WIND PROPULSION: OPERATION WITH HYDROKINETIC TURBINE ENERGY RECOVERY

C Greenhough[1], **RJ Pawling**[1] and **RWG Bucknall**[1]

ABSTRACT

Wind-assistance for ships has seen a resurgence of academic and commercial interest recently driven by stricter regulations on atmospheric pollution from their engines and encouraged by advancements in new wind-assistance technologies which can significantly reduce fuel consumption on many shipping routes. The power available from the wind is sporadic and does not necessarily match a ship's operational profile. Considering this, additional flexibility may be offered when capturing wind energy by combining wind-assistance and energy recovery, such as via the propeller acting as a hydrokinetic turbine with the generated output being connected to the ship's electrical power system. As such, during periods when the wind power exceeds the propulsion demand, the excess energy may be captured and stored. A wing kite and a fixed pitch propeller has been considered for a ship application, with different operational profiles applied under the assumption of a uniform distribution of wind headings. The thrust generated by the wing kite has been modelled together with ship resistance and propeller performance to characterise the potential for energy recovery. Without attempting any improvements to the propeller design, the results have indicated a good level of reduction in fuel consumption when using wind-assistance, which is significantly further improved using hydrokinetic energy recovery.

KEY WORDS

Wind-assistance; kinetic energy recovery; energy efficiency

INTRODUCTION

In the ever-changing geopolitical climate, reliance on foreign countries for energy is increasingly becoming conflicted with a nation's strategic interests. Governments are reliant on the energy provided by other nations to support their own military, and the volatility of oil prices, reliance on individual or small groups of nations, and reducing oil reserves make this model of energy unsustainable in the long run (O'Rourke, 2006). It is therefore desirable for the military to operate in a leaner energy fashion, minimising oil requirements as much as possible and increasing the use of domestic and renewable energy sources (Gougoulidis, 2015).

The Royal Navy is increasingly conducting Operations Other Than War (OOTW), such as patrols, counter-piracy and counter-smuggling, humanitarian aid, and escorts. While the necessity still exists to be able to operate in a high-threat situation, these non-war-fighting scenarios allow the ships to operate in a greener, more eco-friendly and fuel-efficient manner.

Of the many options for energy efficiency technologies, wind power is often shown to have significant benefits to ships (Buckingham, 2010; Pawling et al., 2016). It has seen a resurgence of interest, similar to that seen in the 1970/80's, then caused by an oil embargo with the middle east, and today caused by growing concern for climate change. Where commercial vessels generally have well defined and relatively simple operational profiles, and possibly have the autonomy to alter course slightly if it offers a cheaper overall transit, naval vessels must remain prepared for high-threat situations and must often place tactical and strategic goals above fuel efficiency. The integration of wind-assistance may therefore be more easily facilitated in a naval vessel by offering additional flexibility in the manner in which it can be operated. To this end, hydrokinetic energy recovery may offer a way to compound the benefit provided by wind assistance, by allowing excess wind energy to be harnessed and stored for later use. This would be achieved by operating the propeller as a turbine when wind conditions are favourable, thereby allowing the propulsion system to generator power and maximise the benefit of the wind when suitable.

Figure 1 shows a mock-up of the intended solution, in this case using a commercially available wing kite (SkySails, n.d.) on a Type 45 Destroyer (Shipbucket, 2018), and indicating the bi-directional flow of mechanical power at the propeller. The purpose

[1] University College London

of this study is to investigate how such a solution of using hydrokinetic energy recovery can allow conventional warship propulsion systems to be supplemented by wind-assistance to improve energy efficiency.

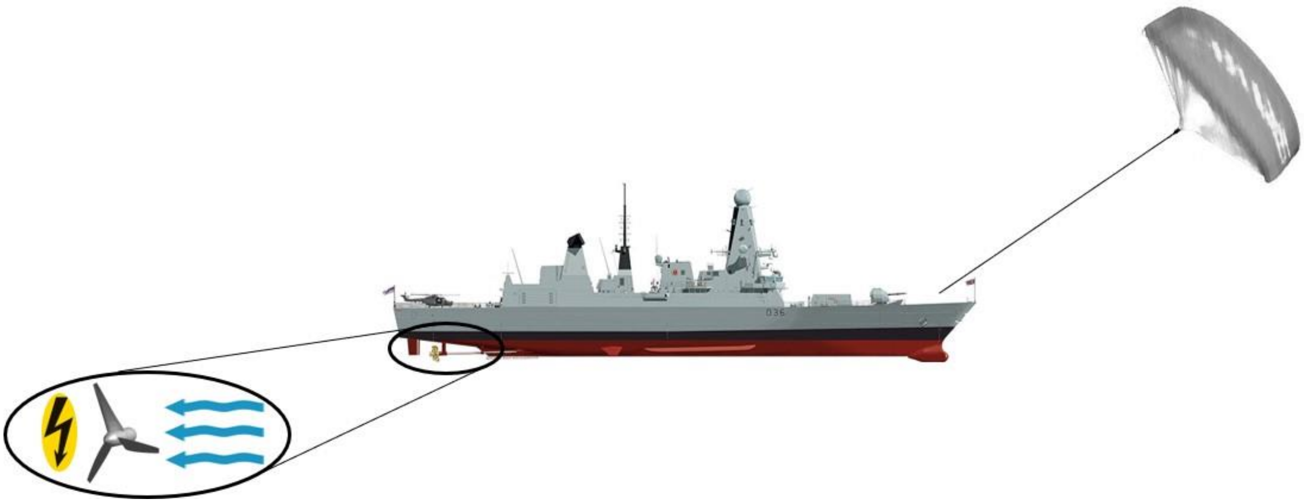

Figure 1 - Mock-up of Wind Assisted Warship with Hydrokinetic Turbine

WIND POWER

Available wind power is proportional to three things: the apparent wind speed relative to the device, the characteristic size of the device, and the efficiency of the device. The apparent wind speed is a function of true wind speed and induced wind speed and is shown in Figure 2. What can be observed from Figure 2 is that as the ship velocity increases, and therefore so does the induced wind, the apparent wind velocity will also change.

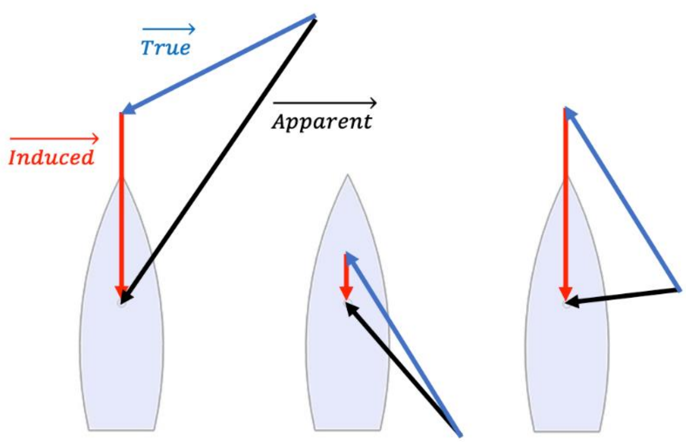

Figure 2 - Various Apparent Wind Vector Diagrams

Wind-assistance devices have a number of impacts on any ship, with some of these impacts being more significant in a military vessel. Perhaps the most significant of these is the deck space requirement, as the top deck of a warship is a tightly packed ecosystem, with the risk of interference with weaponry arcs-of-fire, VLS missile launches, and radar coverage all adding additional requirements to the design. Further issues specific to warship design include the visual and radar signature associated with most wind-assistance devices, and the high likelihood of disturbed wind flow such that flight ops (including UAVs) are put at risk or rendered impossible.

The four main types of wind-assist device are wind turbines, wing kites, wingsails, and Flettner rotors, of which kites eliminate many of the survivability issues associated with wind-assist devices. Wing kites are large parafoils, on the order of up to hundreds of square metres in size, which are anchored to the bow of the ship and operate at over 100m in the air, exploiting the generally higher and less turbulent wind speeds found at greater altitudes. They have a cross-sectional area similar to that of an aerofoil and with the same operating principle, forcing air to flow faster over one side than the other, thereby producing lift, which is transferred via a tether to the ship to provide additional thrust.

They are fully retractable when not in use and require a proportionally smaller deck area than other devices, making them particularly suitable for a warship design, where deck area and signatures are key drivers in design. The fact that they operate at such high altitudes may offer the additional benefit of allowing its' presence to deter illegal activity in far greater areas, which may be suitable for counter-drug/counter-piracy operations. This high operating altitude also poses the additional benefit to potentially increase sensor range, as demonstrated by a collaboration between SEAI and the Irish Naval Service, whereby a relatively modest sized kite is installed to supplement propulsion, while also carrying a number of sensors to facilitate beyond-the-horizon monitoring capabilities (Colm Gorey, 2015).

As the tether cannot support a bending moment, there is no impact on ship stability when using a kite, and since the tether attaches to the ship in the same place that a ship tow would be attached, there are no additional structural requirements. The length of the tether permits operation far above the deck, meaning there is much less risk of equipment interference and the impact on flight ops should be minimal, though it would still be necessary to consider the presence of the tether, as collision could be catastrophic, especially for smaller UAVs.

A drawback of kites is that they are known to have a narrower envelope of suitable wind directions compared to Flettner rotors and wingsails, though when the wind is in the ideal direction, they are able to provide the highest amount of thrust for a given deck space envelope. It is unclear at this stage if a greater maximum thrust or greater range of suitable wind headings will provide a greater overall benefit to a warship, however considering the characteristics and impacts of wing kites, the study herein assumes a wing kite design is implemented as the wind assist device for the nominal ship design.

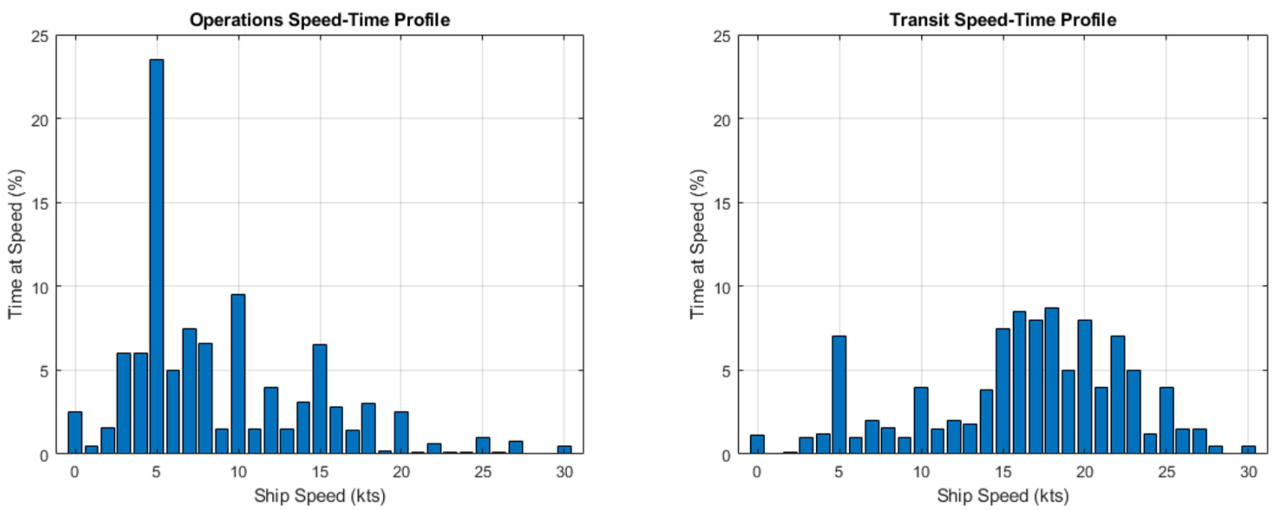

Figure 3 - Operations (left) and Transit (right) Arleigh-Burke Time-Speed Profiles (Smith et al., 2013)

Figure 3 shows ship operational profiles during both operations and transit, as presented by (Anderson, 2013), whereby the operational profile of the Arleigh-Burke Class of the US Navy was investigated. Of particular note is that these warships spend a significant portion of their time at sea at lower speeds, approximately 46% of the time below 8 knots. As noted by Smith et al. (Smith et al., 2013), potential fuel savings are a function of ship speed: the slower the ship transits, the greater fuel savings can be made when compared to the same ship transiting at the same speed but without wind assistance. Considering this suggests that naval vessels may be well suited to wind-assistance based on their operational profile.

It is not clear if self-noise was a concern for the ship at each data point, but there are often times where slow speeds are accompanied by a requirement for a low acoustic signature, which makes wind propulsion a very attractive option. In the case of conducting an Anti-Submarine Warfare (ASW) mission, the reduction of self-noise generated by prime movers and propulsion machinery through the use of wind propulsion could benefit the mission. However, it is noted that even if the conventional propulsion system can be switched off under wind power, there is still the need to provide the service load, which would require prime movers to be running, or have power provided by energy storage, which would be limited in duration.

HYDROKINETIC ENERGY RECOVERY

Hydrokinetic turbines are seeing increasing use in rivers and tidal streams, as they offer a renewable energy source in low-head locations and with minimal environmental impact when compared to hydroelectric dams, which can disrupt flow and local ecosystems(Güney & Kaygusuz, 2010; Khan et al., 2009).

Figure 4 - Example Hydrokinetic Turbine at Low-tide (Quaranta, 2020)

While most instances of hydrokinetic turbines are stationary applications, there are gadgets on the market for smaller sailing vessels. These Commercial-Off-The-Shelf (COTS) products are small turbines designed to be dropped over the stern and dragged for electrical power to provide a few amps of current to support charging of batteries and to power various electronics on board (Nicholson, 2003; WaterLily, 2019).

Concept studies looking at attaching purpose-built turbines to vessels to harvest wind energy typically do not focus on propeller dynamics at all, while the turbine is often modelled by predicting the power coefficient based on blade geometry (Kim & Park, 2010; Ouchi & Henzie, 2017; Terao & Sakagami, 2014). Julia (Julià, 2019) looks at a dual-mode propeller/turbine, also predicting turbine power coefficient based on geometry, however modelling propeller dynamics in propulsion mode by using propeller series data. This disjoint in propulsion/regeneration modelling is avoided by Apsley (Apsley et al., 2007) by using multi-quadrant propeller series data throughout the operating range to understand potential for recovering kinetic energy during a crash stop for a naval vessel instead of an energy producing ship. Series data is useful for such studies as only the torque and thrust are needed to understand the power performance of the propeller, there is less need for a more detailed understanding of flow characteristics.

INITIAL INVESTIGATION

The initial investigation is focussed on developing a model representative of a wind-assisted ship with a dual-mode propeller/turbine to understand the benefit of combining wind-assistance and energy recovery. This will be achieved by developing MATLAB models to represent the ship, propeller, and kite characteristics, based on mathematical models of each. The models will then be combined and have a typical operational profile applied to draw early conclusions of the possible benefit of the concept.

Ship Resistance

The focus of this study is not hull design, nor is the model intended to eliminate generality, therefore it is deemed acceptable to use a basic resistance model which is not strictly based on an existing design. Instead, it shall be indicative of a typical surface combatant, in this case the US Navy Combatant DTMB 5414 unclassified design, shown in Figure 5, similar to the hull form of the in-service DDG-51(Simman, 2008). The ship particulars are shown in Table 1. These were used with the UCL in-house Ship Resistance Calculator, based on a simplified Holtrop Regression Formula, to provide a bare hull resistance estimate, and the predictions are commensurate with ships of a similar size and design.

Table 1 - Ship Characteristics

Characteristic	Value	Units
Length	142	*m*
Beam	19	*m*
Draught	6.15	*m*
Block Coefficient	0.507	-
Prismatic Coefficient	0.618	-
Displacement	8500	*te*

Figure 5 - US Navy Combatant DTMB 5414 Hullform (Simman, 2008)

Propeller Modelling

Design details of current state-of-the-art propellers are proprietary, and in the case of military vessels it is considered sensitive, meaning that performance data and detailed geometry is not publicly available. As such, the standardised Wageningen propeller series data is used for this study.

Table 2 shows the propeller geometry characteristics used for this study. The characteristics are based on the design used by FORCE Technology for manoeuvring tests in model scale of the DTMB 5415 hull form (Simonsen, 2004), however the diameter is set to 6.15m, in line with the DTMB 5415 design. The FORCE Technology tests also use a blade area ratio of 0.58, however owing to the limited data available for the multi-quadrant propeller series, the value used here is 0.7. It should be noted that the FORCE Technology tests used a propeller with 4 blades, while the DTMB 5414 design assumes a 5 bladed propeller, however the number of blades is known to have less of an impact on propeller performance (Carlton, 2012).

Table 2 - Propeller Characteristics

Characteristic	Value	Units
Blade Number	4	-
Blade Area Ratio	0.7	-
Pitch/Diameter Ratio	1.4	-
Diameter	6.15	*m*

The advance angle, β, represents the relative speed of the propeller and the ship and is defined by Equation [1], where V_a is the ship speed of advance, and N and D are the propeller rotation frequency and diameter, respectively. The torque and thrust coefficients, $C_{Q,T}$, are defined using Equation [2], where $A_{Q,T}$ and $B_{Q,T}$ are coefficients read from a lookup table for the K^{th} term of a Fourier series describing the propeller characteristics.

$$\beta = \tan^{-1} \frac{V_a}{0.7\pi ND} \quad [1]$$

$$C_{Q,T} = \sum_{K=0}^{m} \{A_{Q,T}(K)\cos(\beta K) + B_{Q,T}(K)\sin(\beta K)\} \quad [2]$$

The torque and thrust coefficients can be used to calculate the propeller torque and thrust using Equations [3] and [4], respectively, where ρ is the density of seawater, A_0 is the blade disc area, and V_r is the relative advance velocity, defined by Equation [5].

$$C_Q = \frac{Q}{\left(\frac{1}{2}\right)\rho V_r^2 A_0 D} \quad [3]$$

$$C_T = \frac{T}{\left(\frac{1}{2}\right)\rho V_r^2 A_0} \quad [4]$$

$$V_r^2 = V_a^2 + (0.7\pi ND)^2 \quad [5]$$

Kite and Wind Model

The kite model is based on the zero-mass model developed by Wellicome & Wilkinson (Wellicome & Wilkinson, 1984) and implemented later by Dadd (Dadd, 2013).The model does not consider the kite position vector changing with time, rather it assumes the onset velocity vector changes to account for the varying kite and ship speeds. It therefore provides a prediction for onset velocity based on flight trajectory, aerodynamic characteristics, and wind condition, without considering the time domain and assuming gravity and inertial effects are negligible compared to aerodynamic forces and that the tether is straight. Because the kite and tether are assumed massless the system will find equilibrium instantaneously and the net aerodynamic and tether forces remain collinear. Reynolds number effects have also been neglected. The zero-mass model allows the onset velocity of the kite to be predicted according to Equation [6], based only on the kite position, apparent wind speed relative to the ship, and the drag angle of the kite, assuming constant aerodynamic properties during flight.

$$U = V\left(\frac{\cos(\theta)\cos(\phi)}{\sin(\epsilon)}\right) \quad [6]$$

It is assumed the kite path sits on the surface of the flight envelope and can be thought of as the intersection of a cone extending from the kite attachment point on the ship and a sphere with a radius equal to the tether length, centred at the anchor point of the kite to the ship. The trajectory is defined by the average elevation angle and the maximum deviations of the azimuth and elevation angles of the tether from the average position.

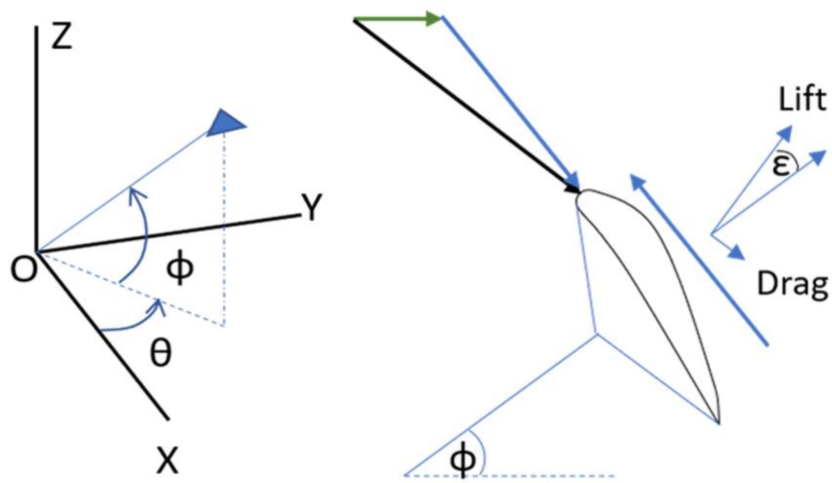

Figure 6 - Kite Coordinate System (left) and Vector Diagram (right)

Owing to boundary layer effects, at higher altitudes there are greater wind speeds and so in general it is beneficial to operate kites as high as possible to maximise line tension. However, in the case of a towing kite the only useful component of line tension is that which acts in the direction of ship motion, meaning that a generally lower elevation angle is ideal. The true wind speed is assumed to vary with altitude according to the logarithmic law as shown in Equation [7].

$$TWS_{h_n} = TWS_{h_{10}} * \frac{\log\left(\frac{h_n}{z_0}\right)}{\log\left(\frac{10m}{z_0}\right)} \quad [7]$$

Figure 7 shows the relative thrust experienced by the ship depending on elevation angle, where relative thrust is defined as the ratio of thrust at a given elevation angle to the thrust at the ideal elevation angle. Based on the change of wind speed with altitude defined in [7], it can be seen that maximum thrust is achieved at an elevation angle of approximately 20 degrees, while increasing the elevation angle reduces the amount of line tension acting in the direction of ship motion.

The kite characteristics are shown in Table 3. They are based on the experimental set up provided by Dadd (Dadd et al., 2010) and represent a mid-size design based on options available from SkySails (SkySail, 2018; SkySails, n.d.).

Table 3 - Kite Characteristics

Characteristic	Value	Units
Kite Area	320	m^2
Tether Length	350	*m*
Lift Coefficient	0.776	-
Drag Angle	9.55	*degrees*

A Weibull distribution has been used to represent the true wind speed distribution. For the purposes of this study the wind direction is assumed to have a uniform distribution, however it is noted that this would not be case in a real-world scenario, partly owing to the fact that the ship may follow particular routes more than others, and also owing to the fact that in higher wind speeds the ship must align with the wind to avoid excessive roll and broadside wave strikes, which will skew the wind direction relative to the ship (Ship Structure Committee, 1999). Equation [8] shows the formula for the Weibull distribution, where the probability of wind speed V_w is a function of the shape factor, k, and scale factor, c.

$$f(V_w; k, c) = \left(\frac{k}{c}\right)\left(\frac{V_w}{c}\right)^{k-1} e^{-\left(\frac{V_w}{c}\right)^k} \quad [8]$$

Selecting appropriate values for the Weibull distribution is of significant importance because the energy consumption when using wind-assist is very sensitive to the assumed wind conditions. For this study, the shape and scale factors used are 2 and 10, respectively. The parameters are based on a prediction method provided by Mao and Igor (Mao & Rychlik, 2017) and are relevant to the Pacific Ocean as an average of the year. Different regions will have different parameters and these values will change depending on the time chosen.

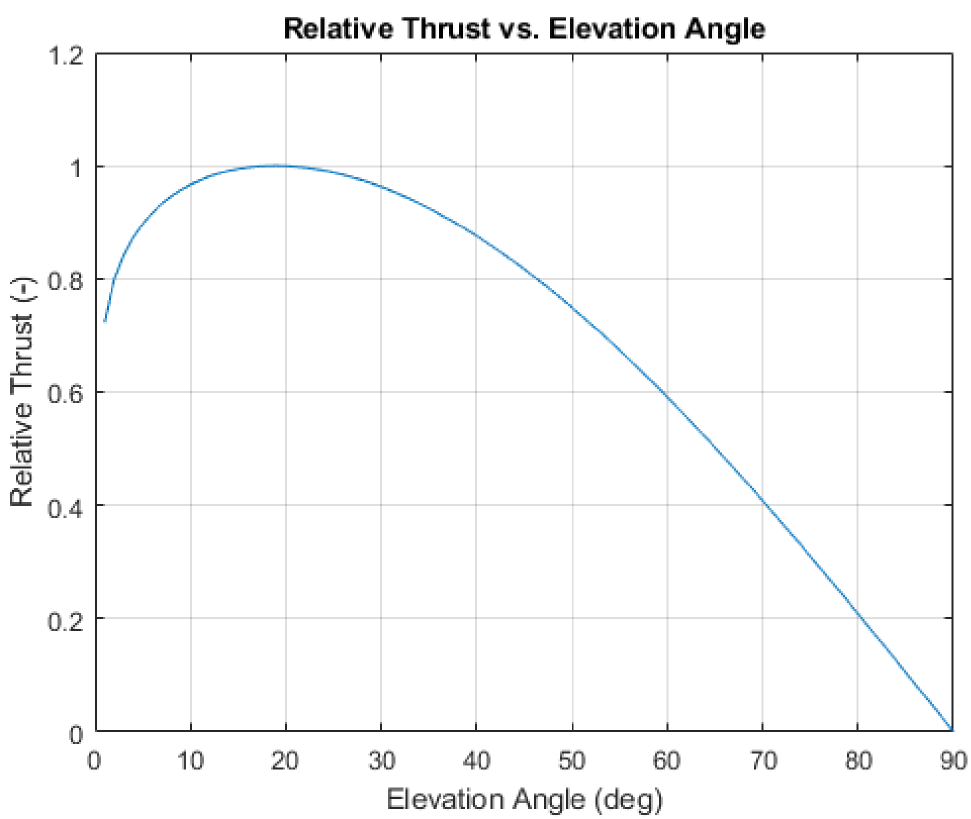

Figure 7 - Relative Thrust vs. Elevation Angle

Results - Propeller Power

Figure 8 shows the power/speed curve for the energy recovery condition. The figure shows the mechanical power either consumed or provided at the propeller when the true wind comes from directly astern and in winds speed of 0 to 20 m/s in steps of 5 m/s. Of note is the 'regeneration zone' observed in Figure 8, whereby the propeller power is negative, indicating reverse power flow as the propeller is acting as a turbine. The magnitude of the reverse power flow increases to a maximum at a different ship speed for each wind speed, above which, the reverse power flow reduces until the propeller begins acting in a propulsion mode and sending power into the water.

Results - Energy Consumption

Figure 9 shows the relative energy consumption over the operational profile, based on the information shown in Figure 3. The energy consumption of the baseline ship with no wind assistance is compared to the scenario of using wind-assistance only, and to the use of energy recovery.

The benefit of using wind-assistance is most significant at lower speeds, as it can be seen the energy consumption reduces with the use of wind-assistance, with the effect reducing above approximately 15 knots. The use of energy recovery further reduces energy consumption, more so at speeds up to 18 knots, though with reducing effect at higher ship speeds. Above 18 knots there is no discernible difference between the wind-assist only and energy recovery conditions.

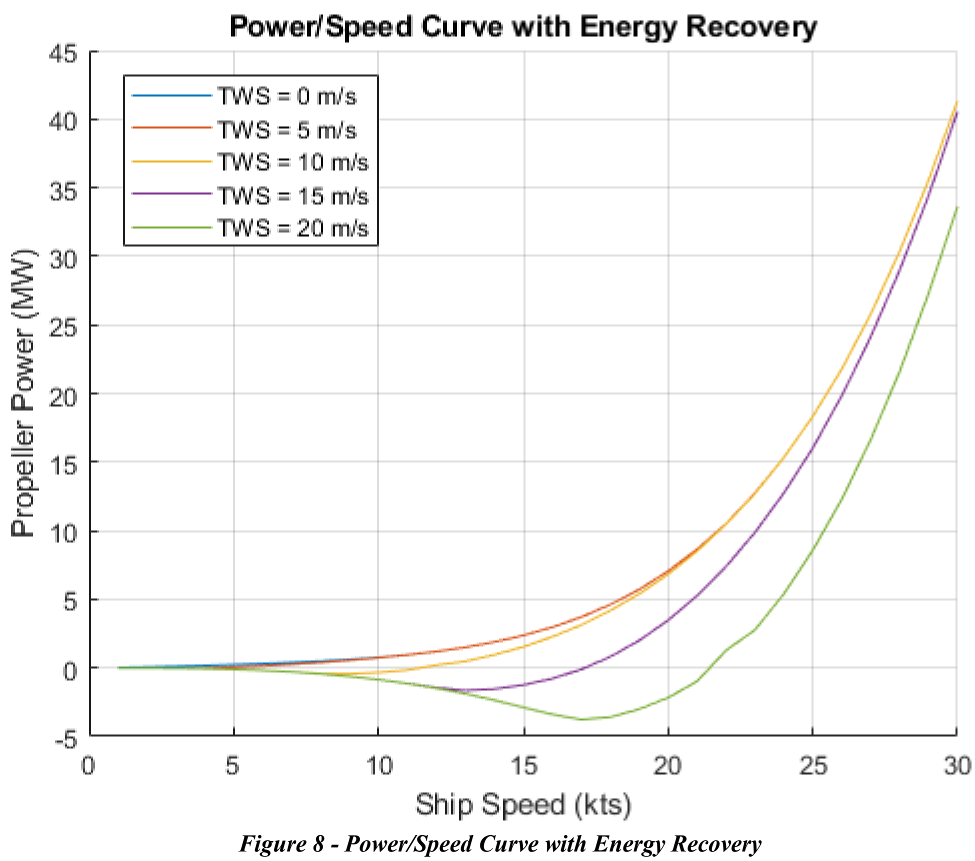

Figure 8 - Power/Speed Curve with Energy Recovery

Figure 9 assumes that the ship travels at exactly the speed demanded based on the original operational profile, however, as can be seen in Figure 8, transiting faster in higher wind speeds allows increased reverse power flow in some conditions. In a real-world scenario it is unlikely for a ship to transit slower when it would be beneficial to go faster (unless flow noise is a concern, for example). As such, it is interesting to understand the benefit if the ship makes full use of available wind energy. Figure 10 shows the relative energy consumption under this more relaxed operating philosophy, whereby the ship is allowed to transit faster if it reduces energy consumption to do so. As with the original profile, the impact of wind-assistance is more prominent at lower speeds, decreasing gradually at higher speeds. The additional use of energy recovery at lower speeds produces a net production of energy for 1, 2, 3, and 4 knots. The additional impact of energy recovery over wind-assist reduces at higher speeds, becoming almost identical at 21 knots and above.

Table 4 - Reduction in Energy Consumption

	Original Philosophy	Relaxed Philosophy
Wind-Assist Only	5.86%	6.14%
Energy Recovery	7.17%	10.26%
Improvement w/ HKER	+22.35%	+67.10%

The change in energy consumption in the various conditions is summarised in Table 4. The use of energy recovery improves the wind-assist only energy reduction by 22.35% using the original profile, and by 67.10% using the modified profile.

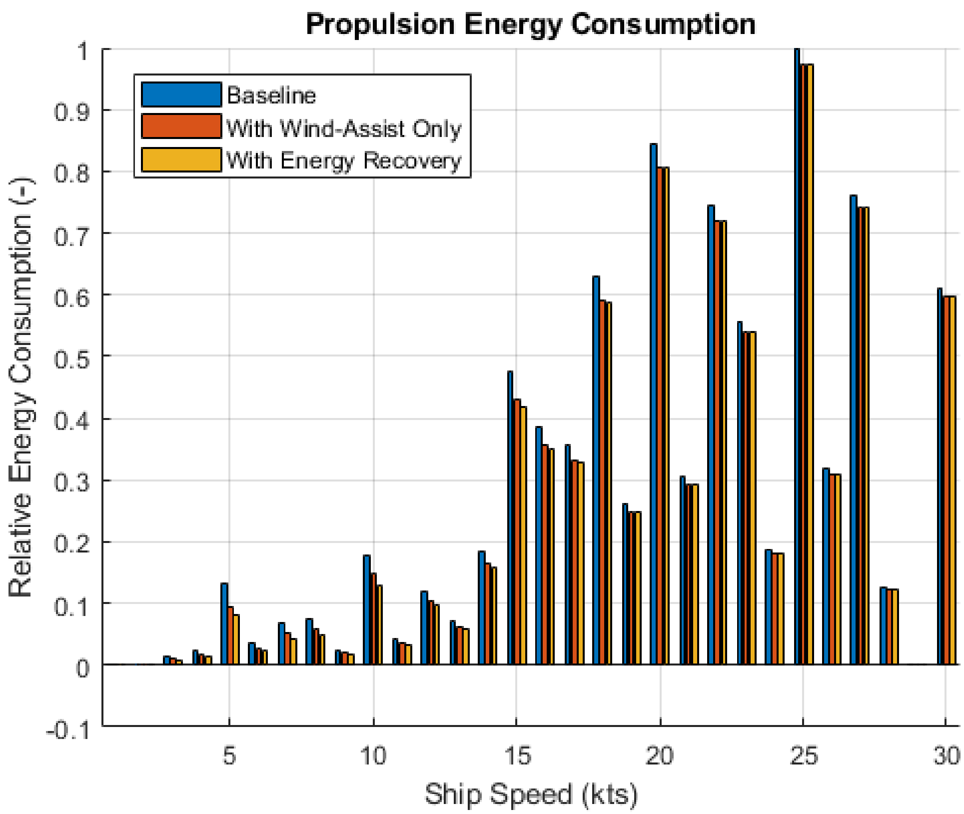

Figure 9 - Energy Consumption – Original Philosophy

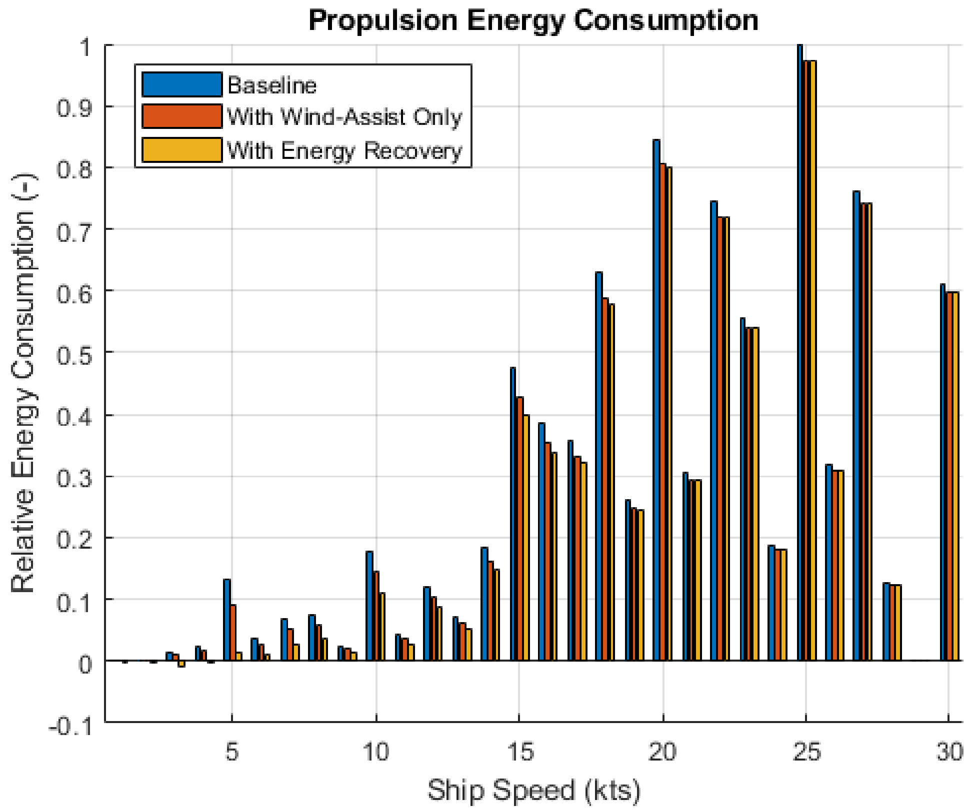

Figure 10 - Energy Consumption – Relaxed Philosophy

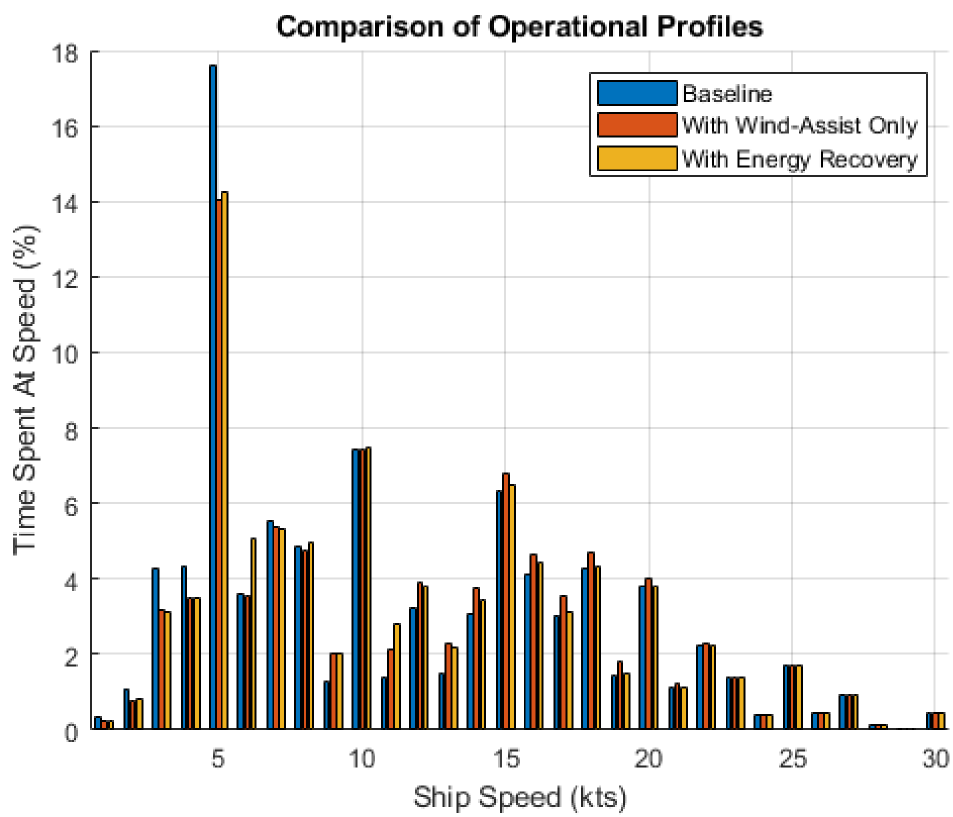

Figure 11 - Comparison of Operational Profiles

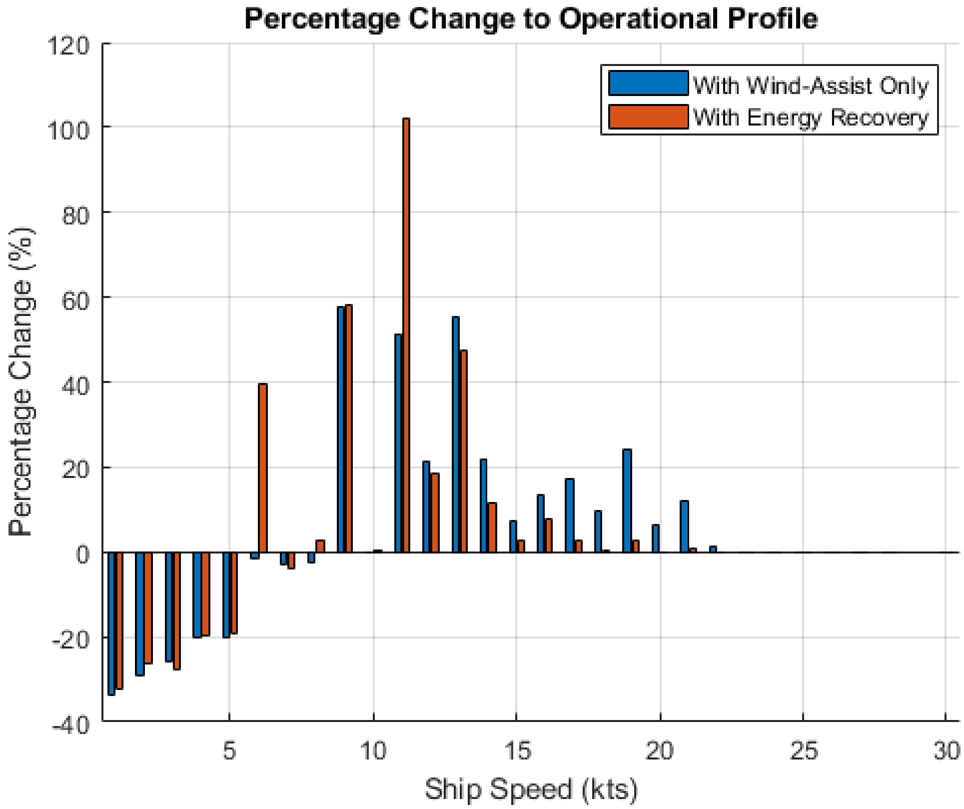

Figure 12 - Percentage Change to Operation Profiles

IMPACT ON SHIP OPERATIONS

Figure 11 shows how the operational profile would change if a minimum speed requirement were adopted rather than an exact speed requirement, for wind-assist and energy recovery. Figure 12 shows the percentage change of time spent at each speed for both wind-assist and energy recovery.

The average speed increases in both cases, with time spent at ship speeds 1 - 5 kts all decreasing. The wind-assist only condition sees a greater occurrence of higher ship speeds, above 12 kts, than the energy recovery condition.

For the wind-assist only condition, the propeller provides minimal reverse thrust to the overall force balance, resulting in an increase in ship resistance to counteract the kite thrust, and therefore a higher ship speed. In the case of the energy recovery condition, the propeller provides considerable reverse thrust while taking energy out of the water, meaning that, for a given kite thrust, the ship will travel slower.

This poses an interesting challenge in terms of operation of the ship and propeller/turbine. This is best highlighted by considering Equation [9] which shows turbine power is proportional to the cube of the ship speed, where C_p is the power coefficient and V_s is the ship speed. This concept herein differs drastically from normal turbines, as the presence of the turbine actually has an impact on the free stream velocity of the fluid within which the turbine acts. Whereas typical hydrokinetic turbine installations will impact the local fluid velocity, the free stream velocity is governed by the tide or river. In this mobile turbine application, the greater the power drawn from the turbine, the greater the proportion of reverse thrust applied by the propeller and therefore the slower the ship is capable of sailing, for a given propeller geometry. There therefore exists a trade-off between maximum ship speed while the propulsion is provided entirely by the wind device, and the maximum reverse power from the propeller.

$$P_{turbine} = \frac{1}{2} C_p \rho A_t V_s^3 \qquad [9]$$

Considering Equation [9] again also highlights the effect of propeller geometry on turbine performance. The power coefficient describes the efficiency of the turbine at converting the kinetic energy of the fluid flow into mechanical energy at the turbine, and is known to be a function of the turbine geometry and the tip speed ratio (Narasimalu & Chellaiah, 2017; Nigam et al., 2017), which therefore highlights the impact of propeller design and blade angle on the power coefficient.

The initial results have indicated that the propeller acts very inefficiently in turbine operation, with the magnitude of the reverse power flow being much smaller than the magnitude of forward power flow when in propulsion operation. This is in agreement with observations made by Apsley (Apsley et al., 2007) and is a consequence of the fact that the blades are designed for propulsion, meaning the majority of the lift generated by the blade is in the direction of ship speed. However, the propeller will act most effectively as a turbine when lift is being generated in the direction of propeller rotation, as this will equate to maximum power take off for a minimal impact on ship speed. Operating in a more efficient turbine mode would require a rotation of the blades about the propeller hub, i.e. with the use of a controllable pitch propeller. Multi-quadrant propeller series data does not publicly exist to characterise propeller performance in this condition.

CONCLUSION

The study herein implemented propeller series data in a novel application to predict propeller performance when acting as a turbine in a wind-assisted ship. The ship resistance model has been based on a nominal warship design and a kite has been assumed as the wind assist device, allowing the propeller to generate reverse power flow under the right conditions.

The wind model has assumed uniform distribution of wind headings; however, this assumption can be improved upon by considering likely ship headings taken in strong winds. It may be worth investigating how sensitive energy recovery is to wind heading and investigating if reasonably small operational changes could have a significant impact on energy consumption.

The investigation thus far has demonstrated that wind assistance offers significant energy savings, especially to a warship owing to their operational profile. This is further improved, and by a significant factor, with the use of energy recovery, even with no changes made to ship operations. If operations can be altered, i.e. by changing ship speed or heading, the benefits of both wind assistance and especially energy recovery can be greatly improved.

REFERENCES

Anderson, T. J. (2013). *Operational Profiling and Statistical Analysis of Arleigh Burke-Class Destroyers*.

Apsley, J. M., Villasenor, A. G., Barnes, M., Smith, A. C., Williamson, S., Schuddebeurs, J. D., Norman, P. J., Booth, C. D., Burt, G. M., & Mcdonald, J. R. (2007). Evaluation of reverse power flow in electric propulsion drives. *Aes*.

Buckingham, J. (2010). Finding the right technologies to reduce fuel consumption. *RINA, Royal Institution of Naval Architects - Ship Design and Operation for Environmental Sustainability - Papers*, *January 2010*, 115–126.

Carlton, J. (2012). *Marine Propellers and Propulsion* (Third). Elsevier.

Colm Gorey. (2015). New Irish-developed smart kite will power ships with renewable energy. *Silicon Republic*.

Dadd, G. M. (2013). *Kite dynamics for ship propulsion*. 215.

Dadd, G. M., Hudson, D. A., & Shenoi, R. A. (2010). Comparison of two kite force models with experiment. *Journal of Aircraft*, *47*(1), 212–224. https://doi.org/10.2514/1.44738

Gougoulidis, G. (2015). Energy-saving Measures for Naval Operations. *6th Annual NMIOTC Conference 2015 Current and Future Challenges to Energy Security in the Maritime Environment*, *February*, 1–8.

Güney, M. S., & Kaygusuz, K. (2010). Hydrokinetic energy conversion systems: A technology status review. *Renewable and Sustainable Energy Reviews*, *14*(9), 2996–3004. https://doi.org/10.1016/j.rser.2010.06.016

Julià, E. (2019). *Concept development of a fossil free operated cargo ship*.

Khan, M. J., Bhuyan, G., Iqbal, M. T., & Quaicoe, J. E. (2009). Hydrokinetic energy conversion systems and assessment of horizontal and vertical axis turbines for river and tidal applications: A technology status review. *Applied Energy*, *86*(10), 1823–1835. https://doi.org/10.1016/j.apenergy.2009.02.017

Kim, J., & Park, C. (2010). Wind power generation with a parawing on ships, a proposal. *Energy*, *35*(3), 1425–1432. https://doi.org/10.1016/j.energy.2009.11.027

Mao, W., & Rychlik, I. (2017). Estimation of Weibull distribution for wind speeds along ship routes. *Proceedings of the Institution of Mechanical Engineers Part M: Journal of Engineering for the Maritime Environment*, *231*(2), 464–480. https://doi.org/10.1177/1475090216653495

Narasimalu, S., & Chellaiah, B. (2017). Pitch angle control for Horizontal axis wind turbine: A comparative study. *2017 Asian Conference on Energy, Power and Transportation Electrification, ACEPT 2017*, *2017-Decem*, 1–6. https://doi.org/10.1109/ACEPT.2017.8168546

Nicholson, D. (2003). No Title. *PracticalSailor*. https://www.practical-sailor.com/systems-propulsion/electrical/towed-water-generator

Nigam, S., Bansal, S., Nema, T., Sharma, V., & Singh, R. K. (2017). Design and Pitch Angle Optimisation of Horizontal Axis Hydrokinetic Turbine with Constant Tip Speed Ratio. *MATEC Web of Conferences*, *95*. https://doi.org/10.1051/matecconf/20179506004

O'Rourke, R. (2006). Navy Ship Propulsion Technologies: Options for Reducing Oil Use - Background for Congress. *Defense*. https://www.fas.org/sgp/crs/weapons/RL33360.pdf

Ouchi, K., & Henzie, J. (2017). Hydrogen Generation Sailing Ship. *Ieee*, 1–5.

Pawling, R., Suarez de la Fuente, S., & Andrews, D. (2016). *THE POTENTIAL USE OF ENERGY SAVING TECHNOLOGIES IN FUTURE PATROL COMBATANTS*. *June*, 15–16.

Ship Structure Committee. (1999). *SEA OPERATIONAL PROFILES FOR STRUCTURAL RELIABILITY*.

Shipbucket. (2018). *Destroyer Type 45 (Daring Class)*. http://shipbucket.com/forums/viewtopic.php?f=12&t=9081

Simman. (2008). *US Navy Combatant, DTMB 5415*. http://www.simman2008.dk/5415/combatant.html

Simonsen, C. (2004). *PMM model test with DDG51 including uncertainty assessment*.

SkySail. (2018). *TOWING KITE TECHNOLOGY*.

SkySails. (n.d.). *Kite drive for yachts*.

Smith, T., Newton, P., Winn, G., & Grech La Rosa, A. (2013). Analysis techniques for evaluating the fuel savings associated with wind assistance. *Low Carbon Shipping Conference*, 1–13.

Terao, Y., & Sakagami, N. (2014). A feasibility study on the ocean higher altitude strong wind energy utilization system. *Oceans 2014 - Taipei*, 1–7. https://doi.org/10.1109/OCEANS-TAIPEI.2014.6964357

WaterLily. (2019). No Title. *WaterLiliyTurbine*.

Wellicome, J. F., & Wilkinson, S. (1984). *Ship Propulsion Kites: An Initial Investigation*.