Dynamic Coupling". Journal of Marine Science and Engineering 8, no. 7: 486. https://doi.org/10.3390/jmse8070486

Bitner-Gregersen, E. M., Eide, L. I., Hørte, T. (2013), "Ship and offshore structure design in climate change", Springer.

Bøckmann, E. and S. Steen (2011). "Wind turbine propulsion of ships". Second international symposium on marine propulsors, Hamburg, Germany.

Bose, N. (2008). "Marine powering prediction and propulsors." The Society of Naval Architects and Marine Engineers, SNAME, ISBN: 0-939773-65-1.

Bound4Blue (2022). "eSAIL's Operational Principle}."https://bound4blue.com/esail/

Bordogna, G., Keuning, L., Huijsmans, R., Fossati, F. V., & Belloli, M. , (2016). "Validation of a simple aerodynamic model capable to pre-dict the interaction effects occuring between two generic wind propulsion systems". In R. H. M. Huijsmans (Ed.), Proceedings of the 12th Inter-national Conference on Hydrodynamics ICHD 2016

Bordogna, G. (2020). "Aerodynamics of wind-assisted ships: Interaction effects on the aerodynamic performance of multiple wind-propulsion systems". https://doi.org/10.4233/uuid:96eda9cd-3163-4c6b-9b9fe9fa329df071

Breukels, J., (2011). "An engineering methodology for kite design". Ph. D. Thesis, Delft Universityof Technology. URL: http://www.kitepower.eu/publications.html

Breukels, J., Schmehl, R., Ockels, W.J., (2013). "Aeroelastic Simulation of Flexible Membrane Wings based on Multibody System Dynamics". Airborne Wind Energy. U.Ahrens, M.Diehl, R.Schmehl(eds.), Springer, Heidelberg. doi: 10.1007/978-3-642-39965-7_16. http://www.kitepower.eu/publications.html

Cadalen, B., et al. (2018). "Modelling and control of a tethered kite in dynamic flight." Journal of Sailing Technology 3(01): 1--24.

Cairns, J., Vezza, M., Green, R., MacVicar, D. (2019). "Numerical and Experimental Comparison of Surface Pressures around a Scaled Ship Wind-Assisted Propulsion System".International Journal of Mechanical, Industrial and Aerospace Sciences.Vol:13, No:11, 2019.

Carter, R.A. (2012). "Watercraft." A companion to the archaeology of the ancient Near East: 347-372.

Carvalho, D., (2019), "An assessment of NASA's GMAO MERRA-2 reanalysis surface winds", Climate, Vol 32, pp. 8261-8281.

Charrier, B., et al. (1985). "Fondation Cousteau and windship propulsion 1980–1985 system Cousteau-Pechiney." Journal of wind engineering and industrial aerodynamics 20(1-3): 39-60.

Charrier, B. (2021). "Interactions between Two Flettner Rotors used for Wind Ship Assisted Propulsion". International Conference on Wind Propulsion, 15-16 September 2021, London, UK.

Chen, G., Chapron, B., Ezraty, R., Vandemark, D., (2002), "A global view of swell and wind sea climate in the ocean by satellite altimeter and scatterometer", Journal of Atmospheric and Oceanic Technology, Vol. 19, pp.1849-1859.

Chen W , Wang H , Liu X , (2023). "Experimental investigation of the aerodynamic performance of Flettner rotors for marine applications". Ocean engineering, 2023.

Chou, T. (2021). "A comeback of wind power in shipping: An economic and operational review on the wind-assisted ship propulsion technology." Sustainability 13(4): 1880.

ClassNK. (2023). "Guideline for Wind-Assisted Propulsion Systems for Ships (Edition 2.0).".

Climate Data Guide (2023), https://climatedataguide.ucar.edu/climate-data/ccmp-cross-calibrated-multi-platform-wind-vector-analysis (last accessed 20/04/2023)

Cooke Associates (2023). "Commercial History of the Walker Wing Sail." from http://www.cookeassociates.com/sports/commercial.php.

Craft, T.J. (2012). Back to the future: Flettner-Thom rotors for maritime propulsion?

Dadd, G. M. (2013). "Kite dynamics for ship propulsion." Engineering Environmental Science

Dallinga, R.P., and Bos, J.E., (2010). "Cruise Ship Seakeeping and Passenger Comfort." In HPAS. HPAS.

De Marco, A., Mancini, S., Pensa, C., Calise, G., DE luca, F., (2016). " Flettner rotor concept for marine applications: a systematic study" . Int. J. Rotating Machinery, 2016.

Dee, D., Uppala, S., Simmons, A., (2011), "The ERA-Interim reanalysis: configura-tion and performance of the data assimilation system", Quarterly Journal of the royal meteorological society, Vol. 137, pp. 553-597.

DNV. (2023). "Det Norske Veritas Rules and Standards.". https://rules.dnv.com/servicedocuments/dnvpm .

Duport, C., (2018) "Modeling with consideration of the fluid-structure interaction of the behavior under load of a kite for auxiliary traction of ships" (Doctoral dissertation, ENSTA Bretagne-École nationale supérieure de techniques avancées Bretagne).

Duport, Chloé & Leroux, J.-B & Roncin, Kostia & Jochum, C & Parlier, Yves. , (2016). "Comparison of 3d non-linear lifting line method calculations with 3D RANSE simulations and application to the prediction of the global load-ing on a cornering kite". Actes des 15èmes Journées del'Hydrodynamique. Available from http://website.ec-nantes.fr/actesjh/images/15JH/Articles/duport.pdf.

Duport, C., Leroux, J.B., Roncin, K., Jochum, C. and Parlier, Y. (2019). "Benchmarking of a 3D non-linear lifting line method against 3D RANSE simulations".. La Houille Blanche, (5-6), pp.70-73.

Dupuy, M., Letournel, L., Paakkari, V., Rongère, F.,Sarsila, S., Vuillermoz, L.(2023). "Weather Routing Benefit for Different Wind Propulsion Systems". The 6th International Conference on Innovation in High Performance Sailing Yachts and Wind-Assisted Ships, Lorient, France, May, 2023.

Dupuy, Maxime. (2023). "About the benefit of optimizing both speed and route in wind assisted ships multi-objective weather rout-ing". In: RINA Wind Propulsion Conference 2023.

Eça, V. Guilherme and M. Hoekstra, (2010). "Code Verification, Solution Verification, and Validation in RANS Solvers," Proceedings ASME Conference ence on Ocean, Offshore, and Arctic Engineering, 2010.

Econowind (2022). "Econology Powered by Wind." from https://www.econowind.nl/.

Eide, K.,Östman, A. and Alterskjær, A. (2023). "Validation of performance prediction program against cyberphysical model tests". Wind Pro-pulsion, 16th – 17th February 2023, London, UK

Eggers, R, and Kisjes, A.S.(2023) "WiSP2 Project on Wind Propulsion Performance Prediction Methods and Manoeuvring." In RINA Wind Propulsion Conference, 2023

Eggers, R. and Kisjes, A.S. (2019) "Seakeeping and Manoeuvring for Wind Assisted Ships," London, United Kingdom, 2019-10.

Eggers, R. (2018), "Prediction methods for team AkzoNobel in the Volvo Ocean Race and wind assisted ship propulsion for merchant vessels", Proceedings of the 25th international hiswa symposium on yacht design and yacht construction, Amsterdam.

Erhard, M. and H. Strauch (2012). "Control of towing kites for seagoing vessels." IEEE Transactions on Control Systems Technology 21(5): 1629--1640.

Ewing, J. A., Laing, A. K., (1987), "Directional spectra of seas near full development", Journal of Physical Oceanography, Vol. 17, pp. 1696-1706.

Fagiano, L. (2009) "Control of Tethered Airfoils for High–Altitude Wind Energy Generation". Ph.D. Thesis, Politecnico di Torino, Torino, Italy, 2009.

Fang, M., Lin, Y., (2013), "The optimization of ship weather-routing algorithm based on the composite influence of multi-dynamic elements", Applied Ocean Research, Vol. 43, pp. 184-194.

Ferrari, V., Kisjes, A. and Quadvlieg, F. (2018). "Quantifying the Uncertainty of the Crabbing Capability." In International Conference on Offshore Mechanics and Arctic Engineering, American Society of Mechanical Engineers.

Fossati, F. and Muggiasca, S. (2011) "Experimental Investigation of Sail Aerodynamic Behaviour in Dynamic Conditions." J. Sailboat Tech 2.

Fritz, F. (2013). Application of an automated kite system for ship propulsion and power generation. Airborne wind energy: 359--372.

Garenaux, M., Schot, J.J.A. (2021). "Flettner rotors performance and interaction effects on the marin hybrid transition coaster". International Conference on Wind Propulsion, 15-16 September 2021, London, UK.

Gauvain, E. (2019) “The un-restrained sailing yacht model tests–a new approach and technology appropriate to modern sailing yacht seakeeping,” 2019.

Gerhardt, F.C., Kjellberg, M., Wigren, I., Werner, S., Razola, M. “The Horns of the Trilemma: Seakeeping Model Tests for a Wind Powered Vessel,” 2021.

Gerhardt, F., Werner, S., Hörteborn, A., Lundbäck, O., Nisbet, J. and Olsson, T., (2021). HORSES FOR COURSES: HOW TO SELECT THE “RIGHT” WIND PROPULSION SYSTEM AND HOW TO MAKE THE BUSINESS CASE. In Wind Propulsion 2021 15-16 September 2021, Online Conference.

Gerhardt, F.C., Kjellberg, M., Wigren,I., Werner, S. (2021)."The horns of the trilemma: Sea-keeping model tests for a wind Powered vessel". International Conference on Wind Propulsion, 15-16 September 2021, London, UK.

Giovannetti, L.M., Gerhardt, F., Kjellberg, M., Alexandersson, M.and Werner, S. (2021). “The art of model testing: Using CFD to adapt traditional tank testing techniques to a new era of wind propelled shipping,” 2022.

Giovannetti, L.M., Banks, J., Turnock, S.R., and Boyd, S.W. (2017). "Uncertaintly assessment of coupled Digital Image Correlation and Particle Image Velocimetry for fluid-structure interaction wind tunnel experiments". Journal of Fluids and Structures, vol. 68, pp. 125-140, 2017.

Giovannetti, L.M., Banks, J., Ledri, M., Turnock, S.R. and Boyd, S.W. (2018). "Toward the development of a hydrofoil tailored to passively reduce its lift response to fluid load". Ocean Engineering, vol. 167, pp. 1-10, 2018.

Giovannetti, L.M. (2020). "Appendages investigation and their effects on maneuvering coefficients for applications in wind assisted ships". Proceedings of 5th International Conference on Innovation in High Performance Sailing Yachts and Sail-Assisted Ship Propul-sion, Gothenburg, Sweden, June 2020.

Giovannetti, L.M. Charalampopoulos, O., Banks, J., Boyd S.W. and Turnock, S.R. (2020). "Developing fluid structure interaction experimental methodologies for dynamic foil measurements". Innov’sail 2020, Gothenburg, 2020.

Giovannetti, L.M., Olsson, F., Alexandersson, M., Werner, S. and Finnsgård, C., (2020), "The Effects of Hydrodynamic Forces on Maneuvrability Coefficients for Wind-Assisted Ships". In International Conference on Offshore Mechanics and Arctic Engineering (Vol. 84379, p. V06AT06A051). American Society of Mechanical Engineers.

Giovannetti, L.M., Stenius, I. (2021). "Review of undewater fluid-structure interaction measuring techniques". 7th High Performance Yacht Design Conference Auck-land, 11-12 March 2021.

Global Wind Atlas, (2022) https://globalwindatlas.info/ last accessed 16th August 2022

Glomeep (2019). "Global maritime energy efficiency partnerships." from https://glomeep.imo.org/. Last accessed 20th August 2022

Hand, M. (2021). "K Line orders LNG-powered bulker fitted with Airseas kite." from https://www.seatrade-maritime.com/shipyards/k-line-orders-lng-powered-bulker-fitted-airseas-kite.

Gracia, L., Wang, H., Mao, W. (2019), “Comparison of two statistical wave models for fatigue and fracture analysis of ship structures", Ocean Engineering, Vol. 187, 106161.

Gruber, K., Regner, P., Wehrle, S., Zeyringer, M., Schmidt, J., (2022), "Towards global validation of wind power simulations: A multi-country assessment of wind power simulation from MERRA-2 and ERA-5 reanalyses bias-corrected with the global wind atlas". Energy, Vol. 238.

Hans Ertel Zentrum für Wetterforschung, (2019), "COSMO regional reanalysis", https://reanalysis.meteo.uni-bonn.de.

Hasselmann, S., (1988), "The WAM model: A third generation ocean wave prediction model", Journal of Physical Ocean-ography, Vol. 18, pp. 1775-1810.

Harada, Y., Kamahori, H., Kobayashi, C., (2016), "The JRA-55 reanalysis: represen-tation of atmospheric circulation and climate variability", Journal of the Meteorological Soci-ety of Japan, Vol. 94, pp. 269-302.

Hersbach, H., Bell, B., Berrisford, P., (2020), "The ERA5 global reanalysis", 2020, Quarterly Journal of the royal meteorological society, Vol. 146, pp. 1999- 2049.

Hirdaris, S.E. and Cheng, F., (2012), June. The role of technology in green ship design (keynote address). In Proceedings of the 11th International Marine Design Conference (IMDC), 1: 21 (Vol. 40).

Hopes, W., Pearson, D., Buckingham, J. (2021). "A CFD Study on Wind Assisted Propulsion Technology for Commercial Shipping". RINA Wind Propulsion Conference, 2021, London, UK.

Kisjes, A., Eggers, R., and Bedos A., (2023). "Steering with Wind Propulsion." In Proceedings of the 19th International Ship Stability Workshop.

Kjellberg, M., Gerhardt, F., and Werner, S. (2022) "Sailing in Waves: A Numerical Method for Analysis of Seakeeping Performance and Dynamic Behavior of a Wind Powered Ship," 2022.

Kobayashi, S., Ota, Y., Harada, A., (2015), "The JRA-55 reanalysis: general specifications and basic characteristics", Journal of the Meteorological Society of Japan, Vol. 93, pp. 5-48.

IACS, (2000), "Standard wave data (north Atlantic scatter diagram)" Rec. No. 34.

International Windship Association (2021). "Technology and Design." from https://www.wind-ship.org/en/technology-design/.

International Maritime Organization. (2002). MSC Resolution 137(76) "Standards for Ship Manoeuvrability." Standards for Ship Manoeuvrability. International Maritime Organization (IMO).

International Maritime Organization. (2001). MEPC.1/Circ.850/Rev.3 "Guidelines for Determining Minimum Propulsion Power to Maintain the Manoeuvrability of Ships in Adverse Conditions." Standards for Ship Manoeuvrability. International Maritime Organization (IMO).

International Maritime Organization. (1974). "International Convention for the Safety of Life at Sea (SOLAS)."

International Maritime Organization. (2010). "Interim Explanatory Notes for the Assessment of Passenger Ship Systems' Capabilities after a Fire or Flooding Casualty." Standards for Ship Manoeuvrability.

International Maritime Organization. (2011), "Reduction of GHG emission from ships, global wind specification along the main global shipping routes to be applied in the EEDI

Calculation of Wind Propulsion Sys-tems”, IMO MEPC 62/INF. 34.

International Maritime Organization (2018) MEPC 72/5/9, 2 February 2018 , “Pro-posed amendments to the 2013 Interim Guidelines for determining minimum pro-pulsion power to maintain the manoeuvra-bility of ships in ad-verse conditions”, Sub-mitted by China.

International Windship Association (2024) Wind Propulsion_ Zero-Emissions Energyu So-lution for Shipping, Annex to MEPC 81/INF.39

Interreg North Sea Region (2021). "Come along on a wind-assist ride aboard Van Dam Shipping's MV Ankie and the newly installed ventifoil system from eConowind." from https://northsearegion.eu/wasp/news/come-along-on-a-wind-assist-ride-aboard-van-dam-shippings-mv-ankie-and-the-newly-installed-ventifoil-system-from-econowind/.

ITTC (2017) Recommended Procedures and Guide-lines 7.5-02-03-01.4, 2017, “1978 ITTC Performance Prediction Method”.

ITTC.(1999). “Testing and Extrapolation Methods High Speed Marine Vehicles Excerpt of ISO 2631, Seasickness and Fatigue - Recom-mended Procedures.” ITTC.

Jehle, C. and Schmehl, R., (2014). "Applied tracking control for kite power systems". Jour-nal of Guidance, Control, and Dynamics, Vol. 37, No. 4, p. 1211-1222.

Jones, L., Prince, M., Hudson, D., Cocks, J. (2019)."Predicted fuel-savings for a flettner ro-tor assisted tanker using computational fluid dy-nam-ics". Wind Propulsion, 15th -16th October 2019, London, UK.

Kalnay, E., Kanamitsu, M., Kistler, R., (1996), “The NCEP/NCAR 40-year reanaly-sis project”, Bulletin of the American Meteoro-log-ical Society, Vol. 77, pp. 437-472.

Kanamitsu, M., Ebisuzaki, W., Woollen, J., Yang, S., Hnilo, J., Fiorino, M., Potter, G., (2002), “NCEP-DOE AMIP-II reanalysis (R-2)”, Bulletin of the American Meteorological Socie-ty, pp. 1631-1643.

Karabelas, S. J., et al. (2012). "High Reyn-olds number turbulent flow past a rotating cylin-der." Applied mathematical modelling 36(1): 379--398.

Karman D. (2016). "Examination of high Reynolds number flow around a spinning cylin-der with different turbulence models" [J]. 2016.

Kjellberg, Martin, Gerhardt, Frederik, and Sofia Werner, (2022). "Sailing in Waves: A Nu-merical Method for Analysis of Seakeeping Per-formance and Dynamic Behavior of a Wind Powered Ship" . Paper presented at the SNAME 24th Chesapeake Sailing Yacht Symposium, Annapolis, Maryland, USA, June 2022.

Kjellberg, M., Gerhardt, F., Werner, S. (2023). "Sailing performance of wind-powered cargo vessel in unsteady conditions". The 6th In-ternational Conference on Innovation in High Performance Sailing Yachts and Wind-Assisted Ships, Lorient, France, May, 2023.

Koster, D., (2015), “Technical report series on global modelling and data assimilation, Vol-ume 43”, MERRA-2: Initial Evaluation of the Climate.

Kukner, A., S. Bulut and A. N. Halilbese (2016). "Renewable energy options and an as-sessment of wind-based propulsion systems for small crafts." Naval Academy Scientific Bulle-tin. \url http://dx. doi. org/10.21279/1454-864X-16-I2-006.

Kume K , Hamada T , Kobayashi H , (2022). "Evaluation of aerodynamic characteris-tics of a ship with flettner rotors by wind tunnel tests and RANS-based CFD"[J].Ocean engi-neering, 2022 (Jun.15):254.

Lades AS (2023). "About Lades AS." from https://ladeas.no/about-lade-as/. Last accessed August 2022.

Laface, M., Arena, F., (2021), "On correlation between wind and wave storms", Journal of Marine Science and Engineering, Vol. 9, 1426.

Lee, H., Jo, Y., Lee, D.J., Choi, S., (2016). "Surrogate model based design optimization of multiple wing sails considering flow interaction effects". Ocean Eng. 121, 422-436. https://doi.org/10.1016/j.oceaneng.2016.05.05

Leloup, R. (2016). "A continuous and analytical modeling for kites as auxiliary propulsion devoted to merchant ships, including fuel saving estimation." Renewable Energy 86: 483--496.

Li, X., Qin, X., Yang, J., Zhang, Y., (2022), "Evaluation of ERA5, ERA-Interim, JRA55 and MERRA2 reanalysis precipitation datasets over the Poyang Lake Basin in China", Interna-tional Journal of Climatology, Vol. 42, pp. 10435-10450.

Lloyd's List (2020). "From the News Desk: Will coronavirus accelerate the use of tech in shipping?". from https://lloydslist.maritimeintelligence.informa.com/LL1131917/From-the-News-Desk-Will-coronavirus-accelerate-the-use-of-tech-in-shipping.

Lloyd's Register. (2023a). "Guidance Notes for Flettner Rotor Approval.". https://r4s.oneocean.com/regulation/page/262879 .

Lloyd's Register. (2023b). "Guidance Notes for the Certification of Masts, Spars and Standing.". https://r4s.oneocean.com/regulation/page/258612 .

Llopis Pascual, A. Bailardi, G. Charrier, B. and Ferrer Desclaux, D. (2023). "Eerodynamic optimi-zation of the esail, bound4blue's suction sail for wind-assisted vessel propulsion". Interna-tional Conference on Wind Propulsion, 16th -17th February 2023, London, UK.

Longyard, W. H. (2005). "A Speck on the sea: Epic Voyages in the most improbable vessels."

Lu, R.,Ringsberg, R.W. (2019). "Ship energy performance study of three wind-assisted ship propulsion technologies including a parametric study of the Flettner rotor technolo-gy". Ships and Offshore Structures, DOI: 10.1080/17445302.2019.1612544

Lu, R. and J. W. Ringsberg (2020). "Ship energy performance study of three wind-assisted ship propulsion technologies including a parametric study of the Flettner rotor technology." Ships and Offshore structures 15(3): 249--258.

Marchaj, C. A. (1988). Aero-hydrodynamics of Sailing.

Maritime Global News (2022). "K Line Orders Airseas Kites for Three More Ships." from https://maritimeglobalnews.com/news/orders-aieseas-kites-three-ev3k1y.

Mason, J.C. (2021). "Quantifying voyage op-timisation with wind-assisted ship propulsion: a new climate mitigation strategy for shipping". In: Doctoral dissertation, The University of Manchester, (UK).

Mazas, L., Andrillon, Y., Letourneur, A., Kerdraon, P. and Verdier, G. (2017). "Comparison of Hydrodynamic Performances of an Imoca 60 with Straight or L-Shaped Daggerboard." INNOV'SAIL, 2017.

Mikulić, A., Katalinić, M., Ćorak, M., Parunov, J., (2020), "The effect of spatial correlation of sea states on predicted extreme significant wave heights along ship sailing routes", Marine Technology Engineering (in press).

Milgram, J. H. (1968). The aerodynamics of sails: 1397--1434.

Mittal, S. and B. Kumar (2003). "Flow past a rotating cylinder." Journal of fluid mechanics 476: 303--334.

Morsy El-Gohary, M. (2013). "Overview of past, present and future marine power plants." Journal of Marine Science and Application 12(2): 219--227.

Morvan, A. , Sacher, M. , Alain Nême, Leroux, J. B. , & Abiven, N., (2021). "Efficient jib-mainsail fluid-structure interaction modelling based on an extended lifting-line theory - valida-tions with semi-rigid sails experiments". The Royal Institution of Naval Architects.

Naaijen, P., V. Koster and R. P. Dallinga (2006). "On the power savings by an auxiliary kite propulsion system." International shipbuilding progress 53(4): 255--279.

Nelissen (2016), "Study on the analysis of mar-ket potentials and market barriers for wind propulsion technologies for ships", Delft, CE Delft

Obakrim, S., Ailliot, P., Monbet, V., Raillard, N., (2023), "Statistical modeling of the space–time relation between wind and significant wave height", Advances in Statistical Climatology, Meteorology and Oceanography, Vol. 9, pp. 67-81.

Oehler, Johannes and Schmehl, Roland, (2019). "Aerodynamic characterization of a soft kite by in situ flow measurement". Wind Energ. Sci., 4, 1–21, 2019 .

Oceanbird (2023). "Oceanbird Wing Sail." from https://www.theoceanbird.com.

Paakkari Ville; Wang, H; Stigler C, (2022). "Voyage optimization with wind propulsion Conference proceedings". In: RINA ICCAS 2022.

Paulig, X., M. Bungart and B. Specht (2013)."Conceptual design of textile kites considering overall system performance". Airborne wind energy: 547--562.

Perkins, T., (2004). "The maltese falcon: The realisation." 22nd International HISWA Symposium on Yacht Design and Yacht Construction: 1-30.

Persson, A., Li, D.Q., Olsson, F., Werner, S. and Dhome, U., (2019). Performance prediction of wind propulsion systems using 3D CFD and route simulation. In 6th International Conference on Computational Methods in Marine Engineering, MARINE 2015; Conference Date: 15 June 2015 Through 17 June 2015; (pp. 19-30). Royal Institution of Naval Architects.

Pierson, W. J., Moskowitz, L., (1964), "A proposed spectral form for fully developed wind seas based on the similarity theory of S. A. Kitaigorodskii", Journal of Geophysical Research, Vol. 69, pp. 5181-5190.

Pili, F., Babarit, A., Bonnefoy, F., Payne, G.S. (2023). "Numerical investigation of the seakeeping of a Flettner ro-tors-propelled catamaran in beam waves". The 6th International Conference on Innovation in High Performance Sailing Yachts and Wind-Assisted Ships, Lorient, France, May, 2023

Podeur, V. (2018). "Fuel economy assessment tool for auxiliary kite propulsion of merchant ship." La Houille Blanche 1(1): 5--7.

Podeur, V. (2016). "Simulation de voyage au long cours pour le calcul d'économies de carburant: application à la propulsion par cerfvolant."

Ran, H., C.E. Janson and B. Allenström (2013). "Auxiliary kite propulsion contribution to ship thrusti". International Conference on Offshore Mechanics and Arctic Engineering, American Society of Mechanical Engineers.

Reche-Vilanova, Martina & Hansen, Heikki & Bingham, Harry. (2021). "Performance Prediction Program for Wind-Assisted Cargo

Ships". Journal of Sailing Technology. 6. 91-117. 10.5957/jst/2021.6.1.91.

Reche-Vilanova M. et al., 2023. "Preliminary study on the propeller and engine performance variation with wind propulsion technologies". Wind Propulsion, 16th-17th February 2023, London, UK.

Rienecker, M., Suarez, M., Gelaro, R., (2011), "MERRA: NASA's Modern-Era Retrospective Analysis for Research and Applications", Journal of Climate, Vol. 24, pp. 3624-3648.

Roach, P.J., (1997). "Quantification of Uncer-tainty in Computational Fluid Dynamics". Ann. Rev. of Fluid Mechanics, vol. 29, pp. 123-160, 1997.

Roncin, K.; Behrel, M.; Iachkine, P.; Leroux, J.-B., (2020). "Benchmark Sea Trials on a 6-Meter Boat Powered by Kite". Appl. Sci. 2020, 10, 6148. https://doi.org/10.3390/app10186148

Royal Institution of Naval Architects, The, (2012). "Development of Amendments to the Criterion for Maximum Angle of Heel in Turns of the 2008 IS Code – Revised Proposal for Amending the 2008 IS Code', IMO SLF55/12," 2012.

Saha, S., Moorthi, S., Pan, H., (2010), "The NCEP climate forecast system reanalysis", Bulletin of the American Meteorological Socie-ty, Vol. 91, pp. 1015-1058.

Sauder, T., Alterskjær, S.A. (2022). "Hydrodynamic testing of wind-assisted cargo ships using a cyber–physical method". Ocean Engineering , Volume 243, Jan. 2022, https://doi.org/10.1016/j.oceaneng.2021.110206

Severi, S. (2022). "Comparison of achieved fuel savings on ships by different wind propulsiondevices using a 3-DoF resistance model". English. Master's thesis. Aalto Uni-versity. School of Engineering, p. 43. URL: http://urn.fi/URN:NBN:fi:aalto-202205223282

Schmidt, A. (2013). E-Ship 1-A Wind-Hybrid Commercial Cargo Ship.

Schot, J.J.A., Eggers, R., (2019), "The Effect of Leeway Angle on the Propeller Performance", Wind Propulsion(London, UK), pp 31 - 39.

Schot，J.J.A., Garenaux， M. (2023). "Modelling of aerodynamic interaction effects for wind propulsion applied in commer-cial shipping: Development of a non-linear lift-ing line method". The 6th International Confer-ence on Innovation in High Performance Sailing Yachts and Wind-Assisted Ships, Lorient, France, May, 2023.

Seddiek, I. S. and N. R. Ammar (2021). "Harnessing wind energy on merchant ships: case study Flettner rotors onboard bulk carriers." Environmental Science and Pollution Research 28(25): 32695--32707.

Staffell, I., Pfenninger, S., (2016), "Using bias-corrected reanalysis to simulate current and future wind power output", Energy, Vol. 114, 1224e39.

Stefanakos, C., (2021), "Global wind and wave climate based on two reanalysis data-bases: ECMWF ERA5 and NCEP CFSR", Journal of Marine Science and Engineering, Vol. 9, 990.

Sumon, Md Daluar Hussain and Osman, Amin.(2021). "A Comprehensive Analysis of the Stability and Powering Performances of a Hard Sail–Assisted Bulk Carrier". Journal of Marine Science and Application. 20. 426-445. 10.1007/s11804-021-00219-w

Suzuki, N., Konda, M., Kutsuwada, K., Utsunomiya, K., (2018), "Comparison of the accuracy of various global wind speed datasets obtained from satellites and reanalyses", Jour-nal of Advanced Marine Science and Technol-ogy Society, Vol. 24, pp. 31-37.

Sverdrup, H. U., Munk, W. H., (1947), "Wind seas and swell: Theory of relations for forecasting", U.S. Navy Hydrographic Office, Washington, DC.

Tillig F, Ringsberg JW, Mao W, Ramne B. (2017). "A generic energy systems model for efficient ship design and operation". IMechE, Part M, J EngMaritime Environ. 231(2):649–666. doi:10.1177/1475090216680672.

Tillig, F., Ringsberg, J.W., (2018). "A 4 DOF Simulation Model Developed for Fuel Con-sumption Prediction of Ships at Sea". Ships and Offshore Structures. https://doi.org/10.1080/17445302.2018.1559912.

Tillig, F., (2020). "Simulation model of a ship's energy performance and transportation costs". Doctoral thesis, Chalmers University of Technology, Sweden.

Tillig, F., Ringsberg, J.W., (2020). "Design, operation and analysis of wind-assisted cargo ships". Ocean Engineering, Volume211, 2020. https://doi.org/10.1016/j.oceaneng.2020.107603

Thomas, T. (2015). "The development of the high-tech DynaRig on sailing superyachts." from https://www.boatinternational.com/yachts/yacht-design/the-development-of-the-high-tech-dynarig-on-sailing-superyachts

Traut, M., et al. (2014). "Propulsive power contribution of a kite and a Flettner rotor on selected shipping routes." Applied Energy 113: 362--372.

Twidell, J. (2021). Renewable energy resources, Routledge.

UK GOVERNMENT (2019), Clean Maritime Plan 2019, Department for Transport, UK

Vahs, M. (2019) "Retrofitting of Flettner Rotors – Results from Sea Trials of the General Cargo Ship "Fehn Pollux"," London, United Kingdom, 2019-10.

van der Kolk, N., (2016a). "Hydrodynamics of wind-assisted ship propulsion: modeling of Hydrodynamic sideforce". In: 24th International HISWA Symposium on Yacht Design and Yacht Construction,14-15 Nov, Amsterdam.

van der Kolk, N., Keuning, J.A.., and Huijsmans, R.H.M. (2016b). "Hydrodynamics of wind-assisted ship propulsion verification and validation of RANS methodology". In Proceedings of the 12th International Conference on Hydrodynamics-ICHD 2016 [148]

van der Kolk, N., Keuning, L.A., and Huijsmans, R.H.M.. (2017). "Hydrodynamics of wind-assisted ship propulsion validation of RANS-CFD methodology". In P. Bot (Ed.), Proceed-ings of the 4th International Conference on In-novation in High Performance Sailing Yachts (INNOVSAIL 2017) (pp. 207-216). [796] Sailing YardResearch Foundation (SYRF).

van der Kolk, N.J., Bordogna, G., Mason, J.C.,Desprairies, P., Vrijdag, A. (2019a) "Case study: Windassisted ship propulsion performance prediction, routing, and economic modelling". RINA Conf.Power & Propulsion Alternatives for Ships, 2019.

van der Kolk, N.J., Keuning, J.A., Huijsmans, R.H.M., (2019b). "Part 1: experimental validation of a RANS-CFD methodology for the hydrodynamics of wind-assisted ships operating at leeway angles". Ocean Eng. 178.

van der Kolk,N.J., Keuning, J.A., and Huijsmans, R.H.M. (2020a). "Hydromechanics of wind-assisted ship propulsion verification of RANS methodology". Ocean Engineering Volume 201, 1 April 2020, 107024DOI: 10.1016/j.oceaneng.2020.107024AB van der Kolk, N.J., Akkerman, I., Keuning, J.A., Huijsmans, R.H.M., (2020b). "Part 2: simula-tion methodology and numerical uncertainty for RANS-CFD for the hydrodynamics of wind-assisted ships operating at leeway angles". Ocean Eng. 201.

van der Kolk, N.J., Akkerman, I., Keuning, J.A. (2021). "Low-aspect ratio appendages for wind-assisted ships". J Mar Sci Technol 26, 1126–1143(2021). https://doi.org/10.1007/s00773-020-00777-8

Viola, I.M., Sacher, M., Xu, J., Wang, F., (2015). "A numerical method for the design of ships with wind-assisted propulsion". Ocean Engineering, 105, pp.33-42, 2015.

Wang, Yonggong Liu, Yanshuo Li, Hongxia, (2022). "Stability Analysis of Airfoil Sail-Assisted Ship Under Combined Wind and Wave Load". Ship &Boat, DOI:10.19423/j.cnki.31-1561/u.2022.04.098.

Wellicome, J. F., and Wilkinson, S. , (1984). "Ship propulsive kites: an initial study". University of Southampton.

Werner, S., Nisbet, J., Hörteborn, A., Nielsen, R., (2021), “Speed trial verification for a wind assisted ship”, Proceedings of RINA International Conference on Wind Propulsion, London, UK.

Werner, S., Gerhardt, F., Santén, V., and Finnsgård, C., (2022a), “Wind Ship Research – How Science Can Support the Transition to Wind Powered Shipping,” Global Conference on Naval Architecture and Ocean Engineering, Changwon, Republic of Korea.

Werner, S., Nisbeth, J., Olsson, F. (2022b) "Speed trial methodology for wind assisted ships", 7th HullPIC Conf., Tullamore, pp.124-140, 2022.

Werner, S., Gerhardt, F., and Kontos, S., (2023) "Key Performance Indicators for Wind-Powered Ships", in the proceedings of RINA Wind Propulsion Conference 2023

Williams, P., Lansdorp, B. and Ruiterkamp R. (2008). "Modeling, simulation, and testing of surf kites for power generation". Proceedings of AIAA Modelling and Simulation Technologies Conference and Exhibit, Honolulu, Hawaii, USA.

Yang, K.K., Kim, Y.C., Kim, K.S., Kim, J., (2019). “RANS Analysis of Propeller Open Water Characteristics in Oblique Flow”, Proceedings of SNAK Autumn Conference (in Korean).

Yasukawa, H., Yoshimura, Y., (2015), “Intro-duction of MMG standard method for maneuvering predictions”, Journal of Marine Science and Technology, Vol. 20, pp 37 - 52.